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Use of fiber helical coils to obtain polarization insensitive fiber devices

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ABSTRACT

Using a new model for the description of the birefringence of a helical coil, it is shown that the birefringence effect on the signal polarization introduced by a fiber device can be canceled out by introducing two helical coils at the required orientation. Experimental results obtained using this modification in a polarization insensitive device (optical isolator) and in a non-polarization insensitive device working at two different wavelengths (wavelength division multiplexer) are presented and discussed. Such modified devices were used in the construction of an erbium-doped fiber amplifier (EDFA) with a full control of the input signal and pump states of polarization.

1. Introduction

The construction of fiber systems built with single-mode fibers, such as fiber optic interferometric sensors and coherent communication systems, relies either on the full knowledge of the polarization state of the light at specific points within the fiber system, and/or on the assumption that the sensing parameter is the sole responsible for the variation of the state of polarization of the signal. Additionally, the design of these fiber systems is often defined by their polarization requirements, given that residual birefringence of single-mode fibers does not preserve the polarization state of light. In some cases, such limitations have led the designers to use only polarization maintaining fibers [1], or special set ups that cancel the unwanted birefringence contribution and allow the implementation of the techniques developed to extract the data [2–5].

Simpler solutions include the use of polarization controllers (PC) to adjust the state of polarization of the light signal. But, since PCs are built with three non-regular fiber windings, their performance cannot be predicted, unless a priori hypotheses on their performance are assumed [6]. Thus, to optimize polarization control two or more PCs are used and adjusted by trial and error [7].

We modified this simpler approach using a new theoretical model developed for a helically wound fiber [8]. This model is based on a careful theoretical and experimental study of the strain-induced birefringence of a helical fiber coil, and includes also the geometrical contribution due to the out-of-plane trajectory described by the light beam traveling along the fiber. The precision of the method here proposed results from the use of this theoretical model.

In this work we demonstrate that two identical helical windings with opposite handedness, built with standard optical fiber, can be used to control the state of polarization of the light beam traveling along the fiber system. If required, this polarization control can be accomplished at each of the system's components, and at the sensing [9] or gain fiber. Such control operates for devices that work over one or more spectral bands such as isolators or pump multiplexers, and does not require the use of polarization maintaining (PM) fibers. We built an erbium-doped fiber amplifier (EDFA), using a combination of two modified devices (isolator and pump multiplexer). The state of polarization of light at specific points (input ends of pump multiplexer and gain fiber) of this fiber system satisfies the operation requirements necessary to analyze the amplification of polarized signals. Using a double helical winding we can also demonstrate that the linear state of polarization of the signal at the gain fiber input was maintained for the amplified output signal. These results validate our technique.

2. Theory

A helix is a uniform out-of-plane curve characterized by its curvature and torsion. It has been shown that due to their geometrical and strain contributions the birefringence of the helical coil described by matrix

$$\mathbf{M}_H = \mathbf{R}(-\theta)\mathbf{R}(b\tau + \beta)\mathbf{M}(\varepsilon, \delta)\mathbf{R}(\theta) \quad (1)$$

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can become the dominant birefringence [8]. In Eq. (1) θ is the azimuth angle of the helical coil, the term $b\tau$ corresponds to the gyration of the birefringence axes due to the helix torsion τ, b is a constant ($\approx$1), β is the topological rotation angle of the reference frame (introduced by the out-of-plane trajectory followed by the light beam [10]).

The rotation matrices $\mathbf{R}(\theta)$ and $\mathbf{R}(b\tau + \beta)$ have the same form but different rotation angle, and using a 3×3 notation [11], can be written as

$$\mathbf{R}(\theta) = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{2}$$

M(ε,δ) is the birefringence matrix of an elliptical retarder with elliptical birefringence angle ε, and retardation angle δ linearly proportional to τ [12]

$$\mathbf{M}(\varepsilon,\delta) = \begin{pmatrix} \cos^2\delta + \cos 4\varepsilon \sin^2\delta & \sin 2\varepsilon \sin 2\delta & \sin 4\varepsilon \sin^2\delta \\ -\sin 2\varepsilon \sin 2\delta & \cos 2\delta & \cos 2\varepsilon \sin 2\delta \\ \sin 4\varepsilon \sin^2\delta & -\cos 2\varepsilon \sin 2\delta & \cos^2\delta - \cos 4\varepsilon \sin^2\delta \end{pmatrix}. \tag{3}$$

2.1. Double helical coil

When two helical fiber coils are used, being the second one identical to the first one, but with opposite handedness, the matrix description of this combination is given by the product

$$\begin{aligned} \mathrm{M}_{2B} &= \mathbf{M}_{H1}\mathbf{M}_{H2} \\ &= \mathbf{R}(-\theta_1)\mathbf{R}(b_1\tau + \tau_0 + \beta)\mathbf{M}(\varepsilon,\tau)\mathbf{R}(\theta_1)\mathbf{R}(-\theta_2)\mathbf{R}(-b_2\tau + \tau_0 \\ &\quad - \beta)\mathbf{M}(\varepsilon,-\tau)\mathbf{R}(\theta_2) \end{aligned} \tag{4}$$

where sub-indices 1 are 2 are used for the parameters related with coils 1 and 2, respectively. Constants b_1 and b_2 have different values because most real fibers present a residual torsion (here denoted as τ_0), and their behavior is different for right- or left-handed twists [13].

