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Proposal to Develop Techniques Using Magneto-Optic and Electro-Optic Effects in Optical Fiber for CTR Diagnostics

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PROPOSAL TO DEVELOP TECHNIQUES USING MAGNETO-OPTIC
AND ELECTRO-OPTIC EFFECTS IN OPTICAL FIBER FOR CTR DIAGNOSTICS

by

G. I. Chandler and F. C. Jahoda

ABSTRACT

We discuss the developing technology of measuring electric and magnetic fields with optical fibers using the Faraday and Kerr effects, magnetostriction, and Sagnac interferometry. We review the measurement of induced birefringence in the presence of natural birefringence. We propose the use of these effects in making measurements in the fusion research program, with ZT-40 as an example.

I. INTRODUCTION

This report addresses the rationale and feasibility of using the magneto-optic (Faraday effect) and electro-optic (Kerr effect) properties of fused silica single-mode optical fibers to measure magnetic and electric fields in controlled thermonuclear reaction (CTR) experiments.

Since the first low-loss (~ 20 dB/km) fibers were created by Corning in 1969, the optical fiber industry has grown dramatically as applications in the communications field have been realized with great success. CTR-Division of Los Alamos National Laboratory has developed this technology to solve problems with electromagnetic interference in data communications, trigger pulse timing, and diagnostics.

Researchers studying the optical properties of communication fibers were inevitably led to the measurement of polarization parameters and the unsurprising discovery of birefringence and photoelasticity.¹ The possibility of doubling the channel-carrying capacity of a single-mode fiber by using both orthogonally polarized modes led to efforts to produce fibers in which the coupling between modes is minimized (so-called polarization-maintaining fibers), and the Kerr and Faraday effects² were used to make measurements on candidate fibers.

Electric power companies used fiber optics very early for isolation when coupling current and voltage measurements down from high-voltage lines. They had also used the Faraday effect to measure line currents, and the idea of using the Faraday effect in fibers to produce a simple, accurate, electrically isolated current measurement is the most important driving force behind efforts to produce very low linear polarization birefringence optical fibers. The British³ and Germans⁴⁻⁶ are far advanced in these areas. An excellent review article was written by Smith.⁷

The Navy has commissioned the Naval Research Laboratories (NRL) to study the entire field of fiber optics sensors, and a great deal of work has been accomplished, with primary emphasis on magnetic field detection and underwater hydrophones. A "Technology Assessment" is produced by NRL at irregular intervals,⁸ and annual workshops are held.

II. PROPERTIES OF FIBERS

An optical fiber can be treated as a dielectric wave-guide and has a specific number of propagating modes dependent on the value of the normalized frequency v :

$$v = \frac{\pi d}{\lambda} (n_1^2 - n_2^2)^{1/2}, \quad (1)$$

where d = diameter of core,

n_1 = index of core,

n_2 = index of cladding, and

λ = wavelength.

$NA = (n_1^2 - n_2^2)^{1/2}$ = numerical aperture, the sine of the half-angle of the fiber acceptance cone.

Table I⁹ lists the number of propagating modes for various ranges of v , the maximum core diameter that applies for 633-nm light, and a (typical) NA of 0.10. Single-mode fibers (really two modes of orthogonal polarization) are commercially available and widely used for high-bandwidth communications

TABLE I
PROPOGATING MODES FOR VARIOUS RANGES OF ν

<u>ν</u>	<u>No. of Modes</u>	<u>d Max (μm)</u>
0 - 2.4048	2	4.84
2.4048 - 3.8317	6	7.72
3.8317 - 5.1356	12	10.36
5.1356 - 5.5201	16	11.12
5.5201 - 6.3802	20	12.86

links. A typical single-mode fiber has a 4- μm core diameter, 80- μm cladding diameter, and a silicone rubber jacket for an overall outside diameter of 500 μm .*

Early measurements¹ revealed that fibers have fairly large intrinsic linear birefringence that is reasonably uniform along their lengths. Additional linear birefringence is induced by bending and clamping stress. Measured values of linear birefringence (expressed in degrees of relative phase retardation per centimeter) are listed in Table II for various fibers as reported in the literature. Some of them are produced in such a way as to deliberately maximize or minimize this parameter. Circular birefringence can be introduced by twisting the fiber, and may be present in the relaxed fiber as well.

