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Coiled-birefringent-fiber polarizers

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Experimental results are presented that illustrate the excellent reproducibility and thermal stability of fiber polarizers made by coiling highly birefringent bow-tie fibers. The effective extinction ratio of the polarizer when used in a fiber-optic gyroscope is shown to be 62 dB.

Fiber polarizers have important and immediate applications in the fiber gyroscope[1] and other polarimetric and interferometric sensors because of their ability to select a single linearly polarized fiber mode, a modal property that can be only partially achieved by using bulk polarizers.[2] To date, the usual approach has been to remove the cladding on one side of the fiber and to suppress one of the polarized modes by contact with a metal coating[3,4] or a birefringent crystal.[5] This has resulted in extinction ratios of 45 (Ref. 4) and 60 dB,[5] respectively (although 90 dB was inferred in Ref. 6), with low loss of the guided mode. We recently demonstrated[7,8] an alternative approach based on operating highly birefringent optical fibers at low V values. In this case the two linearly polarized modes become leaky at different wavelengths, resulting in a wavelength window in which polarizing action occurs. These results, and similar work by Simpson *et al.*,[9] are of primary importance whenever truly single-mode single-polarization operation is required.

Whereas previous work was concerned with the polarizing properties of highly birefringent fibers,[7–9] the present work concentrates on the reproducibility and thermal properties of a practical device, namely, a fiber-optic polarizer made by winding a bow-tie fiber[10] into a coil. The characteristics of the polarizer are measured in the light of the specific requirements of the fiber-optic gyroscope, using a direct method that can readily be applied to other types of fiber polarizer.

Highly birefringent fibers polarize light because, as a result of their large internal stress, one of the polarized modes has slightly stronger guidance than the other. Consequently, when the fiber is bent, a differential bend loss occurs that can be enhanced by a judicious choice of bend radius and operating wavelength[8] to give a polarizer with a large polarization-extinction ratio. However, bending the fiber also produces a small transfer of power from one polarized mode to the other (mode coupling). Design of a high-quality polarizer requires both minimal modal power interchange and large differential modal attenuation. However, as we show below, in fiber-gyro applications it is the differential modal attenuation that is the dominant requirement.

The polarizers were made by winding bow-tie fibers into a close-wound multiturn coil, applying a silicone adhesive, and then removing the coil former. These free-standing coils have well-controlled bending characteristics and permit mode coupling caused by winding tension to be eliminated.[11] Fifteen turns of fiber were used to ensure that the cumulative differential bend loss in the coil far exceeds that likely to be encountered in random bends in the leads, thus making the polarizer insensitive to lead configuration. If required, still further desensitization of the leads could be achieved by employing more turns, using a smaller coil radius,[8] or winding just the coil from fiber reduced in diameter to give a lower V value.

For the present work a coil radius of 15 mm was chosen, since this was the best compromise between the requirement for small size and the degradation in performance observed when using small loops. Smaller loop radii produced an increase in guided-mode loss[8] and an increase in bend-induced mode coupling between the two linearly polarized modes.[12,13]

The excellent reproducibility of the design is demonstrated in Fig. 1 by the measured polarization-extinction-ratio versus wavelength characteristics for three identically constructed polarizers. Also shown is the guided-mode loss measured for one of these polarizers, together with the extinction ratio and guided-mode loss for another embedded in silicone rubber. The curves for packaged and unpackaged polarizers are coincident; at 820 nm, each polarizer has a guided-mode loss of less than 2 dB and an extinction ratio in excess of 25 dB (the limit of our white-light-measuring system). As is shown below, higher values of extinction were measured by using a semiconductor laser.

These typical results clearly show the high reproducibility of the polarizer characteristics when fibers from the same draw are used. Some variability was observed, however, when fibers originating from different draws were used. It is interesting to note that the bend-orientation dependence of the polarizing characteristics[8] does not affect the reproducibility of the polarizers, probably because the fiber is randomly twisted within the coil.

