Integrated magneto-plasmonics for non-reciprocal optical devices

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Integration of optical isolators and circulators has remained for many years a crucial technological issue which makes difficult the insertion of active components in photonic circuits (PICs). More generally, use of non-reciprocal (NR) transmission in photonic systems could considerably enrich possible architectures. The design of optical guided structure with NR functionality requires simultaneous spatial and time-reversal symmetry breakings in the waveguide (WG). Whereas spatial symmetry breaking is easy to obtain by suitable geometrical design, time-symmetry breaking requires non-linear interaction of the propagative wave with the medium. Magneto-optical materials can provide this non-linearity. Especially the transverse magneto-optical Kerr effect (TMOKE) is well-adapted to guiding configurations and thus to integration in PICs. The main magneto-optical materials exploited for TMOKE induced non-reciprocal transmission at telecom wavelengths are garnet oxides like Bi or Ce substituted Ytrium iron garnets (Bi:YIG, Ce:YIG), and ferromagnetic metals like FeCo.

Garnet interferometer lead to the demonstration of 21 dB of isolation at 1550nm in a nonreciprocal SOI device made of a directly wafer bonded Ce-YIG bulk layer [1], with a large footprint. For miniaturization, MO strength can be enhanced using the light confinement and deceleration concepts from garnet photonic crystal [2,3]. A fundamentally different approach consists in using metallic MO cladding layers, like FeCo, and exploit the imaginary part of the TMOKE effect, i.e. the non-reciprocal dichroic loss [4,5]. A TM semiconductor optical amplifier including 50 nm thick FeCo layer deposited on WG, reached isolation ratio of 12 dB without insertion losses [6]. However, the compromise between metal induced losses and TMOKE strength (related to mode confinement in FeCo layer) was never really solved, to reach application compatible performance. One aspect of this work was the special role played by the surface plasmon polariton (SPP) excitation at the ferromagnetic metal interface which causes a concentration of the light near the magneto-optically active interface.

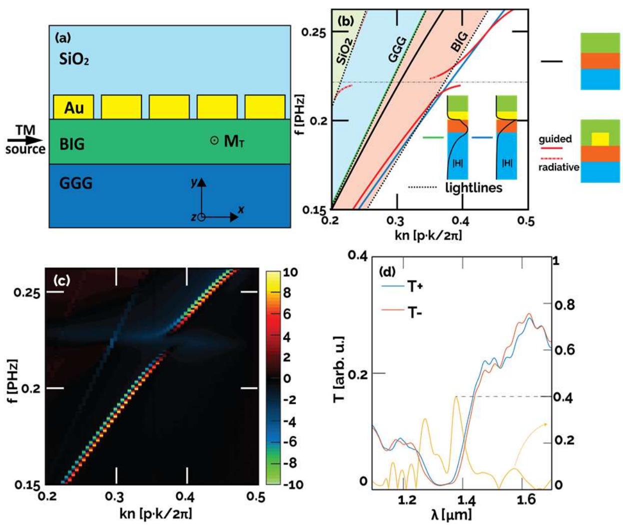

Fig. 1. (a) 1D periodic Au grating on BIG waveguide covered by SiO_2. (b) FDTD calculated band structure of the magneto-plasmonic. (c) Superposition of band structures for $+M_T^{sat}$ and -M_T^{sat}. (d) WG transmittance T and isolation ratio parameter Δ.

With the same idea, huge enhancement of TMOKE with a metallic grating on a MO substrate [7] was demonstrated, in non-guided structures. One significant improvement with respect to the use of FeCo layer comes from the separation here of plasmonic and

MO effects in two different materials (plasmonic metal and MO oxide), allowing the mode energy concentration in the MO and less lossy one. More recently, sign inversion of the non-reciprocal dichroism for a given magnetization direction was also obtained with gold grating deposited on MO garnet thick layer [8], by only grating shape modification. Sign inversion is induced by resonant modes coupling involving both the Fabry-Perot (FP) mode generated in the grating slits, and the SPP mode at the garnet/Au interface, and could be suitably used in a push-pull configuration.

This property is the starting point for a renewal of the integrated isolator design. In this paper we propose to extend it to the TM waveguide configuration with a 1D periodic Au grating on BIG (Bismuth Iron Garnet) waveguide in TMOKE configuration (Fig. 1(a)).

The optical response of the waveguide 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: $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = 2.51^2$ and $\varepsilon_{xy} = -\varepsilon_{yx} = ig(M_T)$, where $g(M_T)$ is the gyrotropy of the BIG material. BIG dispersion is negligible in the study wavelength range and $g(M_T^{sat}) = 0.1$ at the saturation magnetization [9]. 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.

Figure 1(b) represents the band diagram of the proposed structure when the height, period and slits of the grating respectively are h =130 nm, p = 200 nm and s = 20 nm. The grating period is shorter than the 1^{rst} order Bragg condition in order to avoid back reflection. Dash-dotted black lines correspond to BIG, GGG and SiO_2 lightlines. Full and dash-dotted red curves correspond to dispersion curves of the magneto-plasmonic WG. The presence of 1D periodic slits of 20 nm in the gold film introduces the formation of a bandgap at 1.33 µm. This bandgap is attributed to the coupling between Fabry-Perot like slits modes (independent of the waveguide mode k-vector) and the SPP mode (interrupted by the grating slits) related to the blue dispersion curve. Fig. 1(c) presents the superimposition of the band structures for $+M_T^{sat}$ and $-M_T^{sat}$. We clearly observe a shift of the SPP dispersion curves, which highlights the existence of a difference between the wave vectors for waves propagating in forward and backward directions. The corresponding WG transmittances T^+ and $T^-$are represented in Fig. 1(d), together with the isolation parameter $\Delta = abs(T^+ - T^-)/\max(T^+, T^-)$. Two maxima can be distinguished at 1.38 µm, and 1.27 µm on the Δ curve. This shows that, for this specific grating geometry, the NR transmission is enhanced in the vicinity of the bandgap.

To conclude, we have numerically shown that when a magneto-optical bismuth iron garnet waveguide is coupled to a gold grating on its top, surface plasmon polaritons may strongly enhance transverse magnetic-optical Kerr effect especially when guided modes interact with grating slit modes. The TMOKE effect can be tuned by optimization of grating geometry and opens the prospect of achieving an improved integrated isolator.

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