Front. Optoelectron. China 2010, 3(4): 359–363
DOI 10.1007/s12200-010-0121-x

RESEARCH ARTICLE

Simulation model of magneto-optic fiber Bragg gratings and its applications in Sagnac interferometers

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Abstract According to the symmetry of transmission matrix for non-uniform magneto-optic fiber Bragg gratings (MFBGs), the simulation model of the non-uniform MFBGs with bidirectional injection of light has been presented for the Optisystem software. The simulation model is verified by comparing with the Matlab numeric results using the piecewise-uniform MFBG model. As an example, the polarization-dependent loss (PDL) of an MFBG-based Sagnac interferometer (MSI) is analyzed in detail. Simulation results indicate that the magnetic field sensitivity of the MSI system can be improved by optimizing the coupling coefficient of the coupler, and the maximum of peak PDL is up to three times that of the single MFBG structure. The simulation model proposed in the paper is useful for the design of MFBG-based optical information devices.

Keywords magneto-optic fiber Bragg grating (MFBG), Optisystem simulation, polarization-dependent loss (PDL), Sagnac interferometer (SI)

1 Introduction

With the development of optical fiber technology, more and more people take advantage of simulation software commercially available to analyze and design optical devices and systems. However, the simulation tools cannot be used for some advanced or special fiber devices, such as magneto-optic Bragg fiber gratings (MFBGs) [1–4]. In order to effectively investigate the MFBG's potential applications in optical fiber sensing and communication, such as magnetic field sensors with high resolution, dynamic dispersion compensation, and tunable comb filtering, we build up the simulation model of the non-uniform MFBGs with bidirectional injection of light, which is used to simulate the polarization-dependent loss (PDL) of the MFBG-based Sagnac interferometer (MSI). The maximum of peak PDL of the MSI system is up to three times that of the single MFBG structure, which is helpful for future experiments.

Received August 2, 2010; accepted August 28, 2010

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2 Symmetry of non-uniform MFBG's transmission matrix

The so-called non-uniform MFBGs are a class of non-uniform fiber Bragg gratings (FBGs) with the magneto-optic (MO) effects, characterized by the unhomogeneity of refractive index modulation and uniform magnetization along the fiber. In the isotropic MFBGs, the eigen states of polarization (SOP) are left- and right-handed circularly polarized (LCP and RCP) light [4], and then, a uniformly magnetized MFBG can be equivalent to the non-magnetic FBG with the effective refractive index $\overline{n}_{\mathrm{eff}} = n_0 \pm \kappa_m / k_0$ [5], corresponding to the central wavelength $\lambda_c = \lambda_0(1 \pm \kappa_m \Lambda / \pi)$, in which "±" correspond to the RCP and LCP light, respectively. λ_0 is the original wavelength in the absence of magnetic field, n_0 is the average refractive index without the MO effects, $\kappa_m = V_B B$ is the MO coupling coefficient associated with the Verdet constant V_B and magnetic induction B, Λ is the period of the grating, and k_0 is the propagation constant in vacuum. Thus, for the case of unidirectional injection, in which only a light beam is incident into the MFBG, the transmission and reflection of light can be simulated by setting the key parameters in the Optisystem software [5], such as the equivalent refractive index $\overline{n}_{\mathrm{eff}}$, the central wavelength λ_c, and the grating length L.

In what follows, we analyze the symmetry of non-uniform MFBG's transmission matrix for the RCP or LCP light and then find out the relationship between the unidirectional and bidirectional injection cases. According to the piecewise-uniform MFBG model [6], the complex amplitudes of guided light in a non-uniform MFBG can be expressed by the total transmission matrix, which is the production of the transmission matrices for all uniform segments, that is,

$$\begin{bmatrix} A_{\mathrm{R}}^{+}(L) \\ A_{\mathrm{R}}^{-}(L) \end{bmatrix} = T_N T_{N-1} \cdots T_i \cdots T_2 T_1 \begin{bmatrix} A_{\mathrm{R}}^{+}(0) \\ A_{\mathrm{R}}^{-}(0) \end{bmatrix}, \quad (1)$$

where L is the length of the non-uniform MFBG, the superscripts "+" and "−"correspond to the forward- and backward-propagating guided waves, respectively; the subscript "R" represents the RCP light; and $T_n\,(n = 1,2,...,N)$ is the transmission matrix of each uniform segment, which is of the form as follows:

$$T_n = \begin{bmatrix} T_{n1} & T_{n2} \\ T_{n2}^{*} & T_{n1}^{*} \end{bmatrix} \quad (n = 1,2,...,N)\,. \quad (2)$$

