Novel Multi-Wavelength Semiconductor Lasers

by

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Abstract

The technique of wavelength division multiplexing (WDM) is currently attracting considerable interest from the telecommunications and computer industries alike as a means both for increasing the transmission rates of existing fiber-optic links and for attaining enhanced flexibility in future optical networks. Studies of WDM systems have indicated the need for a single-output multi-wavelength laser source whose wavelengths can be controlled to within a small fraction of the inter-channel spacing. Furthermore, a monolithically integrated laser source realized by simple processing techniques would, due to robustness and reduced packaging costs, make WDM a more economically viable option.

This thesis describes the design, fabrication and characteristics of a new type of monolithically integrated semiconductor laser, the multi-stripe array grating integrated cavity (MAGIC) laser, that gives simultaneous multiple wavelength laser emission from a single output port. Each emission wavelength may be independently selected from a comb of "allowed" operating wavelengths that are precisely set at the fabrication stage. The laser is best suited to wavelength spacings >1nm and may be fabricated in different materials systems for operation in different wavelength ranges. This thesis is primarily concerned with fabrication in the InGaAsP/inP materials system for operation in the 1.5μm communication band.

A prototype version of the MAGIC laser has been fabricated; it emits 15 different wavelengths spaced at ~2nm intervals over a ~30nm range around 1.5μm. The spacing is constant to within 0.03nm, the highest as-fabricated wavelength linearity so far recorded for a monolithic multi-wavelength laser source. Absolute wavelength accuracy is ~2nm; exact coincidence with design values may be obtained by temperature tuning the laser mount (0.11nm/°C sensitivity).
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My research was conducted within the context of a group project; I would therefore like to thank my co-workers at Bellcore and, since much of their work is described in this thesis, to identify the aspects of the project for which they were wholly or partly responsible. The research concerns the development of a new type of semiconductor laser; the various stages of development can be roughly categorized as follows:- 1) coming up with the basic device concept, 2) designing the device, 3) developing new processing technologies, 4) fabricating the device and 5) assessing the device's performance. I shall outline the roles played by myself and my co-workers in each of these five categories.

1) Device concept - a bulk-optic multi-wavelength laser comprising a broad-band optical amplifier, an external grating cavity and an array of reflective spatial light modulators has been reported in the literature by Dr. I. H. White of the University of Bath, while a monolithically integrated version of that device was proposed in the literature by Dr. P. A. Kirkby of BNR (Europe) Ltd, Harlow, UK (see Chapter 4 for details and references). Dr. J. B. D. Soole and myself jointly proposed a device that consists of an array of laser amplifiers monolithically integrated with a diffraction grating and a passive output waveguide.
2) Device design - there are a number of different aspects to device design. The first stage is to design the semiconductor layer structure. This includes specification of both the processing techniques that are used to fabricate the device and the order in which they occur in the processing sequence. The layer structure that is described in Section 5.2 was chosen jointly by myself and by Dr. J. B. D. Soole following numerical and experimental evaluations of several different structures (these evaluations, performed mainly by myself, are not described in the thesis). I would like to thank Dr. R. J. Deri (who has since taken up a position at the Lawrence Livermore National Laboratory) for allowing us to use his mode-calculation software and Dr. C. Chang-Hasnain (who has since taken up a position at Stanford University) for an earlier multi-layer design. The next stage in the design process is to specify the device's geometrical layout; the detailed discussion of geometrical design principles that is given in Chapter 6 is my own unaided work. The final stage is to transfer the design onto photomasks; this was achieved by drafting the layouts on a CAD system and by then sending the designs to a commercial photomask manufacturer. The design and procurement of new photomasks was also my responsibility.

3) Development of new processing technologies - fabrication of the laser involves the use of a novel semiconductor etching technique known as chemically assisted ion-beam etching (CAIBE). Dr. A. Scherer built the etching system and operated it until early 1993 when he left to take up a position at Caltech; operation of the etching system was subsequently taken over by Mr. N. C. Andreadakis. The masking technique that is used for the CAIBE etch was devised jointly by Dr. A. Scherer and by Dr. J. B. D. Soole. The other processing techniques are all fairly standard. Despite this, a number of tests were conducted in order to gain information on processing issues such as chemical etch rates and etch profiles; these tests were performed by Dr. J. B. D. Soole, Mr. H. P. LeBlanc and myself.
4) Device fabrication - fabrication of the laser, described in Section 5.3, involves two stages of material growth and a number of intermediate processing steps. The material was grown by Dr. R. Bhat, Dr. C. Caneau and Mr. M. A. Koza. Dr. R. Bhat was primarily responsible for the initial stage of growth, while Dr. C. Caneau was primarily responsible for the semi-insulating InP regrowth. All processing, with the exception of the CAIBE etch, was done by Dr. J. B. D. Soole and Mr. H. P. LeBlanc.

5) Evaluation of device performance - the assessment of our first prototype laser, described in Section 7.2, was performed by myself, while the preliminary assessment of a new design, described in Section 7.3, was started by myself and continued by Dr. J. B. D. Soole after I left Bellcore.

There are many people to whom I am grateful for making the past three years such a memorable, enjoyable and fruitful time. I would like to thank some people in particular.

I am especially grateful to Dr. J. B. D. Soole whose assistance and encouragement, both inside and outside work, has extended well beyond the call of duty. He has provided both the opportunity and the support that has been necessary for me to complete my thesis.

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Dr. E. P. O'Reilly acted as my supervisor while Professor A. R. Adams was on sabbatical leave and helped greatly in my dealings with the SERC.

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Finally, I would like to thank my parents for continuing to encourage me in my studies and for providing moral and financial support when necessary.
Publications

Much of the work that is presented in this thesis has previously been published in journals and conference proceedings. A list of relevant publications is given below.

Journal Papers


Conference Papers


Chapter 1

Introduction

1.1: General Introduction

The role of optical transmission in data communications is currently undergoing a rapid transformation; single-mode optical fiber, once the preserve of the long-haul link, is now found at almost every level of a typical communications network. The information services that are carried on fiber include standard telephone services, media services (such as cable TV) and services for computer-to-computer and computer-to-database connection. The distances that are spanned consequently range from thousands of miles (as is the case for a transoceanic telephone line) to several tens of metres (as is commonly the case for an inter-office computer network).

There are many factors that have contributed to fiber's present-day popularity (a cheap and plentiful supply of raw material, freedom from electromagnetic interference, increased system security, etc.), but above all else, it has been fiber's ability to give low signal attenuation over an essentially limitless bandwidth that has fired the imagination. The two low-loss regions of a single-mode fiber (one at a wavelength of ~1.3μm, and the other at a wavelength of
1.55μm) have a combined bandwidth of roughly 30THz, sufficient to carry ~500 million 64kbit/s voice-grade telephone lines. However, with even the fastest of present-day transmission systems running at a few GHz, this enormous potential remains a largely untapped resource.

The search for ways to access this vast bandwidth initiated considerable interest in a technique known as wavelength division multiplexing (or WDM). The basic idea behind WDM is to transmit light of several different wavelengths along a single fiber at the same time. That this can lead to large increases in transmission capacity is clear to see; if each wavelength carries a separate data stream, then the total transmission rate is equal to the data rate for each individual wavelength multiplied by the number of wavelengths that are used. This technique is made possible by the fact that the different wavelengths do not interfere with one another; each wavelength propagates along the fiber as if it were the only wavelength present.

The increasing diversity of applications for fiber, especially the recent spread of fiber into local-area networks (LANs), has brought about the realization that the benefits of WDM extend well beyond that of simply increasing point-to-point transmission rates. The presence of several wavelengths on the same fiber affords a new degree of system flexibility; the wavelengths may be used to provide service or customer segregation, and even to carry different data formats (e.g. analog and digital). In addition, it is possible to use the different wavelengths to perform many network-oriented functions such as signal routing and switching.

1.2: Subject of the Thesis

This thesis describes the design, fabrication and characteristics of a new type of semiconductor laser that is intended for use as a transmitter source in WDM applications. We have called this new laser the multi-stripe array grating integrated cavity (or MAGIC) laser. The basic properties of the MAGIC laser can be
summarized as follows:-

- The laser is monolithically integrated.
- The laser gives emission at a number of discrete wavelengths.
- Each wavelength is accurately pre-determined at the fabrication stage.
- The wavelengths cover a broad spectral range.
- Each wavelength can be emitted from a separate output port of the device or, alternatively, the wavelengths can all be emitted from a single output port.
- The wavelengths may be emitted either one at a time or in any arbitrary combination.
- Each wavelength is individually addressable and may be independently modulated by direct current injection into an appropriate section of the device.

This thesis is primarily concerned with device fabrication in the InGaAsP/InP materials system for operation in the 1.55μm fiber band. The MAGIC laser can, however, be realized in other material systems (such as the GaAs/AlGaAs system). Much of the subject matter of the thesis is concerned with general design criteria for the MAGIC laser and is therefore not confined to any particular wavelength range. Although a certain amount of freedom exists in the selection of the wavelength spacings, the MAGIC laser is suited to spacings greater than 1nm and is consequently aimed at the regime that is commonly referred to [1] as dense wavelength division multiplexing (or DWDM).

The MAGIC laser is one of a "family" of devices based upon a common integrated-grating technology. Work conducted in the context of this project has, as a consequence, extended to the consideration, design and characterization of other members of the "family"; some mention of these other devices will also be made.
1.3: Contents of the Thesis

Chapter 2

Chapter 2 gives a brief introduction to the architectural concepts that are most commonly used in DWDM optical transmission systems. This helps in establishing general requirements for laser transmitters that are used in such systems and also provides examples of the kinds of applications for which WDM is currently being considered.

Chapter 3

Chapter 3 describes the operating principles, characteristics and drawbacks of the semiconductor lasers that presently appear to be the most promising candidates for use in DWDM systems. Some of these devices are already commercially available, while others are still in the development stage.

Chapter 4

Chapter 4 introduces the basic concepts and operating principles of the MAGIC laser and then goes on to give a brief description of some related components.

Chapter 5

Chapter 5 discusses issues that relate to device structure and fabrication. Details are given of a layer structure in the InGaAsP/InP materials system that is suited to the fabrication of a MAGIC laser that operates in the 1.55μm fiber band. The growth and processing steps that are used in fabricating this structure are then described. The various stages are presented in the same order in which they occur during fabrication; this allows the processing sequence to be followed in a logical fashion from start to finish.
Chapter 6

Chapter 6 discusses issues that relate to the design and geometrical layout of the MAGIC laser. The discussion is illustrated by deriving appropriate device parameters for the case of a laser that emits eight wavelengths with a 4nm spacing across the spectral band 1.53\textmu m-1.56\textmu m. Such a device is suitable for use in a DWDM system that employs Erbium-doped fiber amplifiers.

Chapter 7

A preliminary version of the MAGIC laser has already been fabricated and a second version of the device, based upon a slightly different design, is still under development. Chapter 7 discusses the lasing characteristics of the first working model and also gives some results that have been obtained during initial assessment of the second design.

Chapter 8

Chapter 8 summarizes the findings of this work, draws conclusions based on these findings and discusses some ideas for future work.

In summary, Chapters 2 and 3 contain background material, while Chapters 4 - 8 are concerned with the core topic of this thesis, namely research into the design, fabrication and operation of the MAGIC laser. The basic concept of the laser and its operating principles are introduced in Chapter 4. Chapters 5 and 6 cover materials and processing technologies and device design and layout principles respectively. Experimental results for the MAGIC laser are described in Chapter 7, while Chapter 8 draws conclusions and makes some suggestions for further work.
Chapter 2

Multi-Wavelength Optical Systems

2.1: Introduction

Subsequent chapters describe semiconductor lasers that have been used, or that are being developed for use, as transmitter sources in multi-wavelength optical systems with channel spacings of the order of 1nm (DWDM systems). It is essential, therefore, to first determine the characteristics that are required of these lasers. Unfortunately, a wide variety of WDM-based applications makes evaluation of universal requirements impossible; requirements vary with the particular details of the system in question. General guidelines for the laser devices may, however, be established by considering several classical architectural ideas upon which many of the varied, and often more complicated, system architectures are based. Towards this end, Section 2.2 discusses a typical multi-wavelength point-to-point link, while Section 2.3 examines two general types of architecture that are often used in networking applications.


2.2: Point-to-Point Links

A typical four-wavelength point-to-point link is shown in schematic form in Figure 2.1. Each of the wavelengths ($\lambda_1$ to $\lambda_4$ in the figure) is provided by a separate laser source. A different data stream is encoded onto each wavelength and an external multiplexer device is then used to combine the wavelengths onto the transmission fiber. A demultiplexer device separates the wavelengths at the receiver end of the link so that they may be simultaneously detected; this allows the different data streams to be processed in parallel. The principal advantage of WDM in this particular application is its ability to increase the transmission rate on the fiber without the need to develop faster lasers, photodetectors and electronics. Adding an extra wavelength gives a modular increase in the system's performance; this is an attractive approach for upgrading the capacity of existing fiber links without running into compatibility problems between the operational speeds of new and existing equipment.

![Schematic representation of a four-wavelength point-to-point fiberoptic transmission link. The four wavelengths are numbered $\lambda_1$ to $\lambda_4$.](image)

Early examples of WDM-based point-to-point links used separate optical carriers in each of the two low-loss fiber bands (i.e. at 1.3μm and at 1.55μm) [2]. The wavelength spacing for this type of experiment was therefore ~250nm. The first DWDM point-to-point link was demonstrated in 1985 by a group at AT&T Bell
Laboratories [3]; they combined ten wavelengths in the range 1.529\textmu m to 1.561\textmu m onto a 68.3km length of fiber. Each wavelength carried a 2Gbit/s data stream, giving an overall figure of merit of 1.366Tbit-km/s (defined as the total transmission rate multiplied by the transmission distance).

One of the most important issues in choosing the laser transmitters for such a system is that of wavelength accuracy. The degree of wavelength accuracy that is required depends upon the method that is used to combine and separate the wavelengths. A class of device that is commonly used for combining wavelengths in DWDM applications is the grating-based multiplexer. A schematic example of a grating-based multiplexer is shown in Figure 2.2; this device is similar to the multiplexer that was used in the AT&T experiment [3].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.2.png}
\caption{Schematic representation of a bulk-optic grating-based optical multiplexer. The device that is illustrated multiplexes the signals from 6 different input fibers onto a single output fiber.}
\end{figure}

One end of each of a number of optical fibers are brought together in an array. One of these fibers is used as the multiplexer's output port, while the remainder of the fibers are used as input ports. Coupling between the input fibers and the output fiber is achieved using a collimating lens and grating in a near-
Littrow configuration (for explanation of the Littrow configuration, see a standard optics text, e.g. pp. 427-429 of Reference [4]). The device can be operated as a demultiplexer by reversing the sense of the fibers (i.e. by using the output fiber as an input port and the input fibers as output ports).

The channel passbands of the grating-based multiplexer tend to be fairly narrow. We may make a rough estimate of the spectral width by assuming that the ratio of the channel width to channel spacing is approximately equal to the ratio of the fiber core diameter to the input fiber separation. A typical single-mode fiber has an outer diameter of ~125μm and a core diameter of ~8μm; even with the input fibers touching, we would expect a single-moded multiplexer device with a 2nm channel spacing to have a spectral passband of just 1-2 Å (in reality, techniques for reducing the outer diameter of the fiber may be employed so as to slightly increase the channel passband).

The system's transmission wavelengths must coincide with the channel passbands of the multiplexer to within a fraction of the channel width. Mismatch between the wavelengths and passbands results in excess optical loss within both multiplexer and demultiplexer devices. The operating wavelengths of the laser transmitters must be precisely defined at the fabrication stage or, failing that, they must be tunable to within the tolerance that is imposed by the multiplexer. Even in cases where precise wavelength definition is obtained at the fabrication stage, fine-tuning can be a useful tool for responding to drifts in channel passbands that result from environmental fluctuations such as temperature change. It is clear that this application requires only a slow tuning speed; the tuning range that is required depends upon how far the as-fabricated laser wavelengths are from the desired system values.

Since the principal aim here is to increase the transmission rate on a single fiber, this particular application tends to be considered for long-distance high-capacity links. Relatively high speed modulation of each wavelength is generally required in such instances; coherent detection techniques, requiring narrow laser
linewidths [5], may also be a consideration.

The widespread implementation of WDM in high-capacity point-to-point links has been delayed partly by the expense of having separate transmitter and receiver components for each system wavelength [1]. Technologies that rely upon many separate devices can become prohibitively expensive. This expense is often dominated by the cost of packaging the various components rather than by the cost of the components themselves. This is especially true in single-mode optical systems at 1.55μm where the alignment tolerances between two components can easily be a fraction of a micrometer (one to two micrometers being a typical width for the active region of a semiconductor laser). Such tight tolerances can make alignments susceptible to environmental disturbances such as vibrations and temperature fluctuations; great care and skill must therefore be employed so as to package the components in a way that eliminates such susceptibility.

Simplification at the transmitter end of the link calls for a single laser device that can emit several wavelengths simultaneously from a single output port. A multiwavelength laser of this type could replace both the separate laser transmitters and the external multiplexer device of Figure 2.1. Each individual wavelength should be precisely defined (either at the fabrication stage or by tuning) to match one of the channel passbands of the demultiplexer device used at the receiver end of the link. In addition, it should be possible to independently and simultaneously modulate each of the laser's different wavelengths.

2.3: Networks

A number of demonstrations have shown that multiple wavelengths offer an added degree of flexibility in networking applications [6] - [10]. There are two classical architectural types upon which many of these multi-wavelength networks are based. These are the broadcast-and-select and the wavelength routing networks.
Broadcast-and-Select Networks

Central to the broadcast-and-select network is a device known as a star coupler. A monolithically integrated star coupler of the type that was proposed [11] and demonstrated [12] by Dragone is illustrated in schematic form in Figure 2.3. A slab waveguide functions as a free-space coupling region; this region separates two waveguide arrays that serve as input and output ports. Light coupled into any one of the input ports is guided into the coupling region; once there, the light radiates outwards so that a fraction of it is captured by each of the output ports. The device "broadcasts" the signal from each input to all of the outputs. Such devices are usually designed so that the power from each input is split evenly between the outputs.

Figure 2.3: Plan view of a star coupler. This particular design was first proposed by Dragone [11] and is suited to monolithic fabrication; the free-space region and the input and output ports may be realized using a semiconductor slab waveguide and semiconductor ridge waveguides respectively.

When used in a broadcast-and-select network, the star coupler allows any one of a number of spatially separated transmitter nodes to communicate with any one of a number of spatially separated receiver nodes. Figure 2.4 shows a broadcast-and-select network that relies upon wavelength-tunable lasers for its operation.
Situated at each transmitter node is a wavelength-tunable laser. The output from each laser is coupled into one end of an optical fiber; the other ends of these fibers are coupled to the input ports of a star coupler that is situated at the hub of the network. The star coupler broadcasts the optical signal from each transmitter node to all of the receiver nodes. Each receiver node features a wavelength-selective photoreceiver that can only detect light of a single fixed wavelength (a different wavelength for each node). For the channel spacings that are used in a DWDM system, a wavelength-selective photoreceiver can be realized by placing an optical filter in series with a detector. A connection may be established between a transmitter node and a given receiver node by tuning the transmitter's laser to the passband wavelength of the photoreceiver. The connection may be broken, and a new connection established with a different receiver node, by re-tuning the laser's wavelength.

The lasers used in this application are required to have a total tuning range of at least \((N-1)\Delta\lambda\), where \(N\) is the total number of receiver nodes and \(\Delta\lambda\) is the channel spacing. Thus, with the wavelength spacing on the order of nanometers in a DWDM system, the tuning range that is required can be very large (several tens of nanometers). However, the total tuning range is not the only important
consideration; each laser must be able to tune accurately and repeatably to the passband wavelength of each and every photoreceiver. The degree of tolerance to inaccurate tuning depends upon the width of the photoreceiver passband. Inaccurate tuning causes the signal to be excessively attenuated within the receiver's filter, while non-repeatable tuning results in unpredictability of the received power levels; this latter point requires the photodetectors to have a large dynamic range which in turn leads to reduced receiver sensitivity. Also important is the time that it takes to make a connection between two nodes. The rate at which connections can be established and broken is limited by the tuning speed of the lasers and by the time it takes for the wavelengths to settle down after tuning. Finally, it is worth commenting upon the output power requirements for the lasers. A large number of network nodes implies a high splitting loss in the star coupler. In the absence of optical amplifiers, and for a given receiver sensitivity, increasing the output power of the lasers increases the total number of nodes that can be accommodated.

In addition to the requirement for wavelength-tunable lasers, broadcast-and-select networks could also benefit from a multi-wavelength laser (such as that discussed in Section 2.2). Replacing the wavelength-tunable lasers in Figure 2.4 with multi-wavelength lasers whose wavelengths correspond to the photoreceiver passbands would allow a transmitter node to be connected to any number of the receiver nodes simultaneously.

One of the many applications for the broadcast-and-select architecture is illustrated by the fast optical crossconnect (FOX) network of Reference [6]. This architecture was proposed as a means of interconnecting a series of computer processors to a series of shared memory banks; two star networks (like those in Figure 2.4) are used in this application. The first star network allows each processor to place data into any one of the memory banks by tuning its laser transmitter to the passband wavelength associated with that bank. However, a tunable laser is also situated at each memory bank to allow it to serve data back to
any processor. These connections, from memory bank back to processor, are facilitated by the second star network.

Wavelength Routing Networks

The components that are used in a wavelength routing network are wavelength-selective (unlike the star coupler used in the broadcast-and-select network). This means that the path that an optical signal takes as it travels through the network depends upon the wavelength of the signal and upon the point at which the signal entered the network. A good example of a wavelength-selective component is the grating-based multiplexer that was discussed in Section 2.2. Figure 2.5 shows how eight identical 4x1 grating-based multiplexer/demultiplexer devices can be used to form a wavelength routing network that interconnects eight nodes. The four nodes to the left of the diagram are taken to be the input nodes of the network, while the four nodes to the right of the diagram are taken to be the output or destination nodes. There is, however, nothing to stop the network being used in the reverse sense.

