ABSTRACT

Fiber optic depolarizers both Lyot type and non-conventional one made from single section of a Hi-Bi fiber have been fabricated and tested. Effect of critical design parameters like azimuth of the input polarization, source spectral width, and length of the polarization maintaining fiber on the correlation between the two orthogonal eigen modes are analyzed. These parameters are crucial for reduction of residual degree of polarization resulting miniaturization of the device. Performance results for both types of depolarizers have been compared. It has been shown with precision control of design parameters it is possible to obtain low value of DOP and ER even with small length of the PM fiber. Residual degree of polarization of <1% and extinction ratio of 0.2 dB are measured with diminution of length up to 15cm for non conventional whereas 60cm is required for Lyot depolarizer.

Keywords: Degree of Polarization (DOP), Extinction Ratio (ER), Polarization Maintaining (PM) fiber, Device Under Test (DUT), High Birefringent (Hi-Bi) fiber

1. INTRODUCTION

Fiber optic depolarizers are very attractive devices used in interferometric fiber optic sensors in general and FOG in particular. Depolarization of light is essential in devices where reduction of polarization coupling noise is a key issue. Usually the commercial available fiber optic depolarizers are fabricated based on Lyot condition, where two birefringent fibers with their fast and slow axes aligned at 45° with each other and maintain a length ratio of 1:2. Polarization axes alignment and length ratio, between two fibers are important parameters that determines the performance of a fiber optic depolarizer based on Lyot condition.

Basic requirement of depolarization of a highly polarized light is a birefringent medium but nevertheless it depends on the source characteristics such as source spectral width, length of the birefringent medium over which light is allowed to travel, fiber group delay difference between the two polarization modes and input conditions. The polarization dispersion rather than birefringence is essential to calculate degree of polarization. The differential group velocities associated with the polarization modes of the Hi-Bi lead to the depolarization of the broadband source. Depolarization effect in the birefringent fiber to some extent can be observed with any source for which the group delay difference exceeds the coherence time of the source.

In this paper we have designed, fabricated, and tested high performance depolarizers and compared Lyot and non-conventional one. Section 2 gives the mathematical formalism to calculate DOP at the output of the fiber and accordingly design parameters are optimized. Section 3 describes fabrication and testing of the depolarizer. The variation of DOP with azimuth of input polarization and length of the PM fiber are observed. Simulation results and experimental results are discussed in Section 4.

2. THEORETICAL ANALYSIS

The configuration for the depolarizer of Lyot type and non-conventional type are shown in Fig 1 and Fig 2 where linearly birefringent HiBi fibers are considered. The two eigen polarization modes of the HiBi fiber are excited by launching polarized light at an angle of θ, with respect to fast (or slow) axes. But physical perturbations, couple power between the polarization modes that leads to non zero residual polarizations.

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Here it is assumed that there is no mode coupling between the polarization modes. Inside the fiber propagation constants of polarization modes are functions of the input light frequency $\omega$.

### 2.1 Non-conventional depolarizer

The input light incident to the depolarizer is linearly polarized and is given as follows.

$$
\begin{align*}
\mathbf{E}_\text{in} &= \begin{bmatrix} E_{x}^{\text{in}}(t) \\ E_{y}^{\text{in}}(t) \end{bmatrix} = \begin{bmatrix} \cos(\theta_p) \\ \sin(\theta_p) \end{bmatrix} e^{i\phi_p(t)} e^{i\omega t} 
\end{align*}
$$

(1a)

where the time varying input light is expressed as a complex analytic signal given by

$$
e(t) = 2 \int_0^\infty V(\omega)e^{i\omega t} d\omega$$

(1b)

$$\langle e(t)e^{*}(t') \rangle = 1$$

(1c)

The optical source considered has spectral intensity $V(\omega)$ and center frequency $\omega_0$.

Where $L_c$ is coherence length of the source and $L_d$ is the depolarization length, which is defined as the length over which the two polarization modes inside the fiber loses correlation and still interfere upon recombination.

$$L_c = \frac{\lambda^2}{\Delta\lambda}$$

The propagation in the fiber is given by the transfer matrix

$$
\mathbf{L} = \begin{bmatrix} e^{-\beta_x L} & 0 \\ 0 & e^{-\beta_y L} \end{bmatrix}
$$

(2)

where $\beta_x$ and $\beta_y$ are the propagation constants of the two eigen modes of the fiber.

