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Article *in* Optics and Lasers in Engineering · May 2003

DOI: 10.1016/S0143-8166(02)00049-0

9 authors, including:

Julián Moisés Estudillo-Ayala
Universidad de Guanajuato

José Ruiz-Pinales
Universidad de Guanajuato

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Optics and Lasers in Engineering 39 (2003) 635–643

OPTICS and LASERS in ENGINEERING

Analysis of a Sagnac interferometer with low-birefringence twisted fiber

J.M. Estudillo-Ayala[a,*], J. Ruiz-Pinales[a], R. Rojas-Laguna[a], J.A. Andrade-Lucio[a], O.G. Ibarra-Manzano[a], E. Alvarado-Méndez[a], M. Torres-Cisneros[a], B. Ibarra-Escamilla[b], E.A. Kuzin[b]

[a] *Depto. de Electrónica, Facultad de Ingeniería Mecánica, Eléctrica y Electrónica, Universidad de Guanajuato, A.P. 215-A, 36730 Salamanca Gto., Mexico*

[b] *Instituto Nacional de Astrofísica, Óptica y Electrónica, A.P. 51 y 216, 72000 Puebla, Pue., Mexico*

Abstract

The fiber Sagnac interferometer of low birefringence and twist is analyzed numerically in the linear region. A novel method for measurement of the birefringence of the fiber and the angle of rotation of the axes inside the fiber loop of the interferometer is also presented.

Keywords: Optical fiber; Birefringence

1. Introduction

Since the invention of the Sagnac interferometer of optical fiber by Vali et al. [1] in 1976, many applications of it have been reported. Some of the most recent of them have utilized it as a multiplexer [2], a non-linear mirror [3], or as an optical fiber sensor [4,5]. However, most of these studies have utilized high birefringent fibers and only a few of them have utilized low-birefringent fibers.

In this study, we analyze numerically the linear region of a Sagnac interferometer with twisted low-birefringent fiber. Fiber birefringence is of great importance in many aspects of optical communications and device technology. Birefringence results in degradation of a signal through polarization mode dispersion, which is a key limitation for high-speed optical communications.

*Corresponding author. Fax: +52-464-72400.

E-mail address: julian@salamanca.ugto.mx (J.M. Estudillo-Ayala).

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2. Systems configuration and theoretical study

Fig. 1 shows a fiber interferometer consisting of a directional fiber coupler with its output ports 3 and 4 connected to a birefringent fiber loop by means of two connectors (C_1 and C_2). This coupler has an amplitude ratio α. Both connectors can be rotated in any direction in order to twist the fiber on the loop. One of them can be fixed and the other one can be turned up in order to twist the fiber gradually to a certain number of turns. The beam is coupled to an input port 1 and, when it arrives at the coupler, it is split into two beams towards ports 3 and 4. These beams travel in opposite directions inside the fiber of the loop and come back to the coupler where the interference is produced. Then, at input port 1 we have a reflected beam having an electric field E_1 and at port 2 we have a transmitted beam having an electric field E_2.

The general relationship describing the output electric fields of the interferometer has been taken from [3]. Let E_1 be the electric field of the input beam. The electric field of the transmitted beam is given by

$$E_2 = \begin{pmatrix} E_{2x} \\ E_{2y} \end{pmatrix} = \begin{pmatrix} (2\alpha - 1)J_{xx} & (1-\alpha)J_{xy} + \alpha J_{yx} \\ -\alpha J_{xy} - (1-\alpha)J_{yx} & (1-2\alpha)J_{yy} \end{pmatrix} \begin{pmatrix} E_{1x} \\ E_{1y} \end{pmatrix}, \quad (1)$$

where J represents the Jones matrix of the loop. This matrix is equal to the product of the elements involved in the loop and is given by

$$J = B_1 \cdot C_1 \cdot F_L \cdot C_2 \cdot B_2, \quad (2)$$

where B_1 is a matrix which characterizes the section of the fiber of one arm of the coupler, that is joined to the low-birefringent fiber loop by means of a connector. This matrix is given by

