Detecting Ionising Radiation with Polarised Light

by

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Abstract

Several groups have demonstrated the potential of the Pockels effect in Cadmium Zinc Telluride (CZT) as a means to detect ionizing radiation. Migrating charge carriers are believed to generate the signal detected via the Pockels effect due to the distortions they create within the electric field, however trapped space charge beneath the cathode has been regularly observed which suggests that the signal amplitude is potentially dominated by a large dose element. In this work, the effects of electric field collapse at the location of charge carrier generation, rather than where space charge builds up, is demonstrated. This confirms the potential to apply the technique for imaging dose rate distributions. Charged coupled device (CCD) images representing the changes in electric field within the crystal were taken and the response to illumination from a collimated 1550 nm 4.5 mW IR laser and irradiation from 150 kVp X-rays measured. The data demonstrates that the signal acquired is a combination of both the local change in the electric field at the location where the carriers are being released/generated and an element caused by them becoming trapped, leading to space charge near the cathode. Whilst the presence of both components has been demonstrated, their time response to an IR pulse measured via a photo-diode is the same (within the 6 ms time limitation of the system). This means that when using a Pockels detection system the average change in field can be considered proportional only to the incident dose rate when working in the millisecond regime.

In addition to finding the origins of the detected signal an investigation into the effects of doping a Cadmium Manganese Telluride crystal with vanadium was carried out to see whether the large increases in Pockels constant found in the literature when using doped CZT could be replicated. However, it was found that whilst there is a slight improvement in the constant and hence the sensitivity of the crystals it was not as significant as hoped. A fibre optic Mach-Zehnder interferometer has also been designed and built with the aim of developing further the results from a previous free-space concept demonstrator. In its present condition the effects of environment have been minimised but the detector system struggles with large attenuation losses due to repeated coupling into fibres and is currently not usable, however, increasing the power of the laser and trying to limit even further the free-space elements in the future should remedy this.
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Chapter 1

Introduction

Semiconductor based radiation detectors are widely used to measure both ionising and non-ionising forms of radiation, their principle of operation is analogous to gas detectors however their linear stopping power means that they are more capable of absorbing high energy radiation. A typical semiconductor detector for ionizing radiation converts the energy deposited in the detection medium into free charge carriers, which can then be collected to give an insight into the characteristics of the ionization event. Depending on the set-up of a detector the generated signal can potentially provide information on the energy of the radiation or even on its position and time of interaction \[9\]. Cadmium Telluride (CdTe) and its compounds have become extensively researched due to their high stopping power and ability to function at room temperature and have now become increasingly common as advances in their manufacture have improved the quality of material, this popularity and their optical properties make CdTe and in particular CdZnTe and CdMnTe suitable for use within this project \[29\].

This thesis discusses work on the Pockels detection technique which observes how the charges created in an ionization event affect the electric field within Cadmium based compounds. This approach uses polarised light to detect radiation by observing how the carriers distort a pre-existing uniform field within the crystal. The technique utilizes the electro-optical property known as the Pockels effect, where the refractive index of a material varies with the strength of the electric field it experiences. The distorted field creates variations in
the refractive index which is observed by recording how the polarization direction of transmitted light changes. The main advantage of this approach is that the radiation sensitive electronics can be positioned a long distance from the radiation field as collected charge is not being processed; this potentially means a system built using this technology could be left in-situ within a high flux environment where normally electronic components can become damaged and signals induced in connecting cables due to the proximity of the radiation field. In a similar way to detectors running in continuous current mode, the system should not suffer from dead time as there is no photon counting, thereby removing the associated signal processing overheads and making it possible to operate in higher flux intensities. However the disadvantage of the Pockels detection approach is that it is not currently capable of providing spectroscopy due to it only being sensitive to changes in dose rate and is not capable of identifying on its own whether it is caused by different energy photons or varying incident intensities.

The Pockels electro-optic effect is found in non-centrosymmetric materials where the optical properties such as the refractive index can be varied with an applied electric field. Upon application of a field a phenomenon known as birefringence occurs where the refractive index experienced by light depends upon its polarity and is proportional to the field strength, this can be utilised to apply modulation and other effects on light passing through the material and has found extensive applications in areas such as laser control using Pockels Cells.

The Pockels effect has regularly been used to profile the internal electric field of birefringent semiconductor materials such as Cadmium Zinc Telluride (CZT) with the initial aim of getting a better understanding of the uniformity and the factors affecting it [5].

A common technique used to achieve this is known as Pockels Imaging [5], this method works by passing light through a birefringent material which is polarised at -45° with respect to the direction of the electric field applied to the crystal. The field causes birefringence to occur by changing the refractive index of one orthogonal component and therefore the polarity of any light that passes through it due to relative phase shifts between components. The proportion of light that has been shifted can then pass through a 2nd polariser set at
+45° and the subsequent intensity determined by the CCD camera. If the electric field is not uniform then its variation will appear on the camera readout as changes in intensity.

Work by Prekas et al [2] [3] looked in detail at profiling the electric field of CZT using Pockels Imaging, the focus of the work investigated how the field evolves under a variety of different conditions such as temperature, sample thickness, voltage bias level/direction and irradiation by X-rays. Primarily the results from this work were collected using imaging however the transient current technique was also utilised to verify the findings by evaluating alpha particle induced current pulse shapes to derive the electric field profile. The results of this work will be examined in detail in subsequent chapters however the main conclusions were that under room temperature conditions the CZT samples showed relatively uniform electric field irrespective of sample thickness or voltage bias magnitude, however under positive bias the electric field did appear to peak under the cathode indicating some level of trapped space charge whereas under negative bias it remained uniform throughout the crystal. At low temperature and under X-ray irradiation trapping became much more prominent creating an area of high field just below the cathode and low electric field through the remainder of the crystal, the difference in behaviour between forward and reverse biasing indicates that cold temperatures cause the metal-semiconductor contact properties to change and become less ohmic.

To demonstrate that the Pockels effect can provide information on radiation interacting with the crystal Nelson [15] [21] uses a high intensity neutron/gamma flux from a reactor to irradiate a block of CZT and observes the changes in the electric field. Whilst the basic techniques used are exactly the same as Prekas albeit without X-rays this study showed that it is possible to detect real-time changes in radiation flux via imaging of the electric field. This insight has a lot of potential as it enables the electronics used in standard radiation detectors to either be removed completely or kept away from the beam. This is beneficial in a high flux environment where radiation damage in the electronics is a significant concern.

Recent work by Franc [30] has since shown that it is possible to identify changes in the flux of photons incident on CZT by measuring the electric field. These experiments were done
using non-ionising light from a laser system however aside from how the carriers come to be inside the crystal the physics is the same for ionising electromagnetic radiation and shows that Nelson’s work has practical applications. This work in addition to previous studies also suggested trapped space charge could be countered by illuminating the sample with different wavelengths of light thus returning it to uniform electric field [31].

In order to confirm that changes in X-ray flux could be determined by imaging the electric field and how the Pockels system could be optimised for this purpose Langley carried out experiments and simulations firstly to confirm the process is working as expected and in later work investigations into how contact geometry and sub-band gap illumination affects the performance [4]. The work showed that whilst the system is capable of detecting 50 kV X-rays at 1.6 mGy/s with a 7x7x2 mm Yinnel CZT sample it could not detect gamma radiation from a $^{133}$Ba source with an approximated dose rate of $1.5 \times 10^{-6}$ mGy/s, this is most likely due to the system not being sensitive enough to detect a relatively low activity source rather than an issue with the radiation type. An investigation was also carried out looking at the effects of different contact geometries and it was found that whilst a dot electrode caused polarisation with a high electric field being created the range over which the field varied was larger than when using a planar contact indicating that more accurate measurements could be achieved at this point if the alignment was done accurately.

To find an alternative method to the techniques that have been used to date work done by Lohstroh [7] investigated using a Mach-Zehnder interferometer to measure the electric field. This type of interferometer works by splitting a beam from a laser into two and after reflecting them off of mirrors recombining them using a second beam splitter and then analysing the phase difference between the two recombined beams. The variations in the optical path lengths create a phase difference which manifests as either constructive (phase difference of $2\pi$ or multiples of) or destructive interference. The intensity of the recombined beams will vary sinusoidally with the phase where the maximum will be under constructive interference and the minimum under destructive. By placing the CZT crystal in one of the beam arms it is possible to determine how the electric field is behaving due to the birefringence causing
a relative phase shift. This technique can potentially provide very accurate measurements of
the change in refractive index and whilst it has been proven to work the results suffered from
high levels of noise caused by the phase of the beams gradually shifting over time. This has
been put down to limitations in environmental controls and the conditions under which the
CZT was tested.

This project is split into two distinct parts which run simultaneously, the engineering sec-
tion focusses on developing the interferometer from a table top design to a robust detector sys-
tem based around using fibre optic components rather than free space to provide the stability
and limit environmental factors. The second section investigates the charge carrier dynamics
behind the Pockels technique and the relationship between the irradiation/illumination inci-
dent on the detector and the subsequent detected changes in the electric field. The majority
of work within this area has examined CZT crystals which, due to their inherent properties,
have low hole mobility [29]. In addition, the material typically contains a sufficiently high
concentration of electrically active defects to allow the crystal to become polarized via the
trapping of free charge carriers. This generates a build-up of space charge, changing the local
electric field and hence the refractive index.

As such it is possible that the majority of the detected Pockels signal is formed this way,
especially if measured close to the cathode where the polarization accumulates [3] [29] [32]. If
this is the case then the change in refractive index will have a potentially large time integrated
dose element; with a time scale determined by the re-emission of trapped charges from the
defect states. However, the generation of free charge carriers local to the incident radiation
interaction point are also expected to affect the electric field distribution, possibly in a less
accumulative manner. The potential presence of both effects has been acknowledged in a
previous study however it has not been explicitly identified or measured independently [7].
This work focuses on investigating the detected Pockels signal, confirming whether both
local and trapped space charge induced effects are present and to assess whether there is a
significant difference in the time-scales they operate within.
Chapter 2

Background

2.1 Birefringence

Any given material can generally be described as either isotropic or anisotropic which in the former means that the properties are uniform in all directions and in the latter they are directionally dependant. The optical properties, in particular the refractive index behave in the same way except that the properties are relative to a product of the structure orientation and the polarity of an incident beam.

For anisotropic materials this means that instead of having a single refractive index for all polarisations of light they have a discrete set. Uniaxial crystals are a type of anisotropic material that display these characteristics intrinsically but uniquely have a single axis of symmetry (optic axis) along which the refractive index a component of light, known as the extraordinary ray, experiences is different to that of one whose electric field is perpendicular to it (known as the ordinary ray) [33] [34].

This effect is caused by the atomic binding forces on the electron clouds around the atoms varying depending on their orientation within the crystal lattice of the material [16].

Birefringence is an optical phenomenon shown in anisotropic materials where the refractive index or phase velocity the components of a ray of light experience varies depending on their
polarisation. This effectively causes the beam to ‘split’ as the components move through the material at different velocities.

Whilst birefringence occurs naturally in uniaxial crystals the same effect with two distinct refractive indexes can also be induced in some isotropic materials such as CZT by the presence of an electric field.

### 2.2 Crystal Structure of CZT

\( \text{Cd}_{1-x}\text{Zn}_x\text{Te} \) is an alloy of CdTe and ZnTe which both have a face centred cubic (FCC) lattice structure. When the two are combined a Zinc-blende structure is created which consists of the two lattices inter-penetrated with each other so that the origin of one lies at coordinates 0, 0, 0 and the other at \( \frac{1}{4}, \frac{1}{4}, \frac{1}{4} \) as shown in Figure 2.1.

![Zinc-blende crystal structure](image)

One of the sub-lattices is always made of Te atoms with the other being either Zn or Cd where the proportion of Zn lattices is dependant on the level of doping \( x \). The primary motivation for modifying CdTe by adding Zn is that it reduces the appearance of Te inclusions which act as trapping sites for charge carriers and it increases the resistance by creating a larger band-gap.

Upon application of an electric field the sub-lattices are displaced with respect to each other by the inverse piezoelectric effect which causes strain in a material proportional to the field strength.
This displacement effectively causes a shift in the charged particles throughout the crystal causing different binding energies along different planes. Light will travel slower along planes where the binding forces are strong as the tighter bound electrons oscillate slower as the electromagnetic wave vibrates them causing re-radiated light to be more out of phase thereby slowing the overall beam down.

The change from uniform binding energies is seen optically in CZT as a change from isotropic crystal behaviour to uniaxial and is the basis of the Pockels electro-optic effect.

2.3 Pockels Effect

The relationship between the strength of an electric field and the affect it has on the refractive index of the material it is applied to is known as the Pockels effect.

When an electric field is applied to materials such as CZT it causes a change along the axis parallel to the electric field in the dielectric constant of the medium and thereby the refractive index. Due to this orthogonal light rays travel at different velocities within the crystal and suffer a phase change with respect to each other, this in turn causes a change in the overall polarisation of the light. If the incident light is linearly polarised this phase shift will cause the beam to become elliptically polarised as is illustrated in Figure 2.2 [33][5].

Figure 2.2: Linearly polarized light at 45° (top) and elliptically polarized light (bottom) with corresponding electric field vectors [2]
The change in refractive index is proportional to the electric field strength as shown in Equation 2.1 where $E$ is the electric field strength, $n(E)$ is the modified refractive index, $n_0$ is the field free refractive index and $r_{41}$ is the Pockels coefficient. This means it is possible to calculate the refractive index that light polarised in the same direction as the applied electric field will experience and crucially the opposite is true if the index can be measured experimentally.

$$n(E) = n_0 + (1/2)n_0^3 r_{41} E$$  \hspace{1cm} (2.1)

In CZT $r_{41}$ is between 4.5-5.0 pm/V and $n_0 = 2.8$ \cite{38} \cite{39}.

There are several techniques that are capable of measuring how much the polarisation of light changes as it goes through the birefringent material, the three that are used within this project are described in Section 2.4 and between them they provide sufficient capability to characterise the entire electric field within the crystal via CCD imaging and interrogate specific sections using a photo-diode.

### 2.4 Pockels Detection Methods

The three detection methods that will be discussed are all based on measuring how the incident linearly polarised light changes as it passes through a birefringent medium. Due to this the front end of the systems are very similar however after the light has passed through the crystal it is possible to analyse it in different ways leading to changes in capabilities and characteristics.