Figure 2 shows the wavelength dependence of extinction-ratio and guided-mode loss measured in a fiber polarizer at temperatures in the range −63° to +140°C. The curves are remarkably stable but show a slight decrease in wavelength separation with increasing tem-

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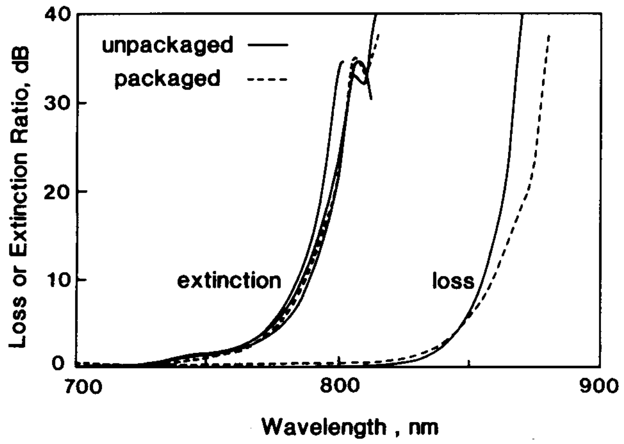

Fig. 1. Spectral-extinction-ratio and guided-mode loss curves for unpackaged fiber coil polarizers (solid lines) and packaged coil polarizers (dashed lines). Extinction ratio is shown for three different unpackaged coils.

perature. At −63°C the separation is 80 nm (at the 15-dB level), while at +140°C the separation reduces to 65 nm, a decrease of about 20% in 200°C. This is attributable to a reduction in birefringence of similar magnitude that occurs over this temperature range.[14] Moreover, it would appear that the small guided-mode loss is somewhat more susceptible to temperature variations than to the extinction ratio, which is fortunate for most applications. From these results it would therefore appear that fiber polarizers of this type are reproducible and show excellent thermal stability over a wide temperature range. Packaged polarizers tested from −20° to 140°C have shown similar behavior.

The requirements for the polarizer in a fiber-optic gyroscope are somewhat more demanding,[1,15,16] since scattering between polarization states must be taken into account. When polarizers are used with coherent sources, their parameters can be described by a Jones matrix J, which relates the amplitude and the phase of the input polarization state to that at the output. By using this description, it can be shown[16] that the effective (intensity) extinction ratio of the polarizer when used in a fiber-gyro is given by the square of the determinant $|J|^2$ of the Jones matrix. In practice, this description for monochromatic light is not particularly helpful, since in many applications the source coherence is relatively low, and after a meter or so of birefringent fiber the polarization phase information is lost. Furthermore, measurements made with monochromatic light are unreliable owing to the strong dependence of the output polarization state on environmental factors.

We have therefore measured an intensity transfer matrix I using incoherent light from a semiconductor laser, where each term is defined as the square of the modulus of the equivalent term in the Jones matrix. Thus we have

$$(x_o, y_o) = \begin{bmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{yx} & \tau_{yy} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix},$$

where (x_i, y_i) and (x_o, y_o) are the input and output intensity polarization states, respectively; τ_{xy} and τ_{yx} represent the power coupled from one polarized mode to the other; and the attenuation α_{xx} and α_{yy} of the x- and y-polarized modes is related to τ_{xx} and τ_{yy} by

$$\alpha = -10 \log_{10} \tau,$$

where α is expressed in decibels.

Apart from the assumption of incoherence, an implicit assumption has been made in the above formulism, namely, that τ_{xy} and τ_{yx} approximate the coupled power experienced by monochromatic light at all wavelengths within the spectral bandwidth of the measurement. A similar assumption is made in the h-parameter formulism, which is defined for monochromatic light but measured using an incoherent source.[12,13] Both assumptions are acceptable if the coupling is random.

The choice of the measurement method for the intensity-transfer matrix requires some care, since both attenuation and cross-coupled power for each mode must be determined. A simple approach involves launching each mode in turn and measuring (x_o, y_o). This approach requires two cutback reference measurements, one for each mode launched. Whereas this is acceptable for the measurement of the low-loss mode ($\tau_{xx} \simeq -2$ dB), determination of the high-loss mode ($\tau_{yy} \simeq -60$ dB) is difficult and often needs repeating. A preferable technique, which requires only one cutback, is as follows:

1. Measure insertion loss α_{xx} for x-polarized light (2 dB, i.e., $\tau_{xx} = -2$ dB).
2. Launching x-polarized light, measure the output extinction ratio $R_1 = \tau_{yx}/\tau_{xx} = -42$ dB with a prism polarizer.
3. Similarly, measure extinction ratio $R_2 = \tau_{yy}/\tau_{xy} = -20$ dB while launching y-polarized light.
4. Measure the power transmission ratio $R_3 = (\tau_{xy} + \tau_{yy})/(\tau_{xx} + \tau_{yx}) \simeq \tau_{xy}/\tau_{xx} = -42$ dB using the prism polarizer at the fiber input.

