STUDY OF LINEAL AND NON-LINEAL TRANSMISSION OF AN OPTICAL FIBER SAGNAC INTERFEROMETER AS A BIDIRECTIONAL DEVICE

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Abstract:

The optical fiber Sagnac interferometer is a versatile system that has been investigated for a variety of applications such as optical switchers, filters, demultiplexers and passive mode-locked laser. In many cases, this arrangement is designed using a symmetrical coupler with two of their ports connected making a loop and generally the analysis have been focused in the transmission of the signal propagated in only one direction. Therefore in the present work a complementary study of the system considering the analysis for the lineal and non-lineal transmission as a bidirectional device has been performed. The experimental setup consists of different optical fiber lengths inside the cavity loop (between 100 and 500 m) with highly twisted singlemode fiber, a quarter wave retarder placed asymmetrically in one arm and a 50/50 coupler. The results have shown that for low optical powers, it is possible to adjust the system transmission in both propagation directions with the rotation of the retarder wave. On the other hand, in high optical power levels, this arrangement showed that the transmission increases slowly for the case when both the input and the output beams have the same polarization. This behavior can be used for pedestal suppression in a light pulse. Furthermore, for the case when the output signal polarization is orthogonal respect to the input one, the transmission changes quite fast. This effect can be used for applications such as the passive mode-locking.

Keywords: Sagnac Interferometer, non-lineal transmission, bidirectional device

1. INTRODUCTION:

In the last decade, the technology based on fiber optics has been quickly advancing due to its many applications such as, fiber optics lasers in continuous and pulsed emission, optical communications where the fiber is used as information transmission medium. They are also used for the development of fiber optic sensors to detect many physical parameters such as, temperature, pressure, strain, etc. The interest is due to the fact that using fiber optics, higher transmission rates can be achieved. Moreover, they can be used in places where it is difficult to access and they are immune to electromagnetic interferences. Another attractive device is the fiber optics Sagnac interferometer (FOSI), which due to its versatility it has many important applications. There are many works that
have been reported about the FOSI where different applications have been showed, such as: optical switching [1-2], demultiplexing [3] and passive mode-locking, where it has been used as saturable absorber, that means, at low power levels the transmission is quite small and almost all the energy is reflected by the device, whereas for high power levels it can be transparent. However up to now there is a lack of work about the FOSI as a bidirectional device and its possible applications such as feedback medium in a Fabry-Perot laser.

In previous work [5] there are reported results of the analysis of the Sagnac interferometer transmission when it was used as a nonlinear optical loop mirror (NOLM). Using a symmetric coupler, highly twisted and a quarter wave retarder plate (QWRP) in the loop, in this work they showed that twisting the QWRP, the transmission variation is from 2% to 82%. However results about the reflectance and bidirectionality of FOSI are not presented.

The FOSI is formed by a bidirectional for four-port coupler (P1, P2, P3 and P4), where the P1 and P2 ports are the inputs, while P3 and P4 are the outputs. The latter are coupled by a portion of highly twisted low birefringence single mode fiber optics. Inside the loop two light beams propagate with opposite directions. The output transmission is the addition of the intensities of these two beams, which can by expressed as equation 1: [4]

\[ T = 1 - 2\alpha(1 - \alpha)[1 + \cos(\Phi_{\text{in}} - \Phi_{\text{out}})] \] (1)

In a FOSI the waves that propagate inside the loop travel the same optical path and, if there is not any other optical element, then the transmission depends just of the coupling coefficient \( \alpha \): [4]

\[ T = 1 - 2\alpha(1 - \alpha) \] (2)

From equation 2 it can be obtained the transmission profile, where it can observed that if the coupling coefficient increases, the transmission decreases to 50% for this particular case (\( \alpha = 0.5 \)), whereas the reflection increases in the same value. However to achieve a maximum transmission, B. Ibarra et al [5] proposed to introduce a QWRP to change the phase between the counterpropagating beams inside the loop and in this way to optimize the output signal of the interferometer. In the present work the analysis of the reflectivity of the FOSI for its applications in the development of Fabry-Perot optical fiber lasers.