A scheme of different shapes and colours is used to make the operation of the network easier to understand. The different colours represent different wavelengths, while the shapes represent the input node at which the light entered the network. All symbols of the same shape originated from the same input, while all symbols of the same colour represent the same wavelength of light. A connection is established between a given input node and a given output node by tuning a laser at the input to the appropriate wavelength as determined from the wavelength assignment table that is given in the lower part of the figure. By re-tuning the laser’s wavelength, the connection may be broken and a new connection established with a different output node. It can be seen from the figure that the origin of a signal arriving at an output may be uniquely determined from the signal’s wavelength. This is not true in the broadcast-and-select network of Section 2.3.
Figure 2.5: An 8-noded wavelength routing network together with its associated wavelength assignment table. This network has been realized using eight 4x1 optical multiplexer/demultiplexer devices. A connection may be established between a given input node (I1-I4) and a given output node (O1-O4) by tuning a laser that is situated at the input node to one of four wavelengths ($\lambda_1-\lambda_4$); the appropriate wavelength may be determined from the assignment table.

The laser requirements for this wavelength routing network are essentially the same as those for the broadcast-and-select network. In other words, a large tuning range allows more nodes to be included on the network, fast tuning is required for rapid setting up and breaking down of connections, while an accurate
and repeatable tuning mechanism is required to prevent excessive and unpredictable attenuation within the wavelength-selective devices. In addition, using multi-wavelength lasers rather than wavelength-tunable lasers would make it possible for a single input node to be simultaneously connected to any number of output nodes. One point that is worth mentioning is that the increasing splitting loss with increasing node number that is inherent to the broadcast-and-select network is not a feature of the wavelength routing network.

One of the principal advantages of wavelength routing networks is that they allow signals to be separated and directed within the optical domain. More conventional routing techniques require conversion to the electrical domain via a photodetector followed by subsequent re-transmission of the signal. In addition, routing components such as the grating-based multiplexer are passive and therefore require no electrical power supply. This offers potential savings in the operational costs of the network.

The passive photonic loop (PPL) architecture of Reference [9] provides a good example of the ways in which wavelength routing can be used in a real network. Customers for a particular service are divided into small groups based upon their locality. Each customer within the group is then assigned two wavelengths; the first wavelength is that upon which the customer receives data from the service provider and the second wavelength is that upon which the customer transmits data back to the service provider. All of the wavelengths travel along a single fiber between the central premises of the service provider and a routing station that is local to the customer group. The local station is then used to route the different signals to the different customers on the basis of their wavelengths.
Chapter 3

Laser Sources for DWDM Applications

3.1: Introduction

This chapter describes the semiconductor lasers that appear to be the most promising candidates for use in the multi-wavelength systems of Chapter 2. Some of these devices are already available, while others are still in the development stage. The lasers are grouped according to whether they give wavelength-tunable or multi-wavelength emission. It should be noted, however, that a multi-wavelength laser can also be operated as a wavelength-tunable source; discrete tuning is achieved by turning just one of the wavelengths on and then turning it off again and turning a different one on.

A basic property of the semiconductor laser is that the spectral gain profile of the active material is many times larger than the longitudinal mode spacing of the resonant optical cavity (provided that the cavity length is greater than a few microns). The laser operates on the mode that has the largest gain margin (defined as the gain minus the loss incurred in one round-trip of the cavity). In the case of the basic cleaved-facet Fabry-Perot (FP) laser, the round-trip loss is essentially the
same for all of the modes and so lasing always occurs on the mode that lies closest to the peak of the gain profile. Wavelength tuning of an FP laser could, in principle, be achieved by spectrally altering the gain profile so that its peak occurs at a different wavelength. It is well known, however, that the mode selectivity mechanism in an FP laser is poor and that an appreciable fraction of the output power occurs in modes to either side of the dominant mode (see any standard text, e.g. Reference [13]). The applications discussed in Chapter 2 require that the power occurs predominantly in a single longitudinal mode (commonly referred to as single-frequency operation) and that the wavelength for each system channel be precisely controlled; an alternative mechanism for wavelength definition and tuning is therefore needed. The degree to which emission occurs on a single mode is measured by the ratio of the intensity in the dominant mode to that in the most intense side-mode; this ratio is known as the side-mode suppression ratio (SMSR).

The laser devices that are discussed in this thesis all use some form of spectral filtering to rearrange the gain margins of the various modes. A filter incorporated into the laser cavity increases the optical loss (and therefore decreases the gain margin) of those modes that lie outside of its passband. With sufficient attenuation from the filter, the dominant mode in the laser's spectral output will be that which lies closest to the center of the passband. Single-frequency operation is achieved if the filter passband is narrow enough to "select" only one cavity mode at a time. Discrete tuning is exhibited by those devices in which the position of the filter passband can be adjusted so as to scan across the cavity modes. This causes the different modes to be selected one after another. Continuous tuning, on the other hand, can be achieved if the wavelengths of the filter passband and of the cavity modes can be adjusted in such a way that they scan in unison. Differences between the various wavelength-tunable lasers lie in the type of filter that is used and in the physical mechanism upon which tuning is based.
All of the multi-wavelength lasers that are described in this chapter comprise a number of wavelength-tunable or single-frequency devices (operating at different wavelengths) whose outputs are coupled together. Differences for these lasers occur mainly in the degree and method of integration that is employed in an attempt to reduce the component count and packaging costs.

### 3.2: Wavelength-Tunable Lasers

**External-Cavity Lasers**

Single-frequency laser emission can be obtained from a standard Fabry-Perot laser diode by using some form of filtered external feedback to replace the spectrally invariant feedback of one of the device's cleaved facets. This is most commonly achieved by using a reflective diffraction grating as an external mirror. A typical example of such a grating external-cavity laser (GECL) is found in Reference [14], while the essential features of the device are shown in Figure 3.1.

![Figure 3.1: Schematic representation of a typical grating external-cavity laser.](image)

One facet of the Fabry-Perot laser chip is anti-reflection (AR) coated in order to "spoil" its reflectivity. Reflective feedback is provided instead by the collimating
lens and diffraction grating. The spectral width of the reflectivity peak (i.e. the filter passband) is determined by the grating resolution, the grating dispersion and the width of the laser diode's active region. With both a good AR coating and efficient feedback from the grating, the external cavity (bounded by the cleaved uncoated facet and the diffraction grating) can have a much larger Q-factor than the cavity that is bounded by the two cleaved facets. The laser then operates on the external cavity mode that lies closest in wavelength to the reflectivity peak.

The laser may be tuned by rotating the diffraction grating. This alters the angle at which the collimated beam of light is incident upon the grating and therefore changes the central wavelength for the filtered external feedback. Rotating the grating does not alter the length of the external cavity and so the wavelengths of the longitudinal modes are unaffected; this mechanism therefore gives discrete tuning. Any external cavity mode that lies within the gain spectrum of the laser diode may, in principle, be selected; a tuning range in excess of 50nm is readily obtained [14] using laser diodes with bulk active regions, while second subband recombination in quantum well (QW) active regions has been used to demonstrate a tuning range of 240nm [15]. Continuous tuning may be achieved by both rotating and translating the grating [16]. Translating the grating towards or away from the FP laser diode changes the cavity length and therefore changes the wavelengths of the cavity's longitudinal modes.

In addition to the large tuning range, the GECL has the advantage of a very narrow linewidth. Replacing the cleaved-facet mirror by an external mirror modifies the laser linewidth by a factor of $\frac{L}{L_t}$ [17], where $L_t$ is the total optical length of the external cavity and $L$ is the optical length of the laser diode's active region. The laser of Reference [14], for instance, exhibited a linewidth of just 10kHz.

The principal disadvantage of the GECL is its relatively slow tuning speed. Even if piezoelectric transducers are used to rotate and translate the grating, the maximum tuning rates that can be achieved are in the microsecond regime. Other disadvantages of the GECL are mainly related to the fact that it is a hybrid device.
The bulk-optic components require careful alignment and stabilization, while care must also be taken to prevent spurious reflections (such as those from a poorly coated laser facet). Residual reflections from the coated facet of the laser diode can give excitation of its internal Fabry-Perot modes; interferometric coupling between these internal modes and the modes of the external cavity can result in poor and unpredictable tuning control.

Filtered external feedback can also be achieved by swapping the diffraction grating of Figure 3.1 for a plane mirror and by then placing an optical filter between the mirror and the AR coated facet of the laser diode. A variety of different filter types may be used to perform this function. An acoustooptic filter [18] has, for example, been used to demonstrate an 83nm tuning range in the 1.3μm band [19]. The disadvantages again tend to be linked to low tuning speeds and to the use of bulk-optic components.

### Tunable DFB Lasers

Of the various monolithic lasers that employ modal filtering techniques, the best known is the distributed feedback (DFB) laser [20]. Light propagating along the laser waveguide structure experiences a periodic variation in its modal effective index. This index variation is caused by variations in the thickness of a semiconductor layer lying either above or below the laser's active region; as a result of this structure, a Bragg grating filter is set up along the entire length of the active region.

The wavelength of a DFB laser can be tuned by changing its operating temperature. This alters the refractive index of the semiconductor and therefore modifies the optical periodicity of the Bragg grating. The fractional change in the laser's operating wavelength is equal to the fractional change in the modal effective index. For a typical DFB laser, the tuning rate is ∼0.1nm/°C [21]. The usefulness of this tuning mechanism is, however, limited by its low speed and small practical tuning range. For lasers operating in the 1.3μm and 1.55μm spectral
bands, nonradiative recombination of carriers in the active region causes threshold currents and efficiencies to be very temperature sensitive [22], [23]. Increasing the temperature causes the output power to decrease. Although this can be compensated for by increasing the injection current, practical temperature changes are limited to $\pm 10^\circ C$; this translates to a tuning range of just $\pm 1$nm.

An alternative method for changing the refractive index of the semiconductor material is by the injection of free-carriers. Changes in the free-carrier density can be effected on a nanosecond timescale and so this is a more suitable control mechanism for applications that require fast tuning. A reduction in index results from the absorption of photons by carriers making both interband transitions (sometimes referred to as the "anomalous" dispersion effect [24]) and intraband transitions (the free-carrier plasma effect).

Electrical tuning, as opposed to thermal tuning, solves the problem of tuning speed, but not that of tuning range. The Bragg grating of a DFB laser is fabricated in a layer that lies directly above or below the active region; the current that is used to inject free-carriers into the grating region is therefore the same current that is used to control the gain. The range over which this current can be varied is somewhat limited. If the current is reduced below its threshold value, then the laser will cease to lase; if, on the other hand, the current becomes too high, then the associated increase in optical power could lead to optically induced device degradation. Furthermore, with the laser operating in the above-threshold regime, variations in the injection current produce relatively small changes in carrier density.

The direct coupling between the wavelength and power controls can be overcome to some extent by using multi-contact DFB lasers [25], [26]. The total injection current for these devices is split in a variable ratio between more than one electrode; this leads to nonuniformity in the distribution of carriers along the length of the laser's cavity. The device of Reference [26] tuned continuously over $\sim 2$nm with a constant output power and a SMSR $> 30$dB. A detailed discussion of the
problems of wavelength-tuning in DFB lasers may be found in Reference [27]. One solution for relaxing the restrictions on tuning range, and also for decoupling the power and wavelength controls, is to spatially and electrically isolate the Bragg region from the gain region in such a way that the two may be independently pumped. The structure of the distributed Bragg reflector (DBR) laser achieves just this and so rather than dwell on the case of the tunable DFB laser, we shall move on to consider the tunable DBR laser in some detail.

**Tunable DBR Lasers**

The simplest form of tunable DBR laser is a two-section device [28], [29], the essential features of which are illustrated in Figure 3.2.

![Figure 3.2: Cross-sectional view of a two-section distributed Bragg reflector (DBR) laser. The cross-section, taken along the length of the laser's optical cavity, reveals an active or gain section that is used to control the laser's output power and a Bragg grating section that is used to control the operating wavelength.](image)

Cavity mirrors are provided by a cleaved facet at one end of the laser's gain section and by the Bragg grating section at the other end. The reflectivity profile of the grating section has a peak at the Bragg wavelength. Separate electrodes give independent control of the currents that are injected into the two sections. Current injection into the gain section controls the output power of the laser, while current injection into the Bragg section controls the lasing wavelength. Total decoupling of
the two functions (light production and wavelength tuning) is expected, provided that the Bragg section has a waveguide structure that is transparent to the operating wavelengths of the laser.

Using free-carrier injection, the maximum spectral range over which the Bragg reflectivity peak can be tuned is approximately 10nm [29]. This limit is a consequence of two different factors. Firstly, the nonradiative Auger recombination rate increases as the cube of the injected carrier density. This causes the rate of change of the refractive index with tuning current to decrease as the tuning current increases. Secondly, thermal heating effects increase as the square of the injection current; the positive index change that results from such heating counteracts the negative index change that results from the presence of the free-carriers.

The two-section DBR laser gives a mixture of discrete and continuous tuning. An index change in the Bragg section affects the cavity length as well as the grating periodicity. An increase in the Bragg current therefore causes both the longitudinal modes and the Bragg wavelength to tune towards shorter wavelengths. The tuning rate of the Bragg wavelength is, however, faster than that of the cavity modes. (The ratio of the two tuning rates is roughly equal to the total device length divided by the length of the Bragg section). As a result, the laser tunes continuously on one mode until a point is reached at which a neighbouring mode is closer to the grating's reflectivity peak. The laser then tunes discretely by jumping to the next mode; each mode hop leaves a gap in the wavelength coverage that is equal to the mode spacing. The continuous tuning ranges that occur between hops are relatively small (typically 1Å-2Å [29]).

The gaps in the tuning range may be avoided by incorporating a third section, known as the phase section, between the gain and Bragg sections [30] - [32]. A three-section device is illustrated in schematic form in Figure 3.3. The waveguide structure of the phase section, like that of the Bragg section, is chosen to be transparent at the laser's operating wavelengths. Free-carriers injected into the phase section alter the mode wavelengths without affecting the position of the
Bragg reflectivity peak. This effect can be used to compensate for the disparate tuning rates of Bragg wavelength and cavity mode wavelengths that results from current injection into the Bragg section. By extending the continuous tuning range of each mode, the ranges covered by neighbouring modes can be made to overlap; this fills in the gaps that occur for the two-section device. The device of Reference [32], for example, could tune to any wavelength in a range of ~8nm using 13 different longitudinal modes.

![Cross-sectional view of a three-section distributed Bragg reflector (DBR) laser. A third section, known as the phase section, is incorporated between the gain and Bragg sections in order to avoid the gaps that occur in the tuning range of the two-section device.]

Figure 3.3: Cross-sectional view of a three-section distributed Bragg reflector (DBR) laser. A third section, known as the phase section, is incorporated between the gain and Bragg sections in order to avoid the gaps that occur in the tuning range of the two-section device.

Complete wavelength coverage is, however, obtained at a price. Firstly, the three-section DBR has a complicated control mechanism (three different injection currents are involved). We saw in Chapter 2 that device tuning must be accurate and repeatable; complicated tuning schemes are more susceptible to drift and, as a consequence, increase the need for monitoring and stabilization techniques. This adds to the cost of the packaged unit. The control mechanism for the three-section DBR laser can be slightly simplified by supplying the current for both Bragg and phase sections from a single source; the output from this supply is split between the two sections in a fixed ratio using load resistors [30]. This approach has been used
to continuously tune a three-section device over 3nm with two current sources [30].

The introduction of the phase section also increases the effect that wavelength tuning has on the output power of the laser. Free-carriers injected into the phase section increases the optical loss within the cavity and therefore increases the threshold current of the laser. If the currents to the gain and Bragg sections are maintained at constant values, then current injected into the phase section causes a significant drop in the output power [30]. Constant output power can be maintained across the laser's entire tuning range by increasing the current to the gain section [30], [31], however, the total current draw of the device can become quite high (in excess of 200mA in the case of Reference [31]). Furthermore, the increase in free-carrier absorption that is caused by introduction of the phase section can lead to linewidth broadening [30], [32]. In covering its entire tuning range, the device of Reference [32] exhibited a broadening of its linewidth from a minimum value of 3-4MHz up to ~16MHz.

As far as the networking applications that were discussed in Section 2.3 are concerned, the principal disadvantage of the tunable DBR laser is the ~10nm limit on the tuning range. Such a small tuning range allows only a handful of network nodes. An extension of the tuning range to 22nm has been demonstrated by using a combination of both forward and reverse biasing of the Bragg region [33]. The reverse biasing is used to invoke deliberate thermal heating so as to tune the device towards longer wavelengths. This approach does, however, slow the tuning speed back down to the microsecond regime.

It was recently suggested that the maximum tuning range of 10nm may be overcome in a four-section DBR device [34]. The successful realization of this device relies upon the ability to fabricate a new type of grating that has periodic peaks in its reflectivity spectrum. The proposed four-section device is illustrated in Figure 3.4; the fourth section consists of an additional grating region that replaces the cleaved facet mirror of the two- and three-section devices. The reflection peaks of the two gratings, shown in the lower part of the figure, are deliberately designed
to have slightly different periodicities; it is this feature that gives rise to the extended tuning range.

Figure 3.4: Cross-sectional view of a four-section DBR laser. The laser’s optical cavity is bounded at each end by a grating mirror. In contrast to two- and three-section devices, the grating mirrors have periodic peaks in their reflectivity spectra. This is illustrated in the lower part of the figure. Moreover, the periodicities of the reflection peaks must be slightly different for the two mirrors.

The laser operates on the cavity mode that is closest to the wavelength at which reflectivity peaks of the two gratings are aligned. It is at this wavelength that the product of the reflectivities of the two gratings is a maximum. If both gratings are tuned in unison, then the tuning principle is identical to that for the three-section device. However, electrical tuning of just one of the gratings can be used to scan the two sets of reflectivity peaks relative to one another. By tuning the peaks of one grating by an amount $\Delta P$, where $\Delta P$ is equal to the difference in the reflectivity
periodicities of the two gratings, the neighbouring pair of peaks is brought into alignment. Although the grating is only tuned by $\Delta P$, the operating wavelength is tuned by an amount $P$, where $P$ is the periodicity of the reflectivity peaks of the second grating (that which isn’t tuned). The tuning range of the device can therefore be extended by a factor of $P/\Delta P$.

Two different approaches have been reported for the fabrication of gratings with periodic reflection spectra [34], [35]. Although a four-section DBR laser has yet to be demonstrated, the gratings of Reference [35], known as super structure gratings (SSG), have been used in the fabrication of a three-section device (consisting of a gain section and two SSG sections). A total tuning range of 101nm in the 1.55$\mu$m band has been demonstrated [36]; this is a ten fold improvement over the range of a conventional two- or three-section device. Since a phase section has not, as yet, been included, gaps will exist in the tuning range (as in the case of the two-section DBR laser). These lasers have achieved fast tuning (3ns) over a broad spectral range (~40nm) whilst maintaining good side-mode suppression (>30dB) [37] and therefore show great promise as transmitter sources in future DWDM broadcast-and-select and wavelength routing networks. The issue of complexity in the tuning mechanism is, of course, further exacerbated by the addition of a fourth section.

**Interferometric Y-Branch Lasers**

Another device that has attained a wide tuning range is the Y-branch laser [38] - [42]. The Y-branch laser features a monolithically integrated Mach-Zehnder (MZ) interferometer and is formed in a straightforward way by branching one end of an FP laser’s active region. The essential features of the Y-branch laser are illustrated in the upper half of Figure 3.5. Unfolding the optical cavity at the right-hand facet, as illustrated in the lower half of the figure, exposes the underlying Mach-Zehnder geometry. The Y-shaped active waveguide, although physically continuous, is electrically divided into a number of different sections. All sections
are injection pumped to provide gain, but may be pumped unequally to induce modal effective index differences.

Figure 3.5: Plan-view schematic of a Y-branch laser (upper part of figure). Although physically continuous, the Y-shaped active region is subdivided through the use of separate electrodes into several electrically isolated sections. Unfolding the optical cavity at the right-hand facet, as illustrated in the lower part of the figure, exposes the geometry of a Mach-Zehnder interferometer.

The broad tuning range of this device may be understood by considering the operating principles of the intracavity Mach-Zehnder filter. Consider light propagating from left to right in the unfolded geometry. The light is split at the first branching point, passes along both upper and lower branches of the device and then recombines at the second branching point. The physical path lengths of the upper and lower branches are denoted as $L_1$ and $L_2$ respectively, while the modal effective indices for the waveguides are denoted as $n_1$ and $n_2$. There is consequently an optical path difference of $(n_2 L_2 - n_1 L_1)$ between light that has travelled via the two branches. Transmission peaks of the filter occur at wavelengths for which the light recombines in phase. The wavelength, $\lambda_p$, of the
filter's p'th transmission peak is therefore given by

\[(n_2L_2 - n_1L_1) = p \cdot \lambda_p \]  \hspace{1cm} (3.2.1)

The wavelength of the transmission peak may be tuned by changing the injection current for one or both of the branches. Suppose that the current for the lower branch is altered; the change in the wavelength of the transmission peak for a given change in the refractive index may, in this case, be found by differentiating Eq. (3.2.1) with respect to \(n_2\). This gives

\[\frac{\partial \lambda_p}{\partial n_2} = \frac{L_2}{p} \]  \hspace{1cm} (3.2.2)

If we substitute for \(p\) from Eq. (3.2.1) and replace the derivatives by small finite changes of \(\Delta \lambda_p\) and \(\Delta n_2\), then we arrive at the following expression for the fractional change in wavelength of the filter's transmission peak

\[\frac{\Delta \lambda_p}{\lambda_p} = \frac{\Delta n_2}{n_2} \times \left( \frac{n_2L_2}{n_2L_2 - n_1L_1} \right) \]  \hspace{1cm} (3.2.3)

We see from Eq. (3.2.3) that, for a given change of refractive index, the tuning range of the Mach-Zehnder filter is enhanced by a factor of \((n_2L_2)/(n_2L_2 - n_1L_1)\) relative to that of a Bragg grating filter. The wide tuning range results from the fact that the shift in wavelength depends upon a change in index relative to the difference in the indices of two waveguides, rather than upon a change in a waveguide's index relative to its absolute value. This may be seen more clearly if we take the case where \(L_1=L_2\); Eq. (3.2.3) then evaluates to

\[\frac{\Delta \lambda_p}{\lambda_p} = \frac{\Delta n_2}{n_2 - n_1} \]  \hspace{1cm} (3.2.4)
A total tuning range of 51 nm has been reported for a symmetrical Y-branch laser \((L_1=L_2)\) [40]. The tuning was discrete, the filter passband selecting individual cavity modes. Quasi-continuous tuning has also been demonstrated, but over much smaller tuning ranges (8 nm was demonstrated by the device of Reference [38]). Good side-mode suppression is difficult to achieve with symmetrical devices (typically 20 dB [38]) and generally requires careful and complicated control of several injection currents. The poor mode selectivity is due to the filter's broad passband. The Mach-Zehnder interferometer has a finesse of only 2 and so the passband is equal to half the free-spectral range (FSR). The optical path length difference, \((n_2L_2-n_1L_1)\), that can be induced in a symmetrical device is fairly small; the symmetrical device therefore operates in a low interference order and has a large FSR.

