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Optics Communications 242 (2004) 191–197
OPTICS COMMUNICATIONS
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Fiber optical loop mirror with a symmetrical coupler and a quarter-wave retarder plate in the loop

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Received 23 April 2004; received in revised form 1 July 2004; accepted 10 August 2004

Abstract

In this paper we report an experimental method to vary the transmission through a fiber optical loop mirror with a symmetrical coupler, highly twisted fiber and a quarter-wave (QW) retarder plate in the loop. We demonstrate that as the QW retarder plate is rotated it is possible to adjust the transmission over a wide range (from around 2% to around 82%) and that by adjusting the twist in the loop nearly ideal operation can be achieved. We provide a detailed theoretical analysis of the operating characteristics.

PACS: 42.81.P; 42.28.G
Keywords: Sagnac interferometer; Optical fibers

1. Introduction

A fiber optical loop mirror (FOLM) consists of a fiber coupler whose output ports are connected together by a piece of long fiber to form the loop. The input beam is split by the fiber coupler into two beams of different intensities for an asymmetrical coupler; it is possible to have equal intensities for the two beams if a symmetrical coupler is used. By means of this fiber coupler, the beams are made to travel along the same fiber path, but in opposite (or counter-propagating) directions. One beam propagates in the clockwise direction, and the other one propagates in the counter-clockwise direction. Upon completion of one round trip, the two beams are recombined in the fiber coupler. The phase difference between the counter-propa-

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0030-4018/$ - see front matter
doi:10.1016/j.optcom.2004.08.020

gating beams determines whether an input beam is reflected or transmitted by the FOLM. If a symmetrical coupler is used the FOLM acts as a perfect mirror. In the nonlinear regimen the FOLM device can be designed to transmit a high-power signal while reflecting it at low power levels. It then acts as a nonlinear loop mirror (NOLM). The NOLM has attracted considerable attention for mode-locking and wavelength demultiplexing [1–6], pedestal suppression on pulses and pulse compressors [7], intensity flattening of a stream of pulses [8], and optical switching [9]. In fact, uncontrolled residual birefringence strongly affects the FOLM operation by requiring complicated polarization adjustments. Furthermore the birefringence is sensitive to the environmental changes and does not allow day-to-day reproducible operation. A common solution of the problem is the use of a highly birefringent fiber in the loop [10,11]. Nevertheless the important parameters such as group velocity dispersion of the available hi-bi fibers are strongly restricted.

In this paper we perform a FOLM experiment using a symmetrical coupler with highly twisted standard SMF-28 fiber and a quarter-wave (QW) retarder plate in the loop. In this case the polarization of the two beams is important in determining the FOLM transmission and reflection properties and we show how to operate the interferometer in a nearly ideal mode that eliminates all residual birefringence in the loop by adding twist to the coupler ports. We also model and simulate the operational characteristics of the FOLM. The transmission behavior is simply controlled by rotating the QW retarder plate.

The FOLM with birefringence was first analyzed and experimentally verified in the seminal paper of Mortimore [12]. We consider new aspects of the FOLM by adding twist, which adds significant advantages. Highly twisted fiber enables day-to-day reproducible operation of the interferometer because it averages the birefringence in the loop. As mentioned above environmental stability has been an impediment to its application in telecommunications and RF photonics technologies. Twist can be used to eliminate the residual birefringence in a standard fiber, which keeps the system simple and reduces the device costs. A twisted fiber NOLM device can be designed also for nonlinear operation preserving all the advantages of the twisted fiber FOLM [9]. In addition, the twisted fiber FOLM provides a new measurement technique to determine the birefringence of a fiber segment [13].

