MEASUREMENT APPLICATIONS (PART 2)

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1. INTRODUCTION

From the initial development of power systems until the present, the measurement of the quantities required for system operation, maintenance, and reliability and for revenue metering have generally relied on an electrical connection between the quantity to be measured and the data recording system. This can be characterized as an electrical measurement approach. With the growth of measurement and control systems based on solid-state circuits, the development of an electronic measurement approach has been a natural evolution. It now appears that the technical and economic conditions are appropriate to stimulate the next advance, the photonic measurement approach.

A photonic system is based on the transport of photons in the same way that an electrical or electronic system is based on the movement of electrons. In an electrical or electronic system, a sensor is used to scale the signal to be measured. This sensor may be a transformer, a capacitor divider, or any similar device. The sensor is connected to the data recording system through appropriate cables. In the simplest type of photonic system, the cable connecting the sensor to the data recorder is replaced with an optical transmitter and receiver joined by a fiber optic cable. The components to configure such a system are readily available and many systems are in use today. This paper, however, focuses on systems which are more completely photonic, i.e., systems in which the signal sensing, the data transmission, and as much of the data recording and analysis as possible are performed using optical rather than electronic components.

This paper is intended to provide an introduction to the physics of photonic measurement systems and some of the engineering aspects of the systems which must be considered in their application. Section 2 describes sensor technology. Optical fiber technology is not covered in any detail in this paper, but Section 3 does highlight some of the fiber properties which are important in photonic systems. The data recording technology which is used with photonic systems is reviewed in Section 4. Examples of photonic systems are presented in Section 5.

To provide an appropriate perspective to the remainder of the paper, it is useful to review some of the forces which are combining to stimulate the development of photonic measurement systems. First, it must be recognized that the ancillary equipment, with high reliability, is being developed by the communications industry. Second, a photonic sensor shows promise of being less expensive than a conventional sensor, i.e., an optical fiber is less expensive than a transformer, for example. Thus, using photonic sensors, the required power system instrumentation may be less expensive than it is today. Third, photonic systems for multichannel recording are being developed which have a lower cost per channel than do electronic recording systems. Fourth, photonic systems open the possibility for new types of measurements which could lead to better design of power system equipment.

2. SENSOR TECHNOLOGY

For this discussion, it is useful to define the sensor as the device which causes the signal to be measured (voltage, current, electric field, etc.) to produce a detectable modification of a light beam. Sensors can be separated into two categories which depend upon the mechanism by which the light beam is modified. The first is an optical effect and, in this case, an electric or magnetic field interacts directly with the atoms, molecules, or electrons in the sensor to produce a change in the index of refraction. The second is a mechanical effect by which the signal to be measured produces a mechanical deformation of the sensor thus producing a change in the optical transmittance through the sensor. These two types of effects are discussed separately.

2.1 Optical Effects

Most optical systems in use or under development today are based on the Faraday effect, the Pockels effect, or the Kerr effect [1-5]. In this section, each of these effects is described and a brief discussion of the properties of measurement systems employing the effects is given.

2.1.1 Faraday Effect

The Faraday effect is a magneto-optic effect, i.e., the application of a magnetic field to a material which exhibits the Faraday effect produces a change in the index of refraction of the material. Figure 1a shows a typical, but idealized, situation in which the light beam that senses the change of the index of refraction propagates colinearly with the magnetic field direction. In this case, the governing equation for the Faraday effect can be written

$$n_r - n_l = \lambda VH/\pi \qquad (1)$$

where n_r is the index of refraction for right circularly polarized light, n_l is the index for left circularly polarized light, λ is wavelength of the sensing light beam, V is the Verdet constant, and H is the magnetic field intensity. To develop a conceptual understanding of the Faraday effect in glasses, it is useful to divide the discussion into two parts. The first deals with materials which have no net magnetic moment called diamagnetic materials. The second deals with materials which possess a magnetic moment called paramagnetic materials.

