INTEGRATED OPTICS POCKELS CELL HIGH VOLTAGE SENSOR

by

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Abstract

In this thesis an integrated optics version of the Pockels cell, to be used for the measurement of high voltage in power transmission systems, is described. The operation of the sensor is based on the electro-optic effect in lithium niobate. The sensing head consists of a waveguide formed by diffusing a strip of titanium in a y-cut lithium niobate substrate. This waveguide (z-propagating) supports two orthogonal modes. An electric field, in which the sensor is immersed, alters the difference in the phase velocities of the two modes and, in turn, alters the polarization state at the output of the waveguide. Polarization maintaining optical fibres transmit light to the sensor head and interrogate its output. The electric field in which the sensor head is immersed can be detected by measuring the change in the polarization state at the output of the sensor.

Also, some of the technological problems encountered in realizing an integrated optics Pockels cell (IOPC) have been addressed and overcome. The photolithographic fabrication of the waveguides, waveguide end preparation, permanent fibre to waveguide butt-coupling, and other fabrication steps have been successfully completed.

Fully connectorized systems have been fabricated and tested to characterize the performance of the IOPC. Various device parameters such as intrinsic phase, half-wave electric field, and extinction ratio have been measured for several devices. The effects of waveguide width and length on the performance of the sensor have been studied. Test results indicate that useful devices, well biased, need to be at least 5 mm long. The linearity of sensor response and noise in the measurements have been investigated. The test results show

that the sensor is capable of metering high voltage AC signals with less than 0.3% error and, therefore, is likely to meet the power industry standards, such as those proposed by Erickson in 1992, for optical high voltage transducers. The stability of the sensor under various conditions has been explored. The piezoelectric resonances of the sensor heads and their effects on the bandwidths of the sensors have been examined. Sensors with large enough bandwidths have been fabricated which have successfully measured the IEC (International Electrotechnical Commission) standard lightning impulses with $1.2\ \mu\text{s}$ front time and $50\ \mu\text{s}$ tail time. The results indicate that one IOPC can be used as a high voltage sensor in several applications such as metering high voltage AC signals, protection, and time-resolved-fault-location.

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To my parents.

Chapter 1

Introduction

Optical means of voltage and current measurement in high voltage environments are attractive alternatives to conventional means, e.g., the potential transducers (PT) or current transformers (CT) now used by the power industry. An optical system's immunity to electromagnetic interference, its non-intrusive nature, and its insulating properties are some of the advantages it has as compared to the conventional systems. These attributes make it desirable to develop such optical systems.

Work on the optical methods of voltage and current measurement in high voltage environments began in the 1970's [1] - [4]. Most optical sensors developed in the 1970's used bulk electro-optic or magneto-optic crystals and were interrogated using free space links. By the end of the 1970's, when the use of high quality optical fibres as optical links was well established, the free space optical link was replaced by the optical fibre [6]. However, bulk sensors employing optical fibres needed lensing systems in the high voltage environment. In the 1980's integrated optical sensors, which did not need any lensing system in the high voltage environment, began to attract more attention [6]. Integrated and fibre optical sensors also offered the advantages of smaller size, lower cost, and, in some cases, larger bandwidths, as compared to bulk optical sensors.

In the last few years, the state-of-the-art optical PT's and CT's have shown a great improvement. Sumitomo Electric Industries, Ltd., (Osaka, Japan) has developed bulk

voltage sensors, utilizing the Pockels effect of $\text{Bi}_{12}\text{SiO}_{20}$ single crystal, and magnetic field sensors, utilizing the Faraday effect of polycrystalline ZnSe and single crystal $\text{Bi}_{12}\text{SiO}_{20}$ [7], [8]. These fibre optics sensors developed by Sumitomo Electric have been reported to have achieved better than 99% accuracy [8]. Cook [9] from ABB Electric Systems (Raleigh, NC) has reported on the development of a magneto-optic current transducer (MOCT) with less than $\pm 0.4\%$ error [10]. Kobayashi et al. [11] have reported on optical CT's with $\pm 0.6\%$ output variation. They have also reported on a bulk optical potential divider using the Pockels effect in $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ single crystal with a ratio error within $\pm 1\%$. These devices have met the standards of JEC (Japan Electrotechnical Commission) 1201 for instrument transformers. Beatty et al. [12] have published the result of a year-long field trial of a high accuracy optical current transducer system. The system measured the electric phase current flowing through a high voltage 230 kV substation transmission line terminal. They have reported a peak error deviation within $\pm 0.6\%$ of the reference standard. Sawa et al. [13] have also reported on optical CT's and PT's which comply with the JEC 1201 standards.

The work at the University of British Columbia on integrated optics sensors started in 1980. Three passive immersion type devices for high voltage measurements were proposed by Ahmed in 1981 [14]. Several integrated optical sensors based on integrated Mach-Zehnder modulators were proposed by Jaeger in 1985 [15], [16]. Here, in this thesis, an integrated optics version of a Pockels cell as a high voltage sensor is examined. This device, proposed by Jaeger [17], is an immersion type device; that is, it measures the electric field in which it is immersed. Because of the restrictions on the orientation of the electric field with respect to the sensor head, these devices are most suitable for measuring voltage

in fixed geometry systems such as SF₆ gas insulated power transmission lines.

The theory of operation of the integrated optics Pockels cell is described in chapter 2. The sensor operation is based on the electro-optic effect in Ti:LiNbO₃ strip waveguides. The sensor consists of a laser as the optical source, polarization maintaining fibres as the optical links, a titanium indiffused strip waveguide in a lithium niobate substrate as the sensing device (the sensing head), and an optoelectronic unit for converting the optical information into electrical signals.

The fabrication of the integrated optics Pockels cells is described in chapter 3. First, waveguide mask design, fabrication of waveguides in lithium niobate by titanium indiffusion, and crystal cutting and polishing are explained. Then the sensor integration is described in detail. It includes fibre preparation, laser-to-fibre and fibre-to-fibre light coupling, permanent fibre to waveguide attachment, and fibre to photo-detecting (optoelectronic) unit connection.

Chapter 4 contains the descriptions and the results of the experiments done to characterize the performance of the sensors. Basic device parameters such as intrinsic phase, half-wave electric field, and extinction ratio are reported for several devices. The effects of device length and strip waveguide width on the performance of the sensor are illustrated. Sensor noise, linearity, stability under various conditions, and piezoelectric resonances are characterized. Also, results of measurements of AC and fast impulse signals, made using the sensor, are presented.

A summary of the work, conclusions, and suggestions for improving the performance of the integrated optics Pockels cell as a high voltage sensor are given in chapter 5.

Chapter 2

Theory

2.1. Introduction

The integrated optics Pockels cell (IOPC) is a field-sensing device primarily developed [17], [18] for high voltage measurement applications in SF₆ gas insulated transmission lines. It is a passive device; in other words, it does not need a power supply or any electronic circuitry in the high voltage environment. It uses optical fibres to transmit the light to and from the sensor in the high voltage environment. The optical fibres are made of insulating materials, hence they provide good isolation between the high voltage environment and the optoelectronic monitoring system (see figure 2.1). Moreover, the optical signals in the fibres are immune to electromagnetic interference. In contrast with the conventional potential transformers (PT's), which load the transmission lines being monitored, the IOPC works in a non-intrusive manner. IOPC's are also expected to be cheaper, in terms of price and maintenance, as compared to their counterparts currently used in the industry.

The conventional PT's used in the power industry are very large and heavy and, therefore, need to be made earthquake-proof. They are usually filled with oil, and use materials such as PCB for insulation. The IOPC, on the other hand, does not need earthquake-proofing because of its small size and weight, and is a better choice as far as the environment is concerned.

Figure 2.1. An integrated optical sensor in a high voltage environment. The optical fibres provide isolation from the HV environment.

Another advantage of the IOPC over conventional PT's is that the output signal of the IOPC is compatible with the electronic signal levels required for the recently merging digital protection systems.

The theory of operation of the IOPC as a high voltage sensor is explained in this chapter. The IOPC is first described in detail, and then a channel waveguide model is used for the initial design purposes. The last section of this chapter is dedicated to the description of the optical field distributions of the modes supported by the IOPC.

2.2. Description of the IOPC

As high voltage sensors, Pockels cells, with various modifications, have been previously used for electric field measurements [19], [20]. The relevant theory of operation and equations for Pockels cell based systems incorporating bulk crystals can be found in the literature [19] - [24].

The integrated optics version of the Pockels cell consists of a strip waveguide supporting the propagation of two orthogonal modes in an electro-optic medium. Application of an electric field to the electro-optic medium alters the birefringence of the waveguide and thus creates a change in the difference between the phase velocities of the two modes propagating in the waveguide. The output of the waveguide is interrogated and the electric field in which the device is immersed is metered by measuring the change in the difference in the phase velocities of the two modes.

Figure 2.2 shows an isometric view of the IOPC. The IOPC is constructed using a strip waveguide fabricated in a y-cut substrate of lithium niobate. The waveguide is formed by diffusing in a strip of titanium, patterned to run parallel to the z crystallographic axis of the substrate. The width and thickness of the pre-diffusion titanium strip is chosen such that the waveguide produced after diffusion supports two orthogonal modes: one TE-like mode with the electric vector of the light substantially polarized parallel to the x crystallographic axis, and one TM-like mode with the electric field substantially polarized parallel to the y crystallographic axis (see figure 2.3).

Typically, polarized light is coupled into the waveguide from a polarization

Figure 2.2. An isometric view of an integrated optics Pockels cell.

maintaining optical fibre. The fibre has two orthogonal axes of polarization, i.e., it supports two modes, one fast and one slow (see figure 2.3). The polarized light from a laser is coupled into one of the orthogonal modes supported by the fibre. In this way, the light is polarized when it exits the fibre. The fibre end is oriented in such a way that equal amounts of optical power are coupled into the TE- and TM-like modes propagating in the waveguide. To do this, the axes of the fibre are substantially at 45° to the x and y crystallographic axes of lithium niobate substrate. The output of the waveguide is interrogated by an optical fibre

Figure 2.3. Optical fibre core to strip waveguide butt-coupling.

similar to the input fibre. The alignment of the axes of the interrogating fibre (output fibre) is also substantially at 45° to the x and y crystallographic axes of lithium niobate crystal.

Once the linearly polarized light is coupled into the waveguide, the TE- and TM-like modes propagate with slightly different phase velocities resulting in an elliptical polarization state at the output of the waveguide. This polarization state is, therefore, waveguide length dependent, and it is possible to bias the device by controlling its length.

Lithium niobate is an electro-optic crystal. Its point group is 3m. Its electro-optic coefficient matrix is [25]:

$$r_{ij} = \begin{pmatrix} 0 & r_{12} & r_{13} \\ 0 & r_{22} & r_{23} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{51} & 0 & 0 \\ r_{61} & 0 & 0 \end{pmatrix} \quad (2.1)$$

where $r_{13} = r_{23}$, $r_{22} = -r_{12} = -r_{61}$, and $r_{42} = r_{51}$. An electric field E_y parallel to the y crystallographic axes of the crystal changes the refractive indices n_x and n_y via the electro-optic effect. These changes are of equal magnitude but have opposite signs since $r_{22} = -r_{12}$. The magnitude of the change in index is given by

$$\Delta n_{x,y} = \left| \frac{n_o^3 r_{22} E_y}{2} \right| \quad (2.2)$$

where n_o is the ordinary refractive index for LiNbO_3 [24]. The TE- and TM-like modes propagating in the waveguide have very similar mode profiles (see section 2.4 in this thesis) and are polarized substantially parallel to the x and y crystallographic axes, respectively; therefore, the application of the electric field E_y will create a change Γ in the phase difference between the two modes at the output of the waveguide where

$$\Gamma = \frac{4\pi \Delta n L}{\lambda_o} . \quad (2.3)$$

The magnitude of Γ is in fact equal to twice the magnitude of the electro-optic retardation for each mode. In equation (2.3), L is the waveguide length and λ_o is the free space wavelength of the light. Combining equations (2.2) and (2.3), Γ can be rewritten as a

function of E_y as follows:

$$\Gamma = \frac{2\pi n_o^3 r_{22} L E_y}{\lambda_o} . \quad (2.4)$$

The half-wave electric field E_π which is defined as the electric field in the lithium niobate substrate needed to create a change of π radians in the phase difference between the two modes ($\Gamma = \pi$) is given by

$$E_\pi = \frac{\lambda_o}{2 n_o^3 r_{22} L} . \quad (2.5)$$

For a device of a particular length, and assuming light of a particular wavelength, E_π is a constant, and Γ can be simply written as a function of the applied electric field E_y as follows:

$$\Gamma = \frac{\pi E_y}{E_\pi} . \quad (2.6)$$

The propagation constants, or equivalently the phase velocities, for the TE- and TM-like modes propagating in the waveguide are slightly different (when there is no electric field applied). This is due to the different boundary conditions at the LiNbO₃/SiO₂ interface for the two modes (SiO₂ forms the optical buffer layer covering the LiNbO₃). For the TE-like mode the continuity of the tangential E vector determines the boundary conditions whereas, for the TM-like mode the continuity of the normal electric displacement vector determines the boundary conditions [22, pp. 3-5]. This intrinsic phase velocity difference results in an intrinsic phase difference ϕ_i between the two modes at the output of the waveguide and is used to bias the Pockels cell. When an electric field is applied, the total phase difference $\Delta\phi$

between the two modes at the output of the waveguide becomes $\Delta\phi = \phi_i + \Gamma$.

