Faraday rotation in coiled, monomode optical fibers: isolators, filters, and magnetic sensors

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It is shown that efficient Faraday rotation can be obtained in a fiber coil if the circumference of the coil is exactly equal to the beat length of the birefringence caused by bending. The essential elements of a practical, compact isolator based on this principle are demonstrated. Forty-five degrees of Faraday rotation were obtained in a 40-turn, 15-mm-diameter coil placed in the field of a permanent magnet (~0.29 T). The design of optical filters and magnetic sensors is also discussed.

Compact devices based on Faraday rotation in optical fibers have not been produced because bend-induced birefringence,[1] even in ultralow-birefringence fibers,[2] acts to quench the rotation.[3] Recently, however, it was demonstrated that by alternating the sense of the magnetic field in successive half-beat-length increments ($L_p/2 = \pi/\Delta\beta$, where $\Delta\beta$ is the fiber birefringence), it is possible to obtain large interaction lengths in spite of the birefringence.[4,5] In this Letter it is shown that the alternating-magnetic-field principle can be applied to a fiber coil in which the dimensions of the fiber and the coil are chosen so that the circumference is exactly equal to one beat length of the birefringence caused by bending. This approach permits the design of a range of compact, efficient Faraday devices, which are easily constructed. In particular, it has yielded an optical fiber isolator that is much more compact and potentially much less temperature sensitive than has been produced to date.[5]

When a uniform Faraday rotation and a uniform linear birefringence are both present in an optical element, the input- and output-polarization states may be related through the use of Jones calculus as follows[3,6]:

$$\begin{bmatrix} E_x(z) \\ E_y(z) \end{bmatrix} = \begin{bmatrix} \cos\frac{\Phi z}{2} - j\,\frac{\Delta\beta}{\Phi}\cos\frac{\Phi z}{2} & -\frac{2F}{\Phi}\sin\frac{\Phi z}{2} \\ \frac{2F}{\Phi}\sin\frac{\Phi z}{2} & \cos\frac{\Phi z}{2} + j\,\frac{\Delta\beta}{\Phi}\cos\frac{\Phi z}{2} \end{bmatrix} \begin{bmatrix} E_x(0) \\ E_y(0) \end{bmatrix}, \quad (1)$$

where x and y are the principal axes of the element, $\Delta\beta = 2\pi\,(n_x - n_y)/\lambda$ is the fiber birefringence, F is the Faraday rotation per unit length, and

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

Thus, for an input linearly polarized along the x direction, the value of $|E_y(z)|/|E_x(0)|$ oscillates along the fiber length and attains a maximum value of only $2F/\Phi$. If, on the other hand, F alternates in sign in successive half-beat-length increments,[4] $|E_y|$ grows monotonically at the expense of $|E_x|$ until $|E_x|$ reaches zero. Thus sufficient optical rotation can be induced by the magnetic field to make the construction of an isolator possible.

Consider now the geometry of Fig. 1. Assuming a uniform magnetic field B, one can write

$$F = VB\cos\frac{z}{R}, \quad (3)$$

where V is the Verdet constant of the fiber (approximately 1.7° $cm^{-1}\,T^{-1}$ at a wavelength $\lambda = 633$ nm for high-silica fiber[4]), R is the radius of the coil, and z is measured along the fiber axis. The condition for efficient interaction is $\Phi = 1/R$, or, if $F \ll \Delta\beta$,

$$\Delta\beta = 1/R. \quad (4)$$

Given an expression for bend birefringence as a function of fiber radius (r) and bend radius[1]

$$\Delta\beta = K\frac{r^2}{R^2}, \quad (5)$$

one can determine the appropriate value of R for a chosen fiber. [Experimentally at $\lambda = 633$ nm we estimate that $K = (7.60 \pm 0.05) \times 10^{7\circ}\ m^{-1}$ for our fiber, compared with 7.7×10^7 in Ref. 1.]

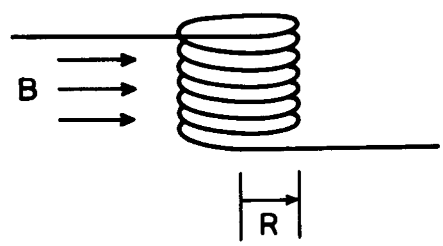

Fig. 1. For a fiber coil of radius R with a uniform magnetic field B parallel to the input and output leads, the component of the field parallel to the fiber axis is given by $B\cos(z/R)$, where z is measured along the fiber axis.

