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Magnetically-induced circular-polarization-dependent loss of magneto-optic fiber Bragg gratings with linear birefringence

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ABSTRACT

The concept of magnetically-induced circular-polarization-dependent loss (MCDL) for magneto-optic fiber Bragg gratings (MFBGs) is introduced. The magnetic field dependency of MCDL for linearly birefringent MFBGs is simulated by use of the equivalent theoretical model given in the paper. This model is mainly composed of an elliptical polarization extractor and a couple of isotropic fiber Bragg gratings (FBGs) with different effective refractive indices. It is shown by simulation that, (1) when the magneto-optic-to-grating coupling coefficient ratio is less than 0.1, the peak MCDL is proportional to applied magnetic induction; (2) the MCDL method is more suitable for the magnetic field measurement than the conventional polarization dependent loss (PDL) for the linearly birefringent MFBGs. As an example, the MCDL of an erbium-doped MFBG (Er-MFBG) is measured and the experimental data are in agreement with the theoretical results. The effective Verdet constant for the Er-MFBG is about −11 rad/(T·m) and the peak MCDL is up to 1 dB at 1.15 T.

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1. Introduction

By means of magnetostrictive or magneto-optic (MO) Faraday effects, fiber Bragg gratings (FBGs) can be used for magnetic control and measurement, with applications to optical fiber communication and fiber sensing [1–5]. The alternating current (AC) and direct current (DC) magnetic field responses of conventional FBGs have been measured by a high sensitive interferometer [3] and the polarization depended loss (PDL) method [5,6], respectively. In fact, only the low linearly birefringent FBGs can be applied to the PDL-based magnetic field measurement [7]. Recently, we investigated the spectrum shift of an erbium-doped FBG resulting from the magnetic tunability of photonic band-gap by the so-called direct edge detection [8].

The MO-based FBGs are also named as magneto-optic fiber Bragg gratings (MFBGs) [8,9], which may be fabricated by utilizing the permanent photoinduced high index changes of terbium (or other rare earth ions) doped alumino-silicate optical fibers [10]. Just like the conventional FBGs, MFBGs may be classified as uniform and nonuniform gratings. A non-uniformly magnetized MFBG is also named magnetically-induced nonuniform FBG (MnFBG). It is shown that, a chirped MnFBG may be equivalent to a non-magnetic chirped FBG, whose chirp phase is the sum of the initial phase of the MnFBG and the integral of magneto-optical coupling coefficient along the whole grating [11]. In general, the coupled-mode theory is applied to the case of uniform MFBGs [9]; for nonuniform MFBGs, the numerical calculation is usually implemented by the piecewise uniform method [12], especially for the cases with linear birefringence [7].

In this paper, an equivalent theoretical model of nonuniform MFBGs with linear birefringence is proposed by the eigenmode analysis and used to build up the OptiSystem simulation system of Gaussian apodized MFBGs with linear birefringence. On the other hand, for further improving the magnetic field response of MFBGs, the concept of magnetically-induced circular-polarization-dependent loss (MCDL) is defined, which is related to the left- and right-handed circularly polarized (LCP and RCP) light. It is shown by simulation that, the peak MCDL is proportional to applied magnetic field and insensitive to linear birefringence. The MCDL method can be regarded as a promising alternate of the conventional PDL method for the MFBG-based magnetic field measurement. As an example, the MCDL of an erbium-doped MFBG (Er-MFBG) is measured and the experimental data are in agreement with the theoretical results.

2. The equivalent theoretical model of linearly birefringent MFBGs

For isotropic MFBGs (without linear birefringence), the eigenmodes are LCP and RCP light. The Faraday rotation of transmitted light is enhanced at the edges of an isotropic MFBG bandgap and can be applied to the magnetic field measurement.

In the presence of linear birefringence inside uniform MFBGs, with the grating perturbation $\Delta n(z) = 2\Delta n_g \cos(2\pi z/\Lambda)$, the slowly varying envelop $A_p^{(s)}(z,t)$ can be expressed as follows [9]:

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$$\frac{\partial A_p^{(s)}(z,t)}{\partial z} = \mathrm{i}s\delta_{pl}A_p^{(s)}(z,t) + \mathrm{i}s\kappa_{p\bar{p}}A_{\bar{p}}^{(s)}(z,t)e^{\mathrm{i}s(\beta_{0\bar{p}}-\beta_{0p})z} + \mathrm{i}s\kappa_g A_p^{(-s)}(z,t)\mathrm{e}^{-2\mathrm{i}s(\beta_{0l}-\beta_B)z} \quad (1)$$

where $s = \pm 1$ correspond to the $+z$ and $-z$ propagating light respectively, the subscript p and $\bar{p}$ represent the x and y polarization components, $\beta_{0p} = k_0 n_{eff,p}$, $n_{eff,x} = n_{eff} + \Delta n_b$, and $n_{eff,y} = n_{eff} - \Delta n_b$, in which n_{eff} and Δn_b are, respectively, the average effective refractive index and linear birefringence of fiber; $\delta_p = \beta_p(\omega_0) - \beta_B = (\omega_0 - \omega_B)n_{eff}/c$ with $\omega_B = \beta_B c/n_{eff}$ and $\beta_B = \pi/\Lambda$, in which c is the velocity of light in vacuum and Λ is the grating period; the magneto-optic coupling coefficient $\kappa_{p\bar{p}} = k_0\Delta\varepsilon_{rp\bar{p}}^{(0)}/(2n_{eff})$ with $\Delta\varepsilon_{rxy}^{(0)} = [\Delta\varepsilon_{ryx}^{(0)}]^* = \mathrm{i}f_1M_{0z}$, in which f_1 and M_{0z} are respectively the first-order magneto-optical coefficient and the z-component of magnetization; and $\kappa_g = k_0\Delta n_g$ is the grating coupling coefficient, in which Δn_g is the amplitude of refractive index perturbation for the grating, and k_0 is the propagation constant in vacuum.

According to Eq. (1), there exist two orthogonal eigen states of polarization (SOP) in uniform MFBGs as follows [7]:

$$\mathbf{P}_+ = \frac{1}{\sqrt{1+\eta^2}}\begin{pmatrix}1\\ \mathrm{i}\eta\end{pmatrix}, \quad \mathbf{P}_- = \frac{1}{\sqrt{1+\eta^2}}\begin{pmatrix}\eta\\ -\mathrm{i}\end{pmatrix} \quad (2)$$

where the ellipticity $\eta = (-\kappa_b \pm \kappa)/\kappa_m$ with $\kappa_b = k_0\Delta n_b$, $\kappa = \sqrt{\kappa_b^2 + \kappa_m^2}$ and $\kappa_m = k_0\Delta n_m = V_B B$, in which the MO coupling coefficient κ_m is equal to the product of the Verdet constant V_B and magnetic induction B, also related to the magnetically induced circular birefringence $\Delta n_m = f_1M_{0z}/(2n_{eff})$. For a typical Tb-doped MFBG with $V_B = 32$ rad/(T·m) [13] and $\Delta n_g = 10^{-4}$, the magnetooptic-to-grating coupling coefficient ratio (MGR) is $r_{mg} = \Delta n_m/\Delta n_g \approx 0.1$ under the applied magnetic field of 1.5 T.

From Eq. (2), the principle axes of the two eigen SOPs are, respectively, parallel to the slow and fast axes of linear birefringence, corresponding to the propagation constants $\beta_\pm = n_{eff}k_0 \pm \kappa$. In other words, a linear birefringent MFBG under uniform magnetic field has an elliptical birefringence of $\Delta n_e = \sqrt{(\Delta n_b)^2 + (\Delta n_m)^2}$. For the two eigen SOPs, the equivalent refractive indices and Bragg wavelengths are different, that is, $n_{eff}^{\pm} = n_{eff} \pm \Delta n_e$ and $\lambda_B^{\pm} = 2n_{eff}^{\pm}\Lambda$. According to the piecewise-uniform grating model [12], the two eigen SOPs of any nonuniform MFBG are fixed along the whole grating only if its elliptical birefringence is constant, i.e. independent of the refractive index changes of grating. Thus, a uniformly magnetized MFBG can be analyzed by means of the eigen SOPs and then an equivalent theoretical model of linearly birefringent MFBGs is put forward, as illustrated in Fig. 1. The elliptical eigen SOP components are firstly extracted from the input light (note that any polarized light can be regarded as the combination of two orthogonal eigenmodes), and then pass through the two isotropic nonuniform FBGs (FBG_1 and FBG_2) with the equivalent refractive indices $n_{eff}^{\pm} = n_{eff} \pm \sqrt{(\Delta n_b)^2 + (\Delta n_m)^2}$ respectively. The length L and the refractive index distribution $\Delta n(z)$ of FBG_1 and FBG_2 are the same as those of the original MFBG. Finally, the transmitted or reflected eigen SOP components from FBG_1 and FBG_2 are recombined into the output of the MFBG.

