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Magneto-plasmonic waveguides for non-reciprocal devices

G. Calò¹, Member, IEEE, G. Magno¹, V. Petruzzelli¹, V. Yam², B. Dagens²

¹Department of Electrical and Information Engineering, Polytechnic University of Bari, Via Orabona, 4, Bari 70125, Italy

²Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, 91120, Palaiseau, France
Tel: (0039) 080 5963217, Fax: (0039) 080 5963410, e-mail: giovanna.calo@poliba.it

ABSTRACT

Reliable communication networks require high-performance, low-cost, efficient, and miniaturized components, especially in the photonic domain. In particular, essential building blocks for photonic integrated systems are optical circulators and isolators. These non-reciprocal elements can enable full integration of the systems, can diversify circuit architectures, and can protect lasers from spurious back reflections in the optical path. Magneto-plasmonic waveguides support asymmetric modes resulting from the Transverse Magneto-Optical Kerr Effect (TMOKE) interaction between Magneto-Optic (MO) materials and coupled plasmonic modes. The induced asymmetry in the mode profiles and the non-reciprocal propagation can be exploited for designing integrated isolators and circulators.

Keywords: magneto-plasmonic waveguides, magneto-optics, non-reciprocal integrated devices, optical isolators, optical circulators, photonic integrated circuits.

1. INTRODUCTION

The continuous development of optical communication technologies demand low-cost, efficient, and miniaturized systems that can efficiently realize data switching, routing, processing functions, and wideband or multi-wavelength operations [1-7]. Photonic integrated circuits (PICs) are among the most promising technologies due to the high performance in terms of transmission speed, bandwidth, energy efficiency, but photonic integration still needs extensive research to implement optical isolator and circulator functions. The realization of integrable non-reciprocal (NR) elements would allow for full system integration, protecting lasers from spurious reflections in the optical path, and would allow for diversification of circuit architectures.

Different integrated solutions have been proposed in the literature for the realization of non-reciprocal components. For example, Magneto-Optic (MO) metals have been used as a top or side cladding to exploit their non-reciprocal behavior, and Transverse Magneto Optic Kerr Effect (MOKE)-induced phase shift was also exploited in garnet interferometers [8-10]. Through direct integration of (Ce:YIG) garnet material, performance and footprint optimization have been achieved with high-Q (quality factor) non-reciprocal resonators or improved interferometers [10-13]. Nonetheless, the current integrated solutions are generally forced to compromise between performance, bandwidth, footprint, and large-scale fabrication.

This paper investigates the non-reciprocal behaviour of integrated plasmonic strip waveguides arising from the magneto-plasmonic effect. This effect, stemming from the interaction between a magneto-optical material and plasmonic modes (SPP – Surface Plasmon Polariton), offers broadband operation since it does not rely on resonant structures. Moreover, thanks to the technological compatibility with virtually any photonic platform, the magneto-plasmonic phenomenon in plasmonic waveguides holds promise for the development of circulators and isolators integrated into different photonic circuits.

2. NON-RECIPROCAL MAGNETO-PLASMONIC STRIP WAVEGUIDES

Fig. 1 (a) shows the cross-section of the analyzed magneto-plasmonic strip waveguide. The metal waveguide is made of gold (Au), with complex permittivity modelled according to [14], deposited on a silicon dioxide substrate, which is typical of integrated photonic platforms such as Silicon on Insulator (SOI). On the sides of the metal strip the magneto-optical dielectric material is considered with refractive index $n_{MO}=2.3$. The superstrate is made of a material with a refractive index equal to that of silicon dioxide $n_{SiO_2}=1.445$.

To incorporate the magneto-optical phenomenon into the electromagnetic analysis of plasmonic modes, the material properties need to be described using a permittivity tensor. In magneto-optical materials, the permittivity tensor has non-zero extra-diagonal elements ε_{ij} and ε_{ji} (with i and j equal to x, y, z according to the chosen coordinate system) with equal values, but opposite signs. In the considered garnet MO material, these coefficients become non-zero due to the application of an external magnetic field. In the absence of the magnetic field, however, the material behaves like an isotropic material.

Considering the reference system in Fig. 1(a), the magneto-optical material, with a magnetic field applied along the z -axis inducing a magnetization M , can be represented by the permittivity matrix:

$$\varepsilon = \begin{pmatrix} n_{MO}^2 & i \cdot g & 0 \\ -i \cdot g & n_{MO}^2 & 0 \\ 0 & 0 & n_{MO}^2 \end{pmatrix} \quad (1)$$

The parameter g represents the gyrotropic coefficient, whereas n_{MO} is the refractive index of the magneto-optical material.

The structure shown in Fig. 1(a) was simulated using a full-wave three-dimensional Finite Difference Time Domain (3D-FDTD) model [15], in which the magneto-optical material and the TMOKE were simulated by incorporating a non-diagonal permittivity matrix. In addition, to account for the effect on propagation, a matrix transformation was performed by determining the eigenvalues and eigenvectors associated with the permittivity matrix. These eigenvectors were then assigned as properties to the calculation grid. In this way, when the gyrotropic coefficient is non-zero, the non-reciprocal effect on the propagation modes can be analyzed.

