Invited Paper

Integrated-Optic Sensors for High-Voltage Substation Applications

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ABSTRACT

Integrated-optic devices for use in high-voltage substations are reviewed. Specifically, two types of integrated-optic Mach-Zehnder and the integrated-optic Pockels cell are described and compared. A system for monitoring the condition of fluid-and-paper insulation systems, such as are used in many current transformers and power transformer bushings, is also described. This condition monitoring system measures the dissipation factor of an insulation system being monitored. It uses an integrated-optic Pockels cell to measure the phase of the voltage on the high-voltage transmission line to which the insulation system is connected. Preliminary results, showing that the system is capable of measuring the dissipation factor to an accuracy of 0.5%, are presented.

1. INTRODUCTION

The potential of electro-optic sensors for use in the power industry has long been recognized [1] - [4]. Most work has focused on systems that used bulk electro-optic crystals as the sensing medium. At the University of British Columbia we have proposed using integrated-optic, electro-optic sensors [5] - [11]. Initial work on the use of integrated-optic devices concentrated on the integrated-optic version of the Mach-Zehnder interferometer as the sensor-head. This work eventually led to the development of an integrated-optic version of the Pockels cell for this purpose. The integrated-optic Pockels cell overcomes several of the problems that are associated with bulk-optic Pockels cells and integrated-optic Mach-Zehnders as the sensor-heads in high-voltage environments.

In this paper, work carried out at the University of British Columbia, toward the development of integrated-optic sensors for use in power utility substations, is reviewed. It begins with a discussion of some of the potential applications of electro-optic sensors within high-voltage substations. This discussion is followed by a brief comparison of bulk-optic and integrated-optic sensors, in which the advantages and disadvantages of each are briefly discussed. Then the work done to develop integrated-optic sensors of both the Mach-Zehnder and integrated-optic Pockels cell types is reviewed. This is followed by a short comparison of the integrated-optic sensor types. Finally, an actual system for monitoring the quality of fluid-and-paper insulation systems in high-voltage substations, and using integrated-optic Pockels cell sensors, is presented along with some preliminary results.

2. Electro-Optic Sensors

2.1 Applications

Electro-optic sensors designed for power utility applications are typically electric-field sensors. For the Mach-Zehnder and Pockels cell type electric-field sensors discussed here, the optical intensity at the output of the sensor-head is usually related to the intensity at the input by a sinusoidal function. This transfer-function has the form

$$I_o = I_i\left[\frac{1}{2} \pm \frac{1}{2}\cos\left(\pi\frac{E_a}{E_\pi} + \phi_i\right)\right] \qquad [1]$$

where I_o is the intensity at the output, I_i is the intensity at the input, E_a is the applied field (internal to the crystal), E_π is the half-wave electric-field, and ϕ_i is the intrinsic phase difference or the bias of the device (in an electroded device E_a and E_π are replaced by V_a and V_π, the applied voltage and the half-wave voltage, respectively). Ideally $\phi_i = \pi/2$, allowing the sensor to operate in a linear region. Figure 1 shows a typical transfer function for a device with an ideal bias.

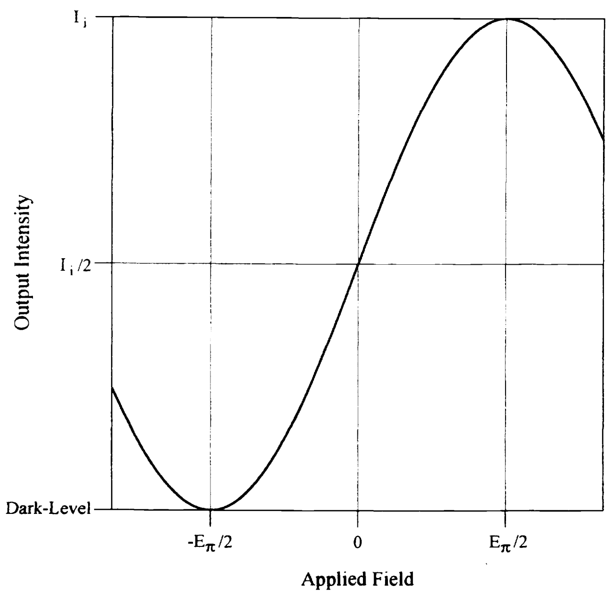

Figure 1. A typical transfer function for an ideally biased Mach-Zehnder or Pockels Cell type device.

