Frequency and Time Domain Measurements of Optical Fibre Response

by

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September 1982
To

my mother for her patience

and in memory of my father
SUMMARY

This thesis examines a new technique for measuring the transfer function of optical fibre waveguide directly in the frequency domain with special emphasis on the phase response.

A detailed theory of the feasibility and limitation of this technique is presented, and its optimisation for optical fibre measurement is discussed.

A complete measurement system has been built and set to perform the measurement automatically under computer control. This system performs both frequency and time domain measurements to determine the transfer function and impulse response of optical fibre.

The transfer function and impulse response of a 100m step-index fibre have been measured using a HeNe laser source (wavelength of 0.6328μm) up to a frequency of 550MHz, and those of a 900m graded-index fibre up to a frequency of 1275MHz using a cw laser diode (wavelength of 0.87μm), using both techniques.

The contribution of different sources of error in both measurement methods is also examined.

Finally the relative advantages as well as disadvantages of the two measurement techniques are discussed.
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LIST OF SYMBOLS

a  radius of optical fibre core
B  bandwidth
c  velocity of light
C  capacitance
e  electron charge
   constant
f  frequency
f_c cutoff frequency
f_n frequency of null amplitude response
F(G) excess noise factor
F(t) time function
FT Fourier transform
G  avalanche gain
G(f) amplitude frequency response of filter
h(t) fibre impulse response
HE_{11} fundamental mode in optical fibre
H(\theta) energy distribution of modes inside fibre
H(f) transfer function
H_1(f) real part of transfer function
H_2(f) imaginary part of transfer function
I  current
IFT inverse Fourier transform
k  Boltzmann constant
K  ionization ratio
L  inductance
   length
m  modulation index
  constant

M  constant

M(\lambda)  specific material dispersion factor

n  integer

n_1  refractive index of fibre core

n_2  refractive index of fibre cladding

N  number of pulse samples
  number of propagating modes in fibre

N.A.  numerical aperture of fibre

p  integer

P  power

PWHA  pulse width at half amplitude

R  responsivity

R_L  load resistance

t  time
  time delay

T  absolute temperature
  period

V  normalized frequency

w  angular frequency

x(t)  input time function

X(f)  input frequency function

y(t)  output time function

Y(f)  output frequency function

\lambda  wavelength

\theta  angle

\theta_c  maximum acceptance angle of light by fibre
\( \theta_o \) \hspace{1em} \text{angle of slowest propagating mode in fibre}

\( \phi(f) \) \hspace{1em} \text{phase response}

\( \phi \) \hspace{1em} \text{phase}

\( \phi_d(w) \) \hspace{1em} \text{differential phase angle}

\( \theta_x \) \hspace{1em} \text{constant phase}

\( \tau \) \hspace{1em} \text{time delay}

\( \Delta f \) \hspace{1em} \text{frequency difference}

\( \Delta \phi \) \hspace{1em} \text{phase difference}

\( \Delta \tau \) \hspace{1em} \text{time delay difference}

\( \Delta w \) \hspace{1em} \text{angular frequency difference}

\( \ast \) \hspace{1em} \text{convolution}
CHAPTER ONE
INTRODUCTION, REVIEW AND SUMMARY

1.1 Introduction

Optical fibres are now the preferred medium for guiding trunk tele-communication signals. Their supremacy depends on their low loss and broad bandwidth capabilities.

Historically it was the development of the laser (Maiman [1] 1960, Javan [2] 1961) and, in particular, the family of semiconductor lasers (Hall et al [3] and Nathan et al [4] 1962), with their short-pulse capability, small size and high efficiency which led to the realisation that optical communication might be possible over broad bandwidths and could be competitive with the coaxial and microwave systems then becoming common.

Following the pioneer work of Kao and Hockam [5] (1966), glass fibre technology has improved rapidly, until today we find transmission losses reduced to levels close to the fundamental limit while immense bandwidths are possible.

This development has taken place concurrently with the digital revolution in electronics so that optical fibre communication is almost exclusively in the digital domain, thus taking full advantage of the capabilities of semiconductor lasers. A typical modern Gallium Arsenide laser is capable of generating optical pulses of about half a nanosecond duration with peak powers of a few milliwatts in continuous wave cw operation. The dispersion in a good modern graded-index multimode fibre will broaden such pulses to around one nanosecond over one kilometre of length, at which point the pulses can be regenerated.
in a repeater. This kind of performance enables one to transmit information in excess of 500 Mbit per km/sec. For longer distances and higher bit rates, single-mode fibre is more promising for achieving maximum spacing.

Since systems operate in the pulsed mode, it has been the almost universal custom to characterise them in this mode. Thus, glass fibre performance is usually quoted in terms of transmission loss per kilometre together with a figure for pulse dispersion per kilometre. Impulse response measurements are an easy and convenient means of characterising glass fibre in terms of its operational performance but are not quite the most fundamental in terms of understanding the behaviour of a guided transmission medium such as this. The bandwidth of a fibre is governed by several factors, one of which is the interaction between the various propagating modes. The understanding of modal behaviour is best acquired by the consideration of the behaviour of continuous waves and for this purpose, characterisation of a fibre by frequency domain methods is to be preferred.

Basically, there are two methods for characterising the response of a linear system. The first of these is by specifying the response of the system to an impulse, the second is by specifying the frequency response. The latter can be directly determined in either of two ways, by exciting the system frequency by frequency individually and measuring the output, or by exciting the system by a broadband stochastic signal such as white noise and measuring the output in the frequency domain. Impulse response and frequency response are, of course, directly equivalent to one another as a Fourier transform pair.
It is the object of this thesis to examine the merits of the frequency domain method of characterising optical fibre and to make comparison with the more common impulse response techniques. Measurements in the frequency domain are in principle rather more difficult to carry out, in particular when the complete response is required, i.e. when both phase as well as amplitude are needed. The thesis shows, however, that a practicable and convenient procedure is possible and that it has certain advantages over time domain methods. In brief the advantages lie in

1. higher signal-to-noise ratio because of the small bandwidth required, i.e. higher accuracy.
2. improved measurement linearity owing to smaller modulation index.
3. direct measurement of the transfer function i.e. no Fourier transform needed.
4. more practicable when it is difficult to obtain large amplitude, short light pulses at some wavelengths.

The arrangement of the material prescribed in the thesis is as follows; Firstly, in the introduction, following a brief review of fibre guides in general, the nature of the dispersion sources in light guides is reviewed to demonstrate the limitation on bandwidth. The various techniques for system characterisation are then examined in some detail together with the nature of the different measurements problems. The second chapter of the thesis describes the equipment designed and built as part of the
work. Chapter 3 describes in detail the problem of measuring the phase part of the transfer function directly in the frequency domain and the technique suggested to solve this difficulty. Also it gives results of the measured transfer function of 100m of step-index fibre up to the frequency of 550MHz using a single frequency Helium Neon laser source with external electro-optic modulator. Chapter 4 describes the time domain measurement technique and presents results of the measured transfer function on the same 100m fibre, then compares these results with those obtained from the frequency domain method. Chapter 5 discusses the method of calculating the fibre impulse response and compares the results obtained from the two alternative measurement techniques. Chapter 6 is devoted to describing the extension of the measurement system's bandwidth up to 1275MHz using a cw laser diode and illustrate its performance by giving results for the measured transfer function and impulse response of 900m of graded-index fibre. The merits of the frequency and time domain methods are examined and discussed in chapter 7.

In summary, this thesis is not a treatise on optical fibres, rather it is a treatise on system characterisation. It is thus a thesis on the subject of electro/optical measurements; optical fibre being the subject of the measurements but the frequency domain technique being the subject of the thesis.
1.2 Review of optical fibre waveguide

To discuss the limitation on the transmission capacity or bandwidth of optical fibre, one has to know the different sources which contribute to the dispersion. An optical fibre waveguide is simply a very thin cylinder (core) made of highly transparent dielectric material of refractive index $n_1$, surrounded by a protective cladding of slightly lower refractive index $n_2$, which is necessary for the total internal reflection of light inside the core (Fig. 1.2.1). The size of the core and the

![Fig. 1.2.1 Ray model of optical fibre waveguide.](image)

difference between the refractive indices $n_1$ and $n_2$ of core and cladding respectively, determine the number $N$ of propagating modes inside the fibre, given approximately by the following relation [6];

$$N = \frac{V^2}{2}$$  \hspace{1cm} 1.2.1

where $V$ is a waveguide parameter sometimes called the normalized
frequency, or simply V-number, and is given by;

\[ V = \frac{2\pi a}{\lambda} \left( n_1^2 - n_2^2 \right)^{1/2} \]  \hspace{1cm} 1.2.2

where \( a \) is the radius of the core,
\( \lambda \) is the wavelength of propagating light.

For values of \( V \) below 2.4, only the fundamental mode \( HE_{11} \) can propagate and under such conditions the fibre is called a single-mode fibre. In a typical case, assuming a refractive index difference of 1% at a wavelength of 1\( \mu \)m, the core diameter should be about 3.6\( \mu \)m to give a value of \( V \) of 2.4. This is very small compared to the dimensions of multimode fibres (20-150\( \mu \)m) which propagate hundreds or thousands of modes.

The dispersion in optical fibres is related to the following mechanisms;

1. **Multipath dispersion**

   Multipath dipersion results from the difference in delay time between rays or modes propagating at different angles inside the fibre core (Fig.1.2.1); it is the dominant source of dispersion in multimode fibre. Typical step-index multimode fibre has multipath dipersion of a few tens of nanoseconds per kilometre. To reduce this effect, fibres with graded-index cores are used to counter the delay over the longer travelled paths by having a smaller effective refractive index than that of the shorter paths (the axial rays). To obtain wide bandwidth fibre needs very precise profiling in the fibre fabrication process. Graded-index fibre manufactured today has small dispersion of less than one
2. **Material dispersion**

Material dispersion is also known as chromatic dispersion. Since the refractive index of the core is a function of wavelength, the various optical frequency components of each ray (when generated by a light source of non-zero spectral width) will travel at effectively different speeds and this will lead to different time delays and thus to dispersion. This source of dispersion is dominant in single-mode fibres, where there is of course no multipath dispersion, but it is also effective in multimode fibres when using light emitting diodes rather than laser diodes, since the former have large spectral widths. The specific material dispersion factor $M(\lambda)$ is defined by [9]:

$$M(\lambda) = \left(\frac{\lambda}{c}\right) \left(\frac{dn}{d\lambda}\right)^2$$

and usually measured in picoseconds per km per root mean square of spectral width (to give a typical value at 0.85\,\mu m it is 100ps/km\,\mu m for germania-doped silica fibres [10]). Material dispersion decreases as wavelength increases above 0.85\,\mu m and crosses zero near 1.3\,\mu m. Hence, the newly developed fibres have been designed to operate near this wavelength since fibre attenuation is also a minimum in this region.

3. **Waveguide dispersion**

Waveguide dispersion arises from the wavelength dependence of the propagation constant of a particular mode [10]. This effect is
very small and negligible for modes not close to cutoff, and since in multimode fibres these modes carry very little energy relative to the others, this dispersion is negligible for this type of fibre. In single-mode fibre the situation is different since the V value is chosen so that only one mode can propagate, and this dispersion is then comparable to the material dispersion. At some wavelength near 1.3\textmu m it has been shown [11] that the value of the waveguide dispersion (about 5ps/km.nm for fused silica fibre), equals that of material dispersion but since the latter has a negative value, cancelation can occur. This is the promised region for very wideband operation of single-mode fibre.

In addition to the above, there are several effects which serve to reduce the dispersion in multimode fibre, like mode coupling, which arises from refractive index inhomogeneities, diameter fluctuation and structural imperfections, and differential mode attenuation which leads to reduction of the effective numerical aperture.

Although single-mode fibre has lower attenuation and dispersion than others, present-day technology is more highly developed for multimode fibre since it is much more practical in use (thanks to its much bigger core size), because of the relative ease of splicing, making connections and of efficient coupling to laser sources. This is especially the case in low to medium bandwidth systems where light emitting diodes can also be used. The work described in this thesis has been concerned with characterisation of multimode fibres, laser sources being used, and hence the main effect observed was multipath dispersion.
1.3 Fibre performance characterisation

Because of the increasing use of pulse code modulation in telecommunication systems and the availability in the optoelectronics market of laser sources that can generate very short optical pulses, such as for example mode locked lasers and semiconductor injection lasers, optical fibre manufacturers have chosen to characterise their fibres in terms of the pulse broadening which occurs after propagation down a certain length of fibre, usually 1km. Consequently, early research has concentrated on studying and measuring the dispersion, as characterised by pulse response, under various conditions such as the method of launch, the fibre length, the bending and so on [12,13,14].

It was realised that the measurement does not provide all the information needed for system design, and knowledge of the baseband frequency response (i.e. amplitude and phase) is necessary to understand fully the behaviour of optical fibre. Gloge [15] was the first to measure baseband frequency response directly in the frequency domain, making use of the beats of a multimode gas laser. His method provided him with the amplitude response but not the phase.

Other workers like Personick [16] and Wittke [17] followed him in using the frequency domain method, with light emitting diodes as the light source, to determine the amplitude response, but only up to the relatively low frequency of 240MHz.

Realising the importance of representing the fibre response in the frequency domain, researchers using the pulse broadening technique added computers and fast Fourier transform equipment to their experiments for computing the fibre transfer function from...
time domain measurements. Wittke [17], Dannwolf [18], and Cohen [19] being prominent. Recently, digitising oscilloscope systems have been used [20]. Disadvantages which early became apparent included the low signal-to-noise ratio (SNR) which results from the large bandwidth needed and the practical constraints on some laser sources at certain wavelengths to generate sufficient power to perform the measurement. Later it was found that errors as large as 100% could occur in computing the phase and amplitude response in this way [21]. Averaging of received pulses [18] as well as including lock-in amplifiers in the measurement system [22], has been found to improve the SNR and hence accuracy. Also, in order to improve detector linearity optical attenuators have been used [18].

Optical sources at a variety of wavelengths have been needed to study the response of a fibre as a function of the wavelength, particularly in the case of graded-index fibre, but when using the pulse broadening technique, studies have been limited to wavelengths at which pulsed lasers are available. A useful alternative is to use an incoherent broadband source in conjunction with narrowband optical filters, to give the required wavelength coverage, and a modulator to vary the intensity. Such a system has been described by Cohen et al [23] in which a Xenon arc lamp was filtered in bands of width between 1.5nm and 10nm over the wavelength range 0.65um to 1.1um, and the amplitude response measured at frequencies up to 1GHz.

This latter frequency domain approach gives a better SNR because narrowband detection can be used. Unfortunately direct measurement of phase distortion is difficult when using, say, 1km
of fibre over a frequency band extending to 1GHz, because, in that case, the actual phase varies almost linearly with frequency over the range about 0 to $10^4 \pi$ radians, whereas the required information comprises the deviation from linearity which is likely to be less than $2\pi$ radians [24]. To counter this difficulty the assumption has been made [23] that the fibre transfer function is of minimum phase behaviour and hence that the phase function could be derived from the amplitude function by means of the Hilbert transform.

Although this method has shown some interesting results [23,25] when compared with the time domain method, it has been reported that the Hilbert transform approach is not in general a very helpful one [24]; although it has given satisfactory results for some fibres, for others it has not done so [21,26].