#### 2.4.1 CCD Imaging

In a Pockels imaging system a CCD camera is used to detect linearly polarised light which is orientated so that its electric field vector is at -45\degree with respect to the field applied to
the crystal. Doing this causes the beam to behave as two orthogonal phase coherent wave components where one can follow the ordinary path (polarisation perpendicular to the electric field) and the other the extraordinary (polarisation parallel to the electric field) [5].

Material specific sub-band gap light is used as this achieves good transmission through the crystal whilst still being detectable by standard CCD cameras such as the Guppy F-044B CCD camera whose limit of detection is at 1000 nm [40]. A white-light bulb is used as the source because with a laser there is a risk of damaging the camera and it is also simpler to uniformly illuminate the crystal with the broader beam.

Upon exiting the crystal the light then interacts with a polariser orientated at $+45^\circ$ so that from the now elliptically polarized light only the components of the original which have had their polarities adjusted will be passed through.

This is illustrated in Figure 2.3 where the first polariser is used to ensure the light from the source is linearly polarised and the CCD camera is employed to measure the intensity of the final beam.

Once measured the intensity of the light can then be used by Equation 2.2 [41] to give the strength of the electric field within the crystal. $\lambda$ is the wavelength of light, $d$ is the distance
of light path through the crystal, $I$ is the transmitted intensity, $I_0$ is the intensity through parallel polarisers.

$$E = \frac{2\lambda}{\sqrt{3}\pi n^3 r_{41} d} \sin^{-1} \sqrt{\frac{I}{I_0}}$$  \hspace{1cm} (2.2)$$

Using a CCD camera enables live images of the electric field to be taken so that any changes can be seen within milliseconds and better understood. This capability means that the technique is an excellent diagnostic tool and it will to be used throughout the project to analyse how the electric field is behaving under the different test conditions. The camera system however does come with quite high technological overheads and can also be easily damaged by laser light, these limitations mean it is unsuitable for use outside of specific laboratory environments.

### 2.4.2 Laser Detection

This technique is based fundamentally on the imaging methodology described in Section 2.4.1 however instead of using a CCD camera to measure the intensity a photo-diode is utilised, as can be seen in Figure 2.4.

![Figure 2.4: Pockels laser system](image)

The advantage of this approach is that there is significantly less equipment required as there is no need for any of the front end lenses and the diode can be read out with a basic oscilloscope rather than a computer. This leads to a much more compact system which as
seen in work by Antonis and in Figure 2.5 can also be focused onto a very small area to enable measurements with spatial resolutions in the order of 20 µm [5].

The readout from this system on an oscilloscope will come either as a power spike if the laser is pulsed or as a shift in the baseline if run in continuous mode. Whilst a single reading is capable of giving the average intensity of the area being illuminated it cannot be used to investigate the overall field profile without taking multiple measurements and 'scanning' the crystal.

Due to its analytical limitations this technique is likely to be of most use when used in combination with the imager to confirm findings and potentially as a final detector system owing to its simple structure.

2.4.3 Mach-Zehnder Interferometry

This technique is different to the previous two detection techniques described as instead of detecting the variation in refractive index by observing the change in polarisation of the detection light it is done by measuring the relative phase shift of two beams where one passes through the crystal.

It has been shown by Lohstroh et al. that it is possible to detect changes in the electric field by using a Mach-Zehnder Interferometer [7] [6]. This type of interferometer works by splitting a beam from a laser into two and after reflecting both arms off of mirrors recombining
them using a second beam splitter. The recombined beams show the variations in the optical path lengths via the phase difference which manifests as either constructive (phase difference of $2\pi$ or multiples of) or destructive interference. The phase difference between the beams should ideally be $\pi$ due to one of the beams receiving one less phase shift from the second beam splitter as the reflection occurs on a surface where the refractive index changes from high-low. This means that whilst one detector is getting a recombined beam with constructive interference the other is receiving a beam with destructive, this can be observed by measuring the intensities of the beams. To position the components so that the optical path lengths are exactly the same is in reality extremely difficult however as long as the phase difference is an odd multiple of $\pi$ the result is the same.

The operation of an interferometer without a measurand is shown in Figure 2.6 where Detector 1 has destructive interference and Detector 2 constructive.

![Figure 2.6: Operation of a Mach-Zehnder Interferometer](image)

Figure 2.7 shows the CZT crystal being placed in beam arm 2, its presence changes the phase of the beam and this shift can be detected as changes in intensity of the recombined beams. As has been previously discussed the level of birefringence within the CZT increases with electric field strength and this should be replicated in the phase shift and hence a change
in the field within the crystal should cause a corresponding change in the intensity seen at the
detectors. A phase retarder has been added to beam arm 1 to fine tune the effective beam
path lengths so that a phase shift of $\pi$ can be achieved at BS2.

To measure the phase shift ($\phi_{\text{shift}}$) the difference in phase prior to changing the electric
field and after must be found. To find the phase ($\phi$) at any given amplitude $A$ the amplitude
of the destructive interference point ($A_{\text{min}}$) and the constructive interference point $A_{\text{max}}$ are
input into Equation 2.3.

$$\phi = \arcsin\left(2 \frac{A - A_{\text{min}}}{A_{\text{max}} - A_{\text{min}}} - 1\right)$$

(2.3)

This can then be used to calculate the electric field strength $E$ using Equation 2.4 where
$n_0$ is the field free refractive index at wavelength $\lambda$ and $r_{41}$ is the Pockels coefficient $l$ is the
path length of light through the crystal.

$$\phi_{\text{shift}} = E \frac{\sqrt{3} n_0^3 r_{41}}{\lambda}$$

(2.4)

Figure 2.7: Detecting the Pockels effect with a Mach-Zehnder Interferometer 

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The work undertaken by Lohstroh et al. [7] and shown in Figure 2.8 proves that changes in an electric field within a CZT crystal caused by either varying the bias or irradiating with X-rays can be detected by observing the induced phase shift using the interferometry method. The phase shift does not increase linearly at lower incident dose rates, 0.3 mA in Figure 2.8 and it is suggested that this could be due to the detection laser covering areas of the crystal with both high and low electric field causing the net phase change to be negligible until higher irradiations where one component begins to dominate, a lack of response at low dose rates has also been observed by Langley when irradiating with a $^{133}$Ba source [4].

![Figure 2.8: Observed phase shift under variable bias voltage and X-ray tube current (Bias = 500 V)](image)

This promising technique has been demonstrated successfully as a free-space system however it is impacted heavily by the environmental conditions such as vibration and changes in temperature, the next step in its development is to design and build a more stable detector which should give more accurate and repeatable measurements of how the electric field is changing.
2.5 Interaction of photon radiation with matter

The main principle behind the Pockels detection technique is that radiation incident on the CZT crystal ionises the atoms it encounters creating charge carriers which, as they move to either electrode distort the electric field around them. The mechanism by which radiation interacts with matter and creates the carriers varies depending on the type and energy of the radiation along with the intrinsic properties of the material such as the band-gap.

This section will focus on electromagnetic radiation and the subsequent charge carriers rather than heavy ions and neutrons as this is the type that is predominately used through the project, both ionising and non-ionising will be discussed.

2.5.1 Electromagnetic Radiation

The energy of a photon determines how it interacts with a given material, radiation above 10 eV is classed as ionising as it is capable of removing electrons from an atom by overcoming their binding energy [9]. Non-ionising radiation has insufficient energy to overcome this although it can still create free carriers, however it does so by a different process.

Ionising

There are three main mechanisms by which ionising radiation interacts with a material: photoelectric absorption, Compton scattering and pair production. The probability of an interaction being of a certain type varies with the energy of the photon, as shown in Figure 2.9 where absorption dominates at lower energies and pair production at the higher end with scattering in between. Before the energy from an incident photon is completely absorbed it will likely undergo a number of interactions with its environment, with the type being determined by the energy present [9] [42] [43].
Photoelectric absorption  During photoelectric absorption the incident photon transfers all of its energy to an absorber atom which subsequently ejects a photoelectron from one of its bound shells which has a kinetic energy \( E_{e^-} \) equal to the energy of the photon \( (hv) \) minus the binding energy \( (E_b) \), Equation \( 2.5 \). The photoelectron usually comes from the K-shell however if the photon energy is lower than the K-shells binding energy an electron from an outer shell can be used.

\[
E_{e^-} = hv - E_b \tag{2.5}
\]

After emitting the photoelectron the absorber atom now has a vacancy in one of its shells which is filled by a nearby higher energy electron (either free or in an outer shell), this then leads to a characteristic X-ray or an Auger electron (equal to the difference in binding energy
being emitted) so that the electron can enter a stable state \[9\] \[12\] \[13\].

**Compton Scattering** In the Compton scattering process an incident photon transfers a proportion of its energy to an electron with the amount dependent on its subsequent scattering angle, as shown in Figure 2.10 and Equation 2.6 \[9\] \[12\] \[13\].

![Compton Scattering Diagram]

Figure 2.10: Compton scattering geometry \[9\]

As can be seen from Equation 2.6 where \(m_0c^2\) is the rest mass energy of an electron (0.511 MeV) the larger the scattering angle of the photon the more energy is given to the scattered electron in accordance with the conservation of energy and momentum.

\[
\frac{h\nu'}{h\nu} = \frac{1}{1 + \frac{h\nu}{m_0c^2}} (1 - \cos \theta)
\]

**Pair Production** If a photon has an energy higher than 1.02 MeV then pair production can take place. During this process an electron-positron pair is created (which has a combined rest-mass energy of 1.02 MeV) inside the coulomb field of a nucleus. The photon is completely absorbed and any energy above 1.02 MeV is shared between the two fermions as kinetic energy.

As the positron slows down and reaches the approximate energy of the thermal electrons in the absorber material it will annihilate with one of them and two 511 keV photons are emitted. The lifetime of positrons is extremely short (up to 1 ns in some semiconductors) and therefore the annihilation radiation is usually seen at the same time as the original pair production interaction \[9\] \[42\] \[43\].
Non-Ionising

If a photon has insufficient energy to cause the photoelectric effect it can still release free carriers inside the absorber material provided that it has enough energy to transfer electrons in the valence band ($E_v$) across the band gap ($E_B$) or those in energy levels between the valence and conduction bands ($E_c$), as illustrated in Figure 2.11 [10].

![Figure 2.11: How non-ionising electromagnetic radiation can move carriers into the conduction band and free those caught in mid-level traps](image)

2.5.2 Charge Carriers

When ionising electromagnetic radiation enters a material it creates a series of electron-hole (e-h) pairs by transferring electrons into the conduction band via the mechanisms discussed in Section 2.5.1 and leaving a positive 'hole' in the valence band.

The number of pairs generated in a specific material is proportional to the energy of the photon and the 'W-Value' ($W_{ehp}$) of the absorber, the Klein Chart in Figure 2.12 shows this by plotting the W-value for different materials against the size of the band-gap. The W-Value is the average amount of energy required to create e-h pairs in a material, for CZT this is between 4.5-5 eV dependant on the amount of Zinc doping [29].
The proportionality of e-h pairs to photon energy means that if the carriers can be collected and measured then the magnitude of the signal they provide will give information about the energy absorbed.

In practice this is achieved by attaching a pair of electrodes to the detector material and applying a potential difference between them thereby creating an electric field. The electrons and holes will drift towards either the anode or the cathode depending on their charge and the resulting amplitude of the current pulse can be measured, this is described in more detail in Section 2.5.3.

The magnitude of the pulse will always vary slightly even with mono-energetic radiation due to Poisson statistical fluctuations which are caused by a distribution in the number of e-h pairs created for a given deposited energy. A Fano factor ($F$) accounts for any departure from the Poisson predicted variance due to the processes that lead to a creation of an individual charge carrier not being independent of each other. This scaling factor is represented simply in Equation 2.7 \[9\]. In CZT the Fano factor has been measured by Redus \[44\] as 0.089+/−0.005.

$$F = \frac{Observed \ variance}{Poisson \ predicted \ variance}$$ (2.7)
2.5.3 Shockley-Ramo Theorem

The Shockley-Ramo Theorem describes the relationship between the detected current signal on an electrode in a detector system to the charge generated by ionising radiation within the detection medium. The theory was developed separately by Shockley [45] and Ramo [46] and originally applied to vacuum tube detectors however it is equally applicable to semiconductors [12].

The induced charge \( Q \) on an electrode for a single charge carrier \( q \) is given by Equation 2.8 and the induced current by Equation 2.9.

\[
Q = -q\psi w(x) \quad (2.8)
\]

\[
i = q\vec{v} \cdot \vec{E}_w(x) \quad (2.9)
\]

It is important to note that the induced current is mainly dependant on the instantaneous carrier velocity \( \vec{v} \) and its position relative to the electrode \( x \) rather than the applied electric field/potential between the electrodes. The \( \vec{E}_w(x) \) term describes the local potential \( \psi w(x) \) and field at the charges’ location caused by electrostatic coupling between the moving and induced charge at the electrode.

The total charge induced on either of the electrodes is given by Equation 2.10 which takes into account the drift length and amount of charge carriers \( N_o \) of both electrons \( (x_e) \) and holes \( (x_h) \) as they move towards their respective electrodes.

\[
\delta Q = qN_o \frac{D}{D}(\delta x_e + \delta x_h) \quad (2.10)
\]

This equation assumes that both carrier types move the entire distance \( \delta x \) and contribute equally to the signal generation as in Figure 2.13.
In reality however the carriers do not have the same transport properties and the slow component (induced charge up to $t_2$) is not always collected.

The charge collection efficiency ($CCE$) calculation seen in Equation 2.11 is used to calculate the percentage of the original created charge carriers ($Q_0$) that are collected and hence make up the integrated current pulse $[9]$.

$$CCE(\%) = \frac{Q}{Q_0} \times 100$$  \hspace{1cm} (2.11)

### 2.5.4 Hecht Theory

The transport properties of a carrier are largely defined by the speed at which it can move through a medium (drift velocity($v$)) and the average time it takes for it to recombine or become trapped (mean lifetime ($\tau$)). The product of these two components is known as the mean free path ($\lambda$) and is different for both electrons and holes as indicated in Equations 2.12 and 2.13

$$\lambda_e = v_e \tau_e$$  \hspace{1cm} (2.12)

$$\lambda_h = v_h \tau_h$$  \hspace{1cm} (2.13)
The lifetime of a specific carrier in a given detector material (e.g. CZT) is usually assumed to be constant and independent of the electric field strength however if the drift velocity is not at saturation then it is possible to increase it by applying an external electric field ($E$), this is shown in Equation 2.14 where $\mu$ is the carrier mobility.

$$v = \mu E$$ \hfill (2.14)

Combining Equation 2.12 and Equation 2.14 gives Equation 2.15 which shows that a carrier’s drift length in a specific material is limited by poor drift mobility or low carrier lifetime, collectively these two parameters are known as the mobility-lifetime product or $\mu\tau$-value.

$$\lambda = \mu\tau E$$ \hfill (2.15)

If a material has low $\mu\tau$-values for its carriers then it is less likely that all of the e-h pairs created in an ionisation event will be collected and hence the CCE will be <100 %.