Electro-optic sensors can be used as voltage sensors in those applications in which the relationship between the electric field and the voltage on the transmission line are well known, e.g., when the voltage is applied directly to the sensor-head [12], in a fixed-geometry electrode configuration such as that inside a gas-insulated transmission line (see figure 2) [10], or in a specially designed housing that "conditions" (or structures) the field [13].

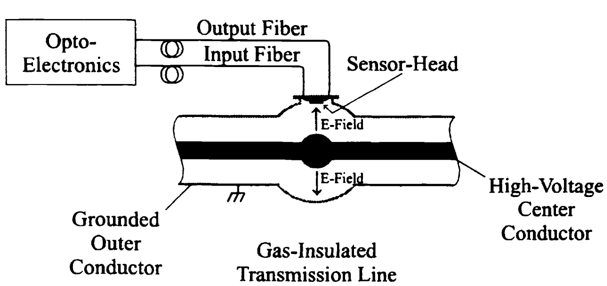

Figure 2. An electro-optic sensor in a fix-geometry electrode configuration, gas-insulated transmission line.

Currently, there are three main areas in which voltage and current information is used in power substations, metering, protection, and monitoring. Metering requires a high degree of accuracy, typically the accuracy for metering must be within 0.3%. Protection requires lower accuracy but faster response times, e.g., fault conditions must be identified and circuit breakers opened within a few cycles if serious damage to capital equipment is to be avoided. Monitoring may require both accuracy, e.g., the fluid-and-paper insulation monitoring system described below, and/or wide bandwidths, e.g., partial discharge monitoring systems, this very much depends on the type of monitoring being performed.

Traditionally, the metering and protection functions have been separate and each has required its own equipment geared towards the particular application. Interest in monitoring is currently increasing, in part due to the age of the installed plant, leading to a rapid increase in the number of systems under development. Furthermore, new areas of interest to the power utilities, such as power quality, are being introduced which will require new types of monitoring systems. Electro-optic sensors are capable of having the accuracies currently required of metering equipment while still having the bandwidths required of protection equipment. Figure 3 shows the response of an integrated-optic Pockels cell to an industry standard 1.2/50 μs/μs lightning impulse. In fact, the bandwidths of integrated-optic devices are so wide [14] that a single sensor could be used for both metering and monitoring partial discharges. The ability to use a single sensor for multiple applications would represent a significant cost savings to the industry. Also, optical sensors can have additional advantages over traditional voltage and current transformers, e.g., they can be non-intrusive, they are inherently insulating, and they are immune to electromagnetic interference.

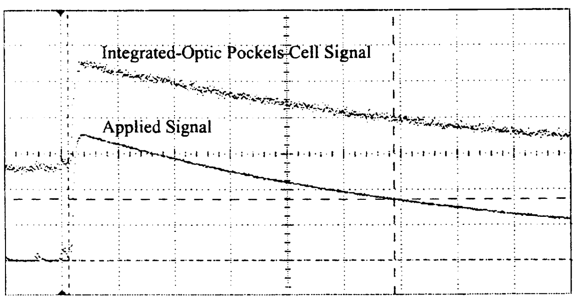

Figure 3. Response of an integrated-optic Pockels cell to a 1.2/50 μs/μs lightning impulse.

The advantages of optical sensors lend them very nicely to some of the new areas of interest to the power industry such as monitoring power quality. Being able to monitor frequencies well above the fundamental (60 Hz) is of particular interest. Figures 4a and 4b show the results of using an integrated-optic Pockels cell to monitor a 60 Hz signal with significant harmonic content. Figure 4a shows the spectrum of the applied signal and figure 4b shows the output signal from the

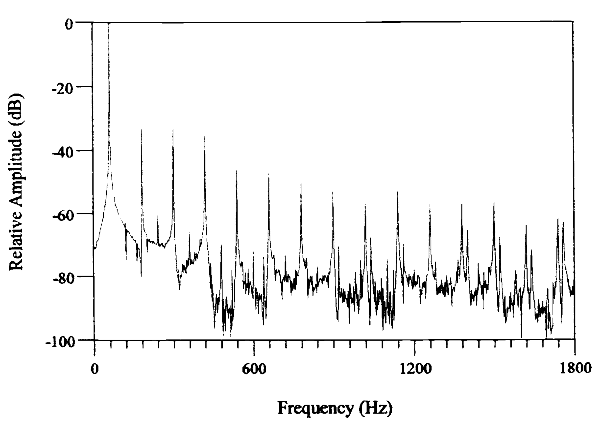

Figure 4a. The spectrum of a 60 Hz signal, with significant harmonic content, applied to an integrated-optic Pockels cell.