The strip structure in Fig. 1 (a) can support Long Range Surface Plasmon (LRSP) and Short Range Surface Plasmon (SRSP) modes, the characteristics of which change as a function of magneto-optic material properties. In particular, the magneto-plasmonic effect induces an asymmetrization of the electromagnetic field intensity. For example, Fig. 1 (b-d) show the E_y component of the electric field of the LRSP mode in the y - z cross-section for different values of the gyrotropy g : (a) $g=0$, (b) $g=+0.1$, (c) $g=-0.1$. The magneto-optic effect concentrates the electromagnetic field on one of the two interfaces between metal and magneto-optical material. When no external magnetic field is applied (i.e. $g=0$), the LRSP is symmetric. However, with a non-zero external magnetic field, the mode concentrates on one interface depending on the propagation direction (i.e. one interface for forward propagation ($g=+0.1$) and the other one for backward propagation ($g=-0.1$)). Similar behaviour is observed for the SRSP.

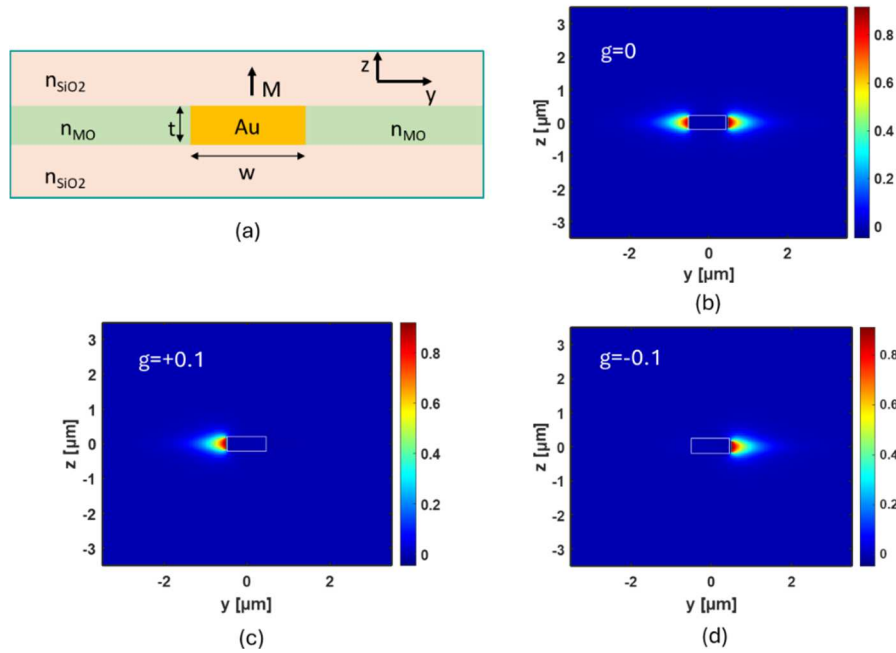


Figure 1. (a) cross section of the magneto-plasmonic strip waveguide, (b-d) Electric field E_y component of the LRSP mode in the y - z cross-section for different values of the gyrotropy g : (a) $g=0$, (b) $g=+0.1$, (c) $g=-0.1$.

In the case of magneto-plasmonic waveguides, an important parameter, that influences the properties of the propagating modes, is the width w of the strip waveguide. Fig. 2 (a) and (b) show the trend of the real (Fig. 2 (a)) and imaginary (Fig. 2(b)) parts of the effective refractive index of the LRSP (dashed curves) and the SRSP (solid curves) as a function of the strip waveguide width w , calculated for different values of the gyrotropy. In this example, the magneto-optical material has refractive index $n_{MO}=2.3$, whereas the thickness t of the gold strip is $t=300$ nm, and the wavelength is $\lambda=1.55$ μm .

As shown in Fig. 2 (a), the real part of the effective refractive indices of the LRSP and SRSP modes are well separated for low values of the width w . However, these curves converge to significantly closer values as the width increases. Additionally, Fig. 2 (b) shows that the imaginary part of the effective refractive index of the SRSP mode (solid curve) is higher than that of the LRSP mode (dashed curve). However, as the width increases, the curves in Fig. 2(b) also converge to significantly closer values.

For NR transmission, both time and spatial symmetries must be broken. While the strip waveguide is spatially symmetric, the TMOKE effect induces a spatial asymmetry within each mode (i.e. LRSP and SRSP). Interestingly, both modes exhibit the same degree of asymmetry, but with opposite repartition between their lobes. Since the excitation of both modes does not induce spatial symmetry breaking, only the less lossy (i.e. the LRSP) should be excited to achieve NR behavior. The trends of the effective refractive indices of the LRSP and SRSP suggest that for low values of the width w , it is possible to selectively excite the mode. In fact, when the width is narrow, the effective refractive indices of the two modes are strongly different. Therefore, in principle, it is possible to excite only one of the two modes by an external electromagnetic field with the same symmetry characteristics (e.g. even symmetry for the LRSP and odd symmetry for the SRSP) and the same propagation constant as the selected plasmonic strip mode.

