

# Twist-induced birefringence in fibers and optical rotation

D. Tentori <sup>\*a</sup>, C. Ayala-Díaz <sup>b</sup>, F. Treviño-Martínez <sup>c</sup>

<sup>a</sup>CICESE/Física Aplicada, carretera Tijuana-Ensenada km 107, Ensenada, B.C., 22860 México;

<sup>b</sup>UABC/Ingeniería, carretera Tijuana-Ensenada km 103, Ensenada, BC, 22860 México;

<sup>c</sup>Universidad Autónoma de Nuevo León/FIME, Pedro de Alba s/n, Cd. Universitaria, San Nicolás de los Garza, N.L., 66450 México.

## ABSTRACT

In this work we present experimental results of the twist-induced birefringence changes for a single-mode erbium-doped fiber with uniform residual birefringence. Two polarimetric methods were used in this study. Both discern evolution of the azimuth and ellipticity angles of the output polarization state. According to these results when the initial residual birefringence is elliptical, the modified optical anisotropy does not enhance its optical activity.

**Keywords:** Optical fiber, torsion, circular birefringence.

## 1. INTRODUCTION

In an anisotropic medium that twists about the direction of the advancing wave, the polarization ellipse of the output polarization state rotates as the twist is increased. This behavior is normally associated with optically active materials; therefore, it has been assumed that twisting a fiber induces circular birefringence [1-9]. It is under this assumption that using different methods several authors have measured the birefringence of twisted fibers [1,2,4-12], and some authors have suggested that the twist-induced optical activity could be used to devise polarization rotators [1,4,13].

In this work we analyze the birefringence changes obtained for a twisted single-mode erbium-doped fiber using two methods based on classical polarization optics and the Poincaré sphere. One of the methods uses wavelength scanning to depict the evolution of the state of polarization of light along the fiber [14], and the other utilizes a monochromatic linearly polarized signal with varying azimuth to determine the polarization eigenmodes [15]. Both methods allow the evaluation of the changes induced on the azimuth and the ellipticity angles of the output polarization state.

## 2. THEORY

A material is said to possess optical activity if the difference from the launched to the emerged state of polarization is only in the azimuth and the ellipticity is constant. The Mueller sub-matrix of a polarization rotator is [16-18]

$$\mathbf{R}(\delta) = \begin{pmatrix} \cos 2\delta & \pm \sin 2\delta & 0 \\ \mp \sin 2\delta & \cos 2\delta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

where  $\delta$  is the retardation angle between the polarization eigenmodes. The upper sign is used for a right rotator and the lower sign for a left circular retarder. Using the three coordinate space of the Poincaré sphere, (S1, S2, S3), the matrix in equation (1) represents a rotation about S3 axis (through the north and south poles of the sphere). Hence, for a retardation angle greater than  $\pi$ , the trajectories described by the evolution of any input polarization state are circles perpendicular to the S3 axis starting on the input polarization state, as it is shown in Fig.1.

Regarding elliptical birefringence, several authors have considered it as the result of the superposition of linear and circular birefringences [1,7,18-20]. Following this approach the Mueller sub-matrix of an elliptical retarder is [16,20].

---

\* diana@cicese.mx; phone 52 646 1750500 xt 25035; fax 52 646 1750553; cicese.edu.mx.