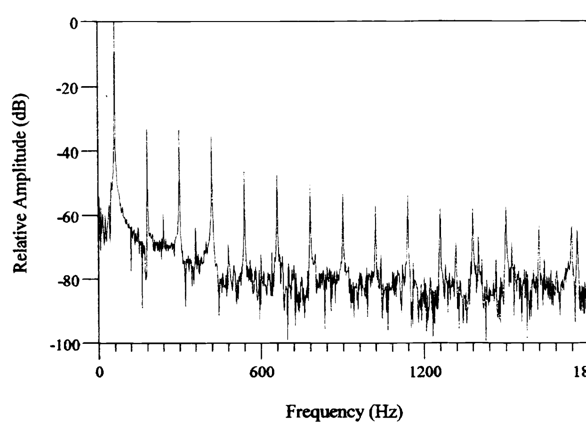

Figure 4b. The spectrum of the processed output from the integrated-optic Pockels cell.

integrated-optic Pockels cell sensor (while both figures show the spectral content only up to the thirtieth harmonic, this particular system was capable of monitoring the signals to 10 kHz).

2.2 Integrated-Optics vs. Bulk-Optics

Integrated-optic sensors have several advantages over bulk-optic ones. For example, an integrated-optic sensor typically requires fewer optical components, lenses, beam splitters, polarizers, etc., as compared to a bulk-optic one. This is especially true at the point of measurement. Figures 5a and 5b illustrate the difference in the number of optical components used at the measurement point for a typical bulk-optic Pockels cell and an integrated-optic Pockels cell, respectively. Also, integrated-optic sensor-heads typically have optical fibers permanently attached to them. The fibers are rigidly bonded to the sensing crystal, reducing the effect of vibration and the possibility of misalignment. Another advantage is that the sensor-heads can be much smaller in size and lower in cost. In integrated-optic sensors sensing is confined to the region of the optical waveguides, which typically have transverse dimensions on the order of several microns and lengths on the order of a few millimeters to a few centimeters. This means that integrated-optic devices require much less material in their fabrication, usually handling, bonding, and packaging issues force them to be larger than is absolutely necessary for their sensing function. Small size has several additional advantages beyond the cost advantage such as integrated-optic sensors can be much less intrusive than bulk-optic ones. This means that they can be more easily incorporated into other pieces of equipment (in a substation such a piece of equipment could be a signal-column as shown below). Another advantage of small size is that in piezoelectric materials the resonances occur at higher frequencies. One advantage of the bulk-optic sensor is that it is easily biased. This can be done, for example, by simply including a quarter-wave plate in the optical system. Nonetheless, it is possible to manufacture integrated-optic Pockels cells with a useable bias, as is discussed below. Another advantage of bulk-optic sensors is that it is possible, using a large device, to apply the entire voltage across the sensor-head [12].

3. INTEGRATED-OPTIC SENSORS

Integrated-optics devices are fabricated using methods that were originally developed for the fabrication of integrated electronics. Generally speaking, integrated-optic devices are planar devices that use optical channel waveguides to direct light within a circuit in much the way that integrated electronics devices use wires to direct electricity. The waveguides used typically have transverse

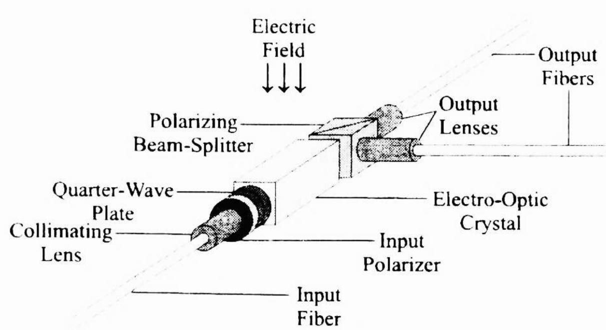

Figure 5a. A typical bulk-optic Pockels cell.