Since the two modes propagating in the waveguide have different phase velocities, the polarization state at the output of the waveguide is generally elliptical. The interrogating fibre is aligned such that its two polarization-maintaining axes are parallel to the major and minor axes of the polarization ellipse at the output of the waveguide. This alignment is substantially at 45° to the x and y axes of the lithium niobate, as mentioned before. The electric vector of the light parallel to that axis of the polarization ellipse which is substantially parallel to the direction of polarization of the linearly polarized input light is the vector addition of the two electric vectors of the TE- and TM-like modes exiting the waveguide. Therefore, the optical power parallel to this axis of the polarization ellipse can be written as

$$P_1 = P_o \times \frac{1 + \alpha \cos(\Delta\phi)}{2} \quad (2.7a)$$

where P_o is the total power out of the waveguide, and α is ideally equal to one. In practice α will be slightly less than one because of alignment imperfections and unequal absorptions of the two modes. The power parallel to the other axis of the polarization ellipse is

$$P_2 = P_o \times \frac{1 - \alpha \cos(\Delta\phi)}{2} . \quad (2.7b)$$

The interrogating fibre transmits the output light to a polarizing beam-splitting cube which separates the light components; i.e., the components parallel to the major and minor axes of the polarization ellipse at the sensor output. Each of the two optical signals is then measured by a photo-detector. The optoelectronic conversion unit normalizes the output signal by instantaneously dividing the signal from one photo-detector (optical power parallel

to one axis of the polarization ellipse) by the sum of the signals from both photo-detectors (total optical power). The normalized output signal, S , is then given by

$$S = \frac{1 \pm \alpha \cos(\Delta\phi)}{2} \quad (2.8)$$

where the sign depends on the photo-detector chosen (giving the optical power in one of the two axes of the polarization ellipse).

For small-signal modulation the transfer function (2.8) is nearly linear for ϕ_i equal to $\pi/2$ radians (90°). As mentioned before, the length of the device can be chosen so that the bias of $\phi_i = 90^\circ$ is achieved.

One important reason for choosing a y-cut substrate, as compared with x-cut, when using propagation parallel to the z axis is providing the ability to bias the device. As explained before, the intrinsic phase difference between the TE- and TM-like modes is responsible for biasing the device. It is also the phase velocities of these two modes which are affected, due to the electro-optic effect, by application of an electric field along the y axis. This would not be the case if the electric field was applied along the x axis. If the Pockels cell was made in an x-cut piece of lithium niobate with the electric field applied parallel to the x axis and with the light propagating parallel to the z axis, the input light would have to be coupled into only one of the two TE-like or TM-like modes in the waveguide in order to sense the electric field (see equation 2.1 and [22], [25]). When the optical power travels through the waveguide in only one of the two orthogonal modes, it is not possible to use the intrinsic phase velocity difference between these two modes to bias the device. In short ϕ_i will be zero regardless of device length.

Another advantage of using a y-cut substrate with propagation parallel to the z axis is that the optical mode profiles for the two TE-like and TM-like modes are essentially the same. Therefore, the polarization state is practically constant across the entire output plane of the waveguide (see section 2.4).

2.3. Channel Waveguide Model

A simple channel waveguide model is used for estimating the parameters necessary for designing and fabricating the strip waveguides. Even though the titanium diffused waveguides have rather different refractive index profiles [27] as compared to our channel waveguide model, the model is good enough for first approximation and order of magnitude estimations. Figure 2.4 shows the cross-section of the channel waveguide model. The substrate for this model has a refractive index n_3 of 2.280 (that of n_o in lithium niobate at $\lambda_o = 633$ nm [22, p. 232]). The channel, imbedded in the substrate, has a refractive index n_2 . The superstrate, on the top of the channel and the substrate, has a refractive index n_1 of 1.46 (i.e., that of silicon dioxide). The effective index method [28] was used to find the minimum device length l that would result in circular polarization ($\phi_i = 90^\circ$) at the output of the waveguide when $\lambda_o = 670$ nm. In order to design and fabricate properly biased devices, the effects of certain parameters such as channel width a , channel depth b , and channel refractive index n_2 on l has to be found. In the case of strip waveguides, the waveguide dimensions and refractive index distribution are determined by factors such as pre-diffusion titanium strip width and thickness, diffusion time, and diffusion temperature.

Figure 2.5 shows a plot of l versus a for two values of n_2 : 2.283 and 2.284. These values were chosen because the typical increase in the refractive index of lithium niobate due to Ti diffusion is about 0.005 [29, p. 790] at the surface of the crystal. Here b is $2\text{ }\mu\text{m}$. The waveguide supports only one TE mode and one TM mode for the range of channel widths plotted. Figure 2.5 clearly shows that l is smaller for wider waveguides; in other

Figure 2.4. The cross-section of the channel waveguide model. a and b represent the channel width and depth, respectively.

words, wider devices will have larger intrinsic phases as compared to narrower devices of the same length. A comparison of these results with the experimental results from the strip waveguides fabricated can be found in section 4.4 of this thesis.

Figure 2.6 shows a plot of l versus b for two values of channel refractive index: 2.283 and 2.284. Here a is $4\text{ }\mu\text{m}$. From figure 2.6, l is expected to be larger for deeper waveguides.

Figure 2.7 shows a plot of l versus channel refractive index n_2 . For this plot, a and b are 4 and $2\text{ }\mu\text{m}$ respectively. The higher the channel refractive index, the shorter a properly biased device can be. However, if n_2 is more than 0.005 larger than n_3 , the waveguide will be multi-mode; i.e., it will support more than one TE and one TM mode.

These plots are used in designing the waveguide masks and fabricating the waveguides. The experimental results from strip waveguides are presented in chapter 4.

Figure 2.5. A plot of the channel waveguide length l which results in circular polarization at the waveguide's output as a function of channel width a .

Figure 2.6. A plot of the channel waveguide length l which results in circular polarization at the waveguide's output as a function of channel depth b .

Figure 2.7. A plot of channel waveguide length l which results in circular polarization at the waveguide's output as a function of channel refractive index n_2 .

2.4. Similarity of the Modal Field Distributions for the Fundamental TE- and TM-like Modes.

For successful operation of the IOPC, it is important that the two guided modes of the waveguide, namely the fundamental TE-like and the fundamental TM-like modes, have similar mode profiles. The reason for this is that the uniformity of the polarization state at the output of the Pockels cell is dependent upon this similarity. The nominal polarization state of the light exiting the waveguide must be a combination of the individual polarization states at all points in the transverse output plane of the waveguide. Having the same optical field distributions over the output plane, for the two modes, means that the ratio of the magnitudes of the electric vectors are equal at all points in the plane, and, therefore, the polarization state at all points is the same; i.e., there is a single output polarization state. Also, the greater the similarity of the optical field distributions is, the closer α in equation 2.8 can be made to its ideal value of one (i.e. for the same power in each mode).

To find the modal field distribution of the guided modes of our strip waveguides, we first need to find the refractive index distribution. Assuming uniform deposition of titanium on the lithium niobate substrate, the waveguide is longitudinally invariant ($\partial n / \partial z = 0$); therefore, $n = n(x,y)$. The increase in the refractive index of lithium niobate due to titanium indiffusion is related to the concentration of the indiffused titanium ions. An often-used model for calculating the titanium ion concentration $C(x,y)$, after complete diffusion of the deposited titanium, is [26], [31]

$$C(x,y) = \frac{1}{2} \frac{\tau}{\sqrt{\pi D_y t}} e^{-\left(\frac{y^2}{4D_y t}\right)} \left[\operatorname{erf}\left(\frac{\frac{W}{2} + x}{2\sqrt{D_x t}}\right) + \operatorname{erf}\left(\frac{\frac{W}{2} - x}{2\sqrt{D_x t}}\right) \right] \quad (2.9)$$

$$D_x = D_{ox} e^{-\frac{Q}{k_B T}} \quad \text{and} \quad D_y = D_{oy} e^{-\frac{Q}{k_B T}}$$

where τ is the pre-diffusion titanium thickness, t is the diffusion time, W is the pre-diffusion titanium strip width, D_{ox} and D_{oy} are the diffusion constants in the x and y directions respectively, Q is the activation energy, k_B is Boltzmann's constant, and T (in Kelvin) is the diffusion temperature.

The increase in the extraordinary refractive index (Δn_e) is linearly proportional to the titanium concentration C . The increase in the ordinary refractive index (Δn_o) after titanium indiffusion is, however, not linearly dependent upon C [27]. A fourth order polynomial fit to the data given in reference [26] was used to estimate Δn_o as a function of C

$$\Delta n_o = \sum_{i=0}^4 a_i C^i \quad (2.10)$$

where $a_0 = -1.65 \times 10^{-5}$, $a_1 = 1.05$, $a_2 = -81.6$, $a_3 = 3.88 \times 10^3$, and $a_4 = -6.64 \times 10^4$. Figure 2.8 shows the ordinary refractive index distribution for a Ti:LiNbO₃ strip waveguide. Here $W = 3.5 \mu\text{m}$, $\tau = 450 \text{ nm}$, $t = 5.5 \text{ hours}$, $T = 1050^\circ\text{C}$, $n_o = 2.280$ (bulk ordinary refractive index for lithium niobate), $D_{ox} = D_{oy} = 1.35 \times 10^8 \mu\text{m}^2/\text{hr}$ [32], and $Q = 2.22 \text{ eV}$ [32]. The titanium density was assumed to be 70% of its molecular mass density.

Figure 2.8. Refractive index distribution for a Ti:LiNbO₃ strip waveguide (from B. Tsou's modelling work, with permission)

The optical field distribution in the transverse plane should satisfy the vector wave equations [30]

$$\nabla_t^2 \overline{E}_t + (n^2(x,y)k_o^2 - \beta^2)\overline{E}_t = -\nabla_t(\nabla_t \ln n^2(x,y) \cdot \overline{E}_t) \quad (2.11a)$$

$$\nabla_t^2 \overline{H}_t + (n^2(x,y)k_o^2 - \beta^2)\overline{H}_t = (\nabla_t \times \overline{H}_t) \times \nabla_t \ln n^2(x,y) \quad (2.11b)$$

where k_o is the free space wavenumber ($2\pi/\lambda_o$), $n(x,y)$ is the refractive index distribution in the transverse plane, $\overline{E}_t$ and $\overline{H}_t$ are the transverse components of the electric field, ∇_t and ∇_t^2 are the transverse gradient and Laplacian operators, and β is the propagation constant in the longitudinal direction. We use a y-cut plate of lithium niobate to fabricate the waveguide lengthwise parallel to the z crystallographic direction; therefore, the vector wave equations for the electric fields become

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \left(\frac{\partial^2 \ln n^2}{\partial x^2} + \frac{\partial \ln E_x}{\partial x} \frac{\partial \ln n^2}{\partial x} + n^2 k_o^2 - \beta^2 \right) E_x = 0 \quad (2.12)$$

for the TE-like mode where n is $n_o(x,y)$, the ordinary refractive index distribution with Ti indiffusion, and

$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \left(\frac{\partial^2 \ln n^2}{\partial y^2} + \frac{\partial \ln E_y}{\partial y} \frac{\partial \ln n^2}{\partial y} + n^2 k_o^2 - \beta^2 \right) E_y = 0 \quad (2.13)$$

for the TM-like mode where, again, n is $n_o(x,y)$. Here, the subscript on E shows the polarization direction of the dominant electric field component. Solving equations 2.12 and 2.13, together with the appropriate boundary conditions, gives the propagation constants β

and the optical field distributions for the modes. Analytical solutions to equations 2.12 and 2.13 are not generally possible. Numerical solutions, on the other hand, can give very good approximate solutions to the equations [26]. We are, however, more interested in the similarity of the mode profiles of the two modes and not the exact mode profiles themselves.