2. Theory

Fig. 1 shows the structure of the FOLM used for the theoretical analysis. It consists of a symmetrical coupler whose output ports are connected through a highly twisted fiber and a QW retarder plate in the loop. The QW retarder plate creates a polarization asymmetry between clockwise and counter-clockwise beams in the loop. In our analysis, each element entering into the composition of

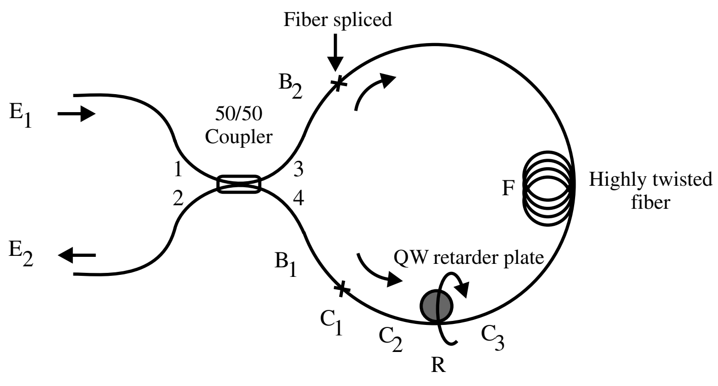

Fig. 1. Schematic structure of the FOLM.

the FOLM is modelled by a matrix. The electric field at the input and at the output of every matrix is presented in the coordinate system coinciding with principal axes at the fiber input and output, respectively. Twist causes rotation of the fiber principal axes and of the corresponding coordinate system. To include this we introduce a matrix for coordinate rotations. Since we experimentally determined that the birefringence of the coupler output ports affects significantly the FOLM behavior, two additional matrices were included in our analysis to describe this effect. The input beam is launched into port 1 and the output power is measured at port 2.

We numerically analyzed the dependence of the transmission on fiber twist using the following relation describing the output field of the FOLM [12]:

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

where α is the intensity coupling coefficient of the coupler and the Jones matrix J can be calculated as a product of the Jones matrices corresponding to each element of the loop:

$$J = B_1 \cdot C_1 \cdot C_2 \cdot R \cdot C_3 \cdot F \cdot B_2, \quad (2)$$

where F is the matrix that represents the twisted fiber, R represent the QW retarder plate, C_1 is the matrix that describe the orientation of the principal axes of the coupler lead (port 4) with respect to the R end, C_2 and C_3 describe the rotation of the QW retarder plate and birefringence at ports 3 and 4 of the coupler is described by matrices B_2 and B_1, respectively.

The highly twisted fiber is the segment labeled F. For the matrix F we use the Jones matrix for a twisted birefringent fiber [14]:

$$F = \begin{pmatrix} \cos\eta - \pi i L_n \sin\eta/\eta & \delta_c/2 \sin\eta/\eta \\ -\delta_c/2 \sin\eta/\eta & \cos\eta + \pi i L_n \sin\eta/\eta \end{pmatrix}, \quad (3)$$

where $\eta = \sqrt{(\pi L_n)^2 + (\delta_c/2)^2}$, $L_n = L_{\text{fiber}}/L_{\text{beat}}$ is the ratio between the fiber length (L_{fiber}) and the beat length (L_{beat}); $\delta_c = 2(1-g/2n)\tau$ is the circular birefringence, n is the fiber refractive index and τ is fiber twist. The parameter g links the circular birefringence and fiber twist. For silica-glass fibers $g = 0.13–0.16$ [15]. We use the parameter $g = 0.145$ in our simulations. As mentioned above g has a range of values given in the literature. Values of g in the range between 0.13 and 0.16 results in a change of the principal peak's value less than 2%. The beat length denotes the fiber length of untwisted fiber at that linearly polarized eigenmodes gain a phase shift of 2π.

For the matrices B_1 and B_2 we use the Jones matrix for a twisted birefringent fiber:

$$B_1 = \begin{pmatrix} \cos\eta_{B_1} - i(\delta_{l,B_1}/2)\sin\eta_{B_1}/\eta_{B_1} & (\delta_{c,B_1}/2)\sin\eta_{B_1}/\eta_{B_1} \\ -(\delta_{c,B_1}/2)\sin\eta_{B_1}/\eta_{B_1} & \cos\eta_{B_1} + i(\delta_{l,B_1}/2)\sin\eta_{B_1}/\eta_{B_1} \end{pmatrix}, \quad (4)$$