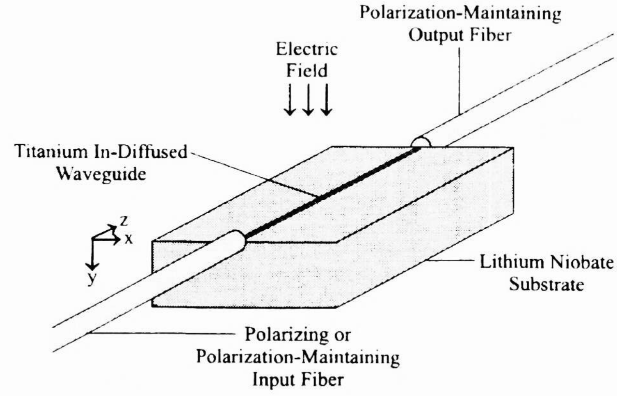

Figure 5b. An integrated-optic Pockels cell.

dimensions that are on the order of several microns and lengths that are on the order of a few millimeters to a few centimeters. The most commonly used substrates for the fabrication of integrated-optic devices are lithium niobate, compound semiconductors (gallium arsenide, indium phosphide, etc.), silicon, and various glasses. Since silicon and glasses do not exhibit the linear electro-optic effect, the most commonly chosen substrates for integrated-optic devices are lithium niobate and the compound semiconductors. Of these, the fabrication technology for low-loss optical waveguides in lithium niobate is the least expensive. Also, lithium niobate is chemically inert, making it very suitable for fabricating devices intended for harsh environments. See reference [15] for some of the properties of lithium niobate.

In lithium niobate the two principal methods used for the fabrication of optical waveguides are titanium in-diffusion and proton-exchange. Proton exchange results in an increase of the extraordinary refractive index of the lithium niobate and of a decrease in the ordinary refractive index. This makes proton exchange appropriate only for devices in which extraordinary modes are to launched but not ordinary modes. In our work we have typically preferred ordinary modes to extraordinary modes, since there is no surface-guiding and since the photo-refractive effect is smaller, and have usually used titanium in-diffusion to fabricate our channel waveguides.

3.1 Integrated-Optic Mach-Zehnders

The integrated-optic Mach-Zehnder is one of the most widely used electro-optic devices. It is widely used in telecommunications systems as well as in sensor systems. Typically, in an integrated-optic Mach-Zehnder light in a single input waveguide is channeled into two branches and then recombined into a single output waveguide. The optical path lengths of the two branches, and hence the relative phases of the light output from the branches, are controlled via the electro-optic effect. The controlled coupling of the branch outputs into the output waveguide results in a transfer function such as that given in equation 1.

3.1.1 The Mach-Zehnder with a Capacitive Divider

In a Mach-Zehnder with a capacitive divider, the capacitor is monolithically integrated onto the substrate containing the Mach-Zehnder [6], [9]. Figure 6 is an illustration of how these devices were used. The metal pad on the substrate acquired a potential that was determined by the capacitance from the pad to the high-voltage conductor and by the capacitance from the pad to the ground-plane, i.e., the substrate formed part of the capacitive divider. The potential acquired by the pad was also the potential difference across the two modulating electrodes of the Mach-Zehnder, one of the modulating electrodes being integral with the pad and the other being connected to the ground-plane. By positioning one of the

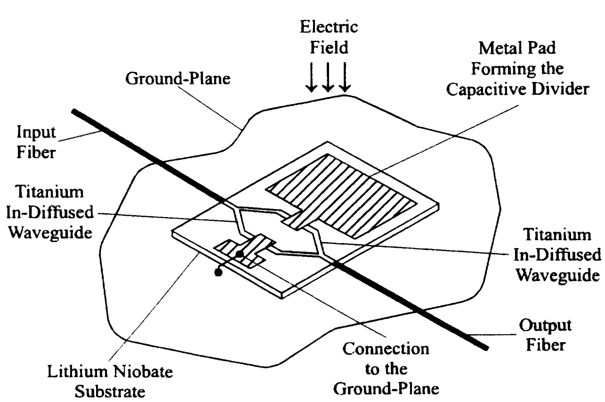

Figure 6. An integrated-optic Mach-Zehnder with a monolithically integrated capacitive divider.

branches of the Mach-Zehnder under the electrode connected to the pad and positioning the other branch under the electrode connected to the ground-plane an optical push-pull action was achieved in the device.