2. THEORY:
The input beam is launched into port P1 and the output power is measured at port P2, which can be expressed as equation 3.

\[ \begin{pmatrix} E_{2x} \\ E_{2y} \end{pmatrix} = \begin{pmatrix} (2\alpha - 1)xx & (1 - \alpha)xy + \alpha x y \\ -\alpha x y - (1 - \alpha)yy & (1 - 2\alpha)xx \end{pmatrix} \begin{pmatrix} E_{1x} \\ E_{1y} \end{pmatrix} \] (3)

where \( \alpha \) is the coupling coefficient of the coupler and the Jones matrix \( J \) can be calculated as a product of the Jones matrices corresponding to each element in the loop as is shown in equation 4.

\[ J = B_1 \cdot C_1 \cdot C_2 \cdot R \cdot C_3 \cdot F \cdot B_2 \ldots \] (4)

where \( F \) is the matrix that represents the twisted fiber, \( R \) represents the QWRP, \( C_1 \) is the matrix that describes the orientation of the principal axes of the coupler with respect to the R. \( C_2 \) and \( C_3 \) describe the rotation of the QWRP and the birefringence of the ports 3 and 4 of the coupler is described by matrices \( B_2 \) and \( B_1 \), respectively.

The Jones matrix \( F \) for a twisted birefringent fiber is given by equation 5.

\[ F = \begin{pmatrix} \cos \eta & \sin \eta \\ -\sin \eta & \cos \eta \end{pmatrix} \] (5)
where \( \eta = \sqrt{(\pi L_n)^2 + (\delta c/2)^2} \), \( L_n = L_{\text{fiber}}/L_{\text{beat}} \), \( L_{\text{fiber}} = \) fiber length, \( L_{\text{beat}} = \) the beat length, \( \delta c = 2(1-g/2n)\tau \) is the circular birefringence, \( n \) is the fiber refractive index, \( \tau \) is the fiber twist. The parameter \( g = 0.13-0.16 \) relates the circular birefringence with the fiber twist. The parameter \( g = 0.145 \) was used in the simulations.

For the matrices \( B_1 \) and \( B_2 \), the Jones matrices for a twisted birefringent fiber given by the expressions 6 and 7 were used

\[
B_1 = \begin{pmatrix} \cos B_1 - i(\deltaIB_1/2)\sin B_1/\eta B_1 & (\delta cB_1/2)\sin B_1/\eta B_1 \\ -i(\deltaIB_1/2)\sin B_1/\eta B_1 & \cos B_1 + i(\deltaIB_1/2)\sin B_1/\eta B_1 \end{pmatrix} \quad \ldots (6)
\]

\[
B_2 = \begin{pmatrix} \cos B_2 - i(\deltaIB_2/2)\sin B_2/\eta B_2 & (\delta cB_2/2)\sin B_2/\eta B_2 \\ -i(\deltaIB_2/2)\sin B_2/\eta B_2 & \cos B_2 + i(\deltaIB_2/2)\sin B_2/\eta B_2 \end{pmatrix} \quad \ldots (7)
\]

where \( \eta B_1 = \sqrt{(\deltaIB_1)^2 + (\deltaCB_1)^2} \) and \( \eta B_2 = \sqrt{(\deltaIB_2)^2 + (\deltaCB_2)^2} \), \( \delta IB_1 = (2\pi/\lambda)L_1\Delta n_1 \) and \( \delta IB_2 = (2\pi/\lambda)L_2\Delta n_2 \), are the linear delays, \( \Delta n_1 \) and \( \Delta n_2 \) are the linear birefringence of the coupler in the ports 4 and 3, respectively. \( \delta CB_1 = 2(1-g/2n)\tau_1 \) and \( \delta CB_2 = 2(1-g/2n)\tau_2 \) are the twist angles of the coupler fiber ends for the ports 4 and 3, respectively.

The matrix \( C_1 \) includes the initial angle between the coupler end axis (port 4) and QWRP axis, \( \theta_1 \), which is at unknown (equation 8)

\[
C_1 = \begin{pmatrix} \cos \theta_1 & -\sin \theta_1 \\ \sin \theta_1 & \cos \theta_1 \end{pmatrix} \quad \ldots (8)
\]

The matrices \( C_2 \) and \( C_3 \) (equations 9 and 10) were used to describe the rotation of the QWRP

\[
C_2 = \begin{pmatrix} \cos \theta_2 & -\sin \theta_2 \\ \sin \theta_2 & \cos \theta_2 \end{pmatrix} \quad \ldots (9)
\]

\[
C_3 = \begin{pmatrix} \cos \theta_2 & \sin \theta_2 \\ -\sin \theta_2 & \cos \theta_2 \end{pmatrix} \quad \ldots (10)
\]

where \( \theta_2 \) is the rotation angle of the QWRP.