Simplified tuning can be achieved if the device is designed with different branch lengths \((L_1\neq L_2)\) [39], [41]. A larger optical path difference, \((n_2L_2-n_1L_1)\), can then be obtained for the same refractive index difference, \((n_2-n_1)\). The Mach-Zehnder filter will, in this case, operate in a higher interference order; this results in a smaller FSR and narrower passband. The asymmetrical device of Reference [41] was tuned through 6.7 nm by adjusting just one of the currents. The small tuning range is a direct consequence of the low free-spectral range. The lasing mode is selected by the filter passband that lies closest to the gain peak of the active material. Operation therefore jumps between neighbouring passbands as they tune relative to the gain peak.

A further variation of the Y-branch laser, coined the Y3-laser, has recently been reported [42]. The Y3-laser combines the wide tuning range of the symmetrical device with the improved mode selectivity of the asymmetrical device. This is achieved by a further stage of branching; one of the branches of an asymmetrical device is itself branched to form a near-symmetrical "Y". The resulting filter transmission function is a composite of the symmetrical and asymmetrical filter functions. The Y3-laser of Reference [42] was tuned over 45 nm with side-mode
suppression ratios (SMSR) as high as 25dB. Unfortunately, no comment was made as to the number of currents that were varied during tuning.

A potential worry for this class of device is the issue of "missing" wavelengths. In all of the Y-branch lasers that have been demonstrated to date, the filter has been unable to select all of the cavity modes that fall within the total tuning range. This is only of concern if one of the missing modes happens to correspond to one of the channels of the system for which the device is intended. This cannot, however, be controlled or determined prior to fabrication. Inability of the device to tune to just one of the system channels will, in many applications, constitute a system failure. There are consequently serious worries concerning the yield rate for these devices.

**Grating-Assisted Directional Coupler Laser**

Another class of tunable filter that is highly suited to monolithic integration is one that uses grating-assisted coupling to transfer energy between two nonidentical waveguide modes. A filter of this type, using grating-assisted co-directional coupling between two vertically stacked nonidentical InGaAsP/InP waveguides, has been reported for use in the 1.55μm wavelength range [43]. This filter has recently been integrated with an active waveguide or gain section to give a tunable laser [44]. The basic elements of this laser are shown in Figure 3.6.

The laser incorporates three different waveguides, the active waveguide of the gain section and the two vertically stacked waveguides that make up the filter section. One end of the active region is terminated by a cleaved-facet mirror, while the other end couples light into the upper filter waveguide. The material compositions for the two filter waveguides are chosen to be transparent to the laser light but different to one another. Evanescent coupling between the two filter waveguides is prevented by their different modal effective indices. Light that couples from the gain section into the upper filter waveguide propagates to its far end; the light then diverges in the region beyond. The far end of the upper
waveguide is distant from the right-hand cleaved-facet of the chip and so optical feedback is very weak.

![Cross-sectional view of a grating-assisted directional coupler laser](image)

**Figure 3.6:** Cross-sectional view of a grating-assisted directional coupler laser [44]. The filter section of this particular device consists of two vertically stacked waveguides that are fabricated to have different material compositions. Co-directional coupling between these two waveguides occurs at certain wavelengths by virtue of a grating structure that is fabricated on top of the upper guide.

Fabricating a periodic grating structure on top of the upper waveguide allows light to couple down to the lower waveguide. Coupling occurs at the wavelength for which the periodicity of the grating makes up the difference in the modal propagation constants (i.e. that for which momentum is conserved). The coupling condition is therefore given by

\[
\frac{2\pi n_2}{\lambda_0} - \frac{2\pi n_1}{\lambda_0} = \frac{2\pi}{\Lambda}
\]

where \( n_1 \) and \( n_2 \) are modal effective indices for the two filter waveguides, \( \lambda_0 \) is the free-space wavelength of the light that is coupled between the two waveguides and \( \Lambda \) is the spatial period of the grating. Rearranging this equation gives

\[
\lambda_0 = \Lambda \cdot (n_2 - n_1)
\]
The coupled light is guided all the way to the far end of the chip where it is reflected by the right-hand cleaved-facet. The feedback to the active region of the laser is therefore much stronger for this light than for that which simply propagates along the upper waveguide.

We see from Eq. (3.2.6) that the passband wavelength of the filter depends upon the difference between two refractive indices, a quantity that can be changed by large amounts using a relatively small absolute index change. We have already seen how the same principle gives a large tuning range for the Mach-Zehnder filter. With its filter section both forward and reverse biased, the laser of Reference [44] could be discretely tuned over a total range of 57nm; the filter selected individual cavity modes that were spaced by 0.15nm. Single-mode operation (with a typical side-mode suppression ratio of 25dB) was observed over a tuning range of 42nm [44].

In addition to the broad tuning range and fast tuning rate, this device has the advantage of a simplified tuning control (the wavelength is controlled by a single injection current). There are, however, areas in which improvements still need to be made; these include the inability to tune to some of the modes within the total tuning range (a problem that is shared with Y-branch lasers) and the large tuning currents (upto 0.95A was used to cover the 57nm range reported in Reference [44]).

3.3: Multi-Wavelength Lasers

A multi-wavelength laser module can be formed by taking a number of single-frequency (or wavelength-tunable) lasers, such as DFB lasers, that are operating at different wavelengths and by then combining their outputs using some form of multiplexing or coupling device. The developments in multi-wavelength laser technology that have been reported to date have mainly consisted of increases in the level of integration of these components.
Hybrid Devices

The first step towards a fully-integrated multi-wavelength laser module is the fabrication of a laser array. Arrays of twenty DFB lasers have been reported in which each laser has a slightly different grating period [45] - [47]. The biggest problem associated with such laser arrays is that of wavelength linearity. In the best case, the as-fabricated wavelengths of the lasers give a channel spacing that is accurate to ±0.3nm [45]; in many cases the accuracy is even worse [46], [47]. With the DFB lasers as discrete components, wavelength errors of this magnitude can be compensated for by adjusting the operating temperatures (a total range of just 6°C in the operating temperature would compensate for a ±0.3nm wavelength error). However, with the lasers integrated into a single array, any temperature control is applied to all of the devices simultaneously. The poor wavelength accuracy means that, for many applications, either the DFB lasers will have to be electrically tuned, or some other kind of tunable lasers, e.g. DBR lasers, will have to be used.

Various methods have been investigated for combining the different wavelengths of laser arrays. The conventional approach is to first couple the output of each laser into one member of a fiber array and then to use either a grating-based multiplexer or star coupler (see Chapter 2) to combine all of the wavelengths onto a single fiber. An example of such a module may be found in Reference [48]. Bulk-optic lenses were used to couple the output from each of four lasers into a separate fiber [48]. The number of lasers whose outputs can be combined in this way is essentially limited by the aperture of the lenses.

Bulk-optic components were also used in a four-wavelength module that directly combined the output of a DFB laser array without the use of an intermediate fiber array [49]. Bonded to the front of each DFB laser was a glass sphere; these spheres functioned as microlenses by collimating the lasers' outputs. The collimated beams were then coupled to a single fiber using a diffraction grating and a conventional bulk-optic lens. The laser array was designed to operate in the
1.55μm band with a 4nm spacing; the wavelengths departed from their design values by up to 0.3nm.

Both of the approaches mentioned above necessitate the use of active alignment techniques in their assembly. With the lasers powered up, the positions of the various optical elements are manipulated so as to give the best achievable coupling. This active alignment process can add appreciably to the module cost and so techniques for passive alignment have also been investigated. Passive alignment of a laser array to a fiber array may be achieved with silicon waferboard technology [50]. This method employs a micro-machined silicon substrate as a platform for hybrid integration. V-grooves are etched into the substrate to hold the optical fibers in place, while mechanical alignment features, such as pedestals and standoffs, are formed to help with positioning the laser array. The positions of the various alignment features are defined by photolithography and so their relative positioning is very accurate. The coupling efficiencies achieved using this technique have, however, been relatively low to date; Reference [50] reported the coupling of an array of four lasers to four single-mode fibers with losses ranging between 12.2dB and 14.6dB.

**Monolithic Devices**

The first demonstration of a monolithic multi-wavelength laser featured an array of three two-section InP/InGaAsP DBR lasers [51]. The Bragg end of each laser coupled light into one of the input ports of a monolithically integrated 1×3 combiner. The combiner consisted of a passive optical waveguide that was branched three ways. An optical amplifier was also integrated onto the chip so as to compensate for coupling losses. The grating periods of the three lasers were identical, but the thickness of the layer into which the gratings were fabricated varied from laser to laser. This resulted in differences in the modal effective indices of the laser waveguides and therefore caused differences in the optical periodicities of the gratings; there was consequently no need to define each grating
individually. The lasers all operated in the 1.55μm region and, with no current injected into the Bragg sections, their wavelengths were separated by 8nm. Each laser had a total tuning range of ~6nm, but because the DBR lasers were two-rather than three-section devices, gaps were present in their tuning ranges.

Recent efforts have been directed towards increasing the number of wavelengths emitted by such devices. A monolithically integrated star coupler of the type discussed in Chapter 2 has been used to combine the outputs of a 21 member DFB laser array [52]. 18 of the 21 lasers were measured (3 would not operate continuously due to insufficient gain); their wavelengths covered the approximate spectral range of 1.515μm to 1.575μm. The DFB lasers were fabricated with different grating periodicities and had a wavelength spacing of 3.7nm ± 0.38nm; the error in the wavelength spacing is therefore more than 10% of the mean value. The lasers exhibited high side-mode suppression (SMSR typically > 35dB), but the output powers were very low (between -20dBm and -42dBm was coupled by each laser into a lensed single-mode fiber for a bias current 20mA above threshold). The low powers are partly due to the splitting loss of the star coupler; optical amplifiers were integrated at two of the coupler's outputs in order to compensate for the losses.

Most recently, a monolithically integrated star coupler has been used to combine the outputs of 16 2-section DBR lasers [53]; 15 out of the 16 lasers were operational. The average as-fabricated wavelength spacing was 6.7Å, but individual wavelengths departed by as much as 1nm from linearity. Tuning of each individual wavelength was in fact possible by both electrical and thermal means, a platinum resistor being placed next to each laser to provide localized heating. This device, like the similar devices of Refs. [51] and [52], required the use of an integrated optical amplifier at the output to compensate for large splitting losses in the coupler.
3.4: Summary

This chapter has described the semiconductor lasers that appear to be the most promising candidates for use in the DWDM systems that were described in Chapter 2. These lasers may be broadly categorized as either wavelength-tunable or multi-wavelength devices, however, multi-wavelength lasers may also be used as wavelength-tunable sources.

In respect of wavelength-tunable lasers, the challenge has been to develop a device whose operating wavelength can be rapidly tuned over a broad spectral range using a very simple control algorithm. Moreover, the laser must be capable of being accurately and repeatably tuned to the wavelength of each and every channel of the system in which it is to be used and must have good spectral characteristics at all of these wavelengths. The main attributes of the wavelength-tunable lasers that have been discussed here are listed in the table on the next page.

The conventional approach to developing multi-wavelength lasers has been to couple together the outputs of a number of single-frequency or wavelength-tunable lasers that are operating at different wavelengths. Although hybrid devices have been realized, the difficulty and cost associated with aligning and stabilizing a number of discrete single-mode components has created a drive towards monolithic integration. The monolithic integration of DFB lasers and two-section DBR lasers with optical splitters such as star-couplers has been demonstrated. One of the main problems that results from the monolithic integration of single-frequency lasers (such as DFB lasers) is that of wavelength accuracy. The as-fabricated wavelength of each channel is, at best, accurate to ~0.3nm and the random nature of the errors makes it difficult to use thermal tuning to overcome them. Another concern for the monolithic devices that have been demonstrated to date is the high splitting loss that occurs in the optical coupler.
<table>
<thead>
<tr>
<th>Device</th>
<th>Main Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GECL</td>
<td>Wide tuning range (up to 240nm already demonstrated [15]). Both discrete and continuous tuning possible. Low tuning speed (μs regime possible using piezos). Narrow linewidth (kHz regime readily achievable). Requires careful alignment and stabilization of bulk-optic components.</td>
</tr>
<tr>
<td>Multi-Electrode DFB Laser</td>
<td>Narrow tuning range (~2nm [26]). Continuous tuning. High tuning speed (ns regime readily achievable). High SMSR (typically &gt; 30dB [26]).</td>
</tr>
<tr>
<td>Two-Section DBR Laser</td>
<td>Fairly narrow tuning range (up to ~10nm [29]). Tunes in discrete hops with small (1-2Å [29]) continuous tuning ranges between each hop. High tuning speed (ns regime readily achievable). High SMSR (typically &gt; 30dB [29]).</td>
</tr>
<tr>
<td>Three-Section DBR Laser</td>
<td>Gaps in tuning range of two-section device are eliminated by introduction of phase section - tuning is quasi-continuous. Penalties - increased complexity in device control mechanism and broadening of linewidth with increasing phase current.</td>
</tr>
<tr>
<td>Four-Section DBR Laser</td>
<td>Tuning range of two- and three-section devices is extended by using two gratings with periodic reflectivities (over 100nm tuning range should be possible [36]). Penalty - further complicates device control mechanism.</td>
</tr>
<tr>
<td>Symmetric Y-Branch Laser</td>
<td>Wide tuning range (over 50nm already demonstrated [40]). Wide ranges achieved with discrete tuning; quasi-continuous tuning possible, but only 8nm range demonstrated so far [38]. High tuning speed (ns regime readily achievable). Difficult to obtain high SMSR (typically 20dB). Complicated control - adjustment of several currents required. Missing wavelengths - some cavity modes not selectable. Relatively simple fabrication.</td>
</tr>
<tr>
<td>Asymmetric Y-Branch Laser</td>
<td>Use of asymmetric branch leads to simplification of wavelength control mechanism relative to that of symmetric Y-branch laser (discrete tuning has been demonstrated over 6.7nm by adjusting just one current [41]). Penalty - reduction of filter FSR and hence of tuning range.</td>
</tr>
<tr>
<td>Y3-Laser</td>
<td>Cross between symmetric and asymmetric Y-branch lasers; designed to combine wide tuning range of symmetric device with simplified control mechanism and narrower filter pass-band of asymmetric device. Improved SMSR (25dB [42]). Information on simplicity of control not yet available.</td>
</tr>
<tr>
<td>Grating-Assisted Directional Coupler Laser</td>
<td>Wide tuning range (discrete tuning over a 57nm range has been demonstrated [44]). High tuning speed (ns regime readily achievable). Simple control - wavelength controlled via single current. Missing wavelengths - some cavity modes not selectable. Reasonably high SMSR (25dB [44]). Large tuning currents (up to 950mA [44]).</td>
</tr>
</tbody>
</table>
4.1: Introduction

This chapter introduces the concept of the multi-stripe array grating integrated cavity (MAGIC) laser, a new type of monolithic multi-wavelength laser that is intended for use in the DWDM systems of Chapter 2.

The multi-wavelength lasers discussed in Chapter 3 were all based upon a common principle, namely the coupling together of the outputs of a number of different DFB or DBR lasers; the MAGIC laser, on the other hand, is based upon a novel two-dimensional external-cavity design. Section 4.2 introduces the basic operating principles of this design through reference to a bulk-optic equivalent model.

Section 4.3 describes concepts for the realization of this design in a monolithic device. The monolithic form is discussed from a purely functional point of view; an in-depth description of the semiconductor layer structure and processing sequence is left to Chapter 5, while geometrical design issues are the topic of Chapter 6.
Many of the features and operating principles of the MAGIC laser, not to mention the techniques used in its fabrication, are shared with certain other monolithic DWDM components. Although aimed primarily at the design and experimental realization of the MAGIC laser, much of the work described in this thesis is also relevant to these other devices; a brief description of some related components is therefore given in Section 4.4.

### 4.2: Operating Principles

A bulk-optic equivalent of the MAGIC laser is shown in Figure 4.1. The device may be thought of as a two-dimensional external-cavity laser; it combines the wavelength control mechanism that is used in a conventional grating external-cavity laser (Figure 3.1) with the wavelength combining function of a grating-based multiplexer (Figure 2.2). This novel device configuration was first suggested in Reference [54].

A bar of Fabry-Perot laser diodes provides an array of individually addressable gain media (active stripe waveguides). One facet of the laser bar is AR coated to "spoil" the reflectivity of the cleaved mirror; this feature is important, as in the case of the conventional GECL, for preventing interferometric coupled cavity effects between the longitudinal modes of the laser diodes and those of the external-cavity.Injecting current into an active stripe causes it to emit light over a broad spectral range. Light emitted from the AR coated facet is collimated by the first lens, diffracted by the grating and brought to focus in the image plane of the second lens. Lying in this image plane is one end (AR coated) of a single optical waveguide (denoted in the figure as the output waveguide). Wavelengths that are diffracted at the correct angle so as to be focussed onto the end of this waveguide are coupled into the output. Coupled light is guided down the output waveguide, is partially reflected by its cleaved uncoated facet and the reflected light then travels the same optical path in reverse. Feedback to the active stripe consequently occurs
over the narrow band of wavelengths that couples between the active stripe and output. This feedback, together with the resonant optical cavity that is formed by the cleaved uncoated facets of the two chips, causes the active stripe to lase. The wavelength of peak optical feedback is different for each stripe of the array and depends upon the stripe's angular position relative to the grating.

![Diagram of the multi-stripe array grating integrated cavity (MAGIC) laser.](image)

**Figure 4.1:** A bulk-optic equivalent of the multi-stripe array grating integrated cavity (MAGIC) laser.

Injecting current into just one of the active stripes results in single wavelength emission from the ends of both the active stripe and output waveguide. Injecting current into a different active stripe gives emission from the output waveguide at a different wavelength. The device can therefore be operated as a discretely tunable source. Current can be switched from one stripe to another at very high speeds and so fast tuning (on a nanosecond timescale) is expected. The tuning mechanism is simple (involving only the redirection of current), efficient
(there are no large tuning currents involved) and reliable (the wavelengths are determined purely by the geometry which, as we shall see, is "frozen" into the device by monolithic integration).

Simultaneous multi-wavelength emission is obtained from the output waveguide by injecting current into several of the active stripes at the same time. Each stripe is individually addressable and so laser emission can occur on either a regular comb of wavelengths (one for each active stripe), or on any arbitrarily selected subset of these channels. The laser can, in principle, have wavelengths extending across the full gain spectrum of the active material and so simultaneous operation on a large number of channels is envisaged.

The wavelengths of the MAGIC laser cannot be individually tuned and so the wavelength spacings must be accurately defined at the fabrication stage. The two-dimensional external-cavity design, as we shall see, is capable of giving as-fabricated wavelength spacings that are an order of magnitude more accurate than those of either DFB or DBR laser arrays. Precise wavelength definition without the need for tuning sections is very desirable when one is looking for a device that has a simple control mechanism. In addition, the use of a grating to combine the wavelengths has a distinct efficiency advantage when many wavelengths are to be considered. Wavelength-selective components (such as gratings) do not suffer from the splitting losses that are inherent to the class of wavelength combiner that has been used in other monolithic multi-wavelength lasers.

The output waveguide of the MAGIC laser can, in general, be either an active stripe waveguide (like those in the array) or a passive waveguide; an active output must, of course, be injection pumped before lasing can occur. An active output provides a second gain region for the wavelengths; this gain region, unlike the gain regions of the active stripe array, is shared between all of the wavelengths. Study of multi-channel amplification by travelling-wave amplifiers has shown that a shared gain medium can give rise to inter-channel crosstalk [55] - [57]. The different wavelengths interact with one another via the homogeneous gain saturation
mechanism. Increasing the optical power of one of the wavelengths leads to a
decrease in the material gain at all other wavelengths; the level of gain
 suppression depends upon the total intensity within the active material rather than
 upon the intensity at any single wavelength. Inter-channel crosstalk of this kind can
 occur with optical intensities as low as 1mW [55]. It is generally to be preferred,
 therefore, that the output waveguide of the MAGIC laser be passive rather than
 active.

Bulk-optic devices similar to that depicted in Figure 4.1 have been reported
 in the literature [58] - [61]. In one such demonstration, the output waveguide was
 replaced by a single-mode fiber loop mirror that consisted of a 50:50 fiber coupler
 with two output ports spliced together [58]. The advantage of this approach is that
 the output port of the laser is automatically coupled to a fiber ready for
 transmission. Simultaneous emission on five wavelengths in the 1.55μm band with
 a spacing of 2.5nm was achieved [58]. A single electrode was used to contact the
tops of all of the active stripes; the different wavelengths could not, as a
consequence, be individually selected. The total threshold current for all five stripes
was 74mA (roughly 15mA per channel) and more than 0.5mW per channel was
coupled out of the fiber for a total drive current of 100mA.