A few groups realised early what has been confirmed above, that there are many advantages to be gained from measuring the fibre transfer function fully in its natural domain, i.e. the frequency domain. Boisrobert et al [27], used a network analyser and a short life time (2 hours) cw injection laser to measure the amplitude and phase response of 700m of a step-index fibre, but no details were given about the differential phase behaviour which corresponds to group delay. Realising the shortcomings of this method, Martin, Cozannet and Boisrobert [28] then changed to a new technique which measures both amplitude and group delay versus frequency using a microwave link analyser over the band 5-45MHz. They claimed good general agreement between their measured results and the expected values but made no comparison with the other possible measurement technique, the pulse technique. The
experimental system complexity (use of mixers, tuned amplifiers and oscillators), adds to the limited bandwidth of the measuring system as disadvantages.

A different and rather complicated technique has been used by Nicolaisen and Hansen [26] for measuring differential phase. The laser source is modulated simultaneously at two frequencies, which are then swept across the frequency band of interest while their separation is maintained at a constant difference. Phase is measured at the fibre output at frequencies which give a maximum in the output amplitude. From these measurements the differential phase can be calculated. Measurements performed on 1150m of graded-index fibre over the frequency range 200–700MHz gave good agreement with the results derived from pulse measurements for frequencies up to 400MHz. However, there was some disagreement for higher frequencies, claimed to be the results of intermediate frequency instability. Complexity is a major drawback of the technique described above which included the need for a variety of mixers and filters. It also needs tightly controlled automatic sampling to determine accurately the points of maximum amplitude response.

It is clear from the above review that a straightforward convenient frequency domain measurement technique is desirable, which is capable of determining the differential phase with a minimum of complexity. The originality of this work lies in the investigation of a direct frequency domain technique to measure the transfer function of optical fibre and to assess critically the advantages as compared to the traditional indirect time domain technique.
2.1 Introduction

The aims of the work described in this chapter were to develop the sources necessary for frequency domain and time domain measurements of optical fibre dispersion. The basic optical fibre measurement system is composed of a light source, optical fibre cable, photodetector and the associated electronic circuitry. The requirement of these components was a high speed of response i.e. capable of operating over a wide frequency band. For time domain measurements, ideally the impulse response should be measured. Consequently, the general aim is to generate the shortest possible test pulse that can be conveniently achieved. In fact, the limit required depends on the dispersion to be measured, thus an overall bandwidth of 1GHz would imply a test pulse of about 1ns. A variety of possible sources were investigated, semiconductor devices being the obvious candidates.

Semiconductor light sources are available in the form of light emitting diodes (LEDs) and laser diodes (LDs). LEDs were found to be not suitable owing to their relatively slow switching times of several nanoseconds. In addition, they have wide spectral width, typically of the order of 20-40nm [29], which leads to complications because of the high material dispersion which results, because this limits the bandwidth of low modal dispersion fibres. For the above reasons, mainly, semiconductor laser diodes are much more suitable, having much faster response of less than a nanosecond, and narrower spectral width, typically,
less than 5nm. These two points ensure a wide frequency band capability for the system. Some other advantages of LDs over LEDs are their higher output power, which is useful for making measurements using long fibres, and their higher efficiency in coupling to fibre, owing to their narrower angle of emission. These features of laser diodes make them almost ideal for use in long length wideband optical fibre communication systems.

However, when this work began, commercially available laser diodes operated only in pulse mode, and hence, they were suitable for time domain measurements only. For frequency domain measurements, sources which can emit light continuously are required. Apart from light emitting diodes, cw lasers are available commercially in the form of gas lasers which can emit cw light in powers from milliWatts to Watts, and have a very narrow spectral width of less than 0.1nm. Modulating the light from these sources is usually done externally by passing the light through an electro-optic modulator. Gas lasers are not practicable for use with optical fibre systems because of their bulky size and modulation difficulty, however, they could be very useful for laboratory measurements. Two types of photodetectors are mainly used with optical fibre communication systems for their high speed of response and practical size. These are PIN and avalanche (APD) photodiodes. A commercially available APD was chosen for the system. This has the wide bandwidth needed (response time less than 0.2ns), in addition APDs have higher sensitivity than PIN diodes owing to their internal gain.
2.2 Pulsed semiconductor laser diodes

Semiconductor laser diodes made of Gallium Arsenide, GaAs, and Gallium Aluminium Arsenide, GaAlAs, have been extensively developed over the past few years. These lasers show many attractive features for use in optical fibre communication systems. Their wavelength of emission lies in the region of 0.8-0.9\textmu m, which is suitable for use with optical fibre, since developed fibres have a window in their spectral loss response at these wavelengths. Recent developments in optical fibre have shown a move in wavelength toward the 1.3\textmu m and 1.5\textmu m region since lower losses and dispersion can be achieved here [30,31]. Hence, new laser diodes made of materials like Indium Gallium Arsenide Phosphide [32], which are suitable for the new wavelengths are of considerable attention now. However for our measurement system the wavelength of operation was of minor importance for the measurements intended.

Laser diodes that were available commercially a few years ago could only be used in pulsed operation at low duty cycles. These lasers were intended for applications like optical data transmission, range finding and intruder detection, with pulse rates limited to about 10MHz. One disadvantage of these sources was their relatively high threshold current which ranges from half to tens of Amperes depending on their output power. Two pulsed laser diodes were investigated for use as optical pulse generators. The first was a double heterostructure GaAlAs type LBA185A manufactured by ITT, which has a relatively low threshold current of 0.5A. It was rated to give 200mW of optical power at 1.3A driving current with duty cycle of 6\%. The other was a
single heterostructure GaAs laser diode type SG2002 manufactured by RCA with threshold current of 3.5A and 2W output power at 10A driving current. The duty cycle for this laser was low (less than 0.1%). Much effort was spent on developing suitable circuits for driving these laser diodes and this work will be described next.

2.3 Current pulse generators

Several pulse generator circuits have been published in the literature. They range from conventional methods of discharging a cable or a capacitor using fast switches like mercury relays [33] or avalanche transistors [34] to modern circuits using step recovery diodes [35] or VMOS FET transistors [36]. Circuits using relays can switch currents of several Amperes in less than a nanosecond, but they are limited to a low repetition rate of only a few hundred pulses per second. Step recovery diodes have been used for generating subnanosecond current pulses of a few tens of milliAmperes at a high repetition rates of few hundred mega-Hertz. Avalanche transistors can switch currents of several Amperes in a very short time, with rates of change of current better than 1A/ns, at moderate frequencies of a few hundred kilo-Hertz. In addition to the above devices a new series of Field Effect Transistors, VMOS FETs, have been recently produced which are capable of switching currents of 1A either ON or OFF in 4ns [36]. Both avalanche and FET transistors were incorporated into circuits for driving pulsed laser diodes as will be discussed next.
2.3.1 Avalanche transistor pulse generator

Avalanche transistors have been used for the generation of electrical pulses with switching times shorter than a nanosecond [37]. Although transistors specifically designed to operate in the avalanche mode are available commercially, they are relatively expensive. However, it is possible to use standard silicon switching transistors in the above mode with subnanosecond switching times. Suitable transistors can be identified by measuring their output characteristic in common base configuration, in which they must show negative differential resistance for small currents [37]. The amplitude of the current pulse which can be generated depends on the transistor breakdown voltage and values of the circuit components. One circuit adopted for the generation of short electrical pulses [37] is shown in Fig.2.3.1.1. In this circuit the width of the output pulse $t_\text{p}$ is given by:

$$t_\text{p} = t_0 - t_2 - t_1$$

2.3.1.1 (see Fig.2.3.1.1)

This circuit has the advantage of generating square pulses of adjustable width. The output pulse shown in Fig.2.3.1.2 has rise and fall times of around 0.3ns and an amplitude of 10V across 25 Ohm effective load, which corresponds to peak current of 0.4A. The disadvantage of this circuit lies in its low output current which is not sufficient for driving the available laser diodes. To increase the amplitude of the current pulse from the avalanche transistor, simpler circuits using one transistor were used as shown in Fig.2.3.1.3. The amount of the peak current generated is
Fig. 2.3.1.1 Circuit diagram for the generation of short pulses.
controlled by the value of the capacitor $C_c$. A triggering signal at the input starts the avalanche process. The maximum repetition frequency is limited by $R_c$, $C_c$ and the transistor power dissipation, to a few hundred kilo-Hertz. In order to determine the performance of the circuit a fast avalanche photodiode (BPW28) was used in the experimental set-up shown in Fig.2.3.1.4 to detect the emitted light pulses from various laser diodes. Fig.2.3.1.5 shows the waveshapes of the detected light pulses from SG2002 and LBA185A lasers when driven with the circuits of Fig.2.3.1.3. The pulse width at half amplitude (PWHA) is of the order of 200ps and the rise time is around 160ps. Optical attenuators were used to prevent excessive light levels falling on the detector. Using the same detector, a BPW28, Plumb [38] has
Fig. 2.3.1.3 Circuits for driving pulsed laser diodes

a. Driver for ITT LBA185A laser diode ($I_{th}=0.5A$)

b. Driver for RCA SG2002 laser diode ($I_{th}=3.5A$)
Fig. 2.3.1.4 Circuit arrangement for detecting light pulses.
Fig. 2.3.1.5 Detected light pulses from
a. LBA185A laser diode
b. SG2002 laser diode
vertical scale 10mV/div
horizontal scale 0.5ns

optical attenuation=20dB

(a)

optical attenuation=28dB

(b)
reported measuring similar pulse widths from a laser. However, Plumb then used a newly developed thin silicon PIN photodiode to measure the same pulse and found a rise time of around 100ps. This suggests that our measurement system is limited in response by the detector.

2.3.2 VMOS FET driver

Until a few years ago, FETs were useful only at low power levels of less than a Watt. However, the recent development of VMOS FETs has now resulted in increased current and voltage capabilities. Switching times of 4ns of 1A have been reported using these new devices. Their input impedance is relatively high, and they thus require a low driving current. However, a high peak driving current is needed to charge or discharge the effective input capacitance of about 65pF. The use of FET drivers for laser diodes was adopted in order to provide pulsed light sources having higher repetition rates because of the improved signal-to-noise ratio this would offer in the measurement system.

Lock [39] used a specially manufactured transistor for use in the avalanche mode to drive a pulsed laser diode LBA185 with 6ns pulses of 1.5A amplitude. But because of the limited repetition rate from these transistors, of not more than 1.5MHz, he used 10 separate pulse generators triggered in sequence and their output currents were added and applied to the laser diode to obtain a repetition rate of about 14MHz. This was done before the appearance of VMOS FETs in the market.

A pulse generator using a VMOS FET transistor type VN66AF manufactured by Siliconix, was built to drive the low threshold
current LBA185A laser diode, and its circuit diagram is shown in Fig. 2.3.2.1. A step recovery diode pulse generator was used for switching the FET driver at a repetition rate of 17MHz. The detected light pulse is shown in Fig. 2.3.2.2. Its PWHA width is around 350ps, which is more than that obtained using an avalanche transistor. This might be due to the fact that the rise time of the driving current was slower in the FET case.

2.4 Ringing phenomena in pulsed laser diodes

It has been shown by some authors [40,41], that laser diodes when driven by sharply rising current pulses show ringing behaviour in their emission. This has been explained as due to some electron-photon resonances [42]. The above phenomena has been observed in our laser diodes. The output light pulses for
Fig. 2.3.2.2 Detected light pulse from LBA185A laser diode when driven from VMOS-FET driver.
vertical scale 20mV/div
horizontal scale 0.5ns/div

different current excitations were measured and are displayed in Fig.2.4.1. The duration of the spikes are very short (less than 0.5ns), and by adjusting the injected current pulse, a single output pulse can be obtained (Fig.2.4.1a).

2.5 Radiation pattern of emitted light pulses

The radiation patterns of the emitted light from the pulsed laser diodes were measured by tracing the far field as shown in Fig.2.5.1, and the patterns obtained are plotted in Fig.2.5.2. The measured patterns of power distribution are far
Fig. 2.4.1 Waveshapes of detected light pulse for different injected current pulse width (W).
\[ W_d > W_o > W_b > W_a \]
horizontal scale 0.5ns/div
from smooth and show many peaks, unlike the specification of the manufacturers which show smooth patterns. The difference could due to the different driving conditions, since specified patterns were measured under long excitation current pulses of 200ns (for SG2002 diode), as compared with our case of only a few nanoseconds. Similar observations have been reported by Cahill [43]. A photograph of the emitted light is shown in Fig.2.5.3, using infrared film. Its elliptical shape results from the rectangular shape of the emitting laser diode area.
Fig. 2.5.2a,b Radiation patterns of LBA185A laser diode.
Fig. 2.5.2c, d Radiation patterns of SG2002 laser diode.
2.6 CW semiconductor laser diode

A new GaAlAs cw laser diode type LCW10, manufactured by Laser Diode Labs, has latterly also been used in our system. It has a low threshold current of about 108mA, as can be seen from its measured power-current characteristic curve shown in Fig.2.6.1, and is capable of high frequency modulation in excess of 1GHz. The maximum output power that could be obtained from this laser is 7mW. This laser has proved very useful because it has made possible doing both time and frequency domain measurements on a long wideband optical fibre using a single laser source. A bias circuit is needed for continuous wave operation, which must supply the laser diode with the appropriate stable dc
current as well as the high frequency modulation waveform. The circuit used for this purpose is shown in Fig.2.6.2. An inductance was used in the dc path to block the modulating signal and a 47 Ohm resistor in the ac path to provide proper 50 Ohm matching to the input driver. The frequency response of the laser transmitter was measured using the experimental set-up shown in Fig.2.6.3. The measured frequency response displayed in Fig.2.6.4 has a flatness of ±2dB across the entire frequency band of 4-1300MHz limited by the network analyser used. The spectrum of the detected light when modulating the laser at 25MHz is shown in Fig.2.6.5. The harmonic components are more than 40dB below the fundamental frequency at a modulation index of 22%, which gives
Fig. 2.6.2 Bias circuit for LCW10 laser diode.

Fig. 2.6.3 Experimental set-up for frequency response measurement of LCW10 laser diode.
2.6.4 Measured frequency response of LCW10 laser diode (4-1300MHz)
vertical scale 10dB/div

Fig. 2.6.4 Measured frequency response of LCW10 laser diode (4-1300MHz)
vertical scale 10dB/div

2.6.5 Spectrum of detected light when modulating LCW10 laser diode at 25MHz.
vertical scale 10dB/div
horizontal scale 10MHz/div

Fig. 2.6.5 Spectrum of detected light when modulating LCW10 laser diode at 25MHz.
vertical scale 10dB/div
horizontal scale 10MHz/div
an indication of the good linearity at the bias level selected (dc current of 120mA).

2.7 **Step recovery diode pulse generator**

It is easier to pulse a cw laser diode than a pulsed laser diode. A step recovery diode (SRD) pulse generator can be used, since the problem of high threshold current does not exist. Step recovery diodes have been used for the generation of extremely fast pulses by virtue of their ability to switch fast from a low impedance when storing charge to a high impedance when the charge is removed. Their application in pulse generation and waveform shaping can be found in various application notes like Hewlett Packard AN918. A circuit which uses an SRD to convert sinusoidal input signals into short unidirectional pulses was used for driving an LCW10 laser diode, and it is shown in Fig.2.7.1. The output pulse width, $t_p$, is determined by the SRD capacitance and the value of the inductor $L$ according to the formula [44]:

$$t_p = \pi \sqrt{LC} \quad 2.7.1$$

The values of the components $L, C, C_T$ and $L$ can be calculated from design formulae [44] for a given pulse width, frequency of operation, output impedance of driver and output load. The output pulse from the circuit is shown in Fig.2.7.2, it has a PWHA width of 0.5ns at a repetition rate of 40MHz. These pulses were used to drive the cw laser diode, and the detected light pulse is shown in Fig.2.7.3. The close correspondence between the input pulse width ($\sim 0.5$ns) and the detected pulse width of 0.6nS gives a good
Fig. 2.7.1 Circuit for converting sinusoidal input into unidirectional pulses using Step Recovery Diode.

