Optical isolators based on magnetoplasmonic subwavelength gratings

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ABSTRACT

We explore the possibility of enhancing the optical isolation in integrated devices by exploiting magnetoplasmonics. By considering an integrated garnet-on-insulator waveguide adjacent to a gold grating, we find that the vertical and horizontal Fabry-Perot resonances (located in the deep-subwavelength grating slits) improve the optical isolation.

Keywords : *optical isolation, magnetoplasmonics, gold grating, Fabry-Perot resonances.*

1. Introduction

Magnetoplasmonics is a paradigm that benefits from the synergy between surface plasmon polaritons (SPPs), occurring at the boundaries of plasmonic and magneto-optical (MO) materials. On the one hand, plasmonics is employed to attain extreme electromagnetic field enhancement and subwavelength localization. On the other hand, MO materials bring non-reciprocity within reach [1]. When dealing with compact integrated structure including plasmonic elements, a suitable MO effect is the transverse magnetooptical Kerr effect (TMOKE), where the applied magnetic field is perpendicular to the plane of incidence of the light. In this effect, whenever the external static magnetic field is inverted from $+M_T^{sat}$ to $-M_T^{sat}$, a change in the intensity of the reflected/transmitted light occurs. The achievement of a large TMOKE response is essential for many applications like optical modulators, switches, and optical isolators. [2]

When they are not coupled with plasmonic elements, lossless MO materials do not lead to significant optical intensity transmission nonreciprocity due to the TMOKE effects. However, a 1.5% enhancement has been reported in non-guided configurations, by using a nanostructured gold grating integrated on top of a transparent iron garnet substrate and with an in-plane magnetization [3][4]. This example constitutes the starting point for the design of a novel integrated isolator. Indeed, TMOKE is the sole MO effect which occurs at the interface of two materials without modifying the wave polarization. It is thus fully compatible with a waveguide configuration. This is the objective of this paper.

Here, we propose the following structure: a 1D periodic Au grating is adjacent to a Bismuth Iron Garnet (BIG) MO waveguide which is deposited on a non-MO Gallium Gadolinium Garnet (GGG) substrate and buried in a SiO_2 superstrate as depicted in Figure 1(a).

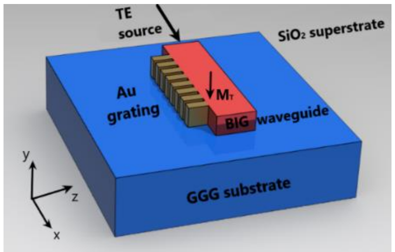

Fig. 1: A MO BIG waveguide on a non-MO GGG substrate with a one-side gold grating. The whole structure is buried in SiO_2. An out-of-plane (normal to the substrate interface) magnetization M_T is applied and a fundamental TE mode is injected in the waveguide.

Such a system breaks spatial symmetry and permits coupling between the waveguide and the grating slits modes. The TMOKE effect is produced at the interfaces of the waveguide and is enhanced by the plasmonic modes. The fundamental TE mode in the waveguide couples to the grating and, in turn, feeds the metal-insulator-metal (MIM) modes inside the slits, leading to vertical and horizontal Fabry-Perot slit resonances. This mechanism contributes to isolation enhancement.

2. RESULTS

The optical transmission in the MO waveguide (BIG) has been calculated using commercial software based on finite difference time domain (FDTD) method extended to the instance of gyrotropic materials. The magnetic film permittivity tensor has the following non zero components: $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = 2.3^2$ and $\varepsilon_{xz} = -\varepsilon_{zx} = ig(M_T)$, where $g(M_T) = 0.1$ is the gyrotropy of the BIG material near $1.3\mu m$. The gold permittivity is described by a Drude model fitting of ellipsometric data. The non-MO (GGG) substrate and the SiO_2 superstrate permittivities are equal to 1.97^2 and 1.45^2, respectively.

In order to study the effect of the gold grating, its coupling to the MO waveguide and its role in achieving isolation, simulations have been performed on a $3\mu m$ long structure.