Another bulk-optic device that uses the two-dimensional external-cavity
design is the multichannel grating cavity (MGC) laser [59] - [61]. The output
waveguide of the MGC laser is integrated onto the same chip as the active stripe
array; the grating is consequently used in a near-Littrow configuration and so only
a single collimating lens is required (in much the same way as the grating-based
multiplexer of Figure 2.2). The output waveguide of the MGC laser is active and is
in fact identical to the active stripes within the array. The MGC laser has been used
to demonstrate simultaneous two-wavelength emission with a spacing of 2.4nm.
Wavelength switching (discrete tuning) between the two channels has also been
demonstrated; the measured switching times were as low as 2ns [60]. Side-mode
suppression has been measured for the MGC laser, but values for the SMR have
so far been limited to a little over 10dB [61]; the suppression of side modes in external-cavity devices will be treated in Chapter 6.

### 4.3: Concepts for Monolithic Integration

In the case of the MAGIC laser, monolithic integration effectively "freezes" the wavelength selectivity into the device. One of the keys to the successful realization of the monolithic MAGIC laser is the etching of a vertical-walled diffraction grating into a semiconductor planar waveguide. The concept of the etched vertical-walled grating is illustrated in Figure 4.2. The figure shows a plane grating that operates in reflection.

![Figure 4.2: Three-dimensional representation of a plane diffraction grating formed in the end of a semiconductor planar waveguide by etching vertically downwards through the waveguide's layer structure.](image)

The planar waveguide essentially forms a two-dimensional free-space region by confining light in the transverse sense, but allowing it to propagate freely in the
waveguide plane. The structure is chosen so that it is transparent to the propagating light, i.e. a passive waveguide is used. A reflective boundary is formed by etching vertically through the waveguide layers to give a semiconductor-air interface. Etching this reflective wall in the form of an array of regularly spaced elements gives the periodic structure of the grating. The figure depicts a collimated beam of light (confined within the waveguide plane) striking the grating at normal incidence. The vertical-walled reflection grating diffracts the beam back into the waveguide; the light remains confined in the transverse sense and is diffracted at an angle to the grating normal.

Examples of etched vertical-walled diffraction gratings have been reported in the literature for several material systems [62] - [66]. Curved reflection gratings have been demonstrated in the SiO₂/Si system [62], the GaAs/AlGaAs system [63] and the InGaAsP/InP system [64], [65]; plane transmission gratings have been demonstrated in the InGaAsP/InP system [66]. Apart from the fact that the grating is etched along a curve rather than along a straight line, the curved reflection gratings are identical to the plane reflection grating of Figure 4.2. Curved reflection gratings have been popular for two reasons. Firstly, the curvature of the grating gives it the ability to focus light as well as diffract it; this property can be exploited to remove the need for separate collimating/focusing elements such as lenses. Secondly, a reflection grating can be used to make a device more compact by folding optical paths back onto one another.

With the above considerations in mind, we have based the design of the MAGIC laser upon a curved reflection grating. A plan-view of the basic device geometry is shown in Figure 4.3; a similar geometry has previously been suggested [54]. A curved focusing grating is etched into one end of a planar waveguide; an array of active stripes and an output waveguide couple light into its opposite end at points that lie along a focal curve of the grating. Light that is coupled from an active stripe into the planar waveguide is free to diverge in two dimensions as it propagates towards the grating. The grating diffracts and
refocuses the light and a narrow band of wavelengths is coupled from each active stripe into the output. The opposite ends of the active stripes and output waveguide (the ends that don't couple into the planar waveguide) are defined by the left-hand cleaved-facet of the chip; the cleaved ends form the mirrors for the laser cavity. It is important to achieve efficient coupling at the active stripe / planar waveguide interfaces, and also at the output waveguide / planar waveguide interface. Efficient coupling into and out of the planar waveguide with negligible back reflection, like the AR coatings of the device in Figure 4.1, prevents coupled cavity effects.

![Plan-view schematic of a multi-stripe array grating integrated cavity (MAGIC) laser.](image)

**Figure 4.3:** Plan-view schematic of a multi-stripe array grating integrated cavity (MAGIC) laser.

### 4.4: Related Components

The etched vertical-walled diffraction gratings, together with techniques for integrating them with other optoelectronic elements, are being considered for use in a variety of monolithic DWDM components. In fact, the MAGIC laser is the third class of device to have employed the etched grating technology. The gratings were first demonstrated in the fabrication of monolithic multiplexer/demultiplexer devices (often referred to as grating spectrometers) [64] - [66]. Etched gratings have also
been used to fabricate demultiplexer-detector devices [67], [68]. Both types of device are illustrated in plan-view in Figure 4.4.

![Diagram of Passive Waveguides and Etched Grating](image)

**MUX / DEMUX**

![Diagram of Detector Array and Etched Grating](image)

**DEMUX-DETECTOR**

*Figure 4.4: Plan-view illustrations of two other monolithic grating-based components that are related to the MAGIC laser. The upper half of the figure shows an optical multiplexer/demultiplexer device, while the lower half shows an optical demultiplexer that is integrated with a detector array.*

The grating spectrometer is formed by integrating an array of passive waveguides with the grating. The operating principles of this device are identical to those of the bulk-optic grating-based multiplexer discussed in Section 2.2. The figure shows light of several different wavelengths being coupled into the spectrometer via one of the passive waveguides (the left-hand cleaved-facet of the chip may be AR coated to help maximize the coupling efficiency). If the wavelengths coincide with the channel passbands of the device, as is the case in
the figure, then each wavelength exits the chip via a different waveguide. In the case of the demultiplexer-detector device, the passive output waveguides are replaced with monolithically integrated photodetectors. The signals that are taken off of the chip are therefore electrical rather than optical.
5.1: Introduction

This chapter considers issues that relate to the semiconductor layer structure and processing techniques that are used in the experimental realization of a MAGIC laser.

Section 5.2 looks at the details of an InGaAsP/InP-based structure that is suited to the fabrication of a MAGIC laser that operates in the 1.55μm fiber band. The discussion explains how passive planar waveguide, active stripe waveguide and output waveguide structures may all be implemented on a single InP substrate and describes the way in which light is confined by and coupled between these different structures. It was noted in Chapter 4 that there is a general preference for the output waveguide to be passive rather than active; the output waveguide that is described here is therefore passive in nature.

Section 5.3 describes the growth and processing steps that are used in fabricating the structure of Section 5.2. The various stages are presented in the same order in which they occur during fabrication; this allows the processing sequence to be followed in a logical fashion from start to finish. Many of the
processing techniques that are described in this section are also relevant to the fabrication of related components (see Section 4.4) and to the fabrication of MAGIC lasers that use different material systems and/or layer structures.

### 5.2: Semiconductor Layer Structure

#### Principles for Active-to-Passive Coupling

The one requirement that has proved most influential in the choice of layer structure has been that for a repeatable and straightforward means of fabricating high-quality transitions between the active stripe waveguides and the passive planar waveguide; the transitions must give a high coupling efficiency and result in negligible back-reflection. We have adopted an approach in which the active layers of the gain regions are vertically integrated above the core layer of the passive planar waveguide [21]. This integration scheme is depicted in Figure 5.1. The figure shows a cross-sectional view of the MAGIC laser along the length of one of the active stripes at the transition point between active stripe waveguide and passive planar waveguide.

The passive planar waveguide structure consists of a core layer of quaternary InGaAsP with a bandgap wavelength, \( \lambda_g \), of 1.3\( \mu \text{m} \) (referred to as 1.3Q) sandwiched between substrate and cladding layers of InP. The thicknesses of the core and cladding layers are 0.3\( \mu \text{m} \) and \( \sim 1.0 \mu \text{m} \) respectively. (For reasons that will become apparent, the cladding consists of Fe-doped semi-insulating InP).

The standard pin structure of an injection-diode is evident in the active stripe region. The n-type layers are the same layers that form the substrate and core of the planar waveguide; the doping levels for the two layers are \( \sim 5 \times 10^{18} \text{ cm}^{-3} \) and \( 1 \times 10^{17} \text{ cm}^{-3} \) respectively. The intrinsic and p-type layers are vertically integrated on top of the planar waveguide core. The intrinsic active region consists of six 80Å InGaAs quantum wells that are separated by 100Å barriers of 1.3Q. Above the MQW stack is a 900Å layer of undoped 1.3Q, a 900Å layer of
undoped 1.2Q (quaternary InGaAsP, $\lambda_g=1.2\mu m$), two p-type InP layers (whose thicknesses are 0.4$\mu m$ and 0.5$\mu m$ respectively and whose doping levels are $1\times10^{17}$ cm$^{-3}$ and $7\times10^{17}$ cm$^{-3}$) and, finally, a 0.2$\mu m$ thick p-type upper contact layer of 1.3Q (doping level nominally $7\times10^{18}$ cm$^{-3}$). Also included in the structure, but not shown in the figure, is a thin (300Å) layer of InP that is situated between the 1.3Q planar waveguide core and the MQW stack; this serves as an etch stop layer during fabrication and will be discussed further in Section 5.3.

![Diagram](image)

**Figure 5.1:** An InGaAsP/InP-based structure that is suitable for the realization of a MAGIC laser that operates in the 1.5$\mu m$ wavelength regime. The figure shows a cross-sectional view of the MAGIC laser taken along the length of one of the active stripes at the transition point between active stripe waveguide and passive planar waveguide.

The thicknesses and bandgap wavelengths of the layers will depart slightly from their design values. Furthermore, the layers will not necessarily be perfectly lattice-matched to the InP substrate. Layer thickness and bandgap wavelength uniformities of ±1.5% and ±5nm respectively are routinely achieved over a 2-inch wafer; variations between different wafers are better than ±1.5% and ±5nm. The
layers are grown in a horizontal reactor by organo-metallic chemical vapor deposition (OMCVD) without substrate rotation (the growth is described in more detail later on); the layers are thickest in the region of the wafer that is closest to the gas source and become gradually thinner as one moves along the direction of gas flow or to either side of the main flow. The lattice mismatch between layers is typically ≤200 parts per million (ppm) ±300ppm.

Schematic refractive index profiles for the two layered structures are shown in Figure 5.2.

![Diagram of refractive index profiles](image)

**Figure 5.2:** Refractive index profiles (with respect to the transverse direction) for the active stripe waveguide and passive planar waveguide structures of the MAGIC laser, together with fundamental transverse mode profiles for the two layered structures (in schematic form only).

The refractive index is higher for materials that have a higher bandgap wavelength (shorter bandgap energy). The highest refractive index is therefore found in the smaller...
quantum wells (bulk InGaAs has a bandgap wavelength of around 1.65\mu m; quantum confinement effects will result in a slightly lower value), while the lowest refractive index occurs in the InP layers (bandgap wavelength \(\sim 0.92\mu m\)).

Also shown in Figure 5.2 are schematic modal profiles; these represent the fundamental transverse modes for the active and passive waveguide structures. The transverse modes of both regions are centred on the 1.3Q planar waveguide core layer. The quantum well layers are thin in comparison to the planar waveguide core and are placed in close proximity to the core and so their presence only slightly alters the optical mode profile. The transverse mode profiles for the two structural regions are consequently very similar; this results in highly efficient modal coupling. The transverse optical confinement factor, \(\Gamma_T\), for the laser's gain region results from overlap of the evanescent field with the quantum well active layers. Even though the peak of the transverse mode is displaced relative to the quantum well active region, it is possible to obtain reasonable values for \(\Gamma_T\) at the same time as obtaining a high coupling efficiency between the active stripe waveguide and the passive planar waveguide.

**Numerically Evaluated Active-to-Passive Coupling Efficiency**

A numerical value for the transverse modal coupling efficiency, \(\eta_T\), between the active stripe waveguide and passive planar waveguide is determined from the overlap integral

\[
\eta_T = \frac{\left[ \int_{-\infty}^{\infty} \phi_1(x) \phi_2(x) \, dx \right]^2}{\int_{-\infty}^{\infty} \phi_1(x) \phi_1(x) \, dx \cdot \int_{-\infty}^{\infty} \phi_2(x) \phi_2(x) \, dx}
\]

(5.2.1)

where \(x\) is the transverse direction and \(\phi_1(x)\) and \(\phi_2(x)\) describe the optical field profiles for the two structures. The field profiles are evaluated using computer software that solves the time-independent one-dimensional wave equation subject
to the boundary conditions that are imposed by the multiple refractive index steps. A discussion of the multi-boundary waveguide problem may be found in a number of texts, see for example Reference [69]. We also calculate the proportion of modal power that occurs in each of the waveguide layers (this allows evaluation of such parameters as $\Gamma_T$) and the modal effective index, $n_{\text{eff}}$, in each structural region.

The boundary conditions for TE modes (electric field vector in the waveguide plane) are different to those for TM modes (magnetic field vector in the waveguide plane); the waveguide structures are birefringent, the modal profiles and effective indices depending upon the polarization of the light. The MAGIC laser, like other semiconductor lasers, operates in the polarization for which the active material provides the highest gain (assuming all optical losses within the laser cavity are equal for the two polarizations). We have fabricated the MAGIC laser with unstrained InGaAs wells; unstrained material is well known to give higher gain for TE polarized light and so profiles were calculated for TE modes only.

Modal calculations require knowledge of the refractive indices of the various layers. The refractive index depends not only upon the material composition, but also upon the wavelength of the propagating mode. We have used the semi-theoretical model of Broberg and Lindgren [70] for the room-temperature dependence of the refractive index of lattice-matched InGaAsP upon material composition and wavelength. Broberg and Lindgren employed the modified single effective oscillator model that was first proposed by Afromowitz [71]; the expression that they give for the refractive index is

\[
n = \left[ 1 + \frac{E_d}{E_0} + \frac{E_d E^2}{E_0^3} + \frac{\eta E^4}{\pi} \ln \left( \frac{2E_0^2 - E_g^2 - E^2}{E_g^2 - E^2} \right) \right]^{1/2}
\]

where

55
\[ \eta = \pi E_d / 2E_0^3 (E_0^2 - E_g^2), \]  
\[ E_0 = 0.595x^2 (1-y) + 1.626xy - 1.891y + 0.524x + 3.391, \]  
\[ E_d = (12.36x - 12.71)y + 7.54x + 28.91, \]  
\[ E = 1.240 / \lambda_0. \]  

and where \( \lambda_0 \) is the free-space wavelength in \( \mu m \), \( x \) is the Ga fraction and \( y \) is the As fraction. The bandgap energy \( E_g \) is related to the As fraction \( y \) according to the relation [72]

\[ E_g [eV] = 1.35 - 0.72y + 0.12y^2 \]  

and the Ga fraction \( x \) is given (also from Ref. [72]) by

\[ x = \frac{0.1894y}{(0.4184 - 0.013y)} \]  

The discrepancy between different models for the refractive index is greatest when the photon energy is close to or above the bandgap energy (see comparison of different models given in Ref. [70]) and so we use experimental values for the refractive index of InGaAs; these values are taken from Reference [73].

Eq.'s (5.2.2) to (5.2.6) apply to undoped material; dopants give rise to free-carriers which, as mentioned in Section 3.3, reduce the refractive index. The change in index due to the free-carrier plasma effect is inversely proportional to the effective mass of the carrier and is therefore more pronounced for electrons than for holes. The change in index, \( \Delta n \), due to the free-carrier plasma effect in the conduction band may be expressed as [74]

\[ \Delta n = \frac{-N\lambda_0^2 e^2}{8\pi^2 \varepsilon_0 c^2 n m_e} \]  

56
where \( N \) is the electron concentration, \( e \) is the electronic charge, \( \varepsilon_0 \) is the permittivity of free-space, \( c \) is the velocity of light and \( m_e \) is the effective mass of the electron which, for the lattice-matched InGaAsP system, may be expressed as [74]

\[
m_e = (0.07 - 0.0308y) m,
\]

(5.2.10)

where \( m \) is the free-electron mass.

Eq. (5.2.9) may be used to calculate corrections to the refractive indices of the n-type substrate and core layers of the MAGIC laser structure. The index of the InGaAs quantum well layers will also be reduced under current injection. It has been theoretically predicted [24] that the injection-current-induced index change of InGaAs at a wavelength of 1.55μm is due to roughly equal contributions from both the free-carrier plasma effect and the "anomalous" dispersion effect. We assume a linear variation of index with carrier density at a rate given by \( \partial n/\partial N = -1 \times 10^{-20} \text{ cm}^3 \) and take the carrier density in the wells to be \( -2 \times 10^{16} \text{ cm}^{-3} \) under normal operating conditions. Experimental values for the rate of change of index with carrier density range from \( -0.7 \times 10^{-20} \text{ cm}^3 \) to \( -1.2 \times 10^{-20} \text{ cm}^3 \) [75], [76], while a value of \( -1.5 \times 10^{-20} \text{ cm}^3 \) has been theoretically predicted [24]. Uncertainty in the value of \( \partial n/\partial N \) is therefore likely to be between 30% and 40%, while the assumed value for the carrier density could easily be out by as much as 50%.

The interband and intraband absorptive mechanisms that lie behind the free-carrier induced index changes are of more concern than the index changes themselves. It is desirable to keep the optical losses within the passive planar waveguide to a minimum; the core layer is therefore only lightly doped \( (1 \times 10^{17} \text{ cm}^{-3}) \). The use of semi-insulating InP for the cladding layer effectively eliminates free-carrier effects in this region. The biggest contribution to free-carrier absorption is expected to come from the doped substrate.

Calculations for the passive planar waveguide structure indicate that it supports a single transverse mode at a wavelength of 1.55μm (it would, in fact,
remain single-moded for core thicknesses up to -0.67\(\mu\)m). The fraction of modal power that is confined in the core layer is 0.53, while the remainder of the power is split almost equally between the evanescent fields that extend into the substrate and cladding layers. The modal effective index for the passive planar waveguide structure is 3.2396 at a wavelength of 1.55\(\mu\)m; calculation accuracy is limited by discrepancies between the actual and assumed values for the thickness and bandgap wavelength of the core layer and also by uncertainty as to the amount by which the presence of free-carriers reduces the index of the substrate. Core thickness and bandgap wavelength discrepancies of ±1.5% and ±5nm each give rise to a ±0.04% error in the effective index. A factor of 2 uncertainty as to the amount by which the index of the substrate is reduced in the presence of free-carriers would lead to a further error of 0.08%. Index errors resulting from residual strain are expected to be lower by an order of magnitude and are consequently ignored [77]. The total error in the calculated value of the effective index could therefore be as much as 0.16%. The uncertainties described above also give rise to an error of ~3% in the calculated value for the fraction of modal power that is confined in the core layer.

For the structure of the active stripe waveguides, the calculated values for the modal effective index and for the transverse confinement factor, \(\Gamma_T\), in the quantum wells are respectively 3.3037 and 0.081 (roughly 0.014 per well). The active structure consists of 19 different layers and so calculation accuracy is determined by uncertainty in a large number of parameters. A 1.5% increase in well thickness, for example, gives rise to a ~0.01% increase in effective index and a ~1.6% increase in \(\Gamma_T\), while the same fractional increase in the thickness of the core layer leads to a ~0.02% increase in effective index and a ~0.5% decrease in \(\Gamma_T\). Overall, taking into account the uncertainties in layer thicknesses, bandgap wavelengths and effects of free-carriers, the errors in the calculated values of effective index and transverse confinement factor, \(\Gamma_T\), are estimated to be ~0.18% and ~4% respectively. The calculated value for the transverse modal coupling
efficiency, \( \eta_T \), at the active-passive transition is 0.89±1%.

The effective index for the passive planar waveguide may be used to
determine the structure's modal propagation constant, \( k \), using the relation
\[ k = \frac{2\pi n_{\text{eff}}}{\lambda_0}, \]
where \( n_{\text{eff}} \) is the modal effective index and \( \lambda_0 \) is the free-space
wavelength of the propagating light. However, in the case of the active stripe
waveguides, light is confined in both the transverse and lateral directions; in order
to evaluate the modal propagation constant for the active waveguides, the modal
distribution in both transverse and lateral senses must be considered.

### Lateral Confinement for the Active Stripe Waveguides

Lateral mode control for the active stripe waveguides is achieved through a
buried heterostructure configuration; this is illustrated in Figure 5.3. The figure
shows a cross section through the active stripe array that is taken at right angles to
the length of the stripes; the ends of three separate stripes are in evidence. The
intrinsic and p-type layers of each stripe form a mesa on top of the 1.3μ core layer.
The structure between the mesas is that of the passive planar waveguide.

![Active Stripe Waveguides](image)

**Figure 5.3:** Cross-sectional view of the MAGIC laser's active stripe array. This
cross-section, taken at right angles to the length of the stripes, illustrates the buried
heterostructure configuration that is used to provide lateral mode control for the
active stripe waveguides. The semi-insulating Fe-doped InP that occurs between
the stripes also provides a current blocking layer; this prevents current that is
injected into the stripes from leaking around the edges of the MQW active region.
The two-dimensional waveguide problem that is presented by the active stripe waveguides may be reduced to two one-dimensional problems by using the effective dielectric constant (EDC) method of Knox and Toulios [78]. A brief explanation of this approach is useful in explaining the lateral confinement mechanism (both for the active stripes and for the output waveguide that is to be discussed shortly).

The first step in the EDC method is to subdivide the two-dimensional waveguide into regions whose structure is laterally invariant; we see from Figure 5.3 that an active waveguide can be subdivided into three such regions, a region having the active structure surrounded on either side by a region having the passive structure. The effective index for each region is then calculated by solving the one-dimensional wave equation in the transverse direction. Following this, the one-dimensional wave equation is solved in the lateral direction for an effective slab waveguide. The effective slab waveguide has one layer for every laterally invariant region of the actual waveguide structure; the thickness and index of a given layer of the effective slab waveguide are equal to the width and effective index respectively of the appropriate region of the actual waveguide. The modal effective index that results from this second calculation takes into account both the transverse and lateral mode distributions and is used to determine the propagation constant of the waveguide.

Figure 5.4 shows how application of the EDC method to one of the active stripe waveguides gives a model for calculating the lateral mode confinement. The indices $n_{\text{eff}}$ and $n_{\text{eff}}^\pi$ in the figure are equal to the modal effective indices that were previously calculated for the active and passive waveguide structures. The lateral modes of the active waveguide are controlled through appropriate choice of the active stripe width $w$. We calculate that a single lateral mode is supported for values of $w$ less than $\sim 1.2\mu$m. It is assumed, for the moment, that a stripe width of 1.2\mu m is used. The lateral confinement factor, $\Gamma_L$, has a value of $0.84 \pm 1.3\%$ and the overall modal effective index, taking into account both transverse and lateral
confinement, is 3.2812±0.13%. The confinement factor, \( \Gamma = \Gamma_T \Gamma_L \), for the quantum well active region is consequently equal to 0.068±5.3%.