Fig. 2.7.2 Pulse generated by Step Recovery Diode pulse generator (Fig. 2.7.1).
vertical scale 1V/div
horizontal scale 0.5nS/div
indication of the laser diode transmitter fast response.

2.8 CW gas lasers

Helium Neon, HeNe, gas lasers are sufficiently inexpensive to use as cw sources. These can emit cw light in powers from milliWatts to Watts and have a very narrow spectral width of less than 0.01nm, since emission can take place only within the Doppler width of the spectral line, which is approximately 1500MHz at 0.6328um. Two HeNe lasers have been investigated for the experiments, a multimode laser model 124 made by Spectra Physics which emits 15mW of cw light, and a 0.5mW single frequency laser model 100 made by Tropel. To modulate the
light from these sources, an external modulator was necessary. For this purpose a Lithium Niobate, LiNbO₃, electro-optic modulator was used, which was built in this department [45]. This modulator has a wideband modulation capability up to 2GHz when used with a HeNe laser [45]. It was the availability of this modulator which made it possible at first to perform frequency domain measurement on optical fibre.

2.9 Static characteristic of electro-optic modulator

The circuit arrangement shown in Fig.2.9.1 was used to measure the static characteristic of the EOM, defined as the relation between the dc voltage applied to the modulator and the detected dc current which corresponds to the intensity of the laser beam. This relation is plotted in Fig.2.9.2. The extinction ratio defined as $\frac{I_{\text{max}}}{I_{\text{min}}}$ is about 7.5. The linear region of operation is limited approximately to input voltages between -30V and +30V, which corresponds to a modulation index, $m$, of about 45% using the formula;

$$m = \frac{(I_2-I_0)/I_0}{(I_1-I_0)/I_0}$$  \hspace{1cm} 2.9.1 \text{(see Fig.2.9.2)}$$

2.10 Modulation of multimode HeNe laser

To study the modulation behaviour of the multimode laser, the experimental set-up shown in Fig.2.10.1 was used. With no modulation applied the detected light signal as displayed on the spectrum analyser is shown in Fig.2.10.2a. The frequencies observed correspond to the beats between the different laser
longitudinal modes, and their separation is about 210MHz which agrees well with that specified for this particular laser (214MHz). When modulating the laser with a 280MHz signal the spectrum becomes as shown in Fig.2.10.2b. It can be seen that the amplitude of the detected modulation is smaller than the components corresponding to the beat frequencies. It is possible to use this laser when modulating at one single frequency, provided that the detected output can be tuned to the modulating signal, which is the case when using a vector voltmeter or a network analyser as is necessary for measuring amplitude and phase.
Fig. 2.9.2 DC characteristic of the electro-optic modulator.

responses, but it is necessary to exclude measurements for which the modulating signal frequency coincides with one of the beat frequencies. However, the problem is more serious in the time domain when the modulator is pulsed. In the time domain, the output display shows a series of short unstable pulses as seen in Fig. 2.10.3, and pulsing of the modulator is useless. For the above reasons a multimode laser is not suitable for the system and it was decided to use a single frequency laser.
Fig. 2.10.1 Circuit arrangement for high frequency modulation of electro-optic modulator.
Fig. 2.10.2 Spectrum of detected laser beam.

(a) no modulation
(b) 280MHz modulation

laser beats at 210, 420, 630, 840 and 1050MHz.

vertical scale 10dB/div
horizontal scale 140MHz/div
2.11 Modulation of single frequency HeNe laser

The single frequency laser used was Tropel model 100. Its optical spectrum was measured and shown in Fig.2.11.1. It can be seen that it is not truely single frequency because other frequency components much smaller than the main one are also present. However, because they are so small, it is in effect a source of a single frequency. The spectrum of the detected light from this laser when under no modulation can be seen in Fig.2.11.2a; it contains three frequency components of about 220, 340 and 560MHz. The 560MHz frequency corresponds to the laser
Fig. 2.11.1 Optical spectrum of single frequency HeNe laser Trope 100.
horizontal scale 320MHz/div

longitudinal beat since the laser cavity length is about 30cm. Fig.2.11.2b shows the spectrum of the detected light when a 100MHz modulation was applied to the modulator. The detected modulation is only about 8dB higher than the highest beat frequency, but this is much better than when using the multimode laser. Looking at the detector output in the time domain, the detected signal when no modulation used is seen in Fig.2.11.3a, which shows that it has a dominant component at around 500MHz. Under 100MHz modulation the time domain output is shown in Fig.2.11.3b. It consists of the 100MHz signal having added to it the other beat frequencies. However, using a tuned detector the extra interference could be highly reduced.

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Fig. 2.11.2 Spectrum of detected light from single frequency laser Trope 100.
  a. no modulation
  b. 100MHz modulation
vertical scale 10dB/div
horizontal scale 100MHz/div
Fig. 2.11.3 Detected light signal from single frequency HeNe laser Tropel 100 as displayed on oscilloscope.

a. no modulation
b. 100MHz modulation

vertical scale 100mV/div
horizontal scale 2nS/div
2.12 Modulation characteristic of the electro-optic modulator

The modulation frequency response of the electro-optic modulator was measured using the circuit arrangement shown in Fig.2.12.1. It can be seen from the low frequency response (Fig.2.12.2) that the amplitude of the detected modulation is far from smooth and contains deep fluctuations due to piezoelectric resonances, however, these fluctuations are greatly reduced above 40MHz to give a smoother response. The flatness of the response above 40MHz is governed by the driver and receiver amplifiers frequency response (Fig.2.12.3) and the mismatch between the 50 Ohm driver and the 27 Ohm input impedance of the modulator.

2.13 Pulsing of the electro-optic modulator

In order to pulse the electro-optic modulator, circuits were needed which can generate short pulses of high power having nanosecond duration. In addition, a repetition rate of these pulses of 40MHz or more was preferred to avoid operation in that region of the modulator characteristic where amplitude fluctuations exist. A high power step recovery diode in a circuit similar to that used earlier with the cw laser diode was tried. To obtain high power pulses, a sinusoidal input of few watts was necessary. A simply designed RF power amplifier using a VMOS FET transistor was used for this purpose, and its circuit diagram is shown in Fig.2.13.1. This amplifier can drive a 50 Ohm load with 5W power at frequencies up to 50MHz. The step recovery diode pulse generator circuit diagram is shown in Fig.2.13.2. The values of the circuit components used were calculated for
Fig. 2.12.1 Circuit arrangement for measuring frequency response of electro-optic modulator.
Fig. 2.12.2 Measured frequency response of electro-optic modulator.
   a. low frequency region 4-50MHz
   b. higher frequency region 50-550MHz
   vertical scale  a. 10dB/div
                 b. 2.5dB/div
Fig. 2.12.3 Measured frequency response of driver and receiver amplifiers.
vertical scale 2.5dB/div
horizontal scale 50-550MHz

Fig. 2.13.1 Circuit of VMOS-FET power amplifier.

operation in the frequency range of 40-50MHz, and the output pulse
obtained is shown in Fig.2.13.3. The peak power of the generated pulse is about 30W and its PWHA width is around 0.5ns at a repetition rate of 40MHz. These pulses were used to drive the EOM modulator, and the photodetected output is shown in Fig.2.13.4. It can be seen that there is a difference between the applied electrical pulse and the detected pulse ($\sim 1.1\text{ns width}$), this could due to the use of a 520MHz amplifier after the detector to reduce the effect of the 560MHz beat frequency from the laser.

2.14 Photodetectors

Photodetectors needed for use in optical fibre system should have small size, low noise, good sensitivity and linearity, high reliability and fast response depending on the bandwidth of the system. PIN photodiodes prepared from silicon and operating at low reverse bias voltage (20–30V), have most of the features mentioned above including fast response which can be less than a nanosecond, but, their sensitivity is usually limited by the noise level of the preamplifier following them. To improve detector
Fig. 2.13.3 Output pulse from Step Recovery Diode pulse generator.
vertical scale 100mV/div
horizontal scale 0.5nS/div
attenuation used=41dB

Fig. 2.13.4 Detected light pulse from electro-optic modulator.
vertical scale 100mV/div
horizontal scale 1nS/div
sensitivity, avalanche photodiodes have been produced. These devices operate at higher bias levels, typically of 150V or more and although they still have fast response times of less than a nanosecond, with their internal multiplication mechanism weak light signals can be amplified several hundred times thus enabling the output current signal to overcome the noise current of the following preamplifier. However, because the shot noise increases more rapidly than the current signal at high values of multiplication gain, a range of gains from 80 to 100 is usually observed to be optimum for signal-to-noise ratio.

Silicon photodiodes have shown good features for use in the wavelength range 0.8-0.9um, where GaAlAs laser diodes emit, and commercially available fibre have minimum loss. For wavelengths beyond 1um and especially 1.3um and 1.5um, where the new generation of optical fibres can have very low loss and wide bandwidth, photodiodes made from materials other than silicon, for example Indium Gallium Arsenide Phosphide [46], have been in the process of development. For our system (0.633um and 0.8-0.9um) a commercially available silicon avalanche photodiode type BPW28 manufactured by AEG Telefunken was chosen for its fast response and good sensitivity. This photodiode has a small sensitive area of 0.2mm diameter, a stated gain-bandwidth product of 200GHz, and low junction capacitance of 1pF. Another good feature of this diode is the fast fall time with no noticeable tailing effect as is observed in some avalanche detectors. The measured gain-voltage characteristic is shown in Fig.2.14.1.
2.15 Biasing of avalanche photodiode

In order to use an avalanche photodiode over a bandwidth which starts from a few mega-Hertz and extends into the giga-Hertz region, it is necessary to mount it so that a good 50 Ohm match between the detector and the rest of the circuit can be obtained. A coaxial mounting has been used, similar to that suggested by Clark [47], and a photograph of the diode in its mounting is shown in Fig.2.15.1. A circuit for dc biasing and coupling of the ac signal from the detector to its load is also needed. One popular circuit known as the bias T is shown in Fig.2.15.2. This circuit provides the dc biasing for the APD through the path CB, while
Fig. 2.15.1 Photo of avalanche photodiode in its mounting.
Fig. 2.15.2 Bias T circuit for APD detector
R=1kΩ, C=4.7nF

Fig. 2.15.3 Measured frequency response of bias T.
vertical scale 0.25dB/div
horizontal scale 4-1300MHz
blocking the ac signal by the high resistance (1kOhm) inserted in the supply path. General Radio 50 Ohm components were used for the bias T coupling capacitor and T junction with the 1KOhm resistor inserted in its arm. The ac transmission characteristic (i.e. amplitude versus frequency) of the bias T was measured in the frequency range 4-1300MHz and is shown in Fig.2.15.3.

2.16 Conclusion

Optical sources capable of wideband frequency modulation have been developed. These consist of a highly coherent HeNe laser capable of cw modulation up to 550MHz limited by the power amplifier required to drive the modulator, and of pulse modulation of 1ns width pulses. Shorter optical pulses of 200ps width have been obtained from pulsed laser diodes, but these sources have the drawback of being not suitable for cw operation necessary for the comparison between the frequency and time domain measurements of fibre dispersion. A latterly obtained cw laser diode capable of cw modulation up to 1300MHz and generation of 0.6ns optical pulses was found very useful and important for extending the bandwidth of the measurement system.
3.1 Introduction

Because of the many advantages offered by the frequency domain methods for measuring optical fibre transfer function, and also owing to the disadvantages of the frequency domain techniques mentioned in chapter 1, it was considered desirable to develop a straightforward technique that can measure the differential phase of the fibre transfer function over a wide frequency range, with good reliability. The measurement of the amplitude part is relatively easy since its variation with frequency is very slow.

The suggested straightforward method was based on measuring the phase of the modulated light envelope at the fibre output at equal frequency intervals throughout the frequency band of interest, with sufficient accuracy to make possible extracting the differential phase from the data obtained. To be able to apply such a simple technique, a detailed knowledge of the phase behaviour in multimode fibre is necessary since this determines the required frequency accuracy of the modulating signal source, and hence the possibility of such a technique.

This chapter discusses, in detail, the theoretical background of the problem of measuring phase directly in the frequency domain, and describes a method developed to perform phase measurement. It then goes on to describe a complete measurement system based on this method and gives some experimental results of the measurement performed on a 100m of step-index fibre.
3.2 The transfer function of multimode fibre

An easy understanding of the transfer function behaviour of a multimode optical fibre can be achieved by using the time domain approach. A simple expression for the time delays that different modes suffer when propagating down a multimode optical fibre waveguide, can be arrived at by using the ray optic model [48]. Fig.3.2.1 shows a simple model for multimode step-index fibre with core and cladding refractive indices $n_1$ and $n_2$ respectively.

The time delay $\tau_0$ that the fastest meridional ray ($\theta=0$) suffers after a length of L metres is given by;

$$\tau_0 = (L/c) n_1$$  \hspace{1cm} 3.2.1

$c$ being the speed of light in free space. The slowest ray propagates at a maximum angle of $\theta_0$ determined by the numerical aperture N.A. of the particular fibre give by;

$$N.A. = \sin\theta_0 = \sqrt{\frac{2}{n_1^2 - n_2^2}}$$  \hspace{1cm} 3.2.2

Fig.3.2.1 Ray model of optical fibre waveguide
where $\theta_c$ is the maximum acceptance angle in air (n=1), and the relation between $\theta_0$ and $\theta_c$ is given by:

$$\sin\theta_0 = \frac{(\sin\theta_c)}{n_1}$$

3.2.3

and the delay $\tau$ of a general oblique ray is $\tau_0/cos\theta$. Hence, the delay time difference $\Delta\tau$ between the general oblique ray and the meridional ray is given by:

$$\Delta\tau = \tau_0((1/cos\theta)-1)$$

3.2.4

$$\Delta\tau = (L/c)n_1((1/cos\theta)-1)$$

3.2.5

The energy distribution of modes (or rays) $H(\theta)$ inside the fibre may take the form [48],

$$H(\theta) = \cos^m\theta$$

3.2.6

where $m$ is a parameter which determines the relative energy carried by the various modes ($m=0$, implies equal excitation of all propagating modes). Assuming that the fibre is loss free and no mode conversion occurs then the output time function in response to an input Dirac pulse is given by the following expression [48];

$$F(t) = \frac{(m+1)t_0^{m+1}}{m+1} \cdot \frac{1}{1-cos\theta} \cdot \text{rect} \left( \frac{\tau_0}{\cos\theta} \right) \frac{1}{m+2}$$

3.2.7

where $\tau_0 \leq t \leq \tau_0/cos\theta_0$
It has also been shown [49] that for \( m=0 \), the impulse response of a fibre will be very near to a rectangular pulse of width \( \Delta \tau = \tau \left( \frac{1}{\cos^2 \theta_o} - 1 \right) \) which has an equivalent amplitude frequency response the function \( \frac{\sin x}{x} \) (Fig.3.2.2), as shown by Steiner et al [48] theoretically and proved by Gloge [15] experimentally. The frequency \( f_n \) at which the first amplitude null occurs corresponds to the delay time difference \( \Delta \tau \) as follows [15];

\[
f_n = \frac{1}{\Delta \tau}
\]

Now, for an ideal impulse time function the phase response has the form shown in Fig.3.2.2, where it is constant but having steps of \( \pi \) radians at null points of the amplitude response. A similar phase response has been obtained experimentally by using pulse measurements and the Fourier transform computation to calculate the phase [17]. However, under practical launching conditions \( (m > 1) \) and because of the presence of differential mode attenuation and mode conversion, the fibre impulse response will deviate from an ideal rectangular pulse, resulting in an amplitude with less deep nulls, or none at all [27] and smoother changes of phase rather than the sudden jumps [26].