It is easily proven that the total transmission matrix of the whole non-uniform MFBG is of the same symmetry as Eq. (2):

$$T_{\mathrm{grating}} = T_N T_{N-1} \cdots T_n \cdots T_2 T_1 = \begin{bmatrix} T_{g1} & T_{g2} \\ T_{g2}^{*} & T_{g1}^{*} \end{bmatrix}. \quad (3)$$

Thus, Eq. (1) can be rewritten as

$$\begin{cases} A_{\mathrm{R}}^{+}(L) = t_g A_{\mathrm{R}}^{+}(0) + r_g' A_{\mathrm{R}}^{-}(L), \\ A_{\mathrm{R}}^{-}(0) = r_g A_{\mathrm{R}}^{+}(0) + t_g' A_{\mathrm{R}}^{-}(L), \end{cases} \quad (4)$$

where $t_g = (T_{g1}T_{g1}^{*} - T_{g2}T_{g2}^{*})/T_{g1}^{*}$, $r_g = -T_{g2}^{*}/T_{g1}^{*}$, $t_g' = 1/T_{g1}^{*}$, and $r_g' = T_{g2}/T_{g1}^{*}$ represent the transmission and reflection coefficients of the forward- and backward-injected RCP light, respectively. Utilizing the relationship of $|t_g|^2 + |r_g|^2 = 1$, one concludes that, $t_g = t_g'$, $|r_g| = |r_g'|$, and the phase difference of r_g and r_g' is $\Delta\varphi = \varphi_r' - \varphi_r = 2(\varphi_t - \varphi_r) + \pi$, in which φ_t and φ_r represent the phase angles of t_g and r_g. For the symmetric MFBG, such as uniform or apodized MFBG, the above-mentioned transmission or reflection coefficients can be simplified as

$$t_g = t_g',\ r_g' = r_g. \quad (5)$$

According to Eqs. (4) and (5), for the case that two light beams are simultaneously launched into a symmetric MFBG in the forward and backward directions respectively (i.e., bidirectional injection), the output characteristics of the MFBG can be derived from those in the case of unidirectional injection. Moreover, one can also build up the simulation model of symmetric MFBGs with bidirectional injection of light by means of the Optisystem simulation software.

3 Simulation model of symmetric MFBGs

First, we discuss the case for the eigen RCP light. In the case, a non-uniform MFBG of bidirectional injection is regarded as the combination of two equivalent FBGs (EFBGs), and the resulting simulation subsystem is shown in Fig. 1(a). The forward or backward output of the subsystem is the superposition of the transmitted and reflected optical field output from the two different EFBGs. It should be emphatically pointed out that the simulation subsystem is applicable only for the eigen SOP. Fortunately, the simulation subsystem can also be used to build up the SOP-independent simulation model of symmetric MFBGs with bidirectional injection of light, as shown in Fig. 1(b). The circular polarizers are used to extract the LCP and RCP components from the incident light, and then, the two components are separately imported to the LCP and RCP subsystems. The optical adders are used to combine the optical field in the same direction.