2.4.1. Channel Waveguide Model Implications

As a first approximation, we will consider the TE-like and TM-like modes of our channel waveguide model in section 2.3. From figures 2.5, 2.6, and 2.7, the length l of the waveguide that would give 90° phase difference between the two modes is expected to be a few millimetres or even larger. The experimental results in chapter 4 also indicate that l is between 5 and 11 mm. This means that after travelling more than $\sim 15,000$ wavelengths along the waveguide, one mode lags the other by $\pi/2$ radians. We can then conclude that the propagation constants of the two modes, or equivalently the effective refractive indices ($\beta = 2\pi n_{\text{eff}}/\lambda_o$), are very close. The difference between the effective refractive indices will be less than 2×10^{-5} which is about 0.5% of the value of the difference between the refractive indices of the channel and the substrate (about 0.004). This implies that the optical energy distribution over the transverse plane (in the channel and cladding) has to be similar for the two modes.

2.4.2. Slab Waveguide Model

Since an analytical solution for slab waveguides is available, a simple asymmetric slab waveguide model is used to illustrate the similarity of the optical mode profiles for the fundamental TE-like and TM-like modes. The slab waveguide can be considered to be a special case of the channel waveguide of figure 2.4 where the channel width is much larger than the channel depth (i.e. $a \gg b$). Figure 2.9 shows the magnitudes of the transverse electric field components as functions of the distance h from the slab-superstrate interface for the fundamental TE and TM modes (equations can be found in reference [33]). h is positive in the superstrate and negative in the slab and the substrate, and the magnitudes of the electric field components are normalized with respect to the modes' optical power. Here $n_1 = 1.46$, $n_2 = 2.284$, $n_3 = 2.280$, $\lambda_o = 670$ nm, $b = 3$ μ m, and $a = \infty$. As can be seen from figure 2.9, the two mode profiles are very similar except in the region very close to slab-superstrate interface. However, due to a large difference between the slab and superstrate refractive indices, the amount of optical power in this region is relatively small (small E in this region, and very small evanescent field in the superstrate). Overall most of the optical power of the two modes passes through the region where the two mode profiles are very similar, and as a result the polarization state at the output is very nearly uniform.

Figure 2.9 also shows quite clearly that the waveguide acts like a weakly guiding waveguide, and the evanescent field in the substrate is quite large. Therefore, because the modal fields of weakly guiding waveguides are nearly TEM waves [30, p. 246], only a weak dependence on the polarization properties of the waveguide exists, and both TE-like and TM-

Figure 2.9. E-field distributions across the slab waveguide for the fundamental TE and TM modes. The solid line shows E_{TE} and the dashed line shows E_{TM} .

like modes have very similar optical field distributions. Furthermore, in a diffused waveguide the differences in the profiles of the two modes should be still less than those illustrated in our example here.

2.4.3. The Vector Wave Equations

As has already been mentioned, the solutions to equations 2.12 and 2.13 give the actual optical field distributions of the fundamental TE- and TM-like modes in the transverse plane. We can use a Hermite-Gaussian function

$$\phi(x,y) = A \left(\frac{y}{w_y} \right) e^{-\frac{1}{2} \left(\frac{x^2}{w_x^2} + \frac{y^2}{w_y^2} \right)}, y \geq 0 \quad ; \quad \phi(x,y) = 0, y < 0 \quad (2.14)$$

to estimate the transverse modal field distribution of the two fundamental modes. The width parameters w_x and w_y in equation 2.14 indicate the extent of the field distribution in the x and y directions, respectively. Equation 2.14 is a reasonable description of the optical field distribution in Ti:LiNbO₃ strip waveguides [26], [34].

In equations 2.12 and 2.13, if the terms involving partial derivatives of n^2 with respect to x and y are small as compared to $\{n^2 k_o^2 - \beta^2\}$, they can be ignored and both vector wave equations 2.12 and 2.13 can be reduced to the scalar wave equations. Ignoring the terms containing partial derivatives of n^2 means that one does not match the vectorial boundary conditions for the transverse electric fields [35]. Since, for the configuration of our devices (y-cut, z-propagating waveguides), n is the ordinary refractive index distribution for both TE- and TM-like modes, $\{n^2 k_o^2 - \beta^2\}$ is the same in equations 2.12 and 2.13 and the scalar wave equations for both modes are identical.

Except at the LiNbO₃-SiO₂ interface, the refractive index in the Ti:LiNbO₃ waveguide changes very gradually as a function of distance (see figure 2.8). Assuming an increase of

about 0.004 in the refractive index of lithium niobate at the surface, due to titanium diffusion (figure 2.8), for most regions in the transverse plane where the optical field intensity is large, the term $\{n^2 k_o^2 - \beta^2\}$ is about three orders of magnitude larger than the sum of the other terms involving the partial derivatives of n^2 in equations 2.12 and 2.13. Therefore, it is reasonable to estimate both 2.12 and 2.13 by one scalar wave equation. Figure 2.10 shows the modal field distribution found for the TE-like, or equivalently for the TM-like, mode by solving the scalar wave equation. Figure 2.10 corresponds to equation 2.14 where w_x and w_y are measured to be $2.22 \mu\text{m}$ and $2.02 \mu\text{m}$ respectively when the optical wavelength $\lambda_o = 670 \text{ nm}$. The results for both the fundamental TE-like mode and the fundamental TM-like mode are identical because the evanescent field in the silicon dioxide layer is assumed to be zero (see equation 2.14); this is, as explained before, a very reasonable assumption (see figure 2.9).

Other researchers [35], [36] have used different numerical methods to solve the scalar wave equations as approximations to the vector wave equations and have calculated the differences between their solutions and the exact solutions, where available. These differences (polarization corrections), including the error due to their numerical methods, have been reported to be very small for weakly guiding waveguides [36].

An important factor in the design of the IOPC, which should be pointed out, is the orientation of the waveguide. The waveguide in the IOPC is a z-propagating waveguide made in a y-cut piece of lithium niobate. Thus, as explained in the preceding few paragraphs, n is the ordinary refractive index distribution and is seen by both the TE- and the TM-like modes. This results in identical scalar wave equations and, in turn, identical

optical field distributions for both modes. If, for example, the direction of propagation were parallel to the x axis instead of the z axis, n for the TM-like mode would be the ordinary refractive index distribution $n_o(x,y)$ (since our crystal is y-cut) and for the TE-like mode (substantially polarized parallel to z axis) would be the extraordinary refractive index distribution $n_e(x,y)$. Since $n_o(x,y)$ and $n_e(x,y)$ are neither equal nor do they have the same dependence on Ti concentration, the scalar wave equations for the two modes would not be identical, and, therefore, the two modes would have significantly different optical field distributions over the transverse plane. As explained in the first paragraphs of this section (2.4), this dissimilarity of the mode profiles should be avoided.

Figure 2.10. Optical field distribution for the TE-like mode or the TM-like mode in the strip waveguide. Free space optical wavelength is 670 nm (from B. Tsou's Hermite-Gaussian modelling work, with permission).

Chapter 3

Fabrication

3.1. Introduction

Lithium niobate is a human-made dielectric material usually grown by the Czochralski technique of pulling from a melt [37]. It was first found to be ferroelectric in 1949 with a Curie temperature of about 1210°C [42]. Its properties were investigated at Bell Laboratories in the 1960's, and the results were published in five papers in 1966 [37] - [41]. It is now one of the most widely used electro-optic materials. This ferroelectric material has a trigonal crystal structure and is characterized by large pyroelectric, piezoelectric, electro-optic, and photo-elastic coefficients. Lithium niobate is naturally birefringent. It has useful acoustic wave properties and a relatively large acousto-optic figure of merit. Furthermore, it exhibits a very strong bulk photovoltaic effect. This effect causes efficient charge migration within the material and in combination with the material's linear electro-optic effect, can produce a significant photo-refractive effect (optically induced refractive index changes).

Lithium niobate is widely used in applications such as acoustic wave transducers, acoustic delay lines, acoustic filters, optical phase and amplitude modulators, second-harmonic generators, Q-switches, beam-deflectors, phase conjugators, dielectric waveguides, memory elements, and holographic data processing devices.

Since the first fabrication of optical waveguides in LiNbO_3 by the in-diffusion of

titanium in 1974 [43], this technology is seen by some [51] as being the most successful in realizing high-quality waveguides in a substrate material, which has excellent optical properties. The high status of integrated optic devices in lithium niobate may be characterized by intensity modulators with a 3 dB electrical bandwidth up to 18 GHz [44], complex switch-arrays with 64 switches integrated on one substrate [45], high-speed low-insertion-loss PSK modulators for coherent systems [46], and fibre coupled devices with insertion loss figures less than 1 dB [47].

3.2. Waveguide Fabrication in Lithium Niobate

3.2.1. Introduction

There are several conditions that a high quality waveguide should satisfy. For our waveguides, the most important conditions are as follows:

- low optical propagation loss,
- fabrication of waveguides supporting only fundamental modes,
- dimensions that allow efficient coupling to optical fibres,
- fabrication reproducibility, and
- fabrication of end facets for efficient fibre-waveguide butt-coupling.

The two commonly-used methods for optical waveguide fabrication in lithium niobate are titanium indiffusion and proton exchange. Proton exchanged waveguides in lithium niobate do not guide light polarized parallel to the ordinary axes (x or y-axis) and, therefore,

are not suitable for our application. We use the titanium indiffusion method to fabricate our devices. Titanium diffusion in lithium niobate is a relatively well-established method [33], [48] for realizing low loss optical waveguides in lithium niobate. Details on the diffusion kinetics and the fabrication technology of Ti:LiNbO₃ waveguides can be found in references [33], and [48]. Figure 3.1 summarizes the fabrication steps for Ti:LiNbO₃ waveguides. Very briefly, the fabrication steps outlined in figure 3.1 are as follows: (a) cleaning and preparing the substrate, (b) metallizing, (c) spinning on photo-resist, (d) masking and exposing the photo-resist, (e) developing and removing the exposed photo-resist, (f) etching the metal, (g) removing the remaining photo-resist, (h) diffusion, and (i) optical buffer layer deposition.

3.2.2. Waveguide Mask

A mask was required to achieve the desired Ti pattern on the surface of the LiNbO₃ substrate before the diffusion process. A strip of Ti had to be deposited on a clean, optically polished, y-cut crystal of lithium niobate. It was aligned parallel to the z crystallographic axis. The width of the waveguide produced after diffusion would be directly dependent on the width of this Ti strip. A three to four micron wide Ti strip, about 45 nm thick, was expected to give a waveguide supporting the fundamental TE- and TM-like modes for $\lambda_o = 670$ nm. To be able to use the mask to build monomode waveguides for longer wave lengths, as well as to get a waveguide with an appropriate bias (see figures 2.5, 2.6), a series of 3 to 10 micron wide strips, increasing in $1/2 \mu\text{m}$ increments, were included on the mask

Figure 3.1. The steps of Ti-indiffused waveguide fabrication in lithium niobate.

(total of 15). The strips were parallel to each other and were at 100 micron intervals so that these 15 strips covered a 1.5 mm wide area. Most of our LiNbO_3 wafers were three inches in diameter and were cut into four equal pieces. Ten repetitions of the pattern covered a 1.5 cm area of the wafer; in this way the available LiNbO_3 was used efficiently. Moreover, if some of the waveguides were damaged during fabrication, the chance of obtaining good waveguides (stable, properly biased, with acceptable throughput) would increase by including such a large number of waveguides.

Properly biased waveguides were expected to be > 3 mm long (see Figures 2.5 - 2.7). To ensure realization of properly biased devices, 33 mm long strips were designed on the mask. This value for the length was imposed on us by the mask layout package that we used.

Fifty micron $\times$ 50 micron squares were also designed between the strips to be used for alignment. The squares on a line parallel to the strips were 1 mm apart (see Figure 3.2).

E-beam technology was used in waveguide mask fabrication because sub-micron accuracy was needed. The mask design was first created on the computer graphic package called ICED (of IC Editors, inc., Santa Clara, CA). The computer design was then converted to a CIF file, and the floppy disk containing the CIF file was sent to the mask manufacturer, Precision Photo Mask LTD (Quebec city), where a chromium on glass mask was prepared.