The Hecht equation 2.16 defines the relationship between the CCE and the carrier’s charge transport properties for an interaction occurring at distance $x$ below the cathode for a planar detector of width $d$ as seen in Figure 2.14.

$$CCE = \frac{\mu_e\tau_e E}{d} \left[1 - e^{\frac{-(d-x)}{\mu_e\tau_e E}}\right] + \frac{\mu_h\tau_h E}{d} \left[1 - e^{\frac{-x}{\mu_h\tau_h E}}\right]$$ \hfill (2.16)
In the case where the interaction depth is a lot shorter than one of the carrier’s mean free path then the equation can be simplified as it can be assumed that only one of the carriers will contribute to the detected signal.

\[
CCE = \frac{\mu \tau E}{d} \left[1 - \exp\left(-\frac{d}{\mu \tau E}\right)\right]
\] (2.17)

The shortened form is extremely useful for characterising detector materials as it is possible to isolate the carriers and study their transport properties separately.

### 2.6 Semiconductor Detectors

A semiconductor is a material type whose electrical conductivity is between that of a conductor (e.g. Gold) and an insulator (e.g. Glass). The conductivity of a material is fundamentally determined by the energy required to promote electrons from the valence band into the conduction band i.e. the band-gap. The difference in band-gap size is illustrated in Figure where the insulator gap is too large for e-h pairs to be thermally generated and the conductor has no gap between the valence and conduction band which means the electrons at these binding energies exist within de-localised orbitals and not fixed to a specific atom.

![Figure 2.15: Band structure in electron energies for insulators, conductors and semiconductors](image)

The band-gap energy \(E_g\) of a semiconductor is small enough to enable some electrons to gain sufficient energy from thermal excitation to move into the conduction band, the
The probability of this happening is given by Equation 2.18 where, \( T \) = absolute temperature, \( k \) = Boltzmann constant, \( C \) = material dependent constant.

\[
p(T) = CT^\frac{3}{2} \exp\left(-\frac{E_g}{2kT}\right)
\]  

\[\text{(2.18)}\]

2.6.1 P-N Junction

The band-gap can have additional (dopant) energy levels. These can be filled by electrons or holes to give it an abundance of that carrier. This creates either p-type materials where the band-gap contains the additional dopant energy levels (acceptors) which can then be filled by electrons from the valence band or n-type where the energy required to excite dopant’s extra electron into the semiconductors conduction band is lower than the original intrinsic materials band-gap [9].

Joining p-type and n-type materials together causes the excess carriers to gradually diffuse across the boundary and recombine with each other creating a volume which has no free net charge, this is known as the depletion or transition region (Figure 2.16). The size of this region is internally regulated due to a potential difference being created between the positive and negative materials [47].

By applying a reverse biased external voltage to the junction the depletion region can be expanded across the entire device. The reverse bias also increases the strength of the electric field and hence the speed and efficiency that free charge carriers (whether thermally generated or from external sources) can be collected at the electrodes.

2.6.2 Metal-semiconductor junction

The work in this project is carried out using planar devices and single crystals which rather than creating a depletion region in the detector via a P-N junction use two metal-semiconductor (m-s) junctions as shown in Figure 2.14 to create either an Ohmic or a Schottky contact.
Figure 2.16: The P-N junction: (a) Schematic showing both p-type and n-type materials (b) Carrier density distributions throughout sample [13]

In a biased device with two Ohmic contacts if either a positive or negative charge is collected at one of the electrodes then one of the same type is injected at the other electrode creating a large leakage current through the material. When Schottky contacts are used charges are not injected at the opposite electrode meaning the leakage current is very low and the device can be used to detect small current pulses created by e-h pairs [14] [9].

When initially creating a m-s junction there is usually a difference for each material in the amount of energy required to release an electron into free space, in metals this is known as the work function ($\theta_M$) which is the difference between the Vacuum energy level and the Fermi level. In semiconductors the energy needed is known as the electron affinity ($\chi$) and is the difference between the Vacuum level and the Conduction band. A large energy gap between the electrode and detector material creates a Schottky contact and a low or negligible energy gap makes an Ohmic [9] [14].

The difference creates a barrier across which carriers from the high work function material cannot cross due to having insufficient energy. It is however possible for the electrons in the other material to lower their energy by crossing the junction. This leaves a positively...
charged hole behind which creates a negative electric field that lowers the band-gap (effectively equalising the work functions) eventually enabling electrons from the high work function material to drift across and recombine with the holes. This continues until thermal equilibrium is reached and the Fermi energy is the same throughout the structure.

This can be seen in Figure 2.17 for the case where the work function of the metal is higher than that of the semiconductor.

![Diagram](image)

**Figure 2.17:** Band diagrams of (a) metal-semiconductor junction before and (b) after thermal equilibrium [14]

Applying either a reverse or forward biased potential across the two electrodes changes the Fermi levels of the materials with respect to each other. In the case shown in Figure 2.18 (a) forward biasing lowers the difference in Fermi level and hence there is a lower potential drop across the semiconductor enabling more electrons to move into the metal than come the other way leading to an increase in current through the junction and Ohmic behaviour.

Reverse biasing (Figure 2.18 (b)) increases the potential across the semiconductor creating a larger depletion region at the junction which is dependant on the magnitude of the potential difference between the electrodes. This means the detector will exhibit Schottky contact behaviour where as current can only flow in the forward direction the reverse leakage current will be much lower than an Ohmic contact.

In the context of this project the contacts are likely to be approximately ohmic as the work function of the gold contacts and the electron affinity of the CZT will be very similar (5.3 eV and 5.2-5.4 eV respectively) [18] [49]. The risk of a high leakage current is acceptable.
as the Pockels techniques observe changes in the electric field and do not need to operate in pulse mode, even with ohmic contacts the leakage is unlikely to be extreme due to the high resistivity of the material. In order to ease interpretation of Pockels Images a uniform field in dark conditions is desirable and therefore the priority is to provide a stable environment and one where the carriers can easily leave the detection medium.

### 2.7 Irradiating the sample

The ability to detect radiation via Pockels has been tested experimentally by Nelson [15] [21] who irradiated the sample with a neutron beam and recorded the response of the crystal by measuring the light transmitted.

As can be seen from Figure 2.19 when the reactor is pulsed there is a corresponding response in the Pockels cell indicating that it is possible to detect changes in the radiation flux with this technique [15].
Later work by Sellin and Prekas [3] used an X-ray source and a CCD camera to image the electric field within a 7x7x2 mm Yinnel CZT crystal and develop an understanding of how the charge carriers behave. The results showed that there is a decrease in electric field strength under the cathode when the crystal is exposed to X-rays, as can be seen in Figure 2.20.

This effect has been attributed to a build-up of positive space charge due to the slow moving holes becoming trapped as they approach the cathode. These results support the
simulations shown in Figure 2.21 made by Bale and Szeles who modelled carrier density within CZT under X-ray irradiation [16] [3].

![Figure 2.21: Simulated carrier densities in a CZT crystal under X-ray irradiation](image)

Whilst a change in the electric field is not a problem in itself having it occur in an increasingly smaller area as the dose increases would require a detection beam to illuminate a specific area of the crystal to get the best response. The larger issue however is that the trapped space charge takes time to dissipate hence reducing the ability of the detector to quickly respond to changes in the flux and as shown by Langley in Figure 2.22 using a 950 nm laser it can take several tens of seconds for the electric field to return to its original state [4].
This means any future system would need to consider either reducing the polarisation of the crystal as much as possible or at least understand how it relates to the instantaneous dose rate so that it can be used continuously for long periods of time and the signal interpreted correctly.

2.8 Trapped Space Charge

In radiation detectors it is common for their detection performance to vary depending on the operating conditions and the intrinsic properties of the material.

Semiconductor detectors, especially those made with CZT are susceptible to a phenomenon known as polarisation. This effect is caused by a build up of charge in the material which then creates its own internal electric field that opposes the externally applied bias and reduces the width of the depletion region within which charge carriers can be efficiently collected, this thereby reduces the CCE and the spectroscopic performance as not all of the charge carriers released into the detector are collected \[50\].

Malm \[17\] suggested that polarisation in CdTe is created by a combination of four mechanisms:
(A) Poor surface quality leading to a build up of bound surface charge.

(B) Dielectric relaxation of an impurity vacancy.

(C) Free carriers becoming trapped by acceptor sites under one of the electrodes.

(D) Releasing carriers in deep traps (acceptor sites close to the valence band) causing an increase in ionised acceptor sites.

Within the context of this project only mechanisms (C) and (D) will be discussed due to the high quality surface preparation of the Redlen bought CZT crystals minimising the bound surface charge and the increased complexity of isolating the effects of dielectric relaxation.

The effect that polarisation has on the electric field ($\delta E$) is approximated by Poisson’s equation (2.19) where $q(N_D - N_A)$ is the net ionised charge density for holes ($N_A$) and electrons ($N_D$), $\epsilon$ is the dielectric constant.

$$\delta E = \frac{q}{\epsilon} (N_D - N_A) \quad (2.19)$$

The (change in) electric field changes with the net space charge and in doing so it also becomes more concentrated towards one of the electrodes (Figure 2.23).

![Figure 2.23: Electric field strength for different carrier densities](image)

The electrode under which the polarisation collects is dependant on the carrier mobilities.
In CZT this is primarily the cathode as the hole mobility (100 cm$^2$ V$^{-1}$ s$^{-1}$) is significantly lower than the electron mobility (1200 cm$^2$ V$^{-1}$ s$^{-1}$) [51].

Upon first inspection polarisation would appear to be detrimental to the performance of a Pockels detection system as the slowly dissipating trapped charge should make the detector unresponsive. However, work by Schwartz [52] suggests that the internal electric field created by the trapped carriers in vanadium doped CZT (effect was not seen in un-doped samples) changes the initial cubic symmetry which appears to increase the Pockels coefficient by several orders from 1-7 pm/V to 900 pm/V making it significantly more sensitive. The study is unclear whether this is a bulk effect and is present across the entire crystal or whether it is limited to a specific area but it does serve as an indication that providing the relationship between the polarisation and the incident radiation can be understood it could improve the dynamic range of the Pockels detection methods although perhaps at the expense of the speed of response.

2.9 Temperature

When a charge carrier becomes trapped the time taken for its re-emission is largely dominated by thermal emission therefore as the temperature reduces the likelihood of there being sufficient photo-excitation to release a carrier also decreases [53].

Work carried out by Prekas and Sellin investigated how the electric field in CZT varies with temperature due to polarisation, the study looked at how and why low temperatures appear to degrade the spectroscopic performance of CZT detectors with the Pockels effect being used to directly image the electric fields [3].

Initial experiments showed the mobility lifetime product reduces with temperature causing a corresponding decrease in the charge collection efficiency, this clearly degrades the spectroscopic performance as less of the charge that is formed from an event is collected and therefore the signal to noise ratio (SNR) is reduced. In order to investigate the mobility lifetime further
time of flight (TOF) experiments were carried out using an alpha source and observing how the current pulse shapes of an event varied over time for different temperatures \[2\].

The results in Figure 2.24 show that at lower temperatures after an initial fast component there is a much slower one which decays slowly down to the baseline. This is indicative of a non-uniform electric field being created as charge generated within a high field area of the detector will drift quicker and form the initial part of the signal. Charge carriers in the low field areas will have low drift velocities and therefore take significantly longer to be collected, it is likely the low temperature has also increased the chance that carriers will become trapped so the slow component of the signal will also consist of thermally released charges \[3\] \[2\].

In order to find out the exact profile of the electric field inside the material Pockels imaging was carried out over the temperature range so that it could be viewed directly.

Figure 2.24: TOF charge pulse shapes at temperatures between 200-300 K \[2\]

Figure 2.25: Electric field profiles at temperatures between 240-300 K in Yinnel crystal \[3\]
The results in Figure 2.25 show that at room temperature the electric field throughout the crystal is quite uniform however at low temperature a high electric field area under the cathode is created which increases down to a temperature of \(\sim 240\) K where there is no further change in the field strength.

It is thought that the reason for this polarisation at low temperatures is caused by the difference in work function between the electrode and the CZT increasing as the band-gap changed due to the temperature. This created a potential barrier encouraging electrons to diffuse towards the contact leaving positive holes behind [2].

The detectors and experiments in this project have all been designed and used at room temperature to encourage an ohmic electrode/crystal contact and to attempt to create as uniform initial electric field as possible.

2.10 Flood Illumination of crystal

As with all semiconductor detectors CZT crystals are sensitive to wavelengths of light which correspond to energies close to the material’s band-gap. Due to the importance of CZT as a detector material work has been done to investigate how these sub-band gap wavelengths effect the crystal and how that can impact on using the Pockels detection technique.

The change in electric field that can be created by illumination is shown in Figure 2.27A and it indicates that as the intensity of the illuminating light increases so does the field strength under the cathode [18, 52].

The work by Prekas and discussed previously in Section 2.9 showed that the electric field varies with temperature causing a similar high field section under the cathode [3]. To ensure that the illumination effect is separate the peak electric field was measured with both the 950 nm LED on and off whilst varying the temperature, the results shown in Figure 2.26 prove that the two phenomena are independent of each other [18].
Work by Burger looked at the effect of illuminating a polarised sample (via 960 nm light) with above band gap 633 nm light parallel to the field through a semitransparent gold contact (cathode). This higher energy light is absorbed by the material quite close to the surface and caused the field to remain significantly more uniform, as can be seen in Figure 2.27 [19].

The reason for this effect is thought to be due to the light releasing trapped charge in the area beneath the cathode allowing the field distribution profile to become dominated by free carriers rather than trapped space charge [19].

The characteristics of the illuminating light have a major influence over how it interacts with a material. Beams with energies lower than the band gap will be able to pass through the entire crystal whereas higher energies will be absorbed. In order to investigate this
relationship a series of studies were carried out looking at how the space charge collection varied with illumination wavelength and power \[54, 20\].

The distance light can penetrate through CZT is governed by its wavelength and as shown in its absorption profiles above band-gap light penetrates significantly less than sub-band gap which is capable of illuminating an entire crystal \[55\]. Whilst increasing the power should not affect the ability of light to penetrate further through the crystal there does appear to be a threshold power specific for each wavelength at which an observable effect on the electric field can be seen, Figure 2.28 \[20\].