$$B_2 = \begin{pmatrix} \cos\eta_{B_2} - i(\delta_{l,B_2}/2)\sin\eta_{B_2}/\eta_{B_2} & (\delta_{c,B_2}/2)\sin\eta_{B_2}/\eta_{B_2} \\ -(\delta_{c,B_2}/2)\sin\eta_{B_2}/\eta_{B_2} & \cos\eta_{B_2} + i(\delta_{l,B_2}/2)\sin\eta_{B_2}/\eta_{B_2} \end{pmatrix}, \quad (5)$$

where $\eta_{B_1} = \sqrt{(\delta_{l,B_1}/2)^2 + (\delta_{c,B_1}/2)^2}$ and $\eta_{B_2} = \sqrt{(\delta_{l,B_2}/2)^2 + (\delta_{c,B_2}/2)^2}$, $\delta_{l,B_1} = (2\pi/\lambda)L_1\Delta n_1$ and $\delta_{l,B_2} = (2\pi/\lambda)L_2\Delta n_2$ are the linear retardances, L_1 and L_2 are the lengths, Δn_1 and Δn_2 are the linear birefringence of the coupler leads in the ports 4 and 3, respectively, λ is the wavelength of the input beam, $\delta_{c,B_1} = 2(1 - g/2n)\tau_1$ and $\delta_{c,B_2} = 2(1 - g/2n)\tau_2$ are the circular retardances, τ_1 and τ_2 are the twist angles of the fiber sections coupled to ports 4 and 3, respectively.

The matrix C_1 includes unknown initial angle between coupler lead axes (port 4) and QW retarder plate axes, θ_1,

$$C_1 = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 \\ \sin\theta_1 & \cos\theta_1 \end{pmatrix}. \quad (6)$$

We use the matrices C_2 and C_3 to describe the rotation of the QW retarder plate,

$$C_2 = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 \\ \sin\theta_2 & \cos\theta_2 \end{pmatrix}, \quad (7)$$

$$C_3 = \begin{pmatrix} \cos\theta_2 & \sin\theta_2 \\ -\sin\theta_2 & \cos\theta_2 \end{pmatrix}, \quad (8)$$

where θ_2 is the rotation angle of the QW retarder plate.

Finally, the matrix that describes the QW retarder plate is R,

$$R = \begin{pmatrix} \exp(i\pi/4) & 0 \\ 0 & \exp(-i\pi/4) \end{pmatrix}. \quad (9)$$

The dependence of the transmission on the rotation angle of the QW retarder plate for the ideal case (i.e., when we assume that the coupler leads have equal twist and birefringence, in this case $B_1 = B_2$) is depicted in Fig. 2. We are considering high twist in the fiber loop ($\tau/L_{\text{fiber}} = 14\pi$ rad/m). We observe that the maximum transmission is 50%, and there are two peaks in a period of π rad. We observe the same behavior of the transmission if we use low or high twist and birefringence but the same values for both coupler leads (i.e, we can use low twist and high birefringence; high twist and low birefringence; and high twist and high birefringence in the coupler leads). The transmission behavior is the same if we use low or moderate twist in the fiber loop, but in this case the maximum transmission is less than 50%.

Ideal operation of a FOLM would have unity for the maximum transmission and zero for the minimum transmission. Fig. 3 shows the dependence of the transmission on the rotation angle of the QW retarder plate when the fibers B_1 and B_2 have same twist ($\tau_1 = \tau_2 = 6\pi$) and different birefringence ($\delta_{l,B_1} = 5\pi/4$ and $\delta_{l,B_2} = \pi/4$). There are still two peaks in a period of π rad but each peak has a different amplitude. The transmission maximum for the first peak is around 70%. We find al-

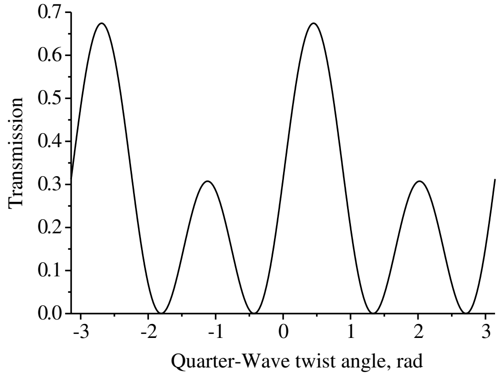

Fig. 3. Transmission vs twist angle of the QW retarder plate when the fibers B_1 and B_2 have same twist ($\tau_1 = \tau_2 = 6\pi$) and different birefringence ($\delta_{l,B_1} = 5\pi/4$ and $\delta_{l,B_2} = \pi/4$).