In diamagnetic materials, the orbital and the spin moments of the electrons cancel. If there is no external field, therefore, the net magnetic moment is zero. If the material is placed in a magnetic field, however, the electronic motion is modified in such a way as to minimize the total field. The index of refraction is modified by the redistribution of the electrons.

The molecules in paramagnetic materials, by contrast, have permanent magnetic dipole moments. The Faraday effect results from the reorientation produced from the interaction between the molecular dipole moments and the external field.

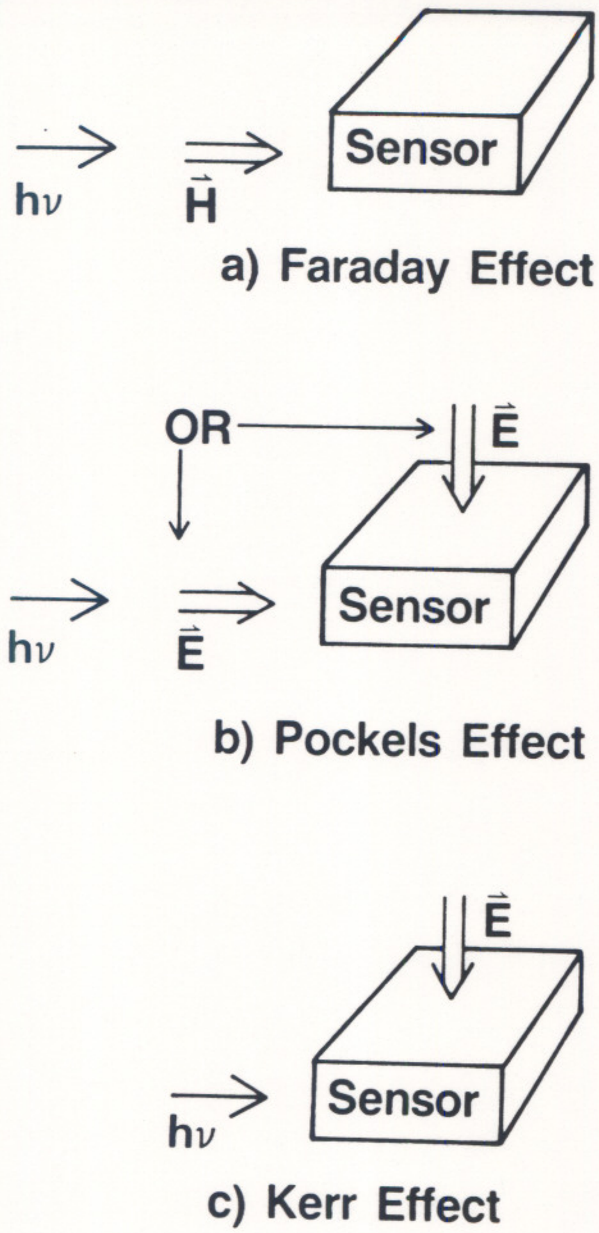

Fig. 1. Typical relative orientations between the electric or magnetic field and the direction of propagation of the light beam for a) the Faraday effect, b) the Pockels efect, and c) the Kerr effect.

Devices based on the Faraday effect can be used to determine the magnetic field or, through a measurement of the magnetic field, to determine the current. In practice, Faraday-effect sensors are typically diamagnetic glasses doped with a paramagnetic material if a larger Verdet constant is required.

It should be noted that the Faraday effect in diamagnetic materials, being an electronic process, is relatively insensitive to variations in temperature. In paramagnetic materials, by contrast, the Faraday effect results from molecular orientation and, thus, it is a temperature dependent phenomenon.