![Figure 2.28: Effect of illuminating cathode with different powers of light A) 950 nm B) 630 nm C) 470 nm \[20\]](image)

...Figure 2.28: Effect of illuminating cathode with different powers of light A) 950 nm B) 630 nm C) 470 nm \[20\]

The flux of photons is dependant on the power of the illumination so potentially the threshold power corresponds to a point where the rate that incident light releases trapped charge overcomes the rate of re-trapping in a similar location.

It is thought that the energy of the illumination also determines the charge carriers released with below band-gap light acting on positive holes caught in mid-level traps and above band-gap freeing electrons in deep traps \[20\]. In CZT the mobility lifetime of holes is significantly lower than that of electrons causing the majority of trapped charge to be made up of the positive carriers. The priority therefore should be focused on releasing holes especially as using sub-band gap light avoids any complications through photo-generation of carriers.

The work that has been carried out so far suggests that it may be possible to release trapped space charge by illuminating the crystal either continuously or at regular intervals.
This could therefore prove useful for the Pockels detection technique as a build up of slow dissipating space charge reduces the ability of the detector to respond quickly to changes in incident radiation.

2.11 Bias Voltage

In semiconductor radiation detectors a voltage is applied to the detector material to create an electric field with which charge that is generated from an ionisation event is moved to the electrodes for collection and processing. The strength of the electric field \( E \) in a simple sandwich structure is governed by Equation 2.20 where \( V \) is the potential difference between the electrodes and \( D \) is the separation between them [9].

\[
E = -\frac{V}{D} \quad (2.20)
\]

The strength of this electric field determines how quickly the charge carriers move however too low a voltage means they travel relatively slowly and risk recombining before collection and too high a voltage will cause the detector material to experience an increase in leakage current leading to electrical breakdown. There is therefore an ideal voltage range each specific detector should be operated in so that the leakage current is kept to a minimum but the charge is still fully collected [9].

Whilst the Pockels detection method does not need to collect the induced charge for detection purposes the electric field is still vital for its operation and needs to remain as stable as possible and fast removal of charge carriers is essential to avoid polarisation. The leakage current however could have a relatively high value provided that it is stable i.e. not close to breakdown. Whilst the stability of the field is important the voltage also needs to correspond with where the crystal is most sensitive to changes in the electric field so that induced charge will have a detectable effect.
Prekas investigated how varying the bias voltage changes the profile of the field in a block of CZT and what the optimum voltage is when the crystal is being used for Pockels imaging.

The results showed as expected the electric field strength increasing linearly with voltage however under a positive bias the field was less uniform than under negative bias, as shown in Figure 2.29 [2].

![Figure 2.29: Electric field in a CZT sample under A) Positive voltage bias B) Negative voltage bias](image)

This is thought to be caused by a change in the behaviour of the metal-semiconductor contact due to material being slightly n-type. Whilst it is not necessary for the field to be completely uniform for the Pockels detection method it is preferred as polarisation is likely to occur during operation and steps should be taken to minimise this as much as possible [2].

In work carried out by Langley an optimum bias voltage was found for a 7x7x2 mm\(^3\) CZT crystal by generating characteristic Pockels curves (Figure 2.30) and calculating at which point the gradient is at its steepest. This value corresponds to the voltage at which the greatest change in intensity is found and should therefore be where the detector is most sensitive to changes in the field [3].
Figure 2.30: Characteristic Pockels curves for a 7x7x2 mm$^3$ CZT crystal [4]

The previous work has shown that it is possible to calculate the optimum voltage for a specific crystal by varying the applied bias and observing how the intensity changes. This technique combined with using a negative bias should give an electric field that is as uniform and as sensitive to changes in the electric field as possible.

2.12 Contact Geometries

The type of contact geometry that is used on a semiconductor detector crystal determines how the charge generated from an ionisation event is collected and has a large influence on its capabilities ranging from simple planar contacts supplying just energy deposition to multiple strips capable of providing positional data as well [9].

Work done by Nelson using the Pockels imaging technique investigated how three different simple contact geometries (Figure 2.31) affected the performance of a CZT crystal as an electro-optic detector when under neutron irradiation [21].

In order to assess which geometry would give the best sensitivity to changes in the electric field characteristic Pockels curves were generated to provide the maximum current and the 1/4 wave gradient.
Figure 2.31: Contact geometries used by Nelson A) Planar-Planar B) Strip-Planar C) Dot-Planar [21] [3]

As can be seen in Figure 2.32 the dot contact (anode) gave both the highest peak current and the steepest gradient at the 1/4 wave point and therefore will provide the largest change in light transmission as the electric field varies [21].

Figure 2.32: Characteristic Pockels curves for planar, dot and strip contacts [21]

A later experiment varied the intensity of the neutron flux and using the 1/4 wave bias for each contact measured how the current in the photo-diode varied, the results are shown in Figure 2.33 [21].

It is clear that there is a larger increase in current in the dot geometry than with the other two contacts meaning that it has an increased sensitivity to a change in the electric field. It has been suggested that the reason for this is that as the electric field is non-uniform and highest beneath the smallest contact (anode) the generated electrons are forced to converge into a smaller volume creating a larger change in the local electric field [21]. If shaping the field so that it peaks under the anode provides better performance then a ring-drift contact (Figure 2.34) could be used to focus the electrons quickly onto a small anode by the means of a series of concentric ring electrodes biased to give a steep voltage gradient.
Langley used the same contact geometries and illuminated the crystal with a 950 nm laser to confirm whether the same effect was seen when using just electromagnetic waves.

The results supported the conclusions found by Nelson and showed that the effect is not limited to irradiation by neutrons, however as can be seen in the images of the transmitted intensity through the crystal (Figure 2.35) the change in intensity is focused on the dot electrode with very little happening throughout the rest of the crystal. This means that in order to get the best sensitivity possible it will be necessary to focus the laser on a very small area [4].
The experiments by Langley were carried out by applying a negative bias to the dot contact and therefore the charge collecting in the high intensity region is likely to be positive holes.

Within this project the contacts will be planar-planar as this will provide a simpler field profile for analysis however it is worth noting that performance can likely be improved by using a dot contact providing the detecting beam can be accurately aligned.

### 2.13 Detection Laser beam

For the Pockels detection technique to work only incident radiation should cause there to be a change in the electric field and it should otherwise remain constant. This requirement needs to be considered when selecting the detection laser as the beam ideally should only have optical interactions with the medium rather than being intrinsically absorbed as the latter could cause charge to be induced or released from traps within the material. As seen in Section 2.10 light with a short wavelength is likely to be absorbed as it approaches the bandgap of the material causing ionisation and a similar effect could be found with a high power laser even when using a sub-band gap wavelength as the amount of light passing through the material is increased and hence more will be absorbed.

In order to investigate what is an appropriate laser to use work has been carried out investigating a variety of wavelengths and powers.
2.13.1 Wavelength

Langley used a monochromator to generate a variety of wavelengths in order to find what a CZT crystal is most transparent to and as the results in Figure 2.36 show the light transmission increases sharply above $\sim 840$ nm which correlates to a band-gap of $\sim 1.5$ eV [4].

![Graph showing transmission percentage of different wavelengths through a CZT crystal]

Figure 2.36: Transmission percentage of different wavelengths through a CZT crystal [4]

This confirms the relationship between the amount of light transmitted and the band gap of the material and due to CZT having a variable gap depending on its composition between 1.4–2.2 eV (564-886 nm) using lasers wavelengths $>1000$ nm should minimise the amount of absorption [4].

2.13.2 Power

As the power of the laser increases more light is likely to be absorbed as the transmission through the crystal is not 100% for any wavelength, as seen in Figure 2.36. Langley suggests that for a 2 mm sample of CZT the performance of the system increases up to the maximum output of a LDM1550 laser at 4.5 mW [4]. These results support previous findings where it was seen that the current measured by the photo-diode in a Pockels laser detector increased with the laser power (Figure 2.37) interestingly the current does not vary linearly which could be related to the sinusoidal term in Equation 2.2 [21].
Whilst it is not unexpected that if more light is input more is readout it does mean that the amplitude of the Pockels curve increases with laser power and therefore the possibility to improve the range of the system [21].

Work by Burger et al. investigated whether polarisation in CZT varied depending on how much of the crystal is illuminated. This was done by taking Pockels images under broad beam illumination and with a 1 mm$^2$ collimated beam. The results can be seen in Figure 2.38 and show that there is no sign of polarisation in the crystal when probing with the collimated beam indicating that if possible broad beam illumination the sample should be avoided [19].

Whilst the work to date has only been done for a limited range of powers and beam sizes it shows that performance improves with higher power and polarisation can be avoided with a collimated or focused beam.
Figure 2.38: CZT Pockels images using 960 nm light for A) Flood Illumination B) Collimated beam at 2 mm above anode C) Collimated beam at 5 mm above anode [19]

2.14 Cadmium Manganese Telluride

The majority of the work done so far investigating the Pockels detection technique has been carried out using CZT as the medium. This has largely been due to it being a well researched material that provides good stopping power for gamma/X-ray radiation alongside displaying the electro-optic effect. There are however a variety of materials that can potentially be used and could well provide better performance than has already been seen.

CMT is fundamentally very similar to CZT as it has a high average atomic number and its Zinc-blende lattice means it is capable of displaying the Pockels effect. The main difference is that Manganese is used instead of Zinc to adjust the band-gap and it has been found that much less of it is needed for the same change, the Mn also has a near-unity segregation coefficient with CdTe which means that it is easier to grow large uniform crystals and both of these factors combined mean it is possible to control the band-gap over a wide range with a more uniform crystal [56].

The disadvantage of CMT is that the development of production techniques has been much slower than those of CZT and as such it is difficult to find crystals with low levels of impurities [57]. One of the biggest challenges is sourcing sufficiently pure Mn is due to its chemical volatility which usually means that it is produced as MnTe and subsequently purified [58].

Papers by Shwartz [52] [59] found CZT doped with Vanadium had a dramatically increased Pockels coefficient of 900 pm/V up from 1-7 pm/V [60]. The work concludes that the increase
is due to the trapping of space charge, however, it is only observed in the doped samples.

As this could potentially improve the sensitivity of the detection technique a variety of CMT:V samples with different doping levels will be tested (CZT:V is difficult to source) to see whether the results can be replicated in a slightly different material and if there is an ideal level of Vanadium in the crystal.

2.15 Fibre-Optics

Optical fibres consist of a transparent glass or plastic core surrounded by a cladding material with a lower refractive index. The fibre acts as a wave-guide for the light as it is transmitted along the length of the core.

The size of the core determines whether a fibre is multi (MM) or single-mode (SM), Figure 2.39. A large core (~50 µm) enables incoming light with more than one transverse electromagnetic mode (TEM) to be transmitted along the fibre via total internal reflection at the core-cladding interface.

![Illustration of multimode and single-mode fibres](image)

Figure 2.39: Illustrates differences in core sizes and number of light paths between (A) Multi-mode and (B) Single-mode fibres

A specific fibre as a finite number of modes that can be guided which is determined by the core size and the wavelength of the light, Figure 2.40 illustrates some of the modes that can be guided by a typical MM fibre.
With a core size ~10 µm the fibre becomes SM and only the fundamental mode (LP_{01}) will be guided. As the light within a SM fibre does not undergo total internal reflection the attenuation and modal dispersion are significantly less making it suitable for applications where losses and noise need to be minimised [24].

### 2.15.1 Polarisation Maintaining Fibres

Polarisation maintaining (PM) fibres are a specialised type of SM fibre which use birefringence to split incident light into two distinct orthogonal components which then recombine upon exiting, this isolation removes any crosstalk between the components so that the light output from this type of fibre has the same polarisation as the input. This is done by placing stress elements either side of the core (Figure 2.41) which mechanically induce the birefringence in a well defined direction [25].

![Figure 2.41: Cross-Sections of two polarisation maintaining fibre designs (A) PANDA (B) Bow-Tie](image)

There are several types of designs, the two most common are illustrated in Figure 2.41 both operate in the same way and provide similar performance levels [24].

### 2.15.2 Fibre Coupling

So that light can be transmitted along an optical fibre it first has to be correctly coupled into one end. It is significantly easier to couple into a MM rather than a SM fibre as the bigger
core allows more flexibility with the positioning and propagation angle of the incoming light, however the equipment required to launch light into both fibre types works in a similar way [25].

For multi-mode fibres the two main considerations for coupling are that the incident light needs to be focussed to a spot size smaller than the diameter of the fibre core (y in Figure 2.42) and the $\theta$ of the light incident on the fibre must be less than the numerical aperture ($NA$) of the fibre. The $NA$ of a fibre describes the range of angles over which light can be coupled into it, irrespective of the material being coupled from [61]. $NA$ is defined in Equation 2.21 where $n =$ refractive index of the material being coupled from and $\theta =$ Maximal half-angle of light that can enter the fibre.

$$NA = n \sin \theta$$ (2.21)

To couple into a SM fibre the Gaussian mode of input laser beam (TEM$_{00}$ in Figure 2.43) needs to match the fundamental mode of the fibre. The amount the integrals of their intensity profiles overlap defines the efficiency of the coupling. To achieve this the incoming beam must be as close to Gaussian as possible and focussed on the fibre core with the exact position and direction precisely aligned [25].
To choose a suitable coupling lens Equation 2.22 is used to find the ideal focal length \( f \) for coupling into a fibre of a specific mode field diameter (MFD), \( \lambda \) is the wavelength and \( D \) the \( 1/e^2 \) diameter of the beam [61] [62].

The MFD is the diameter of a Gaussian beam at which the power intensity has dropped to \( 1/e^2 \) of the maximum power, whilst it can be applied to free-space beams it is most commonly used when describing a SM fibres characteristics [25].

\[
f = \frac{D \pi (MFD)}{4 \lambda}
\]  

(2.22)

2.15.3 Fibre Couplers and splitters

Fibre couplers are optical devices that enable the light in a fibre to be split into one or more outputs or joined with other inputs. In this project only PM couplers/splitters are used which are fabricated by fusing the cores of the fibres together which allows the beam lines to mix.

A PM coupler splits the input(s) power between the output(s) whilst keeping the polarisation the same, different branching ratios are available however for interferometry work only a 50:50 split is useful.