Although the differential phase can vary by not more than \( 2\pi \) radians over a very large frequency range (greater than the fibre 3dB bandwidth), the absolute phase, of course, changes very rapidly. Assuming a fibre core refractive index of 1.5, then for a length of 1km and across a one giga-Hertz frequency band the phase changes by \( 10^4 \pi \) radians, as a consequence of the propagation delay, according to the following formula;
Now, for large bandwidth fibres, the phase, as measured using the swept frequency technique, will appear, when using a phase measuring device as shown in Fig.3.2.3, where it goes through $2\pi$ radians about every 200kHz, for the 1km fibre.

To make a complete phase response measurement one possible procedure is to take several readings of the phase every 200kHz interval, i.e. within one complete $2\pi$ rotation, and in proceeding thus to cover the complete frequency band of interest. Absolute phase is then determined by adding extra $2\pi$ radians to the measured value every time the reading jumps from around $+\pi$ to $-\pi$, as illustrated in Fig.3.2.4. The required phase response is
then given by the departure from linearity of the resultant almost straight line variation of absolute phase (Fig.3.2.5).

Doing frequency domain measurements in this way places stringent requirements on the stability and accuracy of the signal source. For example, referring again to 1km of fibre, for better than 0.1 degree of phase accuracy the source frequency should be stable and accurate to within 60Hz over the whole frequency band of interest. Modern synthesised signal sources are now available which can meet the requirement and the measurement is now thus possible. However, synthesised sources take some time to switch frequency. For the source we have used the time was around 100ms to get within 10Hz of a desired frequency.

Under such conditions (1km fibre, 1GHz bandwidth) the number of phase samples needed (assuming a minimum of only one sample every \(2\pi\) rotation) would be 5000. This is a large number of samples and not only needs much computer storage (for subsequent
Fig. 3.2.4 Obtaining absolute phase response from measured phase values.

calculation of the phase response) but also takes a long time. In this example it would be about 8 minutes.

3.3 Improved procedure for phase measurement

The improved procedure now to be described can greatly reduce the number of the samples required and hence the time needed. It is based on the realisation that one does not actually need to take a sample from every frequency interval containing a full $2\pi$ phase rotation. The problem then is how to resolve the ambiguity which arises i.e. to determine how many complete cycles of phase rotation have occurred between two measurements at widely spaced frequencies.

Refer to Fig. 3.2.5, which illustrates how the actual phase response deviates from a straight line but starts linearly at very low frequencies. It can be shown easily that the deviation of
Fig. 3.2.5 Obtaining differential phase response from absolute phase response.

actual measured phase $\phi(w)$ from the linear part defined by the slope $\Delta \phi_L/\Delta w$ at low frequency (which is the required differential phase $\phi_d(w)$) is given by the following expression;

$$\phi_d(w) = \phi(w) - \phi(w_0) - (w-w_0)\Delta \phi_L/\Delta w \quad 3.3.1$$

Now, consider a practical example, by way of illustration, of measuring phase at equal frequency interval, with many cycles of phase rotation in between them with a result as shown in Fig.3.3.1.

$$\phi(w_1) = \phi(w_o) + p2\pi + \Theta_x \quad 3.3.2$$
Fig. 3.3.1 Sampling of phase once every many $2\pi$ radian rotations.

where $p$ is an integer of unknown value

$\theta_x$ is a constant

Therefore

$$\theta_x = \phi(w_1) - \phi(w_0) - p2\pi \quad 3.3.3$$

$$\phi(w_2) = \phi(w_0) + 2p2\pi + 2\theta_x + \phi_d(w_2) \quad 3.3.4$$

where $\phi_d(w_2)$ is the deviation of $\phi(w_2)$ from linearity defined by the phase difference between $\phi(w_1)$ and $\phi(w_0)$.

Then

$$\phi(w_n) = \phi(w_0) + np2\pi + n\theta_x + \phi_d(w_n) \quad 3.3.5$$

$$\phi_d(w_n) = \phi(w_n) - \phi(w_0) - np2\pi - n\theta_x \quad 3.3.6$$

and from 3.3.3

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\[ n\theta_x = n(\phi(w_1)-\phi(w_0)) - np2\pi \]  

3.3.7

\[ \theta_d(w_n) = \phi(w_n) - \phi(w_0) - n(\phi(w_1)-\phi(w_0)) - 2np2\pi \]  

3.3.8

Now equation 3.3.8 can be compared to equation 3.3.1 leaving aside the term \(2np2\pi\). It can be seen that the term \(n(\phi(w_1)-\phi(w_0))\) is the same as \((w-w_0)\Delta \phi_L/\Delta w\) since \(n\) corresponds to \((w-w_0)/\Delta w\) and \(\Delta \phi_L\) corresponds to \((\phi(w_1)-\phi(w_0))\). The term \(2np2\pi\) can give an ambiguity of some multiple of \(2\pi\) radians, or simply and effectively \(2\pi\) radians. To counter the effect of this ambiguity, \(2\pi\) radians can be added or subtracted to the value of the measured phase whenever there is a change of direction in the slope of the line connecting the actual measured value \(\phi(w_n)\) to the value of the previous sample \(\phi(w_{n-1})\), (i.e. if the phase values of successive samples are increasing there comes a point where suddenly one phase value decreases, \(2\pi\) radians must then be added to this decreased value and all subsequent ones). Alternatively, if the sampling interval is such that the phase values of successive samples are decreasing there comes a point where there is a sudden increase; \(2\pi\) must then be subtracted from this increased value and all the subsequent ones. It is only possible and correct to do this provided the fibre's differential phase does not change by more than \(\pi\) radian between the successive samples, which is valid in practice provided that the frequency difference between the selected samples is not excessively wide.
3.4 Improved technique for direct phase measurement

It is very interesting to observe that if the starting low frequency \( w_o \) is selected to give a zero value for \( \varphi(w_o) \) and that the frequency intervals between the samples can be selected to give a zero value for \( \varphi(w_1) \) (which can be done easily when using computer controlled signal sources) then equation 3.3.8 is reduced to;

\[
\varphi_d(w_n) = \varphi(w_n) - 2np2\pi
\]

In this case, there will be no need for computing the differential phase since the measured phase value will correspond exactly to the actual differential phase and hence the differential phase can be displayed directly on a screen or X-Y recorder.

3.5 Description of the transfer function measurement system

The system for the measurement of the transfer function directly in the frequency domain as developed, is represented by the block diagram shown in Fig.3.5.1. The measurement is performed by modulating the laser source sinusoidally at successive fixed and equal frequency intervals (determined by the fibre bandwidth and the resolution required) through the frequency band of interest using a highly accurate signal generator. After propagation down the optical fibre under test, the amplitude and phase of the detected light envelope are measured by using a vector voltmeter or similar instrument. A computer is used to control the frequency stepping and data storing.

Because of the variation in amplitude and phase responses of
Fig. 3.5.1 Block diagram of transfer function measurement in frequency domain.
the external circuits and devices employed, other than the fibre itself, like amplifiers, detector, laser source etc., it is necessary to eliminate their effects. This can be done by performing the measurement, first, on a short piece of reference fibre and then repeating it after replacing the reference with the fibre under test. The difference between the two measurements will give the response of the test fibre only. This technique has also been used by Dannwolf et al [18].

3.6 Description of the measurement system optics

3.6.1 Launching into optical fibre

The optical arrangement of the system is shown in Fig.3.6.1.1. The laser source was coupled to the optical fibre using a microscope objective lens of numerical aperture higher than that of the fibre under test, in order to excite all the possible propagating modes. The launching condition looked for in our case was to obtain the highest coupling efficiency of light into the fibre. This was achieved by monitoring the photodiode current, which corresponds to the transmitted light through the fibre, while adjusting the position of the fibre input end relative to the focused light spot, using a three dimensional micropositioner, until the maximum current was obtained.
Fig. 3.6.1.1 Optical arrangement of the measurement system.
Fig. 3.6.2.1 Photo of optical fibre mode scrambler.

Fig. 3.6.4.1 Photo of optical fibre end quality.
3.6.2 Mode scrambler

The response of an optical fibre is highly dependant on the launching conditions [12,14]. Also, after propagating in fibre for some distance the light reaches a steady state power distribution owing to the effect of mode coupling and differential mode attenuation, beyond this point the mode distribution will be much less dependant on the launching conditions. This steady state length is not fixed but varies from a few tens of metres for irregular, poor quality, fibres to several Kilometres for fibres of good mechanical quality [50]. Different methods of mode scrambling have been suggested to create conditions at the fibre input end which has the equivalent or a similar effect to that of a long fibre, i.e. less sensitivity to launching conditions. These methods are based on introducing heavy mode mixing, for example by pressing a short length of the fibre between two rough surfaces [50], or by bending it around a sinusoidal serpentine [51]. The latter method was used for its simplicity and a photograph of the mode scrambler is shown in Fig.3.6.2.1. The diameter of the rods is 1cm with spacing of 0.5cm.

3.6.3 Mode stripper

After the mode scrambler, the fibre goes into a liquid like glycerin which has a higher refractive index than the fibre, to remove any light launched into the cladding, so that the propagating light will be confined to the core only.
3.6.4 Fibre joining

In the measurement technique used, fibre connectors are needed. Splices for joining two fibres must provide low loss and must be quick and easy to make. Various techniques have been discussed in the literature concentrating mainly on achieving good alignment, since any misalignment would mean higher coupling loss. Suggested techniques have ranged from using roller ball bearings held together with shrinkable tube [52], V-groove molded plastic [53], loose tube splice [54], to V-groove vacuum chucks [55]. The method used here was suggested by Ulrich et al [56], for making optical waveguides and based on embossing a groove in plastic material. This method was found to be simple; it is easy to obtain a good groove by pressing a short piece of fibre into a perspex block, so that the resulting groove will have almost the same width as the fibre.

Another important factor for achieving a low splice loss is to ensure that the fibre end is flat and perpendicular to the fibre axis. A good quality of fibre end finish has been obtained by scoring the fibre and breaking it under tension. This was achieved by using a machine based on one suggested and demonstrated by Gloge et al [57]. After breaking the fibre, the ends are cleaned by agitation in a solvent like acetone to remove any dirt or pieces of broken glass. To make a good joint, the two ends are aligned in the groove using a microscope, so that they touch, but only very lightly, to avoid damage of the ends by mutual abrasion. An index matching liquid like light paraffin is used for reducing the light reflection at the fibre ends, by putting a drop of it on the joint.

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Fig. 2.6.4.2 Photo of joined optical fibre ends.

Fig. 2.6.4.3 Photo of optical fibre splice connector.
Joint losses obtained have been in the range of 0.16dB to 0.5dB for fibre with numerical aperture of 0.5, and less than 0.5dB for fibre with numerical aperture of less than 0.2. A photograph of the fibre end quality is shown in Fig.3.6.4.1. Fig.3.6.4.2 shows joined fibre ends without using index matching liquid, while the fibre splice connector is shown in Fig.3.6.4.3. Finally, the light emerging from the far end was collimated and refocused onto the photodetector using a microscope objective lenses.

3.7 Transfer function measurement of 100m multimode fibre

The first experimental arrangement used for transfer function measurement using a HeNe laser source is shown in Fig.3.7.1. The light from a 0.5mW single frequency HeNe (0.6328um) laser (Tropel 100), was passed through a wideband electro-optic modulator [45]. A highly stable synthesised signal generator (Hewlett Packard 8660A with RF section type 86602B) of one Hertz frequency resolution was used to provide the modulating signal to the modulator through 0.3W output RF power amplifier (Marconi type TF2175), over the frequency range of 25MHz to 550MHz limited by the driving amplifier. Because of the relatively high RF modulating power driving the modulator, the receiving equipments were placed inside a screened room to prevent direct coupling of the RF signal to the receiver. After coupling the laser to the fibre, the latter was passed into the screened room through a small ventilation hole. The emerged light from the fibre output end was detected by a fast avalanche photodiode (Telefunken type BPW28), and the modulating signal was amplified by a 27dB gain,
Fig. 3.7.1 Experimental arrangement of transfer function measurement system.
Fig. 3.7.2 Photo of experimental arrangement (transmitting equipment).
Fig. 3.7.2  Photo of experimental arrangement (receiving equipment).
520MHz bandwidth amplifier (ENI type 500AP), before displaying its amplitude and phase on the network analyser (Hewlett Packard type 8754A). Photographs of the experimental arrangements are shown in Fig.3.7.2.

A program was written (Appendix I) to enable a microcomputer (Commodore 3032) to step the modulating frequency from 25MHz to 550MHz at intervals of 25MHz while reading the network analyser output at each frequency through an analogue to digital converter and storing the amplitude and phase data. The sampling frequency interval was selected for convenience and other intervals could equally well be used.

The measurement was performed first on a short piece (about 60cm) of reference fibre. The amplitude and phase were measured over 10 sweeps through the frequency band, to improve the accuracy of the measurement and an example of the resulting averaged amplitude and phase response is shown in Fig.3.7.3. The length difference between the optical path and the reference signal path was adjusted to obtain as nearly as possible a constant phase difference. This is for convenience when calculating the actual phase response of the fibre under test. The reference fibre was then removed and replaced by an experimental sample of 100m length and the measurement repeated. The sample was a step-index fibre (type BP102) which has a quoted attenuation of 5.1dB/km at 0.9um and numerical aperture of 0.177. The measured amplitude and phase response is shown in Fig.3.7.4.

The amplitude part of the transfer function was calculated by subtracting the reference fibre response from the 100m response and plotted in Fig.3.7.6, relative to the amplitude at 25MHz.
Fig. 3.7.3 Measured amplitude and phase responses when using 60cm of reference fibre.

(considered to be 0 dB). Fig. 3.7.5 shows the absolute phase response which corresponds to the 100m fibre only i.e. after subtracting the reference fibre response from the measured 100m fibre response and then using the technique suggested in section 3.3. To calculate the differential phase response using equation 3.3.1, the slope $\Delta \phi / \Delta \omega$ of the linear part of the phase at low frequency must be determined accurately, since even a small error in $\Delta \phi / \Delta \omega$ will cause an appreciable error in the calculated differential phase. This error can be eliminated by recognising that, at low frequencies, the differential phase is equal to zero. Based on this assumption, the linear slope was then determined as
Fig. 3.7.4 Measured amplitude and phase responses when using 100m step-index fibre.

the one which gave the nearest low frequency response of the differential phase to zero and is shown in Fig.3.7.6. From Fig.3.7.6, it can be seen that the 3dB optical bandwidth (6dB electrical) of the test fibre is 303MHz and the phase distortion at this frequency is 24 degrees.

As a conclusion, the transfer function of a 100m optical fibre has been measured up to 550MHz frequency using direct frequency domain technique. Although, theoretically, the highest frequency of the measurement by this technique can be high in the giga-Hertz region when using several kilometres of fibre length, but, we were limited practically at the time of this measurement by the availability of the proper laser source. However, our next
step was to extend the measurement system capability as will be discussed in chapter 6.