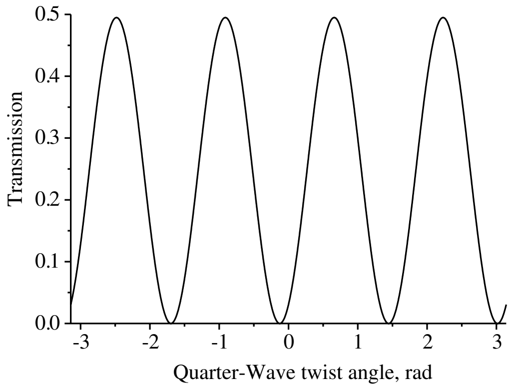

Fig. 2. Transmission vs twist angle of the QW retarder plate in the case of $B_1 = B_2$.

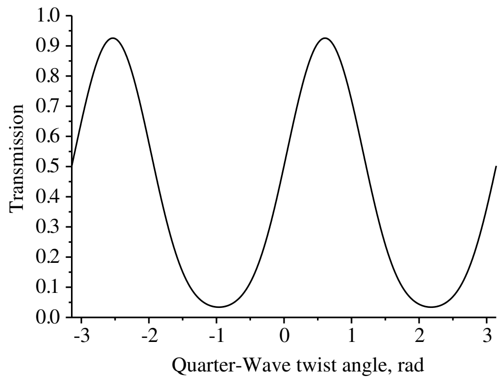

Fig. 4. Dependence of the transmission on the rotation angle of the QW retarder plate when we used high birefringence in one of the coupler leads ($\delta_{l,B_1} = 9\pi$ and $\delta_{l,B_2} = \pi/4$).

most the same transmission behavior if we use different twist in the coupler leads.

When we increase the birefringence in one of the coupler leads the second peak is decreasing. So, when we apply high birefringence in one of the coupler leads it is possible to eliminate the second peak. Fig. 4 shows the dependence of the transmission on the rotation angle of the QW retarder plate when we used high birefringence in one of the coupler leads ($\delta_{l,B_1} = 9\pi$ and $\delta_{l,B_2} = \pi/4$). We have only one peak in a period of π rad, the transmission maximum is around 90% and the minimum is around 3%. So, by rotating the QW retarder plate, it is possible to control the behavior of the transmission. We use L_{fiber} = *100 m and* L_{beat} = 19 m for Figs. 2–4. This analysis provides the path for achieving nearly ideal operation of the FOLM with a single transmission maximum and minimum per period with high contrast between them.

3. Experimental results

The experimental setup is illustrated in Fig. 5. The laser radiation from a laser diode is coupled to an input (port 2′) of a 0.5/0.5 coupler 1. We used Tektronix TOP160 single-mode laser source with 190 μW output power and 1550 nm wavelength. The coupler 1 provides the measurements of reflected power from the FOLM (port 1′). From the output (port 4′) of the coupler 1 the radiation is launched into a 0.5/0.5 coupler 2 (port 1) forming the FOLM. The output leads of the coupler (ports 3 and 4) are spliced to the highly twisted fiber and a QW retarder plate. The twist of the fiber wounded on the spool was around 44 rad/m. We applied extra twist to the 1-m long, unwounded spans connecting the spool and the coupler ports. The extra twist allows the birefringence adjustment of the spans and affects the FOLM transmission. We used a motor mechanism to uniformly rotate the QW retarder plate during the measurement. To avoid errors associated with the loss in the couplers, we measured both transmitted and reflected power, and calculated the transmission from both data.