3. OptiSystem simulation system of linearly birefringent MFBGs

In what follows, the above-mentioned theoretical model will be performed by the OptiSystem simulation software. Unfortunately, the elliptical polarizer mentioned in the theoretical model is unavailable in the software. Here, we present a scheme capable of simultaneously extracting two eigen SOP components. The elliptical polarization extractor consists of a polarization splitter, a polarization rotator, a coupler, a phase shift, and a couple of polarization controllers, as shown in Fig. 2. The optical field output from this extractor can be deduced from the Jones matrices of the optical devices as follows:

$$\begin{pmatrix}1 & 0\\ 0 & -\mathrm{i}\end{pmatrix}\begin{pmatrix}\sqrt{1-C} & \mathrm{i}p\sqrt{C}\\ \mathrm{i}p\sqrt{C} & \sqrt{1-C}\end{pmatrix}\begin{pmatrix}E_{inx}\\ E_{iny}\end{pmatrix} = \sqrt{1-C}\begin{pmatrix}E_{inx} + \mathrm{i}p\sqrt{\frac{C}{1-C}}E_{iny}\\ p\sqrt{\frac{C}{1-C}}E_{inx} - \mathrm{i}E_{iny}\end{pmatrix} \quad (3)$$

Clearly, two output ports of this extractor respectively correspond to right- and left-handed elliptically polarized light with the ellipticity $\eta = \sqrt{C/(1-C)}$ (C is the coupling coefficient). For the optical coupler, $p = 1$ and $C = \eta^2/(1+\eta^2)$.

In the OptiSystem simulation system of linearly birefringent MFBGs, as illustrated in Fig. 2, a couple of optical adders are, respectively, used to synthesize the transmitted or reflected light at the outputs of the MFBG. The transmission and reflection spectra are monitored by the optical spectrum analyzer (OSA), and an optical filter analyzer is also useful for the phase spectrum. In addition, the parameters of FBG_1 and FBG_2 used in simulation include the equivalent refractive indices $n_{eff}^{\pm}$, the central wavelengths $\lambda_B^{\pm}$, the grating's length L, and the DC and AC coupling coefficients Δn_{dc} and Δn_{ac}.

4. Magnetically-induced circular-polarization-dependent loss

Firstly, the magnetically-induced circular-polarization-dependent loss is defined in unit of dB as follows:

$$\mathrm{MCDL}(\lambda) = \left|10 \times \log_{10}\frac{T_{\mathrm{RCP}}(\lambda)}{T_{\mathrm{LCP}}(\lambda)}\right| \quad (4)$$

where $T_{\mathrm{RCP}}(\lambda)$ and $T_{\mathrm{LCP}}(\lambda)$ are the transmission spectra of a MFBG for the input RCP and LCP light, respectively. By use of the OptiSystem simulation system in Fig. 2, $T_{\mathrm{RCP}}(\lambda)$ and $T_{\mathrm{LCP}}(\lambda)$ for linearly birefringent MFBGs is easily obtained and then the MCDL spectrum can be calculated from Eq. (4), as plotted in the insert of Fig. 3. The MFBG's parameters used in the OptiSystem simulation are listed in Table 1. The OSA's resolution is 0.1 nm. From Fig. 3, the peak MCDL is 3.29 dB at the wavelengths of 1549.935 nm and 1550.079 nm. It should be pointed out that, by using the piecewise uniform method, we also calculated the transmission spectra of the Gaussian apodized MFBG, and the numerical results are in agreement with the simulation data obtained from the OptiSystem simulation system. The MFBG's OptiSystem simulation system is also applied to the bi-directional transmission, such as the MFBG-based Sagnac interferometer [14].

Fig. 3 shows the magnetic field dependencies of the peak MCDL and PDL for the cases with $\Delta n_b = 0$ and $\Delta n_b = 10^{-5}$. It can be seen from Fig. 3 that, the peak MCDL and peak PDL are equal only for isotropic MFBGs and the existence of linear birefringence is responsible for an intrinsic PDL of 3.3 dB at $r_{mg} = 0$; by comparison, the peak MCDL is extremely close to zero in this case. On the other hand, when $r_{mg} < 0.1$, the influence of linear birefringence on the peak MCDL is almost negligible and the maximum error is less than 0.12 dB relative to the case of $\Delta n_b = 0$. In this case, the peak MCDL, corresponding to a fixed wavelength, is proportional to applied magnetic field, just as in the isotropic MFBG. In a word, the MCDL has the advantage of being insensitive to linear birefringence over the conventional PDL and is more suitable for magnetic field measurement and sensing.

5. Experimental results and discussion

In the experiment, the magnetically-induced circular-polarization-dependent loss (MCDL) is measured for an erbium-doped

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