Design and Performance of Tuned Fiber Coil Isolators

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***Abstract*—Optical isolators using coiled single-mode fibers with controlled birefringence have been thoroughly analyzed and tested experimentally. Isolation ratios as high as 44.5 dB with insertion losses (excluding coupling and polarizer losses) of 0.3 to 0.4 dB have been obtained at 633 nm. Analysis indicates that these devices will have >20-dB isolation over a spectral range of 2.5 nm or a temperature range of 36°C.**

I. INTRODUCTION

THE PRODUCTION of devices based on the Faraday effect in single-mode optical fibers is made difficult by the low Verdet constant of fused silica [1] and the fact that linear birefringence in the fiber, either inherent or induced by bending, acts to quench the rotation [1]-[3]. Recently, however, several experimental studies [3], [4] have demonstrated that it is possible to nearly eliminate the quenching by alternating the sense of the magnetic field along the fiber in increments equal to half of the birefringence beat length. Fiber lengths sufficient for useful devices can then be employed.

Such devices are unusual in that they are tuned; since the beat length is (to first order) linearly proportional to wavelength, for a fixed periodicity of the magnetic field, there is only a narrow range of wavelengths over which an efficient interaction can take place. The extent of this range is determined by the total birefringence (i.e., the total number of beat lengths) present.

A coil of fiber in which the beat length is exactly equal to the circumference, placed in a magnetic field perpendicular to the coil axis, satisfies the condition for efficient interactions. If such a coil is wound from an inherently low birefringence fiber, such as spun fiber [5], the beat length may be controlled by choosing the diameter of the coil relative to the diameter of the fiber so that precisely the required amount of birefringence is induced by bending. Recent analysis and testing [4] of this configuration has shown that the efficiency is half that which would be obtained with a uniform magnetic field in the absence of birefringence. In this paper we extend the analysis of these devices and describe the design and performance of optical isolators using this principle.

II. GENERAL ANALYSIS

The performance of the coil may be studied by adapting prior theoretical work on Faraday rotation in the presence of linear birefringence. We use the following Jones calculus equation which relates the input and output polarization states for a medium in which both linear birefringence and uniform Faraday rotation are present [2]:[1]

$$\begin{vmatrix} E_x(z) \\ E_y(z) \end{vmatrix} = \begin{vmatrix} \cos\frac{\phi z}{2} - j\,\frac{\Delta\beta}{\phi}\sin\frac{\phi z}{2} & -\frac{2F}{\phi}\sin\frac{\phi z}{2} \\ \frac{2F}{\phi}\sin\frac{\phi z}{2} & \cos\frac{\phi z}{2} + j\,\frac{\Delta\beta}{\phi}\sin\frac{\phi z}{2} \end{vmatrix} \times \cdot \begin{vmatrix} E_x(0) \\ E_y(0) \end{vmatrix}. \tag{1}$$

E_x and E_y are the optical field components parallel to the axes of birefringence, $\Delta\beta = 2\pi(n_x - n_y)/\lambda$ is the fiber birefringence per unit length, F is the Faraday rotation per unit length that would appear if there were no birefringence, and

$$\left(\frac{\phi}{2}\right)^2 = \left(\frac{\Delta\beta}{2}\right)^2 + (F)^2. \tag{2}$$

For the coil, the tangential component of the magnetic field varies sinusoidally with length. We take

$$F = VB_0 \cos(z/R) \tag{3}$$

for a coil of radius R placed in a linear magnetic field B_0 and with a Verdet constant V in the fiber. The tuning condition is $\phi = 1/R$, or for $F << \Delta\beta$

$$\Delta\beta = 1/R. \tag{4}$$

Equation (1) with the substitutions of (2), (3), and (4) may by evaluated numerically. One result is that, for small values of F, the transfer of power between the two polarizations follows approximately a $\sin^2$ (or $\cos^2$) law [4]. Specifically, for the case of light initially plane-polarized parallel to the x-direc-

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[1] This equation was incorrectly stated in [4].