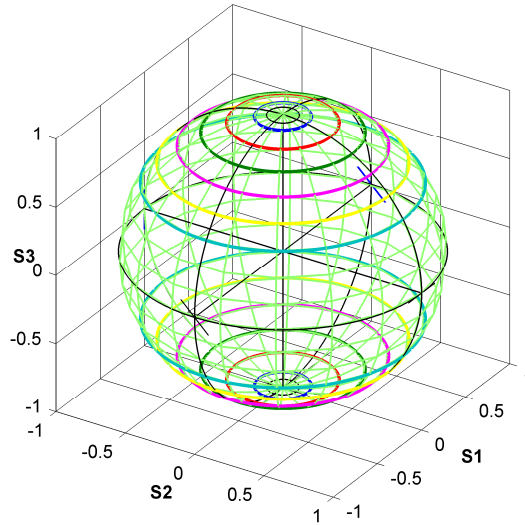
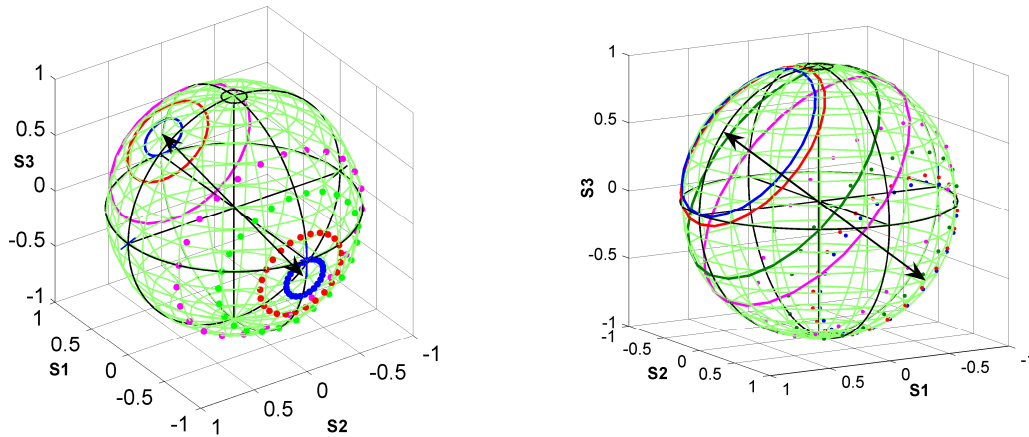


Fig. 1. For a rotator, the trajectories described by the evolution of the input polarization state depict circles around the  $S_3$  axis. For an input linear polarization the trajectory coincides with the equator line.

$$\mathbf{M} = \begin{pmatrix} 1 - 2 \cos^2 \sigma \sin^2 \delta & -\cos \sigma \sin 2\delta & -\sin 2\sigma \sin^2 \delta \\ \cos \sigma \sin 2\delta & \cos 2\delta & \sin \sigma \sin 2\delta \\ -\sin 2\sigma \sin^2 \delta & -\sin \sigma \sin 2\delta & 1 - 2 \sin^2 \sigma \sin^2 \delta \end{pmatrix}. \quad (2)$$

In Eq.(2)  $\delta$  is the retardation angle between the polarization eigenmodes ( $\pi/2 - \sigma$ ), equal to twice the birefringence ellipticity angle and, the azimuth angle of the fast birefringence axis is zero.



a)  $\zeta = 5^\circ$

b)  $\zeta = 20^\circ$

Fig. 2. For an elliptical retarder, the trajectories described by the evolution of the input polarization state depict circles around an axis whose inclination angle  $\zeta$  equals twice the ellipticity angle of the retarder.

For an elliptical retarder (general case of a homogeneous retarder), the trajectories described by the evolution of an input polarization state depict circles about an axis of symmetry that crosses the Poincaré sphere at the polarization eigenmodes (Fig.2) [14]. The angle  $\zeta$  between this symmetry axis and the plane of the equator is twice the ellipticity angle [18]. When  $\zeta = \pi/2$  the retarder is circular, and when  $\zeta = 0$  the retarder is linear.

Following the procedures developed for classical polarization optics some authors [19-20] describe the elliptical retardation in terms of its linear and circular components as

$$\delta = \sqrt{(\delta_l/2)^2 + (\tau + \delta_c/2)^2}; \quad (3)$$

where  $\delta_l$  is the linear retardation,  $\delta_c$  is the circular retardation and  $\tau$  is the twist of the axial axis. Under this scope, an enhanced circular birefringence should produce an ellipticity angle greater (see Fig.2b) than the initial. This hypothesis is tested here using the experimental procedure described below.

### 3. EXPERIMENT

To study the birefringence changes induced by twisting the fiber we used wavelength scanning and the Poincaré sphere [14]. Since the torsional stress in cold fibers is related to small birefringence changes, we selected a fiber whose wavelength scanning results could be easily related to those of an elliptical retarder (Fig.2).

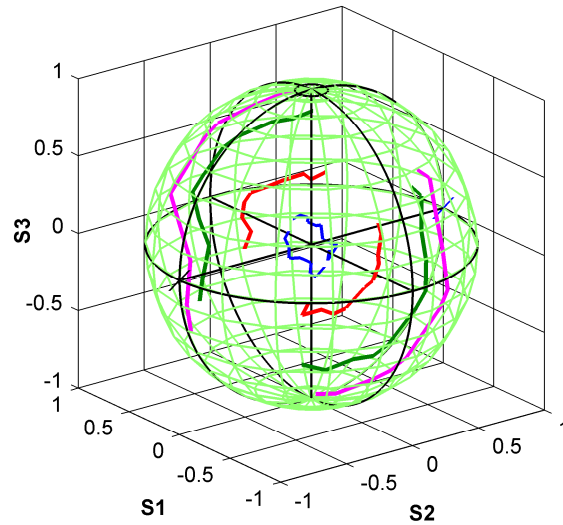


Fig. 3. The wavelength scanning results, obtained for the INO 402K5 single-mode erbium-doped fiber, show that it behaves as an elliptical retarder.