3.2.3. Sample Preparation

In order to successfully fabricate low-loss waveguides, it was important to ensure that

Figure 3.2. The waveguide Mask. The actual mask consisted of ten repetitions of the above pattern. Units in μm .

the lithium niobate substrates were very clean before fabrication. The typical preparation of the lithium niobate wafers was as follows: the wafers, typically 1 mm thick and 3 inches in diameter, were coated with about 500 nm of aluminum (for protection) and then cut into four equal quadrants using a wire saw (model 850 abrasive slurry wire saw from South Bay Technology, Temple City, CA). Two 600 ml beakers and a few tweezers and sample holders were cleaned in Alconox. The aluminum was then removed in four hundred ml of a 1:1 solution of phosphoric acid and DI water at 50 degrees. The wafers were put in the acid solution for about 10 minutes for the acid to dissolve the aluminum. Next, the solution with the wafers immersed was ultrasonically agitated for about 5 minutes. After cooling, the wafers were placed in a flowing DI water bath for about 15 minutes, and then they were blown dry using compressed nitrogen. Later devices were made on thinner (about 0.4 mm

thick) wafers of lithium niobate by the same process.

3.2.4. Titanium Deposition, Patterning, and Etching

Typically, a layer of Ti, ~ 45 nm thick, was evaporated onto the polished side of the lithium niobate wafers in the CHA metal vapour deposition system (from CHA industries, a division of Carl Herrmann Associates, Inc., Menlo Park, California). To pattern the Ti, Shipley S1400-27 photo-resist (from Shipley Company, Inc., Newton, MA) was applied to the samples. The samples, with the photo-resist on them, were spun at 4000 rpm for about 30 seconds to form a thin uniform layer on the substrates. The photo-resist was then pre-baked at 70°C for about 25 minutes. After the samples cooled, they were aligned with the waveguide mask using the Karl Suss MJB3 mask aligner (from Karl Suss America, Inc., Waterbury, Vermont). The strips on the mask, used to form the waveguides, were aligned to run parallel to the z crystallographic axis of LiNbO₃ samples. The photo-resist was then exposed for 22 seconds to UV light ($\lambda_o = 320$ nm) from a Karl Suss Model 505 UV lamp at 277 watts. After the samples cooled, the photo-resist was developed in 200 ml of a 1:1 solution of DI water and Shipley MF-312 developer for about 100 seconds followed by 15 seconds in a DI water rinse (in a cascade bath) and one minute in DI water bath (in a beaker). Finally, the samples were blown dry using compressed nitrogen.

The excess titanium was removed by the active ion/plasma etching system model PK-12 (from Plasma Therm, Inc., Kresson, NJ) using CF₄. Typically, the etch took 7 minutes at 500 mtorr chamber pressure and 58°C chamber temperature. The CF₄ flow rate was 140

sccm per minute. The remaining photo-resist was removed by putting the samples in Microstrip 2001 (from Shipley Company, Inc.) at about 85°C for 5 minutes, and then ultrasonically agitating the Microstrip for about 4 minutes. Then the samples were transferred to a DI water bath for about 10 minutes followed by an isopropyl alcohol bath for about 5 minutes. Finally, the samples were blown dry, using compressed nitrogen, before the diffusion. Figure 3.3 shows a thickness scan on one of the samples by a Tencor Instrument's (Mountain View, CA) Alpha-Step 200 profilometer indicating that the Ti layer on this sample was about 400 angstroms thick.

Figure 3.3. A scan by Alpha-Step 200 profilometer to measure the thickness of pre-diffusion titanium layer.

3.2.5. Titanium Indiffusion

For the first few samples, the titanium patterns were diffused into the lithium niobate at 1030°C for about five and half hours in a Thermco Products' (Orange, CA) Mini Brute diffusion furnace. The diffusion was done in flowing oxygen at one litre per minute. The diffusion temperature and time were 1050°C and six hours respectively for some later devices.

3.2.6. Silicon Dioxide and Silicon Nitrite Deposition

A few samples were put in the Sputtering System Model 3140 (from Perkin-Elmer, Norwalk, CT) with a silicon dioxide target, and about two thousand angstroms of SiO₂ were sputtered onto the samples¹. For later fabrications, we used thicker SiO₂ layers (about six thousand angstroms).

3.2.7. Metal Electrode Deposition

As it eventually turned out, the final devices would not have any metal electrodes on them. The integrated optics Pockels cell is an immersion type device that measures the

¹In order to see if a silicon nitride buffer layer can also give low loss waveguides, two other samples had about 3300 angstroms of Si₃N₄ deposited in the Plasma Therm's model PK-12. The samples with nitride buffer layer did not produce usable waveguides, and this approach was not pursued any further.

electric field and hence does not need any electrodes; however, electrodes were often deposited on wafers during the preliminary laboratory tests. When necessary, the samples were put in the CHA, and ~500 angstroms of titanium, ~2000 angstroms of gold, and ~5000 angstroms of aluminum were deposited on both sides of the wafers. The titanium was used as an adhesion promoting layer. The gold layer was to be the electrode, and the aluminum layer was used only for protection during later cutting and polishing.

3.2.8. Cutting and Polishing the Waveguides

The samples containing the waveguides were cut from the wafers using a South Bay Technology's (Temple City, CA) Model 850 Abrasive Slurry Wire Saw. The wafers were first mounted on a graphite block using sticky quartz wax (from South Bay Technology) which melts at 70°C. Then the graphite block was mounted on an aluminum block using the same wax. The aluminum block was fixed in the saw and the wafers were cut. The stainless steel wires, 0.015 inch thick, would last for about 25 minutes on average. Each three-centimetre-long cut took about 15 minutes on a one millimetre thick wafer. An effort was made to ensure that the ends of the waveguides would be perpendicular to the waveguides. After cutting all four sides of each waveguide block, the wax was heated, and the wafers were removed and cleaned in trichloroethylene.

For every sample, a similar piece of lithium niobate, with no waveguides in it, was cut in the same crystallographic directions and glued on the waveguide side of that sample. UV curable optical adhesive was used as the glue to obtain a minimal (sub-micron) glue

thickness. It is very important to keep the glue layer very thin so that no large polishing particles can get stuck in it during polishing; these relatively large (order of microns) particles can come out of the glue layer in the finer stages of polishing and scratch the crystal end, ruining the final polish.

There were several reasons for using such cover pieces. Firstly, the waveguides, which resided on one side of the wafer, would be polished without any bevelling of the crystal edge. Secondly, when mounting the sample on a metal piece for fibre attachment, this cover piece would be glued to the metal piece and act as a stress reducing medium, caused by the different thermal expansion coefficients of the metal and the LiNbO_3 crystal. Thirdly, and most importantly, using the cover pieces helped to solve the problem of fibre to waveguide butt-coupling: it is reasonable to believe that the optical adhesive used for fibre to waveguide coupling would continue to cure and contract slowly with time; when cover pieces were not used (e.g. for the first IOPC made in the lab), the lower half of the fibre end which was against the crystal edge had very little glue in front of it and therefore would not move much due to this contraction. The upper half of the fibre end, on the other hand, did not have any thing but a blub of glue in front of it; this glue could contract and pull the fibre out of alignment (mostly angular misalignment). When the cover pieces were used, the upper and lower portions of the fibre end would encounter similar conditions, with regard to the glue, and the angular misalignment would not occur.

The ends of the waveguides were polished using Buehler's (Lake Bluff, IL) Ecomet 4 variable speed polishing/grinding wheel and the Automet 2 power head. The speed of the polishing wheel (Ecomet 4) was at its minimum setting (50 rpm) and was in the direction

opposite to the direction of the rotation of the polishing jig. The first batch of the samples were polished as follows: they were first mounted in a polishing jig, and their ends were rough ground (240 grit grinding paper) at ten pounds pressure until the samples containing the waveguides and their cover pieces were levelled with each other; then, the rough grinding was continued for another 10 minutes at one pound. Next, the samples were fine ground (600 grit paper) for 10 minutes at ten pounds followed by 30 minutes at one pound in each of the two possible rotation directions. At last, the waveguide ends were polished for 10 minutes at 10 pounds and 20 minutes at one pound in each direction using one micron alumina slurry on a polishing cloth. At each stage through the grinding and polishing, the waveguide ends were checked under microscope to control the improvement in the polishing. Finally, the samples were removed from the jig and cleaned in trichloroethylene, isopropyl alcohol, and DI water, and blown dry with nitrogen.

Later devices were polished through similar steps with some variations in grinding, polishing materials, and timings, as the procedure was constantly being updated and improved.

3.3. System Integration

3.3.1. Introduction

When the fabrication of the waveguides was completed, the sensor was assembled as shown in Figure 3.4. Here is a brief outline of the assembly procedure: first, the polarized laser light was coupled to the polarization preserving fibre. Great care was taken to couple most of the light into only one of the two perpendicular polarization axes of the fibre. Next, the light from the fibre was coupled to several waveguides on a block of lithium niobate, and the best waveguide, which gave high power, good bias (near 90° intrinsic phase), and was single mode, was chosen. The block of lithium niobate was then glued on an aluminum block, and the fibre was glued to the waveguide and the aluminum block. After gluing, this fibre was separated from the laser at its connector and was used as the output fibre; note that the orientations of the input and the output fibres with respect to the waveguide are virtually identical (see chapter 2). Another piece of fibre, to become the input fibre, was then connected to the laser and the other end of the chosen waveguide just like the first fibre. The output fibre (which was attached first) was then connected to the optoelectronic conversion unit.

The detailed process of assembling the sensor is explained in the following sections.

Figure 3.4. System set-up for the integrated optics Pockels cell high voltage sensor.

3.3.2. Optical Source

The optical power source for the IOPC was a LaserMax Inc.'s (Rochester, NY.) LAS-200-670 index-guided diode laser. The laser composition was InGaAlP, and it was operating in CW mode (Continuous Wave); the operating optical wavelength was 670 nm (red), and the laser output power was about 9.5 mW. Allowing 20 dB loss of optical power from the laser through the sensor to the detectors, we expected to receive about 0.1 mW of optical power at the diode photo-detectors. This 0.1 mW power can be well-detected by the photo-detectors with relatively little noise.

The laser light had to be better than 200:1 polarized for our device to have a large On/Off ratio (see chapter 4) and low noise. The output of the laser was tested, and it was about 370:1 polarized which was quite satisfactory.

Another point of consideration in choosing the laser was the amount of noise in the laser output. The accuracy of measurements can be directly affected by the RIN noise of the laser light. Our LAS-200-670's noise was low enough for our measurements, and up to 99.8% accuracy in measurement was obtained through filtering for 60 Hz measurements. If a wide bandwidth of operation or higher accuracy is required, it is advised to choose a laser with less noise (which will probably cost more).

3.3.3. Fibre Preparation

The fibres used for the IOPC were model F-SPV circular-core single-mode birefringent polarization-maintaining optical fibres (from Newport Instruments Canada Corp., Mississauga, Ontario). The core and cladding diameters were 4 and $125 \pm 2 \mu\text{m}$ respectively, and the fibres were single mode for red light ($\lambda_o \sim 630 \text{ nm}$). The numerical aperture of the fibres was about 0.1.

The fibres needed to be connectorized at the ends where they were to be attached to the laser, detectors, or other fibres, and Oz Optics' (Carp, Ontario) SMPC-02 connectors (NTT/FC type) were used for this purpose. The ends of the fibres to be attached to the Ti:LiNbO_3 waveguides, on the other hand, did not need any connectors. The ends of the fibres which needed to be connectorized were soaked in trichloroethylene for about one

minute, and then the jacketings were removed for about 4 centimetres. A two-part epoxy was applied to the claddings, and the fibres were put through the ferrules of the connectors. After about ten minutes, when the epoxy had cured, the ferrules, and the fibres in them, were ready for polishing.

The fibre ends needed to be well polished to avoid scattering the light coming to or leaving the fibres. Buehler's FIBERMET optical fibre polishing machine was used for polishing the ends of the fibres. Using different adaptors, the polishing machine could be used for both connectorized and bare fibre polishing. By cleaving the fibres before polishing, the best polishing results, in the shortest times, could be achieved. In general, bare fibre polishing was very much faster than connectorized fibre polishing because of the relatively large ferrule end which had to be polished with the fibre. However, greater care was necessary for bare fibre polishing because very little additional pressure would break the fibre; the fibre feed control on the polishing machine had to be set to a very slow speed to avoid fibre fracture. The fibre ends were first polished on the rough polishing disk (3- μm alumina) until no chips or fractures were remaining on them. Sometimes, bare fibres had to be re-cleaved and the polishing had to be repeated in order to get rid of chipped fibre ends. The rough polishing time could be as short as five minutes for well-cleaved carefully-fed bare fibres or as long as two hours for connectorized fibres. In cases where there were some chips in the connectorized fibres, hand grinding the fibre first (using a specially made jig) could significantly improve the rough polishing time. After rough polishing, about 5 to 20 minutes of fine polishing on the 0.3- μm micron polishing disk would complete the fibre polishing. The fibre ends were then cleaned with some DI water and alcohol. During

polishing, the ends of the fibres were periodically checked under a microscope to monitor the progress.