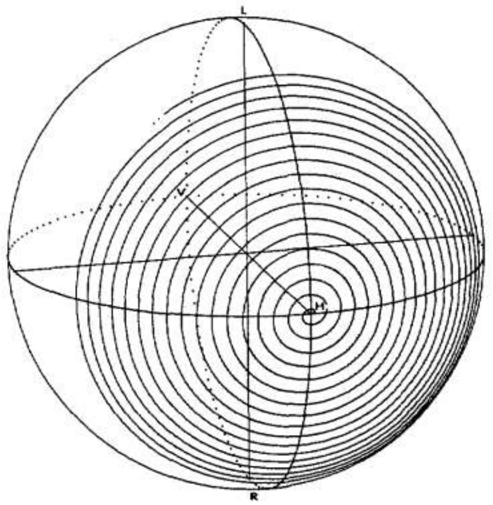

Fig. 1. Poincaré sphere representation of the polarization state along a tuned fiber coil, for a linearly polarized input parallel to one axis of the bend-induced birefringence. Coil diameter = 2 cm, $B = 0.3$ T.

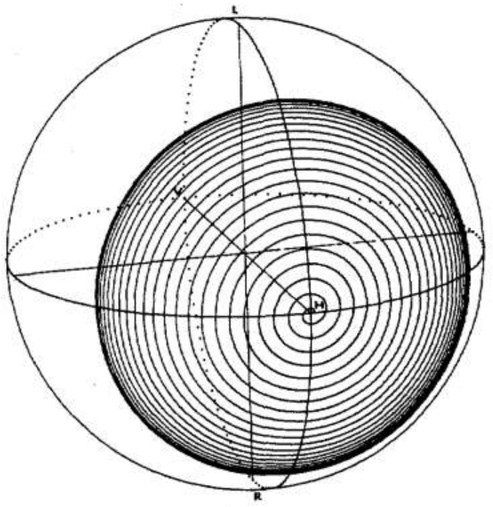

Fig. 2. Poincaré sphere representation of the polarization state along a detuned fiber coil, for a linearly polarized input parallel to one axis of the bend-induced birefringence. Δ_t = total birefringence error = π rad.

tion, one obtains

$$\left|\frac{E_y(z)}{E_x(0)}\right|^2 \approx \sin^2\left(\frac{VB_0z}{2}\right). \tag{5}$$

The factor of 1/2 in the argument indicates that the presence of birefringence and the sinusoidally varying magnetic field together lead to an efficiency that is half what would be obtained with a straight nonbriefringent fiber in the same field. For a Verdet constant [3] of 1.7°/cm · T at 633 nm, a coil diameter of 2 cm, and a magnetic field on 0.3 T, approximately 25 turns (~1.5 m of fiber) are required to achieve a 50-percent transfer of power from one polarization to the other, equivalent to 45° of rotation.

The device may be studied further by computing the exact polarization state along the coiled fiber and examining the results using a Poincaré sphere. Again for the case of light initially plane polarized in the x (horizontal) direction, the Poincaré sphere representation is shown in Fig. 1. The trajectory is seen to trace out a spiral with constant pitch which would, for a long enough coil, fill the entire sphere, collapsing to the point representing the vertical (y) state, then returning to the horizontal state and repeating the process. In each turn of the spiral, which corresponds to a turn of the coil, the trajectory passes through the equator (linear polarization) twice, once with a positive and the other with a negative rotation relative to the input. To achieve a linear polarization at exactly 45° to the input state, the parameters must be adjusted so that the trajectory passes through the equator exactly 90° from the input state. This is most easily achieved by varying the magnetic field slightly.

If the coil is detuned, that is, if at the wavelength of operation the beat length is not exactly equal to the circumference, the conversion of power from one polarization to the other cannot be complete. On the Poincaré sphere, this is indicated by a decrease in the pitch of the spiral with successive turns. Eventually, as shown in Fig. 2, the spiral attains a maximum diameter, whereupon it begins to collapse toward the original state rather than approaching the orthogonal state.

The most important parameter governing the performance of the coil is the total birefringence error Δ_t. This turning parameter is defined for a given wavelength as the difference between the total birefringence of the coil (in radians) and $2\pi N$, where N is the number of turns. For the case of Fig. 2, Δ_t was π rads. This corresponds to a fractional error in winding a 25-turn coil of 2 percent, and is insufficiently accurate to achieve a 45° rotation.