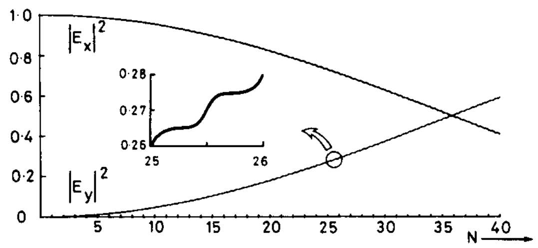

Fig. 2. Power in each of the orthogonally polarized modes as a function of the number of turns N for the case in which $E_x(0) = 1$ and $E_y(0) = 0$. See text for other parameters.

Figure 2 shows a numerical evaluation of Eq. (1) under the substitutions of Eq. (3) and (4) for the case in which $E_x(0) = 1$ and $E_y(0) = 0$, i.e., linearly polarized light launched parallel to the x axis. Values appropriate to readily available fiber ($r = 75\ \mu$m, which gave $R = 7.46$ mm) and magnet ($B = 0.29$ T) were also assumed.

The expected monotonic growth of $|E_y|$ with z is observed, reaching the condition $|E_y| = |E_x|$ at $\Delta\beta z \approx 36 \times (2\pi)$, that is, for about 36 turns or 169 cm. When $\Delta\beta z$ equals an integer multiple of π, the state of polarization is linear, making an angle of $\pm\tan^{-1}[|E_y(z)|/|E_x(z)|]$ with the x axis (one sign applies to even multiples and the other to odd, depending on the sense of the magnetic field).

The exact analytic expressions for $E_y(z)$ and $E_x(z)$ are obviously complex. However, by restricting attention to values of $\Delta\beta z = N2\pi, N = 0, 1, 2 \ldots$, that is, for complete turns, one can show either numerically or analytically that

$$T_\perp \equiv \frac{|E_y(z)|^2}{|E_x(0)|^2} \approx \sin^2\left(\frac{VBz}{2}\right). \tag{6}$$

The magnitude is thus half of what would be observed in a nonbirefringent fiber in a uniform magnetic field.

The effect of failing to match the polarization beat length exactly to the coil circumference can also be determined numerically. If

$$\Delta\beta = (1 + \delta)/R, \tag{7}$$

the magnitude of the effect is reduced according to the curve shown in Fig. 3.

One might verify the above analysis by studying the characteristics of a coil as a function of wavelength, there being a wavelength at which Eq. (4) is satisfied exactly. We choose, as an alternative, to demonstrate that devices can be designed for use at a specified wavelength if a small amount of tension-coiled birefringence[7] is added to the bending birefringence.

A nonmagnetic, expandable former was constructed with a radius of $R = 7.65$ mm such that $\delta \simeq -0.025$, giving a total mismatch in 40 turns of about 2π. The coil was wound by using a single layer of 150-μm-diameter spun fiber[2] with N.A. = 0.107. The fiber was single mode at $\lambda = 633$ nm and was protected by a 295-μm-diameter silicone jacket.

It was found, as expected,[1] that the slow axis of the fiber was nearly aligned with the coil axis at both input and output and that the total birefringence was tunable over several multiples of π by gently expanding the former. The coil was placed in the gap of a permanent magnet having a measured magnetic flux density of 0.29 T. With a linear-input polarization parallel to the slow axis, the power in each of the orthogonal output polarization states was measured as the fiber tension was increased. The results are shown as the individual points in Fig. 3.

A practical isolator design based on this principle consists of a coil giving exactly 45° of rotation placed between polarizers oriented so that light passing through the input polarizer will pass through the output polarizer.[5] Light traversing the device in the reverse direction will, however, be rotated an additional 45° and will therefore be blocked by the input polarizer.