The linear birefringence of the fiber may be related by stress-optic theory¹⁰ to the ellipticity of the core, and fibers with very high birefringence have been produced by deliberately deforming the core.¹¹ Those who work in this area typically specify the "beat length," the distance for the retardation to change by a factor of 2π , and that distance has been reduced to < 1 cm. This is one way to produce a polarization-maintaining fiber and is favored by American workers at Corning, ITT, and Bell Labs.

*ITT Type 1601 single-mode fiber. ITT Electro-Optical Products Division, 7635 Plantation Road, Roanoke, VA 24019

TABLE II
REPORTED VALUES OF LINEAR BIREFRINGENCE

<u>Fiber Description</u>	<u>deg cm⁻¹</u>	<u>Date</u>	<u>Investigators</u>
Single-mode, 3.8- μ m core	1.1	1972	Kapron et al. ¹
Graded index, 50- μ m core	58	1975	Papp and Harms ⁶
Liquid core, 94- μ m core	0	1975	Aulich et al. ⁵
126- μ m core, N _a -SiO ₂ -B ₂ O ₃	0.7	1978	Aulich et al. ⁵
110- μ m core silica	0.06	1978	Aulich et al. ⁵
5- μ m core silica CVD	0.06	1978	Aulich et al. ⁵
4.7- μ m core silica	66	1976	Ramaswamy et al. ¹⁰
2- μ m/3- μ m elliptical core	277-72	1979	Ramaswamy et al. ¹¹
5- μ m core silica CVD	0.1	1978	Schneider et al. ¹³
7- μ m core	.25	1978	Smith ¹⁹
9- μ m core silica SV1	.022	1979	Norman et al. ³

The European approach is to produce very round, stress-free fibers of very low linear birefringence. This is done at Siemens AG¹³ and the University of Southampton.³

There are multimode fibers listed in Table II with rather low birefringence. These are not generally suitable for making polarization preserving devices because the light is depolarized rather quickly, apparently because of strong coupling between modes. Single-mode fibers maintain the degree of polarization very well. We note a distinction here between the degree and the state of polarization (SOP); the latter changes because of birefringence, but that change need have no effect on the former. It is possible to launch a single mode in a multimode fiber, but it is difficult, and the geometry of most practical fiber devices will quickly cause the energy to spread to the other modes. For these reasons most fiber sensor work is done with single-mode fibers.

The Faraday effect is the consequence of circular birefringence caused by a longitudinal magnetic field. The phenomenon of circular birefringence causes a rotation of the plane of linearly polarized light. Equivalently, in terms of circularly polarized basis vectors of opposite sense, it is a phase retardation between those vectors. The rotation angle of linear polarization is given in general by

$$F = V \int \vec{H} \cdot d\vec{\ell} , \quad (2)$$

or

$$F = V \oint \vec{H} \cdot d\vec{\ell} = VI \quad (3)$$

for closed loops linking the current I . The Verdet constant V is expressed in rad amp^{-1} . For silica at 633 nm, $V = 4.68 \times 10^{-6} \text{ rad A}^{-1}$ (See Ref. 7).

The electro-optic Kerr effect is the production of linear birefringence with a transverse electric field, and the phase retardation is given by

$$\beta = \pi \ell B_K E^2 , \quad (4)$$

where E = transverse field strength, volt cm^{-1} ,

ℓ = exposed length, cm, and

B_K = Kerr constant, measured² in a silica fiber as $9 \times 10^{-15} \text{ cm V}^{-2}$.

III. POLARIZATION MEASUREMENTS

The state of polarization of light traveling along a fiber evolves according to the characteristics of the fiber. Any fiber has orthogonal fast and slow axes (linear birefringence) that rotate along the length of the fiber. If one thinks of the SOP at any point along the fiber as the ellipse traced by the end of the electric field vector, that ellipse is characterized by an angle with respect to the local fast fiber axis (azimuth)(see Fig. 1). The ellipticity and azimuth evolve with the local values of the fast and slow axis indexes of refraction, or the specific linear polarization phase retardations, and the azimuth alone evolves with the local circular birefringence (generated by shear stress caused by twisting or by magnetic fields). One can see that when both types of birefringence are present, the evolution of the SOP is not simple--it may be visualized to some extent in the

so-called Poincaré sphere representation. (See Ref. 2 and a book on polarized light such as Shurcliff,¹⁴ Swindell,¹⁵ or Azzam and Bashara.¹⁶)