The sample we used is a single-mode erbium-doped silica fiber (INO, mod. 402K5) with elliptical residual birefringence (Fig.3). The fiber has a core diameter of  $\sim 3.8 \mu\text{m}$ , output diameter of  $250 \mu\text{m}$ , single mode cut-off near  $850 \text{ nm}$ ; length  $1.61 \text{ m}$ . We used eleven wavelengths within the  $1530\text{--}1580 \text{ nm}$  range to study the birefringence changes induced by a torsional stress, for each linear input polarization state. The evolution of polarization along a straight birefringent single-mode fiber at rest was determined for various conditions of twist.

When using wavelength scanning, the azimuth angle of the linear polarization state defines the radius of circular trajectories associated to the evolution of the polarization state of light for a specific elliptical retarder [14]. To analyze the birefringence changes induced by twist in such trajectories, keeping the same input state of polarization and the same orientation of the fiber input is crucial. The experimental set up we employed to evaluate the evolution of the state of polarization along the fiber [14] includes a polarization analyzer (Agilent 8509C). This device requires: 1) a reference frame generated for each wavelength, and 2) equal input and output signals. Both points were achieved using a collimated beam of light in which the state of polarization is controlled by a calcite prism polarizer. In our experimental set up, from the input to the output ports, the collimated beam traveled by air. In order to keep the same input conditions each time the sample was removed from the optical set up (when a different wavelength was used) we used FC/PC connectors at the fiber ends. Due to the presence of these connectors the torsional stress was varied from 1 to 10 full turns, using 1 turn steps ( $3.9 \text{ rad/m}$  to  $39 \text{ rad/m}$ , step  $3.9 \text{ rad/m}$ ).

Finally, considering results recently reported in the literature, we included 15 full turns ( $58.5 \text{ rad/m}$ ) [21]. It is important to mention that for this fiber, from 1 to 10 turns we obtained an elastic deformation, while for 15 turns the deformation

was no longer elastic.

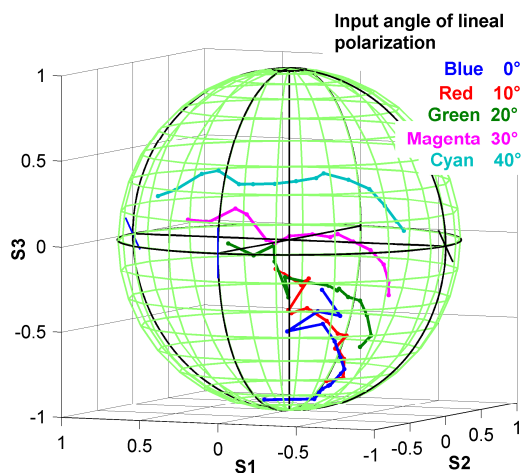


Fig. 4. Wavelength scanning results obtained by twisting the fiber 3.9 rad/m.

#### 4. RESULTS

The wavelength scanning results obtained for one (3.9 rad/m) and 15 full turns are shown in figures 4 and 5, respectively. The trajectories are not circular, which suggests two possible explanations: 1) the twisted sample does not behave as a homogeneous retarder, or 2) the fiber behaves as a homogeneous retarder, but the evaluation procedure is not correct because birefringence dispersion is not negligible [14].

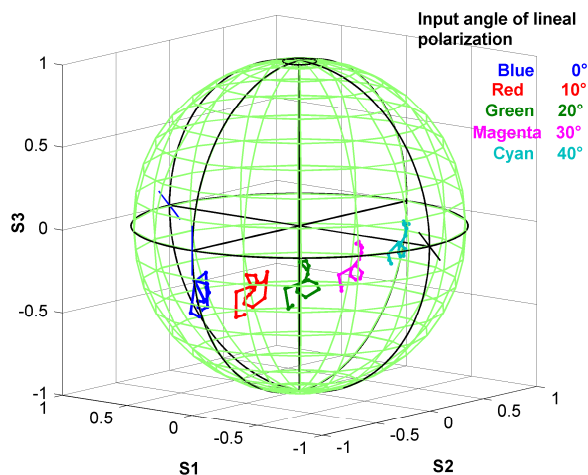


Fig. 5. Wavelength scanning results obtained by twisting the fiber 58.5 rad/m.