2.1.2 Pockels Effect

The Pockels effect is an electro-optical effect, i.e., the application of an electric field to a material exhibiting the Pockels effect produces a change in the index of refraction in the material. For the Pockels effect, the change in the index of refraction is proportional to the electric field to the first power. The fundamental equation which describes the Pockels effect is

$$\Delta n = n_o^3 r_{ij} E \qquad (2)$$

where r_{ij} is an appropriate tensor element, n_o is the index of refraction in the absence of the applied field, and E is the applied field. The equation for the Pockels effect is typically written as a tensor equation because the relative orientations of the applied field, the light beam, and the structure of the material are important. For the Faraday effect described above, the field and direction of propagation of the light beam are colinear. In addition, the glass which is amorphous, has no inherent directionality. In the case of the Pockels effect, however, the electric field may be either colinear with or perpendicular to the light path as shown in figure 1b. Moreover, Pockels effect sensors are typically crystals so they have intrinsic axes of symmetry. The response is determined not only by the nature of the crystal but also the angles which the applied field and light beam make with the crystal's axes of symmetry. Tensor algebra is a natural choice to describe this situation.

2.1.3 Kerr Effect

The Kerr effect is an electro-optical effect in which the change in the index of refraction is proportional to the square of the electric field. It should be noted that in this work, we are only considering the electro-optic Kerr effect. A magneto-optic Kerr effect does exist but it applies to phase shifts involved in reflection from a magnetized surface; it has not been used for voltage or current measurement.

Systems using the electro-optic Kerr effect frequently use liquid sensors and the orientation between the light path and the applied field is shown in figure 1c. In this case the basic equation describing the electro-optic Kerr effect is

$$n_{\parallel} - n_{\perp} = \lambda B E^2 \qquad (3)$$

where $n_{\parallel}$ is the component of the index of refraction parallel to the applied field, $n_{\perp}$ is the component perpendicular to the field, λ is the wavelength, B is the Kerr coefficient, and E is the electric field.

The Kerr effect at low frequency arises mainly because the molecules in the optically active material tend to align with the applied electric field. This alignment produces an isotropy in the index of refraction. Thus a light beam polarized in the direction of the applied field and one polarized perpendicular to that direction will propagate at different velocities.

2.2 Mechanical Effects

A mechanical effect is defined as the interaction between an elastic deformation and a light wave to produce an altered output light wave. Nelson [3] classifies these as elastooptic effects. The elastooptic effects are also known as photoelastic effects, piezooptic effects, electrostrictive effects, or magnetostrictive effects depending on the application and/or the source of the elastic deformation. The mechanical effects have been identified which result from strain in the optical material and separate effects have been identified which result from rotation of the lattice of the optical material. The latter process is classified as a rotooptic effect.

For power industry applications, it is generally true that systems in which the behavior is governed by elastooptic effects have the narrowest electrical bandwidth. Those which depend upon atomic or molecular reorientation have an intermediate bandwidth. Those which depend upon electronic redistribution have the widest bandwidth. It should be emphasized that a system's response is frequently due to more than one physical process. A crystal used for Pockels effect measurement, for example, may produce a signal which is a result of both an electrooptical effect and a mechanical effect at low frequency (e.g., below 10^5 to 10^6 Hz) and a purely electrooptical effect at higher frequencies. A device exhibiting a mixed response may be calibrated to perform a specific measurement, but the frequency response, the wavelength response, and the temperature dependence of the response are difficult to predict.

3. OPTICAL FIBERS

The above introduction to the operation of the optical sensors also provides some information concerning the properties of optical fibers which are imposed by electrical sensors. Equations 1, 2, and 3 show that the electric or magnetic field changes the polarization state of the light beam. Ideally, therefore, one would select a fiber which has no effect on the polarization state, unless a fiber is being used as a sensor. Multimode fibers do not preserve polarization, so their usefulness is limited to applications in which only intensity information is required. This can be a significant constraint in some applications but not in others. The type of system in which multimode fibers can be and are used is one in which a fiber is used to transmit unpolarized light to the sensor, the light is polarized at the sensor, the sensor changes the polarization state in response to an electric or a magnetic field, a second polarizer is used to convert the change in polarization state to a change in intensity, and the intensity-modulated light beam is transmitted to the detector. This type of system is shown schematically in the upper part of figure 2.

