Fiber recirculating delay-line tunable depolarizer

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A new type of all-single-mode fiber depolarizer, based upon a $2 \times 2$ coupler and a recirculating delay line and useable with a coherent light source, is proposed and demonstrated. The reduction in the degree of polarization is examined theoretically and experimentally. Design criteria and principles are discussed. With a narrow-band laser source, the degree of polarization was tuned between 99.8% and 1.15%. Experiments illustrate how this depolarizer can eliminate the effects of induced polarization fluctuation in a polarization-sensitive fiber-optic system. The experimental results support the theoretical model.

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1. Introduction

In the research areas of erbium doped–fiber amplifiers, fiber-optic sensors and coherent communications, the stability of the polarization state is an important characteristic in determining system performance. A given polarization state launched into the fiber evolves into other states after a short distance. At the end of a long fiber, the state of polarization may vary in time if the fiber's birefringence changes as a result of environmental fluctuations (e.g., temperature) or mechanical disturbances. The undesired polarization variations cause polarization hole burning in erbium doped–fiber amplifiers and reduce overall system performance. In interferometric fiber sensors and coherent communications systems, variations in polarization of the received wave create signal fading.

High-birefringence fiber (although costly in the lengths and components required for communications applications) would overcome these problems. Fiber depolarizers (e.g., the Lyot depolarizer) prevent signal fading by reducing the mutual coherence between the two orthogonal polarization components of the broadband source (e.g., a superluminescent diode). However, for narrow-band sources, such as typical commercial laser diodes, this approach is not an option because of the long lengths of high-birefringence fiber required. Other methods that succeed with single-mode fibers include the polarization controller with a servo control system and polarization modulation techniques.

We describe a new technique for the single-mode fiber depolarizer based on a fiber-optic recirculating delay line. It has the advantages of simple structure, all-single-mode fiber construction, economics (because low-cost commercial laser diodes can be used in the system), tunable degree of polarization, and arbitrary input polarization state without requiring any birefringence axis alignment. The tunable depolarizer that we describe is especially suitable for laboratory applications.

The degree of polarization (DOP), defined as the fraction of the optical power that is polarized, is used to characterize the performance of the depolarizer. Several authors have provided theoretical treatments. A general expression for the degree of polarization in an anisotropic single-mode fiber was reported previously. Mode-coupling theory has also been used and confirmed experimentally. In this paper we take a different approach and present a calculation of the degree of polarization based on the coherence matrix. The model of the depolarizer is characterized by the birefringence in an ordinary single-mode fiber. The birefringence of the recirculating fiber delay line to maximize the depolarization is numerically obtained. The output degree of polarization is calculated with an arbitrary input state of polarization. Experiments confirm the theoretical analysis on the amount of depolarization as well as the application to reduce the polarization noise in a single-mode fiber system.
2. Theory

A. Transfer Matrix

The fiber-optic recirculating delay line is made by connecting one of the input ports to one of the output ports of a directional coupler, as illustrated in Fig. 1. For a single-mode fiber, linear birefringence, circular birefringence, and axis rotation are present simultaneously and distributed over the fiber's entire length. We characterize the recirculating delay line as consisting of a linear retarder \( R_\ell \) in series with a circular retarder \( R_c \).\(^{12,13} \) The coherence matrix for this model is

\[
R_\ell (\delta_\ell, \theta) = \begin{bmatrix}
\exp[i(\delta_\ell/2)] \cos^2(\theta) + \exp[-i(\delta_\ell/2)] \\
2i \sin(\theta) \cos(\theta) \sin(\delta_\ell/2)
\end{bmatrix}
\]

\[
R_c (\delta_c) = \begin{bmatrix}
\cos(\delta_c/2) & \sin(\delta_c/2) \\
-\sin(\delta_c/2) & \cos(\delta_c/2)
\end{bmatrix}
\]

where \( \delta_\ell \) is the linear retardation of the linear retarder, \( \theta \) is the azimuth of the fast axis of the linear retarder, and \( \delta_c \) is the circular retardation of the circular retarder. Equations (1) and (2) are also known as Jones matrices.\(^{14} \)

