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An effective method for improving diffraction performance of magnetostatic backward volume wave-based magneto-optic Bragg cells by using an appropriately tilted bias magnetic field in YIG film plane ☆

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Abstract

The universal magneto-optic (MO) coupled-mode equations for magnetostatic waves (MSWs) and guided optical waves (GOWs) under arbitrarily tilted bias magnetic fields are presented for the first time and, as an example, applied to the noncollinear Stokes interaction between the incident TE_0-mode light and magnetostatic backward volume wave (MSBVW) excited by single-element microstrip line transducer in yttrium–iron–garnet (YIG) film. Our calculation indicates that, for the case of magnetization parallel to the MSBVW propagation direction, the diffraction efficiency (DE) is equal to the mode-conversion efficiency of the diffracted lights (MCDE) and the calculated curve of relative DE for the MSBVW-based MO Bragg cell in pure YIG waveguide is in good agreement with the experimental data. In contrast, the diffraction performance can be greatly improved by optimizing the bias magnetic field and the DE gain can be increased by 6.3 dB in the tangentially magnetized film. The angular dependences of the DE and the corresponding Bragg angle upon the magnetization direction are also discussed in the paper.

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1. Introduction

Magneto-optic (MO) Bragg interaction of guided optical waves (GOWs) with magnetostatic waves (MSWs) propagating in MO thin-film waveguides such as the yttrium iron garnet–gadolinium gallium garnet (YIG–GGG) structure can lead to the diffraction effect of the GOWs. The resulting MSW-based Bragg cells and devices, such as frequency spectrum analyzers, light modulators and deflectors, can be developed with applications to signal processing and communications [1]. The subject will draw more attention since the new class of MO Bragg devices is capable of providing all standard functions implemented using the acousto-optic Bragg cells and can operate at much higher carrier frequencies of microwave signals, typically from 0.5 to 40 GHz by simply varying bias magnetic fields, and also at much faster modulation speeds due to much higher velocities of the MSW [2]. Thus, it has become one of key issues how to further improve the diffraction performance of MO Bragg cells. In our articles [3–5] and Kolokoltsev's experiments [6], it has been made clear that an appropriately inclined bias magnetic field can help to the improvement of diffraction efficiency (DE) of the GOWs by the magnetostatic forward volume waves (MSFVWs). However, to the best of our knowledge, the cases with magnetostatic backward volume waves (MSBVWs) and magnetostatic surface waves (MSSWs) under inclined bias magnetic fields have not been reported until now. In this paper, the more general case of *arbitrarily*

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tilted bias magnetic field is studied and the universal MO coupled-mode equations in this case are presented for the first time and applied to the noncollinear interaction between the GOW and the MSBVW. Our calculation shows that the MO Bragg diffraction of the GOW by the MSBVW can further be optimized by using an appropriately inclined bias magnetic field deviating from the direction of MSBVW propagation in the YIG film plane. For example, a 6 dB DE improvement can be achieved at the carrier frequency of 4.7 GHz. It should be pointed out that the universal MO coupled-mode equations presented in the paper may also be applied to the interaction of GOWs with MSFVWs or MSSWs since the MSW modes are dependent on the magnitude and direction of bias magnetic fields.

2. Dynamic magnetization of the MSW under an arbitrarily inclined bias magnetic field

The pure YIG–GGG waveguide is in free space and a bias magnetic field $\boldsymbol{H}_0$ is applied that is strong enough to get the saturation magnetization $\boldsymbol{M}_\mathrm{s}$ inside the YIG film. The effective *internal* DC magnetic field $\boldsymbol{H}_\mathrm{i}$ can be expressed as the sum of the applied field $\boldsymbol{H}_0$, the effective anisotropy field $\boldsymbol{H}_\mathrm{A}$ and the demagnetizing field $\boldsymbol{H}_\mathrm{d}$, namely, $\boldsymbol{H}_\mathrm{i} = \boldsymbol{H}_0 + \boldsymbol{H}_\mathrm{A} + \boldsymbol{H}_\mathrm{d}$. Due to the complicated orientation-dependence of the anisotropy field on the magnetization, for simplicity, we neglect the time-varying component of the anisotropy field and introduce an *effective external* field $\boldsymbol{H}_\mathrm{e} = \boldsymbol{H}_0 + \boldsymbol{H}_\mathrm{A}$with the direction angles (θ, φ), as shown in Fig. 1. For small anisotropy field ($\boldsymbol{H}_\mathrm{e} \approx \boldsymbol{H}_0$), after considering the surface demagnetizing filed $\boldsymbol{H}_\mathrm{d}$, the internal magnetic field $\boldsymbol{H}_\mathrm{i}$ can be determined as follows: $H_\mathrm{i} \sin\theta_\mathrm{i} = H_\mathrm{e} \sin\theta$ and $(H_\mathrm{i} + M_\mathrm{s})\cos\theta_\mathrm{i} = H_\mathrm{e}\cos\theta$, where θ_i is the direction angle of the effective internal field $\boldsymbol{H}_\mathrm{i}$ with respect to the normal to the film surface [6]. The $+y$-propagating MSBVW is excited by using a single-element microstrip line transducer deposited on the pure YIG film. The MO Bragg diffraction is induced by the noncollinear interaction between the MSBVW and the incident light in the TE$_0$ mode through the Faraday and Cotton–Mouton effects.

