

Regular Articles

Magnetically-controllable optical multi-stability in magneto-optic fiber Bragg gratings with potential applications to multi-level all-optical regeneration



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ABSTRACT

Starting with the nonlinear coupled-mode equations of guided optical waves in the magneto-optic fiber Bragg grating (MFBG), the amplitude transfer curve of the transmitted light is numerically calculated for the incident right-circularly polarized wave, and the multi-stability is analyzed by introducing the parameter of jitter suppression. It is shown that, (i) the performance of amplitude jitter suppression in the stable states of high level is better than that of low level; (ii) the jitter suppression in the multi-stable regions can be enhanced when the magnetic field is applied to the MFBG in the opposite direction of the incident wave; and (iii) by adjusting the applied magnetic field, the multi-stable levels can be tuned flexibly, which is helpful for developing the intelligent all-optical devices for multilevel regeneration.

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1. Introduction

In order to further improve the transmission capacity of optical communications, high-order signal modulation formats and some new multiplexing technologies have been used in the practical optical networks since recent years [1,2]. Multilevel signals are capable of being more bit capacity at a given symbol rate, but it requires higher optical signal-to-noise ratio (OSNR) because of the reduced symbol distance. Currently, the performance of multi-level signal transmission system is mainly improved by some electric-processing technologies for the application to the trunk links [3]. At the same time, all-optical regeneration schemes for multilevel signals have also been taken into account, which is necessary for future high-speed optical switching networks. Multilevel signal regeneration needs step-like transfer functions in amplitude or phase. However, at the present time, the desirable regenerators for multilevel modulation formats are hardly available due to the difficulty in simultaneously deriving amplitude and phase regeneration regardless of a few schemes [4–10]. For example, the all-optical regeneration of DPSK can respectively be obtained by phase preserving limiter [5], amplitude regenerator with format conversion [6], nonlinear optical fiber loop mirror (NOLM) [7] or the phase sensitive amplifier (PSA) [8]. Multilevel

amplitude regenerative structures based on NOLM and directional interference were theoretically proposed by Sorokina [9] and Hierold [10], respectively. Recently, we put forward a scheme to realize all-optical regeneration of 4-PAM signal, which is based on the optical multi-stability in fiber Bragg grating (FBG) [11]. This scheme has some unique advantages of small volume, fast response speed and easy integration with optical fiber, suitable for high-speed optical fiber communication systems. In fact, the nonlinear effects and switching characteristics in the FBGs, such as nonlinear pulse switching behavior [12], bi-stable threshold and hysteresis properties [13], all-optical flip-flop [14] and bi-stability of highly doped fiber [15], have been involved, especially with the experimental demonstration of pulse switching [16].

For the above-mentioned multilevel regeneration schemes, the resulting systems can be designed by optimizing some parameters on condition that the characteristics of input signals are given, that is, their adaptability and flexibility are limited. In this paper, we make use of the optical nonlinear effects in magneto-optic fiber Bragg grating (MFBG) to realize the magnetically controllable optical multi-stability in accordance with different characteristics of input signals, including the input level and fluctuation range, which is useful for developing the intelligent all-optical devices for multilevel regeneration. The MFBGs can be fabricated by doping rare earth elements in FBG or writing gratings in YIG fibers. The mode conversion caused by magneto-optic effect plays an

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important role in the optical nonlinear coupling process due to its dependency on the states of polarization of light, on the basis of which the magnetically controllable optical signal processing is realized [17–19].

Strictly speaking, in nonlinear systems in which feedback mechanism is involved, the dynamic behavior should be taken into account. However, the dynamic analysis based on the nonlinear coupled-mode equations of guided optical waves in fiber Bragg gratings becomes much more complicated because of the existence of the time derivative terms and the incomplete boundary condition. A solution to the problem has been presented in our previous articles [20]. For simplicity, the static analysis of nonlinear fiber Bragg gratings is presented in this paper, which is still helpful for investigating the magnetic field response. In the quasi-steady approximation, the transmission characteristic of continuous waves can be taken into account. As an example, the amplitude transfer curve of the transmitted continuous wave from the MFBG is numerically calculated here for the incident right-circularly polarized light, and the inherent multi-stability can be analyzed by introducing the jitter suppression parameter. It is shown that, the performance of amplitude jitter suppression in the multi-stable regions becomes better and better with the increase of input level, and can be greatly enhanced when the magnetic field is applied to the MFBG in the opposite direction of the incident wave.

2. Optical multi-stability in MFBGs and its description

The nonlinear transmission properties of guided optical waves in MFBGs can be described by the magneto-optic nonlinear coupled-mode equations. The eigen-modes of guided waves in magneto-optic gratings with the absence of linear birefringence are circularly polarized. The fiber nonlinearity, grating and magneto-optic effect can be regarded as perturbations relative to an ideal fiber-optic waveguide structure. For the case with continuous waves, the complex amplitudes of the forward or backward left- and right-circularly polarized guided optical waves $A_{R,L}^{(s)}$ satisfy the nonlinear coupled-mode equations as follows [17]:

$$s \frac{\partial A_R^{(s)}}{\partial z} = i(\delta + \kappa_m)A_R^{(s)} + i\kappa_g A_R^{(-s)} + i\gamma_c \left[|A_R^{(s)}|^2 + 2|A_L^{(s)}|^2 + \frac{9}{4}|A_R^{(-s)}|^2 + \frac{7}{4}|A_L^{(-s)}|^2 \right] A_R^{(s)} \quad (1a)$$