B. Noninterferometric Condition and Output Intensity

For a Lyot depolarizer,\(^5 \) or a depolarizer based on a Mach–Zehnder fiber delay-line structure,\(^{15} \) to reduce the mutual coherence of the orthogonal polarization modes, the birefringent differential group delay must be longer than the coherence time of the light source. Similarly, the light depolarization of our fiber-optic recirculating delay-line structure occurs only when the resonant, or interferometric, behavior in the ring has been eliminated (or reduced to a negligible amount). This condition will be satisfied when the length of the fiber delay line is much longer than the coherence length of the light source; that is, \( L_d > l_{coh} \), where \( L_d \) is the recirculating length of the fiber delay line and \( l_{coh} \) is the coherence length of the light source. This condition can be easily achieved in practice by use of a low-cost, narrow-band laser-diode light source together with a \( 2 \times 2 \) single-mode fiber coupler. A \( 2 \times 2 \) fused single-mode coupler with 1 m of fiber pigtail at each port yields a delay line \( \sim 2 \) m in length, far beyond the coherence length of a commercial laser diode. For example, the coherence length is approximately 0.5–2 mm for the narrow-band laser diode (1–2-nm spectral width) used in our work. Each recirculating beam passing through the delay line is incoherent with all the others. Therefore there are no interferometric effects associated with the multiple recirculating beams. Because of this we can ignore the \( \pi/2 \) phase difference between the beams emerging from ports 3 and 4 of the directional coupler in Fig. 1.

To calculate the output of the recirculating delay line, we assume that there are no losses in the system, that the input wave \( J_i (\psi, \chi) \) has normalized intensity \( I_i \), and that \( K_c \) and \( K_d \) are the coupling matrices from port 1 to port 4 and port 1 to port 3, respectively. Then,

\[
J_i (\psi, \chi) = \frac{I_i}{2} \left[ 1 + \cos(2\psi) \cos(2\chi) + i \sin(2\psi) \cos(2\chi) - i \sin(2\psi) \cos(2\chi) \right]
\]

\[
\frac{\sin(2\psi) \cos(2\chi) + i \sin(2\psi) \cos(2\chi)}{\sin(2\psi) \cos(2\chi) - i \sin(2\psi) \cos(2\chi)}
\]

\[
(3)
\]

where \( \psi \) and \( \chi \) are the azimuth and ellipticity of the (arbitrary) input polarization state of \( J_i (\psi, \chi) \) and \( k \) is the coupler’s coupling coefficient (whose value lies between 0 and 1). When the wave \( J_i \) passes through a birefringence device whose birefringence matrix is denoted by \( M \), the coherence matrix representation of the emerging wave is

\[
J' = MJM^+,
\]

where \( M^+ \) is the Hermitian conjugate of \( M \). This is the transformation law for the coherence matrix in the quasi-monochromatic approximation. The model of the birefringence matrix of the delay line for each recirculating wave can be described as

\[
M_0 = K_d,
\]

\[
M_1 = K_c R R K_c,
\]

\[
M_2 = K_c R R K_c R R K_c,
\]

\[
M_3 = K_c R R K_c R R K_c R R K_c
\]

\[
\vdots
\]

\[
M_n = K_c (R R K_c)^{n-1} R R K_c,
\]

where \( M_0 \) is the birefringence matrix for the wave directly passing through the coupler, \( M_1 \) is the matrix
for the wave making one trip through the delay line, $M_2$ is the matrix for the wave making two trips passing through the delay line, and $M_n$ is the matrix for the wave making $n$ trips through the delay line. Therefore the output matrix of each individual recirculating wave is

$$J_n' = M_n J_n M_n^*,$$

$$J_1' = M_1 J_1 M_1^*,$$

$$J_2' = M_2 J_2 M_2^*,$$

$$\ldots$$

$$J_n' = M_n J_n M_n^*.$$  \hspace{1cm} (7)

The total emerging wave at the output port, $J_e$, is the summation of each individual recirculating wave. Thus

$$J_e = J_0' + J_1' + J_2' + \cdots + \sum_{n=0}^{\infty} J_n'.$$ \hspace{1cm} (8)

The total intensity of the emerging wave is given simply by the trace of the coherence matrix $J_e$:

$$I_e = Tr J_e.$$ \hspace{1cm} (9)

Because we assume a lossless system, the emerging intensity is the same as that incident. That is,

$$I_e = I.$$ \hspace{1cm} (10)

All the power will emerge at the output port if there are no interferometric effects in the lossless fiber delay line. This result is also required by the principle of conservation of energy. The actual loss of a recirculating delay-line coupler includes the excess loss in the coupling region and the attenuation in the fiber. This loss is very small for well-designed couplers (of the order of 0.1–0.2 dB).