A PM splitter separates the incident beam into two orthogonal components which can then be measured independently at the output ports [25].
Figure 2.40: Electric field profiles of accepted linearly polarized (LP) modes in a typical MM fibre. [25]
Figure 2.43: Free-space intensity profiles from the fundamental Gaussian TEM$_{00}$ to the higher order TEM$_{33}$ [25]
Chapter 3

Experimental methods

3.1 CZT/CMT Sample Preparation

The Redlen CZT crystal was supplied polished and with one gold planar electrode and a co-planar grid. The grid was wired together to act as a planar electrode and the crystal mounted on a printed circuit board (PCB).

The CMT and the method of passivation for the freshly cut raw crystals was supplied by the Institute of Physics in the Polish Academy of Sciences, to prepare them for use they were mechanically polished with decreasing grades of $\text{Al}_2\text{O}_3$ powder (3, 0.3 and 0.05 $\mu$m) using a UNIPOL-810 Precision Lapping machine and then etched with bromine methanol (2% and 0.1% concentrations) to remove any mechanical imperfections and the surface oxide layer, 90 nm sputtered gold planar electrodes were then applied using an EMITECH K575XD Turbo sputter coater and the remaining surfaces passivated using deionised water, methanol and acetone for 30 seconds each to reduce the surface leakage current.

3.2 Electrical Characterisation

The samples current-voltage characteristics are measured using a Keithley 487 picoammeter to apply a bias voltage and record the resulting current, Figure 3.1. The crystals are connected
in series with a resistor (10 kΩ for measurements up to 500 V) so that if electrical breakdown occurs the voltage supply has sufficient time to shut off before the current input is damaged. Bias voltages up to 3 kV are applied via an Ortec 556 high voltage supply (with a 1.2 MΩ resistor), the Keithley is still used to measure the current.

![Figure 3.1: (A) IV experiment setup (B) Equivalent electric circuit](image)

The Keithley is controlled by a LABVIEW program running on a PC, this enables the voltage step size and the time between measurements parameters to be changed easily.

### 3.3 Spectroscopic Characterisation

In order to assess the response of a device to ionising radiation a series of spectroscopic measurements and analysis is carried out. A typical setup is used where the integrated current pulse from the detector (which is proportional to the amount of energy deposited) is amplified by an eV products-550 preamp and an Ortec 570 shaping amplifier using a 10 µS shaping time into a usable voltage pulse and then sent through a Canberra multichannel analyser (MCA) to produce a energy spectrum, this is illustrated in Figure 3.2.
Repeating the measurement with a range of bias voltages and recording how the full energy peak varies in the spectrum it is possible to calculate the CCE by comparing the expected peak position to the measured one. The pulse amplitudes were calibrated and used to calculate the CCE by using Equations 3.1-3.3 with an 1.87 pF charge terminator ($C_{Test}$) and a test pulse generated from a pulser output ($V_{Pulser}$) where, $ehp$ is the number of electron-hole pairs produced and $W$ is the energy required to generate an electron hole pair and $E_{Pulser}$ is the signal amplitude in Coulombs.

$$Q_{pulser} = V_{Pulser}C_{Test} \quad (3.1)$$

$$ehp = \frac{Q_{pulser}}{1.6e^{-19}} \quad (3.2)$$

$$E_{Pulser} = ehp \times W \quad (3.3)$$
The CCE will change for different energies of radiation due to the penetration depth varying causing generated carriers to travel further through the material and thereby increasing the probability of recombining or becoming trapped, therefore repeating the measurement using a variety of sources provides extra insight into the devices spectroscopic characteristics.

3.4 IR Transmission Characterisation

To determine a crystal’s IR transmission properties a Cary 5000 spectrophotometer was used to illuminate the sample with wavelengths between 200-2000 nm and the percentage of light which passes through the crystal is recorded. The wavelength range equates to photon energies of 0.62-6.20 eV, this should encompass the band-gap energy of CZT which, depending on the amount of Zinc present varies between 1.4-2.2 eV [63].

Illuminating with energies below the band-gap releases carriers caught in mid-level traps and this will be observable as changes in the transmission percentage. If precise photon energies can be identified then this could be used to depolarise a polarised crystal by illuminating it with those wavelengths.

3.5 Pockels Imaging

The Pockels imaging system shown in Figure 3.3 and described in Section 2.4.1 is used to generate pictures of how the electric field inside a birefringent material develops under various operating conditions. The set-up uses an Allied Visions Technology GUPPY F-044B NIR CCD camera, two crossed polarisers and a 980 nm narrow band pass filter combined with a series of lenses to focus and remove wavelengths generated by the 50 W white light lamp that the CZT crystal is sensitive to.

Throughout this project the CCD is set so that the image is created using a 4 second acquisition time, and as the carrier lifetimes are significantly shorter (16-160 µs for electrons
and 3-30 ns for holes), the measurement does not capture the fast component of the signal. This means that the data is not sensitive directly to the changes in electric field as the carriers drift to the electrodes but, instead, it observes a trend averaged over the acquisition time.

A common way of assessing a material's optical quality for the Pockels effect is to generate a characteristic Pockels curve by measuring the transmitted light intensity. This is done in a sandwich geometry by varying the bias applied to the crystal and recording how the transmitted intensity changes, a typical Pockels curve is shown in Figure 2.32 where a ThorLabs PDA10CS InGaAs photodiode and a ThorLabs LDM1550 1550 nm laser has been used instead of a CCD hence the y-axis being measured in amps.

The interesting characteristics of the curve are its peak amplitude and the bias at the 1/4 wave point, the former shows the maximum variation in light passed through the 2nd polariser a material can achieve which corresponds directly to the amount of birefringence. The 1/4 wave point is where the gradient of the graph is at its steepest and therefore at this bias voltage the material is at its most sensitive to changes in the electric field, the sharper the gradient the more sensitive it is.

The ideal characteristics vary depending on the intended use for example if a curve has an extremely steep gradient it will be very sensitive to changes in the electric field however it is unlikely to be able to measure large changes due to a limited range. For the purposes of this project a curve with a balance of both characteristics is preferred so as to provide reasonable sensitivity over as large a range as possible.
3.6 Crystal Illumination / Irradiation

To investigate the effects of 1550 nm laser light and 150 kVp X-rays on the field profile the Pockels Imager was set-up and either a 4.5 mW LDM1550 laser or a 3 kW Comet X-ray tube with a tungsten target (MXR-225/22) is positioned so that the beam-line is perpendicular to the detection light path, as seen in Figure 3.4.

![Figure 3.4: Laser Polarisation set-up](image)

The initial experiments described in Section 4.4 use the Yinnel CZT with an uncollimated laser and a beam size of 2.6 x 3.0 mm aligned with the centre of the crystal. In order to record the localized response to the release of charge carriers, the work in Section 4.5 predominately uses a collimated 1 x 10 mm² laser beam and an 1 x 20 mm² X-ray beam, collimation was achieved by using a Thorlabs VA100/M adjustable mechanical slit for the laser and spaced lead bricks (positioned to be 110 mm thick) for the X-rays.

So that the effect on the electric field from the laser can be tested at different locations
across the crystal the laser module and collimator are attached to a vertical translation stage enabling the Pockels Imager alignment to be maintained during the scanning. The collimated laser beam is scanned down the crystal from top to bottom in 0.50 ± 0.01 mm increments using a micrometer controlled translation stage and CCD light transmission images captured via a GUPPY F-044B NIR CCD camera using a 4 second acquisition time.

For both the X-ray and laser sources, the distance between the collimator and crystal is 5 cm and from the source to collimator 10 cm, leading to a total of 15 cm from the crystal to the source in the laser set-up and 30 cm with the X-rays due to the additional thickness of the collimator.

Whilst varying the width of the laser beam the initial power output of the laser is decreased as the collimator is widened in 0.25 mm increments to maintain a constant level of illumination (0.5 mW) on the crystal. This is monitored via an Ophir 3A-P laser sensor connected to a Nova 2 energy meter and positioned in-line with the laser with the crystal in-between.

In the experiments where the power of the laser is varied a set of neutral density filters are positioned in the beam-line before the crystal to attenuate the light.

3.7 Time Response

To investigate the time taken for the change in electric field within a CZT crystal during illumination/irradiation to return to the flat field created with only a bias applied, the Fibre-optic Laser Detector described in Section 3.8 is used with a CGR-101 Circuit Gear Oscilloscope attached to a PC so that the decay times after the crystal is illuminated by 980 nm light from a 75 mW IR LED for 20 s can be recorded and analysed. The Fibre-optic system incorporates a focused detection beam-line which is used to scan down the crystal in 0.5 mm increments measuring the decay time at each point.

To calculate the decay time a sigmoidal Boltzmann curve is fitted to the rising edge of the IR pulse, as shown in Figure 3.5A. The curve is differentiated and the width of the resulting
peak, shown in Figure 3.5B, is measured to 1.75 standard deviations. This width is selected to avoid including the knees of the sigmoidal plot which regularly depart from the raw data.

The IR LED’s turn-off time has been measured directly as 6.4 +/-0.1 ms using this technique.

![Figure 3.5: (A)Photo-diode voltage output from IR pulse with sigmoidal fit on rising edge (B) Differentiated sigmoidal fit from IR pulse rising edge](image)

3.8 Fibre-Optic Detector Designs

At the beginning of the project the systems for laser and interferometry Pockels detection methods were proof of concept bench top designs. Whilst this was sufficient for the work carried out by Langley and Della-Rocca respectively the systems have now been redesigned with the aim to make their results more repeatable and the detector itself more robust.

3.8.1 Designs

The new designs have moved the detectors away from purely free-space systems and have incorporated fibre optic components to achieve the performance improvements required.

The two designs are modular so that the basic structure can stay the same and only the fibres are swapped to transition between the two topologies. Both systems use SM15-PR-U25A-H polarisation maintaining (PM) fibres (with a 1550 nm laser module) however they will be utilised in different ways.
In the laser detection system shown in Figure 3.6, the beam is aligned so that the linearly polarised light passes along the slow axis of the PM patch cable. The fibre chuck is rotated so that the light enters the lens polarised at 45° with respect to normal. The beam becomes elliptically polarised as it passes through the crystal due to the field induced birefringence. A 1x2 PM splitter rotated so that its slow axis is perpendicular to the patch cables is then used to separate the light into its orthogonal components. Light transmitted along the slow axis comprises entirely of light that has gone under birefringence and upon splitting this can then be detected at Port 1 by an attached photo-diode.

The expected beam path outside of the fibres is given in Figure 3.7 where the RMS4X infinity corrected lens converts the divergent light from the optical fibre into parallel rays which are then focused by a MPD149-M01 parabolic mirror onto the sample. The light output from the crystal is then reflected back through another lens and into the splitter.
The interferometer system replaces the patch cable with a 1x2 coupler (DC1) and the splitter with a 2x2 coupler (DC2), the fibre chucks are rotated so that the slow axes are parallel to normal and a LCC1111T-C phase retarder is added to the reference beam arm. A simplified version of the interferometer design is shown in Figure 3.8. The couplers impart a $\frac{\pi}{2}$ phase shift on the coupled beam relative to the transmitted beam, in DC1 only beam B is coupled however both couple in DC2. The phase-shift means that it is possible to create constructive and destructive interference at the detectors (D1 and D2) and use it as an interferometer.

Figure 3.7: Free-space beam path

Figure 3.8: Fibre optic Mach-Zehnder interferometer [27]
The light leaves the laser and passes along the slow axis of the PM fibre until it reaches DC1 where it splits 50/50 with one half continuing along path A and the other undergoing a phase shift before entering path B. Beam path A then passes through the crystal where it experiences a phase-shift relative to the strength of the electric field. Beam B goes through a phase retarder which is used to correct for the differences in path length between the two beams so that constructive and destructive interference is achieved at D1 and D2. Both beams are then 50/50 coupled in DC2 so that the light at D1 is a combination of half the non-phase shifted beam A light and half the π shifted light from beam B. The light in D2 is a combination of the $\frac{\pi}{2}$ shifted light from beams A and B. In this configuration D1 experiences destructive interference and D2 constructive when there is no phase shift due to the sample, with an electric field applied to the crystal the amplitude of D1 will increase as D2 decreases in proportion field strength and subsequent shift.

The coupling from the laser to the first fibre and into and out of the retarder assembly will be done using Thorlabs FibrePorts. Using Equation 2.22 (Section 2.15) with MFD = 9.9 µm, $D = 2.6$ mm and $\lambda = 1550$ nm from the P5-1550PM-FC-2 fibre and the LDM1550 Laser module respectively the optimum value for $f = 13$ mm \[64\]. The closest FibrePort to this focal length is the PAF-X-11-PC-C.

The full schematic for the interferometry design can be seen in Figure 3.9 which shows how the fibres for the Laser Detector in Figure 3.6 (A) and (C) have been replaced by couplers and the retarder added.
Exploded design schematics and their associated sub-assemblies can be found in Appendix A.

3.8.2 Adapted Designs

During the building of the original designs it was discovered that the attenuation of the signal caused by coupling into the fibres meant that it was not possible to get a detectable signal at the photo-diodes. Due to the unavailability of a higher power laser module the system was redesigned to reduce the losses.

In order to reduce the number of times required to couple from free-space into a fibre the first one (either the P5-1550PM-FC for the Laser Detector or the PMC1550-50B coupler for the interferometer) was removed and reverted back to a free-space design. The lens assemblies (C and D in Figure 3.6) were also removed to reduce the amount of light reflected, (D) was
replaced by a Fibreport as this was measured to attenuate less, the updated designs are shown in Figure 3.10 and Figure 3.12.

Figure 3.10: Adapted laser detector concept drawing

A beam-splitter replaces the coupler in the interferometer, this imparts a larger phase shift of $\pi$ on the reflected beam so a further shift of $\frac{3\pi}{2}$ is needed to ensure that interference is measured at the diodes. As the LCC1111T-C phase retarder is limited to phase changes of less than that (Figure 3.13) the diode is mounted on a micrometer controlled XY stage and moved until a minimum is achieved, the retarder is then used for fine tuning.

Once at a minimum with one of the photo-diodes the phase retarder is used to find the maximum amplitude output. These limits correspond to complete constructive and destructive interference and can then be input into Equation 2.3 to calculate the $\phi$ at any given amplitude.

The crystals bias voltage is then turned on and the new phase shifted amplitude ($V^*$) as

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well as maximum \( V_{\text{max}}^* \) and minimum \( V_{\text{min}}^* \) are measured, a schematic of the oscilloscope traces to be analysed is shown in Figure 3.11.