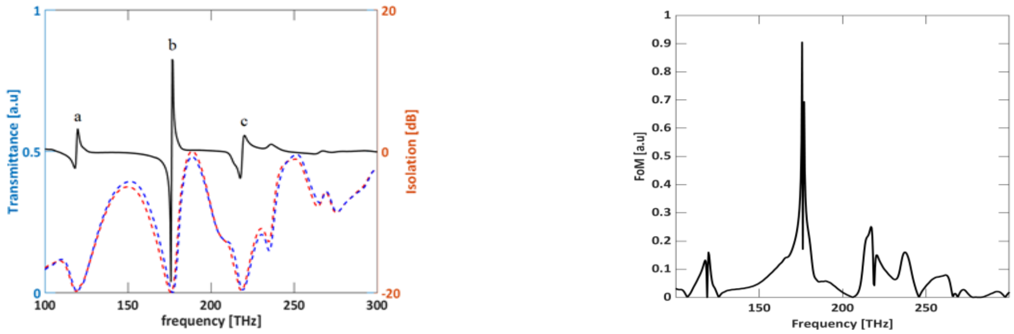

Fig. 2: (a) Transmission (red, blue) and Isolation ratio (black) in dB versus frequency for a device length of 3μm. (b) Figure of Merit of the proposed isolator structure.

In order to exploit the existence of both the horizontal and the vertical Fabry Perot modes within the grating slits, we consider here the case of gold elements having a width (along z direction) w_{Au}=0.9μm. Forward and backward transmissions and isolation ratio in dB are represented in Figure 2(a), and the Figure of Merit (FoM) which is defined as the ratio of isolation (dB) to the insertion losses (dB) is represented in Figure 2(b).

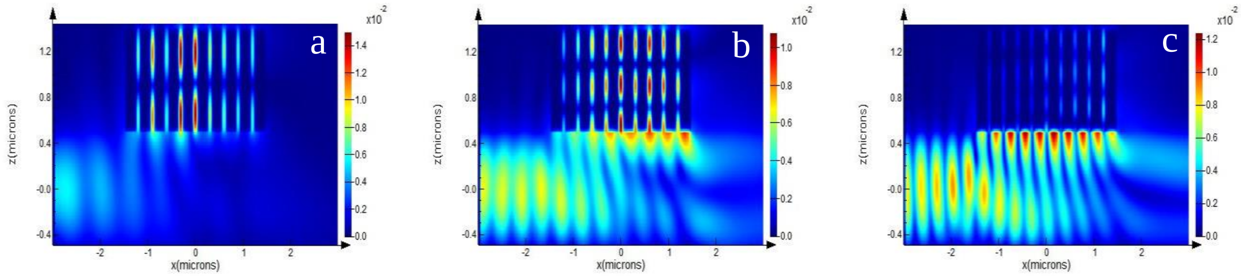

Fig. 3 Top view of the magnetic field maps $|H|$ of the points a, b and c denoted on the isolation curve of fig 2 (a).

The forward and the backward transmission curves in Figure 2, show three preeminent resonant dips where higher isolation occurs. Looking at the magnetic field maps in Figure 3, we can clearly identify that these resonant dips corresponds to the 2nd, the 3rd and the 4th order horizontal Fabry-Perot modes. Whenever there exists a coupling between the waveguide mode and the FP modes excited in the slits, we observe an increase in the isolation. The highest value of the FoM in Figure 2(b) corresponds to the point b in Figure 2(a) and to the field map 2 of Figure 3.

The spectral position of these cavity resonances can be well fitted with the FP equation expressing the round-trip resonance. [5]

$$2n\pi = \varphi_{r1} + \varphi_{r3} + 2k_0 n_{eff} w_{cav}, \qquad n \in \mathrm{Z} \tag{1}$$

Where w_{cav} is the length of the Fabry Perot cavity, (in this case w_{Au}) and φ_{ri} is the reflection phase shift of the slit mode at each end of the cavity; $i = 1$ is for the permittivity of BIG and $i = 3$ is for the permittivity of SiO_2. The effective index n_{eff} is given by the fundamental TE mode of the whole transverse structure.

CONCLUSION

In this work, we have numerically shown that when a MO-BIG waveguide is coupled to a gold grating adjacent to it, surface plasmon polaritons may strongly enhance transverse magnetic-optical Kerr effect especially when guided TE modes interact with slit FP modes. The TMOKE effect can be tuned by optimization of the grating geometry and opens the prospect of achieving an integrated isolator for TE mode.

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