The intensity-transfer matrix I was measured using

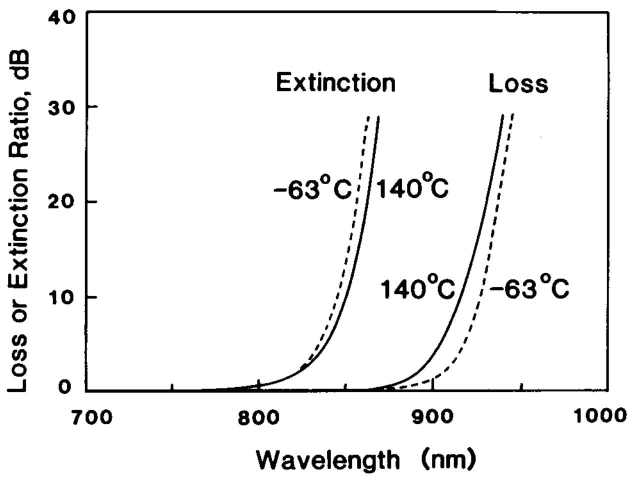

Fig. 2. Temperature dependence of the spectral extinction ratio and guided-mode loss for an unpackaged fiber-coil polarizer.

a 820-nm semiconductor laser having a 5-nm spectral width. The fiber had a beat length of 1.2 mm, and therefore the output is effectively polarization incoherent for lengths greater than 20 cm; the total length used was several meters.

By using the above series of measurements, the polarization intensity-transfer matrix can be calculated:

$$I = \begin{bmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{yx} & \tau_{yy} \end{bmatrix} = \begin{bmatrix} \tau_{xx} & \tau_{xx}R_3 \\ \tau_{xx}R_1 & \tau_{xx}R_2R_3 \end{bmatrix} = \begin{bmatrix} -2 & -44 \\ -44 & -64 \end{bmatrix} \text{dB}.$$

For random, uniform mode coupling along the fiber length, we expect that $\tau_{xy} = \tau_{yx}$, and this is indeed confirmed by our measurement. Furthermore, the value of −44 dB corresponds approximately to that calculated for a coil of 15-mm radius.[12] Note, however, that the measurement of τ_{yx} may be limited by the field curvature of the fundamental mode,[2] whereas that for τ_{xy} is not. This is because τ_{yx} is measured by using a polarizer at the fiber output, thus causing both major and minor field components to be recorded, even when only one mode is present. On the other hand, the determination of τ_{xy} requires no polarization selection at the fiber output and therefore avoids the problem of field curvature. Despite this uncertainty in τ_{yx}, the fact that τ_{xy} and τ_{yx} were found to be equal suggests that in this case we were not limited in our measurements by the presence of minor field components.[2]

It is clear from the above that the effective extinction ratio $|J|^2$ of this fiber polarizer when used in a gyro with monochromatic light is 62 dB. Therefore, if a broadband source is treated as a summation of coherent sources, each seeing $|J|^2 = 62$ dB, then the net effective extinction ratio of the polarizer will also be 62 dB. The polarizer is thus dominated by the attenuation of the y-polarized mode (α_{yy}) and not by the polarization cross coupling (τ_{xy}, τ_{yx}). Orientation of the fiber polarization axes with the plane of the bend could further reduce the mode coupling, but this does not at present appear worthwhile.

In conclusion, we have demonstrated the simplicity of fiber polarizers made by coiling highly birefringent bow-tie fibers. The polarizers exhibit excellent reproducibility and thermal properties. The performance of the polarizers when used in a fiber-optic gyroscope has been discussed for both coherent and incoherent sources, and, by using a new measurement method, an effective extinction ratio of 62 dB has been achieved.

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