![Figure 3.11: Schematic of an oscilloscope trace from a typical photo-diode output operating within the interferometer](image)

Figure 3.11: Schematic of an oscilloscope trace from a typical photo-diode output operating within the interferometer

![Figure 3.12: Adapted Interferometer detector concept drawing](image)

Figure 3.12: Adapted Interferometer detector concept drawing
Figure 3.13: Variation of LCC1111T-C phase retarder with bias voltage [28]
Chapter 4

Experimental Results

4.1 Correlation between Pockels signal and induced photocurrents in Yinnel material

A set of experiments has been carried out to investigate the current-voltage (IV) characteristics of the Yinnel CZT crystal used by Della-Rocca [6] during his initial experiments on the interferometry detection method. The crystal is 7x7x2 mm$^3$ and is mounted on a PCB via gold paste and identical 90 nm sputtered gold planar contacts. The aim of this work is to investigate the cause of the unusual phase shift response of the crystal at low fluxes discussed in Section 2.4.3.

This will be achieved by measuring the current response of the crystal with a Keithley 487 picoammeter, as seen in Section 3.2 under 50 kV irradiation at X-ray anode currents between 20-1000 µA. The CZT sample was biased at voltages of +/-500 V and positioned under a 50 kV X-ray tube, due to its sensitivity to visible light the experiments were carried out in a darkened room to minimise the effects. The incremental change in the 20-300 µA range was 20 µA and from 300-1000 µA the increment was 100 µA.

Having an insight into how the current within the crystal behaves at different fluxes should help identify whether the charge collection at lower dose rates is affecting the phase
shift response and give further details on the challenges faced when using the interferometry technique to measure changes in the electric field.

### 4.1.1 Results

Polarisation effects are predominately seen in CZT samples with Schottky contacts and as can be seen in Figure 4.1, the contacts in our sample are approximately Ohmic which should allow carriers to pass through easily and space charge to not build up as much as with blocking contacts. There is a difference however between the forward and reverse bias plots indicating that the switch in direction changes the transport properties of the electrodes. The plateau at +50 V is repeatable however it is thought to be caused by the test system rather than a feature of the crystal contacts.

![Figure 4.1: IV plot of the Yinnel CZT sample](image)

The results displayed in Figure 4.2 show how the dark current in the CZT varies over a period of 25 minutes under +/-500 V bias. There are clearly two different profiles depending on whether a positive or negative bias is applied to the top electrode. Under +500 V the dark current decreases quickly for the first 2 minutes by approximately 0.2 µA (absolute current) and then remains fairly stable from then on. The current with -500 V bias appears to behave slightly differently, there is a small initial increase in absolute current in the first 2 minutes but it is an order of magnitude lower (around 0.02 µA) and then it stabilises completely.
As the majority of the measurements carried out by Della-Rocca used a positive bias it is possible that a contributing factor to the noise seen on the results originated from not leaving sufficient time for the dark current to stabilise.

![Figure 4.2: Dark current of CZT sample under +/-500 V bias](image)

The remaining measurements were carried out under a varying X-ray flux with both positive and negative bias conditions. The results in Figure 4.3 display how the current in the CZT under a +500 V bias varies as the X-ray tube is turned on. The initial starting current varies slightly throughout these measurements as the crystal took time to discharge, as such the results have been normalised to zero by subtracting the dark current before the X-rays are turned on so that a direct comparison can be made between the positive and negative polarities. The segmented appearance of the plots on Figure 4.3 and Figure 4.4 is caused by a relatively low sample rate of 3 s has being used.

As expected the current increases with the flux due to an increase in energy being deposited in the crystal and the created charge subsequently being collected. In all of the traces above 60 µA there is an initial sharp increase in current as the tube is activated and then a gradual settling for around 10 seconds as it stabilises.

A possible reason for the starting current varying as the experiment progresses is the CZT
Figure 4.3: Photo-current in the CZT crystal under +500 V bias with a variety of 50 kVp x-ray fluxes. 

Crystal becoming polarized as a build-up of space charge is being formed. Previous work by Wang et al. [65] showed that as the X-ray flux incident on the detector increased so did the amount of space charge and the work by Matz [66] described a phenomenon called afterglow where the space charge trapped in deep traps slowly decays away via the leakage current after the bias and the radiation source is deactivated. There are several trapping levels between 0.0-1.0 eV in CZT which have been studied in depth via photo-induced current transient spectroscopy (PICTS).

The results at negative bias of -500 V are shown in Figure 4.4. Under this polarity the starting current remained stable throughout the experiment indicating that the slow decay seen under positive bias does not occur when it is negative. It is therefore likely that the afterglow current is dominated by one type of charge carrier and as the hole mobility is significantly worse in CZT than the electrons [51] it is likely to be the cause.

The results in Figures 4.5 and 4.6 show the average photo-current produced under a variety
of different X-ray fluxes, this has been calculated using data gathered after 20 seconds so that the initial step change from the X-ray generator is not included.

Under a -500 V bias the relationship between the flux and the photo-current is quite linear as can be seen in Figure 4.5, this indicates that under these conditions the crystal is behaving as expected where a higher amount of energy being deposited in the material results in a linearly proportional increase in the charge carriers created and then collected as current.

The results in Figure 4.6 where a +500 V bias is used show the relationship has become more sigmoidal with the current starting to plateau beyond 800 µA.

These characteristics could go some way to explain some of the results that Della-Rocca saw in his experiments as there are similarities in plot shape between these results and those shown in Figure 2.8 where there is a similar low response at lower X-ray tube currents. The higher current plateauing however is not seen in the interferometry results indicating that whilst the photo-current is beginning to saturate it is still possible to detect changes in the field. As both should ideally be linear and such a response was achieved under reverse bias it
is possible that the shape was actually caused by applying a +500 V bias and thus impacted by the contacts different charge transport properties and that if operated with a reverse bias a more linear response will be generated.

Figure 4.6: Average photocurrent of CZT sample under +500 V bias

4.1.2 Conclusions

The results show that the crystal behaves differently depending on whether a forward or reverse bias is applied. The IV plot shows a more Schottky relationship under forward thereby
increasing the likelihood of polarisation and as the literature supports the idea that there is a build-up of positive space charge which can take a significant time to dissipate through the afterglow effect. This is likely to be one of the main reasons for the observed discrepancy seen previously in the interferometry experiments by Lohstroh at low X-ray fluxes. Fortunately the IV results with a negative bias are more stable so future work will be done under these conditions to improve the system response.

4.2 Characterisation of CMT with varying V doping

To test whether the amount of Vanadium doping within a CMT crystal has a detectable affect on the electro-optic characteristics, in particular the Pockels constant five crystals (Table 4.1) with a variety of V content were sourced from crystal growers at the Institute of Physics of the Polish Academy of Sciences and prepared using the method described in Section 3.1. Nominally the samples are cut along the (1,1,1) Miller indices which enables \( r_{41} \) to be calculated via the Pockels curve and Equation 2.2 however as X-ray diffraction measurements have not been carried out this has not been independently verified.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Annealed</th>
<th>Nominal Vanadium content (cm(^{-3}))</th>
<th>Nominal Manganese Content (%)</th>
<th>Dimensions (mm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>5x10(^{13})</td>
<td>5</td>
<td>9.50x9.75x2.90</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>5x10(^{13})</td>
<td>5</td>
<td>9.50x9.75x2.90</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>1x10(^{12})</td>
<td>5</td>
<td>9.50x9.75x2.90</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>5x10(^{15})</td>
<td>5</td>
<td>9.50x9.75x2.90</td>
</tr>
<tr>
<td>5</td>
<td>Yes</td>
<td>2x10(^{17})</td>
<td>5</td>
<td>9.50x9.75x2.90</td>
</tr>
</tbody>
</table>

Table 4.1: CMT Samples supplied by Institute of Physics of the Polish Academy of Sciences

After processing only Sample 2 was suitable for use as the others suffered from low resistance (in the order of k\(\Omega\)) in hence high levels of leakage current, likely due to a combination of the differing levels of doping / whether an anneal took place and surface defects left by the manual polishing process.

Despite only having one usable crystal it was still passed through a series of characterisation tests starting with an IV profile and then measuring the electro-optic response to varying bias voltage and laser illumination.
4.2.1 Current-Voltage

The CMT crystal displays Schottky behaviour as can be seen from the IV plot shown in Figure 4.7. Due to the measurement equipment (Keithley picoammeter) being limited to +/- 500 V the positive electrical breakdown point is not shown however based upon where the HV supply used in the later tests overloaded it is at approximately 800 V. Calculating the resistivity from the IV gives a value of $2.7 \pm 0.2 \times 10^8 \ \Omega\text{-cm}$ which is similar to that found in literature ($10^8 - 10^9 \ \Omega\text{-cm}$) [57], this value is calculated from the positive linear portion of the plot between 0-500 V.

![Figure 4.7: CMT Current-Voltage plot](image)

4.2.2 Pockels Curve

The Pockels images in Figure 4.8 show that the crystal exhibits the Pockels effect when either a positive or negative bias voltage is applied to it. The transmission intensity distribution however is clearly not uniform which is likely due to trapping sites within the crystals bulk,
the relatively uniform image in Figure 4.9 shows that whilst the surface of the crystal is not completely smooth there is no evidence of the non-uniformity seen in Figure 4.8 which suggests that it is not contributing to the appearance of the high intensity "fringes" via surface defects or leakage. The image in Figure 4.9 shows that there is some stress induced birefringence occurring which appears to be in a similar location to the Pockels induced fringes which suggests that the two could be related, potentially by higher concentrations of dopants in those areas causing trapping.

Figure 4.8: CCD camera Pockels transmission images under: A) -500 V Bias B) +500 V Bias. Red and green rectangles indicate the areas used to measure the differences in Pockels constant between areas of low and high light transmission

Figure 4.9: CCD camera Pockels transmission images with A) Parallel Polarisers and 0 V Bias B) Crossed Polarisers and 0 V Bias
The exact location of the fringes is dependent on whether the bias voltage is negative or positive and as can be seen in varying of the magnitude of the bias between Figure 4.8 and Figure 4.10 the areas of high intensity get larger as the bias increases.

Figure 4.10: Pockels transmission images under: A) -300 V Bias B) +300 V Bias

The crystal’s response to 1550 nm laser illumination can be seen in Figure 4.11, 4.12, 4.13 and 4.14, it shows that the electric field for both polarities does appear to change slightly once free carriers are introduced. Despite the lack of uniformity the intensity in Figure 4.14 do not appear to show any large increase in intensity under the electrodes and there is an increase across at least half of the crystals bulk which indicates either the more prominent structural features mask the kind of polarisation seen in the Yinnel CZT crystal or that it may simply be less prevalent in CMT:V.
Figure 4.11: Effect of 1550 nm laser irradiation on CMT crystals under +500 V bias, averaged across width of crystal

Figure 4.12: Effect of 1550 nm laser irradiation on CMT crystals under +500 V bias, averaged across height of crystal
Figure 4.13: Effect of 1550 nm laser irradiation on CMT crystals under -500 V bias, averaged across width of crystal

Figure 4.14: Effect of 1550 nm laser irradiation on CMT crystals under -500 V bias, averaged across height of crystal
In order to get an estimation of the Pockels constant \((r_{41})\) the average transmission intensity across the crystal was measured as a function of bias voltage, the results can be seen in Figure 4.15 and Figure 4.16. The curves give \(V_{\pi/4} = 289 \pm 5 \) V and \(V_{\pi/4} = 297 \pm 12 \) V respectively which in turn means \(r_{41} = 13.6 \pm 0.2 \times 10^{-12} \) m/V and \(r_{41} = 13.2 \pm 0.2 \times 10^{-12} \) m/V according to Equation 4.1 (Section 4.3), where \(d = 2.90 \pm 0.05 \) mm, \(\lambda_0 = 980 \) nm, \(n_0 = 2.8\), \(l = 9.50 \pm 0.05 \) mm.

\[
V_{\pi/4} = \frac{\lambda_0 d}{2\sqrt{3}n_0^3 r_{41} l}
\]  

(4.1)

Figure 4.15: Negative Bias CMT Pockels Curve
The refractive index used ($n_0=2.8$) is estimated from [67], however a direct comparison may not be valid as the quoted value is measured at a temperature of 4 K and as the refractive index of a material is expected to increase with temperature [68] the real value of $n_0$ for this sample could be higher meaning the Pockels constant would be lower however these results are higher than the 3.5 +/- 0.2 pm/V found in literature [69].

As the crystal does not have uniform intensity Pockels curves were generated from the bright and dark areas, as indicated in Figure 4.8. The results are shown in Figure 4.17 and Figure 4.18 for negative bias, the highest intensity areas of the crystal have $r_{41}=16.3 +/- 0.2$ pm/V and at the lowest intensity $r_{41}=11.7 +/- 0.2$ pm/V. Several of the points in Figure 4.18 were excluded so that the $sin^2$ fit could still be used.
Figure 4.17: Negative bias CMT Pockels curve measured over high intensity area of crystal

Figure 4.18: Negative bias CMT Pockels curve measured over low intensity area of crystal
4.2.3 Conclusions

Despite the estimated values for the Pockels constant varying between 11.7 - 16.3 +/-0.2 pm/V all of the predictions are higher than the 8.4 +/- 0.6 pm/V measured in the Yinnel CZT sample and in the literature values of un-doped CMT. Therefore although the value is significantly lower than the results shown by Shwartz [52] where CZT was doped, there is still an increase which supports the hypothesis that vanadium doping could improve these materials for use in Pockels detection techniques. The difference in Pockels constant between the bright and dark areas also supports the conclusions from Shwartz where the extremely high values were attributed to trapped space charge changing the crystals cubic symmetry. It is unlikely that this would be uniformly distributed throughout the crystal and would instead be focused around any impurities and potentially the cathode, creating the fringes pattern seen in our work.

4.3 Characterisation of Redlen CZT Crystal to ensure suitability for use in Pockels experiments

The Yinnel CZT crystal that has been used previously by Langley and Della-Rocca for their Pockels experiments and in Sections 4.1 and 4.4 has been replaced by two 1 cm$^3$ CZT samples made by Redlen (Figure 4.19).

Figure 4.19: Redlen CZT crystal
As opposed to the Yinnel CZT the Redlen crystals are still readily available and have reportedly higher purity than the Yinnel samples, the larger size also means that the Laser Scanning experiments described in Section 3.6 more data-points can be collected between the electrodes so that the scans can identify changes within the electric field easily and at a higher level of detail [70].