The other extreme occurs when, for example, the optical fiber is used as the sensor. A configuration typical of that used in the measurement of current using the Faraday effect in an optical fiber is shown in the lower part of figure 2. In this example, the polarized light is transmitted through the fiber so a single mode fiber is required. Another confounding factor which typically occurs in this application is mechanically induced birefringence. As mentioned above, strain can produce birefringence in transparent materials. In fact, this phenomena has long been used in the mechanical analysis of particular materials [6]. A single mode fiber generally exhibits strain birefringence because, after the fiber is drawn, it is not annealed sufficiently for the strain to relax. Even if it were, mechanically induced birefringence would still occur because of the strains produced as the fiber is coiled and mounted in the appropriate position for measurement. In general, optical compensation for this strain birefringence can be made.

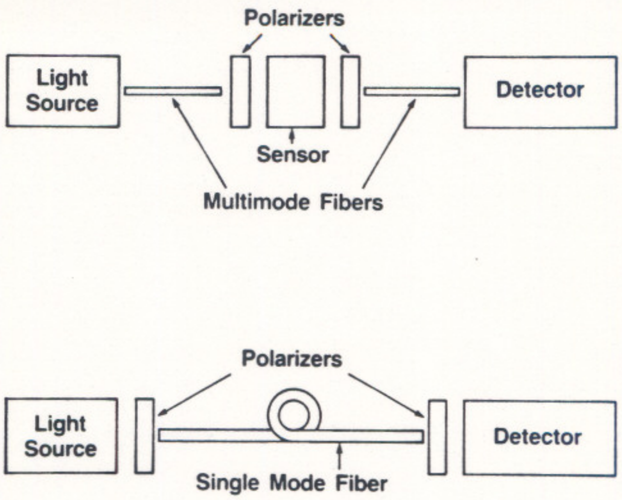

Fig. 2. The upper sketch shows a system in which polarization need not be preserved through the optical fibers, so multimode fibers can be used. The lower system shows a fiber optic sensor which must preserve the polarization state of the light beam so that a single mode fiber is used.

4. DATA RECORDERS

One of the keys to the widespread application of photonic measurement systems is the development of data recording systems which are well suited to photonic applications. The most basic form of a detector is a photodiode or a photomultiplier connected to a waveform recorder. The waveform recorder may be an analog oscilloscope or chart recorder or it may be a digital system in which the waveform is digitized and stored in memory. This approach to detection is available, reliable, and dependable but it offers limited improvement over existing systems. Work is now in progress to develop improved sensor technology.

The principal thrust in the development of these new detectors is the application of two-dimensional sensor arrays. Sandia National Laboratories has developed a photonic detection system which uses a two-dimensional sensor array and a high speed camera to obtain, in digital form, multichannel, intensity vs. time data [7]. The design goals were to obtain improved bandwidth and accuracy at lower cost per channel than can be attained using electronic waveform recorders. This system is being evaluated so a full performance comparison has not yet been published. Preliminary operating experience, however, indicates that the design goals have been met.

Staff at the National Bureau of Standards are also using two-dimensional arrays -- but in this case they are using them to obtain data which are unavailable using conventional measurement systems. They are using the Kerr effect to measure the electric field in transformer oil [8]. As can be inferred from equation 3, if the light beam can be spatially resolved in two dimensions then the electric field can also be resolved in two dimensions. Most of the data obtained to date have been one dimensional, i.e., the electric field as a function of position along a line. Limited two-dimensional data have been taken to assist in the determination of the processes which take place at the interface between the transformer oil and paper [9]. This system will be described in more detail in the following section.

5. EXAMPLES

5.1 Current and/or Magnetic Field Measurement

Sensors developed to date generally respond to the applied magnetic field. The inference of a current from the field measurement can be made in one of two ways. The more direct method is probably to construct the sensor so that it encircles the conductor. One can then invoke Ampere's Law

$$\int \vec{B} \cdot d\vec{\ell} = \mu I, \tag{4}$$

where B is the magnetic flux density, ℓ is the distance around a closed path, μ is the permeability, and I is the current, to relate the measured signal to the current passing through the sensor. If one knew the Verdet constant of the material used in the sensor and the sensor geometry, one could in principle determine the current with no additional calibration. In practice, however, it is usually more convenient to calibrate the device by applying a known current and measuring the response.