Nevertheless, it is possible to measure circular birefringence in the presence of linear birefringence. In Fig. 2 we see a conceptualization of a measurement system. Linearly polarized light is incident on the end of a fiber with its plane of polarization parallel to one of the fiber axes. The output beam is split into orthogonally polarized beams, their axes at angles of $\pi/4$ with respect to the fast and slow axes of the fiber at that end. We describe the procedure for location of the fast and slow axes of the fiber in the appendix. The intensity I_1 , I_2 of each beam is measured with a photodiode, and the intensity-normalized quantity T ,

$$T = \frac{I_1 - I_2}{I_1 + I_2}, \quad (5)$$

is calculated with analog electronics^{17,18} or, as we propose, by computer with analog-digital converters for data acquisition.

According to Smith¹⁹ T is related to the several birefringence and optical parameters by

$$T = -2 \cos(\delta_2 + \eta) \sin \chi \sin \frac{\phi}{2} \left(\cos^2 \frac{\phi}{2} + \cos^2 \chi \sin^2 \frac{\phi}{2} \right)^{1/2}. \quad (6)$$

The parameters in Eq. (6) are defined by reference to Figs. 3 and 4, in terms of F and δ_1 . In Fig. 3, the fiber is shown in three parts: an initial leading section of length ℓ_0 between the input optics and the field-measurement region having total phase retardation of $\delta_0 = \ell_0 \delta_s$, where δ_s is the linear retardation per unit length of the fiber; the field-measurement region of length ℓ_1 , of total retardation δ_1 and Faraday rotation angle F ; and third, another field-free "lead" region connecting to the output optics with length ℓ_2 and retardation δ_2 . The parameters χ and ϕ are defined by the trigonometric relationships of the right triangle shown in Fig. 4; and finally,

$$\eta = \tan^{-1} (\cos \chi \tan \frac{\phi}{2}) \quad . \quad (7)$$

Note that δ_0 does not appear.

Equation (6) could be used directly with a computer to find F and so determine the magnetic field or current because all other parameters are previously determined. However, the study of three limiting cases of Eq. (6) is instructive and helpful in laboratory work.

Case 1: $F \gg \delta_1/2$, δ_2 (low linear birefringence).

In this limit $\sin \chi \rightarrow 1$, $\cos \chi \rightarrow \delta_1/2F$, $\phi/2 \rightarrow F$, $\sin \phi/2 \rightarrow \sin F$, $\cos \phi/2 \rightarrow \cos F$, and $\cos (\delta_2 + \eta) \rightarrow 1$. Substituting into Eq. (6) and using a double-angle trig identity, we get simply

$$T \approx -\sin 2F \quad . \quad (8)$$

Case 2: $F \ll \delta_1/2$, $\delta_2 \ll \delta_1$.

Again using Fig. 4, $\phi \rightarrow \delta_1$, $\sin \chi \rightarrow 2F/\delta_1$, $\cos \chi = \delta_1/\phi \rightarrow 1$, $\sin \phi/2 \rightarrow \sin \delta_1/2$, $\cos \phi/2 \rightarrow \cos \delta_1/2$, $\tan \phi/2 \rightarrow \tan \delta_1/2$ so that $\cos (\delta_2 + \eta) \rightarrow \cos \delta_1/2$. Substituting into Eq. (6) and using the double angle identity we get

$$T \approx -2F \frac{\sin \delta_1}{\delta_1} \quad . \quad (9)$$

A better approximation for Case 2 with values of δ_1 and F in the same range is suggested by Smith in Ref. 7:

$$T \approx 2F \frac{\sin \phi}{\phi} \quad . \quad (10)$$

Case 3: A clever approach^{20,21} allows normal fibers of moderate values of δ_s to be used by biasing F with circular birefringence induced by twisting the fiber. Then F is replaced by $\alpha + F$, where $\alpha = g\tau$; g is a constant relating the induced circular birefringence α to the twist per unit length τ , and has values in the range 0.1 - 0.16. We get $F + \alpha \gg \delta_1/2$, δ_2 , with the result the same as in Case 1 if we set $\alpha = n\pi$, with $\delta_2 = m\pi/2$ and n and m integers, and then

$$T \approx -\sin 2F .$$

(11)

Note that Case 1 gives the justification for making very low linear birefringence fibers for current sensing, whereas Case 2 argues for high linear birefringence for the same measurement. We intend to explore the practical advantages and limitations of all three cases.