Another point concerning the efficiency of interaction is the phase of the spatially periodic magnetic field. The field is most efficient at producing rotation, or equivalently in transferring power from one polarization to the other, when the polarization state is linear. For a linear input state, this means that a cosine dependence (input and output leads parallel to field) is chosen in (3) rather than a sine dependence (leads perpendicular to field) which would be more convenient experimentally. Fig. 3 shows the computed transfer of power between the two states for three different spatial phases, for the case of a linearly polarized input at 45° to the axes of birefringence. If the input state is parallel to either axis of birefringence, a different situation occurs. In this case the polarization state does not change until acted upon by the magnetic field so either a sine or cosine field dependence may be used. In an isolator, however, this cannot be put to use since input and output states cannot both be along the axes).

III. COIL FABRICATION

Birefringence induced in a fiber by bending on a uniform radius is given, to a good approximation [6], by the expression

$$\Delta\beta = K_\lambda r^2/R \text{ deg/turn} \tag{6}$$

where r is the radius of the fiber, R is the radius of the bend, and K_λ is a coefficient equal to about 4.9×10^8 deg/turn at a wavelength of 633 nm. For commonly available single-mode fibers with outer diameters between of 100 and 200 μm, the coil diameters necessary to achieve the required $\Delta\beta = 360$ deg/turn are thus between 6.6 and 26.5 nm.

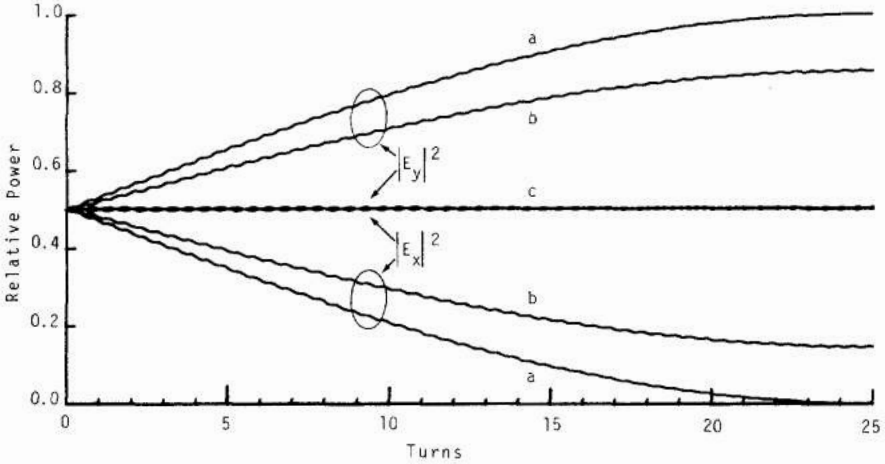

Fig. 3. Transfer of power between the x- and y-polarizations for three different spatial phases of the magnetic field. (a) $B = B_0 \cos (z/R)$. (b) $B = B_0 \cos (\pi/4 + z/R)$. (c) $B = B_0 \sin (z/R)$.

In general, it is found that by measuring the outer diameter of the fiber accurately and using (6) one may readily produce coils that are within 1-2 percent of having the proper birefringence/turn at a specified wavelength. For most devices, however, this is insufficiently accurate and in an earlier work [4] it was necessary to wind the coil on an expandable former so that additional stress could be applied, thereby tuning the coil to the desired wavelength. Although this tuning feature is desirable, it may not be possible to achieve the stability required for a practical isolator using the expandable former.

Further experiments have shown that, while K_λ may vary slightly from fiber to fiber, the bend birefringence of a specific fiber is quite reproducible. This has allowed the fabrication of free-standing coils that are tuned for a specified wavelength to an accuracy of better than 0.1 percent.

The coils used in the work reported here were wound from 180-μm-diam fibers having a 300-μm-diam silicon rubber jacket. The index difference between the core and the depressed inner cladding was about 0.22 percent. The preform was spun [5] during pulling to essentially eliminate all inherent linear and circular birefringence.

The optimum former diameter for coils designed to operate at 633 nm was found to be 21.85 nm (22.15-μm coil diameter to fiber axis) for this fiber. Twenty five to twenty seven turns of fiber were closely wound on a solid former of this diameter and coated with additional silicon rubber. After curing, the former was removed, leaving a completely free-standing coil, which was then placed into a structure suitable for testing.

To test for possible temperature variations in the bend birefringence, a coil was placed in a water bath and its net birefringence measured polarimetrically over the range from 10 to 60°C (Fig. 4). The temperature coefficient of bend birefringence was found to be approximately 0.011 percent/°C. This is somewhat lower than had been measured previously [7] and predicted from stress analysis [8].