$$B_1 = \begin{pmatrix} P_1 & Q_1^* \\ Q_1 & P_1^* \end{pmatrix}, \quad (3)$$

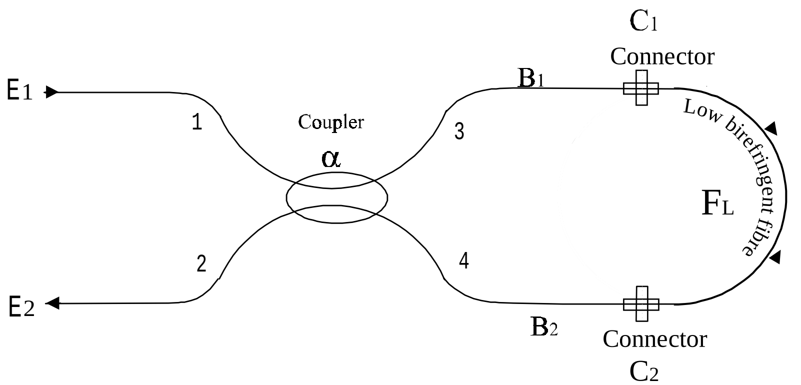

Fig. 1. Sagnac interferometer proposed.

$$P_1 = \cos\eta_{B_1} - j(\delta_{1B_1}/2)\sin\eta_{B_1}/\eta_{B_1}, \tag{3a}$$

$$Q_1 = (\delta_{C_1}/2)\sin\eta_{B_1}/\eta_{B_1}, \tag{3b}$$

$$\eta_{B_1} = \sqrt{(\delta_{1B_1}/2)^2 + (\delta_{C_1}/2)^2}, \tag{3c}$$

where $\delta_{1B_1} = (2\pi/\lambda)L_1\Delta n$ represents the linear delay, L_1 represents the length of the fiber of an arm, λ represents the wavelength, $\Delta n = n_1 - n_2$ represents the linear birefringence, $L_b = \lambda/\Delta n$ represents the repetition length and $\delta_{c_1}/2 = (1 - g/2)t_1$. For silica-glass fibers $g \approx 0.16$ [6] and t_1 represents the twist of arm B_1 in rad/m.

C_1 represents the orientation of the principal axes of the fiber of the coupler of port 3 with respect to the laboratory axes at the input of the loop (connector C_1). It is given by

$$C_1 = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}. \tag{4}$$

The matrix F_L characterizes the low-birefringent fiber loop in which one of its terminals is twisted by means of a rotating connector. It is given by

$$F_L = \begin{pmatrix} P & Q^* \\ Q & P^* \end{pmatrix}, \tag{5}$$

$$P = \cos\eta - j(\pi L_n)\sin\eta/\eta, \tag{5a}$$

$$Q = (\psi_0 L_n + \delta_c/2)\sin\eta/\eta, \tag{5b}$$

$$\eta = \sqrt{(\pi L_n)^2 + (\psi_0 L_n + \delta_c/2)^2}, \tag{5c}$$

where L_n represents the ratio between loop length and repetition length, ψ_0 represents the orientation of the axes of the fiber and $\delta_c/2 = (1 - g/2)\cdot t$, where t represents the twist of the fiber loop in radians per unit length.

C_2 represents the orientation of the axes of the fiber of the coupler of port 4 with respect to the fiber loop. It is given by

$$C_2 = \begin{pmatrix} \cos(\psi_0 L_n + t) & -\sin(\psi_0 L_n + t) \\ \sin(\psi_0 L_n + t) & \cos(\psi_0 L_n + t) \end{pmatrix}, \tag{6}$$

where Ψ_0 represents the angle of rotation of the principal axes of the fiber, t represents the twist in radians per unit length and L_n represents the ratio between loop length and repetition length.