3.3.4. Laser to Fibre Coupling

Oz Optics' HPUC-23-670-p-1 high power laser to fibre source couplers were used for coupling the laser light to the fibre. The HPUC coupler basically consisted of a focusing lens, to focus the laser light on the fibre core, an adjustable stage to be used for moving and tilting the fibre end (in the connector), and a female adaptor for the SMPC-02 connector.

The laser output was first checked to make sure that it was well collimated. If it was not, the lens at the output of the laser could be adjusted to improve the collimation. Then the HPUC adaptor was fixed at the laser end, and the connectorized end of the fibre was tightened on the female adaptor in front of the HPUC coupler. The light going through the HPUC coupler was focused through its lens on the core of the fibre by adjusting the screws on the tilt stage. The output of the fibre was focused through a lens on the photo-detector of an optical power meter (Newport's model 835), and the fibre output was monitored while adjusting the tilt stage. Several tries and adjustments were necessary to achieve reasonably good coupling: for our single-mode, short wavelength fibre, more than 20% coupling was considered to be reasonably good.

After an initial adjustment to obtain about 2 mW optical power out of the fibre (note that laser optical output was about 9.5 mW), we needed to worry about the polarization adjustment. The laser light needed to be coupled to only one of the two polarization

maintaining axes of the input fibre; otherwise, the light exiting the fibre would not be well polarized ($>200:1$). The ratio of the power in one polarization direction of the fibre to the power in the other polarization direction (extinction ratio) was measured using a polarizing beam splitting cube (Newport model 05FC16PB5) and the optical power meter. The beam splitting cube, just in front of the detector, was first rotated such that a maximum power was read on the detector. Then, the cube was further rotated (about 90°) until a minimum power was read. The ratio of these two powers gives the extinction ratio. As the laser light had a 370:1 polarization, an extinction ratio of about 370 was ideally desired. The screw on the back of the fibre connector (SMPC-02) could be rotated by hand to rotate the ferrule in the connector. In this way, while having the connector tight in the female adaptor of the HPUC coupler, the ferrule of the connector was rotated and the extinction ratio was measured until an extinction ratio of about 340 was obtained. Then, the tilt stage was further adjusted to improve the coupling efficiency. Thirty percent power coupling, which is quite satisfactory, could be typically obtained; i.e., close to 3 mW of optical power would come out of the fibre. At the end, the rotation screw on the back of the connector was glued to the connector, using a two-part epoxy, to avoid further rotation of the ferrule and hence to maintain the polarization.

3.3.5. Fibre to Fibre Coupling

A completely integrated system consists of a laser, input fibre, the waveguide in lithium niobate crystal, the output fibre, and the detecting circuit all permanently attached to

each other. It was desired to have a modular system where the light source, the lithium niobate sensor, and the photo-detecting circuits were not attached to each other in the lab, rather they could be connected to each other after installing the sensor in the field. To achieve such a modular system, connectors were used within the input and the output fibres. The two Ti:LiNbO_3 waveguide ends were attached to two short (1 m long) fibre pieces in the lab, and the other ends of these short fibres were connectorized. Two other long (about 50 m) pieces of fibre, each connectorized on both ends, were used to bring the light from the laser to the short input fibre, and to take the output of the Pockels cell from the short output fibre to the photo-detecting circuit (see figure 3.4). Oz Optics' SMPC-02 connectors were used for this connectorization. SMPC-03 (from Oz Optics) female adaptors for fibre to fibre coupling were used to match two connectors and achieve fibre to fibre coupling.

Fibre to fibre coupling was achieved in the following steps: the laser light was first coupled to one of the connectorized long fibres as explained in the previous section. Then, the other end of the long fibre was connected to the connectorized end of the short fibre through the SMPC-03 adaptor. It was very important to maintain low coupling loss and high extinction ratio through this fibre to fibre coupling. SMPC-03 adaptors were relatively precisely made, and it was possible to obtain less than 1 dB coupling loss at the connection. While monitoring the light coming out of the bare end of the short fibre, the screws on the back of the SMPC-02 connectors attached to the SMPC-03 adaptor were turned (and therefore so did the ferrules in the connectors) until the output of the short fibre had an extinction ratio very close to that of the long fibre connected to it. After obtaining a good extinction ratio (about 250:1), the screws on the back of the connectors were glued so that

they could not turn any further, and therefore, the alignment and the extinction ratio could be maintained in the long term. The connectors could be detached from or re-attached to each other as required as soon as the glue was completely cured.

After one connection was complete, the long fibre was detached from the laser, and the other short and long fibres were connected in the same way (as explained in the previous paragraph).

Our fibre to fibre couplings had fairly good results: power loss was typically about 1 dB, and the extinction ratio would drop from about 340:1 (25.3 dB) to about 250:1 (24.0 dB) due to the coupling.

3.3.6. Fibre to Waveguide Coupling

Several lithium niobate samples were first tested to find a device (waveguide) with the proper bias and good throughput (more information on this later in this section). After choosing the sample which had the good device in it, and before permanent attachment of the bare fibre to the waveguide in lithium niobate, the lithium niobate crystal had to be fixed on a metal block. The metal block, usually made of aluminum or steel, was modular and consisted of three pieces (see figure 3.5): a middle piece about one centimetre longer than the waveguides, and two side pieces each about three centimetres long. This metal block was about 5 mm thick and 25 mm wide. The three pieces could be precisely connected by pins to ensure that they would maintain one flat surface without sharp edges after being put together; it was important to avoid sharp metal edges because the sensor had to be placed in very high electric field regions.

IMPRUV-349 (from Loctite Canada Inc., Mississauga, Ontario) optically-clear UV curing adhesive was used as the glue. The lithium niobate cover piece (see section 3.2.8) was glued on the middle metal piece such that the waveguide ends were about 0.5 cm from the middle piece's edges; in this way the fibre positioner could be brought close to the waveguides, and therefore, only about 1 cm of fibre had to hang out of the positioner. If the piece of fibre hanging out of the positioner was longer, the fibre would bend slightly due to its weight, and the positioning accuracy would be decreased.

The polished bare fibre was put in the micro-positioner and was rotated until the polarization direction of the output of the fibre was substantially at 45° to lithium niobate

Figure 3.5. The metal base for the Pockels cell to be mounted on.

wafer's surface; in this way equal amounts of light would be coupled into the TE-like and TM-like modes of the Ti:LiNbO_3 waveguide. Then the fibre was brought close to the crystal edge, where the waveguide ends were, and the positioner was adjusted to couple the light from the fibre to one of the waveguides. A lens at the other end of the waveguides focused

the light coming out of the waveguides through the polarizing beam-splitting cube onto the optical power detector. Using an aluminum plate electrode on the top of the crystal, and the other metal piece (already glued) at the bottom of the crystal, an electric field was applied to the crystal in the y-direction. The output power as a function of the applied voltage to the electrodes was obtained on the scope (see chapter 4), and the intrinsic phases (bias) of the waveguides in the crystal were measured one after another. Then a single-mode waveguide (guiding only two modes: the fundamental TE-like and the fundamental TM-like modes) with an intrinsic phase of close to 90° and relatively good throughput was found for permanent attachment to the fibre. The waveguides which had three to four micron wide pre-diffusion Ti strips were generally single-mode whereas the wider waveguides were multi-mode.

After finding the best waveguide in the wafer as explained above, the fibre had to be glued to the waveguide's end. Again Loctite's IMPRUV 349, optical adhesive was used for bonding. Without changing any other micro-positioner adjustments after having found the appropriate waveguide, the fibre was pulled back for about 3 mm. Next, the fibre end was pushed into a blob of the adhesive which was held in front of the fibre. It was then pulled out in such a way that very little glue remained at the end of the fibre. Then the fibre was pushed forward by the positioner until it was again in contact with the waveguide (with the glue in between). Fine adjustment on the positioner allowed the fibre to be aligned for maximum coupling. The adhesive worked as a partial index matching medium and further improved the coupling by about 50%. After maximum coupling was achieved, the glue was cured for about 3 minutes by exposing it to ultra-violet light from a Norland Opticure Light Gun (Norland Products Inc., New Brunswick, NJ).

Figure 3.6. The curved plexiglass piece used in fibre attachment.

This connection had a very good accuracy and stability because very little glue was used at the end of the fibre; consequently, further shrinkage of the glue during the cure did not disturb the alignment. However, due to the small area of the bond, the bond could withstand only small forces. To solve this problem, the fibre was fixed on the plate about 3 to 4 mm behind the bond in the following way: a small piece of plexiglass, flat on one side and rounded on the opposite side was made; it was about 2 mm wide, 8 mm long, and 1 mm thick at the centre (see figure 3.6). The plexiglass was pushed underneath the fibre from the side until the rounded side of the plexiglass was just touching the fibre. Then the plexiglass was glued to the metal plate, and, in turn, the fibre was glued to it. Further shrinking of this large blob of glue would not affect the alignment significantly because this bonding was

several millimetres away from the fibre-waveguide interface. In summary, the coupling accuracy was obtained by that very small connection at the end of the fibre, and the strength of the connection was obtained by this larger attachment at about 3 mm behind the fibre-waveguide bond. This successful technique of fibre to waveguide bonding was suggested by Dr. M. Belanger of the National Optics Institute, Ste. Foy, Quebec.

At this stage, the fibre was released from the micro-positioner, and the side metal piece was attached and glued permanently to the middle piece, which had the device on it. Another plexiglass bonding of the fibre to the metal plate was done in the middle of the side metal piece, and about 1 cm of the fibre, behind this bond, was glued (using two-part epoxy) on the metal piece for further strengthening the fibre-waveguide attachment.

After attaching the first fibre to one side of the waveguide, this fibre was used as the output fibre; this fibre was detached from the laser at the connector, and the direction of the polarization axes of the fibre was marked on the connector for further use (for connection to the detector). The second fibre was attached to the laser in the same way that the first fibre had been attached to the laser (see laser to fibre coupling section in this chapter). Then the bare end of the second fibre was bonded to the waveguide, just like the first fibre bonding, as explained in the preceding few paragraphs. The only difference was that for the second fibre bonding (the input fibre), we did not need to test the waveguides to find an appropriate device; the appropriate device was already chosen. The properly oriented fibre was brought close the other edge of the crystal using the micro-positioner. The micro-positioner was adjusted while the output of the previously bonded fibre, the output fibre, was being monitored by an optical power meter. When the optimum coupling was achieved, the

input fibre was bonded to the waveguide in the way that was explained above (see figure 3.7).

Figure 3.7. The picture of a completed IOPC.

The total input fibre to output fibre loss was typically 10 to 13 dB. The major contributors to this loss were input fibre to waveguide coupling loss, waveguide attenuation in the lithium niobate, and waveguide to output fibre coupling loss.

3.3.7. Optoelectronic Conversion Unit

At the detecting end, the output of the fibre was focused through a graded index

SELFOC lens and was passed through a polarizing beam splitter (Newport model 05FC16PB5). The beam splitter was positioned such that it would separate the light coming out of the two orthogonal axes of the interrogating (output) fibre. The two separated components were measured using photo-detectors (in the later systems, model 1801 from New Focus Inc., Mountain View, CA was used), and the optical powers were converted to voltages. An electronic conversion unit basically consisting of operational amplifiers was made (not by the author) to process the received signals and to produce a normalized output. The output of the unit was basically the ratio of the signal from one of the detectors to the sum of the signals from both of the detectors (the total power received from the output fibre). This normalization would ideally make the measurement insensitive to the variations in the coupling efficiency or in the laser power with time.

System integration was completed after attaching the output fibre to the optoelectronic conversion unit, and the sensor was ready for field testing.

Chapter 4

Results

4.1. Introduction

Tests were done on the IOPC's to characterize their performance under various conditions. In this chapter the results of these tests are presented. Some experiments were conducted to measure basic device characteristics, such as device intrinsic phase (bias), extinction ratio, half-wave electric field, and throughput. Other experiments were designed to detect and/or measure other effects such as how the waveguide width or length affected the intrinsic phase, linearity, noise, piezoelectric resonance frequencies of the crystals and their effect on the bandwidth of the sensor, and the effect of temperature on the sensor performance. These effects are described in the following sections.