Prior to the crystal being used it is characterised to ensure that it behaves as expected and to choose the appropriate operating conditions to use. The samples electrical, optic and spectroscopic properties are examined by the methods explained in Section 3. Nominally the samples are cut along the (1,1,1) Miller indices which enables $r_{41}$ to be calculated via the Pockels curve and Equation 2.2 however as X-ray diffraction measurements have not been carried out this has not been independently verified.

### 4.3.1 Current-Voltage Characteristics

In contrast to the symmetrical Yinnel it is unknown what type of electrical properties the contacts on the Redlen have, the dark current measurement for the crystals in Figure 4.20 show that overall the contacts appear non-symmetric and from 0-(-)3 kV there is a linear ohmic relationship and under the larger positive biases it begins to breakdown for both crystals. It is possible that both of the contacts are Schottky and the breakdown voltage under negative bias is greater than 3 kV. Between +/- 2 kV the IV behaviour for both crystals is approximately ohmic as predicted in Section 2.6.2 due to the similar energy gaps for gold and CZT. Therefore to remain in the ohmic behaviour region and to comply with the results found in the Yinnel crystal in Section 4.1 a maximum bias of -2 kV will used, this should enable the non-linearity seen in the Yinnel IV’s to be avoided.
4.3.2 Gamma Spectroscopy

A series of gamma spectroscopy measurements were taken to develop an understanding of how the Redlen crystals behave when irradiated. This was done with a variety of sources to see how the results changed for different energies. It can be seen in Figure 4.21 (a) that the crystal is capable of resolving the full energy peaks for low energy photons such as the Ba-133 30 keV X-ray and 80 keV gamma however at higher energies it struggles due to the sandwich structure. Figure 4.21 (b) shows that there is a lot of low energy tailing when using a Co-57 120 keV gamma and the Ba-133 356 keV gamma in Figure 4.21 (c) cannot be seen at all and instead is replaced by a high energy tail. These limitations would most likely be overcome if operated as a co-planar grid however this would create a more complex electric field which will complicate the Pockels analysis [70].
Figure 4.21: Example Redlen crystal spectra in Crystal B for: (a) Ba-133 (X-ray and Gamma), (b) Co-57 (Gamma), (c) Ba-133 (Gamma)

This is not a completely unexpected result when using the detector in a sandwich planar geometry as due to the crystal being very large the distance the holes have to travel is much longer when the photon energy is higher as it is more penetrative and can create e-h pairs further away from the cathode leading to a higher likelihood that they will be trapped before they can be collected and contribute to the current pulse.

This is supported by the CCE plot in Figure 4.22 which shows that as the energy increases less of the ionised charge is collected. The plot also shows that the efficiency seems to plateau from 200 V suggesting that at this point the mean free path of the majority of charge carriers is sufficient to avoid becoming trapped provided they are created in close proximity to the cathode. The measured CCE results from the Redlen crystal B gives $\mu\tau_e$ values of $(16.4 \pm 4.1) \times 10^{-3} cm^2 V^{-1}$ and $(15.2 \pm 4.3) \times 10^{-3} cm^2 V^{-1}$ when measured using the Ba-133 80 keV peak and the Co-57 122 keV peak respectively, these are very similar to the
$22 \times 10^{-3} + / - 6 cm^2/V$ claimed by Redlen with in their 1 cm$^3$ crystals [71]. The measurements were repeated using the 30 keV gamma and with crystal A however the signals were too noisy to evaluate, especially when using the higher gain at the lower energy.

Errors on the $\mu \tau_e$ values have been calculated based on the FWHM of the peaks as in some cases they were quite broad ($\approx 20$ keV).

Figure 4.22: CCE of Redlen crystal B use 80 and 122 keV gamma rays

4.3.3 Pockels Curve

The Pockels curve for the Redlen crystals (Figure 4.23 and Figure 4.24) shows that by fitting a $sin^2$ function the highest measured gradient ($V_{\pi/4}$) for Crystal A can be found at $-1.600 +/- 0.004$ kV and $-2.000 +/- 0.016$ kV for Crystal B, however as the entire sinusoidal curve could not be produced due to the limitations on the bias that can be applied by the equipment this is still an estimation.
Using Equation 4.1 (Section 4.2) to calculate the Pockels constant \( r_{41} \) with \( d=10.00 \pm 0.05 \) mm, \( \lambda_0=980 \) nm, \( n_0=2.8 \), \( l=10.00 \pm 0.05 \) mm gives \( r_{41}=7.84 \pm 0.39 \) pm/V and \( r_{41}=6.210 \pm 0.031 \) pm/V for Crystals A and B respectively. These values are similar to the 8.4 \( \pm 0.6 \) pm/V found in the Yinnel sample and the 5.5 pm/V in work done by Cola [38].
4.3.4 IR Transmission

Using the Cary 5000 spectrophotometer the crystals IR transmission characteristics were captured. The results in Figure 4.25 show that the transmission increases rapidly beyond 840 +/-1 nm due to the energy of the photons being below the band gap of the material. Converting this to energy with the Planck–Einstein relation shows that the threshold corresponds to a band gap of 1.48 +/-1 eV which is within the expected range for CZT [29].

Below 1.48 eV the transmission line does not have a sharp cut-off indicating that the sample does have some trapping sites which can be released at lower energies however there are no obvious sudden changes on transmission to indicate a large density of the same energy of site.

![Graph showing IR transmission characteristics](image)

Figure 4.25: Redlen crystals IR transmission characteristics as a function of wavelength

4.3.5 Conclusions

The characterisation work shows that the crystals whilst not suitable for spectroscopic work in a planar-planar configurations due to their size appear to be sufficiently electrically stable
to allow Pockels measurements to be taken.

The contacts appear to be non-symmetric with a Schottky relationship present under forward biasing and ohmic when reversed, between +/-2 kV both polarities are fairly linear and when this combined with the location of the quarter wave point means that the most appropriate bias voltage with these crystals is -2 kV as this minimises the risk of variable leakage current and it is approximately where the Pockels curve gradient is at its steepest.

4.4 Laser Polarisation

In the work by Langley [4] a Yinnel CZT crystal was imaged with 980 nm light from a lamp whose intensity had been adjusted to reduce polarisation. The LDM1550 laser however outputs light of significantly higher intensity so to investigate whether it causes an observable effect on the electric field Pockels images were taken whilst the crystal was also illuminated by the laser light, as described in Section 3.6.

The CCD image in Figure 4.26 and the corresponding intensity plot in Figure 4.27 show that prior to laser illumination the field, excluding deformities at the edges (which are similar to those observed by Yang et al), is quite uniform [72].

Under illumination from the 1550 nm laser the crystal becomes polarised, as displayed by
the dashed plots in Figure 4.27, which is likely caused by the freeing of trapped space charge which is then re-trapped around the cathode as suggested by Washington [13].

Figure 4.27: Pockels image intensity in CZT crystal with (a) the IR laser on (dashed line) and off (solid line) at +500 V (grey) and -500 V (black) bias (b) a range of sample heights that enable the CZT to be scanned in increments of 0.2 mm, with the laser collimated to a 0.1 mm narrow beam [7]

Repeating the experiment with a 0.1 mm collimated beam scanned vertically up the crystal in 0.2 mm increments, Figure 4.27 shows that to a lesser extent the polarization still builds up.

It is interesting to note that the location of the peak intensity stays roughly in the same place irrespective of which part of the crystal is being illuminated. This indicates that instead of measuring the effect of charge on the electric field as it is generated locally around the beam the majority of the change in intensity comes from the polarization beneath the cathode which may contain a time integrated charge element meaning that the measured intensity may not correlate directly to the rate of charge generation. There is however variation in the peak shape as the beam intensity increases due to the collimation which is likely caused by the
increased numbers of released carriers increasing the polarisation.

4.4.1 Conclusions

The experiments show that the 1550 nm laser causes polarisation within the CZT sample and the level of this appears to vary with the power of the laser beam as the difference in profile plot shapes when illuminating with full beam compared to collimated gives sharper intensity peaks under the cathode. As seen in the CMT results where the "fringes" are likely caused by space charge build up around impurities these results also indicate that polarisation is potentially generating the majority of changes within the Yinnels electric field rather than the local variations from charge generation.

4.5 Crystal scanning

4.5.1 Laser Illumination

The results in Section 4.4 showed that at least part of the detected Pockels signal is caused by trapped space charge within the crystal, away from the location of the released/generated carriers.

To investigate whether a local effect is present within the detected signal the sensitivity to varying the width and power output of an 1550 nm laser and an 150 kV X-ray generator is measured.

The crystals are imaged using the CCD camera and beam line set-up described in Section 3.6 which creates an image of how the electric field changes under a variety of illumination and irradiation conditions.

It can be seen in Figure 4.28A and B that there is little light transmitted through the crystal at 0.00 V bias and a fairly uniform field under 2.00 kV bias which indicates that the level of stress induced birefringence caused by any defects is minimal [73].
Figure 4.28: Raw Pockels images of 1 cm³ Redlen CZT crystal under (A) 0.00 V bias, (B) -2.00 kV bias without laser illumination, (C) -2.00 kV bias with full beam laser illumination.

The profile plots seen in Figure 4.29 are generated by subtracting one image with only the bias voltage applied (Figure 4.28B) from one with the bias and the laser (e.g. Figure 4.28C) activated. This is done to counteract any non-uniformity present in the birefringence due to crystal geometry, defects etc. The results show that a localized effect is detectable. As the laser is scanned down the crystal there is a clear change in transmitted light intensity where the laser beam releases the carriers.
Figure 4.29: (A) Local changes in electric field profiles within a CZT crystal under -2.00 kV bias caused by illuminating with a collimated 1550 nm laser beam at a variety of different beam positions in respect to the top electrode. (B) CCD light transmission image with laser at 2.0 mm. (C) Laser at 6.0 mm. (D) Laser at 9.0 mm distance from the cathode.

The results in Figure 4.30 show that as the collimated beam widens the FWHM of the transmitted light distribution increases, excluding the data point at 0.5 mm which is caused by Fraunhofer diffraction through the collimator thereby giving an effective beam width of \(~1.5\) mm [74]. The same relationship is seen when measured at different points throughout the crystal. A linear fit with 95% confidence bounds is displayed in Figure 4.30, which encapsulates all the data points within 1 standard deviation.
Figure 4.30: Variation in FWHM of intensity dip with increasing collimator width at different beam positions in the crystal under -2 kV bias, error bars are calculated from the Gaussian fits of the "peaks".

This combined with the results in Figure 4.31, where a linear relationship between the power of the laser and the peak light intensity is shown, means that any detected signal will contain a localised effect and hence will be sensitive to changes in the radiation/illumination beam intensity and position. The outlier highlighted in the FWHM plot is attributed to the low power of the laser, causing the intensity dip to be very close to the noise floor. This meant that while an absolute intensity could be estimated, the peak was not symmetrical, so a Gaussian fit and hence the FWHM measurement was very sensitive to the choice of fit region causing the result to become distorted. It is expected that if the peak could have been
resolved accurately, the FWHM value would have been similar to those at higher powers. In addition the error bars on that point are also too small as it is calculated via the Gaussian fit; uncertainties of approximately +/- 0.5 mm are more realistic for this data point.

\[
y = a + bx
\]

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<tr>
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Figure 4.31: Variation in the amplitude of the peak in electric field strength (measured at 4.5 mm from cathode) when increasing laser power (red) under -2.00 kV bias, the FWHM remains approximately constant (blue) with the error calculated via the standard deviation.

4.5.2 X-ray Irradiation

As the Pockels detection technique is intended to be used with ionizing radiation parts of the experiment are repeated using a X-ray beam. Irradiating the entire CZT crystal with 150 kVp X-rays at 5 mA generates a build-up of space charge beneath the cathode under both bias directions (Figure 4.32). This supports the laser results which suggest polarisation forms part of the detected signal. The fringes of high and low light transmission at the cathode are likely caused by a large electric field in the area. As seen in Equation 2.2 the transmitted light has a sinusoidal relationship with the field strength which can potentially create this oscillating wave pattern as the field gets stronger nearer the cathode.
Figure 4.32: (A) Transmitted light intensity profiles under entire crystal X-ray irradiation with cathode at the top and bottom of the crystal. (B) CCD light transmission image with -2.00 kV applied to the top electrode. (C) CCD light transmission image with -1.75 kV applied to the bottom electrode.

To confirm that the local effects from the charge carriers released using the IR laser also occur with X-ray generated free charge carriers, a 1 mm collimated X-ray source is used to irradiate the crystal. The beam is positioned at the 5 mm point and varied over a range of X-ray tube currents.

Unlike when using the collimated laser, the crystals electric field is changed significantly
at locations where the collimated X-ray beam is not intended to be interacting which creates a CCD image similar to that shown in Figure 4.33C where the bottom half of the crystal displays lower light transmission and the top shows higher due to the building up of space charge. This is likely due to X-rays scattering off the lead collimator and managing to reach the crystal by another route, hence generating charge carriers throughout the CZT. It is possible to analyse this type of image by removing a variable baseline generated by tracing the 0.1 mA profile along with the 2.00 kV background image to isolate the area around the incident X-rays and to enable fitting a Gaussian distribution, as seen in Figure 4.33A and B.

![Figure 4.33: (A) Light transmission profile under 1.0 mA, 150 kV X-ray irradiation at 5 mm below cathode, baseline to be used is shown in red. (B) Resulting Gaussian peak from baseline subtraction. (C) CCD image of crystal under irradiation with baseline overlaid.](image)

However, clearer images are achieved if an image under bias and a low X-ray flux is subtracted (images with an X-ray tube current of 0.2 mA are used) as this reduces the
scattering effects and enables the location of the collimated X-ray beam to be identified easily, an example of this is seen in Figure 4.34. A light transmission profile such as in Figure 4.34B can then be generated by averaging the images along 3.5 mm of the Y-axis (corresponding to the 1/e intensity drop = 3.55 mm of the 150 kV X-rays, based on a linear attenuation coefficient = 4.852x10^{-1} cm^2/g and a CZT density = 5.8 g/cm^3 [8]).

Figure 4.34: (A) CCD image of crystal under irradiation at an X-ray tube current of 0.6 mA with 0.2 mA image subtracted (area between red and green markers is the section analysed) (B) Resulting light transmission profile

The FWHM and maximum intensity can then be calculated to create Figure 4.35 which demonstrates that the peak height initially increases as expected with the current up to 1 mA creating the linear plot shown in Figure 4.35. However, as can be seen in the inset of Figure 4.35, the intensity plateaus beyond 1 mA.
Figure 4.35: Main: Variation in the depth of intensity dip (measured at 5 mm from cathode) with increasing X-ray tube current up to 1 mA (red) under -2.00 kV bias, the FWHM remains almost constant (blue). Inset: Same data expanded up to 10 mA.