Finally, the matrix \( R \) that describes the QWRP is given by equation 11 [5].

\[
R = \begin{pmatrix} e^{i\pi/4} & 0 \\ 0 & e^{-i\pi/4} \end{pmatrix} \quad \ldots (11)
\]

Since the objective is to study the reflection of the OFSI, the input beam must be launched through to port \( P_2 \) and the output must be measured at port \( P_1 \) (equation 12).

\[
\begin{pmatrix} E_{x1} \\ E_{y1} \end{pmatrix} = \begin{pmatrix} (2\alpha-1)jxx & (1-\alpha)jyx \\ -\alpha jxy & (1-2\alpha)jxx \end{pmatrix} \begin{pmatrix} E_{x2} \\ E_{y2} \end{pmatrix} \quad \ldots (12)
\]

And the Jones matrix of the loop can be calculated by equation 13.

\[
J = B_2 \ast F \ast C_3 \ast R \ast C_2 \ast C_1 \ast B_1 \quad \ldots (13)
\]

In the system described in the present work, the phase shift and a variation in the transmission profile is attributed to a QWRP inserted in the loop, which introduces to the system a cross-phase modulation (XPM).

In the case of the nonlinear region, the NOLM transmission function is given by equation 14.

\[
T = \frac{1}{2} - \frac{1}{2} \cos(\beta - 2\alpha) \cos(\beta - 2\alpha + \frac{1}{4}P_{in}) \quad \ldots (14)
\]
3. RESULTS

In figure 2 there are shown the transmission and reflection in function of the angle variation of the QWRP, which is located asymmetrically inside the interferometer loop. For the ideal case, it is assumed that the coupler has the same alignment between its axes (fast and slow) and they have the same birefringence (B1 = B2). It is observed that the transmission function presents maxima of around 50% while the reflection presents maxima of 100%, as it was expecte.

In figure 3 there is shown the dependency of the transmission and reflection in function of the QWRP angle when a phase shift is induced to the counterpropagating beams inside the interferometer loop. This means that, in this particular case the birefringence B1, which corresponds to the fiber portion from P3 to P4 is larger than the one for B2, which corresponds to the fiber portion from P4 to P3. From these plots it can be observed that there are still maxima in π radian range; however each maximum has different amplitude. The first maximum is approximately 75% and the second one is around 23%. The reflection shows a complementary behavior respect to the transmission, i.e. when it presents a maximum, the transmission is minimal.
When the difference between the birefringences that experiment the counter propagating beams inside the loop is quite large, the low amplitude peaks are eliminated. Figure 4 shows the behavior of the transmission and reflection in function of the QWRP rotation angle when high birefringence is used in one of the coupler ports. Its observed just one maximum in a π radian range, the reached transmission is approximately 98% and de minimum is around 0%. Therefore it is possible to obtain a reflection maximum of approximately 100% with a minimal transmission. Furthermore the transmission and reflection peaks width is increased. This characteristic can be employ as a bidirectional element in a Fabry-Perot cavity.

![Figure 4) Transmission and Reflection profiles for B1 >> B2](image)

It was also performed an analysis in the nonlinear region for the case when the port 3 birefringence is much larger than the one of port 4 at the coupler that forms the OFSI (B1>>B2). Figure 5 shows the obtained results for a pumping power from 0 to 60 W. from the figure it can be observed that the peak with the lowest amplitude was eliminated and a profile with peaks of the same amplitude was obtained. It can be also observed that for a pumping power range from 0 to 20 W the transmission changes from a minimum value of 0% to 80% and for pumping power larger than 20 W the transmission minimum begins to increase reaching a value of approximately 18% for a pumping power of 60 W. At this power the maximal transmission remains; however as slight deformation appears. This is probably due to nonlinear effects generated inside the fiber.

![Figure 5) Transmission profiles for B1 >> B2](image)

4. CONCLUSIONS.
In the present work an analysis of the transmission and reflection of a OFSI was performed. For this analysis a highly twisted standard single-mode optical fiber and a QWRP asymmetrically located inside the loop to change the birefringence of the beams that propagate from P3 to P4 (B1) and from
P4 to P3 (B2). This procedure was performed for the cases of low and high pumping powers. The results showed that when $B_1 >> B_2$, the transmission and reflection profiles are the optimal since the low amplitude peak elimination is achieved, obtaining transmission values from 0% to 98% and a reflection from a minimum of 2% to a maximum 100% for the case of low pumping powers (from 0 to 20 W). On the other hand, for the case of high pumping power (from 20 to 60 W), a maximum transmission of 80% was achieved, while the minimum of the transmission increases up to 80% approximately. With these results it is possible to determine the OFSI optimal operation conditions to be used for the above mentioned purposes, such as in a Fabry-Perot cavity.

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