Fig. 3.7.5 Absolute phase response of the 100m fibre only.
Fig. 3.7.6 Transfer function of the 100m step-index fibre.
CHAPTER FOUR

TIME DOMAIN TECHNIQUE OF OPTICAL FIBRE TRANSFER

FUNCTION MEASUREMENT

4.1 Introduction

In the previous chapter a method developed to measure the transfer function of an optical fibre directly in the frequency domain (F.D.) has been described and tested on a 100m length of step-index multimode fibre. To be able to judge the quality of the results i.e. the amplitude and (especially) the phase responses of the fibre and hence the strength of the method, a comparison with some other measurement technique is necessary.

Since the current method of obtaining the transfer function uses the time domain (T.D.) technique i.e. pulse broadening measurement and Fourier analysis, it was found very suitable and practical to compare the obtained results with those from the T.D. technique. A very good advantage in using the T.D. technique for comparison, is that all the propagation conditions of light in the fibre, which have a very big effect on fibre response, can be kept the same as those during the F.D. measurement, which leads to the most realistic comparison possible.

This chapter describes the time domain measurement technique, an automated measurement system which performs such measurements, and the results of this measurement performed on the same 100m fibre. Finally a comparison is made between the results obtained by this method and those of the previous chapter.
4.2 Description of the time domain method

The block diagram of the time domain measurement system is shown in Fig. 4.2.1. A short light pulse is normally obtained by pulsing the laser source. The light is coupled into the fibre under test using the optics described in chapter 3, and the output pulse from the fibre is then detected by a fast photodiode, amplified and displayed on a sampling oscilloscope.

A computer is usually used to control the experiment, store the data of the sampled pulses, and then process them. The measurement is performed first on a short length of fibre and repeated on the fibre under test to remove any effect due to the frequency response of the measurement system being not constant. The light pulse should be very short so that its high frequency components, beyond those of the fibre bandwidth, can be received with a good signal-to-noise ratio. The T.D. method has been used from early times to measure the amount of pulse broadening of a fibre length which gives the maximum possible limit of data transmission. The broadening of the light pulse can be specified using the following relation:

\[ t_b = \sqrt{t_o^2 - t_i^2} \]  

where \( t_b \) is the pulse broadening at half amplitude

\( t_i \) is the input pulse width at half amplitude

\( t_o \) is the output pulse width at half amplitude

The terms "input" and "output" pulses refer to pulses at the output of short (reference) and long fibres respectively. The pulse broadening can be determined directly by measuring the
Fig. 4.2.1 Block diagram of time domain measurement system.
different pulse widths as displayed on an oscilloscope screen.

The need to know the transfer function of the fibre necessitated the employment of a computer in the measurement system for the processing of the sampled pulses. In order to calculate the transfer function, the first step is to Fourier transform the sampled pulses of the reference fibre \( x(t) \) and long fibre \( y(t) \) to their equivalent responses \( X(f) \) and \( Y(f) \) respectively in the frequency domain. Hence;

\[
x(t) \xrightarrow{FT} X(f) \quad 4.2.2
\]
\[
y(t) \xrightarrow{FT} Y(f) \quad 4.2.3
\]

where \( \xrightarrow{FT} \) represents the Fourier transform operation.
The transfer function of the fibre \( H(f) \) is then calculated from the relation:

\[
H(f) = \frac{Y(f)}{X(f)} \quad 4.2.4
\]

\( H(f) \) is a complex function which contains the details of both amplitude and phase response and can be expressed as follows;

\[
H(f) = |H(f)| \exp(j\phi(f)) \quad 4.2.5
\]

where \( |H(f)| \) is the amplitude response

\( \phi(f) \) is the phase response

Since the Fourier transform operation gives the values of \( X(f) \) and \( Y(f) \) in terms of their real and imaginary parts hence;

\[
H(f) = H_1(f) + jH_2(f) \quad 4.2.6
\]

The amplitude and phase responses can be obtained in the usual way;

\[
H(f) = \sqrt{H_1^2(f) + H_2^2(f)} \quad 4.2.7
\]

and

\[
\phi(f) = \arctan(H_2(f)/H_1(f)) \quad 4.2.8
\]

The differential phase response is then determined using the
Choosing the sampling time interval of the detected light pulses is of considerable importance. To avoid aliasing errors at high frequency when calculating the frequency response of a pulse, it is necessary to sample at time intervals $\Delta t$ which correspond to a Nyquist frequency above that of the measurement system bandwidth. The frequency interval $\Delta f$ between the points calculated for the frequency domain function is determined by the assumed period $T$ of the pulse train i.e.:

$$\Delta f = \frac{1}{T} \quad (4.2.9)$$

$T$, of course, is given by $N\Delta t$ where $N$ is the number of samples taken.

4.3 Time domain measurement arrangement

The experimental arrangement used for the time domain measurement is shown in Fig.4.3.1. The part of the circuit from the electro-optic modulator to the preamplifier following the photodetector was kept the same as that of the frequency domain measurement. The light was modulated by driving the modulator from a high power step recovery diode short pulse generator (30W peak, 40MHz repetition rate into 50 Ohm load), before launching into the fibre under test. The light pulse, detected by a fast avalanche photodiode, was amplified and displayed on a sampling oscilloscope (Tektronix type 7403N, with 75ps rise time sampling head type S2). Two outputs from the oscilloscope were available, one proportional to the amplitude (i.e. Y-axis) and the other proportional to the time (i.e. X-axis). These analogue outputs were connected to the computer through an analogue to digital
Fig. 4.3.1 Experimental arrangement for time domain measurement system.
A converter for monitoring and sampling.

A program was written on the computer (Appendix I) to perform the sampling of the displayed pulse at regular time intervals while sweeping the time base slowly from an external saw tooth signal generator. The sampling time interval used was 78ps, which corresponds to a Nyquist frequency of 6.4GHz, which lies well above the bandwidth of the measurement system limited by the 520MHz receiver amplifier. To improve the signal-to-noise ratio of the detected pulse, a low pass filter was used after the sampling oscilloscope, in addition to the averaging of the data over several sweeps.

To prevent small reflections (due to imperfect matching) in the receiver circuit i.e. at the bias T, amplifier or oscilloscope, interfering with the main pulse, the length of the various coaxial cables were chosen so that such reflections were delayed enough relative to the main pulse to separate them in time.

Since the launching condition is an important factor which affects the fibre transfer function, and in order to ensure the same conditions during both time and frequency domain measurements (for more accurate comparison), both measurements were performed together first on the reference fibre and then on the 100m fibre.

A typical detected pulse as sampled from the output of the reference fibre is plotted in Fig.4.3.2; its PWHA width is 1.01ns. When the reference fibre was replaced by the 100m experimental sample the output was as shown in Fig.4.3.3; and its PWHA width is 1.71ns. Using the relation 4.2.1, the calculated pulse spread was found to be 1.38ns.
When calculating the frequency response of the obtained pulses, it was desired that the frequency response components i.e. amplitude and phase should be found at frequency intervals $f$ of 25MHz for better comparison with the frequency domain measurements. Given that $t$, the sampling interval, was 78ps the number of samples $N$ required should be 512 and hence the period $T$ of the pulse train equal to 40ns. In fact the sampled period was about 8ns and extra samples were assigned a value equal to that of the base line. In each case, the amplitude response or attenuation was calculated in dB relative to the lowest frequency of 25MHz, and the phase in degrees. Fig. 4.3.4 shows the
Fig. 4.3.3 Detected light pulse when using 100m fibre.

calculated amplitude and phase response of the reference fibre, while Fig. 4.3.5 shows those of the 100m fibre.

The amplitude part of the transfer function was calculated directly as the difference between the two responses and is shown in Fig. 4.3.7. To determine the absolute phase response of the transfer function, the absolute responses of both fibres were calculated first (using the method described in chapter 3), and the difference between them then taken. A result is shown in Fig. 4.3.6. The differential phase response was calculated from the absolute response using the same procedure followed in the frequency domain measurement and is shown in Fig. 4.3.7.

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Fig. 4.3.4 Amplitude and phase responses (using reference fibre) as calculated from pulse measurement.
Fig. 4.3.5 Amplitude and phase responses (using 100 m fibre) as calculated from pulse measurement.
Fig. 4.3.6 Absolute phase response of the 100m fibre.
Fig. 4.3.7 Transfer function of the 100m step-index fibre.
4.4 Comparison with frequency domain measurement and conclusion

For comparison of the transfer function of the 100m fibre derived by the two techniques, the amplitude and phase responses are plotted together in Fig.4.4.1. The 3dB optical bandwidth is about 303MHz and the phase distortion at this frequency is 22.5 degrees corresponding to about 303MHz and 24 degrees from the frequency domain measurement. Both amplitude and phase responses show good agreement with a maximum amplitude difference at 550MHz of about 1dB, and a maximum phase difference of less than 5 degrees over the whole frequency band. This can be considered a good result taking into account the possible different
contribution to errors in the two measurements. These will be discussed in chapter 7.

The close agreement between the results obtained by the two different methods indicates that the two approaches are almost equivalent to each other as should be expected theoretically. The question now is; if both methods give virtually the same results, then, what is the point of using the frequency domain technique?

To answer this question it is necessary to mention a few important points. The power level used to drive the electro-optic modulator, which determines the modulation depth and hence the signal-to-noise ratio at the output of the photodetector, was about 0.3W in the case of the frequency domain measurement, while in the time domain measurement pulses of 30W peak power at 40MHz repetition rate were used (i.e. there was a driving power ratio of about 100). This shows one of the advantages of the F.D. technique, in that it needs only a small modulation level to perform the measurement with good accuracy. The small modulation level, of course, leads to improved linear response of the photodetector [50]. Also, in cases when it is difficult to obtain high amplitude short width light pulses from laser sources at certain test wavelengths [23], and therefore restrictions exist on the amount of signal-to-noise ratio that could be achieved by T.D. methods, the F.D. must be the preferred solution. The agreement between the results is a consequence of the good SNR achieved in the F.D. by having narrow band detection (20kHz), and in the T.D. by having higher modulation depths and averaging (the signal-to-noise ratio achieved in the frequency domain was about 47dB). For longer wideband fibres the frequency domain method
should have even greater advantages as will be seen in chapter 6.

In addition to the above mentioned advantages, our frequency domain technique has proved that the direct measurement of fibre phase response is no longer a formidable matter [24], but is very possible to be obtained in a simple and reliable way as our results confirm it, and hence there is no need for using the unreliable Hilbert transform method to calculate the phase response in cases where the amplitude response only could be measured in the frequency domain.
CHAPTER FIVE
DETERMINATION OF OPTICAL FIBRE IMPULSE RESPONSE

5.1 Introduction

The impulse response of optical fibre is an interesting parameter which gives a direct measure of the dispersion (in time) suffered by an impulse of light after propagating down a length of fibre, and is defined by the following relationship;

\[ y(t) = h(t) * x(t) \]  

where \( h(t) \) is the fibre impulse response
\( x(t) \) is an input pulse applied to the fibre
\( y(t) \) is the output pulse from the fibre
* is convolution operation

The impulse response \( h(t) \) is the equivalent in the time domain of the transfer function \( H(f) \) in the frequency domain, and the two represent a Fourier transform pair, i.e.;

\[ \begin{align*}
FT & \quad H(f) \\
IFT & \quad h(t)
\end{align*} \]  

where \( \text{FT} \) is the Fourier transform operation
\( \text{IFT} \) is the inverse Fourier transform operation

Because of the above relationship, an easy approach to calculating the impulse response is by obtaining the transfer function first, and then taking the inverse Fourier transform of it.

So far, the only successful method for calculating the impulse response has been from time domain measurement. The frequency domain method has not been used because of the lack of means for measuring the phase response which is necessary for the impulse response calculation. Some workers [23,24] in this field have tried to estimate the phase response from the measured amplitude
response in the frequency domain (because of its suitability in some cases), by assuming a minimum phase function and thus obtaining the phase using the Hilbert transform, and hence calculating the impulse response. But this approach has not been successful, because the phase response thus obtained was not sufficiently accurate.

This chapter describes a method for calculating the impulse response of fibre from the time domain measurement, a particular problem that arises, and a possible solution to it. Also, a method of calculating the impulse response from the frequency domain measurement is described and a comparison between the results of the two methods is made.

5.2 Impulse response calculation from time domain measurement

To determine the impulse response of an optical fibre, the time domain approach will first be discussed since it is the method currently used, also because it gives an easier understanding of the problem. The transfer function of 100m test fibre was calculated in chapter 4 using the time domain method. Now, in order to determine the impulse response of this fibre, the direct and easy way is by taking the inverse Fourier transform according to the relationship 5.1.2. However, the transfer function needed for the calculation of the impulse response, is the complete one which includes the positive and negative frequencies. Fig.5.2.1 shows an example of a complete transfer function as obtained, usually, from the T.D. method. In this example the number of frequency samples N is equal to 8. For a real time domain function, which is the case of the fibre impulse
response, there is symmetry between the positive and negative parts of the transfer function around the frequency where \( n = N/2 \) as given by the following relations:

\[
H_1(f_n) = H_1(f_{n'}) \quad 1 \leq n \leq (N/2) - 1 \tag{5.2.1}
\]

\[
H_2(f_n) = -H_2(f_{n'}) \quad 1 \leq n \leq (N/2) - 1 \tag{5.2.2}
\]

\( n' = N - n \)

where \( H_1(f_n) \) = real part at positive frequency \( f_n \)

\( H_1(f_{n'}) \) = real part at negative frequency \( f_{n'} \)

\( H_2(f_n) \) = imaginary part at positive frequency \( f_n \)

\( H_2(f_{n'}) \) = imaginary part at negative frequency \( f_{n'} \)

Calculating the impulse response of fibre by directly taking the inverse Fourier transform of the derived transfer function leads usually to an oscillatory response due to the high frequency...
errors in the transfer function created by the division of small quantities (i.e. \( \frac{Y(f)}{X(f)} \)). The effect of this error can be reduced by using a weighting function in the computation. This function can be likened to a low pass filter. The filter used here was a simple analogue low pass filter (Butterworth filter), having an amplitude response \( G(f) \) given by:

\[
G(f) = \sqrt{\frac{1}{1+e^{2(f/f_c)^M}}} \tag{5.2.3}
\]

where \( f_c \) = filter cut off frequency

\( e \) and \( M \) are constants chosen to determine the steepness of the filter slope in going from the passband to the cutoff band. Since the transfer function calculated has both positive and negative frequencies, with symmetry between them, it is necessary to filter both in symmetrical fashion. This was done through all filtering processes of the transfer function when calculating the impulse response.

However, to determine the proper cutoff frequency of the filter so that it will not affect the signal information of the transfer function, some checking must be made on the impulse response obtained to determine its accuracy. This checking was done by convolving the input pulse (i.e. the pulse from the reference fibre), with the impulse responses obtained by calculation using a selection of cutoff frequencies and comparing the computed output pulses with the original output pulse from the 100m fibre.