The matrix B_2 characterizes the section of the fiber of the arm of the coupler at port 4, which is joined to the low-birefringent fiber loop by means of a connector. It is given by

$$B_2 = \begin{pmatrix} P_1 & Q_1^* \\ Q_1 & P_1^* \end{pmatrix}, \tag{7}$$

$$P_2 = \cos \eta_{B_2} - j(\delta_{lB_2}/2) \sin \eta_{B_2}/\eta_{B_2}, \tag{7a}$$

$$Q_2 = (\delta_{C_2}/2) \sin \eta_{B_2}/\eta_{B_2}, \tag{7b}$$

$$\eta_{B_2} = \sqrt{(\delta_{lB_2}/2)^2 + (\delta_{C_2}/2)^2}. \tag{7c}$$

The sequence of elements for the Jones matrix is shown in Eq. (2). This corresponds to the Jones matrix for the loop of our interferometer with uniformly twisted fiber. The transmitted intensity is given by $I_{\text{out}} = K|E_{\text{out}}|^2$, where K is a constant which depends on the units that we are using. The transmittance T is given by

$$T = \frac{I_{\text{out}}}{I_{\text{in}}}. \tag{8}$$

Eqs. (3)–(7) were substituted in Eq. (2), which in turn was substituted in Eq. (8). These equations were simulated numerically for different parameters (Fig. 2–7). In these calculations, the length of the arms as well as their twists were equal. What we have varied are the length of the fiber and the twist of the loop (F_{L}).

Fig. 2 shows the output transmittance as a function of the twist for different values of the length of the fiber (L). The length of the fiber is equivalent to one and a half of the repetition length. We can see in this figure that for zero twist, the transmittance is

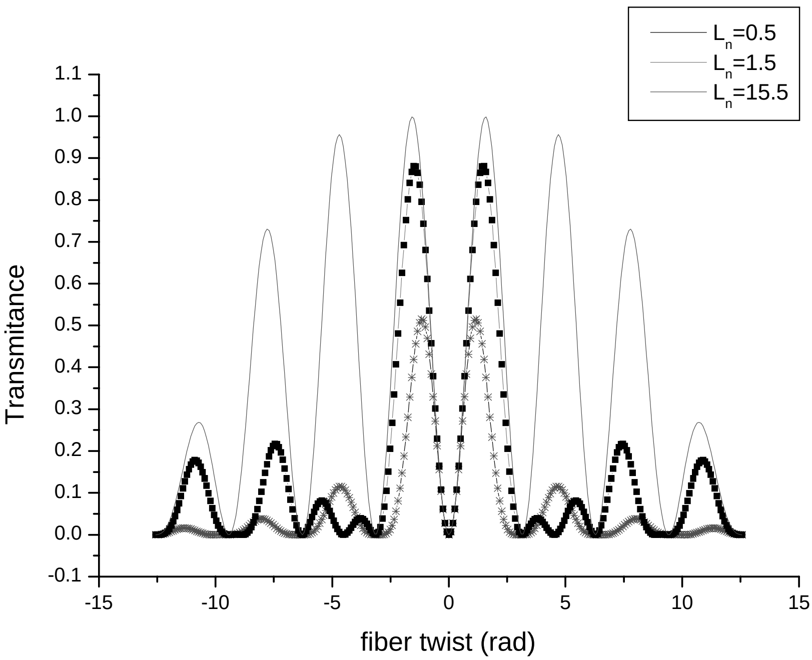

Fig. 2. Dependency of the transmittance versus twist ratio, for fiber length equal to L/L_{b} ratio with integer values plus 1/2.