For the coil described above the rotation was approximately 50°, so the correct rotation could presumably have been obtained by removing about four turns. However, since there is no requirement that the magnetic field be uniform, it is easier to move the coil to the edge of the gap, where the field is slightly weaker. Assuming that this adjustment is made accurately, the principal factor determining the performance of the isolator is the error in achieving and maintaining the beat-length-matching condition. Mismatch has two adverse consequences. One is that light traveling in the forward direction is incompletely transmitted by the output polarizer. The second, and more important, is that light traveling in the reverse direction is incompletely blocked by the input polarizer. These points require further study, but preliminary analysis suggests that for $|\delta| < 10^{-3}$ the reverse attenuation should be greater than 25 dB (optical) and the additional forward loss negligible. This value of δ is readily attainable with the expandable coil.

In the event that tension adjustment of the coil can be eliminated, the optical rotation should be stable with time and temperature. We are now able to produce formerless coils that have $|\delta| < 0.005$ at a specified

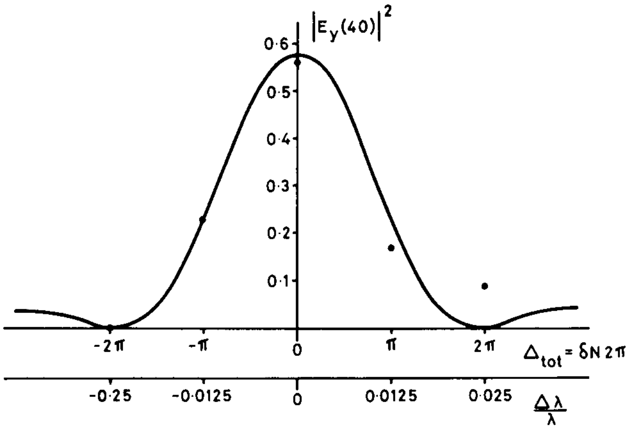

Fig. 3. Power, $|E_y(z = 40\ \text{turns})|^2$, converted to the orthogonal mode for a 40-turn coil [$|E_x(0)|^2 = 1, |E_y(0)|^2 = 0$] as a function of the total mismatch $\delta N2\pi$. Individual points were obtained by applying tension to the coil to vary the fiber birefringence. Lower abscissa shows the spectral response that would be obtained if the coil were used as an optical filter.

wavelength, and it is likely that improved techniques will reduce that value. If tension adjustment cannot be eliminated, a more stable, expandable former design may achieve the same result. Unlike in the case of Ref. 5, temperature tuning of the birefringence in the input and output leads is not a problem when spun fiber is used.

The other remaining difficulty is minimizing the loss resulting from bending. The coil described above had a loss of about 6 dB. It is possible to reduce this loss considerably by slightly increasing the N.A. of the fiber, increasing the outer diameter of the fiber and hence the coil diameter, and increasing the magnetic field so that fewer turns are required.

The device has obvious applications as a compact, nonconducting magnetic-field sensor. If the input and output polarizers are located along the fast and slow axes (or vice versa), the transfer function is given by Eq. (6). An extinction ratio of, for example, 10^{-4} for the polarizers limits the minimum detectable field to about 10^{-3} T for the coil described above. Alternatively, one may choose a configuration such that $E_x(0) = E_y(0)$, in which case Eq. (6) is, in effect, shifted by $\pi/4$, and the sensitivity of the device becomes $\mathrm{d}T_\perp/\mathrm{d}B = Vz/2$. Assuming a maximum detector current of 1 mA and a shot-noise-limited detector, it should be possible to detect a field of the order of 10^{-8} T. Interferometric methods,[8] although more complex, will reduce the minimum detectable field still further.

Since there is only one value of λ for which matching is obtained, the device is also useful as an optical filter in, for example, wavelength-division multiplexing. By relabeling the horizontal axis in Fig. 3 in terms of relative wavelength, $\Delta\lambda/\lambda$, the half-power spectral width of the 40-turn coil between crossed polarizers is found to be about 2%. Increasing the coil length to give 90° rotation would increase the transmission and narrow the bandwidth.

In conclusion, we have demonstrated analytically and experimentally that efficient Faraday rotation can be achieved in accurately wound coils of optical fiber. The magnitude of the effect is half of that which would be found in a nonbirefringent fiber in a uniform magnetic field. A class of compact devices, analogous to those based on Faraday rotation in bulk materials, can thus be designed. Of these, the essential elements of a practical isolator have been demonstrated experimentally.

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