Fig.5.2.2 shows the impulse responses calculated using a range of cutoff frequencies from 100MHz to 550MHz in 50MHz steps, while Fig.5.2.3 shows the corresponding resultant output pulses. Considering first the output pulses, it can be seen that using a
Fig. 5.2.2 Calculated impulse responses of the 100m fibre from T.D. measurement for different filter cutoff frequencies.
Fig. 5.2.3 Calculated output pulses when using 100m fibre for different filter cutoff frequencies.

\[ f_o = 100 \text{ MHz} \]
low cutoff frequencies, the resultant pulse shape is broad and highly symmetric around its peak, but with increasing frequency it starts changing until it reaches a stable shape at about 450MHz, above which the changes are very small. This means that the contribution from the higher frequencies to the pulse is very small at this point. Consequently this cutoff frequency can be considered as the proper upper limit for the pulse spectrum.

Fig. 5.2.4 shows both the calculated and measured output pulses from the 100m fibre. As can be seen, the agreement between the two is good. The small difference between them is probably contributed to by the effect of the filter on some of the signal frequency components.
The impulse response (Fig. 5.2.2), can be seen to show continuous changes in its shape as the filter frequency increases and at a cutoff frequency of 550MHz, small oscillations start to be seen. Hence the proper cutoff frequency cannot, actually, be decided by looking at the impulse response only, but rather must be taken as that when the calculated output pulse reaches a stabilized shape, which occurs at a cutoff frequency of 450MHz. For comparison, the impulse PWHA width as measured from Fig. 5.2.2 is about 1.3ns, while the pulse spread calculated in chapter 4 was 1.38ns, the difference is about 6%. This can give an idea of the amount of error introduced in the calculation of the impulse response.

5.3 Impulse response calculation from frequency domain measurement

Since the transfer function of the test fibre was determined from the F.D. measurement (chapter 3), it was interesting to calculate its equivalent impulse response, as well, using data obtained from this domain. However, to calculate the impulse response from the above transfer function, two important points should be considered;

1. the negative part of the transfer function is needed. This can be derived from the positive part (measured) using the set of relations 5.2.1 and 5.2.2.
2. if the measured transfer function is limited in frequency (in our case to 550MHz), it is necessary to extrapolate above this frequency, in order to avoid having a sharp cutoff. This was done
by substituting the value of the coefficient at the highest
frequency of measurement (550MHz) for all frequencies above this.
Although not strictly accurate it proves successful on the basis
that, since low pass filtering is to be applied, the effect of the
high frequency components will be reduced smoothly and the result
should be more accurate than would have been the case using a
sharp cutoff.

The impulse response of the fibre as thus derived using
several different cutoff frequencies of the low pass filter is
plotted in Fig.5.3.1. Here again the resultant shape of the
impulse response is sensitive to the cutoff frequency assumed, and
although there is a good agreement with those calculated from the
time domain measurement at cutoff frequencies between 200MHz and
400MHz, there are some differences at higher frequencies. For
comparison, the impulse responses from both techniques are plotted
together for the same case (450MHz cutoff frequency) in Fig.5.3.2.
The agreement between the two as can be seen is fairly good,
taking into consideration the different assumptions made and the
difference in their transfer functions.

5.4 Conclusion

So far, we have tested two methods which measure the
dispersion of optical fibre, the frequency domain (transfer
function), and the time domain (impulse response). Both methods
have given satisfactorily agreed results. Although the impulse
response characterisation of dispersion is useful as a direct
measure of pulse broadening especially in digital systems, in view
of its shape sensitivity to the necessary filtering process, it is
Fig. 5.3.1 Calculated impulse responses of the 100m fibre from F.D. measurement for different filter cutoff frequencies.
suggested that an expression which does not rely on signal processing of the measured data should describe the fibre response in a more reliable way. This expression could be very well the transfer function. Because the frequency domain method does not need even the Fourier transform computation, which is necessary for the time domain technique, it should have the highest reliability, in addition to its promise of higher accuracy.
6.1 Introduction

After establishing that fibre dispersion can be measured successfully using direct frequency domain techniques, steps were taken to extend the method by increasing the bandwidth of the measurement system above 550MHz, and the fibre length to several hundred metres. For this purpose a continuous wave (cw) laser diode was obtained lately. The easy driving and modulation of this laser at frequencies above 1GHz provides a great advantage over the HeNe single frequency laser which requires an electro-optic modulator. In addition, its wavelength of 0.87um, which lies in the low loss region of optical fibres produced commercially at this time, makes it possible to work with wideband fibres longer than 100m. Measurements similar to those made previously using the HeNe laser were performed with the new laser diode on a 900m length of graded-index fibre. This chapter describes the extended measurement system briefly (since it has the same principles described in chapters 3 and 4), with comparison of the measurement results between the frequency and time domain techniques.
6.2 Frequency domain measurement

The experimental arrangement for the frequency domain measurement is shown in Fig.6.2.1. In this system the cw laser diode (Laser Diode Labs type LCW10) was directly modulated from the synthesised signal generator (no power amplifier was needed). The optics part was the same as before with the addition of a collimating lens after the laser because of the output light diversion. A wideband preamplifier of 1300MHz bandwidth and 26dB gain (Hewlett Packard type 8447D) was used after the photodetector to cover the frequency of the measurement. A program was written (Appendix II) to enable the computer to perform the sweeping of the modulating frequency from 25MHz to 1275MHz (limited by the available signal source and the network analyser) in steps of 25MHz while sampling the amplitude and phase of the detected modulation at the fibre output. The measured amplitude and phase responses when using a reference and 900m of graded index fibre (that has attenuation of around 2.5dB/km at 0.9um wavelength) are plotted in Figs.6.2.2 & 6.2.3 respectively. The complete transfer function of the test fibre i.e. amplitude and differential phase response is shown in Fig.6.2.4. The 3dB optical bandwidth is found to be about 379MHz and the phase distortion at this frequency is 3 degrees.
Fig. 6.2.1 Experimental arrangement for transfer function measurement in frequency domain.
Fig. 6.2.2 Measured amplitude and phase responses when using reference fibre
Fig. 6.2.3 Measured amplitude and phase responses when using 900m of graded-index fibre.
Fig. 6.2.4 Calculated transfer function of the 900 m fibre from frequency domain measurement.
6.3 Time domain measurement

For the time domain measurement, the experimental arrangement is shown in Fig.6.3.1. The laser diode was driven from a low power step recovery diode short pulse generator (pulse width about 0.5ns) at a repetition rate of 45MHz. The displayed detected light pulse on the sampling oscilloscope was sampled at time intervals of 39ps, which corresponds to a Nyquist frequency of 12.8GHz, which is much higher than the bandwidth of the measurement system. The detected pulse when using a reference fibre is plotted in Fig.6.3.2; its PWHA width is 0.625ns. The measurement was repeated after replacing the reference fibre by the 900m fibre, and the detected pulse is shown in Fig.6.3.3; its PWHA width is 1.52ns. The pulse spread of the test fibre is found to be 1.38ns.

6.3.1 Transfer function

The transfer function was calculated as before by Fourier transforming the input and output pulses. In this calculation the number of pulse samples \( N \) used was 1024 to get frequency samples \( \Delta f \) every 25MHz. The calculated frequency responses of the pulses from the reference and test fibres are shown in Figs.6.3.1.1&6.3.1.2 respectively. The transfer function derived from the above responses, using the same procedure as previously, is plotted in Fig.6.3.1.3. The 3dB optical bandwidth of this fibre is about 382MHz and the phase distortion at this frequency is 4.24 degrees which is in excellent agreement with that obtained from the frequency domain measurement of 379MHz and 3 degrees.
Fig. 6.3.1 Experimental arrangement for time domain measurement.
To compare the transfer functions obtained from the two different techniques, these are plotted together in Fig.6.3.1.4. The amplitude part of the responses shows good agreement within 0.6dB up to 600MHz, above which the difference increases to a maximum of 3dB at the minimum amplitude point near 650MHz. The difference above 600MHz lies outside the error range of the frequency domain measurement and can be contributed by the following possible factors:

1. some difference in either the optical spectrum or radiation pattern of the emitted light from the laser diode when using sinusoidal modulation and pulse modulation, which has been reported for semiconductor lasers [58].
Fig. 6.3.3 Detected light pulse when using 900m fibre.

2. errors arise from the Fourier transform calculation of the transfer function.

3. the accuracy of the time domain measurement, which will be discussed in the next chapter.

The phase response shows good agreement, within 7 degrees, up to 600MHz and a maximum of 15 degrees for the rest of the frequency range. Again, the difference can be contributed by the above mentioned factors. In general, the shapes of both the amplitude and phase responses from the two techniques show very good agreement. The similarity between the obtained transfer function shape and the theoretically predicted model (chapter 3) for equal excitation of fibre modes i.e. the $(\sin x)/x$ function,
Fig. 6.3.1 Amplitude and phase responses when using reference fibre as calculated from pulse measurement.

indicates nearly equal excitation of modes in our experiment and also only a small amount of mode coupling in the test fibre.

6.3.2 Impulse response

The impulse response of the 900m test fibre was calculated by taking the inverse Fourier transform of the transfer function (obtained from time domain measurement) and plotted in Fig. 6.3.2.1 again for different filter cutoff frequencies of 400MHz to 1300MHz in steps of 100MHz. Again, by convolving the output pulse from the reference fibre with the variously derived impulse responses,
Fig. 6.3.1.2 Amplitude and phase responses when using 900m fibre as calculated from pulse measurement.

a set of output pulses were obtained as shown in Fig. 6.3.2.2. It can be seen from Fig. 6.3.2.2, that the calculated pulse reaches a stable shape when 800MHz is used as the cutoff frequency, which can thus be taken as the proper upper limit for the pulse spectrum. Fig. 6.3.2.3 shows the estimated and measured output pulses from the 900m fibre. The agreement between the two can be said to be very good considering the filter effect on the high frequency of the pulse spectrum. The estimated impulse response (Fig. 6.3.2.1) shows continuous changes in its shape with oscillations growing for filter cutoff's above 800MHz, thus, the
acceptable one is at that frequency. The PWHA width of the impulse response is about 1.33ns which is in good agreement with that obtained directly in section 6.3 of 1.38ns.

Following the same principles used previously to calculate the impulse response from the frequency domain, impulse response estimates for different cutoff frequencies are shown in Fig.6.3.2.4. By comparing these impulses with those from time measurement the agreement is good, apart from the high frequency oscillation noticed in the time domain impulses at high filter cutoff frequencies. In Fig.6.3.2.5 the impulse responses when using an 800MHz filter are plotted together, for the two
Fig. 6.3.1.4 Transfer functions of the 900m fibre from T.D. and F.D. measurements.

techniques, and the agreement is very good.

6.4 Conclusion

The results obtained in this chapter prove again the capability of the frequency domain technique of measuring the dispersion of optical fibre and especially the phase response over a wide bandwidth using several hundred metres of fibre. However, the agreement of the results obtained by the frequency domain method and those from the time domain is very good only at the low frequency band up to 600MHz, due to many factors affecting the measurement accuracy which will be discussed in some detail in the next chapter.
Fig. 6.3.2.1 Calculated impulse responses (from T.D. measurement) for different filter cutoff frequencies.
Fig. 6.3.2.2 Calculated output pulses (from T.D. measurement) when using 900m fibre for different filter cutoff frequencies.
Fig. 6.3.2.3 Calculated (solid line) and measured (dashed line) light pulses when using 900m fibre.
Fig. 6.3.2.4 Calculated impulse responses (from F.D. measurement) for different filter cutoff frequencies.

\[ f_0 = 400 \text{ MHz} \]
Fig. 6.3.2.5 Calculated impulse responses from F.D. and T.D. measurements for $f_c=800\,\text{MHz}$.
CHAPTER SEVEN
DISCUSSION AND CONCLUSION

7.1 Introduction

In the previous chapters, a description was given of the determination of the dispersion characteristics of two lengths of optical fibre in the frequency domain, by using the two methods of direct frequency domain and indirect time domain measurements. In spite of the good agreement between the results, there were, still, some differences. This chapter discusses the different sources that could have contributed to errors in both measurements, as well as the merits and disadvantages of the methods.

7.2 Sources of error

There are many factors which can affect the accuracy of the measured fibre responses by the two techniques, and contribute to the difference between them. These sources of error can be divided into two categories, which are factors related to the behaviour of the laser source itself under modulation and others related to errors contributed by the measuring instruments. The first includes, possible differences in the laser source's light characteristic when modulated differently, i.e. using pulse or continuous wave modulation. For the measurement system which uses an external electro-optic modulator with a HeNe laser source, it was emphasised [59] that the modulator should not introduced phase shifts between the different parts of the optical spectrum of the modulated light, since these shifts depend generally on the
modulation depth and could have different effects when performing
time or frequency measurements. This source of difference would
have negligible contribution in our case, since the light source
used was effectively a single frequency laser.

The fact that the HeNe source used was a highly coherent one,
might suggest some other effect operating on the measurement which
is known as the phenomenon of modal noise. Modal noise occurs
when a highly coherent laser is used as the light source and is a
function of the characteristics of fibre, joints and the source.
It appears as unwanted amplitude modulation of the received
signal, the depth of this modulation being extremely sensitive to
the slight mechanical disturbance of the fibre [60,61,62]. In the
measurement performed using HeNe laser, the changes in amplitude
and phase from run to run were appreciable but relatively small
compared to what might be expected [62]. This can be understood
as due to the fact that the fibre used was a step-index which
propagates many modes, in addition to the low loss of the fibre
joints (i.e. good coupling of modes from fibre to fibre), which
has been shown [62] to reduce the modal noise effect. In the
other measurement system which uses a cw multimode laser diode,
the above effect of modal noise could not exist owing to the lower
coherence of the source, however, there is another factor which
might have been significant. This is the increase in the optical
linewidth of the laser source when the applied modulating current
changes quickly [58]. This could have different effects in
frequency and time domain measurements because of the different
driving conditions, i.e. variable frequency sine wave and short
pulse respectively. Attempts were made to minimise this effect by
using the same bias current and also near modulation depth in both
measurements, since the emitted light spectrum is sensitive to
these factors. In addition to the above factors, others which
could contribute to the measurement reliability are the long term
stability of the laser sources, and the mechanical stability of
the experimental set-up, both of which are very important
especially in the case of HeNe laser. The combined effect of the
factors mentioned is difficult to estimate, and it may be better
to judge their effect from the repeatability of the measured
quantities. The second category includes sources of possible
error related to the measuring instruments. These factors are;

1. Nonlinearity.
2. Noise.
3. Quantization error.

and will be discussed separately as follows,

1. Nonlinearity

The main source of nonlinearity comes from the avalanche
photodiode. Devices like PIN photodiodes have a large linear
dynamic range since the number of electrons generated in their
external circuit is equal to that of the photons captured by their
active area. In avalanche detectors, the number of electrons
produced depends not only on the number of photons captured, but
also on the avalanche gain, which is essentially of random nature.
At high light intensities and high avalanche gain, current induced
saturation of the carrier multiplication has been observed [63] to
effectively reduce the multiplication factor and hence the
linearity is less than for a PIN photodiode. Since nonlinearity distorts the shape of the detected optical modulation, some error must be expected. The nonlinearity of the APD detector used in the measurement system (Telefunken type BPW28) was measured by comparing its harmonic distortion when subject to illumination having a single modulation frequency, with that from a highly linear PIN photodiode. The set-up for this measurement is shown in Fig. 7.2.1. A cw laser diode (LCW10) was biased to produce the least harmonic distortion in its output when modulated at a frequency of 25MHz and modulation depth of 22%. The harmonic content of the modulating signal generator was first checked by looking at its displayed spectrum which is shown in Fig. 7.2.2. The amplitude of the different harmonics are more than 50dB down relative to the fundamental component. A highly linear PIN photodiode (Hewlett Packard type 5082-4220), which has a specified linearity within 1% over a dynamic range of 100dB, was used as the reference. In order to observe the effect of varying the light intensity on the harmonic amplitudes, optical attenuators were used to vary the light level by 20dB. Fig. 7.2.3 shows the spectrum of the detected modulation for different light intensities. For all of these spectra, the amplitude of any harmonic relative to the fundamental is more than 43dB down or less than 0.7%, which gives an indication of the good linearity of the laser diode at the chosen operating point. The above measurement was then repeated after replacing the PIN by the APD detector, over a dynamic range of 27dB. The spectra of the detected modulation is shown in Fig. 7.2.4, where it can be seen that the amplitude of any harmonic over this dynamic range is more
Fig. 7.2.1 Experimental arrangement to measure nonlinearity of photodetectors.