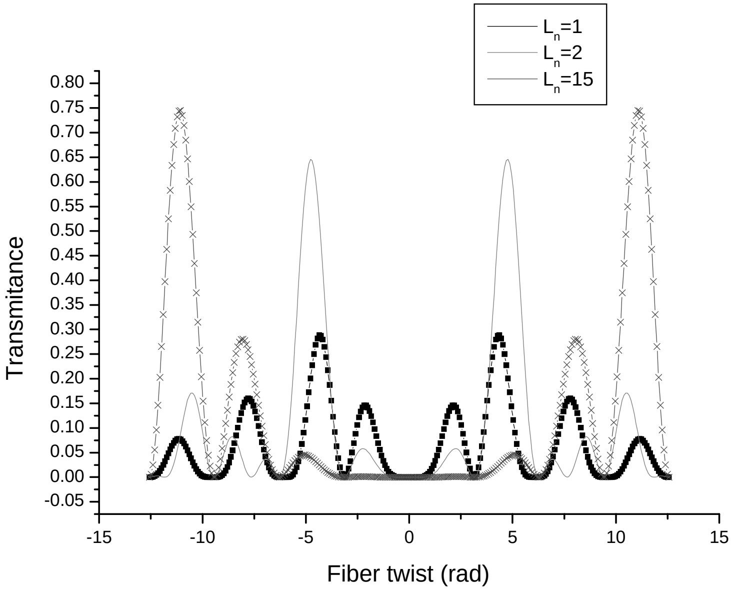

Fig. 3. Dependency of the transmittance versus twist ratio, for fiber length equal to L/L_b ratio with integer values.

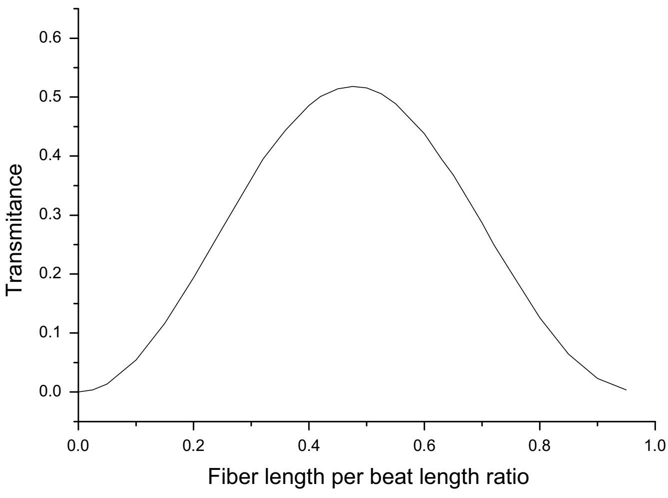

Fig. 4. Dependency of the first output transmittance maximum versus the fiber length and the repetition length ratio, for L/L_b ratios from 0 to 1.

equal to zero. As we turn the fiber in both directions for a twist >1 rad, we can always obtain a maximum near 1 for lengths of the fiber with ratios $L/L_b = 1.5, 2.5, \ldots, 15.5, 16.5, N + 1/2$. We can also see in this figure that the two central peaks are obtained with a small twist in the fiber loop and correspond to the highest

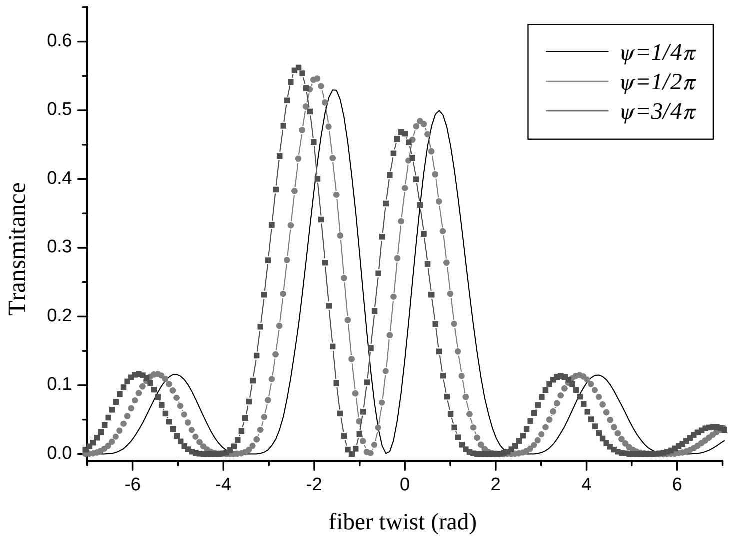

Fig. 5. Theory dependency of the transmittance versus fiber twist degree, considering different axis rotation degrees with $L_n = 0.5$.