If we assume, that the fiber behaves as a homogeneous retarder, their polarization eigenmodes can be determined using a monochromatic signal. We determined the azimuth, and ellipticity angles of the polarization eigenmodes of the twisted sample, using a method developed for homogeneous retarders [15]. Keeping the sample in the optical set up, we launched a polarized signal using these values, following the procedure described in Ref.15. At the fiber output, the azimuth and ellipticity angles of the polarization state of the emerged signal were not close to the predicted eigenmode.

This behavior showed that the launched polarization state was not a principal state of polarization.

This procedure was repeated for the eleven wavelengths previously used, and for all of them the polarization eigenmodes predicted by the model did not correspond to principal states of polarization. This analysis disproves the previously suggested explanation.

A third option could be to assume that these results are different from those that would be obtained for standard fibers or other single-mode erbium-doped fibers. Here, it is important to mention that the trajectories shown in figure 5 indicate that this is a general result since the trajectories are similar to those reported for standard cold twisted fibers [3] and standard spun fibers [22]. Furthermore, using wavelength scanning [14] we obtained similar trajectories for a straight sample (1.56 m) of a spun single-mode erbium-doped fiber (3M FS-ER-7A28), as we can see in Fig. 6.

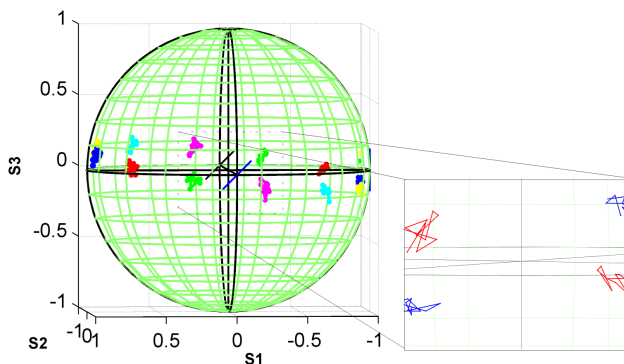


Fig. 6. Wavelength scanning results obtained for 3M FS-ER-7A28 single-mode erbium-doped fiber. Each set of points was obtained using a different azimuth angle of the linear input polarization. The inset zooms on four of these trajectories.

In addition to the matrix model presented in Section II, and the perturbation approximation [1], the effect of twist on the residual birefringence of the sample has also been described using independent matrices [8] or birefringence vectors [1,3,7,21] to represent torsion and the residual birefringence. These models are based on the phenomenological behavior observed for the evolution of the polarization state of light. Since they are empirical descriptions, using them it is difficult to discuss whether or not optical activity is induced or enhanced by torsion.

On the other hand, using classical polarization optics, the analysis is straightforward. The experimental results of the evolution of light polarization along the fiber (Figs. 4 and 5) do not indicate that the fiber birefringence is approaching the behavior expected from a sample in which the optical activity is being enhanced due to torsion (Fig. 1 and 2). But, they do indicate that the initial optical anisotropy ceases to behave as that of a homogeneous retarder. And, this was verified using a second polarimetric technique developed for homogeneous retarders [15, 23]. We can also mention that the shorter lengths obtained for these trajectories indicate lower birefringence dispersion. Therefore twisting decreases its polarization mode dispersion [22].

## 5. CONCLUSIONS

The study of changes induced on the azimuth and ellipticity angles of the output polarization state demonstrates that the anisotropy of a twisted single-mode fiber cannot be described using the polarization matrix of a homogeneous retarder [23]. Therefore, torsion cannot be used to produce fiber rotators.

The application of a torsional stress to a cold single-mode fiber reduces its polarization mode dispersion.

Further work is required to fully understand the polarization phenomena related to twist induced birefringence.

### Acknowledgements

This work was supported by Conacyt-DAIC, project G37000-E and by the scholar ship granted to César Ayala Díaz by Conacyt. The F. Treviño-Martínez appreciates the valuable support of the Sub direction Academic and direction of FIME, and rector of UANL.