Our devices were fabricated on z-cut lithium niobate substrates [9]. They had x-propagating waveguides. This allowed either an ordinary or an extraordinary mode to be launched into the waveguide; in our case we launched an ordinary or TE-like mode in order to avoid the surface-guiding problems associated with lithium out-diffusion, which can occur simultaneously with the in-diffusion of titanium. Various devices were designed which had half-wave voltages ranging from 21 to 106 V. Since our sensors operated in the small-signal linear region, these devices required that only a few volts be induced on the capacitive divider when the voltage on the transmission line was at its maximum value.

We successfully fabricated devices of this type and tested them in the laboratory. Voltage amplitude measurements at 60 Hz were repeatedly performed, at room temperature, giving rms errors of $<0.3\%$. Nevertheless, these devices have some significant shortcomings. The first is establishing a bias of $\sim\pi/2$, which is necessary if the device is to operate in the small-signal linear region. This requires precise control of the optical path lengths in each of the branches which is very difficult to achieve in a repeatable fashion; even for identical devices, fabricated simultaneously on the same substrate, there is a significant variation in the bias, reducing the yield that one can expect [9]. Another problem is the bias change as a function of temperature. The devices studied exhibited a relatively large temperature dependent change in bias of about $1.25\,°/°C$.

3.1.2 The Mach-Zehnder with Domain Inversion in One Branch

Another possible way to fabricate an integrated-optic, electro-optic field sensor is to use domain inversion in one of the branches of a Mach-Zehnder [11]. Inverting the ferroelectric domains inverts the spontaneous polarization and, subsequently, the linear electro-optic effect in the branch [16]. In such a device both branches are subjected to the same electric field and the modulation of the output comes about due to the electro-optic effect in the inverted region being opposite to that in the non-inverted regions. Figure 7 shows an integrated-optic Mach-Zehnder with a domain-inverted region in one of the branches.

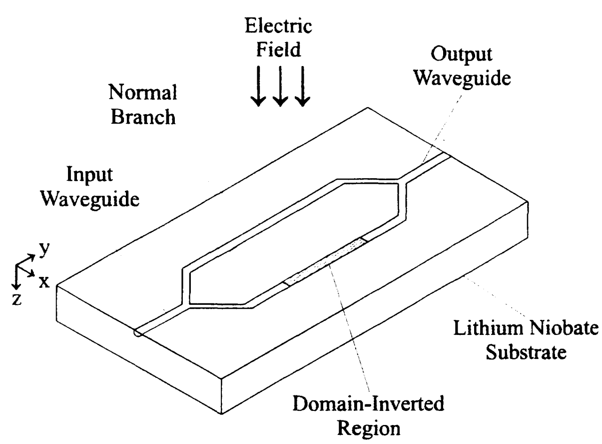

Figure 7. An integrated-optic Mach-Zehnder with a domain-inverted region in one branch.

One way of achieving domain inversion is to in-diffuse a large dose of titanium into a z-cut lithium niobate substrate followed by a heat treatment, this was the method that we employed. In our devices, first a large dose of titanium was in-diffused forming the domain-inverted regions then a smaller dose of titanium was in-diffused to form the waveguides.

Under controlled conditions these devices were capable of measuring 60 Hz signals with a sufficiently high degree of accuracy, i.e., with rms errors of ~0.3% at room temperature. While devices of this type have the advantage that they do not have integrated metal electrodes, but are emersion-type devices, they still have several significant shortcomings. The principal problem that was encountered was the completely random biases of the fabricated devices. This is to be expected since the large dose of titanium changes the optical length of the domain-inverted region in an uncontrolled fashion. Also, the bias change as a function of temperature was much larger than for the other device types studied, about a factor of four greater than for similar Mach-Zehnders with monolithically integrated capacitive dividers.