$$s \frac{\partial A_L^{(s)}}{\partial z} = i(\delta - \kappa_m)A_L^{(s)} + i\kappa_g A_L^{(-s)} + i\gamma_c \left[|A_L^{(s)}|^2 + 2|A_R^{(s)}|^2 + \frac{9}{4}|A_L^{(-s)}|^2 + \frac{7}{4}|A_R^{(-s)}|^2 \right] A_L^{(s)} \quad (1b)$$

where $s = \pm 1$ are corresponding to the forward and backward propagating directions; $\delta = (\omega - \omega_B)\bar{n}/c$ is the phase mismatch, ω and ω_B are respectively the frequency of the input light and the Bragg frequency; $\kappa_g = \pi\Delta n/\lambda_0$ is the grating coupling coefficient, λ_0 is the wavelength of the input wave; γ_c is the nonlinear coefficient of the MFBG; $\kappa_m = Bv$ is the magneto-optic coupling coefficient, B is the magnetic field intensity, v is the Verdet constant; $\bar{n}$ and Δn are respectively the average refractive index and the refractive index variation. From Eq. (1), the nonlinear transmission properties of guided optical waves in the MFBGs can be completely determined by $\kappa_g L$, δ/κ_g , γ_c/κ_g and κ_m/κ_g , in which κ_m/κ_g is called the magnetic-grating coupling ratio, associated with the intensity of magnetic field.

In principle, the MFBG-based optical signal processing for high-order modulation formats can be analyzed by means of the amplitude and phase transfer characteristics. Here, for the purpose of explaining the magnetically-controllable multi-stability, only

the amplitude transfer functions are taken into account in the paper; similarly, the phase transfer functions can also be derived from Eq. (1) by the transfer matrix method [11]. The left- or right-circularly polarized light can be analyzed the same way. As an example, the case with the incident right-circularly polarized light is investigated here and then Eq. (1) can further be simplified for the amplitude transfer curve. Fig. 1 gives a typical amplitude transfer curve from the input $|A_R^+(z=0)|$ to the output $|A_R^+(z=L)|$. The following parameters are reasonably taken in our calculation [21]: $\kappa_g L = 12$, $\delta/\kappa_g = 1.4$, $\gamma_c/\kappa_g = 0.4 W^{-1}$ and $\kappa_m/\kappa_g = -0.1$. The other parameters, such as λ_0 , $\bar{n}$ and Δn can be deduced from the four parameters above. From Fig. 1, the amplitude transfer curve for the right-circularly polarized light is stair-like and there exists many “one-to-one” stable states from the input to output amplitudes. The multi-stability is extremely useful for suppressing the amplitude jitter or noise of input optical signals. That is, an MFBG-based multi-stable regenerator should match with the amplitude levels of input multi-level signals, otherwise the symbol errors occur at the adjacent levels [11].

At any given point (x_0, y_0) on the amplitude transfer curve, its slope dy/dx is closely related to the ability of suppressing the amplitude fluctuation. For a 2R (re-amplifying and re-shaping) regenerator, its amplitude transfer characteristics can be represented by the normalized slope $k_A = \frac{dy}{dx} / \frac{y_0}{x_0}$, in which the influence of linear amplification on the amplitude transfer function is eliminated. Hence, we introduce the parameter $S_A = 1/k_A$ to measure the performance of jitter suppression. The larger S_A , the better the re-shaping performance is. In the regions of $S_A > 1$, the amplitude jitter of an input signal can be suppressed; otherwise, the amplitude jitter is amplified ($0 < S_A < 1$), even in the unsteady regions ($S_A < 0$). Thus, the points with $S_A = 1$ can be used to determine the input or output dynamic range of the multi-stable devices, as well as the optimal operating points corresponding to the maximal $S_A^{\max}$. Fig. 1 shows that the performance of jitter suppression at the optimal operating points increases with the input or output levels. In a word, as the characteristic parameter of the amplitude transfer curve, the jitter suppression parameter S_A can be used for the design of multi-level regenerators.

3. The influence of magnetic field on the multi-stability of MFBG

In what follows, we investigate the multi-stability of the magnetically controllable MFBG devices according to the S_A curve.

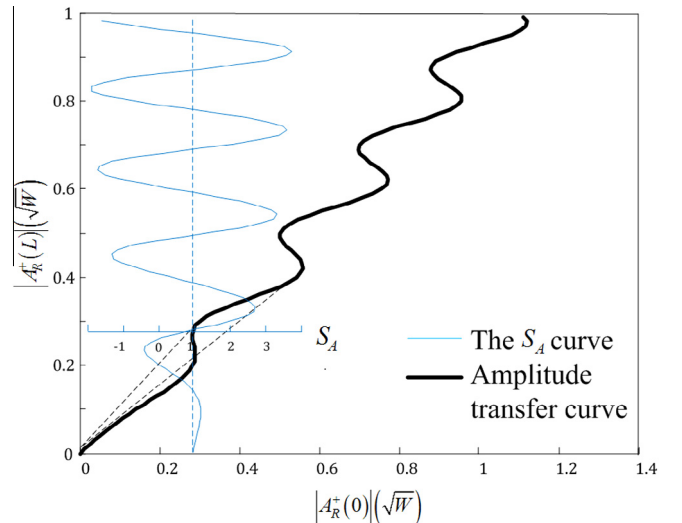


Fig. 1. The amplitude transfer and jitter suppression curves for the multi-stable MFBG.

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