C. Output State of Polarization

From Eq. (8), the output polarization state of $J_n'$ with respect to $J'_1(\psi, \chi)$ is determined by the birefringence matrix $M_n$, while $M_n$ depends on the values of $n$, $\delta$, $\theta$, $\delta_c$, and $k$. Thus the $J_n'$ also depend on the values of $\psi$, $\chi$, $n$, $\delta$, $\theta$, $\delta_c$, and $k$. Therefore the state of polarization of each recirculating beam ($J_0'$, $J_1'$, $J_2'$, $\ldots$, $J_n'$, $\ldots$) at the emerging port might be different due to the birefringence of the recirculating delay line and will be dependent on the birefringence matrix $M_n(\delta$, $\theta$, $\delta_c)$ and the input wave state $J'_1(\psi, \chi)$.

D. Depolarization

Because of the incoherent recirculation of the input wave, the emerging wave is a superposition of different polarization states with different intensities. From Eqs. (6) and (7) of the birefringence model of the fiber delay line, each recirculating beam adds an additional term $R R K_d$ to the calculation. The birefringence matrix of $R R K_d$ contributes to the variation of the incoming polarization and the matrix $K_d$ decreases the intensity of each recirculating beam in proportion. Depolarization occurs by incoherent averaging over the many different polarization states of the recirculating beams. This depolarization depends on careful selection of the birefringence (linear and circular) of the recirculating delay line, the coupling coefficient ($k$), and the input polarization state. The degree of polarization (DOP) of the emerging wave can be obtained in terms of the elements of $J_e$. It is given by

$$DOP[\%] = \left[ 1 - \left( \frac{\text{det} J_e}{\text{Tr} J_e} \right)^2 \right]^{1/2},$$ \hspace{1cm} (11)

where the positive value of the square root is to be taken. The det $J_e$ is the determinant value of $J_e$, and Tr$J_e$ is the trace of the coherence matrix.

3. Numerical Simulation

As described in the preceding analysis, the degree of polarization of the emerging wave $J_e$ is a function of input polarization $J'_1(psi, chi)$, birefringence of the fiber delay line [i.e., $R(\delta, \theta)$ and $R_c(\delta_c)$], number of recirculating trips $n$, and coupling coefficient $k$. Because the single-mode fiber is polarization sensitive to its environment, the polarization state reaching the active area of the fiber coupler typically varies slowly with time. Therefore the input polarization state of $J'_1(\psi, \chi)$ should cover all possible states of polarization in any simulation. The azimuth and ellipticity are in the range

$$-\pi/2 \leq \psi \leq \pi/2,$$ \hspace{1cm} (12)

$$-\pi/4 \leq \chi \leq \pi/4.$$ \hspace{1cm} (12)

The recirculating number $n$ is selected to obtain an emerging intensity (i.e., Tr$J_e$) greater than 99% of the input intensity. Figures 2–4 show the degree of polarization dependence upon the parameters $\delta$, $\theta$, and $\delta_c$ when the input polarization was scanned over the ranges specified in relations (12). The maximum and minimum degrees of polarization were recorded for each of the parameters ($\delta$, $\theta$, and $\delta_c$) scanned in steps of 15°. For the linear birefringence $\delta$, dependence shown in Fig. 2, the conditions were $k = 0.67$, $\theta = \pi/3$, and $\delta_c = \pi/3$ (chosen arbitrarily). For the azimuth $\theta$ variations in Fig. 3, the conditions were $k = 0.67$, $\delta = \pi/3$, and $\theta = \pi/3$ (also chosen arbitrarily). For the circular birefringence $\delta_c$ variations in Fig. 4, the conditions were $k = 0.67$, $\delta_c = \pi/3$, and $\theta = \pi/3$ (also chosen arbitrarily). From a review
of Figs. 2–4, the optimum conditions for obtaining the maximum depolarization were determined to be $\delta_l = \pi$, $\theta = \text{arbitrary}$, and $\delta_c = \pi$. More generally, the optimum conditions are given by