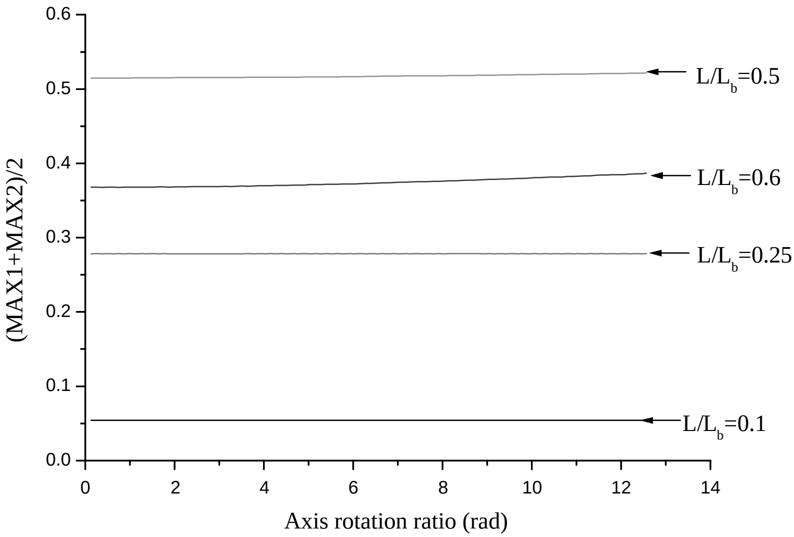

Fig. 6. Average dependency of the first two maximums versus the fiber's main axis rotation.

transmittance. The remaining peaks correspond to lower transmittances and a greater twist in the fiber loop of the interferometer.

Fig. 3 shows the transmittance as a function of the twist for lengths of the fiber equal to multiples of the repetition length. This figure also shows that in order to obtain a high transmittance, the twist must be greater than one radian in contrast

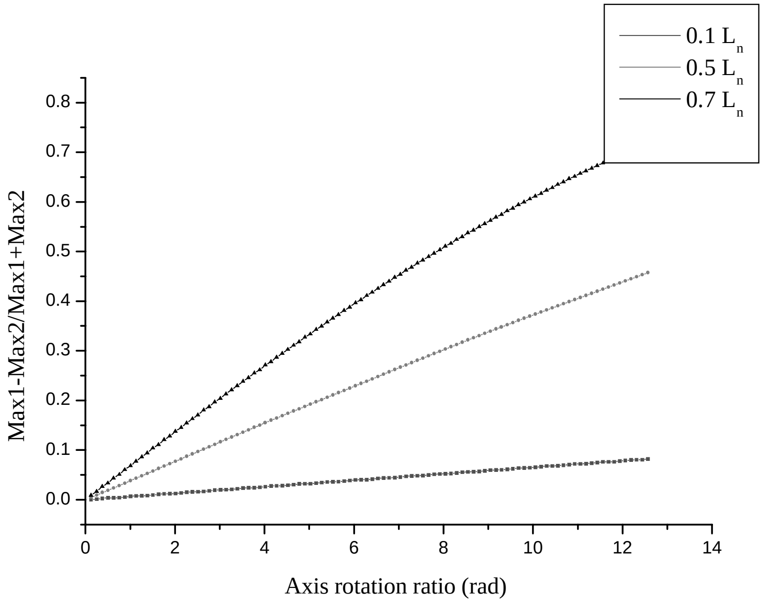

Fig. 7. Dependency of the two main maximums sum versus the fiber's main axis rotation of the interferometer's loop.

with the previous figure. We can also see that the peaks at the center of the figure are lower than those of the extremities and as the length of the fiber increases, the twist must be greater in order to obtain high transmittances.

From Figs. 2 and 3, we have shown that it is important to know the repetition length (birefringence) of our fiber in order to obtain the desired results for the transmittance or the reflectance of our interferometer.

Fig. 4 shows the value of the first peak of the output transmittance as a function of the ratio between the length of the fiber L and the repetition length L_b for values in the interval [0,1]. We can see in this figure that we can obtain different values of the transmittance by varying the repetition length. From this figure, we can find the birefringence of our optical fiber. That is, we can find experimentally the maximum transmittance by using the Sagnac interferometer for a fiber length L. Knowing this, we can find the value of the ratio L/L_b with the help of that figure. Then, as we know the length of the fiber, we can calculate L_b and therefore we can know the value of Δ_n.