4.2. Basic Device Parameters

Some device (waveguide) parameters had to be measured before we attached the fibres in order to find devices with acceptable performances. Here, the basic parameters of interest were the device intrinsic phase (close to 90° was desired), the half-wave electric field, the extinction ratio (on/off ratio), and the optical throughput.

For preliminary testing, metal electrodes, evaporated on both sides of the crystal ($\pm y$

faces), were used to apply voltage and create an electric field in the crystal. Final tests were done on completed devices which, of course, did not have metal electrodes; parallel metal plates were used to generate the electric fields in which the devices were tested. Because of the air gap between the plates and the crystal, fairly large voltages (of the order of 1 kV) had to be applied to the plates to obtain a significant electric field in the crystal. For example, for a one millimetre thick crystal of lithium niobate and a one millimetre thick air gap between the plates and the crystal, application of 0.7 kV to the plates would create an electric field of about 10 V/mm in the crystal ($\epsilon_y \sim 72$ [22] for lithium niobate). With metal electrodes evaporated on the crystals we were able to work with lower voltage levels for our preliminary tests. Compared to the example above, with evaporated electrodes on the crystal (air gap thickness = 0), 10 V/mm electric field in the crystal could be obtained by applying only 10 volts to the electrodes. For devices with metal electrodes evaporated on the crystal, the half-wave electric field is equal to the half-wave voltage (applied to the electrodes) divided by the crystal thickness.

The electric-field-in/normalized-optical-intensity-out transfer function of the IOPC was given in chapter 2 (equation 2.8) as

$$S = \frac{1 \pm \alpha \cos\left(\frac{\pi E_y}{E_\pi} + \phi_i\right)}{2} \quad (4.1)$$

where E_y is the electric field in the crystal in the y crystallographic direction, and E_π , ϕ_i , and α are device-dependent parameters (see section 2.2). These parameters can be experimentally determined by obtaining the transfer function on the oscilloscope. We define the extinction

ratio R as the ratio of the peak-to-peak intensity of the modulated signal to the maximum output intensity of the Pockels cell [15]; i.e. $R = [(2\alpha / (1+\alpha))] \times 100\%$. R , as defined here, can be easily measured from the transfer function obtained on the oscilloscope (see figure 4.1 for example), and α can be calculated from R . Considering that the input light is not perfectly polarized (e.g. about 250:1 out of the fibre), and other imperfections exist in the fabrication process, extinction ratios less than 100% are expected in the experimental results.

Figure 4.1 [18] shows the transfer function of one of the devices fabricated. The voltage applied to the electrodes on the sample was measured on channel 1 of our HP 54600 digital oscilloscope (from H.P., Palo Alto, CA), and the optical intensity out of the Pockels cell, measured using a Newport Model 835 optical power meter, was obtained on channel 2 of the oscilloscope. The oscilloscope is being used in X-Y mode where channel 1 is displayed on the x axis and channel 2 on the y axis.

The lithium niobate sample containing this device was 16.2 mm long and nominally 0.4 mm thick. The pre-diffusion titanium strip width was 3 μm , and its thickness was 55 nm. From this transfer function the half-wave electric field, E_π , was measured to be about 270 V/mm. The theoretical value of E_π , given by equation (2.5)

$$E_\pi = \frac{\lambda_o}{2 n_o^3 r_{22} L} \quad (4.2)$$

was about 260 V/mm, very close to the experimental value. The parameters of equation (4.2) were explained in section 2.2.

The intrinsic phase difference can be measured from the transfer function (figure 4.1)

Figure 4.1. The electric-field-in/optical-intensity-out transfer function of an IOPC. The sample length and thickness are 16.2 mm and 0.4 mm respectively.

to be

$$\phi_i = 180^\circ \times \left(\frac{E_m}{E_\pi} \right) \quad (4.3)$$

where E_m is the absolute value of the negative electric field to be applied to achieve minimum output intensity. ϕ_i was measured to be about 95° on the transfer function in figure 4.1. R was also measured from the data points on the transfer function; it was better than 99.2%.

Figures 4.2a and 4.3 through 4.8 show the transfer functions obtained on the oscilloscope for some other devices. Device parameters for these figures are listed in table 4.1; note that the transfer functions here are not normalized (see section 2.2).

Table 4.1. Device parameters for figures 4.2 through 4.8

Figure Number	Sample Length (mm)	Sample Thickness (mm)	Pre-Diffusion Ti Width (μm)	Half-wave Voltage (V)	Intrinsic Phase (Degrees)	Extinction Ratio (%)
4.2	28.5	0.4	4.0	60	464	> 99
4.3	28.5	0.4	3.0	62	310	96
4.4	16.2	0.38	4.0	116	280	99
4.5	8.4	0.4	3.0	201	50	99.4
4.6	8.4	0.4	4.5	201	94	97
4.7	7.1	0.4	3.5	235	101	99
4.8	5.3	0.38	4.0	353	84	97

Figure 4.2b shows the applied voltage and the measured output intensity as functions of time for the device whose transfer function is shown on figure 4.2a. The upper signal in figure 4.2b shows the voltage applied to the electrodes on the crystal, and the lower signal shows the optical intensity out of the sensor measured by an optical power meter.

A bias of $\phi_i \sim 90^\circ$, and a large extinction ratio were not the only critical factors for choosing a device. For a waveguide to be selected for sensor fabrication, it also had to have good optical throughput. If the attenuation in the waveguide was too large, very little optical power would reach the photo-detectors; and therefore, the photo-detector noise would become significant as compared to the received optical signal. This would, of course, degrade the accuracy of the measurements.

For our photo-detectors, about $50 \mu\text{W}$ of optical power was required to achieve fairly good signal to noise ratios ($> 30 \text{ dB}$ after filtering). In the preliminary tests, where no

fibre attachment was done, and no index matching medium was used, typically about 0.3 mW total optical intensity would reach the photo-detectors. In these tests the optical power out of the input fibre was about 2.5 mW (laser output ~ 9 mW), and the light out of the waveguides was focused through a lens and the beam-splitter on the photo-detectors. For sensors completely integrated in their final forms, typical losses due to fibre-waveguide butt couplings with the addition of the waveguide attenuation were about 10 to 13 dB (see chapter 3). In other words, over 50 μ W (the target value) of optical power would reach each of the two photo-detectors.

(a)

(b)

Figure 4.2. (a) The transfer function of an IOPC. (b) The applied voltage (upper trace) and the measured output intensity (lower trace) as functions of time. The horizontal line shows the dark level.

Figure 4.3. The transfer function of an IOPC. The horizontal line shows the dark level. Device parameters are listed in table 4.1.

Figure 4.4. The transfer function of an IOPC. The horizontal line shows the dark level. Device parameters are listed in table 4.1.

Figure 4.5. The transfer function of an IOPC. The horizontal line shows the dark level. Device parameters are listed in table 4.1.

Figure 4.6. The transfer function of an IOPC. The horizontal line shows the dark level. Device parameters are listed in table 4.1.

Figure 4.7. The transfer function of an IOPC. The thick horizontal line shows the dark level. Device parameters are listed in table 4.1.

Figure 4.8. The transfer function of an IOPC. The horizontal line shows the dark level. Device parameters are listed in table 4.1.

4.3. Effect of Device Length on the Intrinsic Phase Difference

One of the most important factors in the performance of the IOPC is the intrinsic phase of the device. The applied-electric-field-in/optical-intensity-out transfer function of the Pockels cell, equation (4.1), is basically a sinusoidal function with some DC offset. For the measurements made by the Pockels cell to be accurate, the device should be operated only in the linear region of its transfer function; therefore, it needs to be biased at $\phi_i \approx 90^\circ$ (or an odd multiple of 90°).

The light entering the waveguide can be well polarized ($> 200:1$) at 45° to the x and y crystallographic axes of the lithium niobate crystal. This results in nearly equal amounts of optical power being coupled to the TE-like and the TM-like modes propagating in the waveguide. The propagation constants, and therefore the phase velocities, for these two modes, travelling in the waveguide, are slightly different; as a result, at the output of the waveguide, these two modes will have some phase difference which we call the intrinsic phase difference or, simply, the bias (see chapter 2). This intrinsic phase difference appears in the transfer function (4.1) as ϕ_i . If it is 90° , equation (4.1) can be re-written as

$$S = \frac{1 + \alpha \sin\left(\frac{\pi E_y}{E_\pi}\right)}{2} . \quad (4.4)$$

For applied electric fields much smaller than E_π , the approximation of $\sin(x) \approx x$ will introduce negligible error, and the transfer function can be considered linear.

The propagation constants of the two TE- and TM-like modes, and consequently the

bias, depend very much on the fabrication parameters of the waveguide. However, it is not easy to control fabrication parameters, such as pre-diffusion Ti strip width and thickness, and the diffusion time and temperature, accurately to achieve the required bias (for a pre-determined device length). If, on the other hand, after waveguide fabrication, the device is cut to a length where the two modes are out of phase by $\pi/2$ radians (90°), the device will have the proper bias.

We expected that the device bias was linearly dependent on the length. To verify this assumption, a few devices were cut at different lengths and their intrinsic phases were measured. Figures 4.9 through 4.11 are plots of device biases as functions of device lengths for these devices. Allowing for about ten percent error in the measurements, the graphs establish the validity of the above assumption.

It should be noted that because of the different fabrication parameters, different devices' intrinsic phases should not be compared as functions of their lengths only. Each line on figures 4.9 - 4.11 represents one device which was cut back to different lengths and tested through several steps. Moreover, the devices represented in each of the figures 4.9, 4.10, and 4.11 are at most 200 μm apart.

In conclusion, we can now fabricate a waveguide first, and after measuring its bias, we can cut it to a length which will result in it having the proper bias. For example, if the fabricated device is 15 mm long and has a bias of 135° , it can be cut back to 10 mm so as to have an intrinsic phase of about 90° .

Figure 4.9. The effect of the device length on its intrinsic phase (bias) (sample 1).

4.4. Effects of Pre-diffusion Titanium Width on the Device Performance

The pre-diffusion titanium strip width directly affects the width of the waveguide produced by the diffusion of that strip into the lithium niobate. There are two ways that the waveguide width affects the performance of the IOPC. First, the number of modes that are

Figure 4.10. The effect of the device length on its bias (sample 2).

guided depends on the waveguide dimensions. If the waveguide is too narrow, it will not guide the light (obviously a problem), and if it is too wide, it will guide more modes than just the two fundamental TE- and TM-like modes; in short, the device will be multi-mode. The modal field distributions (mode profiles) and the effective propagation constants for higher order modes are different from those of the fundamental modes; therefore, the

Figure 4.11. The effect of the device length on its bias (sample 3).

inclusion of the higher order modes affects the bias, the extinction ratio, and some other parameters of the device. In order to be able to control device parameters, and therefore performance, we would like to have waveguides which guide only the fundamental TE-like and TM-like modes.

We fabricated devices with their pre-diffusion titanium strips 3 to 10 μm wide. The

strip widths were increased by $0.5\ \mu\text{m}$ from one device to the next. Devices with pre-diffusion titanium strip widths of 3.0 , 3.5 , or $4.0\ \mu\text{m}$ were generally single-mode; i.e. they would guide only the fundamental TE-like and the fundamental TM-like modes. Wider waveguides were generally multi-mode with some of the $4.5\ \mu\text{m}$ wide ones being single-mode. The pre-diffusion Ti strip thickness was between 40 and $55\ \text{nm}$ for various devices.

The second way that the waveguide width affects the performance of the sensor is by its effect on the device bias. Figure 2.5 demonstrates the effect that the waveguide's width has on the bias of a channel waveguide (see section 2.3). This figure clearly shows that the waveguide length l which gives circular polarization at the output is smaller for wider waveguides; in other words, wide devices will have larger intrinsic phases as compared to narrow devices of the same length.

Titanium indiffused waveguides, however, have rather different refractive index profiles [27] as compared to our rectangular channel waveguide model. We conducted an experiment to measure the waveguide bias as a function of its pre-diffusion Ti strip width for several waveguides in a single crystal: the result is plotted in figure 4.12. To have a valid comparison among different waveguides, we have to make sure that they were fabricated under identical conditions. All the devices represented in figure 4.12 were on the same lithium niobate sample, and the devices in each cluster had, at most, $200\ \mu\text{m}$ between them. Therefore, it is fair to assume that all fabrication parameters, except for the pre-diffusion Ti strip width, were virtually the same for the devices in one cluster. Figure 4.12 clearly indicates that wider devices have generally larger intrinsic phases as was suggested by our channel waveguide model. The slope of the least squares fit line is about $90^\circ/\mu\text{m}$, and the

devices are 16.2 mm long.