**Figure 5.4:** Application of the effective dielectric constant (EDC) method to the two-dimensional waveguide problem that is presented by the buried heterostructure configuration of the MAGIC laser's active stripe waveguides. The EDC method simplifies calculations by reducing the two-dimensional problem to two one-dimensional problems.

We have already calculated the transverse modal coupling efficiency, \( \eta_T \), at the interface between an active stripe waveguide and the passive planar waveguide. Knowing the propagation constants for the two waveguides means that we can, in addition, calculate the Fresnel reflectivity at the interface. Using the values for the effective indices that have been given above, we calculate a Fresnel power reflectivity of just 0.004%.

The buried heterostructure configuration provides a second function (in addition to that of lateral mode control). By blocking the flow of current around the active regions, the semi-insulating InP ensures that current that is injected into an active stripe is channeled into the quantum wells.
The Passive Output Waveguide

A passive output waveguide may be realized in a straightforward manner by forming a ridge in the cladding layer of the passive planar waveguide structure; a ridge waveguide of this type is illustrated in schematic form in Figure 5.5. The ridge is formed by removing cladding layer material from the regions to either side of the proposed position of the waveguide. Removal of material reduces the effective index of the waveguide structure; the effective index $n_{\text{eff}}^I$ in the region of the ridge is thus higher than the effective index $n_{\text{eff}}^{\text{II}}$ in the regions to either side. The lateral modes that are supported by the output waveguide are determined by the amount of cladding material that is removed (this determines the lateral effective index contrast) and by the width of the ridge (i.e. waveguide width).

$\text{Fe:InP}$

$\text{n-InP}$

$\text{Fe:InP}$

$\text{n-InGaAsP, } (\lambda_g=1.3\mu m)$

$\text{n}^+\text{-InP}$

$\text{Optical Mode}$

$\text{n}_{\text{eff}}^I$ | $\text{n}_{\text{eff}}^{\text{II}}$ | $\text{n}_{\text{eff}}^I$ | $\text{n}_{\text{eff}}^{\text{II}}$ | $\text{n}_{\text{eff}}^I$

\textbf{Figure 5.5:} Cross-sectional view of a passive ridge waveguide that would be suitable for use as the MAGIC laser's output. The ridge is formed by simply removing material from the cladding layer of the passive planar waveguide structure.
5.3: Processing Sequence and Techniques

The MAGIC laser structure of Section 5.2 is grown on a (100) n⁺-InP substrate by low pressure (76 Torr) organo-metallic chemical vapor deposition (OMCVD) at 620°C. Fabrication involves two stages of growth and a number of intermediate processing steps.

**Initial Growth**

The first step is to grow the active structure across the full area of the device; the following layers are therefore grown on the n⁺-InP substrate:– (i) a 0.5μm n⁺-InP buffer layer, (ii) the 0.3μm n-lnGaAsP (λ_g=1.3μm) waveguide core layer, (iii) the 300Å InP etch-stop layer, (iv) the undoped MQW active region, (v) the two 900Å undoped InGaAsP grading layers (λ_g=1.3μm and λ_g=1.2μm respectively), (vi) the two layers of p-type InP (total thickness 0.9μm) and (vii) the 0.2μm upper contact layer of p-type InGaAsP (λ_g=1.3μm).

**Formation of Active Mesas**

As already seen, each active waveguide consists of an isolated stripe of the active structure; these stripes are formed by selectively removing the p-type and undoped layers with a combination of dry and wet etching through a SiO₂ mask. A 2500Å layer of SiO₂ is deposited on the surface of the wafer by plasma vapor deposition (PVD). The wafer is then spun with 1.2μm of positive photoresist which is patterned by standard contact photolithography; stripes of photoresist running in the [110] direction are left on top of the oxide where active waveguides are desired, while the photoresist is removed from the rest of the chip so as to expose the oxide underneath. The exposed oxide may be removed by reactive ion etching (RIE) with C₂F₆; the etch rates for the oxide and photoresist are similar and so all of the oxide and most of the protective photoresist remain on top of the semiconductor in the active stripe regions. The masking for the active stripes is now complete and so the next stage is to etch the p-type and undoped layers in the unmasked regions;
Figure 5.6 (a) shows the region for the active stripe array prior to etching. The etching for the active mesas is performed in three stages:-

(i) Ion milling is used to remove the upper p++-InGaAsP (λg=1.3μm) contact layer and approximately half to three-quarters of the two p-type InP layers; roughly 0.75μm of material is removed in total. Ion milling also removes the protective layer of photoresist from the active waveguide regions. Figure 5.6 (b) shows the structure in the active stripe region after ion milling; the etch is anisotropic and non-selective and gives a nearly vertical profile.

(ii) A selective InP etch (HCl:H₃PO₄, dilution ratio of 1:3) is then used to remove the remaining p-type InP; the etchant stops on the 900Å undoped 1.2Q layer. The structural profile after completion of the InP etch is illustrated in schematic form in Figure 5.6 (c). Defining the stripes to lie along the [110] direction causes the wet etch to undercut the SiO₂ mask (and the upper InGaAsP contact layer).

(iii) Finally, a selective quaternary etch (H₃PO₄:H₂O₂:H₂O, dilution ratio of 1:1:8) is used to remove the 900Å undoped 1.2Q layer, the 900Å undoped 1.3Q layer and all of the layers of the MQW stack; the etchant stops on the 300Å InP etch-stop layer (not shown in the figures) that lies between the MQW stack and the 0.3μm 1.3Q waveguide core layer. The etch rate for the quaternaries depends upon their material composition, the rate becoming slower as the composition approaches that of InP. The undercutting that occurs with the wet etch consequently forms a "waist" in the active region; this "waist" is illustrated in Figure 5.6 (d). The widths of the active regions are therefore determined by the SiO₂ mask width and also by the final wet etching process. Chemical etching can therefore be used as an additional means of controlling the lateral mode profiles of the active stripe waveguides.
Figure 5.6: Cross-sectional view of the active stripe region of the MAGIC laser during various stages of stripe definition (see text for details).
Semi-insulating InP Regrowth

Formation of the active stripe mesas is now complete and the device is ready for the second stage of growth. The wafer is returned to the OMCVD reactor with the SiO₂ masks intact for selective area regrowth of ~1.0μm of Fe-doped semi-insulating InP (Fe concentration in the high 10^17 's cm⁻³). The oxide masks prevent growth from occurring on top of the active mesas; growth occurs in all of the unmasked regions from which the p-type and undoped layers have been removed. The Fe-doped InP layer completes the passive planar waveguide structure and also completes the formation of the buried heterostructure configuration for the active stripe waveguides. When the regrowth is complete, the wafer is taken out of the OMCVD reactor and the SiO₂ masks are removed from the top of the active stripes using a buffered HF solution.

Grating Fabrication

The next stage of processing is to etch the vertical-walled diffraction grating into the planar waveguide structure. A composite oxide/chrome mask is used for the grating etch. Firstly, between 5000Å and 6000Å of SiO₂ are deposited across the full area of the chip by PVD. The chip is then spun with 0.5μm of positive photoresist and the grating pattern is transferred from a photomask to the photoresist by standard contact lithography. Accurate positioning of the grating is important since the operating wavelengths of the MAGIC laser are determined by the geometry of the grating, active stripes and output waveguide; our contact aligners allow one to achieve alignment tolerances of ±0.8μm. A light-field photomask is used to pattern the photoresist; photoresist therefore remains in the area that is to be etched, but is removed from the remainder of the chip so as to expose the oxide layer underneath. Figure 5.7 (a) shows the grating region after photolithographic patterning.
Figure 5.7: The diffraction grating of the MAGIC laser during various stages of fabrication (see text for details).
The chip is then placed in an electron-beam evaporator and a 350Å layer of chrome is deposited on the surface. Because, in the grating region, the chrome layer is formed on top of the photoresist, both may be removed by dissolving the photoresist in acetone (i.e. by the standard lift-off procedure); this exposes the oxide layer underneath. The exposed oxide is then removed by RIE with C2F6 in order to complete the formation of the composite oxide/chrome mask that is used for the grating etch process. Figure 5.7 (b) illustrates the way in which the surface of the chip, except in the area that is to be etched to form the grating, is protected by this oxide/chrome mask.

The diffraction grating is formed by etching vertically downwards through the planar waveguide structure to a depth of ~3μm by a process of chemically assisted ion beam etching (CAIBE) [79]. A 1500V Xe+ sputtering beam is used in conjunction with a reactive gas flux of Cl2. With appropriate control of the ion energy, ion flux and reactive gas flow rate, the CAIBE process can give a highly anisotropic non-selective etch [79]. A non-selective etch is essential for avoiding any step-like functions in the profile that can result from having layers of varying material composition. A highly anisotropic etch is required to produce a vertical grating; tilted grating walls can reflect light into the planar waveguide substrate. The grating tilt, as determined using a scanning electron microscope (SEM), is typically between 2° and 4°. The loss that is incurred as a result of this tilt is estimated to be between 0.04dB and 0.16dB. Figure 5.7 (c) shows the grating region of the MAGIC laser after completion of the CAIBE etch; the etching process erodes the chrome layer of the mask and also a proportion of the oxide layer. The CAIBE process, when properly controlled, can produce the very smooth sidewalls that are required for a high efficiency grating.

**Grating Metallization**

The grating reflectivity may be improved by coating the etched wall with a layer of metal (the semiconductor-air interface gives a power reflectivity of only
Diffusion of the grating metallization into the semiconductor, resulting in degradation of the grating's performance, can however be a problem if the metal contacts for current injection (still to be formed) are thermally annealed. We therefore use aluminium, a metal having a relatively low diffusion coefficient, on the grating. Cohesion of the aluminium to the semiconductor can be rather poor; we therefore deposit a quarter-wave layer of aluminium oxide onto the grating wall prior to putting down the aluminium. The calculated power reflectivity for this composite coating is 0.91.

The wafer is spun with 1.2μm of +ve photoresist and the photoresist is patterned so as to form an opening in the region of the grating. The quarter-wave layer of aluminium oxide is then deposited on the grating wall by PVD. 500Å of aluminium (the skin depth of aluminium at 1.55μm is roughly 60Å) is then deposited on top of the oxide layer by angled electron-beam evaporation. A further layer of aluminium oxide is deposited on top of the aluminium in order to prevent oxidation. The photoresist mask is then dissolved in acetone so as to remove the reflective coating from everywhere but the grating region.

Fabricating the Output Waveguide

As discussed in Section 5.2, a passive output waveguide may be fabricated by forming a ridge in the surface of the planar waveguide structure. The ridge is fashioned by removing material from the cladding layer in regions to either side of the desired position of the waveguide (see Fig. 5.5). Material is removed by reactive ion etching through an oxide mask with an H₂/C₂H₄ gas mixture. The chip, with the exception of the grating region, is already covered with SiO₂ (left over from fabricating the grating) and so no further deposition of oxide is required. The chip is spun with 1.2μm of positive photoresist and is patterned by standard contact photolithography. The photoresist is removed from two 50μm wide regions; the length of the regions determines the length of the output waveguide, while their separation determines the ridge width. As with the grating, the positioning of the
output waveguide is very important and is accurate to within ±0.8μm. The oxide that is exposed in the two 50μm wide openings is removed by reactive ion etching with \( C_2F_6 \) and the remaining photoresist is then washed off with acetone. It should be noted that there is no oxide covering the grating region; the grating must therefore be protected by alternative means prior to etching the output waveguide. The grating is protected by a thick layer of photoresist that is applied locally with a pipette (and which is removed again at the end of the processing stage). The \( H_2/C_2H_4 \) reactive ion etch for the output waveguide may now be performed; the etch depth depends upon the refractive index contrast that is sought.

**Contact Metallization, Wafer Thinning and Cleaving**

All of the functional elements of the MAGIC laser, namely the active stripe waveguides, the diffraction grating and the output waveguide, have now been formed. However, before the device is complete, contact metal is required for current injection into the active stripe waveguides and the chip must be cleaved to provide output facets.

We first form a p-type electrode on top of each active mesa. The chip is spun with 1.2μm of positive photoresist and the photoresist is patterned so as to open up a narrow (2.5μm) stripe along the length of each active waveguide. Reactive ion etching with \( C_2F_6 \) is then used to remove the oxide in the openings, so exposing the p++-1.3Q upper contact layer of each mesa. The photoresist is then washed off with acetone and a new layer of photoresist is spun on the chip. Again, the photoresist is patterned so as to open up a stripe above each active waveguide, however, the width this time is 20μm. The p-type metal is then deposited on the chip by electron-beam evaporation; first a 200Å layer of Ti is deposited and then an 8000Å layer of Au. Standard liftoff is then employed to remove the metal from around the 20μm contact stripes.

A single n-type contact is used on the reverse side of the device, but before it can be formed, the chip must be thinned to allow for subsequent cleaving. The
wafer is chemically thinned to approximately 0.25mm by lapping with a bromine/methanol solution (between 2% and 10% bromine, depending on the etch rate required). Electron-beam evaporation is then used to deposit the following sequence of metals on the reverse side of the chip:- 100Å Ni, 350Å Ge, 500Å Au, 350Å Ni and 2000Å Au. Finally, the chip is cleaved in a direction perpendicular to the active stripes in order to form the output facets.
Chapter 6

Device Design

6.1: Introduction

Chapter 4 showed that the MAGIC laser comprises a curved diffraction grating, an active stripe array and an output waveguide; Chapter 5 showed how these elements can be implemented in the InGaAsP/InP material system for operation in the 1.55μm regime. This chapter describes how to optimize the design and layout of the elements.

The MAGIC laser is based upon the Rowland circle solution [80] for circular gratings. This focal solution is described in Section 6.2; consideration is given to the solution's basic form and also to a method for correcting focal aberrations. Section 6.2 also introduces general design features and nomenclature that are assumed throughout the remainder of the chapter.

Section 6.3 discusses factors that determine the laser's wavelength spacing. This leads us to adopt a systematic approach to grating parameter selection. We illustrate this approach by deriving suitable grating parameters for a MAGIC laser that operates over a 30nm range in the region 1.530μm to 1.560μm. This example device is used again in subsequent sections for illustrative purposes.
Section 6.4 discusses the influence of finite lateral mode sizes upon the efficiency with which light couples back-and-forth between the active stripes and output waveguide. The topics covered here include grating magnification and wavefront-tilt effects.

Section 6.5 discusses the issue of grating size. It is important that the grating be large enough to collect all of the light that is coupled into the planar waveguide by the active stripes and output waveguide. We evaluate the size of grating that is appropriate for the example device of Section 6.3. This allows us to assess the importance of the aberration effects discussed in Section 6.2.

Section 6.6 is concerned with the spectral purity of the MAGIC laser's operating wavelengths. Side-mode suppression ratios are theoretically estimated for the example device of Section 6.3.

### 6.2: General Configuration

#### The Rowland Circle Solution for Circular Gratings

Figure 6.1 shows a circular diffraction grating of radius of curvature R, together with a second circle of radius R/2. The latter is known as the Rowland circle [80]. The Rowland circle is constructed in such a way that its circumference is tangential to the grating surface at the point O. This point is known as the grating pole. If the projection of the grating spacing onto the tangent to the grating that passes through O (shown as the w axis in Figure 6.1) is a constant, d, then light originating from a point source A on the Rowland circle will be focussed to another point B lying on the same circle. The focal point is wavelength dependent by virtue of the dispersive nature of the grating. With A and B defined by their angular positions $\alpha$ and $\beta$ relative to the grating normal at the pole, the focal point may be found for any general wavelength from the relation
\[ d(\sin \alpha + \sin \beta) = \frac{p \lambda_0}{n} \]  

(6.2.1)

where \( p \) is the order of interference, \( \lambda_0 \) is the free-space wavelength and \( n \) is the index of refraction for the propagating light. In this special case (for which the locus of the focal points is restricted to the Rowland circle), the angles of incidence and diffraction are related by the same equation (Eq. (6.2.1)) as in the case of a planar grating.

**Figure 6.1:** Geometry of the Rowland circle solution for a circular grating. The grating forms an image of point A at point B; A and B both lie on the Rowland circle.

**Focal Aberrations and their Correction**

Although Eq. (6.2.1) allows us to calculate the image position, it tells us nothing about the image quality. Such information may be obtained by evaluating an expression for the path length (AP+BP) for a ray that is incident upon the grating...
at some general point P. This problem has been considered by Beutler [81] for the case of a spherical grating with A and B at arbitrary positions (not confined to the Rowland circle). Beutler showed that the path length may be expressed as a series of terms in the coordinates of P. Although Beutler's general terms are fairly cumbersome, our specific case leads to significant simplification. Firstly, simplification results from the two-dimensional nature of our system which, for example, sets terms associated with astigmatism to zero. The reduced dimensionality makes it possible to specify the path length in terms of a single coordinate of P - the w coordinate (the zero point being the grating pole). The path length \((AP+BP)\) may therefore be expanded in a series of the form

\[
(\ AP + BP \ ) = (AO + BO) + F_1(w) + F_2(w) + F_3(w) + \cdots
\tag{6.2.2}
\]

where each individual term may be identified with some aspect of the either the focal position or the image quality. Further simplification results from positioning A and B upon the Rowland circle. The difference \(\Delta L\) in path length for rays passing via P and O may, in this case, be expressed as

\[
\Delta L = [(AP+BP) - (AO+BO)] = -w(\sin \alpha + \sin \beta)
+ \frac{w^4}{8R^3} \left[ \frac{\sin^2 \alpha}{\cos \alpha} + \frac{\sin^2 \beta}{\cos \beta} \right]
+ \frac{w^5}{8R^4} \left[ \frac{\sin^3 \alpha}{\cos^2 \alpha} + \frac{\sin^3 \beta}{\cos^2 \beta} \right]
\tag{6.2.3}
\]

where the expansion has been performed up to the 5th order in \(w\).

As we shall see, it is generally possible to use a grating that has dimensions that are small in comparison to the radius of curvature \(R\). In this case, if the grating is used in the region around O (i.e. it is centred at \(w=0\)), the increasing power of \(R\)
in the denominator of the terms in Eq. (6.2.3) causes their magnitude to decrease with increase in the order of \( w \).

For the grating to diffract light from A and for the light to then constructively interfere at B, the path length for the rays passing via any two neighbouring grating elements must differ by an integral number of wavelengths. The integer in this case is the order of interference \( p \). If one grating element has an end at O, then other grating elements should be located around the grating surface such that their corresponding ends are defined by points for which

\[
\Delta L = kp \frac{\lambda_o}{n} \quad (6.2.4)
\]

where \( k \) is an integer that gives the "number" of the grating element (i.e. the \( k \)th element counted from O) and which takes both +ve and -ve values.

We initially consider the region around the grating pole. In this region \( w \ll R \) and so the magnitudes of the fourth and fifth order terms in Eq. (6.2.3) are negligible in comparison to the wavelength. The \( w \) coordinate of the \( k \)th grating element may therefore be found from the expression

\[
-w_k (\sin\alpha + \sin\beta) = kp \frac{\lambda_o}{n} \quad (6.2.5)
\]

This shows that the region of the grating around O will focus light of wavelength \( \lambda_o \) from A to the point B provided that the grating spacing in this region has a constant projection \( d_0 \) onto the \( w \) axis. The constant \( d_0 \) is given by

\[
d_0 = \left| \frac{w_k}{k} \right| = \frac{p \lambda_o}{n(\sin\alpha + \sin\beta)} \quad (6.2.6)
\]

We note that Eq. (6.2.6) is identical to Eq. (6.2.1); this confirms the validity of the
focal solution that was presented earlier. Eq. (6.2.6) describes the "classic" circular grating from Rowland's era. The ruling engine technology that was used at the time gives a linear stepping function that is ideally suited to producing a spacing that has a constant projection onto the grating's tangent.

The focal solution for the "classic" circular grating is, however, based upon the assumption that certain high order terms in the path length expansion may be neglected. The magnitudes of these terms increase as one moves away from the grating pole; the assumption breaks down when the neglected terms become comparable in magnitude to the wavelength of the light. The neglected terms describe path length errors that destroy the phase coherence at the focal point. These edge-effects are similar to those seen in lenses, the term of fourth order in \( w \), for example, being analogous to spherical aberration.

Since the grating of the MAGIC laser is defined by photolithography, we are free to set the spacing for each individual grating tooth when designing the photomask. This allows us to "tailor" the spacing so that it no longer has a constant projection onto the \( w \) axis. This technique may be used to modify the imaging properties of the grating in a way that reduces the edge-effects.

An equivalent equation to Eq. (6.2.5), but one that is now correct up to the 5th order in \( w \), may be written as

\[
\frac{kp \lambda_o}{n} = -w_k (\sin \alpha + \sin \beta) + \frac{w_k^4}{8R^3} \left[ \frac{\sin^2 \alpha}{\cos \alpha} + \frac{\sin^2 \beta}{\cos \beta} \right] + \frac{w_k^5}{8R^4} \left[ \frac{\sin^3 \alpha}{\cos^2 \alpha} + \frac{\sin^3 \beta}{\cos^2 \beta} \right]
\]  

(6.2.7)

An aberration-corrected grating may therefore be realized by placing the grating elements at positions \( w_k \) that are determined by solving Eq. (6.2.7). For this correction method to be effective, the magnitude of the lowest order neglected term must be a small fraction of a wavelength (less than, say, a quarter wavelength) at
either extreme of the grating. The correction may, of course, be performed for only one wavelength even though the grating is to be used over a finite spectral range. Residual aberration effects will exist for other wavelengths and so the correction should, in general, be performed for the central wavelength in the desired operating range.

By including the higher order terms in Eq. (6.2.7), it has become necessary to give a more general definition to the parameter \( d \). The "tailored" spacing of an aberration-corrected grating no longer has a constant projection onto the \( w \) axis. It has, however, been seen that the positions of the grating elements remain unchanged in the region around the grating pole \( O \) (\( d_0 = d \)). In addition, we note that at \( O \) the actual grating spacing is identical to its projection onto the \( w \) axis. We therefore define \( d \) to be the actual grating spacing at \( O \); in this way its value remains unaffected by the correction process.