Varying the relative alignment of coil 2 with respect to coil 1 it is possible to get

$$\mathbf{R}(\theta_1)\mathbf{R}(-\theta_2)\mathbf{R}(-b_2\tau + \tau_0 - \beta) = \mathbf{1}. \tag{5}$$

The product of the elliptical retarders wound in opposite directions also is reduced to a unitary matrix

$$\mathbf{M}(\varepsilon,\delta)\mathbf{M}(\varepsilon,-\delta) = \mathbf{1}, \tag{6}$$

and using Eq. (6) we can see that $\theta_1 - \theta_2 - b_2\tau + \tau_0 - \beta = 0$. Hence

$$\mathbf{R}(-\theta_1)\mathbf{R}(b_1\tau + \tau_0 - \beta)\mathbf{R}(\theta_2) \approx \mathbf{1} \tag{7}$$

when the difference between right- and left-handed torsion is small. In our experience, this condition is fulfilled by fiber SMF-28 or SMF-28e [13].

According to the previous matrix description, the combination of two helical coils with opposite handedness can be used to cancel out the polarization dependence introduced by the fiber coils. Since, according to Poincaré Equivalence Theorem (which states that any optical element containing no absorbing components can be described using an equivalent optical model consisting of one linear retarder and one rotator only) [14], it is evident that using different relative orientations between the helical coils it is possible to deliver any specific state of polarization.

3. Experiment

3.1. Optical isolator

Initially we worked with a polarization insensitive optical isolator. In this case one helical coil was built using the input fiber arm; using the output pigtail, the second coil was built as the first one, keeping the same curvature and pitch, but opposite handedness (Fig. 1). The matrix description for this modified optical isolator is

$$\mathbf{M}_{H1}\mathbf{I}\mathbf{M}_{H2}, \tag{8}$$

where $\mathbf{I}$, the identical matrix, corresponds to the polarization insensitive polarization isolator without the fiber pigtails.

A polarization analyzer (Agilent 8509C) was used to measure the input and output states of polarization for each signal wavelength (the complete optical set up was described in Ref. [15]).

3.2. Pump multiplexer (WDM)

A 980/1550 multiplexer (WDM) is a polarization sensitive device with two input ports, one for the pump (980 nm) and the other one for the signal (1530–1560 nm). This device combines both beams into a single fiber. The modified WDM, is shown in Fig. 2.

A set of two identical helical coils with different handedness was built along the signal arm and a similar pair was built along the pump arm. In Fig. 2 we have drawn only the 90% output port.

The matrix description for the modified signal path is

$$\mathbf{M}_{H1}\mathbf{M}_{H2}\mathbf{M}_{WDM}\mathbf{M}_{ofs}, \tag{9}$$

where for each signal wavelength, $\mathbf{M}_{H1}$ and $\mathbf{M}_{H2}$ are the polarization matrices of the two helical coils, $\mathbf{M}_{WDM}$ is the polarization matrix of the multiplexer without the fiber pigtails and $\mathbf{M}_{ofs}$ is the polarization matrix of the output fiber pigtail.

The matrix description for the modified pump path is

$$\mathbf{M}_{H1}\mathbf{M}_{H2}\mathbf{M}_{WDM}\mathbf{M}_{ofp}, \tag{10}$$

where for the pump wavelength, $\mathbf{M}_{H1}$ and $\mathbf{M}_{H2}$ are the polarization matrices of the two helical coils, $\mathbf{M}_{WDM}$ is the polarization matrix of the multiplexer without the fiber pigtails, and $\mathbf{M}_{ofp}$ is the polarization matrix of the output fiber pigtail.

For the signal (or pump), the orientation of the double helical coil must be adjusted to deliver an output signal that combined with the additional birefringence of the output pigtail (for the wavelength under consideration) reproduces the input circular polarization state.

The state of polarization of the input light beam (signal or pump wave) was measured using two different instruments. A polarization analyzer Agilent 8509C, was used for the signal range (1520–1570 nm), and a polarimeter ThorLabs PA460 for the pump wave (980 nm). As we can see in Fig. 2, the optical set ups used for both wavelength bands were similar.

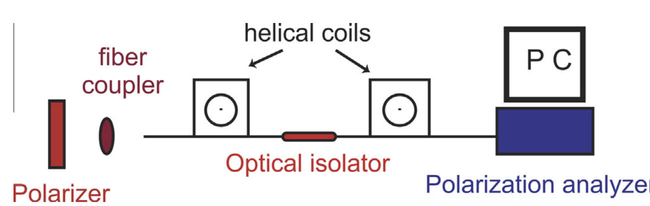

Fig. 1. The input fiber arm was used to build one helical coil. The other helical coil keeping the same geometrical parameters (curvature and pitch) but opposite handedness was built with the output pigtail.