By definition, transmission is the ratio of the transmitted power (port 2) and the input power of the FOLM. To eliminate the effects of losses, we estimated the input power by the sum of the transmitted and reflected power for the FOLM. With these considerations, the transmission equation is: Transmission = $P_{\text{transmitted}}/(P_{\text{transmitted}} + P_{\text{reflected}})$, where $P_{\text{reflected}}$ is two times the power measured in the port 1′ of the coupler 1. We used InGaAs detectors connected to an oscilloscope for transmitted and reflected power measurements. To measure the transmission we rotate the QW retarder plate. The FOLM is made of 100 m of low birefringence, highly twisted Corning SMF-28 standard fiber, which was fusion-spliced with the

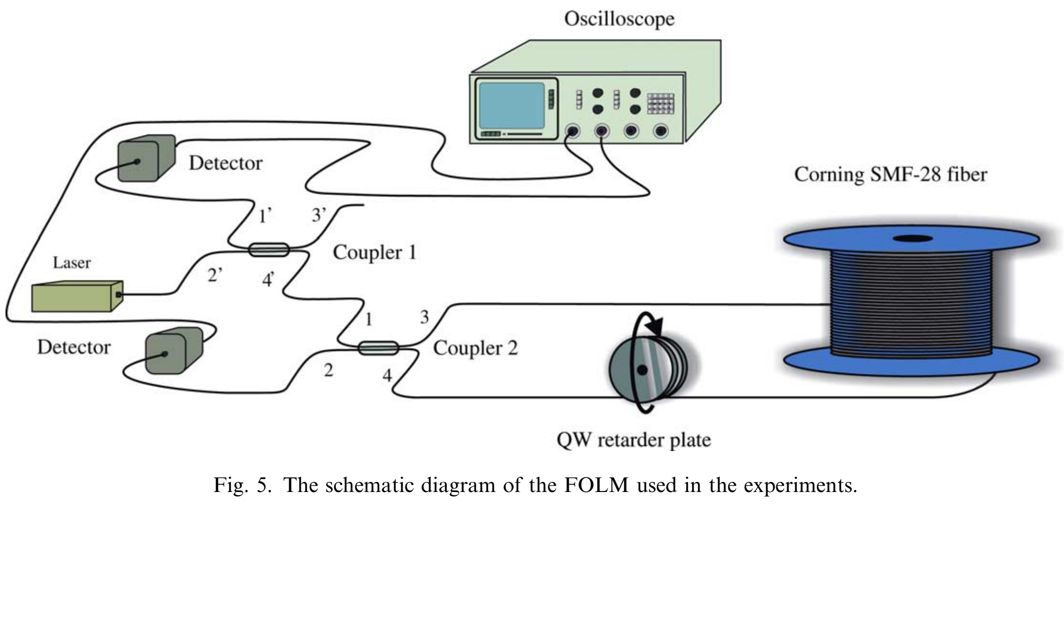

Fig. 5. The schematic diagram of the FOLM used in the experiments.

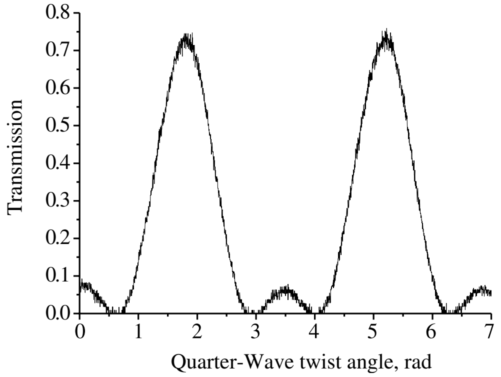

Fig. 6. Experimental dependence of the transmission vs twist angle of the QW retarder plate. The fiber twist in the loop is around 44 rad/m.

output ports of a nearly symmetrical fused coupler (coupling ratio $r = 0.51$). The beat length of this fiber is 19 m [16]. At one end, the fiber is wrapped on a cylinder (with a properly chosen diameter) to form a QW retarder plate.

Fig. 6 shows the transmission versus QW retarder plate angle when we used highly twisted unwounded fiber spans. High twist eliminates residual birefringence of the spans. Nevertheless we observe two peaks in a period of π rad with different transmission; the first one is bigger than the second one with the maximum of the transmission equals 75%. For the small peak the transmission is around 8%. This result is similar to the transmission characteristics displayed in Fig. 3. It shows that some residual birefringence still exists. The most probably that is birefringence in the coupler which is not affected by fiber twist.