**Basic Device Layout and Associated Nomenclature**

Figure 6.2 illustrates the relative geometrical positioning of the active stripe array, diffraction grating and output waveguide of a MAGIC laser that is based upon the Rowland circle solution for a circular grating. One end of each active stripe and one end of the output waveguide terminate on the Rowland circle. The locations of these ends are specified through reference to their angular positions relative to the grating normal at \( O \): the angle \( \beta_i \) gives the position of the \( i \)th active stripe (where \( i \) is an integer between 1 and \( N \) and \( N \) is the total number of stripes), while the angle \( \alpha \) gives the position of the output waveguide. The lasing wavelength \( \lambda_i \) of the \( i \)th active stripe may be found directly from Eq. (6.2.1) by substituting \( \beta_i \) for \( \beta \), \( \lambda_i \) for \( \lambda_0 \) and \( n_{eff,i} \) for \( n \) (where \( n_{eff,i} \) is the modal effective index of the MAGIC laser's passive planar waveguide structure at wavelength \( \lambda_i \)). The shortest wavelength in the output spectrum of the device is generated by the stripe with the smallest value of \( \beta_i \) (i.e. \( \beta_i = \beta_1 \)), while the longest wavelength is generated by the stripe for which \( \beta_i \) is greatest (i.e. \( \beta_i = \beta_N \)).
We have seen that aberration effects are minimized by using the region of the grating that lies around the pole. This can be achieved if we align the active stripes and the output waveguide so that they all point towards O. However, fabrication issues (i.e. wet etching profiles and formation of the output facet by cleaving) make it desirable to have the active stripes parallel to one another and along a crystallographic axis. We therefore consider the design of a device for which the active stripes are parallel; the array is arranged so that the central stripe (angular position $\beta_c$) lies along an axis that passes through O (the z-axis in Figure 6.2). We assume that the output waveguide is a passive ridge waveguide of the type discussed in Chapter 5. The profile of the RIE etch that is used to fabricate this waveguide is insensitive to the crystallographic orientation. We therefore allow the output waveguide to curve; the output waveguide is parallel to the active stripes at its cleaved end, but points towards O at the end that terminates on the Rowland circle.

![Figure 6.2: Application of the Rowland circle geometry to the implementation of a MAGIC laser.](image)
6.3: Wavelength Spacing

This section considers what limits, if any, there are to the channel spacing that can be achieved using the laser configuration that is depicted in Fig. 6.2; this will tell us how many wavelength channels can be obtained within a given spectral range.

Grating Dispersion

The wavelength spacing of the MAGIC laser decreases with decreasing inter-stripe separation and also with increasing linear dispersion $dy/d\lambda_o$ (measured along the circumference of the Rowland circle in the region of the active stripe array). Concerns over inter-channel crosstalk (due to electrical and thermal effects) make small inter-stripe separations undesirable; factors limiting the linear dispersion are, however, less clear.

An equation for the linear dispersion $dy/d\lambda_o$ may be derived by differentiating Eq. (6.2.1) with respect to $\lambda_o$ (with $\alpha$ held constant) to obtain the angular dispersion $d\beta/d\lambda_o$ and by then converting the small angular changes $d\beta$ into linear changes $dy$ parallel to the y-axis. The expressions that are derived in this way are

$$\frac{d\beta}{d\lambda_o} = \frac{p}{n_{\text{eff}} \cos \beta} \left( 1 - \frac{\lambda_o}{n_{\text{eff}} \frac{dn_{\text{eff}}}{d\lambda_o}} \right)$$  \hspace{1cm} (6.3.1)

$$\frac{dy}{d\lambda_o} = R \cdot \cos(2\beta - \beta_c) \frac{d\beta}{d\lambda_o}$$  \hspace{1cm} (6.3.2)

$$\frac{dy}{d\lambda_o} = \frac{R p}{n_{\text{eff}} d} \cdot \cos(2\beta - \beta_c) \left( 1 - \frac{\lambda_o}{n_{\text{eff}} \frac{dn_{\text{eff}}}{d\lambda_o}} \right)$$  \hspace{1cm} (6.3.3)
It should be noted that the refractive index $n$ of Eq. (6.2.1) has been replaced by the modal effective index $n_{\text{eff}}$ of the MAGIC laser's passive planar waveguide structure.

Eq. (6.3.3) has been separated into three distinct factors that each have their own physical significance. The first factor, $R_p/n_{\text{eff}}$, essentially controls the magnitude of the linear dispersion. The second factor, $\cos(2\beta-\beta_c)/\cos\beta$, describes dispersion non-uniformity around the point $\beta=\beta_c$. In order to have a constant channel spacing one must use an array whose stripe separation varies from one stripe to the next; this fact must be taken into account when specifying a minimum value for the inter-stripe separation. Figure 6.3 shows that the dispersion non-uniformity becomes more pronounced as the angular position $\beta_c$ of the active stripe array increases. The third contribution to the linear dispersion is provided by the term $[1-(\lambda_0/n_{\text{eff}})(d\lambda_{\text{eff}}/d\lambda_0)]$; this term describes the effects of chromatic dispersion and may be expressed alternatively by the ratio $n_g/n_{\text{eff}}$, where $n_g$ is the group index of the passive planar waveguide.

![Graph showing the variation of the angular part of the expression for linear dispersion](image)

**Figure 6.3:** The variation of the angular part of the expression for linear dispersion (measured along the circumference of the Rowland circle) in the region of the central active stripe (see text). Curves are shown for four values of the angular position $\beta_c$ of the central stripe.
Selecting Grating Parameters for Maximum Dispersion

A large linear dispersion is obtained by using a grating of large radius of curvature, R, and small spacing, d, in a high diffraction order, p. Increase in the radius of curvature leads to a proportional increase in the dimensions of the device (the distance from the center of the array to O, for example, is simply $R \cos \beta_c$).

There are several reasons to favour a small device; these include lower material costs, lower optical losses in a round-trip of the cavity (resulting, for example, from reduced free-carrier absorption) and higher direct modulation rates for each of the laser's channels. The maximum modulation rate is directly related to the time that it takes for light to make a round-trip of the cavity. External-cavity lasers are, in general, poorly suited to direct frequency modulation [82] (this is because the presence of the external cavity makes the operating frequency fairly insensitive to changes in the injection current); current injection can, however, be used to provide direct amplitude modulation. In the case of return-to-zero (RZ) operation, it can take up to 100 cavity round-trip times for the intensity and spectral characteristics of the laser emission to approach their dc values [83]. Modulation rates of 100 Mbit/s, for example, can consequently demand a round-trip time of as little as 0.1 ns; this corresponds to a cavity length of just ~4.5 mm (higher modulation rates may be expected for non-return-to-zero operation with the laser biased above threshold since, in this case, the laser mode is already set up). In light of the above, let us consider how to optimize the values of p and d before we trade off wavelength spacing against device size.

We first note that the free-spectral range of a grating operating in the p'th order is given by $\lambda_0/p$. If the integrity of the wavelength of each and every channel is to be assured, then the wavelengths that are diffracted from each active stripe to the output waveguide in the (p-1)'th and (p+1)'th orders must, under all pumping conditions, experience less gain in a cavity round-trip than the wavelength that is diffracted to the output waveguide in the p'th order. This may be guaranteed by arranging that the free-spectral range be greater than the width of the gain
spectrum. This effectively places an upper limit on our choice of \( \rho \). A typical MQW active region can provide gain over a spectral range of roughly 100 nm. Using the grating in the 15'th order results in an FSR of \( \sim 100 \) nm for operation around 1.55 \( \mu \)m. This would guarantee the integrity of each and every wavelength of a device that is designed to operate over the entire gain spectrum.

Secondly, we note that light from each active stripe can be diffracted by the grating straight back to the same stripe (or, indeed, to another stripe). This unwanted feedback may be prevented by appropriately blazing the grating and by carefully choosing its spacing. The blazing is used to control the angular position of the Fraunhofer envelope function of the grating's diffraction pattern; the peak of the envelope function may be centered upon the output waveguide in order to give a high stripe-to-output coupling efficiency. Light incident upon the grating is uncollimated and so a variable blazing angle is required. The grating spacing may then be used to control the angular width of the envelope function; the angular width determines the relative magnitudes of the stripe-to-output and stripe-to-stripe coupling efficiencies. The envelope width increases as \( d \) decreases and so the issue of direct-feedback to the active stripes effectively places a lower limit on our choice of \( d \).

It should be noted that the width of the Fraunhofer envelope function also affects the uniformity of the stripe-to-output coupling efficiencies; this fact should be borne in mind when selecting a value for \( d \). If we assume that the grating blazing is optimized for the diffraction of light between the center of the array and the output waveguide, then active stripes that are situated near the center of the array will have a higher stripe-to-output coupling efficiency than those that are situated towards the edges of the array. A rough guideline for minimizing such effects is to ensure that the full width at half maximum (FWHM) of the envelope function is greater than the angular width \( (\beta_N - \beta_1) \) of the active stripe array.

If the grating blazing is, as discussed above, optimized for the center of the active stripe array, then the grating element facets in the region around the pole will
be orientated at an angle of \((b_c + \alpha)/2\) relative to the \(w\)-axis. The size of these facets is therefore equal to \(d\cos[(b_c + \alpha)/2]\). As was mentioned above, the light that is incident upon the grating is uncollimated and so a variable blazing is required. There will therefore be a slight variation in the size of the grating element facets around the circumference of the grating; the facet size gets slightly larger in the direction of \(+ve\ w\) and slightly smaller in the direction of \(-ve\ w\). We use the mean value when calculating envelope widths for the diffraction pattern. The effective aperture width, \(d'\), that is responsible for the profile of the Fraunhofer diffraction envelope is found by projecting the actual width of the grating element facet onto a line that is perpendicular to the direction of the envelope maximum; this gives the expression

\[
d' = d\cos\left[\frac{(b_c + \alpha)}{2}\right]\cos\left[\frac{(b_c - \alpha)}{2}\right]
\]

We take the envelope function to be identical to the Fraunhofer pattern produced by a uniformly illuminated slit of width \(d'\).

**Example**

The issues that have been discussed above are best illustrated by considering a specific example; we shall consider the design a MAGIC laser that operates over a spectral range of 30nm centered at 1.545\(\mu m\). Such a device would be suited to a multi-wavelength optical system that employs Erbium-doped fiber amplifiers. We shall assume that \(b_c\) has a value of 60\(^\circ\) and shall design the laser to operate in the 15\(^{th}\) order (thereby giving an FSR of \(-100nm\)). The design shall be based upon the structure that was discussed in Chapter 5.

We start by evaluating values for the modal effective index, \(n_{eff}\), of the MAGIC laser's passive planar waveguide structure. Figure 6.4 shows the variation of the modal effective index in the spectral range 1.530\(\mu m\) to 1.560\(\mu m\); the index was calculated for 16 wavelengths spaced by 2nm. A linear least-squares fit to the
data (shown in the figure by the solid line) gives the expression

\[ n_{\text{eff}} = 3.6303 - 0.2522\lambda_0 \]  

(6.3.5)

where \( \lambda_0 \) is in microns.

**Figure 6.4:** Variation of the modal effective index, \( n_{\text{eff}} \), of the MAGIC laser's passive planar waveguide section as a function of wavelength in the spectral region 1.53\( \mu \)m to 1.56\( \mu \)m. The square symbols represent calculated values for 16 different wavelengths, while the solid line represents a linear least-squares fit to the data.

As was previously discussed, our task is to select a low value of \( d \) so as to obtain a high dispersion, but to ensure that its value is large enough to prevent significant direct-feedback to the active stripes. We note that the intensity of the first subsidiary maximum of the envelope function relative to that of the principal maximum is 0.047 (see, for example, pp. 405 of Reference [4]), i.e. in excess of 13dB down. By choosing \( d \) so that the angular half-width of the envelope function
(principal maximum to first zero point) is smaller than the angular separation ($\beta_1 - \alpha$) between the output and the closest active stripe, we would expect the coupling efficiency for any stripe back to itself to be roughly 13dB lower than the stripe-to-output coupling efficiency. We shall use this criterion as a first step in determining the lower limit on $d$; we shall then consider relative stripe-to-output and stripe-to-stripe coupling efficiencies that result from using a value of $d$ that is close to this limit.

Eq. (6.2.1) is used to calculate the angular position $\alpha$ of the output waveguide for any value of $d$ (using $\beta = \beta_c = 60^\circ$, $n = n_{\text{eff},c} = 3.241$ and $\lambda_o = \lambda_c = 1.545\mu$m). This value of $\alpha$ can then itself be used in Eq. (6.2.1) to derive values for $\beta_1$ and $\beta_N$. Figure 6.5 (a) shows curves of both ($\beta_1 - \alpha$) and the envelope half-width (maximum to first zero point) for an aperture of width $d'$ plotted as a function of $d$. The decreasing magnitude of ($\beta_1 - \alpha$) that occurs as the value of $d$ is reduced is primarily the result of an increase in $\alpha$; this may be seen from the plots of Figure 6.5 (b). We see from Figure 6.5 (a) that the half-width of the Fraunhofer envelope is smaller than ($\beta_1 - \alpha$) for $d > 4.4\mu$m. A value for $d$ of $4.5\mu$m would therefore seem suitable.

We now use our values of $p$ and $d$, and also our data on the modal effective index, $n_{\text{eff}}$, to determine a value for the linear dispersion. The discussion may be simplified by considering the dispersion at the center of the array where, since $\beta = \beta_c$, the term in Eq. (6.3.3) that is associated with dispersion non-uniformity evaluates to 1. In this case the linear dispersion is given by $(R \rho / n_{\text{eff},c} d) \cdot (n_g / n_{\text{eff},c})$. The ratio of the group index to the modal effective index evaluates to $\sim 1.120$ at $1.545\mu$m (the magnitude of this term varies by only 0.25% over the entire 30nm spectral range). Using the values $p = 15$, $d = 4.5\mu$m and $n_{\text{eff},c} = 3.241$, one finds that approximately $1.15\mu$m/nm of dispersion is obtained per mm of grating radius $R$. If, for example, the grating radius were $10\mu$m, wavelengths with a 1nm spacing could be generated at the output with a stripe separation of approximately $11.5\mu$m. Alternatively, the same grating could be used to produce a comb of wavelengths
with a 2nm spacing from an array whose stripe separation is approximately 23μm.

Figure 6.5: (a) Dependence upon the grating spacing, d, of both the angular separation (β₁-α) between the output waveguide and nearest active stripe and the angular width (maximum to first zero point) of the Fraunhofer diffraction envelope. The curves correspond to a MAGIC laser operating over a spectral range 1530nm-1560nm using a grating operating in the 15'th order. The angular position β₀ of the center of the active stripe array is 60° and the refractive index is 3.241. (b) The individual variations of β₁ and α.
We must now decide upon a wavelength spacing and stripe separation for our example device; this will then determine the radius of curvature that must be used. Let us consider a device that generates 8 wavelengths with a 4 nm spacing from stripes that are separated by ~50 μm (we assume that the lowest wavelength occurs at 1.531 μm so as to maintain the center of the spectral output range at 1.545 μm). This device would require a grating that has a radius of curvature of between 11 mm and 12 mm. We select a value of 12 mm for R; this results in a value of 6 mm for the distance \( R \cos \beta_c \) between the center of the active stripe array and the grating pole \( O \).

We are now in a position to examine the effect that the envelope function has upon the stripe-to-output coupling uniformity and also upon the relative value of the direct-feedback coupling for each of the 8 stripes of our example device. The angular position of each stripe is calculated using Eq. (6.2.1). The value of the envelope function associated with each stripe is then evaluated at two points: at the output waveguide and at the stripe itself. Figure 6.6 (a) shows the stripe-to-output coupling efficiencies (normalized to the value of the coupling efficiency that would be obtained for a stripe at \( \beta=\beta_c \)); we see that the coupling between the active stripes and the output waveguide is uniform to within 0.5 dB (~10%). Figure 6.6 (b) shows the direct-feedback coupling efficiencies where, for each individual stripe, the normalization is performed relative to the stripe-to-output efficiency. In all cases, direct coupling back into the stripe is suppressed by more than 13 dB relative to coupling into the output waveguide.
Figure 6.6: (a) Nonuniformity in stripe-to-output coupling coefficients (caused by the shape of the Fraunhofer diffraction envelope function). The values of \( d \) and \( R \) are 4.5\( \mu \)m and 12mm respectively; other device parameters are as for Figure 6.5. The device depicted has eight active stripes separated by roughly 50\( \mu \)m and gives a wavelength spacing of 4nm. The coupling coefficients are normalized to the value that would be obtained for a stripe positioned at the center of the array (i.e. at \( \beta = \beta_0 \)). (b) Coupling coefficients for diffraction directly back to the active stripes. The coefficient for each stripe is normalized relative to its stripe-to-output coupling coefficient.
If the output waveguide has an uncoated facet, then there will be a ~5dB loss (in the form of useful emission) at this facet for light coupled into the output. Light that propagates from an active stripe to the output waveguide and back again experiences two passes of the grating in a cavity round-trip. This is to be compared to the one pass experienced by light that is diffracted straight back to the stripe. In the case of material whose gain is spectrally flat, the suppression of direct-feedback that is achieved by our choice of \( d \) would allow for a difference in the optical losses of almost 8dB for these two different diffraction situations. In practice this is a pessimistic estimate as the gain of the active material is not spectrally flat; the peak of the gain spectrum can be arranged to coincide with the operating wavelengths and to be spectrally distant from the direct-feedback wavelengths. This results in a higher gain for the desired operating wavelengths than for the unwanted direct-feedback wavelengths.

6.4: Lateral Modes

The previous two sections have considered diffraction of light in the lateral plane between two points on the Rowland circle. However, the lateral modes of the active stripes and of the output waveguide have finite width; the ends that terminate on the Rowland circle therefore act as slit-like rather than point-like sources. This section examines some of the ways in which these finite lateral mode sizes influence the design and performance of the MAGIC laser.

Grating Magnification

We first examine the issue of grating magnification. Let us assume that the output waveguide supports a single lateral mode that has a Gaussian profile of spot-size \( \omega_0 \) (maximum to 1/e of the field profile). If the lateral mode is small in comparison to the dimensions of the external cavity (\( \omega_0 \ll R \)), then we may write \( \omega_0 = R \cos \alpha \cdot 2\Delta \alpha \), where \( 2\Delta \alpha \) is the angle that is subtended by the lateral mode (total...
width $2\omega_o$) at the grating pole.

In diffracting light from the output waveguide to an active stripe, the grating forms an image of the output's lateral mode at the end of the active stripe. Let us consider light that is diffracted at a general angle $\beta$ and take the spot-size of the image that is formed there to be $\omega'_o$. In an analogous way to before, we may write $\omega'_o = R\cos \beta \cdot \Delta \beta$, where $2\Delta \beta$ is the angle subtended by the image (total width $2\omega'_o$) at the grating pole.

If we now differentiate Eq. (6.2.1) with respect to $\beta$ for constant wavelength, we find that

$$\cos \alpha \cdot \frac{d\alpha}{d\beta} = -\cos \beta \quad (6.4.1)$$

It therefore follows that, if $\omega_o << R$, $\cos \beta \cdot \Delta \beta = \cos \alpha \cdot \Delta \alpha$, and so $\omega'_o = \omega_o$. The circular grating used in the Rowland circle geometry therefore gives a magnification factor of 1.

**Lateral Mode Coupling Efficiencies**

We now examine what effect the finite lateral mode widths have upon the efficiency with which light is coupled back-and-forth between the active stripes and the output waveguide. Efficient coupling is achieved partly by matching the lateral mode profile of the active stripes to that of the output waveguide (it was seen above that the magnification factor of the grating is 1). However, wavefront-tilt effects will cause the coupling efficiencies to be higher for stripes at the center of the array than for those at the edges of the array. These effects occur as a consequence of the active stripes not pointing towards the grating pole O.

Figure 6.7 represents the situation that exists in the lateral plane for the coupling of light from the output waveguide to an active stripe at angular position $\beta_i$. The incoming light that is to be coupled to the active stripe propagates along the
line that passes from the grating pole to the center of the stripe. The propagation direction consequently makes an angle of \((\beta_l - \beta_c)\) with the axis of the active stripe.

**Figure 6.7:** Light coupling between the output waveguide and one of the active stripe waveguides situated at angular position \(\beta_i\). The active stripe does not point towards the grating pole and so the direction of propagation for the incoming light (that which is to be coupled into the active stripe) makes an angle \((\beta_l - \beta_c)\) with the stripe's axis. This gives rise to wavefront-tilt effects that degrade the coupling efficiency.

The tolerance of the lateral mode coupling efficiency to these wavefront-tilt effects may be estimated by calculating the overlap integral for two Gaussian modes of equal spot-size at different tilt angles \((\beta_l - \beta_c)\). Figure 6.8 shows the results of these calculations for several spot-sizes; the coupling efficiencies decrease as the spot-size of the lateral mode increases.
Figure 6.8: Tolerance of the stripe-to-output coupling efficiencies to wavefront-tilt effects. The coupling penalty (given in dB's) was calculated by evaluating the overlap integral for two identical Gaussian modes (of spot-size $\omega_0$) whose wavefronts are tilted relative to one another.

Example

Let us now consider the magnitude of the wavefront-tilt effects for the example device that was presented in the previous section. We assumed a value of 60° for $\beta_c$ which, together with the values we derived for the parameters $p$, $n_{eff,i}$ and $d$, gives values of approximately 58.2° and 61.9° for the angular positions $\beta_1$ and $\beta_8$ of the two stripes at either extreme of the array. The largest value of $|\beta_1-\beta_8|$ is therefore 1.9°. The lateral modes of the active stripes and output waveguide are typically controlled to have spot-sizes of between 1μm and 2μm. We therefore expect the stripes at either extreme of the array to have an excess coupling loss due to wavefront-tilt effects of less than 1dB. It should be noted that the value of $\alpha$ for the example device is ~46.3° and so the angular separation ($\beta_c-\alpha$) is 13.7°; much larger wavefront-tilts and coupling losses would therefore occur if the output
waveguide of this example device is not curved to point towards the grating pole.