Fig. 7.2.2 Spectrum of the modulating signal at the output of the signal generator.
vertical scale 10dB/div
Fig. 7.2.3 Spectra of detected modulation when using PIN photodiode. Difference of 20 dB attenuation between a and b.

vertical scale 10 dB/div
Fig. 7.2.4 Spectra of detected modulation when using avalanche photodiode. Difference of 27 dB attenuation between a and b.

vertical scale 10 dB/div
than 42dB down (i.e. less than 0.8% ) relative to the fundamental frequency, which is very nearly as good as the linear PIN photodiode.

The fact that the APD detector has shown a good linearity depends on a very important factor, which is the avalanche gain used. In this measurement (as well as the fibre dispersion measurements), the gain used was relatively low (less than 15) since the amount of average received light was relatively high. The detector dissipation was about 60mW, and knowing the specified maximum power dissipation to be 100mW, it was preferred to operate at lower gain, which should result in more linear detector performance and greater stability.

The effects of nonlinearity on time and frequency domain measurements are different. In general, it has a bigger effect on pulse measurement since the dynamic range needed is more than that of a continuous wave measurement. Its error contribution depends on the amount of nonlinear distortion of the particular photodiode, dynamic range used and even on the shape of the received signal, i.e. the relative spectral contents of the detected modulation. Using a PIN photodiode with nonlinearity of 0.1dB (2.3% ) over 30dB of dynamic range, Dannwolf et al [18], have shown that an error of less than 0.25dB can result at half power frequency for moderately low signal levels when using the Fourier transform to calculate fibre frequency response from pulse measurements. This error increased to 1.1dB when using an avalanche photodiode. Comparing the nonlinearity of the mentioned PIN diode (0.1dB over 30dB range), with the one used (HP type 5082-4220), (0.05dB over 100dB range), it can be concluded that
the expected error from time domain measurement should be less than 0.25dB at half power frequency i.e. at the 6dB point of the amplitude response, and increases continuously at higher frequencies. For the frequency domain measurement the error should be much less since only one frequency was used at a time.

2. **Noise**

Another factor which affects the accuracy of the measurement is the signal-to-noise ratio. In the frequency domain method this is relatively high since the measurement is performed at one frequency at a time and narrowband detection is used. The detected light signal from the laser diode at 25MHz modulation was displayed on the spectrum analyser as shown in Fig.7.2.5. The

![Fig.7.2.5 Spectrum of the detected light modulation at 25MHz. I.F. bandwidth=100kHz. vertical scale 10dB/div](image)

frequency at a time and narrowband detection is used. The detected light signal from the laser diode at 25MHz modulation was displayed on the spectrum analyser as shown in Fig.7.2.5. The
ratio of signal-to-noise power is about 52dB when using 100kHz bandwidth, i.e. 58dB at 20kHz bandwidth during the measurement, since the 20kHz represents the I.F. bandwidth of the network analyser filter. The contribution of the spectrum analyser to noise was checked to be small compared to that from the receiver, which was the APD detector followed by a preamplifier. In order to know the contribution of different noise sources to the signal-to-noise ratio, SNR, this SNR was calculated and compared with the measured one.

The signal-to-noise ratio defined as the mean square of the output signal divided by the mean square deviation from the average can be expressed by the following formula (for avalanche photodiode) [64]:

$$\text{SNR} = \frac{(RmGP)^2}{2ReG^2F(G)PB+4kTB/R_L}$$

where $(RmGP)^2$ is mean square current of signal

$2ReG^2F(G)PB$ is mean square current due to shot noise

$4kTB/R_L$ is mean square current due to thermal noise

$R$ is responsivity Ampere/Watt

$e$ is electron charge $1.6 \times 10^{-19}$ Coulomb

$G$ is avalanche gain

$m$ is rms modulation index

$P$ is average received optical power (Watt)

$B$ is bandwidth (Hertz)

$kT$ is Boltzman's constant $X$ absolute temperature $=4.15 \times 10^{-21}$

$R_L$ is load resistance (50 Ohm)

$F(G)$ is excess noise factor $= KG+(2-(1/G))(1-K)$
K is ionisation ratio

A PIN photodiode (HP type 5082-4220) was used first as the detector, followed by 26dB gain amplifier. The collimated light from the laser diode was focused on the detector, and the signal-to-noise ratio as displayed on the spectrum analyser was measured to be about 67dB at 30kHz bandwidth. To calculate the SNR, the following substitutions were made:

\[
m = 0.16 \\
R = 0.32 \text{ A/W} \\
G = 1 \\
P = 1.25 \text{mW} \\
F(G) = 1 \\
B = 30 \text{kHz} \\
\text{amplifier noise figure} = 10 \text{dB}
\]

The quantities of signal and different noises were calculated to be as follows;

- signal mean square current \( = 4.1 \times 10^{-9} \text{ A}^2 \)
- shot noise mean square current \( = 3.8 \times 10^{-18} \text{ A}^2 \)
- thermal noise mean square current \( = 9.96 \times 10^{-17} \text{ A}^2 \)

It can be seen from the above figures that the thermal noise determined by the amplifier noise figure, is much bigger (about 26 times) than the shot noise, which is normally the case with PIN photodiodes when using small load resistance like 50 Ohms. The SNR expected from calculations is accordingly about 76dB which is 9dB more than that measured. To find out the factors behind the 9dB difference, two checks were made. The first was to measure
the true mean square noise level by using an RF power meter which showed that the noise level is about 4dB less than the displayed one, hence, the measured SNR is now 71dB. The second was to check the amount of possible noise that is coming from the laser source itself. This was done by blocking the light falling on the detector and measuring the change in noise level, which was found to be about 11dB. Now, knowing that the shot noise is much less than the thermal noise contribution of the amplifier, then, this extra noise must come from the laser source itself. Noise fluctuation in the output of laser sources, arise from the amplification of quantum fluctuations of the population of electrons and photons in the optical cavity, and Thompson [65] has shown that the percentage noise power could be as high as 0.5% of the total emitted power. In our case this was 11dB above the thermal noise (of $9.9 \times 10^{-17} \text{A}^2$) or $1.25 \times 10^{-15} \text{A}^2$, which means that its percentage of the detected average power is 0.009% at 30kHz bandwidth. Now by adding this extra noise to that calculated, the expected SNR will be reduced to 65dB which is 6dB less than that measured of 71dB. Hence, because of this source noise, one can expect there will be limitations on the maximum SNR obtainable, which is 71dB at 30kHz bandwidth.

When replacing the PIN photodiode with the avalanche photodiode BPW28, the displayed SNR was 66dB at 10kHz bandwidth, i.e. 70dB true SNR. The following substitutions were made for calculating the SNR:

\[
m = 0.16
\]
\[
R = 0.365 \text{ A/W}
\]
G = 6
P = 0.18 mW
K = 0.094
B = 10kHz

the value of K used was quoted by Brain [66] as that measured for typical BPW28, and the obtained results are as followes;

- signal mean square current = $3.98 \times 10^{-9} \text{A}^2$
- thermal noise mean square current = $3.32 \times 10^{-17} \text{A}^2$
- shot noise mean square current = $1.66 \times 10^{-17} \text{A}^2$
- source noise mean square current = $4.2 \times 10^{-16} \text{A}^2$

The expected SNR is calculated to equal 69.3dB when considering the source noise, which is very near to the measured value of 70dB. In this case the advantage of using an APD to improve the SNR was not appreciable because of the relatively high average optical power received. The main advantage of using the APD detector was its higher bandwidth (rise time of 160ps) than that of the PIN diode (rise time of 1ns). The measured SNR when using the HeNe laser source was 47dB at 20kHz bandwidth, which is lower than that obtained with the laser diode. The degradation could be attributed to the lower modulation index used (2%), which was limited by the driving power available to the electro-optic modulator.

In the time domain measurement and because of the great difference in the bandwidths, 520MHz (in HeNe system) and 1300MHz (in laser diode system), from 20kHz of the frequency domain measurement, the signal-to-noise ratio is worsened by about 45dB. Averaging of the detected pulses could improve this ratio, but
even if this improvement compensated completely for the 45dB difference, there would still be the fact that the relative amplitude of the spectral content of the pulse at high frequency is lower than at low frequency by up to 11dB (for HeNe system) and 15dB (for laser diode system), and this gives the frequency domain an extra advantage at high frequencies over the time domain technique.

3. Quantization error

The quantization error results from converting the analogue data obtained at the output of the measuring instruments (sampling oscilloscope and network analyser) to digital numbers to be read into and stored in a computer. The amount of this error depends on the resolution of the analogue to digital converter used, which in our system was an 8bit converter, and the dynamic range of the measured quantities.

When sampling the time pulses displayed on the sampling oscilloscope, the maximum error in the amplitude of samples relative to the peak pulse amplitude was less than ±0.6% for all the different detected pulses. For the quantized amplitude and phase at the output of the network analyser, the maximum errors were 0.2dB and 1.5 degree respectively. The contribution of the quantization error to the accuracy of the optical fibre transfer function measured in the frequency domain, is very straightforward to determine, because of the directness of the method, however, it is more difficult to estimate the error when using the time domain method, since the digitized pulses must undergo Fourier transformation into the frequency domain. An important point regarding the frequency dependance of the quantization error is
that in the frequency domain measurement this error is constant over the whole frequency band, but with the time domain method this error will affect the high frequency band more than the lower, which is another disadvantage of the pulse technique.

The overall effect of the error sources discussed above which could possibly have led to the differences found in the two measurement techniques, is very difficult to estimate since they interact with each other in a complex way. In addition, it is necessary to differentiate between the factors of the first category, which may lead to different transfer functions even if the measurement system is perfectly accurate, and those of the second category related to instrumentation imperfection. Hence, it is preferable to look at the repeatability of the measured data and comment on the results.

7.3 Transfer function measurement using HeNe laser

Consider first the difference between the measured transfer function of the 100m fibre obtained by the time and frequency domain techniques, which is shown in Fig.7.3.1. It can be seen from this figure that the difference in amplitude is within less than 0.63dB up to 500MHz, and increases to 0.9dB and 1.12 dB at 525MHz and 550MHz respectively. The difference in phase lies within 5 degrees for the whole frequency band. Now, consider the repeatability of the measurement in the frequency domain by plotting the amplitude and phase variations of 8 runs relative to the first run, and for both the reference and 100m fibres. These are shown in Figs.7.3.2&7.3.3. The repeatability of the amplitude response (reference) is within 0.6dB, while the phase is within
7.5 degrees generally. For the 100m fibre, the amplitude repeatability starts with 0.2dB at low frequency and increases with frequency up to a maximum of 1.6dB at 550MHz. The phase response shows close similarity to the amplitude behaviour with increasing deviation at higher frequencies and within 13.5 degree generally. It can be noticed from the figures that the repeatability of the measured data is not randomly distributed with respect to the first run especially in the case of the long fibre. The main contribution to the fluctuation in the measurement seems to come from noise like sources. However, it can be seen that generally the fluctuation increases when using
Fig. 7.3.2 Repeatability over 8 runs of measured amplitude (a) and phase (b) responses using reference fibre from F.D. measurement (HeNe laser)
Fig. 7.3.3 Repeatability over 8 runs of measured amplitude (a) and phase (b) responses using 100m fibre from F.D. measurement (HeNe laser)
100m fibre and at high frequency. Although it could be argued that the deterioration in repeatability is a function of the signal-to-noise ratio, which reduces with longer fibre and at high frequency, the fact that the variation in amplitude and phase values has taken almost unidirectional shift with big jumps at some frequencies suggests that it is not the signal-to-noise ratio (47dB measured) that is causing the fluctuation, but rather another source most probably the modal noise, which has been noticed when using coherent sources. In our measurement system it was noticed that merely pressing the optical fibre will change the amplitude of the detected signal from the fibre as well as changing the speckle pattern of the emergent light. This phenomenon has been applied [67] to transmit information (in one way) from different points along a fibre to its end, by using piezo-electric transducer clipped on the fibre to convert the input electrical signal into phase modulation of the coherent light propagating down the fibre.

Because of the coherence of the laser source, any small vibration or mechanical instability of the entire measurement system, especially the important fibre joints, will affect mode coupling from fibre to fibre i.e. launching conditions as well as the propagation inside the fibre. It is argued here that the effect of the above mentioned factors is expected to be greater for the longer fiber, because the difference in delay between the fast and slow modes is bigger than that of the reference fibre, and at higher frequencies since high frequency modulation suffers more group delay than low frequency. Anyhow, averaging was performed over the number of runs to obtain mean value response,
which made it possible to compare with time domain measurement over short time.

A possible look at the effect of quantization error and noise (including modal noise) on the calculated transfer function from the time domain measurement could be made by using the method suggested by Zoboli [21]. This method is based on sampling the detected pulses at the fibre output at a rate much higher than the required Nyquist frequency. Hence, the sampled pulse can be divided into the equivalent of several separate pulses sampled at a lower rate, but still satisfying the Nyquist limit. Then, each new pulse is Fourier transformed into the frequency domain, separately, and compared with the others. For example, in our case the detected pulses were sampled at 78ps intervals, which corresponds to a Nyquist frequency of 6.4GHz, which is much higher than the spectral content of the pulse since the system bandwidth was limited by the use of a 520MHz preamplifier in the receiver section. Now, samples were selected every 312ps interval, which corresponds to a maximum frequency of 1.6GHz, and hence four different pulses were obtained. The amplitude and phase responses of the different pulses, at the output of both the reference and 100m fibre are shown in Figs.7.3.4&7.3.5. It can be seen that the variation in amplitude responses of the reference and 100m fibres lies within 0.7dB and 1.2dB respectively through the whole frequency band. Although this is comparable with the variation noticed in the frequency domain repeatability, but, it should be clear that the frequency domain measurement describes the short term stability, while the time domain results describe mainly the noise and quantization error effects, after averaging over 10
Fig. 7.3.4 Amplitude (a) and phase (b) response variations of different samples of light pulse when using reference fibre (HeNe laser).
Fig. 7.3.5 Amplitude (a) and phase (b) response variations of different samples of light pulse when using 100m fibre (HeNe laser).
runs, on the calculated frequency response. The phase responses of the reference fibre (Fig.7.3.4) shows a continuous, very nearly linear shift, which is due to the constant delay between the different sampled pulses. This delay is 80ps between the successive pulses and correspond to a phase shift of about 16 degree at 550MHz. The difference between the calculated phase shifts (from wt) and those of Fig.7.3.4, is less than 1.8 degrees at 550MHz.

For the 100m fibre (Fig.7.3.5), this is rather different, for although the shift is close to linear at low frequency, it deviates from linearity at higher frequencies, and the difference is 4.1, 2 and 8.3 degrees respectively at the maximum frequency. The linear shift in phase does not affect the differential phase response, hence the reference fibre contribution to error is very small, and the main error contribution should come from the 100m fibre especially at high frequencies. It can be noticed from the results that there is a close similarity between the frequency and time domain measurements results, where, both of them show more variation for longer fibre and higher frequencies.