$$
\delta_l = \pm (2m + 1)\pi, \quad \theta = \text{arbitrary},
$$

$$
\delta_c = \pm (2m + 1)\pi,
$$

(13)

where $m = 0, 1, 2, \ldots$. To determine the degree-of-polarization dependence on the coupling coefficient $k$, we chose the optimum condition of $\delta_l$, $\theta$, and $\delta_c$ from Eqs. (13) and varied the input polarization state over the ranges specified in relations (12) in steps of 1°. The input degree of polarization was unity. Figure 5 illustrates the result where we recorded the maximum and minimum possible degrees of polarization for coupling coefficient $k$ in the range 0–1 with steps of 0.05. As seen from Fig. 5, the optimum depolarization is obtained when $k \approx 2/3$. The degree of polarization goes as low as 0.1% (30 dB) as illustrated in Fig. 6 for an input degree of polarization of unity (at the optimum condition $k \approx 2/3$). The analysis assumed no losses in the system. The simulated results (Fig. 6) show that the proposed fiber delay-line structure with appropriate coupling coefficient $k$, induced birefringence $R_l(\delta_l, \theta)$ and $R_c(\delta_c)$ in the loop, and suitable input polarization state $J_l(\psi, \chi)$ is capable of varying the degree of polarization between 100% and 0.1%. This performance is confirmed by the experiments described in Section 4.

4. Experiments and Results

A. Degree of Polarization

The experimental setup used to measure the degree of polarization is shown in Fig. 7. Ports 2 and 4 (referring to Fig. 1) of a 2 × 2 fused single-mode fiber coupler were spliced together with a mechanical splicer to form the recirculating loop. Coupling into the recirculating loop (port 1 to port 4) was greater than that directly through the coupler (from port 1 to 3). A commercial low-cost laser diode (670-nm...
wavelength) was used as a light source. It has a narrow-band optical spectrum with linewidth in the range of 1–2 nm. The operating driving current and temperature of the laser diode were stabilized in the experiments. An objective lens was used to couple light into and out of the fiber. The input polarization state of $I_0(\psi, \chi)$ was arbitrarily selected by adjusting the polarization controller PC1 at the input to the coupler. The polarization controller PC2 in the recirculating loop was used as a tunable birefringence plate (retarder), effectively allowing variations in the values of $R_l(\delta_l, \theta)$ (Ref. 16) and $R_c(\delta_c)$ (Refs. 16–18). The output polarization state of each recirculating beam was changed accordingly. The degree of polarization was measured with the compensator and analyzer (Glan–Thompson prism). The extinction ratio of the Glan–Thompson prism in our investigation is better than $-50$ dB. The depolarization of the tunable depolarizer was confirmed by measuring the degree of polarization at the output. Experimentally, the degree of polarization is

$$DOP[\%] = 100 \frac{I_{\text{max}}(\epsilon, \theta_a) - I_{\text{min}}(\epsilon, \theta_b)}{I_{\text{max}}(\epsilon, \theta_a) + I_{\text{min}}(\epsilon, \theta_a)}, \quad (14)$$

where $I_{\text{max}}(\epsilon, \theta_a)$ and $I_{\text{min}}(\epsilon, \theta_b)$ are the maximum and minimum observed intensities for all possible states of polarization at the optical powermeter. The intensities were measured by rotation of the compensator (which changes the retardation, $\epsilon$) and analyzer (which changes the orientation, $\theta_a$). Both polarization controllers, PC1 and PC2, were adjusted to yield all possible degrees of polarization at the output. By careful adjustment, the maximum and the minimum (highest and lowest) degrees of polarization that could be achieved were 99.8% and 1.15%. The coupling ratio of the $2 \times 2$ directional coupler was measured to be 2.45 (port 4 power/port 3 power) at 670 nm. The difference between 2.45 and the analytical optimum of 2.0 (for $k = 2/3$) is that the practical fiber delay-line coupler in our work is not lossless. It has excess loss and splicing loss, which are compensated by more power sent into the recirculating loop. The insertion loss (excess loss of the coupler and splice loss) was measured to be 0.28 dB. The experimental data and performance were repeatable once the polarization controllers and splices were installed.