In the following, the validity of the simulation model will be made sure by comparing with the Matlab numeric results using the piecewise-uniform MFBG model [6]. For this purpose, we assume that two beams of linearly polarized light with the optical power of 1 and 0.5 mW are simultaneously incident into an apodized MFBG in the forward and backward directions, respectively. Figure 2 shows the backward output power and phase spectra from the apodized MFBG with the MO coupling coefficient $\kappa_m = 10\ \mathrm{m}^{-1}$, which are obtained from the Matlab numerical calculation and the Optisystem simulation. In Fig. 2, the following parameters are used: the central wavelength $\lambda_c = 1550$ nm, the grating's length $L = 2$ cm, the grating's period $\Lambda = 535$ nm, the refractive index modulation $\Delta n = 1 \times 10^{-4}$, and the apodized parameter $s = 0.6$. In the Optisystem simulation, the resolution of the optical spectrum analyzer (OSA) is 0.01 nm, and the optical filter analyzer is used to achieve the information on the phase spectrum. In Fig. 2, the Optisystem simulation results are identical with the Matlab numerical ones.

4 MFBG-based Sagnac interferometer

The characteristics of MFBG's bidirectional transmission are involved in the MFBG-based Sagnac interferometer (MSI), as shown in Fig. 3(a). The incident optical field E_i is splitted into two optical paths by a coupler and then simultaneously injected into the MFBG clockwise and counter-clockwise. E_r and E_t are the reflected and transmitted optical fields, respectively. The polarization controllers (PCs) in the MSI system are used to compensate for the linear birefringence in the fiber loop. The magnetic field B is applied along the MFBG of length L. According to the MFBG's simulation model, the MSI