## REFERENCES

- [1] R. Ulrich, A. Simon, "Polarization optics of twisted single-mode fibers," *Appl. Opt.* 18(13), 2241-2252 (1979).
- [2] M. Monerie, P. Lamouler, "Birefringence measurement in twisted single-mode fibres," *Electron. Lett.* 17(7), 252-253 (1981).
- [3] W. Eickhoff, Y. Yen, R. Ulrich, "Wavelength dependence of birefringence in single-mode fiber," *Appl. Opt.* 20(19), 3428-3435 (1981).
- [4] P. Graindorge, K. Thyagarajan, H. Arditty, M. Papuchon, "Scattered light measurement of the circular birefringence in a twisted single mode fiber," *Opt. Commun.* 41(3), 164-168 (1982).
- [5] S.C. Rashleigh "Origins and control of polarization effects in single-mode fibers," *J. Lightwave Technol.* 1(2), 312-331 (1983).
- [6] A. Bertholds, R. Dändliker, "Determination of the individual strain-optic coefficients in single-mode optical fibers," *J. Lightwave Technol.* 6(1), 17-20 (1988).
- [7] H.Y. Kim, E.H. Lee, B.Y. Kim, "Polarization properties of fiber lasers with twisted-induced circular birefringence," *Appl. Opt.* 36(27), 6764-6769 (1997).
- [8] D. H. O. Bebbington, A. S. Siddiqui, "Analytical description of backscattered states of polarization in polarization optical time-domain reflectometry measurements on uniformly twisted linearly birefringent optical fiber," *J. Opt. Soc. Am. A* 17(12), 2260-2266 (2000).
- [9] M. Wegmuller, M. Legre, N.Gisin, "Distributed beatlength measurement in single-mode fibers with optical time-domain reflectometry," *J. Lightwave Technol.* 20(5), 800-807 (2002).
- [10] T. Chartier, C. Greverie, L. Selle, L. Carlus, G. Bouquet, L. Montmorillon, "Measurement of the stress-optic coefficient of single-mode fibers using a magneto-optic method," *Opt. Express* 11(20), 2561-2566 (2003).
- [11] A.M. Smith, "Birefringence induced by bends and twists in single-mode optical fibers," *Appl. Opt.* 19(15), 2606-2611 (1980).
- [12] T. Tanemura, K. Kikuchi, "Observation of elliptical polarization rotation in a long twisted fiber," *Opt. Lett.* 31(7), 882-884 (2006).
- [13] R. Ulrich, M. Johnson, "Single-mode fiber-optical polarization rotators," *Appl. Opt.* 18(11), 1857-1861 (1979).
- [14] F. Treviño-Martínez, D. Tentori, C. Ayala-Díaz, F.J. Mendieta-Jiménez, "Birefringence assessment of single-mode optical fibers," *Opt. Express* 13(7), 2556-2563 (2005).
- [15] D. Tentori, C. Ayala-Díaz, F. Treviño-Martínez, F.J. Mendieta-Jiménez "Evaluation of the residual birefringence of single-mode erbium-doped silica fibers," *Opt. Commun.* 271(1), 73-80 (2007).
- [16] S.T. Tang, H.S. Kwok, "3×3 Matrix for unitary optical systems," *J. Opt. Soc. Am. A* 18(9), 2138-2145 (2001).
- [17] E. Collett, [Polarized Light. Fundamentals and applications], Dekker, New York, 214-216 (1993).
- [18] D. S. Kliger, J. W. Lewis, C. E. Randall, [Polarized Light in Optics and Spectroscopy], Academic Press, San Diego, 69-75 (1990).
- [19] R.C. Jones, "A new calculus for the treatment of optical systems. Properties of N-matrices," *J. Opt. Soc. Am.* 38(8), 671-685 (1948).
- [20] C. Tsao, [Optical Fibre Waveguide Analysis], Oxford University Press, New York, 100-101 (1992).
- [21] T. Tanemura, K. Kikuchi, "Circular-birefringence fiber for nonlinear optical processing," *J. Lightwave Technol.* 24(11), 4108-4119 (2006).
- [22] R.E. Schuh, X. Shan, A. S. Siddiqui, "Polarization mode dispersion in spun fibers with different linear birefringence and spinning parameters," *J. Lightwave Technol.* 16(9), 1583-1588 (1998).
- [23] D. Tentori, C. Ayala-Díaz, E. Ledezma-Sillas, F. Treviño-Martínez, A. García-Weidner, "Birefringence matrix for a twisted single-mode fiber: Geometrical contribution," *Opt. Commun.* 282(5), 830-834 (2009).