Figure 4.12. Device bias as a function of pre-diffusion titanium strip width.

Similar measurements on other devices with different lengths and fabrication conditions gave a change in bias per unit width per unit length of between 4.2 and 5.7°/ $\mu\text{m}/\text{mm}$ [18]. This variation of the device bias based on the device width can improve the practicality of fabricating properly biased devices. For example, several waveguides with 3 to 4 μm wide initial Ti strips, at 0.1 μm steps, can be made in one crystal. After cutting the crystal at a length which is expected to give a properly biased device, all the devices on

the crystal can be tested for their biases, and the one with the best bias can be chosen for fibre attachment.

4.5. Sensor Linearity and Noise

IOPC high voltage sensors can find applications in metering, protection, and fault location in power distribution systems. Currently, there are no widely accepted standards for integrated optical sensors; however, Erickson [49] has suggested some values and ranges as standards. Translating from his charts [50], these ranges are approximately as follows: in metering an error of no larger than 0.3% from 40 Hz to 4 kHz is allowed for a dynamic range of 1 pu (per unit), for protection an error of 2% to 6% can be tolerated from 0.1 Hz to 30 kHz for a dynamic range of 2.2 pu, and for fault location the error in measurement can be 6% to 8% above 30 kHz for a dynamic range of 2.4 pu. Clearly, there can be trade-offs between the bandwidth of the sensor and the accuracy of its measurements for different applications.

Figures 4.13, 4.14, and 4.15 show the result of measurements on a fully connectorized IOPC. The lithium niobate crystal comprising the sensor was about 8 mm long, 6 mm wide, and 0.4 mm thick. The electric field was applied using a metal plate parallel to the metal base on which the crystal was mounted. The air gap between the crystal and the high voltage plate was about 1.5 mm. The upper trace in figure 4.13 represents the applied signal, and the lower trace is the signal out of the sensor. The output of the sensor was AC coupled and band-pass filtered (10 Hz - 2 kHz) to reduce noise.

Figure 4.13. Small signal operation of the IOPC. The upper trace shows the applied signal, and the lower trace shows the filtered output of the sensor.

Figure 4.14 is a graph of the rms output of the sensor versus the rms applied signal (60 Hz). Each data point corresponds to application and measurement of one signal to the sensor. Here, the output of the sensor was band-pass filtered between 10 Hz and 2 kHz. The straight line is a least squares fit to the measured data. The rms deviation of the measured data points from the straight line is about 0.27%. This deviation includes device non-linearities and noise.

Figure 4.15 is a graph of the sensor output as a function of the applied sinusoidal signal. The output of the sensor was band-passed filtered between 37 Hz and 4 kHz, and the straight line is a least squares fit to the data points obtained by the digital scope (HP 54600). There are more than 300 data points in the graph, sampled at 0.02 ms time intervals. To reduce the scope quantization noise, the samples were averaged over 9 samples. This

Figure 4.14. The rms output of the sensor vs. the rms applied signal.

averaging also acts as a digital low pass filter with its cut-off at over 5 kHz ($1/0.18 \text{ ms}^{-1}$). Since the rms deviation of the data points from the line is about 0.3%, this device meets the standards suggested by Erickson [49].

There were several sources of noise in the measurements. Laser noise, device induced noise (due to optical damage in the waveguide), photo-detector noise, and the scope A/D

Figure 4.15. The sensor output as a function of the applied sinusoidal signal. Taken over a single cycle.

quantization noise were some major sources of noise in our measurements. The photo-detector noise was negligible unless the device throughput was very low. For optical powers more than $50 \mu\text{W}$ reaching the photo-detectors, the detector signal to noise ratio would be sufficiently high. For the experiment the result of which is plotted in figure 4.15, the device throughput was, nevertheless, fairly low, and only few μW of optical power reached the

detectors. Most of the detector noise was eliminated by the band-pass filter. Detector noise, laser noise, and device induced noise are generally spread across a large frequency range, and their effects can be significantly reduced by band-pass filtering. For example, the signal plotted in figure 4.15 would have about 5% rms noise instead of 0.3% if the upper frequency of the band-pass filter used was 20 MHz instead of 4 kHz. In addition to filtering, we could use better (low-noise) lasers and detectors to reduce the noise.

Our scope quantization noise, on the other hand, had to be treated differently as the scope was not a part of the Pockels cell sensor. The scope used 8 bit digital units to store the measured values. This means that at least 0.2% of the rms deviation from the straight line fit to the data points can be due to the scope quantization noise. In conclusion, the signal from the sensor can be monitored on analog instruments or better digital equipment to minimize this quantization effect.

The noise induced in the device is believed to be mostly due to the optical damage caused by the photo-refractive effect in the waveguide [51, p. 5]. It is reported [51] that in order to keep the photo-refractive effect negligible when working with 633 nm light, the optical power through the waveguides should not exceed a few micro-Watts. This was obviously not the case for our devices; optical powers over 200 μW passed through some of these waveguides operating with $\lambda_o = 670$ nm light. Nevertheless, as it was reported before in this section, we were able to limit the error to 0.3% (as required by Erickson's standard) by filtering. To further improve this, we can build a system operating at longer wavelengths since, for example, it is reported [52] that for 1.3 μm light, the photo-refractive effect in lithium niobate waveguides would be negligible for an optical power below 20 mW.

The approximation of $\sin(x) \approx x$ also introduces more than 0.3% error if x is larger than 0.14 radian (8°). For the experiments resulting in figures 4.13, 4.14, and 4.15, the applied signal was kept sufficiently low ($[\pi E_y/E_\pi] < 0.1$ rad). However, it is desired to be able to increase the dynamic range without increasing the noise or the non-linearities, and therefore, to decrease the normalized error in the measurements. Numerical processing of the output of the sensor is one of the ways to increase the dynamic range without sacrificing the linearity. For example, the approximation of $\sin(x) + a \sin^3(x) \approx x$ can introduce less than 0.1 percent error for absolute values of x less than 0.55 radian (31°) if the constant " a " is chosen properly ($a = 0.188$). This error is significantly lower than the error due to $\sin(x) \approx x$ approximation (see figure 4.16). For implementing this technique, when metering a 60 Hz signal for example, the output of the sensor can be AC coupled so that only the sinusoidal signal would remain. Then a digital signal processing unit can be designed to sample the output and to carry the tasks of additions and multiplications in real-time to achieve better device performance.

4.6. Stability

One of the important considerations in the performance of integrated optical devices is the stability of device parameters. For example, for our IOPC, the changes in parameters such as the bias or the throughput of the device with time has to be considered in order to have correct measurements made by the sensor.

Figures 4.17a and 4.17b show the transfer functions for one device after turning the

Figure 4.16. The percentage error introduced by the trigonometric approximations.

laser source on for one minute and two hours respectively. A bias drift of about 2° occurred in about two hours. However, when the laser source was left on for a longer time, the bias did not shift further; in fact, it became quite stable after several hours. Because the laser can, and should, be kept on at all times in applications such as high voltage metering, the original drift can be over-looked as long as the stabilized bias is close to its intended value

(a)

(b)

Figure 4.17. Applied-voltage-in/optical-intensity-out transfer function of an IOPC (a) one minute and (b) two hours after turning on the Laser.

of 90° . Moreover, this drift depends mainly on the wavelength and on the optical power [51], [53]. It should be negligible for lower optical powers or longer wavelengths. As mentioned before, at visible wavelengths the power should be kept under a few micro-Watts to avoid the photo-refractive effect [52] and the DC drift [53] whereas typically over $100 \mu\text{W}$ of optical power passes through our waveguides. We can make IOPC's operating at longer wavelengths, for example $1.3 \mu\text{m}$, in order to further improve the sensor performance [53].

Another point of concern is the stability of the total optical power reaching the detectors. If the laser power increases or decreases, due, for example, to changes in the power supply, the amount of optical power reaching each detector will change. If the signal detected on each photo-detector was independently considered, this power fluctuation would cause an error in the measurement (would add a DC offset to the measured signal). This is, however, not a problem for our sensors because, according to the design of the system, the optoelectronic detecting circuit normalizes the signal from one of the photo-detectors with respect to the total power passing through the device (sum of the signals measured on the two photo-detectors). Thus, the response of the sensor (see equation 2.8) would be independent of the fluctuation in the optical power.

The effect of temperature change on the performance and specially on the bias of the sensors is another major point of consideration. The bias can be influenced by the temperature in several ways: longitudinal expansion or contraction due to temperature changes can alter the optical path length in the crystal and, therefore, affect the bias; or the refractive indices along the different axes of the crystal can be changed due to a change in temperature; this will in turn change the phase velocity of the light passing through the

waveguide and can affect the bias.

We conducted an experiment to measure the effect of temperature on the bias of the device. The room's temperature was about 20°C for our experiment. An aluminum heating stage underneath the lithium niobate crystal was electrically heated, and the temperature of the heating stage was measured using a thermometer. Figure 4.18 shows a plot of various waveguides' intrinsic phases as functions of stage temperature. The straight lines are least squares fits to the data points for different devices. The worst case bias change with temperature was about 0.7°/°C with typical values being about 0.5°/°C. The best case values were about 0.3°/°C. These devices were 28 mm long; therefore, the bias change per unit temperature change per unit length was about 0.02°/°C/mm. For our final devices, about 6 mm long, the bias change would be about 0.1°/°C. The linearity of the sensor response is, of course, affected by the sensor bias; however, under small signal modulation, for short devices, this bias change, due to temperature change, would introduce less than a few tenths of a percent error.

This bias change can also be accounted for electronically by post-processing the output of the IOPC. For example, a digital sampling unit and a micro-computer can help improve the performance in the following way: the sampler can sample the output of the IOPC and transfer the digital results to the computer. The parameters of the transfer function of the device, i.e. E_T , ϕ_i , and α , are measured at the time of fabrication and are stored in the computer. Rearranging equation 2.8 (where the + sign is used), E_y can be found as a function of the normalized signal S as

Figure 4.18. Intrinsic phase variation as a function of temperature.

$$E_y = \frac{\left[\text{Arccos} \left(\frac{2S - 1}{\alpha} \right) - \phi_i \right] \cdot E_\pi}{\pi} \quad (4.5)$$

Note that $\sin(x) \approx x$ is not assumed any more. For fast reference, E_y - S pairs from equation 4.5 can be stored in a table in the memory of the computer, and the value of E_y can be looked up for the value of S received from the sampler.

One obvious benefit of this system is that as the dynamic range of the sensor increases we are no longer restricted to the linear region of the transfer function. Nevertheless, we still need to make sure that $\{\pi E_y/E_\pi - \phi_i\}$ stays between 0 and π radians at all times (the peaks of the transfer function should not be exceeded). Another benefit of this system is that the computer can measure ϕ_i periodically and update the $E_y - S$ pairs table according to equation 4.5. This will eliminate the effects of bias change regardless of the reason as long as $\{\pi E_y/E_\pi - \phi_i\}$ stays between 0 and π radians. Note that from equation 4.5,

$$\phi_i = \text{Arccos} \left(\frac{2S_o - 1}{\alpha} \right) \quad (4.6)$$

where S_o is the normalized response when $E_y = 0$. For instance, when metering a 60 Hz signal, S_o is the value of S sampled at about 4.17 ms (one fourth of a period) after detecting the maximum or minimum value of S (a peak-detector is needed for this purpose).

4.7. Piezoelectric Resonances

The piezoelectric resonances of the lithium niobate substrate can limit the usable bandwidth of the sensor. They can disturb the optical power passing through the device, or even break the crystal, and, therefore, should be avoided or damped as much as possible. If the first resonance frequencies are not high enough, the sensor may not be useful for fast (lightning) impulse measurements.

Lithium niobate is a piezoelectric crystal of point group 3m with a reduced piezoelectric coefficient matrix as follows [25, p. 299]:

$$d_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & d_{15} & d_{16} \\ d_{21} & d_{22} & 0 & d_{24} & 0 & 0 \\ d_{32} & d_{32} & d_{33} & 0 & 0 & 0 \end{pmatrix}$$

where $d_{21} = -d_{22}$, $d_{16} = -2 d_{22}$, $d_{15} = d_{24}$, and $d_{31} = d_{32}$.