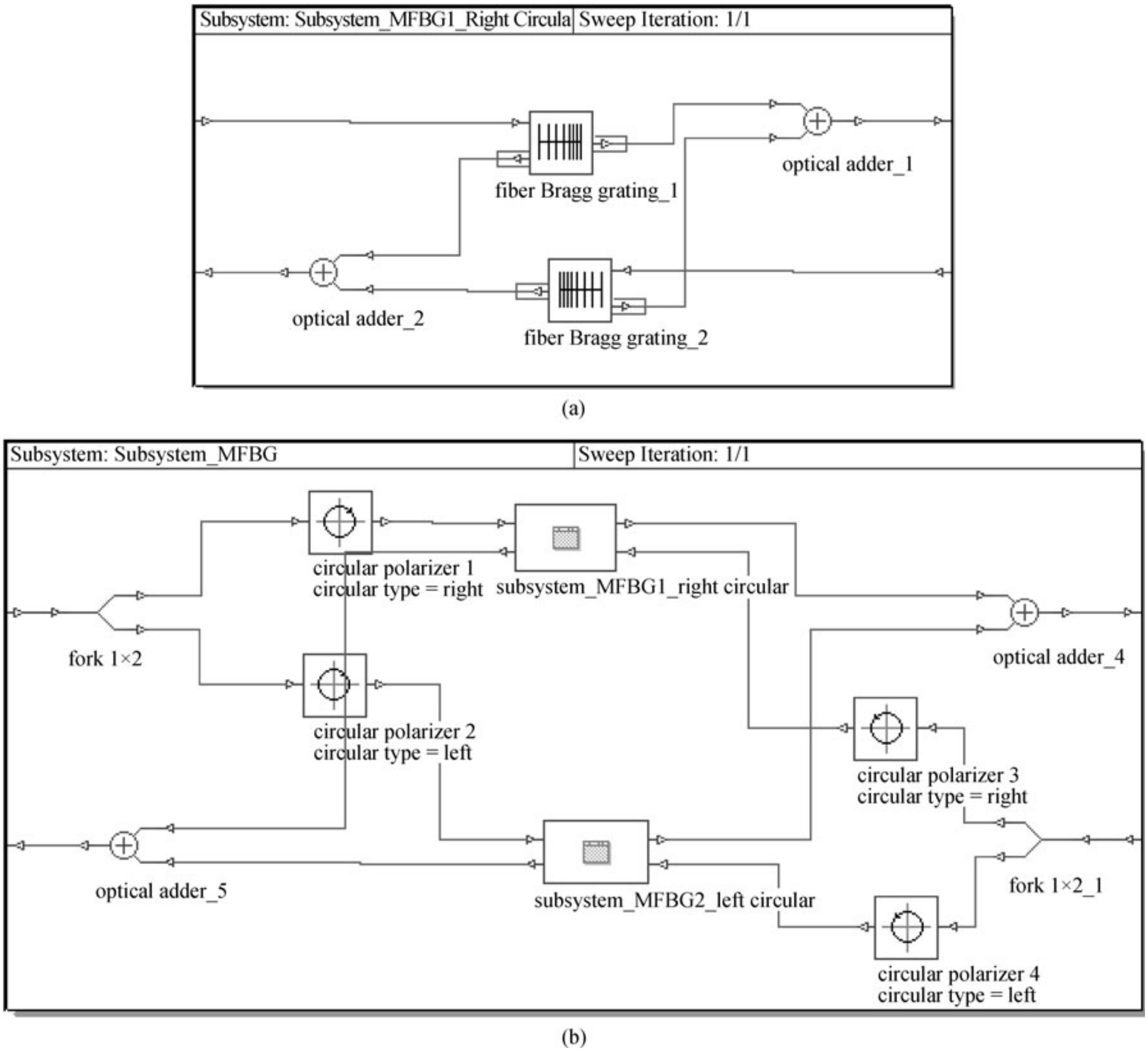

Fig. 1 Optisystem simulation of symmetric MFBGs. (a) RCP simulation subsystem of symmetric MFBGs; (b) simulation model of symmetric MFBGs with bidirectional injection of light

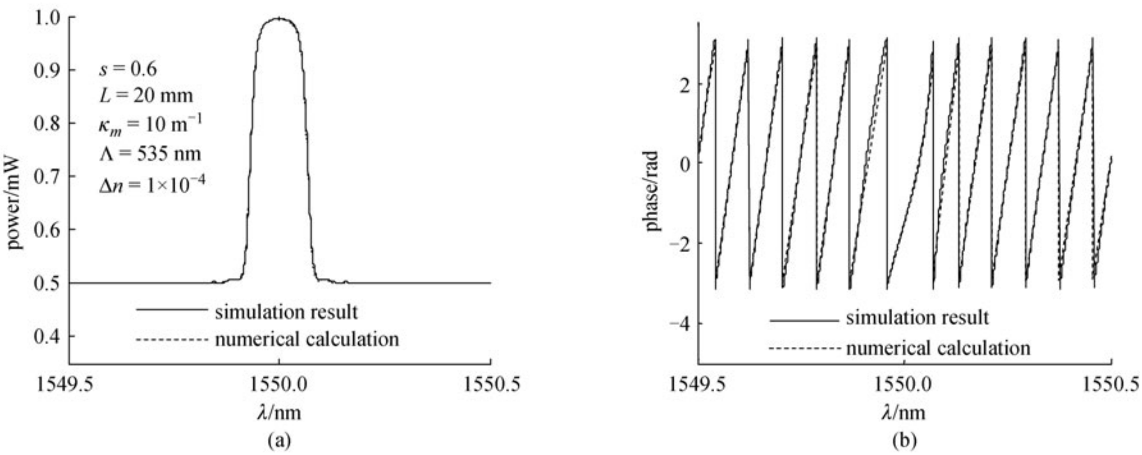

Fig. 2 Comparison of Optisystem simulation with Matlab numerical calculation. (a) Power spectrum; (b) phase spectrum