B. Application: Polarization-Sensitive Fiber-Optic System

To demonstrate that this tunable single-mode fiber depolarizer could reduce the polarization noise in a single-mode fiber system, 20 m of single-mode fiber and a polarization controller (PC3) were spliced to the output of the tunable fiber depolarizer. The experimental setup is illustrated in Fig. 8. The analyzer was set at an arbitrary azimuth and acted as a polarization-sensitive device in the fiber system. The polarization controller PC3 was used as a variable fiber birefringence plate to generate polarization fluctuations in the single-mode optical fiber system. The output intensity of the detected light was monitored by an oscilloscope, while the birefringence in the system was varied in a random fashion by adjusting polarization controller PC3. Figure 9 shows the results of this experiment. The left side of the oscilloscope trace was obtained without adjusting the polarization controller PC3, and the right side of the trace was obtained while randomly adjusting the polarization controller PC3. Figure 9(a) shows the results with the degree of polarization adjusted to 99.8%. The random fluctuation in Fig. 9(a) is caused by the random polarization changes induced by variation of the polarization controller PC3. Figure 9(b) shows the results with the degree of polarization adjusted to 1.15%. Now the output is unaffected by changes in the output state of polarization as produced by adjustment of the polarization controller PC3.

![Tunable Single-Mode Fiber Depolarizer](image1)

**Fig. 7.** Experimental setup to measure the degree of polarization. LD, laser diode; O, objective lens; DC, single-mode fiber $2 \times 2$ directional coupler; PC1 and PC2, polarization controllers; C, compensator; A, analyzer, PM, optical powermeter.

![Tunable Single-Mode Fiber Depolarizer](image2)

**Fig. 8.** Experimental setup for application of a tunable depolarizer in a polarization-sensitive system. LD, laser diode; O, objective lens; DC, single-mode fiber directional coupler; PC’s, polarization controllers; SMF, single-mode fiber; A, analyzer; PM, photodetector with preamplifier; O/P, output to oscilloscope.

The experimental results clearly indicate that the tunable depolarizer can change the degree of polarization of the input light between 99.8% and 1.15%, confirming the theoretical analysis. Better results were not observed owing to the limited sensitivity of the receiving equipment. Our experiments also prove that the polarization noise of a polarization-sensitive fiber-optic system can be vastly diminished by depolarizing of the light with this tunable depolarizer.

Because of polarization drift in the fiber loop, the degree of polarization at the output will change with time. This polarization drift, caused by environmental fluctuations, is a low-frequency effect. With this depolarizer constructed on an optical table and protected by a cover isolated from external disturbances, the polarization drift time was quite long (several minutes), allowing experiments to be conveniently done. If desired, the degree of polarization...
could be monitored for changes by using a $2 \times 2$ coupler tapping a small part of the output light and measuring the degree of polarization with a compensator–analyzer combination.

5. Conclusion

We have described a new concept and structure for depolarizing a coherent light wave, based on a single $2 \times 2$ coupler with a recirculating delay-line scheme. The theoretical model was established on the basis of the coherence matrix. The reduction of the degree of polarization of a narrow-band light source was examined theoretically and experimentally. The experimental results support the model. The experiments proved that the degree of polarization could be tuned over the range 99.8% and 1.15%. Results were limited by the test instruments. The experiments also show that this tunable depolarizer successfully reduces the polarization noise in a polarization sensitive single-mode fiber system. The features of this depolarizer are (1) all single-mode fiber components; (2) a simple and low-cost structure; (3) no need for an expensive light source (such as the superluminescent diode required in the Lyot depolarizer); (4) possible high output power, because a high-power laser source can be used; (5) tunable degree of polarization; and (6) no required input polarization axis alignment. Many applications can be found in laboratory experiments, for example, the testing for polarization dependence of fiber-optic sensors and fiber-optic components.

References