An electric field parallel to the y crystallographic axis in lithium niobate produces longitudinal strain along the x and y axes (piezoelectric coupling via d_{21} and d_{22}) and shear strain in the y-z plane (piezoelectric coupling via d_{42}). If the frequency of the applied field and the subsequent strain is such that a standing acoustic wave is produced in the crystal, the crystal will resonate. For example, the crystal will show a first longitudinal (extensional) resonance along the x axis (the width of the crystal) at a frequency $f_r = v_s/\lambda \approx v_s/2w$ [54], where v_s is the speed of sound in lithium niobate, w is the crystal width, and λ is the wavelength of the standing acoustic wave. In other words, the piezoelectric resonance frequency is inversely proportional to the crystal dimensions. The piezoelectric resonance frequencies for several unclamped samples were measured in the laboratory; the inverse first order resonance frequencies ($1/f_r$) as functions of the widths and the lengths of the crystals are plotted in figures 4.19 and 4.20 respectively. For these devices, the crystal thickness was much smaller than the width or the length of the crystal (thickness $\sim 0.4 \mu\text{m}$); consequently, the piezoelectric resonance along the y axis (the thickness of the crystal) occurs at a much higher frequency as compared to those along the x axis or in the y-z plane. The solid lines in figures 4.19 and 4.20 are least squares fits to the data points. The speed of sound in lithium niobate, v_s , is measured from the slopes of these solid lines to be about 6.8 km/s

which is very close to 6.78 km/s reported by Turi et al [55] or other values reported in the literature [22, p. 374].

Figure 4.19. Inverse of the fundamental piezoelectric resonance frequency as a function of sample width.

The waveguides in lithium niobate are only a few microns wide or deep; thus, the crystal can be made as thin and narrow as a few tens of microns. This means that the

Figure 4.20. Inverse of the fundamental piezoelectric resonance frequency as a function of sample length.

extensional piezoelectric resonances can be at as high as a few tens of mega hertz. On the other hand, to obtain devices with proper intrinsic phase difference (90°), the samples cannot be much smaller than a few millimetres in length (see section 2.3). Therefore, the shear resonance frequency cannot be much larger than 1 MHz. The shear resonance in the y-z

plane seemed to be much weaker than the extensional resonances in our experiments. The reason for this phenomenon is probably the higher acoustic attenuation for the shear waves than that for the extensional waves in lithium niobate [55]. For unclamped samples, the shear resonance appeared to affect the amplitude of the received signal by less than 20% in our experiments whereas the extensional resonance along the width of the crystal was very strong and in few cases broke the crystal. We hope that we can eliminate the effect of the shear resonance by damping, electronically compensating, or a combination of the two, and consequently increase the bandwidth of the sensor to several mega hertz. Nevertheless, even if the bandwidth of the sensor is limited by the shear resonance, with a bandwidth of 1 MHz (3 mm long device), a sensor can successfully measure fast impulses of 1.2 μ s rise time or locate a fault within 75 metres (for time-resolved-fault-location applications).

Figure 4.21 shows a frequency scan from 2 kHz to 2 MHz on a sample glued on an aluminum block. The sample was 0.4 mm thick, 2.8 mm wide, and 7 mm long. The half-wave voltage for this device was about 240 volts, and the applied signal was about 30 volts peak-to-peak. The x axis on the graph represents the frequency (linear scale), and the y axis shows the output intensity (linear scale). The first major resonance (extensional) appears to be at about 1 MHz. Because of the damping, the resonance effect did not seem to be as severe as it was for the unclamped samples; i.e., the sample did not break, and the disturbance on the amplitude of the received signal was less than 50% here. The effect of shear resonance seems to be negligible in this scan. This sample was also used for impulse tests that are reported on in the next section.

Figure 4.21. Frequency scan from 2 KHz to 2 MHz (x axis, linear scale) for an IOPC glued on an aluminum plate.

4.8. Impulse Measurements

One of the applications of high voltage sensors is monitoring high voltage switching and lightning impulses in research laboratories. Standard switching impulses have a virtual front time of about 250 μs and a tail time of about 3000 μs . The virtual front time, T_f , is defined [56] as:

$$T_f = 1.67 \times (T_{90} - T_{30})$$

where T_{30} and T_{90} are the amounts of time that it takes for the signal to increase from zero to 30% and 90% of its maximum amplitude, respectively. The tail time, T_t , or the "time to half value" is the time that it takes for the signal to drop to 50% of its maximum value [56]. The IEC (International Electrotechnical Commission) standard for lightning impulse is the

1.2/50 impulse with $\pm 30\%$ tolerance for the front time ($1.2 \mu\text{s}$) and $\pm 20\%$ tolerance for the tail time ($50 \mu\text{s}$). If the bandwidth of the sensor used for the impulse measurement is not large enough, fast impulses will cause the sensor to resonate. The fastest signal here is the lightning front time of $1.2 \mu\text{s}$. If the device does measure this fast signal without going into resonance, it can measure all slower signals successfully.

The circuit in Figure 4.22 was used for creating the impulse signals. This was a simplified version of the model developed and analyzed by Creed and Collins [56]. When the switch was in position "a", the DC source would charge up the capacitor C_g . When the switch was turned to position "b", C_g would discharge in the circuit and create the impulse signal at the terminals of capacitor C_s . The theory developed by Creed and Collins was used for finding the original values for the circuit elements. The original values were then slightly changed after the circuit was connected to the sensor in order to obtain the impulse signal wanted. C_g was about 50 nF , C_s about 1 nF , R_t about $1.5 \text{ k}\Omega$, and the value of R_s was altered to obtain different rise times (front times). Figures 4.23 through 4.27 show the results of some impulse tests on the glued sample whose frequency scan was presented in figure 4.21. The lower traces in the scope pictures are the applied signals measured directly at the contacts to the sensor. The upper traces are the output optical intensity of the sensor. Where the rise time on the signal was measured on the figures, Δt was $(T_{90} - T_{30})$; for example $\Delta t = 0.72 \mu\text{s}$ corresponds to a $1.2 \mu\text{s}$ front time. We can see that the sensor measurement was quite acceptable for front times as fast as $0.5 \mu\text{s}$. The sensor showed some resonance (figure 4.27) when the signal rise time was faster than $0.1 \mu\text{s}$. Even for this fast signal where some disturbance can be clearly observed in the peak of the output signal, the

resonance was quite rapidly damped and the output was not severely disturbed. To summarize, the sensor is certainly capable of monitoring the switching and the lightning impulses because $1.2 \mu\text{s}$ is the fastest rise time (or fall time) needed to be measured in these signals.

Figure 4.22. Impulse generation circuit.

Impulse signals have a wide band of frequency components; therefore, a large bandwidth is necessary for systems intended to measure them, as explained before. For this reason the output of the sensor was not low-pass or band-pass filtered in a narrow band, and the amount of the noise in the output was large as compared to that of an AC signal measuring system (see section 4.5). Here, the upper band of the low-pass filter was at about 20 MHz. The minimum tolerance in the impulse measurements is much less strict than that in the AC signal metering (see section 4.5 and reference [49]); therefore, the noise is not as significant a factor here as it is in the case of the AC signal metering. Our measurements

(figures 4.23 - 4.27) did in fact meet the required standard (error and noise < 6%) suggested by Erickson. Moreover, using better photo-detectors, a better laser, and a low-pass filter with a cut-off at about 2 MHz could further enhance the performance of the system for impulse measurements.

Figure 4.23. 5.7 μ s rise-time impulse. $R_s = 0.25 \text{ M}\Omega$.

(a)

(b)

Figure 4.24. 1.2/50 μs impulse with (a) 10 $\mu\text{s}/\text{div}$ and (b) (inverted for clarity) 1 $\mu\text{s}/\text{div}$ time scales. $R_s = 5.5 \text{ K}\Omega$.

(a)

(b)

Figure 4.25. $0.9 \mu\text{s}$ rise-time impulse with (a) $10 \mu\text{s}/\text{div}$ and (b) (inverted for clarity) $1 \mu\text{s}/\text{div}$ time scales. $R_s = 3.3 \text{ K}\Omega$.

Figure 4.26. $0.1\ \mu\text{s}$ rise-time impulse. $R_s = 300\ \Omega$.

Figure 4.27. Less than $0.1\ \mu\text{s}$ rise-time impulse. $R_s = 150\ \Omega$.

Chapter 5

Conclusions and Recommendations

5.1. Summary and Conclusions

An integrated optics version of the Pockels cell (IOPC) has been developed for use as a high voltage sensor. The theory of operation of the sensor has been described, and a normalized-optical-intensity-out/electric-field-in transfer function has been derived for the sensor. A channel waveguide model has been used for estimating the parameters necessary for designing and fabricating the strip waveguides, and fully connectorized sensors have been fabricated.

One of the major challenges in developing the IOPC has been to overcome the technological obstacles encountered in device fabrication. The technological problems that needed to be dealt with, such as permanent fibre to waveguide butt-coupling for single-mode polarization-maintaining (PM) fibres, were not always straight forward and easily solved. Still, such problems needed to be successfully addressed in order to fabricate the complete sensor systems that we tested as laboratory prototypes.

Experiments have been conducted to determine the performance of the sensor. Parameters such as half-wave voltage, intrinsic phase, and extinction ratio, have been measured for several devices, and the effect of sensor head waveguide geometry on the intrinsic phase has been studied. For instance, it has been shown that the intrinsic phase is

dependent on the pre-diffusion titanium strip width; therefore, it is possible to fabricate several devices with various pre-diffusion titanium strip widths on one lithium niobate substrate and find a waveguide with the proper intrinsic phase ($\sim 90^\circ$) after diffusion.

The performance of the sensor under various conditions has been investigated in the laboratory. Sensor linearity and noise have been studied; the test results indicate that the sensor is capable of measuring AC signals with less than 0.3% error and, therefore, meets the standards suggested by Erickson [49] for the sensors to be used in high voltage metering applications.

The stability of the sensor response has also been studied. For example, the change in the intrinsic phase of the sensors with time or change in temperature has been examined; it is concluded that these effects, when accounted for, do not introduce a significant error into the measurements. Piezoelectric resonances of the sensor head and their effects on the sensor bandwidth have also been explored; it has been shown that sensors with 1 MHz bandwidths can be easily realized. Finally, the IOPC has been demonstrated to be capable of measuring lightening impulses with front times faster than $1.2 \mu\text{s}$ (the IEC standard for high voltage lightening impulse).

In conclusion, the experiments indicate that the IOPC can meet the standards [49] required for most high voltage applications, i.e., AC voltage metering, protection relaying, and fault location on high voltage transmission lines. With all the advantages, both technological and economical, that IOPC's offer over conventional potential transformers (PT's), it is believed that IOPC's can replace the conventional PT's used in the power industry.

5.2. Recommendations for Future Work

As a first step in the continuation of this project, field testing of the IOPC is recommended. Laboratory tests are not sufficient to ensure the successful application of these devices in the environments in which they are likely to be employed. Long term stability and environmental tests, for example, need to be performed.

In order to improve the polarization of the light entering the sensor's head, one can use polarizing optical fibres between the sensor head and the input PM optical fibre. At the output, an optical-fibre polarization-splitter can be used to separate and direct the two polarizations interrogated into two ordinary (non-polarization maintaining) single-mode fibres. Currently, it appears that using two relatively inexpensive single-mode fibres, as compared to using a single, more expensive, PM fibre, from the sensor head to the optoelectronic detecting unit will be more cost effective. Furthermore, the effect of the crosstalk between the two modes of the output PM fibre (even though not very significant) will disappear.

For further research in this field, it is recommended to develop an IOPC operating at $\lambda_o = 1.3 \mu\text{m}$. At longer wavelengths in the infrared, certain adverse effects such as DC drift and optical damage are expected to be negligible for optical powers as large as 20 mW passing through the sensor head's waveguide [52], [53]; at wavelengths in the visible range, on the other hand, the optical power should not exceed a few micro-Watts. Solid state photo-detectors used in the optoelectronic conversion unit generally have better signal to noise ratios at higher powers; therefore, having larger optical powers reaching the photo-detectors reduces the percentage error due to noise. Other advantages of operating at this wavelength, as

compared to visible light, are that the attenuation in the fibre is significantly less, and the alignment for couplings and connectorizations are easier and more efficient.

It is also recommended to develop a real-time high-accuracy digital signal acquisition and processing unit to be integrated with the detecting circuitry. This unit can include a dedicated micro-computer which performs functions, such as filtering, on the received optical signal. This can improve the accuracy and the dynamic range of the sensor significantly.

Besides its application as a high voltage sensor, the subject of this thesis, the IOPC is likely to find other applications. For instance, the facts that it can be intrinsically phase biased, has already shown better than 20 dB extinction ratios ($R > 99\%$), has no Y-branches, and can be easily fabricated in great lengths with little loss, make it a very promising device for use as a high-speed optical modulator with bandwidths in the microwave to millimetre wave range.

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