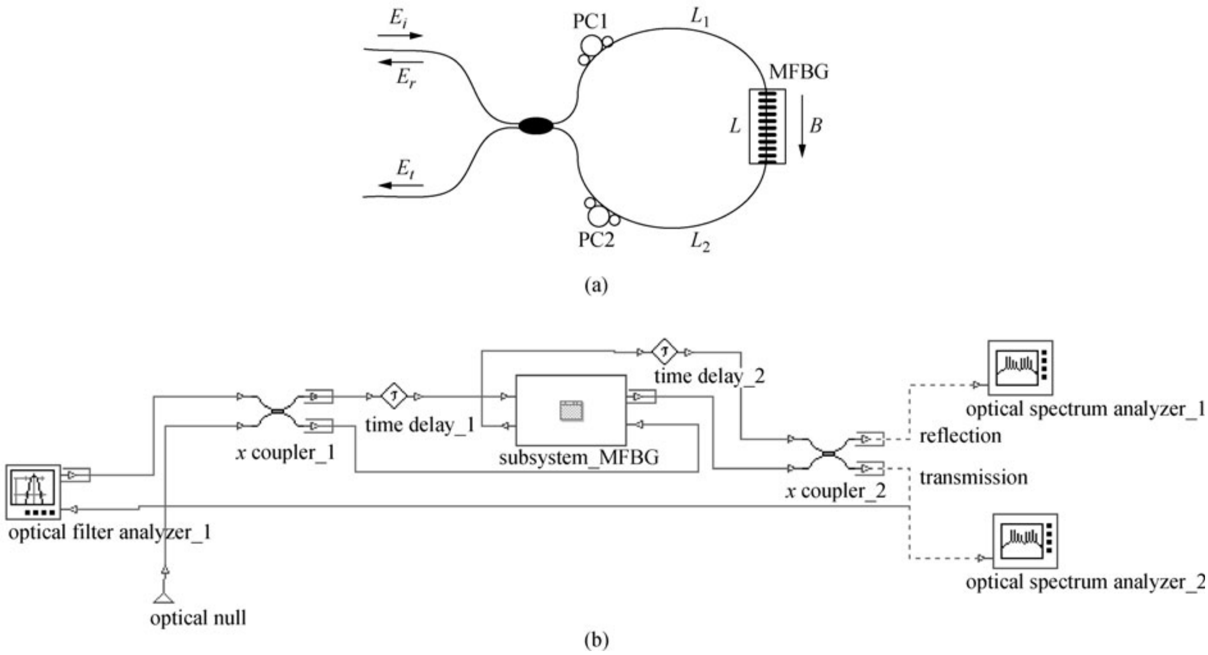

Fig. 3 MFBG-based Sagnac interferometer system. (a) MFBG-based Sagnac interferometer (MSI); (b) Optisystem layout file for MSI system

system can be simulated by the Optisystem layout file, as shown in Fig. 3(b). The linearly polarized light generated by the optical filter analyzer is launched into the MSI system. The reflected and transmitted optical spectra of the MSI system are displayed by the OSA of 0.1nm resolution. The tail fibers L_1 and L_2 are equivalent to the time delay lines in the Optisystem layout file.

The output characteristics of the MSI system can be analyzed by adjusting the MFBG's MO coupling coefficient κ_m. In the paper, we focus on the polarization-dependent loss (PDL) of the MSI system with $\Delta L = L_1 - L_2 = 0$. Note that the PDL spectrum of the MSI system should be derived from the reflected light; on the contrary, the PDL of the single MFBG structure is calculated from the transmitted light [7]. By employing the same analysis process, as used in Ref. [8], the transmittivity of the uniform-MFBG-based system for the incident RCP light is expressed as follows:

$$T = \frac{\left[(1-2\rho)\sqrt{(\delta+\kappa_m)^2/\kappa_g^2-1} + 2\sqrt{\rho(1-\rho)}\sinh\left(\sqrt{(\delta+\kappa_m)^2-\kappa_g^2}L\right)\cos(\beta\Delta L)\right]^2}{\cosh^2\left(\sqrt{(\delta+\kappa_m)^2-\kappa_g^2}L\right)-(\delta+\kappa_m)^2/\kappa_g^2}, \tag{6}$$

where ρ is the coupling coefficient. Obviously, when $\kappa_m = 0$, Eq. (6) is reduced to the same formula, as given in Ref. [8]. For the case with $\rho = 0.5$ and $\Delta L = 0$, the reflection spectrum of the MSI system is identical with the transmission spectrum of the corresponding MFBG.