Temperature can be a problem in a highly stressed fiber because of the interaction between coefficients of expansion, the stress-optic coefficients, and birefringence. The high birefringence fibers (Case 2) use severely deformed cores to achieve that property and hence may be expected to show considerable temperature sensitivity. The same is true of fibers twisted as in Case 3. Clearly, the most desirable fiber would appear to be the low linear birefringence type that is not available in the US.

We compared values calculated from Eqs. (6) and (8) for ZT-40 conditions and a single-turn loop of silica fiber of very low birefringence (2 deg m^{-1}). This includes a 1.5-m loop length and 2-m leads. The values obtained agreed to about 1%. Equation (6) is plotted in Fig. 5 for the parameters discussed. The peak occurred near 180 kA, so that to make a Faraday optical loop for ZT-40, we would need some means of detecting which side of the peak or the following zero one was on (similar to counting whole fringes in an interferometer), or we could use a different number of turns. At 400 kA the Faraday rotation for one turn would amount to about 107 degrees.

In Fig. 6 we convolve the transfer function of Fig. 5 with a ZT-40 I_ϕ waveform for two different values of peak current, 195 kA and 390 kA. The sinusoidal nature of the polarimeter output causes wide variation of sensitivity depending on current level. Obviously it is best to use this technique on the steep part of the response curve, preferably on the first cycle; that is, with current less than around 100 kA. This technique is best used to look for "fine structure" in high current levels, however, by biasing the device to get to a steep part of the curve. The expected resolution is around 1%, or 1000 amps, for a one-turn loop of fiber and carefully adjusted analog electronics.

IV. SAGNAC INTERFEROMETER

Arditty reported²² at the Integrated Optics and Optical Communications Conference this year in San Francisco (IOOC '81) that the Faraday effect was measured by using optical fiber in a Sagnac interferometer. This is a technique widely discussed for use in rotation sensing (optical gyrosopes) and promises to be simpler and more sensitive than the direct optical polarimetric method just described.

Figure 7 illustrates the concept. The linearly polarized output of a laser passes through a beam splitter and a circular polarizer and is incident on both ends of a fiber optic loop. The output is circularly polarized (only one polarization is needed) so that the light traveling in both directions has the same (say left-hand) polarization. The component of magnetic field along the fiber modifies the indexes of refraction for left-handed polarization differently for each direction of travel, increasing it for one and decreasing it for the other, so that there is a net phase shift of $2F$ between the

counter-propagating beams around the loop. The light is recombined on the beam splitter-detector combination and a fringe shift is observed.

The apparatus can be further improved with a clever scheme for phase modulation analogous to heterodyning as described in Ref. 22. Sensitivity depends on the number of turns of fiber and the current-carrying conductors. Depending on all these parameters, measurements can be made over a large range, bounded by counting many fringes on the high end and the very small fractional fringe counts reached by heterodyning principles on the low end.

An advantage of using the Sagnac interferometer approach is that the phase modulation and detection methods developed for inertial rotation sensors (fiber-optic gyros) are available and less susceptible to common mode polarization effects, and similar in many respects to techniques commonly used in CTR for various interferometer diagnostics.

V. MAGNETOSTRICTION

A third approach²³ to measuring magnetic fields involves coating a fiber with magnetostrictive material and measuring the strain effects with the fiber as one arm of a Mach-Zehnder interferometer. The fiber could also be bonded in some way to a chunk of magnetostrictive material. The Mach-Zehnder interferometer measures fiber strain regardless of source, and any field that can be used to produce a strain in some material that can in turn be bonded to an optical fiber is susceptible to measurement in this way. We visualize using discrete magnetostrictive sections distributed along the fiber to produce devices analogous to sine-cosine coils.

VI. KERR ELECTRO-OPTIC EFFECT

Using the Kerr effect is much more difficult because of the small value of the Kerr constant for silica, $9 \times 10^{-15} \text{ cmV}^{-2}$. For a field such as exists in the dense z-pinch, $E \sim 25$ to 75 kV-cm^{-1} , the retardation amounts to 1.8×10^{-5} to $1.6 \times 10^{-4} \text{ rad cm}^{-1}$ of exposed fiber. An exposed length of 1 to 10 m would be required to get 1 deg of retardation.