3.3 The Integrated-Optic Pockels Cell

The sensor-head of the integrated-optic Pockels cell consists of a piece of y-cut lithium niobate containing a z-propagating waveguide [10], see figure 5b. The dimensions of the pre-diffusion titanium strip can be chosen prior to the diffusion process so that the waveguide formed will support only the fundamental TE-like and the fundamental TM-like modes. When an electric field is applied parallel to the y-axis of the crystal the optical indicatrix is changed in such a way that equal but opposite changes occur in the mode indices of the TE- and TM-like modes. Polarized light is coupled into each of the modes at the input of the waveguide using a polarizing or polarization-maintaining optical fiber. The input light is polarized so that its electric field is oriented at about 45° to the x- and y-axes of the substrate, so that nearly equal amounts of power at coupled into both modes. Since in a y-cut, z-propagating, waveguide the transverse optical field distributions are determined by the ordinary refractive index distribution, the mode-profiles for the TE- and TM-like modes are nearly identical. The amount of power in each of the modes can be controlled to obtain nearly circular polarization across the entire output plane when there is a $\pi/2$ phase difference between the TE- and TM-like modes at the output, i.e.,when the bias is $\pi/2$ (for other values of the bias the output will be uniformly elliptical in the output plane).

The applied electric field causes the ellipticity of the polarization ellipse at the output to change. The output is interrogated using a birefringent, polarization-maintaining fiber. The powers parallel to the principal axes of the output polarization ellipse are given by equation 1 where the plus sign corresponds to the power parallel to one axis and the minus sign corresponds to the power parallel to the other. The fast and slow axes of the output fiber are aligned with the principal axes of the output polarization ellipse (i.e., at an inclination of about 45° to the x- and y-axes of the substrate) so as to couple the power parallel to one of the principal axes into the fast mode of the fiber and to couple the power parallel to the other principal axis into the slow mode. In this way the output fiber acts as an analyzer. The powers in each of the fiber's modes are separated and measured individually.

It might be tempting to fabricate the integrated-optic Pockels cell sensor-head in such a way as to take advantage of lithium niobate's large r_{33} electro-optic coefficient, however, there are several reasons for not doing this. First, if a Pockels cell were designed so that one of the modes was an ordinary mode and the other was an extraordinary mode, as in an x- or y-propagating waveguide formed in a z-cut substrate, the differences in the refractive index distributions would lead to significantly different mode-profiles for the TE- and TM-like modes. This would result in the polarization state across the output plane of the sensor-head being non-uniform which, in turn, would lead to a degradation in the on/off ratio of the device. Such a device would also forfeit two of its principal advantages over the Mach-Zehnder type devices discussed above, the ability to bias it and its much reduced sensitivity to temperature, see the discussion below. Other reasons for not doing so have been mentioned above, e.g., it avoids surface-guiding and the photo-refractive effect is smaller.

In the laboratory, under controlled conditions, these devices were able measure 60 Hz signals with accuracies in excess of 0.3%. They had the lowest bias changes with temperature of the devices studied, about 0.014°/°C/mm (or about 0.14°/°C for a one centimeter long device) [17]. The integrated-optic Pockels cell has the advantage of having two complementary output signals which allows the signals to be normalized, the bias to be tracked, and the output to be relinearized. Another significant advantage of the integrated-optic Pockels cell is that it is possible to fabricate devices having desirable biases. This can be done because there is a small modal birefringence exhibited by the in-diffused channel waveguides used in the Pockels cells. The amount of modal birefringence is dependent on the transverse shape of the waveguide. Therefore, by fabricating numerous waveguides next to each other, in the same substrate, having slightly different pre-diffusion titanium strip-widths, each waveguide will have a unique bias when the crystal is cut and polished [10]. Provided that a sufficient number of waveguides are fabricated in the substrate, it is possible to pick one that has a useful bias. This is done without adding to the cost of the finished device since, as mentioned above, the finished sample is many times larger than is necessary for the sensing function, e.g., for handling, bonding, and packaging purposes.

3.4 The Integrated-Optic Pockels cell vs the Integrated-Optic Mach-Zehnders

The integrated-optic Pockels cell has two major advantages over the Mach-Zehnder type sensors discussed above. First, in it the amount by which the bias changes with temperature is about an order of magnitude less than for the Mach-Zehnder with capacitive divider and forty times less than for the Mach-Zehnder with domain inversion. Second, it is possible to manufacture integrated-optics Pockels cells with waveguides that have useful biases. Furthermore, the Pockels cell provides two complementary optical output signals that can be used to normalize the signals, to track the bias, and to relinearize the output, knowing the bias may also provide a means for estimating the temperature of the sensor-head. Two complementary output signals can also be achieved for Mach-Zehnder type devices, however, to obtain them would require a significantly more complex design, taking up much more real-estate on the substrate, and two output fibers to interrogate the two signals.