The second method is to use a small sensor to measure the magnetic field at one point (or at several points) and to infer the current from an adequate knowledge of the geometry. This approach usually relies on in situ calibration.

The sensor can be made of bulk glass or from an optical fiber. Many glass types are available for use as bulk sensors and selection is generally made on the basis of sensitivity and temperature dependence [10]. A much narrower range of materials is available for fiber sensors but the simplicity of the device makes development attractive in a number of applications. It should be stressed that fiber optic magnetic field sensors, and current sensors, are being developed along two very different physical principles. One is the Faraday effect, a magnetooptical effect [11, 12], while the other is magnetostriction, a magnetomechanical effect [13].

The Faraday effect can be observed in a fiber itself while any inherent magnetostrictive effects in a fiber are too small to be significant. To obtain a larger signal, the fibers are typically coated with a magnetostrictive material, e.g., nickel. Magnetostrictive sensors generally have much higher sensitivity than do Faraday sensors. Because the magnetostrictive effect is mechanical while the Faraday effect is molecular, Faraday effect sensors can have a much greater bandwidth. In addition, Faraday effect sensors are dielectric while magnetostrictive sensors are coated with a conductive material and this difference may be significant in some high voltage applications.

Figure 3 shows diagrams of a fiber system and a bulk type sensor. The operating principle of each of these sensors is the Faraday effect. These two systems were selected to highlight two different approaches to the same measurement situation. Both of these systems were developed to measure submicrosecond, megampere pulses in a laboratory environment. Systems intended for substation measurements have been described in earlier reviews [14, 15].

Both of these systems have been used successfully for their intended application and development continues to improve each approach. A consideration with a bulk sensor is that voltage or current pulses are frequently accompanied by acoustic shock waves (thunder is a well known example). A bulk sensor, being rigid, must be designed to endure these occasional shock waves without mechanical damage. The coil of optical fiber is inherently less sensitive to this type of damage because it tends to uncoil rather than shatter. Techniques to mitigate the effects of mechanically-induced birefringence in the fiber coil continue to be developed.

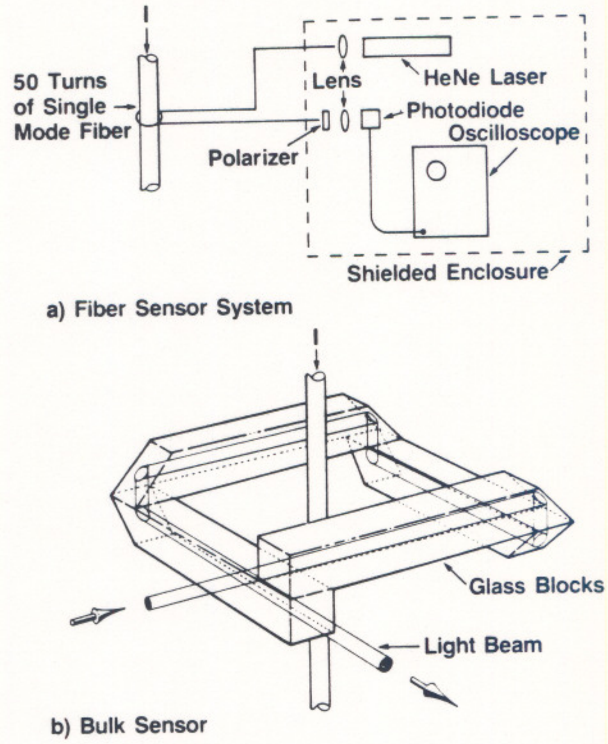

Fig. 3. The upper diagram, a, shows a fiber optic current sensor based on the Faraday effect with ancillary equipment. The lower diagram, b, shows a glass block sensor which encircles the current to be measured. The ancillary equipment which would be used with the bulk sensor is generally the same as that used with the fiber sensor.