The PDL, as the intrinsic parameter of an optical system, may be calculated from the output spectra of two orthogonal eigen SOPs. For the MSI system, the PDL is defined as

$$P_{\mathrm{PDL}}(\lambda) = \left|10\lg\frac{R_R(\lambda)}{R_L(\lambda)}\right|,$$

where $R_R(\lambda)$ and $R_L(\lambda)$ represent the reflectivity of the eigen RCP and LCP light, respectively. Figure 4 plots the PDL spectra $(\Delta\lambda = \lambda - \lambda_c)$ of the MSI systems based on the uniform and Gaussian apodized MFBGs with $\kappa_m =$ 1 m^{-1} and the apodized parameter $s = 1$. The grating's parameters are taken as follows: $\Lambda = 535$ nm, $n = 1.449$, $\Delta n = 1 \times 10^{-4}$, and $L = 1$ cm. In Fig. 4, the peak PDL of the apodized-MFBG-based MSI system is less than that of the uniform-MFBG-based MSI system.

It is shown by simulation that the peak PDL is directly proportional to the MO coupling coefficient in small signal approximation. Thus, the magnetic field sensitivity may be defined as

$$S_k = \frac{\mathrm{d}P_{\mathrm{PDLpeak}}}{\mathrm{d}\kappa_m},$$

which is dependent on the coupling coefficient ρ, as plotted in Fig. 5. When the coupling coefficient $\rho = 0.65$, the magnetic field sensitivity is up to 0.64 dB·m, which is

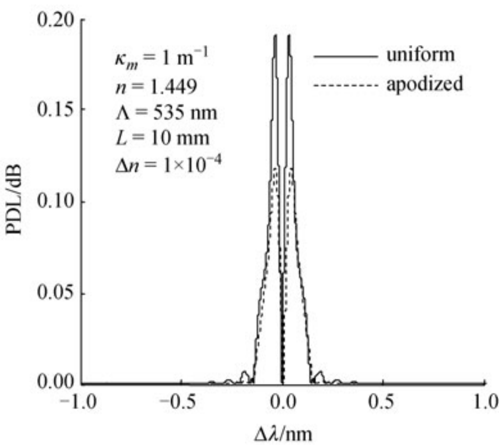

Fig. 4 PDL spectra of MSI systems using uniform and apodized MFBGs

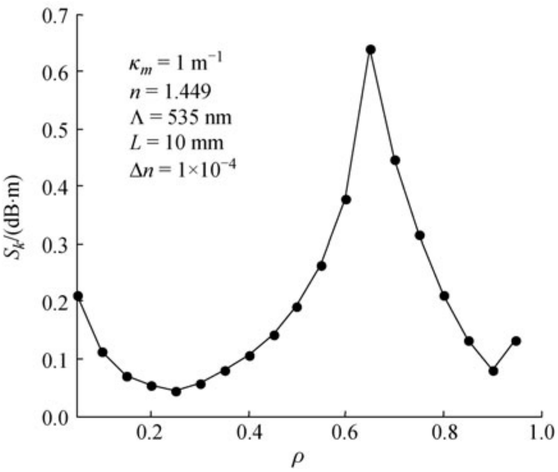

Fig. 5 Magnetic field sensitivity of MSI system with uniform MFBG

three times that with $\rho = 0.5$. In other words, an appropriately optimized MSI system possesses larger magnetic field sensitivity than the corresponding MFBG structure.

5 Conclusion

According to the symmetry of non-uniform MFBG's transmission matrix, a symmetric MFBG of bidirectional injection can be regarded as the combination of two EFBGs for the eigen SOP, and then, the simulation model of symmetric MFBGs independent of the incident SOP is presented. As an example, an apodized MFBG is investigated by using the piecewise-uniform FBG model and the Optisystem simulation model. The validity of the simulation model is confirmed by comparing with the Matlab numeric results. In the paper, the MFBG's simulation model is used to simulate the MSI systems, and the magnetic field sensitivity of peak PDL is analyzed by the Optisystem software. The simulation results indicate that the peak PDL of the MSI system can be increased by optimizing the coupling coefficient of the coupler.

Acknowledgements This work was supported by the National High Technology Research and Development Program of China (No. 2009AA01Z216) and by Program for New Century Excellent Talents in University (NCET-08).

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