IV. ISOLATOR DESIGN AND PERFORMANCE

An optical isolator can be constructed by placing a coil designed to give exactly 45° of rotation between polarizers oriented at 45° to each other (Fig. 5.) Light transmitted by the input polarizer is rotated and passes through the output polarizer without attenuation. Light traveling in the reverse direction, however, is rotated on additional 45° and is blocked by the input polarizer.

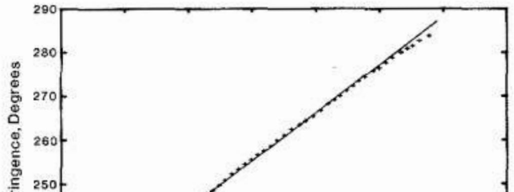

Fig. 4. Net birefringence of a fiber coil versus temperature. Fiber diameter = 180 μm. Jacket diameter = 300 μm; former diameter = 21.85 nm; Approximately 27.5 turns. Straight line corresponds to 0.011 %/°C temperature coefficient of the bend birefringence.

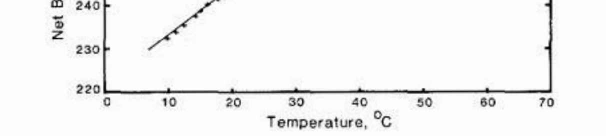

Fig. 5. Schematic representation of a tuned fiber-coil isolator.

Any departure from optimum characteristics in the rotation element serves to increase the forward attenuation and to decrease the reverse attenuation. These effects may be evaluated quantitatively using the techniques described in Section II. The forward and reverse attenuations as a function of the tuning parameter Δ_t are plotted in Fig. 6 For $|\Delta_t| < 0.1\,\pi$ rads (18°), the analysis predicts a negligible forward attenuation, a reverse attenuation of >20 dB, and thus an isolation ratio of >20 dB.

The curves in Fig. 6 prove to be essentially independent of the number of turns in the coil provided the length of fiber and field strength are such as to give exactly 45° rotation when the coil is properly tuned. For a given coil, it is thus straightforward to predict the spectral or temperature range over which a specified level of performance can be maintained. A 25-turn coil at 633 nm, for example, should provide >20-dB isolation

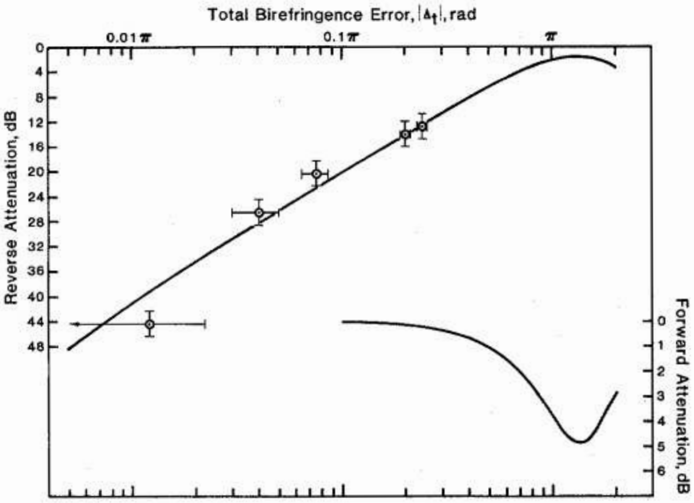

Fig. 6. Computed and experimental reverse attenuation and computed forward attenuation versus the tuning parameter $|\Delta_t|$.