6.5: Grating Size

Size Requirements and their Estimation

This section examines the issue of grating size. Failure by the grating to collect all of the light from the stripes or from the output waveguide results in compromised coupling efficiencies. The obvious consequence of using too small a grating is that it "spills" some of the light; a second issue, however, is that of image broadening.

In order to determine the size of grating that is required, we first assume (as in the previous section) that the lateral modes of the active stripes and output waveguide have a Gaussian profile; we then consider the divergence of the Gaussian modes as they propagate towards the grating in the planar waveguide section of the device. Consider, for example, light that is coupled into the planar waveguide by an active stripe at the center of the array. If the origin of the y-z cartesian frame in Fig. 6.2 lies at the point where this stripe terminates on the Rowland circle, then the spot-size of the mode originating and diverging from this stripe is governed by (see, for example, Reference [84])

\[ \omega(z)^2 = \omega_0^2 \left[ 1 + \left( \frac{\lambda_c z}{\pi \omega_0^2 n_{eff,c}} \right)^2 \right] \]  

Finding the two points of intersection between the equation for the spot-size \( \omega(z) \) and the equation of the grating surface gives us the width of the illuminated portion of the grating; this portion collects in excess of 95% of the light. The w coordinates (coordinates along the tangent to the grating at the pole, see Fig. 6.1) of the two
points of intersection are given by

\[
w = R \left[ \sin \beta_c \cos \beta_c + \tan \phi \sin^2 \beta_c \right] \\
\quad + \left( \tan \phi \cos \beta_c - \sin \beta_c \right) \cdot \left( \tan^2 \phi + \cos^2 \beta_c \right)^{1/2} \\
\quad \left( \tan^2 \phi + 1 \right)
\]

(6.5.2)

where \( \tan \phi = \pm \left( \lambda_c / \pi \omega_0 \eta_{eff,c} \right) \).

**Example**

Let us now consider the size of grating that would be suitable for our example design. With \( R=12 \text{mm} \), \( \beta_c=60^\circ \), \( \lambda_c=1.545 \mu\text{m} \), \( \eta_{eff,c}=3.241 \) and \( \omega_0=1.5 \mu\text{m} \), Eq. (6.5.2) evaluates to \( w=+0.98 \text{mm} \) and \( w=-1.43 \text{mm} \) for the +ve and -ve signs of \( \tan \phi \) respectively. The portion of the grating that is illuminated by light that originates from the output waveguide may be found from Eq. (6.5.2) by replacing \( \beta_c \) with \( \alpha \); this gives \( w=+1.15 \text{mm} \) and \( w=-1.27 \text{mm} \). A grating that extends between \( w=+1.25 \text{mm} \) and \( w=-1.5 \text{mm} \) would seem to be suitable for this device.

Knowledge of the grating's size and radius of curvature allows us to assess the importance of the aberration effects that were discussed in Section 6.2. With \( \beta=\beta_c=60^\circ \) and \( \alpha=46.3^\circ \), we find that at the grating's upper extreme, \( w=+1.25 \text{mm} \), the terms in Eq. (6.2.3) of fourth and fifth order in \( w \) have magnitudes of \( -0.84(\lambda_c / \eta_{eff,c}) \) and \( -0.13(\lambda_c / \eta_{eff,c}) \) respectively. The magnitudes of these terms at the grating's lower extreme, \( w=-1.5 \text{mm} \), are \( -1.73(\lambda_c / \eta_{eff,c}) \) and \( -0.33(\lambda_c / \eta_{eff,c}) \). These terms can therefore contribute more than a quarter wavelength to the optical path length; higher order terms give contributions that are less than a quarter wavelength for all points on the grating surface. The performance of the example device would therefore benefit from using an aberration corrected grating whose elements are positioned according to Eq. (6.2.7) (i.e. corrected up to the fifth order in \( w \)).
As previously noted, the aberration correction can be performed for one wavelength only; if we perform the correction for the central wavelength, $\lambda_c=1.545\mu m$, then we find that at the lowest and highest operating wavelengths, $\lambda_1=1.531\mu m$ and $\lambda_8=1.559\mu m$ respectively, the residual path length errors at either extreme of the grating are less than a tenth of a wavelength. The aberration correction is therefore effective over the entire spectral range of operation.

### 6.6: Spectral Purity

**Side-Mode Suppression Ratio (SMSR)**

This section examines the spectral purity of the MAGIC laser's operating wavelengths. Previous sections have assumed that a single wavelength couples between each active stripe and the output waveguide and that it is at this wavelength that the stripe lases. This picture needs modifying on two counts. Firstly, a finite band of wavelengths, rather than a single wavelength, may be coupled between an active stripe and the output. Secondly, lasing can only occur on the discrete longitudinal modes that are supported by the optical cavity.

Consider light coupling between the $i$'th active stripe of the array and the output waveguide. The linear dispersion on the Rowland circle at the end of the output waveguide, measured perpendicular to the line that passes through the grating pole, is equal to $(R_p/n_{\text{eff},i})d(n_g/n_{\text{eff},i})$. We may make a rough estimate of the output's acceptance bandwidth (the spectral range of wavelengths that couples into the output) by dividing its lateral mode size $2\omega_0$ by the linear dispersion; the acceptance bandwidth is therefore $(2\omega_0)(n_{\text{eff},i}d/R_p)(n_{\text{eff},i}/n_g)$. We shall assume that this acceptance band (or passband) is centered at $\lambda_i$.

The longitudinal mode spacing, $\Delta\lambda_i$, for wavelengths in the region of $\lambda_i$ is (see, for example, pp. 32 of Ref. [13])
\[ \Delta \lambda_i = \frac{\lambda_i^2}{2n_g L_i} \quad (6.6.1) \]

where \( L_i \) is the total length of the optical cavity. \( L_i \) may be expressed as

\[ L_i = R\cos \beta_i + R\cos \alpha + L_{st,i} + L_{op} \quad (6.6.2) \]

where \( L_{st,i} \) is the length of the active stripe and \( L_{op} \) is the length of the output waveguide. Eq. (6.6.1) assumes that the group index is uniform throughout the length of the cavity; this is a good approximation for the integrated structure of the MAGIC laser. The total number of longitudinal modes that can couple into the output may then be estimated by dividing the acceptance bandwidth by the longitudinal mode spacing; this gives the expression \( (2\omega_0) \cdot (n_{\text{eff},i} d / R p) \cdot (2L_i n_{\text{eff},i} / \lambda_i^2) \).

It should be noted that, since the length of the optical cavity increases roughly in proportion to the grating radius \( R \), the number of modes is approximately independent of \( R \). A small number of modes is achieved by using a grating of small spacing \( d \) in a high order \( p \), i.e. the same strategy for maximizing the dispersion that was presented in Section 6.3.

The above approach gives an estimate of the number of longitudinal modes that appear in the output spectrum of the channel, but gives no information as to their relative intensities. The efficiency with which light couples to the output (and also from the output back to the stripe) varies from mode to mode. The dominant mode in the output spectrum is that for which the coupling efficiency is highest, i.e. the mode whose wavelength is closest to \( \lambda_i \); the other modes will be suppressed relative to this mode by virtue of their lower coupling efficiencies. The side-mode suppression ratio of a conventional external-cavity laser (such as that illustrated in Fig. 3.1) has been explained by McIlroy through the use of a linear amplifier model [85]; the model leads to the following result.
Eq. (6.6.3) may be applied directly to the MAGIC laser (the MAGIC laser is, after all, a two-dimensional external-cavity laser). Here $P_0$ is the power that is emitted from the cleaved facet of the active stripe in the dominant longitudinal mode. $\tau_{\text{cavity}}$ is the time that it takes for light to complete a round-trip of the optical cavity, while $\tau_{\text{stripe}}$ is the time that it would take for light to make a round-trip of just the active stripe. The quantity $\Delta \lambda_{\text{sp}}$ is the FWHM of the spontaneous emission spectrum of the active stripe. The parameter $B$ is the bi-molecular recombination coefficient for carriers within the active region, while $N$ is the electron density (it is assumed that the electron and hole densities are equal). The quantities $R_{\text{facet}}$, $R_{\text{ext}}$ and $\Delta R_{\text{ext}}$ all refer to power reflectivities; $R_{\text{facet}}$ is the reflectivity of the active stripe's cleaved facet, $R_{\text{ext}}$ represents the effective reflectivity of the external cavity for the dominant longitudinal mode and $\Delta R_{\text{ext}}$ is the difference between the effective reflectivity of the external cavity for the dominant mode and the most intense side-mode. $n_{\text{eff}}$ is the modal effective index within the active stripe, $h$ is Planck's constant, $\lambda_0$ is the free-space wavelength of the dominant mode and $\Gamma$ is the optical confinement factor within the stripe's active region.

Eq. (6.6.3) depends upon the ratio $\Delta R_{\text{ext}}/R_{\text{ext}}$, and so we need only determine the relative effective reflectivities of the external cavity (as opposed to absolute values). These may be found in the following way. Firstly, we assume that the dominant mode has a wavelength of $\lambda_1$ (i.e. one of the longitudinal modes coincides with the center of the stripe-to-output passband). The most intense side-mode therefore occurs at a wavelength of $\lambda_1 + \Delta \lambda_1$ (or, for that matter, $\lambda_1 - \Delta \lambda_1$). Light diffracted from the active stripe to the output waveguide is focussed onto the end of the output so as to form an image of the active stripe's lateral mode; for the dominant longitudinal mode this image is centered with respect to the lateral mode profile of the output, while for the side-mode it is laterally offset by an amount
$\Delta \lambda_i (R_p/n_{\text{eff},i})d (n_g/n_{\text{eff},i})$ (equal to the mode spacing multiplied by the linear dispersion). Overlap integrals of the images of the active stripe's lateral mode profile with the lateral mode profile of the output waveguide give us the relative coupling efficiencies for the two longitudinal modes. The relative effective reflectivities of the external cavity are then obtained by squaring the relative coupling efficiencies (to account for the fact that coupling between the stripe and output occurs twice in a round-trip of the cavity, firstly from stripe to output and secondly from output back to stripe).

**Example**

We may now apply Eq. (6.6.3) to our example device. Typical values are adopted for the parameters $B$, $N$ and $\Delta \lambda_{sp}$; these are $B=2.3 \times 10^{-16} \text{ m}^3 \text{s}^{-1}$, $N=1.5 \times 10^{18} \text{ cm}^{-2}$ and $\Delta \lambda_{sp}=85 \text{ nm}$ [85]. We use values of 0.068 and 3.28 for the optical confinement factor, $\Gamma$, and the modal effective index, $n_{\text{eff}}$, respectively (these values were calculated in Chapter 5 for a stripe width of 1.2$\mu$m and a wavelength of 1.55$\mu$m; the magnitudes of these parameters will vary slightly with stripe width and wavelength). The power reflectivity, $R_{\text{facet}}$, of the active stripe's cleaved facet is assumed to have a value of approximately 0.3. The total length, $L$, of the optical cavity (assuming a value of 1mm for the length, $L_{op}$, of the output waveguide) is roughly 18mm; this gives a value of $-0.39$ns for $\tau_{\text{cavity}}$. The active stripes of our example device have lengths of $\sim 3$mm; this gives a value of $-0.07$ns for $\tau_{\text{stripe}}$.

Such long active stripe lengths are a direct consequence of using a common cleaved facet to define the ends of both the stripes and the output waveguide; a stripe positioned at $\beta_c$, for example, has length $L_{st,c}=R \cos \alpha \cos (\beta_c-\alpha)-R \cos \beta_c+L_{op}$. Schemes for reducing the lengths of the active stripes will be discussed later. The 18mm cavity length gives a longitudinal mode spacing, $\Delta \lambda$, of 0.018nm (using a value of 3.63 for the group index $n_g$). If we assume, as before, that the lateral mode spot-size of the active stripes and of the output waveguide is 1.5$\mu$m, then we find that $\Delta R_{\text{ext}}=0.044 R_{\text{ext}}$. Figure 6.9 shows the side-mode
suppression ratio, as determined from Eq. (6.6.3), for different values of the output power $P_o$; powers upto 1mW are considered. Eq. (6.6.3) predicts that, for our example device, side-mode suppression ratios in excess of 30dB (1000) can be obtained with very modest output powers (>0.5mW).

Figure 6.9: Calculated side-mode suppression ratio for our example MAGIC laser (see text for device details and assumptions) as a function of output power in the dominant longitudinal mode.
Chapter 7

Results

7.1: Introduction

This chapter describes progress that has been made in the experimental realization of the MAGIC laser.

Section 7.2 discusses a preliminary version of the MAGIC laser that has already been fabricated. The design of this device is slightly different to that considered in Chapter 6 and is somewhat un-optimized in nature. Despite this, we are able to demonstrate the basic operational principles and most of the desired laser characteristics.

We are currently developing a second laser that is very similar in design to the example device of Chapter 6. This laser has not, as yet, been fabricated. Initial assessment of the design has, however, been carried out by fabricating a monolithic grating spectrometer device that is based upon the same geometry. Section 7.3 describes work in this area.
7.2: First Experimental Device

Device Details

Our first MAGIC laser is based upon the structure of Chapter 5, but has a slightly different layout to that considered in Chapter 6. The most obvious difference occurs in the detail of the output waveguide; the device has no separate passive output, just an array of parallel active stripes. The center of the array points towards the grating pole and the grating is blazed so as to couple light directly back to the stripes. The essential features of the device are illustrated in Figure 7.1.

![Figure 7.1: Schematic plan-view layout of the prototype MAGIC laser.](image)

This layout was used purely due to considerations of convenience and time. The underlying geometry is identical to that which had already been used for fabricating monolithic grating spectrometers [59] (compare Fig. 7.1 to Fig. 4.4); photomasks required to realize this geometry were readily available to us. Although the mask set is not entirely suited to the design of a MAGIC laser, it has allowed us to fabricate a prototype device that successfully demonstrates most of the basic concepts.

The grating's radius of curvature is 18mm and its spacing, d, is ~4.5μm. The grating is not corrected for aberration and the individual grating elements are all blazed at the same angle (with the grating element facets perpendicular to the line that passes from the center of the active stripe array to the grating pole). The
grating was metallized with 110Å of titanium followed by 3000Å of gold (as opposed to the aluminium metallization described in Chapter 5); it was decided not to thermally anneal the electrical contacts for the active stripes lest the metal on the grating diffuse into the semiconductor. The laser is designed to operate in the 16th order of diffraction; this gives a free-spectral range of ~97nm at 1.55μm.

There are 51 active stripes spatially separated by ~40μm; the exact separation varies slightly in order to maintain a constant wavelength spacing. The stripe lengths range from ~800μm to ~3.75mm; the length of the stripes in the central region of the array is ~2mm. The distance between the stripes and the grating pole is ~10mm; overall dimensions are 14mm × 3mm. In the case of the grating spectrometer device for which the photomasks were originally designed, the grating collected light from an input guide that had a lateral mode spot-size of ~4μm. We were therefore forced to use fairly wide active stripes in order to prevent excessive "spilling" of light by the grating; the active region widths alternate between 6μm and 7μm.

Characteristics: Current Injected into a Single Active Stripe

Current was initially injected into just one active stripe at a time. This causes the active stripes to lase by virtue of direct-feedback from the grating. The laser was operated under pulsed conditions (pulse width =200ns, pulse rate =2kHz). Light emitted from the cleaved facet of each stripe was coupled into a lensed single-mode fiber and was then examined with the aid of a 0.1nm resolution optical spectrum analyzer (OSA). No temperature stabilization was employed for these preliminary measurements.

Laser emission was observed from 9 stripes in the central region of the array. The emission wavelengths, plotted in Figure 7.2, were in the range 1500.0nm to 1530.1nm. Each wavelength was determined using the OSA's "peak-search" function; wavelengths are quoted down to 0.01nm (the OSA was initially calibrated against a He-Ne laser).
Figure 7.2: Lasing wavelengths obtained from the prototype MAGIC laser by injecting current into a single active stripe at a time. Lasing occurs by virtue of direct-feedback to the stripes from the grating. Nine discrete wavelengths were obtained (shown in the figure by the square symbols). The solid line is a linear least-squares fit to the data; its slope indicates a wavelength spacing of 3.77nm.

The stripes that lase are those whose direct-feedback wavelengths coincide most closely with the peak of the active material’s spontaneous emission spectrum; the direct-feedback wavelengths for these stripes experience higher gain than the direct-feedback wavelengths for stripes at the edges of the array. In addition, due to the nature of the grating’s blazing, these stripes experience the strongest feedback.

The channel spacing, as determined from the slope of a linear least-squares fit to the data of Figure 7.2, is 3.77nm. The deviation of each of the 9 wavelengths from the nominally uniform spacing is shown in Figure 7.3; the RMS deviation is just 0.07nm. The operating wavelengths are within 2nm of the design values.

The various sources of wavelength error can be sub-divided into two classes, those that give a systematic error, i.e. one that is the same for all channels, and those that give random errors that vary from channel to channel.
The most significant source of systematic error is the discrepancy between the actual and calculated values for the modal effective index of the passive planar waveguide structure. As previously discussed in Chapter 5, layer thickness and refractive index uncertainties typically give rise to a ±0.16% error in the calculated value for the modal effective index; this translates into a ~2.5nm error in the laser's operating wavelengths. A second possible cause of systematic error is misalignment of the grating relative to the active stripe array. As discussed in Chapter 5, the relative alignment is accurate to within ±0.8μm, corresponding to a ~0.08nm wavelength error.

Random errors are caused by competition between longitudinal modes (the calculated mode spacing is ~0.028nm for a ~12mm cavity length) and by factors that affect the positioning of the active stripes relative to one another. Such factors include variations in photoresist development and semiconductor etching that occur during active stripe formation and errors in the positioning of the stripes on the photomask itself. Development and etching variations depend upon the type of photolithography that is employed, the type of photoresist that is used and the details of the etching process; we estimate a positioning error of ±0.25μm for our
stripe formation process, corresponding to a wavelength error of ~0.025nm. Photomask errors occur because design patterns are digitized to a grid prior to being transferred to the photomasks; the cell size of the grid is equal to the resolution of the electron-beam source that is used to write the mask. The highest resolution that is available with the machine used to produce our masks is 0.1μm; this means that features can be positioned on the photomask to an accuracy of only ±0.05μm, corresponding to a wavelength error of ~0.005nm.

From this analysis of wavelength errors, we see that the absolute wavelength errors of our prototype MAGIC laser are as expected from consideration of the discrepancy between the actual and calculated values for the modal effective index of the passive planar waveguide structure. The non-linearity of the wavelengths is, however, slightly larger than the ~0.057nm that is expected from consideration of the various sources of random wavelength error. This higher level of non-linearity is caused by room temperature fluctuations between successive measurements. This was demonstrated by mounting the MAGIC laser on a thermo-electrically cooled stage whose temperature can be controlled and stabilized. Figure 7.4 shows wavelength deviations that were measured with the temperature of the mount stabilized at 20°C; the RMS deviation is reduced to just 0.03nm, i.e. ~1% of the wavelength spacing. The wavelength of one of the channels was measured as a function of the laser's operating temperature; this gave a value of +0.11nm/°C for the temperature sensitivity. A temperature change of 0.28°C would therefore be required to produce a 0.03nm change in wavelength; the operating temperature is, however, controlled to better than ±0.1°C and so the 0.03nm deviation that has been measured represents the real departure of the wavelengths from linearity.
The as-fabricated wavelength linearity demonstrated by the MAGIC laser is unrivaled for a monolithic multi-wavelength laser source; the accuracy of the wavelength spacing is an order of magnitude higher than that obtained using DFB or DBR lasers. This high degree of wavelength linearity is partly due to the precise photolithographic definition of the device geometry. Also important is the fact that all of the wavelengths are determined by the same wavelength-selective element, namely the grating external-cavity; as a result of this, any variation in the thickness or composition of the planar waveguide layers affects all of the wavelengths equally. In the case of a DFB or DBR laser array, each separate laser has its own individual wavelength-selective element. Variations in the thickness or composition of layers differ from one laser to another and so each wavelength is affected by a different amount.

The threshold currents, $I_{th}$, for the 9 channels are plotted in Figure 7.5. The currents are quite high, ranging from roughly 85mA to 120mA. This is partly due to the large widths and lengths of the active stripes; for a current of 100mA, a stripe width of 7μm and a stripe length of 2mm, the current density is only 714A/cm². Decreasing both the active stripe lengths and widths to more conventional values, e.g. 1mm and 1-2μm respectively, is expected to lead to significantly reduced
threshold currents. The effect of reducing the stripe widths is clearly demonstrated in Fig. 7.5; the alternating stripe widths used in this device cause the threshold current to alternately increase and then decrease as one goes from one stripe to the next. It should be noted that benefits gained from reducing the stripe lengths will be offset to some extent by an increase in the threshold current density.

Figure 7.5: Threshold currents for our prototype MAGIC laser. The data is for the nine wavelength channels that may be selected by injecting current into a single active stripe at a time.

Figure 7.6 shows a typical light-current characteristic for the emission from an active stripe. The power values represent the instantaneous intensity within each pulse; the time-averaged powers were first measured using an optical power meter and the results were then scaled appropriately. The differential quantum-efficiency \[ \frac{\text{(useful photon emission rate)}}{\text{(photon generation rate)}} \] is just 1-2%. 

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Examine the output spectra of the stripes on the OSA revealed that the intensities at the lasing wavelengths were typically 25dB above the background of spontaneous emission. Increasing the duty cycle caused the intensities at the lasing wavelengths to decrease relative to this background; all evidence of laser emission disappeared from the OSA trace when the duty cycle was increased above ~30%. Failure of this device to operate continuous-wave is put down to electrical heating effects. Electrical characterization of the active stripes indicated series resistances under forward bias of ~11Ω (resistances under reverse bias were in the 100MΩ range, indicating good active region isolation). The high forward-bias resistances are attributed to our decision not to thermally anneal the electrical contacts for the stripes and also to lower than expected p-type doping in the InGaAsP (λg=1.3μm) upper contact layer of the active structure.