Another possibility might be to use liquid-core fiber, with a high- B_K liquid in the core. Liquids have Kerr constants 2 to 4 orders of magnitude greater than silica, and a respectable retardation would be available for centimeter lengths with a liquid such as nitrobenzene (12.7 rad cm^{-1} at 75 kV cm^{-1}). Liquid-core fibers have been made for years to avoid some birefringence problems, but are out of vogue at present. We have contacted some fiber manufacturers who have told us such fibers can be made easily on special order, but at a minimum inner diameter of about 25 to $50 \mu\text{m}$, too large for single-mode operation at visible wavelengths.

VII. FIBER AVAILABILITY

The low linear birefringence fibers mentioned above are only available in Europe. We have purchased 100 m of such fiber from the University of Southampton for $\sim \$600$. Siemens AG has given us 10 m of their low birefringence fiber in exchange for a promise of reporting our results to them. An American firm, Valtec Corp., has shown an interest in learning the University of Southampton process.

ITT Electro-Optics Division in Roanoke, Va. produces high stress-induced birefringence fibers with elliptical cores that serve as polarization maintaining fibers. They also produce quantities of single-mode fiber for communications purposes. We have samples of each, as well as samples of single-mode fibers from Corning and Fiber Communications, Inc., now part of

Times and no longer producing single-mode fiber. ITT is a major supplier of fiber to NRL for their research and is also engaged in producing optical fiber couplers that greatly simplify the construction of interferometers.

VIII. WORK IN PROGRESS

We are building two analog polarimeters such as those described in Refs. 17 and 18 for laboratory work. If a polarimetric diagnostic were developed to be used on say, ZT-40, we would expect to do the signal processing with a CAMAC interface to the Prime 400 using modules already in-house. The analog polarimeters are designed for a 500-kHz bandwidth and might be marginally suitable for field use, but computer processing the data as described should produce more precision and better frequency response. We also propose to pursue the SAGNAC interferometer approach. We feel it has the most promise in terms of sensitivity, ease of fabrication, and minimization of operator attention in an on-line diagnostic. Much of the necessary hardware is not yet available in CTR, however.

There are peripheral technologies that must be mastered in parallel with the main effort. These include the abilities to handle and splice single-mode fiber and to create optical couplers, and so we have purchased a commercial fusion splicer. We also need to characterize fibers and have been looking at commercial devices for that purpose. To use interferometric methods, we must build phase modulators, and to produce light properly polarized for our needs, we must make fiber optic devices that are the equivalent of variable wave plates or Babinet-Soleil compensators.²⁴

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Fig. 1. General polarization ellipse defining azimuth and ellipticity.

Fig. 2. Coordinates for measuring circular birefringence in the presence of linear birefringence. Input polarization is parallel to one of the (local) fiber axes. The two orthogonal output analyzers are at $\pm \pi/4$ radians to the (local) fiber axes.

Fig. 3. Schematic of apparatus for fiber polarization measurement. See text for definitions of symbols.

Fig. 4. Definition of χ and $\phi/2$ in terms of Faraday rotation angle F and linear retardation phase angle δ_l in measurement section.

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Fig. 5. Plot of the normalized intensity response of polarization analyzers vs current for single-loop silica fiber wound on ZT-40.

Fig. 6. Convolution of typical ZT-40 I_ϕ current waveform with Fig. 5 for two different peak currents, showing time response of normalized intensity polarization analyzer.

Fig. 7. Conceptual arrangement of Sagnac interferometer for greater sensitivity current sensing.

APPENDIX

LOCATION OF THE FAST AND SLOW AXES OF FIBER TRANSMISSION

A setup similar to Figs. 2 and 3 is used, so that the linearly polarized light is incident on the fiber end at a variable angle ϕ to an arbitrary reference direction, and so that the analyzers also can be rotated to a variable angle ψ to some reference direction. Now the degree of linear polarization T ,

$$T = \frac{I_1 - I_2}{I_1 + I_2} , \quad (A-1)$$

is measured after first rotating the analyzer axes to maximize I_1 and minimize I_2 . The angle ϕ at which T is maximized corresponds to the fast or slow axis, and $\phi \pm \pi/2$ is the other. The analyzer axes at $T_{\max}$ also correspond to the fast and slow axes. This technique does not determine which is which, nor does it matter for our purposes. For more information see Ref. 6.