The profiles in Figure 4.36 are generated by subtracting a biased image without X-ray irradiation from an irradiated one show that beyond 1.0 mA, parts of the plots reach the same level as the 0.00 V background profile (the -2.00 kV bias with no X-rays has been subtracted which makes the 0.00 V profile displayed non-uniform) indicating that the electric field has completely collapsed in these areas leading to the peak height becoming artificially limited and departing from the linear fit.
Figure 4.36: Transmitted light intensity profiles at various X-ray tube currents at -2.00 kV bias and with a 0.00 V bias background profile, all plots have the -2.00 kV bias with no X-rays profile subtracted.

The X-ray and laser data sets show that it is possible to differentiate between the effect on the electric field of charge carriers generated locally to the position of the incident beam and those accumulated near the cathode. Being able to distinguish between the two means that the detection beam can be directed so that it passes through the crystal in such a way that only the local effect is measured.

The areas of high field beneath the cathode have been attributed to polarisation or trapped space charge which will contain a time integrated element making it proportional to the dose incident on the crystal. The local field changes however are more likely to be closely associated with the instantaneous changes generated by the creation/release of carriers which would potentially give a more accurate representation of the incident dose rate if it could be isolated and measured.
4.5.3 Conclusions

The results show that the signal measured via the Pockels detection technique is likely to be a combination of both local carriers, near the location of the incident beam and polarisation under the cathode influencing the electric field. Both effects have been measured under IR laser illumination, where the carriers are released from traps, and from ionizing X-ray irradiation, where the carriers are generated via electron-hole pairs.

Due to the ability to differentiate between the two effects based on their location, effort should be taken when using this detection technique to focus the detection beam away from the cathode. If this is done then the majority of the detected signal should arise from the localised changes which are more likely to provide an accurate measurement of the dose rate.

It should be remembered that it is potentially possible to widen the dynamic range (in one direction) by moving the bias voltage away from the quarter wave point therefore the saturation limits found in this work are not fundamental and are rather caused by the camera/bias applied.

4.6 Pockels Signal Decay Time Results

4.6.1 Results

The results in Section 4.5 showed that the distortion of the electric field within a CZT crystal is caused by charge carriers generated in close proximity to the incident beam and by trapped space charge beneath the cathode. This polarisation contains a dose element as it builds up over time which could potentially take a long time relative to the carriers created locally to respond to changes in the dose rate.

To investigate whether there is a detectable difference in response time between the two areas the experiment described in Section 3.7 is set-up which enables the time taken to recover from an IR pulse to be measured at different points within the crystal.
The errors on the focussed beam decay time points are variable and some habe not been calculated due to there being only one successful measurement at that point. This is due to the CGR-101 oscilloscope having a 1 s dead time between each 1.5 s reading which causes any IR pulse edges that occur within that to not be detected. The time limit of the system is dependant on the turn-off time of the IR LED which has been measured as 6.4 ms by directly illuminating the diode.

The red data-points on both Figure 4.39 and Figure 4.37 correspond to where the response from the IR diode goes negative at LED turn on rather than positive, this occurs in close proximity to the cathode and matches approximately with the "fringes" seen in Figure 4.38.

Figure 4.37: Pockels signal amplitude after a 980 nm IR pulse, measured at different points across the CZT crystal. Red markers indicate responses which have flipped their polarity.

The extracted amplitudes to the IR pulse in Figure 4.38 show a larger response around the cathode which matches previous results with polarised crystals.
The results in Figure 4.39 show that there is no detectable difference in decay time at any position throughout the crystal and in comparison to the decay time when using an unfocused broad beam which illuminates the majority of the crystal, all results are within 10 ms.
4.6.2 Conclusions

The results from measuring the decay time at different points of the crystal show that despite the trapped space charge being present and observable as shown by the pulse amplitude plots and inverted responses near the "fringes" there is no detectable systematic difference in the electric fields recovery time with all areas returning to baseline level between 5-20 ms.

As the 6.4 ms turn-off time for the IR LED is within this range it is likely that this is the limiting factor and the electric field can respond quicker however within these experimental constraints there is no difference in time response between areas of largely locally produced charged carriers and those dominated by polarisation.

4.7 Fibre-Optic Interferometer Testing

In order to test the new interferometer design functions as expected the response to varying the bias voltage on a Redlen CZT crystal within the test beam line (Beam Line A in Figure 3.8) is measured. The phase retarder is used to find the sensitive quarter wave point and once the bias voltage is applied changes in the diodes output can then be measured and converted to a phase shift using Equation 2.3 (Section 2.4.3).

4.7.1 Results

To test whether focussing the detection beam has reduced its impact on the electric field a Pockels image is taken and compared with one of the collimated beam images from Section 4.5.1. The results in Figure 4.40 show that the focused beam, as expected, has a slightly smaller width. There is also less change in the field below the beam towards the anode which is likely due to the focussed light being better controlled and not experiencing reflections or diffraction from the collimator.
The results in Figure 4.41 show that there does not seem to be a detectable change in phase using this interferometer design and it isn’t possible to reproduce those seen by Della-Rocca [6].

Figure 4.41: Measured phase shift in a Redlen CZT crystal when varying the applied bias voltage
However, the outputs from the photo-diodes did change as the bias was varied and as can be seen in Figure 4.42 where the crystal is also moved vertically so that the beam passes through it at different distances from the top electrode, the system does respond to changes in the electric field within the crystal.
Figure 4.42: Combined photo-diode responses for varying biases at (A) 1 mm from the top cathode, (B) 3 mm, (C) 5 mm, (D) 7 mm and (E) 9 mm

As the plots show the response across the crystal is different, around the cathode area and close to the anode the output drops approximately sinusoidally after an initial increase and
in the middle of the crystal (Figure 4.42 C and D) where the output increases quite linearly. When varying the bias and measuring the response with the basic Laser Detection topology a Pockels Curve is produced which is sinusoidal in nature, it is possible that the results here are caused by the same relationship.

It is likely a combination of things that cause the interferometer to not detect changes in phase shift despite being sensitive to variations in the electric field. The main issue is down to the increased difficulty in finding the interference limits due to the inclusion of the micrometer stage as this makes it very easy to misalign the beam line with the FibrePort resulting in focussing on a local minima rather than the destructive limit.

This combined with the precise alignment required when using PM fibres and the beam line direction changing slightly with the refractive index of the crystal (if it’s not perfectly perpendicular) makes accuretly measuring the limits extremely challenging.

Despite not being able to demonstrate that the interferometer is sensitive to variations in phase shift it still responds to changes in E-field, the plot in Figure 4.43 shows that when the crystal is illuminated by a 980 nm LED at incrementing powers there is an increase in diode response height.
To improve the performance of the design the initial focus should be on getting a stronger signal using all of the fibre components so that the free-space beam splitter can be replaced and hence ease the process of finding the maxima and minima. To do this a higher power laser should be used, a 35 mW NP Photonics RFLS-50 has been used successfully by Macdonald for a similar application and their work found that laser module with line-width <3 kHz provided best results [75]. Other relatively simple adjustments such as reflecting the beam line back through the crystal to multiply the phase shift and using more sensitive photo-diodes should help. The work by Macdonald also demonstrated that if a 3x3 combiner with a 120° phase difference between the three arms is used instead of the 2x2 combiner then it is guaranteed that there is at least one detector in a high response region and then by using the triature analysis approach described by Dolan the change in refractive index can be extracted [76]. A more drastic change of approach would be to remove all free-space elements and replace the standalone CZT crystal with an in-fibre component thus avoiding all complications from coupling in and out of fibres.

Figure 4.43: Combined photo-diode output to illumination from a 980 nm IR LED
4.7.2 Conclusions

The results from the testing of the fibre interferometer show that whilst the focussed beam-line has improved the impact of the laser on the electric field, there are several limitations to the design that cause it not to function exactly as expected. The largest challenge is due to the free-space elements and the need to repeatedly couple in and out of the fibres, it is likely results could be improved by increasing the signal strength or using more complex optical fibres such as a 3x3 combiner or having the detection medium (CZT or some other suitable material) embedded within the fibre.
Chapter 5

Conclusions

5.1 Conclusions

The work carried out prior to this project showed that when a biased birefringent semiconductor device is irradiated the subsequent distortion of the electric field and change in refractive index via the Pockels effect can provide information on the incident radiation dose rate [5] [15] [21].

The largest change in the electric field throughout the previous work is consistently found beneath the cathode which is caused by a build up of positive space charge becoming trapped in acceptor sites making the crystal polarised [17] [29] [3]. As polarisation builds up over time a component of the detected change in the electric field from the affected areas will be proportional to the dose rather than the dose rate and it is not clear whether the obtained Pockels signals are dominated by either one or even whether both distort the field.

Results from Shwartz [52] also suggested that doping CZT crystals with Vanadium can potentially increase the Pockels coefficient making the change in refractive index significantly larger and more responsive to variations in the electric field.

The first experiments using the Yinnel crystal and illuminating with a 1550 nm laser confirmed that a polarisation element in the detected Pockels signal is present beneath the
cathode and that it is also possible to simulate X-ray irradiation using laser light due to it releasing carriers caught in trapping sites. To investigate this further and due to the unavailability of any more Yinnel samples two 10 x 10 x 10 $mm^3$ Redlen crystals were purchased that provided the ability to illuminate/irradiate areas of the crystal far enough away from the cathode that the impact of incident radiation could be observed in isolation from any trapped charge near the cathode.

A set of CMT crystals doped with vanadium were also procured to test whether the impressive results seen by Shwartz could be replicated in a similar material. These were the first Pockels measurements done with CMT:V and the characterisation showed that despite a slight increase in Pockels constant above that predicted in the CZT/CMT literature and found in our own work the value is significantly lower than that reported with Vanadium doped CZT.

The characterisation of the Redlen samples IV curves in as done by Bell et al. with previous CZT samples revealed planar-planar non-symmetrical contacts which under a -2 kV bias displayed ohmic properties and provided uniform images of the electric field in both crystals [77]. These were subsequently imaged whilst being irradiated and illuminated by 1 mm collimated X-ray and laser beams which showed that a Pockels detection technique signal averaged across an entire crystal is likely to be a combination of both local carriers created around the location of the incident beam within the crystal and polarisation under the cathode. The observation of both these elements independently of each other showed that if the detection beam is targeted away from the cathode then it should minimise the dose element contained within the signal.

Due to the time integrated component of the polarisation the decay response at different points across the crystal was then measured to determine whether there is a detectable difference in the time taken to recover from an IR pulse. The results indicated that despite the technique showing a higher amplitude response and inverted signals due to the areas of high electric field near the cathode and the polarisation "Fringes" there was no observable systematic difference in the electric fields recovery time. Responses across the crystal varied between
5-20 ms and as the IR LED’s turn-off time is 6.4 ms if differences exist between polarised and local changes they are on a shorter time-scale and thus obscured by the experimental constraints. This means that despite the distortion of the electric field being generated from different sources depending on the area crystal the average change in field can be considered only proportional to the incident dose rate when working in the millisecond regime. However, when interested in faster response times and for any theoretical model based on this detection method both components should be considered. Owing to the number of variations just within the crystal itself this is complex and therefore a semi-empirical approach may be most suitable for practical applications.

As part of the work to develop the interferometer technique and to explain some of the results seen by Lohstroh and Della-Rocca [7] the IV characteristics under X-ray irradiation were recorded. These showed that different responses occurred depending on whether a forward or reverse bias is applied to the crystal. When using the former the resulting plot shape on a X-ray flux against crystal photo-current graph bears resemblance to the interferometer results, reverse bias however provides a linear response indicating that the change in bias direction and thus the transport properties of the electrodes could be the reasons for the discrepancies previously seen at low X-ray fluxes.

An attempt was then made to move the tabletop free-space interferometer into a robust fibre-optic based detector. The results showed that whilst focussing the beam-line reduces the impact of the laser on the electric field the difficulties in aligning the small PM fibre cores with respect to the crystal are challenges which require more engineering to overcome. However despite these limitations responses to IR illumination were detected and the Laser Detection set-up was used successfully during the time response experiments [7].

As part of any future work the interferometer design may be more successful with higher power and sensitivity components or by changing the design slightly to enable triature analysis as demonstrated by Macdonald [75]. There is even potential to embed the detection medium within the fibre to minimise the alignment challenges.

There is a lot of scope in terms of future work concerning developing an understanding
of the physics and mechanisms behind the Pockels techniques. The most beneficial would likely be to develop a theoretical model that correlates the number of charge carriers released within a material to the effect this has on the electric field. Having this will help explain any deviations from predicted values even if a semi-empirical approach is used to account for inconsistencies in the materials. As seen by some of the previous studies the performance of the Pockels techniques can be potentially improved by changing the contact geometry to focus the carriers into a smaller area or illuminating with light of different wavelengths to release trapped charges [21]. Progression in any of these areas will move this novel technique closer to becoming a exploitable detector system.
Bibliography


[40] A. V. Technology, “Av guppy f-044b nir datasheet,”


Appendices
Appendix A

Fibre-Optic Designs
A.1 Fibre-Optic Detector Designs

Figure A.1: Exploded Interferometer Design
Figure A.2: Exploded Adapted Interferometer Design
Figure A.3: Exploded Laser Detector Design

- (A) Photodiode Assembly
- (B) Fibre Coupler
- (C/F) Lens Assembly
- (D/G) Mirror Assembly
- (E) Base and XYZ Translation Stage
- (F) Crystal Mount and Translation Stages
- (G) PM Patch Cable
- (H) Laser Assembly
Figure A.4: Exploded Adapted Laser Detector Design
A.2 General

A.2.1 Original

Figure A.5: Exploded Photo-Diode Assembly
Figure A.6: Exploded Lens Assembly

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Figure A.7: Exploded Mirror Assembly
Figure A.8: Exploded Base and XYZ Translation Stage
Figure A.9: Exploded Crystal Mount and Translation Stages
A.2.2 Updated

Figure A.10: Exploded FibrePort Assembly
Figure A.11: Exploded Laser Assembly v2
A.3 Topography Specific

A.3.1 Interferometer

Figure A.12: Exploded Retarder Assembly

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Figure A.13: Exploded Retarder Assembly v2
Figure A.14: Exploded Beam-splitter Assembly

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Figure A.16: 2x1 PM Fibre Coupler
A.3.2 Laser

![Diagram of PM Patch Cable]

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Figure A.17: PM Patch Cable