It can be concluded that the fluctuations in the repeatability of measurements were sufficiently small over short times, that by averaging the data, and in spite of the appreciably different effects of error sources in frequency and time domain techniques, the agreement between the transfer function obtained by the two methods can be said to be surprisingly good.
7.4 Transfer function measurement using laser diode

To compare the transfer function from time and frequency domain measurements of the 900m graded index fibre, the difference between them is plotted in Fig.7.4.1. From this figure, it can be seen that the difference in amplitude is within less than 0.55dB up to 575MHz. This difference increases where the amplitude shows a minimum in its characteristic (minimum SNR) to a maximum of 3.3dB near 650MHz, above which it stays within less than 2dB. The phase difference shows fluctuations with less than 8 degrees through the whole frequency band except the region between 675MHz and 875MHz where it shows a maximum of up to about 16 degrees.

To look at the repeatability of amplitude and phase from
frequency domain measurement, the difference over 5 runs is plotted in Figs.7.4.2&7.4.3. For the reference fibre the variation in amplitude lies within 0.2dB, which is within the quantization error of the analogue to digital converter used, for the whole frequency band. The phase data shows generally a repeatability of 1.5 degree which is within quantization error. When using the 900m fibre, the amplitude variation stays generally within 0.2dB up to 650MHz, above which it increases to be within 0.2-0.4dB, and the maximum of 0.8dB occurs at the minimum amplitude response. The phase variation is within less than 3 degrees up to 650MHz and shows a maximum of up to 7.5 degrees in the region of 650-750MHz where the differential phase response has its sharpest change, above which it lies within 4.5 degrees.

It can be noticed here that the fluctuation in both amplitude and phase over the frequency band is highly symmetrical, unlike that of the HeNe system, which could be very well due to the different nature of the causes in the two systems. In this measurement, it is beleived that the variation from run to run is contributed to by the stability of the measurement sytem as well as the noise, since both the phase and amplitude data of 900m fibre show more fluctuatuins around the frequency band where the amplitude has its minimum i.e. lowest signal-to-noise ratio.

Now, to examine the effect of noise and quantization error on time domain measurement, similar calculation to that performed on the pulses in the HeNe system were made and the results are shown in Figs.7.4.4&7.4.5. The amplitude variation (reference fibre) is less than 0.55dB across the whole frequency band, while that of the 900m fibre shows small variation of within 0.5dB up to 650MHz
Fig. 7.4.2 Repeatability over 5 runs of measured amplitude (a) and phase (b) responses using reference fibre from F.D. measurement (cw laser diode)
Fig. 7.4.3 Repeatability over 5 runs of measured amplitude (a) and phase (b) responses using 900m fibre from F.D. measurement (cw laser diode)
Fig. 7.4.4 Amplitude (a) and phase (b) response variations of different samples of light pulse when using reference fibre (cw laser diode).
Fig. 7.4.5 Amplitude (a) and phase (b) response variations of different samples of light pulse when using 900m fibre (cw laser diode).
and increases up to 1dB above that. Fig.7.4.5 which represents
the phase variation of the reference fibre, shows nearly linear
deviation caused by the constant time delay between the different
pulses, and it differs from the theoretically calculated linear
shift by 2.3 , -1.95 and -3.1 degrees at maximum frequency. The
phase of the 900m fibre show small deviation at the highest
frequency from linearity, within less than 4.5 degrees, but more
deviation in the frequency range of 550MHz up to 900MHz, around 6
degrees, which in fact is the region of minimum amplitude response
and maximum phase change.

After discussing the contribution of different sources to the
measurement accuracy, it can be said that agreement between the
transfer functions obtained from the two measurement techniques is
very good and within the accuracy of the measuring instruments up
to 550MHz. Above this frequency, the agreement is still good but
the difference is now higher than could be due to measurement
system accuracy alone, especially those of the frequency domain
measurement, which leads to the conclusion that other factors like
laser source spectral width changes under different driving
conditions and possible nonlinearity effects could be behind the
difference.

A general conclusion is arrived at, which describe the merits
of the two measurement techniques and their practicability as
followes;
1. Frequency domain technique
   A. Advantages
   1. high signal-to-noise ratio

   This is the result of using narrow band detection, and in our
measurement we obtained a SNR of 58dB at 20kHz bandwidth. Signal-to-noise ratio could be improved by using a vector voltmeter of say 1kHz bandwidth and a low noise preamplifier, although its maximum value could be limited by the source noise of the laser itself.

2. high linearity

Owing to the use of narrow band detection, large amplitude modulation of the laser is not necessary to achieve a high SNR as is the case with time measurement. This means that the dynamic range of the optical modulation received at the detector is much smaller, which leads to higher linearity and hence accuracy.

3. directness

The amplitude and phase parts of the transfer function are directly measured rather than calculated. This has the advantage, that the instrumentation errors can be estimated at each frequency separately, in addition there is less computational error (which there is in the time domain method), which was shown [21] to be increasing with frequency to high values.

4. accurate fibre characterisation

Narrow linewidth laser sources can be used in this method, with much smaller optical spectrum broadening expected, since the modulation depth can be very small. This will result in better characterisation of the optical fibre itself, rather than determination of the combined response of fibre and laser source broadening, especially for wide band fibres, where the broadening is expected to have appreciable effect on bandwidth measurement.

5. in some circumstances, it may be practically difficult to modulate the laser source at high peak power, and in this case the
frequency domain technique offers an excellent alternative. It is frequent that systems designers prefer to work with frequency domain curves of amplitude and phase responses in designing transmission systems, especially if some form of equalization is to be applied to the detected signal [50], as well as to calculate the effect of pulse spreading on the sensitivity of optical receivers.

B. Feasibility and limits
1. Highly accurate and programmable synthesised signal sources with 1 or 2Hz frequency resolution, which are necessary for phase measurement are available commercially now, with frequency up to 2.6GHz, together with phase and amplitude measuring instruments.
2. The 2Hz frequency resolution produces, theoretically, an uncertainty in phase of about 0.4 degree for fibre lengths of 100km (practically determined by the SNR) through the entire frequency band, unlike that of time domain technique which gives an error of about 18 degrees at 1GHz due to sampler timing error of 50ps [68].

C. Disadvantages
1. The necessity to have access to both fibre ends at the same place, makes it impractical for field measurement [50], if phase is required.
2. The relatively high cost of the required synthesised signal generator, which is not a basic instrument in most microwave laboratories. The vector voltmeter and microcomputer are considered to be basics in most modern laboratories.
2. Time domain technique

A. Advantages
1. relatively low cost of the instruments required, like a sampling oscilloscope which is a basic instrument in most laboratories together with the microcomputer.
2. direct access to both fibre ends at the same place is not necessary, which makes it practical for field measurements.

B. Disadvantages
1. low signal-to-noise ratio, because of the wideband required for pulse transmission, especially at high frequencies, and hence the need for detected signal averaging.
2. high nonlinearity, due to large dynamic range of optical signal, and the need for optical attenuators to reduce it.
3. accuracy of the calculated transfer function deteriorates at high frequencies due to noise and Fourier transform computations.

Final conclusion

The original contribution of this thesis lies in;

i) A careful examination of the problems involved in measuring the transfer function directly in the frequency domain.

ii) The development of a method of measuring the phase response of a long fibre and, in particular, the idea used to avoid the need for tight sampling in order to overcome the many cycles of phase rotation in a long fibre.
iii) The design and construction of the components parts of a test system for performing optical fibre response measurements at frequencies up to the microwave region, and adapting it for fully automated computer control.

iv) Performing a set of measurements on different fibres and making a critical comparison of the frequency and time domain methods.

As a final conclusion, it can be said that the frequency domain method is more accurate for measuring fibre response, especially at the development or manufacturing stage, where both fibre ends are accessible at the same place. While the time domain technique can be used for practical testing and checking of the whole transmission system behaviour, including the laser source and receiver, in the field.
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APPENDIX I

Program to perform time and frequency domain measurement of optical fibre transfer function using HeNe laser

10 J=0
20 DIMA(250)
30 DIMX(250)
40 FORI=1 TO 250
50 A(I)=0
60 NEXTI
70 OPEN1,8,4
71 OPEN2,8,5
80 GET#1,A$
81 IF A$=""GOTO80
90 S1=ASC(A$)
100 IF S1<>20 GOTO80
111 GET#1,A$
112 IF A$=""GOTO111
122 S2=ASC(A$)
123 IFS2<>25 GOTO111
140 FOR I=10 TO 220 STEP 2
150 X(I)=20 +I
160 GET#1,A$
161 IF A$=""GOTO160
170 S=ASC(A$)
180 IFS<X(I) GOTO160
190 IFS=X(I) GOTO220
220 GET#2,B$
221 IF B$=""GOTO220
240 Z=ASC(B$)
241 PRINTZ
250 A(I)=A(I)+Z
260 NEXTI
270 J=J+1
275 PRINTJ
280 IFJ<10 GOTO 80
290 CLOSE1
300 CLOSE2
310 STOP
320 OPEN2,1,1,"DATA1"
330 FOR I=10 TO 220 STEP 2
340 PRINT#2,A(I)/J
345 NEXTI
350 CLOSE2
360 STOP
900 DIMP(30,10)
910 DIML(30,10)
1001 OPEN2,8,1
1002 OPEN3,8,2
1003 OPEN1,19
1004 PRINT#1,"400C"
1005 E=1
1006 FOR J=1 TO 10
1008 I=1
1010 FOR F=25 TO 550 STEP 25
1012 X=F/10
1014 B=INT(X)
1016 D=X-B
1018 IF D=0 THEN F$="000000"
1020 IF D<>0 THEN F$="000000"
1022 IF X<10 GOTO 1030
1024 C=B/10
1026 H=INT(C)
1028 A=10000*D+1000*G+100*H
1029 GOTO 1031
1030 A=10000*D+100*B
1031 A$=STR$(A)
1032 G$="("
1033 PRINT"#1,F$;A$;G$
1036 TA=TI
1038 IF TI-TA<30 THEN 1047
1041 ON E GOTO 1049, 1055
1044 GET"#2,C$
1046 IF C$='M' GOTO 1049
1048 M=ASC(C$)
1050 P(I,J)=M
1052 PRINT P(I,J)
1054 GOTO 1061
1057 GET"#3,B$
1059 IF B$=""GOTO 1054
1062 N=ASC(B$)
1064 L(I,J)=N
1066 GOTO 1061
1068 I=I+1
1070 NEXTF
1072 NEXTJ
1074 STOP
1076 E=E+1
1078 NEXTI
1080 NEXTJ
1082 STOP
1084 OPEN#1,1,1,"AM1"
1086 FOR J=1 TO 10
1088 FOR I=1 TO 22
1090 PRINT"#1,L(I,J)
1092 NEXTI
1094 NEXTJ
1096 CLOSE1
1098 CLOSE2
1100 CLOSE3
1102 OPEN#1,1,1,"PH1"
1104 FOR J=1 TO 10
1106 FOR I=1 TO 22
1108 PRINT"#1,P(I,J)
1110 NEXTI
2115 NEXTJ
2120 CLOSE1
2130 STOP
APPENDIX II

Program to perform time and frequency domain measurements of optical fibre transfer function using cw laser diode

10 J=1
20 DIM A(250,3) , X(250)
25 FOR J=1 TO 3
30 FOR I= 1 TO 250
40 A(I,J)=0
50 NEXT I
55 NEXT J
57 J=1
60 OPEN1,8,4
70 OPEN2,8,5
80 GET#1,A$
90 IF A$="" GOTO 80
100 S1=ASC(A$)
110 IF S1>20 GOTO 80
120 GET #1,A$
130 IF A$=, , n  GOTO 120
140 S2=ASC(A$)
150 IF S2<>25 GOTO 120
160 FOR I=10 TO 220 STEP 2
170 X(I)=20+I
180 GET#1,A$
190 IF A$="" GOTO 180
200 S=ASC(A$)
202 GET#2,B$
204 IF B$="" GOTO 202
206 Z=ASC(B$)
210 IF S<X(I) GOTO 180
220 IF S=X(I) GOTO 260
260 A(I,J)=Z
272 PRINT Z
280 NEXT I
290 J=J+1
300 PRINT J
310 IF J<3 GOTO 80
320 CLOSE1
330 CLOSE2
340 PRINT"FINISHED PULSE MEASUREMENT"
345 STOP
350 OPEN2,1,1,"DATA1"
360 FOR I=10 TO 220 STEP 2
370 PRINT#2,A(I,2)
380 NEXT I
390 CLOSE2
395 PRINT"START PHASE-FREQUENCY MEASUREMNT"
397 PRINT"SET FREQUENCY TO 300MHZ"
400 STOP
410 DIMP(100,10),L(100,10)
420 OPEN 2,8,1
430 OPEN 3,8,3
440 OPEN 1,19
450 PRINT "O00C"
460 E=1:K=1
480 F1=25 : F2=450
490 FOR J=1 TO 5
500 FOR F=F1 TO F2 STEP 25
510 X
520 FOR I=1 TO 3
530 X(I-1)/10)
540 NEXT I
550 FOR I=0 TO 2
560 X(I)-10*X
570 NEXT I
580 X(0)+100*X(2)+X
590 X$=STR$(X
600 F$="000000" : G$=""
610 X$=F$+X$+G$
620 PRINT ",X$
630 TA=TI
640 IF TI-TA <30 THEN 640
650 ON E GOTO 660,720
660 GET#/2,C$
670 IF C$=""GOTO660
680 M=-ASC(C$)
685 W=F/25
690 P(W,J)=M
700 PRINT F, P(W,J)
710 GOTO 790
720 GET#/3,B$
730 IF B$=""GOTO720
740 N=ASC(B$)
745 W=F/25
750 L(W,J)=N
760 PRINT F, L(W,J)
770 GOTO 790
790 NEXT F
800 NEXT J
801 K=K+1
802 IF K=2 THEN PRINT "SET FREQUENCY TO 900MHZ"
803 IF K=3 THEN PRINT "FINISHED PHASE MEASUREMENT"
804 IF K=3 THEN PRINT "START AMPLITUDE MEASUREMENT"
805 IF K=3 THEN PRINT "SET FREQUENCY TO 300MHZ"
806 IF K=4 THEN PRINT "SET FREQUENCY TO 900MHZ"
808 IF K=5 THEN PRINT "FINISHED AMPLITUDE MEASUREMENT" : GOTO 870
810 STOP
820 IF F=475 GOTO 840
830 IF F=1300 GOTO 864
840 F1=475: F2=1275
850 GOTO 490
864 STOP
870 E=E+1
880 IF E=2 GOTO 480
890 CLOSE 1
900 CLOSE 2
910 CLOSE3
920 OPEN 1,1,1,"AM1"
930 FOR J=1 TO 5
940 FOR I=1 TO 51
950 PRINT#1,L(I,J)
960 NEXT I
965 NEXT J
970 CLOSE1
980 STOP
990 OPEN 1,1,1,"PH1"
1000 FOR J=1 TO 5
1010 FOR I=1 TO 51
1020 PRINT#1,P(I,J)
1030 NEXT I
1040 NEXT J
1050 CLOSE1
1060 STOP
1070 END
2000 FOR I=10 TO 60 STEP 2
2010 PRINT(A(I,1),A(I,2)
2020 NEXT I