4. A Dissipation Factor Monitoring System

At the University of British Columbia there has been considerable work conducted toward developing a condition monitoring system for the fluid-and-paper insulation systems that are used in many current transformers and power transformer bushings [18]; dissipation factor is widely believed to be the best indicator of the health of fluid-and-paper insulation systems. This monitoring system measures the dissipation factor of an insulation system on-line and in real-time. It does this by accurately measuring the phase of the voltage on the high-voltage line and the phase of the current through the insulation system. The current through the insulation system can be measured at the capacitance-taps (cap-taps) of current transformers and bushings.

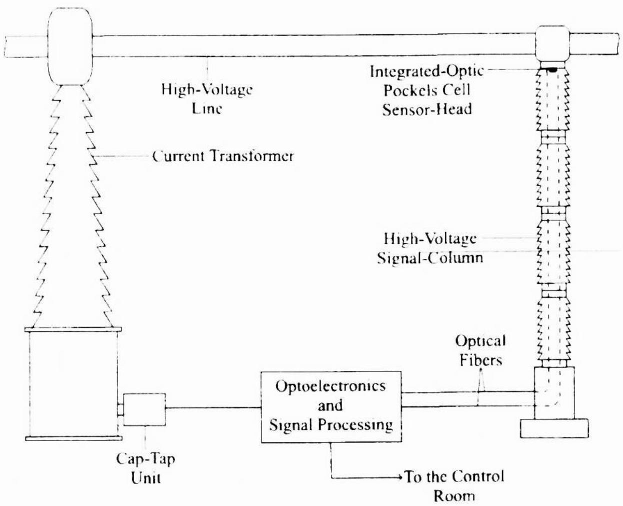

Figure 8. An integrated-optic Pockels cell based dissipation factor monitoring system.

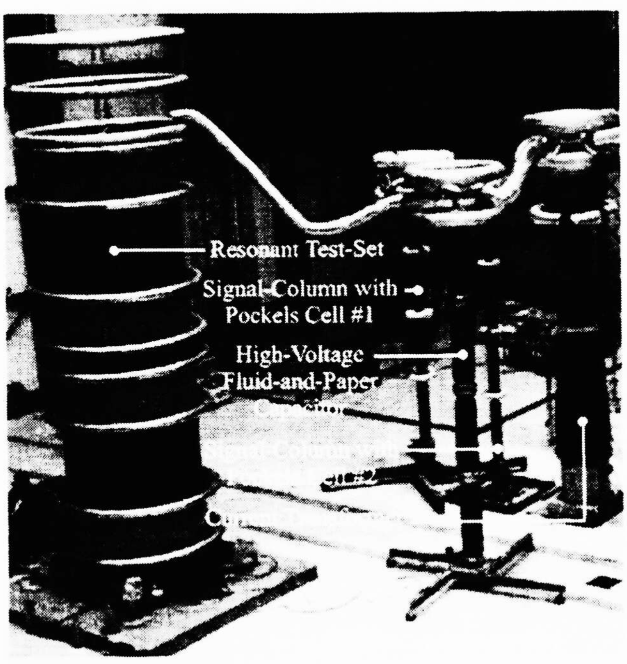

Figure 9. Experimental set-up used to measure the dissipation factor of fluid-and-paper insulation systems. Shown are a resonant test-set, two signal-columns containing integrated-optic Pockels cells, a high-voltage fluid-and-paper capacitor, and a current transformer.

The system has several components; the principal ones being an integrated-optic Pockels cell, several cap-tap units containing low-dissipation factor capacitors (more than one insulation system can be monitored using a single Pockels cell), and an optoelectronics and signal processing unit. The optoelectronics and signal processing unit accepts the input signals and stores the calculated values of the dissipation factor. As shown in figure 8, the integrated-optic Pockels cell is connected to the high-voltage line at the top of a high-voltage signal-column. Light is supplied to the Pockels cell from a laser and light from the Pockels cell is interrogated by photo-detectors, all located on an optoelectronics board. The optical signals are carried to and from the high-voltage environment, where the Pockels cell is located, on optical fibers inside the signal-column. The capacitors that interrogate the insulation currents are connected in series with the insulation systems being monitored. They are connected to the cap-taps of the devices being monitored and supply measurement signals to the system via shielded, twisted pairs of wires. The capacitors in the cap-tap units have been chosen so as to provide low-voltage signals to the signal processing unit. Figure 9 shows the system in the High-Voltage Laboratory at Powertech Labs Inc., where the testing was performed (two integrated-optic Pockels cells were tested simultaneously). Also shown in figure 9 is a high-voltage fluid-and-paper capacitor that was part of a capacitive divider used to monitor the output voltage from the resonant test-set.