By proper twist of the unwounded spans we have got the transmission similar to the calculated one shown in Fig. 2, see Fig. 7. We observe two similar peaks in a period of π rad and the maximum of the transmission is around 50%. This dependence of the transmission on the QW retarder angle shows that we eliminated the effect of residual birefringence. In the case of Fig. 7 we made 2 turns in the QW retarder plate.

The transmission with two equal maxima equal to 50% corresponds of ideal FOLM with no effect of the residual birefringence. It occurs if the coupler leads have no birefringence, that is not realistic, or if they have the same birefringence and twist, or if the birefringence is compensated by twist. It is difficult to get the conditions for the same birefringence and twist in both of the coupler leads. Nevertheless our results show that it is easly to adjust the lead twist to obtain the ideal FOLM characteristic.

From our prior analysis we expect that when we increase the birefringence in one of the coupler leads the small peak will disappear and the big

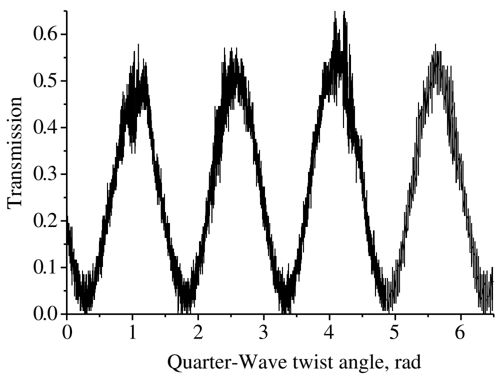

Fig. 7. Experimental dependence of the transmission vs twist angle of the QW retarder plate. By proper twist of the unwounded spans, it is possible to get the transmission similar to Fig. 2.

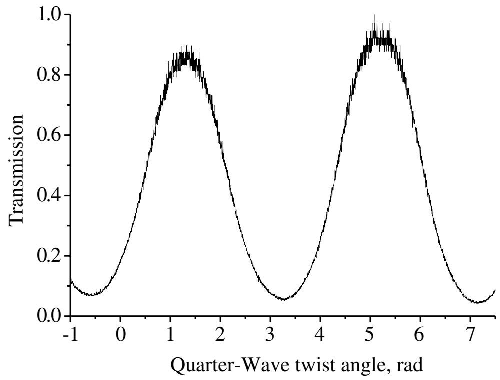

Fig. 8. Experimental dependence of the transmission vs twist angle of the QW retarder plate. The fiber twist in the loop is around 44 rad/m. We increase the birefringence in one of the coupler leads.

peak will be close to 100% of the transmission, see Fig. 6. Therefore, we further increased the birefringence in port 3 of coupler 2 and found it is possible to eliminate the second peak, see Fig. 8. In this figure we indeed observe only one peak in a QW plate rotation period of π rad. In this case, when we rotate the QW retarder plate is possible to change the transmission from minimum transmission around 2% to maximum transmission around 82%.

When Figs. 6–8 are put together it demonstrates a simple procedure to change the transmission of FOLM that would enable a panoply of applications based on the birefringent and twisted FOLM.

4. Conclusions

In conclusion, we have presented an experimental analysis of the transmission behavior in a FOLM with a QW retarder plate and highly twisted fiber in the loop. We have demonstrated that as the QW retarder plate is rotated that it is possible to adjust the transmission over a wide range (from around 2% to around 82%) and the operating characteristics can be adjusted by using fiber twist to achieve nearly ideal operation of the FOLM when residual birefringence of all elements does not affect the FOLM operation. The theoretical analysis is in good agreement with our experimental results and gave the first indication of how to proceed in the experiment. The FOLM presented here operates stably with repeatable operation settings; it will be useful for developing photonic devices based on nonlinear polarization rotation and the FOLM incorporates standard fiber.

Acknowledgements

B. Ibarra-Escamilla was supported by CONACyT Project J36135-A. J.W. Haus was supported by National Science Foundation Grant INT-0226945.

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