Following few mathematical steps the output time varying electric field is given by

$$
E_x(t) = \cos(\theta_p) \int_0^\infty V(\omega) e^{i(\omega-\beta_x L)t} d\omega
$$

(3)

For a broad band source expanding $\beta(\omega)$ in Taylor's series

$$
\beta(\omega) = \beta_{x0} + (\omega - \omega_0)\beta_{x0} + \Lambda
$$

(4)

Where, $\beta_{x0} \equiv \beta_x(\omega_0)$ and $\beta_{x0} = \frac{d\beta_x}{d\omega}|_{\omega_0}$

Considering only up to first order

$$
E_x(t) = \cos(\theta_p)e^{i(\omega-t-\beta_x L)} e^{i(\omega-t-\beta_x L)}
$$

(5)

Similarly,

$$
E_y(t) = \sin(\theta_p)e^{i(\omega-t-\beta_{y0} L)} e^{i(\omega-t-\beta_{y0} L)}
$$

(6)

Degree of polarization is defined as the fraction of the intensity of light polarized ($I_{pol}$) to the total intensity ($I_{tot}$) and is determined from coherency matrix $J$ of the output light.
\[ J = \left< E^o, E^{o*} \right> = \begin{bmatrix} E^o_x E^{o*}_x \\ E^o_y E^{o*}_y \\ E^o_z E^{o*}_z \\ E^o_x E^{o*}_y \end{bmatrix} \]  

(7)

Where ‘*’ signifies Hermitian transpose.

Degree of polarization is given by:

\[ DOP = \frac{I_{pol}}{I_{tot}} = \left[ 1 - \frac{4 \det J}{(\text{Tr} J)^2} \right]^\frac{1}{2} \]  

(8)

\[ \det J = \frac{1}{4} \sin^2 (\theta_p) \left( S_0^2 - S_1^2 \right) \]  

(9)

Where, \( S_0 = 2 \int_0^\infty \left| \gamma (\omega) \right|^2 d\omega \) 

(10)

\[ S_1 (L) = 2 \int_0^\infty \left| \gamma (\omega) \right|^2 \cos (\omega_0 - \omega) \delta \tau_s L d\omega \]  

(11)

\[ \delta \tau_s = \frac{d \Delta \beta}{d \omega}, \quad \Delta \beta = \beta_y - \beta_x \]

Parameter \( S_0 \) can be shown equivalent to incident light power

\[ S_0 = \text{Tr} \left< E^m, E^{m*} \right> \]  

(12)

and parameter \( S_1 \) depends on light source spectral distribution, fiber group delay difference, and fiber length.

Using eqs (9), (10), and (11) the final expression for DOP is

\[ DOP(\theta_p) = \left[ 1 - \left( \gamma \right) \sin^2 (\theta_p) \right]^\frac{1}{2} \]  

(13)

Equation (12) yields DOP at the output of the single section of the Hi-Bi fiber. Where \( \gamma (L) = \frac{S_1 (z)}{S_0} \) defines the mutual correlation function between the two eigen polarization modes and takes minimum value for equally split powers between two polarization modes. Absolute value of the correlation function \( |\gamma| \) is a function of light source characteristics and incident conditions. With light incident at 45° to the fast and slow axes, degree of polarization solely depends on \( |\gamma| \) and approaches zero, when absolute value of mutual correlation function tends to zero. The reliance of DOP on the above mentioned factors establishes the design parameters. So critical design parameters are azimuth of the electric vector of the input light, fiber length, and coherence time of the source.

### 2.2 Lyot depolarizer

The degree of polarization for the Lyot depolarizer is obtained as:

\[ DOP(\theta_p) = \left( \cos^2 (\theta_p) \gamma^2 (L_2) + \frac{1}{2} \sin^2 (\theta_p) + \gamma^2 (L_1) + \gamma^2 (L_1) \right) \]  

Fig 2
\[-\gamma(L_1 + L_2)\gamma(L_2 - L_1)\cos \Delta \beta_0 L_1 + \frac{1}{2}\left[\gamma^2(L_1 + L_2) + \gamma^2(L_2 - L_1)\right]\]
\[-\sin 2\theta \gamma(L_1 + L_2)\gamma(L_1 - L_2)\cos \Delta \beta_0 L_1 \sqrt{2}\]

(14)

where $\Delta \beta_0 = \beta_0 (\omega_0) - \beta_0 (\omega_2)$

The Lyot depolarizer is obtained with two pieces of Hi-Bi fibers with their birefringent axes aligned at 45° and length ratio of 1:2 is maintained between $L_1$ and $L_2$ for minimal necessity. With this condition satisfied the output degree of polarization becomes independent of the azimuth of the input polarization $\gamma(\theta)$. From equation (14) for any azimuth of the input polarization to get DOP zero at the output it requires:

$\gamma(L_1) = 0, \gamma(L_2) = 0, \gamma(L_1 + L_2) = 0$ and $\gamma(L_2 - L_1) = 0$

The degree of coherence $\gamma(L)$ for for Gaussian source is given as

$\gamma(L) = \exp \left[\left(-\frac{\Delta \delta \tau}{2\sqrt{\ln 2}}\right)^2\right]$

(15)

where $\Delta \delta$ is spectral width of the source and $\delta \tau$ is the differential group delay of the fiber. Depolarization length is given as $L_d = \frac{2\sqrt{\ln 2}}{\Delta \lambda \delta \tau}$

3. FABRICATION

Fabrication setup

The fabrication setup comprises a semi automatic active alignment system having four degrees of freedom ($x, y, z, \theta$), splicing machine, broadband sources, polarizer, lightwave polarization analyzer (Agilent 8509C) and extinction ratio meter (PEM 320). The fiber used for experiment is a polarization maintaining fiber having large birefringence ($B$) given by $4.2 \times 10^{-4}$; beat length ($L_b$) is 3.7mm at 1550 nm and differential group delay $\delta \tau$ is $1.66ns/Km$. Depolarizers of both type are fabricated with high birefringent fiber. The critical factor is the angular orientation with respect to the slow and fast axis of the high birefringent fiber, at which light is incident to the fiber. The figure depicts the experimental setup used. It consists of broadband source, in our case, which is superluminescent diode (SLD), precision alignment system, and light wave polarization analyzer (LPA) used for characterization of the depolarizer. The polarized broadband sources used for the experiment are SLDs with central wavelengths ($\lambda_0$) 1545.442 nm and 1543.398 nm and spectral widths ($\Delta \lambda$) 36.29 nm and 49.415 nm respectively. Spectrums of both SLDs are examined on spectrum analyzer, which were almost Gaussian.

Fig 3 illustrates the experimental setup used for non-conventional depolarizer. With the help of alignment system light is coupled to the fiber with precision rotation. The length of the PM fiber used for the experiment is 2m, which is very large compared to the depolarization length $L_d$ observed with both the sources used. So for a good approximation mutual correlation function is taken to be zero. The output is allowed to fall on the detector of the light wave polarization analyzer and degree of polarization at the output of the fiber is observed with the LPA. The DOP at the output of the depolarizer is constantly monitored for various input azimuths. The curve is plotted between DOP and azimuth of the input light. The minimum DOP was observed at azimuth of 45°. In the 2nd experiment we have used the same setup but different lengths of fibers. With this experiment we have shown with a broadband source, if there is a precision control of azimuth of the input light (equal excitation of both polarization modes) with a small section of high birefringent fiber we can get a very low DOP. The repeatability of the DOP values is also observed.

Fig 4 portrays the experimental setup for Lyot depolarizer. The experiment is similar to the 2nd part of the above one. For comparison of non-conventional type and Lyot type, length of both pieces of PM fiber was cutback periodically but length ratio of 1:2 between them is maintained. The experiment was performed with both broadband sources and DOP at the output is lettered.
4. RESULTS

The results obtained for non-conventional depolarizer are shown below. Theoretical and experimental findings are differentiated by solid line and stared dots respectively. Fig 5 describes effect of length of the fiber on the DOP for the two broadband sources 36.29 nm and 49.415 nm. Fig 6 shows variation of DOP with azimuth of the input light. There is good correlation between theoretical and experimental values. The minimum DOP observed is at azimuth of 45°. Fig 7 illustrates effect of source spectral width on performance of the depolarizer with parametric variation of length.
The simulation and experimental results for Lyot depolarizer are shown in Fig 8, which depicts variation of DOP with length of the fiber used. In all the experiments carried out, the results are in well agreement with theory.

5. CONCLUSION

The performance of the fiber optic depolarizer both for non conventional and Lyot depolarizer with various critical parameters is investigated. The residual DOP <1% is achieved with PM fiber 15cm for non conventional depolarizer and 60cm for Lyot type with the broad band polarized source. For larger linewidth 49.415 nm, for PM fiber length of 15cm we obtained DOP of 0.5%, where as for lower line width 36.29nm, for the same length we obtained DOP of 1%. The residual value may be attributed to polarization mode coupling between the two eigen modes. For practical applications non-conventional depolarizer is more suitable as almost same DOP is obtained for smaller size of the device in comparison to the Lyot depolarizer. Being small in size it facilitates miniaturization and can be easily incorporated in devices such as fiber optic interferometric sensors where polarization control is a key issue. But limitation with this depolarizer is, the input light to be linearly polarized.

REFERENCES