Since the capacitors in the cap-tap units are in series with the insulation systems, the voltage signals measured across them, representing the insulation currents, are in phase with the applied voltage. This can be compensated for by accurately shifting the phase of one of the signals. Here the signal from the integrated-optic Pockels cell, representing the applied voltage, is shifted backward in phase by a quarter-cycle (to shift the voltage signal first its frequency is accurately calculated and then a time delay is applied). It is now possible to use the standard equation (see for example [19])

$$\tan\delta = \tan\left[\arcsin\left(\frac{1}{\pi N|v|\,|i|}\int_0^{2\pi N} v(t)\,i(t)\,dt\right)\right] \qquad [2]$$

where N is an integer, $v(t)$ is the applied voltage (the shifted signal), and $i(t)$ is the insulation current, to calculate the dissipation factor.

Typically, fluid-and-paper insulation systems degrade relatively slowly. However, when a system fails in the field it typically fails catastrophically, exploding and causing damage to adjacent equipment. The signature of an impending failure is a relatively rapid increase in an insulation system's dissipation factor (taking place over hours or days as opposed to weeks or months). During such an episode the insulation system's dissipation factor increases from 1% or below to several percent (~10%) in a few tens of hours [20]. The system described here takes a data point about once every 5 seconds. Figure 10 shows data collected from a high-voltage current transformer over a 1800 min (30 hr) period by the system. Also shown in figure 10 is data collected concurrently using a high-precision, high-voltage capacitive divider. The maximum difference between the measurements taken by the two systems is 0.5%, which meets the requirements for an effective monitoring system of this type. Figure 11 shows daily-average data collected from a particular current transformer over a 90-day period by the same system (data was not collected every day but only at certain times, mostly evenings and weekends).

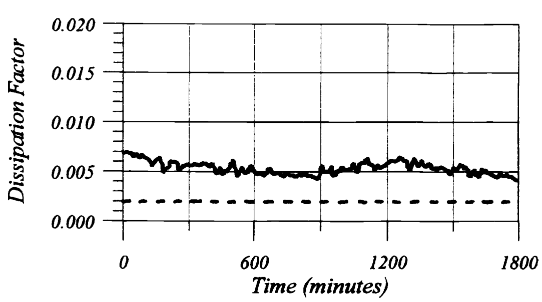

Figure 10. Dissipation factor data taken from a high-voltage current transformer over a 1800 min (30 hr) period. Data taken using an integrated-optic Pockels cell — solid curve. Data taken using a high-precision capacitive divider — dashed curve.

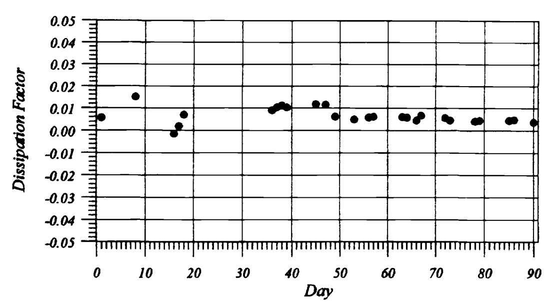

Figure 11. Daily average dissipation factor data taken from a high-voltage current transformer over a 90-day period.

5. SUMMARY

In this paper, work being carried out at the University of British Columbia, toward developing integrated-optic sensors for high-voltage substation applications, has been reviewed. The advantages of integrated-optic, electro-optic sensors, as compared to bulk-optic ones, have been discussed. Three types of integrated-optic, electro-optic sensor studied have been described and their respective advantages and shortcomings discussed. Finally, a specific application of and integrated-optic Pockels cell, as part of a fluid-and-paper insulation system monitoring system, has been discussed and preliminary results have been presented.

6. ACKNOWLEDGEMENTS

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