5.2 Electric Field and/or Voltage Measurement

Electric field and voltage measurement are made with systems employing the Pockels or the Kerr effect. A good example of the versatility of the approach is found in a Pockels effect system which has been developed both for voltage measurement and for electric field measurement [16]. The system uses a bismuth silicon oxide single crystal as the sensor because it has a relatively low temperature sensitivity. The probe itself measures 1.9 x 1.2 x 0.9 cm and has been used to measure the electric field as a function of position in selected electrode geometries. If one knows the geometry and if space charge is negligible, one can use the device to determine the voltage by measuring the electric field at a point and by calculating the voltage. It should be noted that a Pockels effect device designed to operate in a substation was configured as a parallel plate capacitor in a porcelain housing. The sensor measured the field in the capacitor and was calibrated to determine the applied voltage [14].

It should be emphasized that corona can be a significant source of error when an electric field sensor is used to measure the voltage. Corona can produce a voltage and time dependent change in the conductor geometry and the space charge density in the surrounding environment.

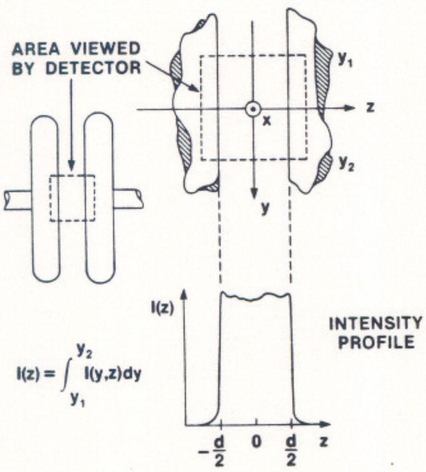

Fig. 4. Detector view of the gap between parallel-plate electrodes. The intensity profile I(z) is shown for the entire area scanned by the detector.

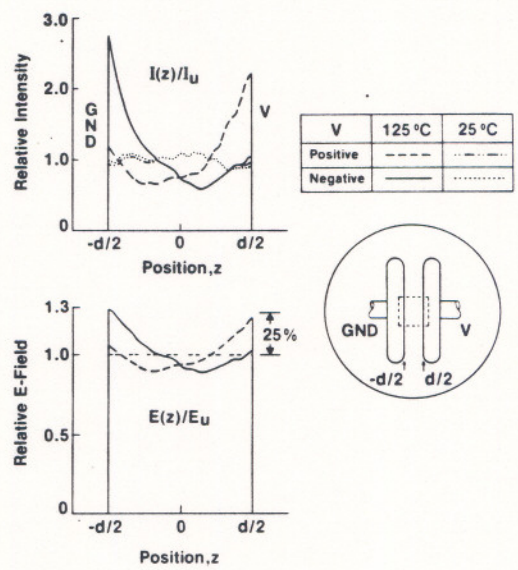

Fig. 5. Light intensity and electric field profiles as functions of position for 25°C and 125°C. These data were taken at 70 kV dc. The dashed box in the inset shows the area over which the light intensity was measured. In the upper graph, only the dotted line is shown where the 25°C profiles overlap. In the lower graph, a double dashed line is used to indicate that the 25°C electric field was uniform.

As mentioned above, the electrooptic Kerr effect has been used to determine electric field distributions and space charge density in transformer oil [8, 9]. Figure 4 shows a typical measurement of the optical transmission between parallel plates along a line from one plate to the other. Figure 5 shows the electric field distribution along a similar line at two different temperatures. The significance of these data for this discussion is that it is possible, using an electrooptical technique, to measure the electric field distribution, and, using the one dimensional Maxwell equation

$$\rho = \varepsilon \, dE(z)/dz \tag{5}$$

to determine the space charge density ρ in transformer oil. This system has been used to measure the space charge in pure and in contaminated oil as a function of temperature, to measure the effect of oil-paper and oil-pressboard interfaces as a function of temperature, and to investigate the relationship between the breakdown strength of an oil sample and the space charge density in the oil.

6. ACKNOWLEDGMENTS

Partial support was received from the Electric Energy Systems Division of the U. S. Department of Energy for some of the experimentation and analysis which support this paper. In addition, the author would like to thank B. Frey for assistance in the preparation of this manuscript.

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