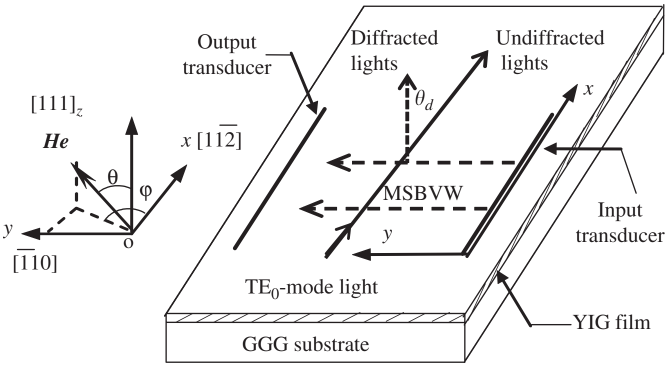

Fig. 1. Noncollinear interaction between the GOW and the MSBVW in the YIG-GGG waveguide.

By application of magnetostatic approximation and boundary conditions, after some rather tedious manipulations, we can obtain the MSW dynamic magnetization in terms of the effective complex envelope vector $\boldsymbol{g}_\mathrm{m}$ as follows

$$\boldsymbol{g}_\mathrm{m} = G_s \begin{pmatrix} \dfrac{\beta + s\cdot K_s}{\alpha + s\cdot K_s}(\mathrm{i}K_s\chi_{12} - \alpha_2\chi_{13})A - (\mathrm{i}K_s\chi_{12} - \beta_2\chi_{13})B \\ \dfrac{\beta + s\cdot K_s}{\alpha + s\cdot K_s}(\mathrm{i}K_s\chi_{22} - \alpha_2\chi_{23})A - (\mathrm{i}K_s\chi_{22} - \beta_2\chi_{23})B \\ \dfrac{\beta + s\cdot K_s}{\alpha + s\cdot K_s}(\mathrm{i}K_s\chi_{32} - \alpha_2\chi_{33})A - (\mathrm{i}K_s\chi_{32} - \beta_2\chi_{33})B \end{pmatrix}, \tag{1}$$

where

$$G_s = \frac{-\pi K_s \tilde{J}_x(K_s)}{(\alpha_2 - \beta_2)(\beta + s\cdot K_s)d}, \quad \tilde{J}_x(K_s) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} J_x(y)\mathrm{e}^{\mathrm{i}K_s y}\mathrm{d}y, \quad J_x(y)$$

is the current distribution function

$$A = \frac{4\pi^2(1 - \mathrm{e}^{-\alpha_2 d})}{\alpha_2 d(\alpha_2^2 d^2 + 4\pi^2)}, \quad B = \frac{4\pi^2(1 - \mathrm{e}^{-\beta_2 d})}{\beta_2 d(\beta_2^2 d^2 + 4\pi^2)},$$

$$\alpha_2 = \mathrm{i}K_s\frac{(\mu_{23} + \mu_{32}) + s\sqrt{\varDelta}}{2\mu_{33}},$$

$$\beta_2 = \mathrm{i}K_s\frac{(\mu_{23} + \mu_{32}) - s\sqrt{\varDelta}}{2\mu_{33}}, \quad \varDelta = (\mu_{23} + \mu_{32})^2 - 4\mu_{22}\mu_{33},$$

$$\alpha = -\mathrm{i}K_s\mu_{32} + \alpha_2\mu_{33}, \quad \beta = -\mathrm{i}K_s\mu_{32} + \beta_2\mu_{33},$$

where $s = \pm 1$ correspond to the MSWs propagating in the $+y$ and $-y$ directions, respectively; d and K_s are, respectively, the film thickness and the wave number of the MSW, and the tensor elements χ_{ij} (or μ_{ij}) can easily be obtained by transforming the susceptibility (or permeability) tensor at normal magnetization. In addition, the frequency band to excite the MSBVW can also be given in the form: $\sqrt{\Omega_H^2 + \Omega_H\cos^2\varphi\sin^2\theta_\mathrm{i}} \leqslant \Omega \leqslant \sqrt{\Omega_H^2 + \Omega_H\sin^2\theta_\mathrm{i}}$ with $\Omega_H = H_\mathrm{i}/M_\mathrm{s}$ and $\Omega = 2\pi f/(\gamma M_\mathrm{s})$, where γ and f are the gyromagnetic ratio and the MSW frequency, respectively. The upper limit is independent of the angle φ and the MSBVW bandwidth at $\theta = \varphi = 90^\circ$ is maximal. Obviously, the excitation of the MSW modes depends on the magnitude and direction of internal bias magnetic fields and RF drive frequencies.

3. The universal MO coupled-mode equations

An additional electric polarization $\Delta\boldsymbol{P}$ as the perturbation will result from the MO effects and, under ordinary circumstances, for the case of the incident TE$_0$-mode light, three additional light waves, namely, those of the diffracted