If we consider a change in the rotation of the principal axis of the fiber loop, by keeping constant the loop-length/repetition-length (L_n) ratio, as well as the birefringence of the arms, we can find the transmittance as a function of the twist of the fiber. By considering the rotation of the axes when we have a fiber-length/ repetition-length ratio $=0.5$ as shown in Fig. 5, we can realize that there is an asymmetry between the two main peaks, one of the peaks is higher than the other one. As the rotation angle of the axes increases, the asymmetry increases. This figure shows that for $\Psi_0 = 1/4\pi, 1/2\pi, 3/4\pi$ the axes are somewhat rotated as shown in Fig. 4, where we have shown the transmittance as a function of the twist of the fiber for different angles of rotation of the axes.

Fig. 6 shows the average value of the two first peaks of the transmittance (Fig. 5 shows the two principal asymmetric peaks) as a function of the rotation rate of the axes. We can see that the sum of the transmittances corresponding to the first two peaks is constant as the angle of rotation of the principal axes of the fiber varies. As a result, we can say that it does not matter if the peaks are asymmetric because their average stays constant for every value of the length of the fiber.

We have developed this practical method for measuring the angle of rotation of the axes of the fiber loop. It consists in varying the angle of rotation of the axes of the fiber and then calculating the ratio between the difference and the sum of the two principal peaks as shown by the following equation: $S = (MAX1 - MAX2)/(MAX1 + MAX2)$. This simulation has been made for the following fiber-length/repetition-length ratios: 0.1, 0.5 and 0.7. From this simulation, we have obtained the plot shown in Fig. 7. In order to measure the angle of rotation of the axes, we measure the two principal peaks and with the help of this plot we can obtain the angle of rotation of the axes.

Fig. 8 shows the experimental results for the transmittance as a function of twist when the arms of the interferometer are adjusted (their lengths and twist value are approximately the same, length = 1 m). As we can see, the curve presents two main peaks. So, we have calculated the average value of these two peaks. Then, with the help of Fig. 4, we have obtained a repetition length = 12.98 m. This value is approximately the same for other fibers of different length.

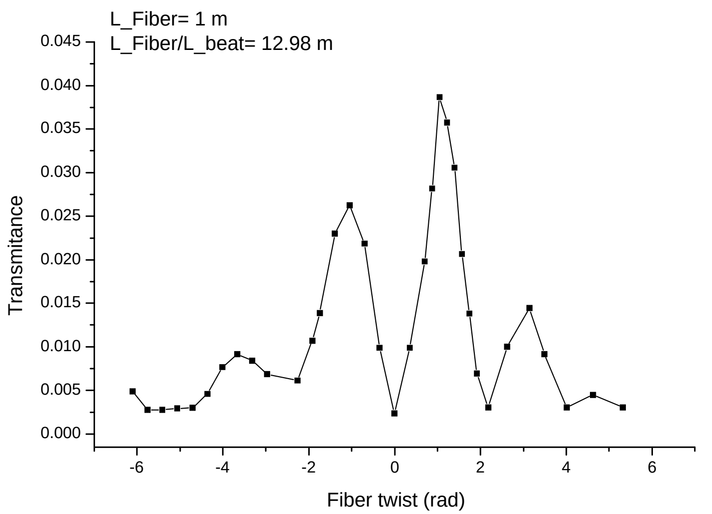

Fig. 8. Experimental dependence of transmittance and the fiber twist ratio; fiber length, 1.0 m.

3. Conclusions

We have analyzed numerically the Sagnac interferometer and proved that for lengths of the fiber loop equal to one and a half of the repetition length of the fiber, we can obtain high transmittances (≈ 1). For a twist slightly >1 rad and for lengths of the fiber loop equal to the repetition length plus one, we can obtain low transmittances. With the same twist as for the other lengths, we must have a greater twist in order to obtain high transmittances.

We have presented a very simple technique for low-birefringence measurements based on the dependence of the Sagnac interferometer's transmission on twist. We have also presented a method for measuring the angle of rotation of the principal axes of the fiber.

Acknowledgements

This work was supported by CONACYT with projects J35313-A and J32018-A.

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