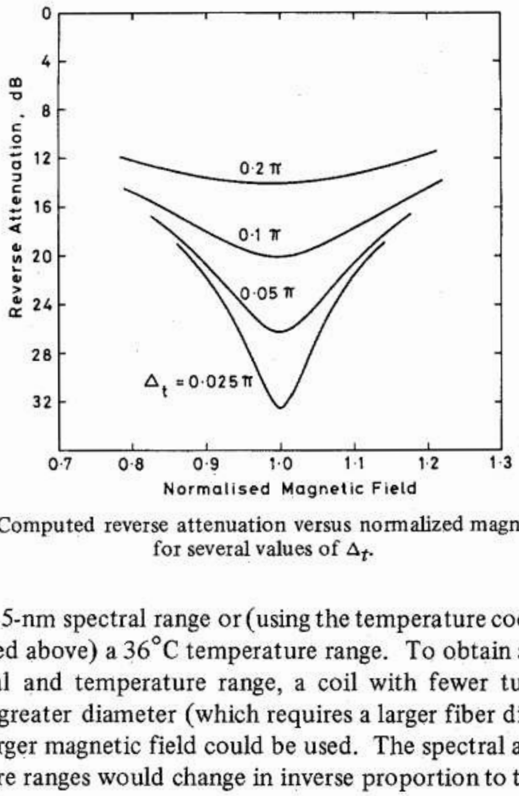

Fig. 7. Computed reverse attenuation versus normalized magnetic field for several values of Δ_t.

over 2.5-nm spectral range or (using the temperature coefficient reported above) a 36°C temperature range. To obtain a greater spectral and temperature range, a coil with fewer turns and either greater diameter (which requires a larger fiber diameter) or a larger magnetic field could be used. The spectral and temperature ranges would change in inverse proportion to the number of turns.

The easiest method of adjusting the coil to provide exactly 45° of rotation is to vary the magnetic field. For the coils described above, the required field is slightly less than 0.3 T. In Fig. 7 the reverse attenuation is plotted as a function of normalized magnetic field for several values of Δ_t. The optimum field is seen to be essentially independent of Δ_t and the sensitivity to field magnitude sufficiently low so that adjustment for optimum performance is relatively easy. Field variations, for example from permanent magnet aging, should also not be a problem.

A fixture incorporating the elements shown in Fig. 5 was used for testing. Film polarizers with a measured extinction ratio of 49 dB and 10 × microscope objectives selected for low birefringence were used. A silicon p-i-n detector with an integral current mode op amp provided linear detection over a sufficient dynamic range. By reorienting the polarizers, either end of the coil could be defined as the input. The magnetic field was provided by a permanent magnet with a field strength of 0.3 T and gap dimensions of 2.5 cm × 2.5 cm diam. Since a uniform field was not required, it proved easiest to adjust the field for exactly a 45° rotation by moving the coil to the edge of the gap region.

The turning parameter Δ_t was first determined by inserting a Babinet-Soliel compensator between one polarizer and the coil before the coil was placed in the magnetic field. Then, with the field optimally adjusted, the forward or reverse attenuation was obtained from transmission measurements with the polarizer nearer the detector in its normal and orthogonal positions. Losses from the polarizer, coupling, and fiber bending were thus excluded. Bend loss was measured separately and found to range between 0.3 and 0.4 dB for the coil measured.

Five coils, prepared in the manner described and designed to have slightly different values of Δ_t at 633 nm, were tested with a HeNe laser. The forward attenuation resulting from detuning was found to be negligible compared to measurement uncertainty in all cases. The reverse attenuation for each of the coils is shown in Fig. 5. Agreement with theory is very good for the coils having the higher values of $|\Delta_t|$. For the smaller values of $|\Delta_t|$ the differences between theory and experiment are believed to result from stress-induced birefringence in the coil leads. The best value of reverse attenuation (and isolation ratio) among these coils was 44.5 dB, a value that compares favorably with other attempts to produce fiber isolators [9], [10] and with bulk [11] and integrated [12] optical isolators as well.

The effect of birefringence in the leads requires further study. However, based on preliminary analysis and testing of these coils, it appears that depending on its sign relative to that of Δ_t and its location, lead birefringence may either enhance or diminish the isolation ratio. Such enhancement appears to have occurred in the best of the coils tested.

It should be straightforward to extend this work to the production of an all-fiber isolator using one of several designs [13]-[15] for a fiber polarizer or using recently developed single polarization fiber [16], [17]. It should also be possible to construct devices for use in the 1.3- or 1.5-μm regions using the same principles. However, since the Verdet constant diminishes with wavelength in most glasses, it will be necessary to use coils with more turns, a higher magnetic field, or a combination of the two. The use of nonconventional doponts in the fiber core may also be helpful.

V. CONCLUSION

This work demonstrates that optical isolators with isolation ratios greater than 40 dB and insertion losses of a few tenths of a decibel can be routinely produced. Design curves, indicating the accuracy required in fabrication, have been computed and verified; these curves also allow projections of spectral width and temperature stability. Additional work on understanding the effects of birefringence in the leads and on new materials should result in further improvements in device characteristics.

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