The laser's longitudinal modes are spaced too closely to be resolved by the optical spectrum analyzer and so we examined the fine mode structure within the output spectrum of each channel with a scanning Fabry-Perot interferometer. The
duty cycle was increased to 20% for these measurements in order to counter poor detection sensitivity in the interferometer. Up to 9 longitudinal modes were observed in the spectral output of each stripe; the mode spacing was measured at 0.027nm (in agreement with the calculated value) and the dominant longitudinal mode was >8dB above the side-modes. As discussed in Chapter 6, reducing the widths of the active stripes and hence the lateral mode spot-sizes is expected to give single-mode operation.

The near-field pattern of the laser's emission was examined by using an objective lens to image the cleaved output facet onto an infra-red video camera (an IR vidicon). The profile of the near-field pattern suggested that up to 3 lateral modes were contributing to the emission. Although up to 7 modes could be supported by the 6-7μm wide stripes, lower confinement and weaker feedback inhibits lasing on the higher modes. Reduction of the stripe widths can be expected to give single lateral mode as well as good single longitudinal mode operation.

Characteristics: Single-Output Emission

The mode of operation described above, with current injected into a single stripe at a time, results in emission of each wavelength from a different output port. The mode of operation discussed in previous chapters, however, involves the emission of multiple wavelengths from a single output port. This can be achieved in our prototype device by using one of the active stripes as the common output waveguide. Current is simultaneously injected into the output stripe and one or more secondary stripes. The stripes are chosen such that the gain at their direct-feedback wavelengths is insufficient for them to lase on their own. However, if the direct-feedback wavelengths for the output stripe and secondary stripes are on opposite sides of the active material's gain peak and are also roughly equidistant from the peak, then the wavelengths that couple between the secondary stripes and the output will roughly coincide with the gain peak. Laser emission occurs on these wavelengths as a consequence of the higher gain. The peak of the
spontaneous emission spectrum, as previously noted, coincides with the direct-feedback wavelengths for the stripes in the central region of the array. Single-output emission is therefore achieved by choosing the output stripe and secondary stripes to be symmetrically displaced about the array center. Figure 7.7 shows the stripe arrangement that is used to obtain two different wavelengths from a single output port of the prototype device. Current is injected into those stripes that are shown in solid black.

Figure 7.7: Plan-view schematic of our prototype MAGIC laser showing the current injection scheme that is used to obtain simultaneous emission of two different wavelengths (denoted in the figure as $\lambda_1$ and $\lambda_2$) from a single output port. Current is injected into those active stripes that are shown in solid black.

We first demonstrate wavelength-switchable emission from a single output port (i.e. discrete tuning). Current is injected into the output stripe and into one secondary stripe. The device was operated under the same pulsed conditions as before; light emitted from the cleaved end of the output stripe was coupled into a lensed single-mode fiber for examination by the optical spectrum analyzer.

Laser emission was observed on a total of 15 different wavelengths covering the spectral range 1507.0nm to 1533.6nm. The output wavelengths are plotted in Figure 7.8. The wavelength spacing, as determined from the slope of a linear least-squares fit, is 1.89nm. The channel spacing is therefore half that obtained when current is injected into a single active stripe; this is exactly as expected. The
wavelength spacing is extremely constant; the RMS deviation of the wavelengths from the fit is just 0.06nm (the wavelengths were measured without temperature stabilization).

![Graph showing wavelength spacing](image)

**Figure 7.8:** Fifteen different lasing wavelengths that were obtained from a single output port of the MAGIC laser. An active stripe is first chosen as the output waveguide; current is then injected into both this stripe and one other stripe. The wavelength that is emitted by the output stripe is changed by changing the identity of the second stripe into which current is injected. The solid line represents a linear least-squares fit to the data; the channel spacing, as determined from the slope of the fit, is 1.89nm.

Figure 7.9 shows a compilation of spectral traces, one for each of the 15 wavelengths, that were recorded on the OSA. A constant current of 215mA was injected into the output stripe; the current injected into each secondary stripe was typically 160mA (secondary stripe currents of between 70mA and 100mA were required to reach laser threshold). The lasing intensities are between 15dB and 25dB above the common background of spontaneous emission. There was no evidence of laser emission at the output stripe's direct-feedback wavelength. This is the result of using a stripe for which the direct-feedback wavelength lies well into the wings of the gain spectrum of the active material.
Simultaneous emission of up to 4 wavelengths from the same output stripe has also been demonstrated; any combination of the laser's "allowed" operating wavelengths may be selected. Figure 7.10 shows a number of examples of simultaneous two-wavelength emission. The bias for the output stripe was held constant at 200mA while different combinations of secondary stripes were injection pumped. Secondary stripe injection currents of ~90mA were required to reach lasing threshold; the traces in the figure were obtained using currents of ~150mA.

All of the laser intensities lie ~20dB above the background of spontaneous emission. The background, seen more clearly here than in Figure 7.9, exhibits no Fabry-Perot resonances. The absence of any such structure is a testament to the negligible residual reflectivity of the interface between the active stripes and the planar waveguide. There are, however, some small peaks at positions that correspond to some of the laser wavelengths; the origin of this structure is presently unclear.
Figure 7.10: Simultaneous emission of two wavelengths from a single output port; each wavelength may be independently selected from the MAGIC laser's comb of "allowed" operating wavelengths. Different two-wavelength combinations are shown, illustrating emission across a 16nm range. The traces were taken with a 0.1nm resolution optical spectrum analyzer; the bias for the output stripe was 200mA, while the injection current for each secondary stripe was ~150mA.

Figure 7.11 shows several examples of simultaneous three-wavelength emission and an example of simultaneous four-wavelength emission. Again, the bias current for the output stripe was 200mA, while secondary stripe injection currents were ~150mA. The laser intensities are 15-20dB above the background of spontaneous emission which, as in the two-wavelength case, is essentially featureless. Simultaneous operation on an even greater number of wavelengths is expected to give similar results. We were limited here in the number of channels that we could drive by the logistics of injecting current into the stripes. Current was injected via needle probes that made direct contact with the stripes (no contact wires were bonded to the device) and we were unable to fit more than five current probes into the bench space that surrounded the laser mount.
It was previously noted (Section 4.2) that having a shared gain medium, such as the output stripe of our prototype device, can give rise to inter-channel crosstalk via the homogeneous gain saturation mechanism. With this in mind, we have examined inter-channel crosstalk for the case of simultaneous two-wavelength operation. We measured the change in the output power $P_1$ of a single wavelength that occurs as a result of increasing the power $P_2$ at a second, different, wavelength. The intensity of the first wavelength emission in the absence of any second wavelength emission is denoted $P_{10}$. Figure 7.12 shows a plot of the relative power $P_1/P_{10}$ of the first wavelength emission against the relative power $P_2/P_{10}$ of the second. The injection currents for the output stripe and first secondary stripe were maintained at 200mA and 150mA respectively. Data points are shown for four different wavelength spacings: ~2nm, ~4nm, ~6nm and ~8nm (i.e. 1, 2, 3 and 4 channel intervals).
Figure 7.12: Inter-channel crosstalk for the case of simultaneous two-wavelength emission. The figure shows changes in the power $P_1$ at one wavelength as the power $P_2$ at a second, different wavelength increases. The quantity $P_{10}$ represents the power at the first wavelength in the absence of any second wavelength emission. Data points are shown for four different wavelength spacings, corresponding to 1, 2, 3 and 4 channel intervals.

The steady-state output power at one wavelength is seen to decrease with increasing power at the second wavelength; a ~2dB reduction occurs for a power of $P_{10}$ at the second wavelength. The effect is approximately independent of the channel spacing. This behaviour is consistent with wavelength interaction via the homogeneous gain saturation mechanism [55]. Crosstalk of comparable magnitude to that found here has recently been predicted [86] and experimentally demonstrated [87] for the MGC laser (one of the bulk-optic devices similar to the MAGIC laser previously discussed in Section 4.2). For the MGC laser, it was shown that the crosstalk could be compensated by superimposing a component of the injection current of each secondary stripe onto the injection current of the output stripe [87]; crosstalk-induced power reductions of less than 0.05dB were demonstrated [87]. Similar performance may be expected for the MAGIC laser. This approach does, however, result in a more complicated control mechanism for the
device. We believe that prevention of crosstalk through the use of a passive output, thereby maintaining the simplicity of the device's control mechanism, is a more attractive proposition.

7.3: Preliminary Assessment of a New Design

Device Details

We are currently working on a second version of the MAGIC laser; the design of this device is very similar to that of the example device of Chapter 6. The values for the grating parameters $R$, $d$ and $p$ are 13mm, 5μm and 17 respectively; the FSR is therefore ~90nm at 1.55μm. A number of different gratings have been designed; these include gratings with graduated blazing angles, gratings whose elements all have the same blazing angle and gratings both with and without corrections for aberration. The gratings with graduated blazing angles are subdivided into nine regions of constant blazing; the blazing angle changes in ~2° increments between neighbouring regions (the FWHM of the Fraunhofer envelope function is calculated to be ~8°). The laser is designed to have eight active stripes that are separated by ~55μm; the distance between the active stripe array and grating pole is ~6.5mm.

The curved passive output waveguide was designed by following an optimization procedure that is presented in Reference [88]. The waveguide is optimized for a lateral refractive index contrast of ~0.01 and consists of a straight section of width 3μm that is connected end to end with a curved section whose width and radius are 8.5μm and 2.4mm respectively. The straight section is designed to be single-moded with a spot-size of ~2μm, while the curved section is designed to operate as a single boundary waveguide (a mode of operation that is commonly referred to as the "whispering gallery" regime). A lateral offset of ~2.5μm [89] is used between the centers of the two sections so as to minimize transition losses at the junction; the calculated transition loss is ~0.2dB [89].
Although this laser has not, as yet, been fabricated, initial assessment of the new design has been carried out by using the photomasks to fabricate a grating spectrometer that is based upon the same geometry. This was achieved by replacing the active stripes with an array of ten passive ridge waveguides. The waveguides are 3μm wide (i.e. identical to the straight section of the curved output waveguide) and were formed at the same time as the output. The layer structure is identical to that which is used in the passive planar waveguide section of the MAGIC laser, i.e. an InP substrate, a 0.3μm InGaAsP ($\lambda_g=1.3\mu m$) core and a ~1.0μm InP cladding layer; the layers are, however, undoped. The grating has a variable blazing angle, but is not corrected for aberration; devices using aberration-corrected gratings have yet to be fabricated.

**Preliminary Assessment**

The grating spectrometer was evaluated using a tunable external-cavity semiconductor laser whose wavelength can be varied in 0.001nm steps. A lensed single-mode fiber was used to couple light into the waveguides within the array, while light was collected from the output waveguide using a tilted mirror and an objective lens; the lens was used to focus the near-field image of the output facet onto a calibrated IR vidicon.

The central wavelengths of the passbands of the ten channels are plotted in Figure 7.13; the wavelengths were determined directly from the laser controller. The absolute wavelengths differ by ~0.8nm from the design values. This absolute wavelength error is well within the range that is expected on the basis of possible discrepancy between the actual and calculated values for the modal effective index of the planar waveguide (as was previously discussed for the MAGIC laser of Section 7.2). The wavelength spacing, determined from a linear least-squares fit to the data, is 3.56nm; the RMS deviation of the data points from the fit is just 0.02nm.
Figure 7.13: Passband wavelengths of a ten-channel grating spectrometer that was fabricated in order to assess the mask set for a new MAGIC laser. The central wavelength of each channel was determined using a tunable semiconductor laser whose wavelength can be varied in 0.001 nm steps. The solid line represents a linear least-squares fit to the data; the channel spacing, as determined from the slope of this line, is 3.56 nm, while the RMS deviation of the data points from the fit is just 0.02 nm.

Channel crosstalk is -35 dB for the central channels and -30 dB for the outermost channels (due to reduced throughput efficiency). Values for the FWHM of the channel passbands range from 0.5 nm to 0.8 nm; the mean value is 0.61 nm with an RMS deviation of 0.1 nm. At ±0.9 nm from the channel center the suppression is typically ~20 dB, while at ±1.2 nm one sees a diffuse background that is ~35 dB down from the peak (~30 dB for the outermost channels).

The passbands are somewhat broader than the value of ~0.25 nm that is calculated for diffraction-limited operation. Image broadening is probably caused by a combination of material non-uniformity, grating aberration and grating aperiodicity, while the diffuse background is most likely caused by scattering from grating roughness and rounded grating element edges. Non-uniformity of the thickness, composition and strain of the material layers gives rise to local variations.
in the modal effective index of the planar waveguide; these variations can distort
the wavefronts of light that propagates within the guide. Grating aperiodicity can
occur at the photomask level as a consequence of the digitization process that was
discussed in Section 7.2. A ±0.05μm fluctuation in the position of the grating
elements corresponds to a ~±π/4 fluctuation in the phase of light that arrives at the
output waveguide via the different elements. Grating aperiodicity can, to a large
extent, be avoided; the grating spacing is approximately constant in the region
around the grating pole (see Chapter 6) which makes it possible to design the
grating in a way that avoids digitization errors in this central region.

Figure 7.14 shows the relative throughput of the ten channels; the coupling
efficiency into the different waveguides is constant to within ±0.5dB.

![Graph showing relative throughput](image)

**Figure 7.14:** Relative throughput of each of the grating spectrometer's ten
channels (square symbols), together with the variation in throughput that is
expected from consideration of Fraunhofer envelope and wavefront-tilt effects
(solid curve).

The throughput is uniform for the four central channels, but is down by ~6dB at the
two outermost channels. This fall-off occurs somewhat faster than is anticipated
from consideration of the Fraunhofer diffraction envelope and wavefront-tilt effects; the predicted fall-off resulting from the combination of these two factors is represented by the curved line. The origin of this discrepancy is, at present, unclear. The smooth variation of the experimental data indicates high quality (and presumably low loss) of the ridge waveguides within the array.

Similar performance was observed for both TE- and TM-polarized light. The measured value of the birefringence was repeatably 4.8nm, which is slightly larger than the calculated value of 4.2nm.

An absolute value for the optical loss of one of the central channels has been measured using a technique that is based upon Fabry-Perot cavity resonances [90]. The cleaved facets of the output waveguide and each input waveguide form an optical cavity; a number of FP (or cavity) modes consequently exist within the passband of each channel (the same cavity modes upon which the MAGIC laser operates). The channel throughput depends upon whether light is resonant or antiresonant with an FP mode. The single-pass optical loss of the cavity may be determined from the ratio $K$ of the resonant and antiresonant throughputs; the loss (in dB) is given by [90], [91]

$$\text{Loss} = -10 \log \left[ \frac{1}{\sqrt{K} - 1} \right]$$

where $R_{\text{facet}}$ is the geometric mean of the power reflection coefficients of the two facets. Optical losses measured by this technique are independent of the coupling efficiency and are consequently insensitive to drifts in the optical set up.

A single-pass loss of $10\text{dB} \pm 0.5\text{dB}$ was measured for the grating spectrometer. This value is comparable with the best reported to-date for a reflection grating spectrometer ($10-17\text{dB}$ [92]). The value of $K$ was determined directly from the IR vidicon by tuning the external-cavity laser in 0.001nm steps around the central wavelength of the channel passband; the value of $R_{\text{facet}}$ was...
assumed to be 0.27 [90] (this slight reduction from the commonly used value of 0.30 accounts for off-vertical facets of OMCVD grown material [90]).

Optical losses have also been measured for several test waveguides that are situated next to the grating spectrometer. These include both straight waveguides and S-bends; the straight waveguides are identical to the straight waveguides of the spectrometer, while the S-bends are each made up of two curved waveguides that are identical to the spectrometer’s output waveguide. These measurements indicate that the propagation loss in the straight waveguides is ~2.5dB/cm and that the transition loss at the junction between a curved and straight section is ~1.5dB. The measured value of the straight-to-curve transition loss is considerably larger than the theoretically predicted value of 0.2dB; the discrepancy between these two values is believed to be due to over-etching of the waveguides.

If we attribute ~0.5dB to propagation loss in the straight waveguides and 1.5dB to transition loss at the junction between the straight and curved sections of the output waveguide, then ~8dB of the spectrometer’s loss remains to be accounted for. The ~0.6nm FWHM of the channel passbands indicates that the image of the input waveguide that is formed at the end of the output waveguide has a spot-size of ~7μm; this degree of broadening would result in a ~2.5dB penalty for coupling into the output. The remaining 5.5dB is due to scattering that arises from grating roughness and rounded grating element edges, reflection of light into the substrate as a consequence of tilt in the grating wall, imperfect grating reflectivity and diffraction of light into other orders.
Chapter 8

Discussion

This thesis has presented a new type of monolithic semiconductor laser, the multi-stripe array grating integrated cavity (MAGIC) laser, that gives emission at a number of discrete wavelengths from a single output port. The "allowed" operating wavelengths of this MAGIC laser may be independently selected in any arbitrary combination; the device therefore functions as both a discretely tunable and a multi-wavelength laser source.

A preliminary version of the MAGIC laser has been successfully fabricated in the InGaAsP/InP material system for operation in the 1.55μm low-loss fiber band. This device emits 15 different wavelengths across a spectral range of ~30nm (wavelength spacing = 1.89nm). As-fabricated wavelength linearities as high as ±0.03nm have been demonstrated; this is the highest value achieved by a monolithic multi-wavelength laser source and is an order of magnitude higher than has been reported for arrays of DFB and DBR lasers. Such precise wavelength spacing is due to accurate photolithographic definition of the laser geometry and also to the laser's novel two-dimensional external-cavity design which allows all of the wavelengths to be defined by the same wavelength-selective element.

Absolute wavelength values differ from those of the design by ~2nm. These errors are consistent with discrepancies between actual and assumed values for
the composition and thickness of material layers. Absolute errors can be corrected to some extent through the use of thermal tuning. Changing the laser's operating temperature allows one to sweep the entire comb of wavelengths without appreciably changing the wavelength spacing. The measured value for the temperature sensitivity is $+0.11\text{nm/}^\circ\text{C}$ and so the operating wavelengths may be placed anywhere within the 1.89nm wavelength interval by tuning the temperature through $\pm9^\circ\text{C}$.

Precise wavelength definition without the need for tuning of individual channels gives rise to a very simple laser control mechanism. Each wavelength is pre-determined by the laser geometry and may be selected by simply injecting current into the appropriate active region. Selection of each wavelength is fast (wavelength switching on a nanosecond timescale is expected), efficient (no large tuning currents are required) and very reliable (the geometry is "frozen" into the device).

Another attractive feature of the MAGIC laser is that its fabrication involves only two stages of material growth, standard photolithography and dry and wet etching techniques. The use of standard processing techniques makes a device amenable to high volume manufacture, an important issue when widespread implementation is envisaged.

There are a number of characteristics of the preliminary device that illustrate a need for further development; these include poor side-mode suppression (~8dB), high threshold currents (in our demonstration of single-output emission, 215mA was injected into the output stripe and 70-100mA was then required by each secondary stripe in order to reach the lasing threshold), large device size (14mm × 3mm) and low differential quantum efficiencies (~1-2%).

Higher SMSR values and lower threshold currents can be achieved by simply reducing the width of the laser's active regions. The active region widths for the preliminary device are 6-7μm; reduction to a more conventional value, say 1-2μm, might be expected to give SMSR values as high as ~30dB and a three-fold
reduction of all currents. One of the side-effects of using narrower widths is that a larger grating must be used. Greater attention must then be paid to the grating blazing (use of a variable blazing should be considered) and to grating aberration effects. Grating aberrations contribute to image broadening which, in turn, adversely affects both the laser's side-mode suppression ratio and the cavity round-trip losses. Minimization of cavity round-trip losses is particularly important since they affect threshold currents, differential quantum efficiencies and the maximum achievable spectral operating range. A method for designing an aberration-corrected grating that involves "tailoring" the grating's spacing has been discussed in detail. One of the other possible sources of image broadening that has been mentioned is error in the positioning of the individual grating elements. Such positioning errors could be reduced by using projection lithography rather than contact lithography to define the grating.

Reduction of the laser's size would result in a number of benefits; these include lower material costs, higher maximum modulation rates and further reduction of cavity round-trip losses. Lower losses would be expected on account of: (i) reduced free-carrier absorption in the doped substrate and (ii) reduced material non-uniformity induced image broadening, both of which would be brought about by reduction of the distance travelled in the planar waveguide.

For a given wavelength spacing, a device may always be made smaller so long as the separation between the active stripes is also made smaller. However, concerns over thermally and electrically induced inter-channel cross-talk require that active stripes be widely spaced. A possible solution to this problem is for each active stripe to be stopped short of the diffraction grating's focal curve (the Rowland circle) and to be coupled instead into one end of a passive ridge waveguide whose other end is then itself terminated on the grating's focal curve (the opposite ends of the active stripes being terminated, as in the preliminary device, by the cleaved facet of the semiconductor chip). These ridge waveguides could be curved so that the spacing between their ends on the Rowland circle is much closer than the
spacing of the active stripes; reduced dimensionality through the use of curved waveguides has previously been demonstrated for both monolithic grating spectrometer [65] and demultiplexer-detector [67] devices.

There are, in fact, other potential advantages to be gained from using passive ridge waveguides as intermediaries between the active stripes and the Rowland circle. Firstly, the passive ridge waveguides could be curved in such a way that they all point towards the grating pole; this would totally eliminate cavity round-trip losses that result from wavefront tilt-effects. Secondly, since the active stripes would no longer be forced to terminate on the Rowland circle, one would have more freedom in choosing their lengths; the lengths could be chosen so as to minimize the threshold currents of the different channels or, alternatively, the lengths could be arranged so as to equalize all of the threshold currents.

Initial experimental results for the MAGIC laser, together with its potential for further improvement, suggest suitability for use as both a discretely tunable and multi-wavelength transmitter source in future DWDM systems. The direct modulation rate for each channel, owing to relatively long cavities, will probably be limited to somewhere on the order of 100Mbit/s. The MAGIC laser will consequently be most suited to use in networking applications that make use of its excellent wavelength accuracy and simplicity of control, rather than to use in high-capacity point-to-point links where high modulation rates are the principal concern.
References


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