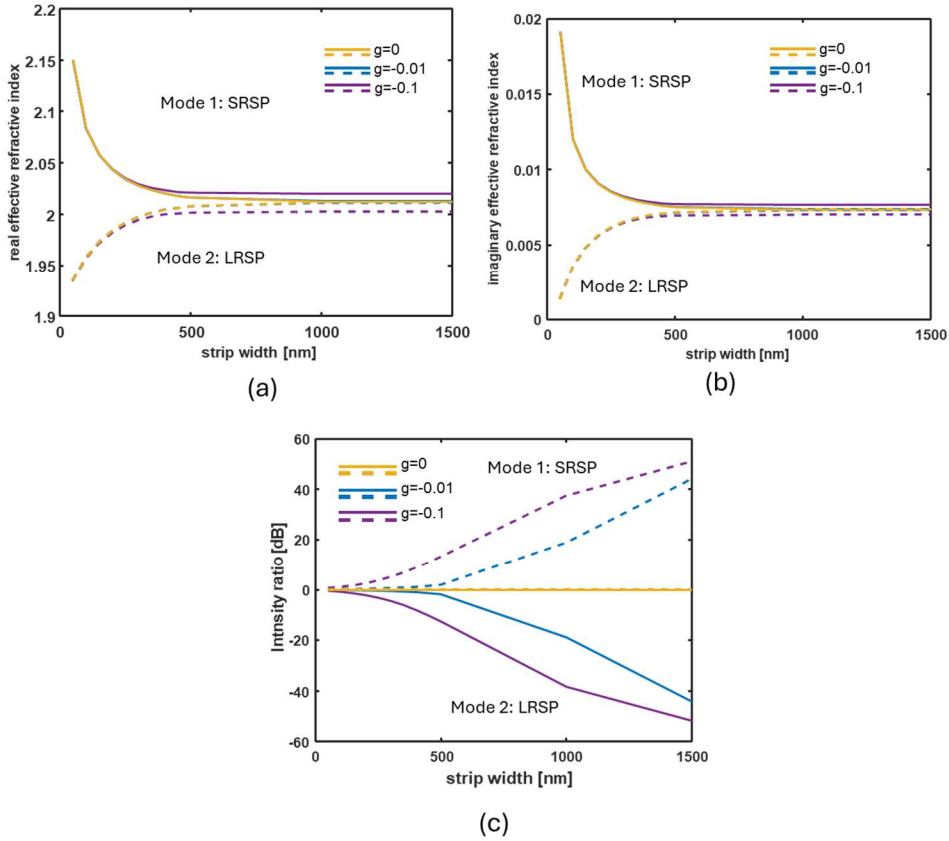


Figure 2. (a) Real part and (b) imaginary part of the effective refractive index, and (c) intensity ratio as a function of the strip waveguide width w , calculated for different values of the gyrotropy. The magneto-optical material has refractive index $n_{MO}=2.3$, whereas the thickness t of the gold strip is $t=300$ nm.

The asymmetrization of electromagnetic field strength due to the magneto-plasmonic effect can be quantified by defining the intensity ratio (IR) as the ratio, expressed in dB, of the maxima of the electric field modulus $|E|$ at metal-dielectric interfaces calculated as:

$$IR = 20 \log_{10} \left(\frac{\max_{y \geq 0} |E|}{\max_{y < 0} |E|} \right).$$

Figure. 2 (c) shows the intensity ratio IR for the SRSP (solid curves) and LRSP (dashed curves) modes as a function of the width of the magneto-plasmonic strip waveguide, calculated for different values of the coefficient g . As it can be seen from Figs. 2 (c), the intensity ratio increases with the width of the magneto-plasmonic strip waveguide for non-zero g values. This behavior can be explained by considering that each mode (i.e LRSP and SRSP) can be seen as the superposition of modes localized at the individual metal-dielectric interfaces. When the metal strip is narrow, the modes at the two interfaces are strongly coupled and the magneto-plasmonic effect is less apparent. Conversely, by increasing the width w , the modes at the two interfaces become weakly coupled and

the magneto-plasmonic effect is more efficient, resulting in higher asymmetry. Thanks to the mode asymmetry and to the non-reciprocal behaviour, the magneto-plasmonic effect in strip waveguides can enable the implementation of isolators or circulators [16-17].

3. CONCLUSIONS

The analysis of three-dimensional magneto-plasmonic strip waveguides has been reported, highlighting the effects of the gyrotropic coefficient g and of the geometric parameters of the propagating modes. The trends in the effective refractive indices of the LRSP and SRSP suggest that, for low values of the width, it is possible to select the desired propagation mode by exciting only one of the two. The investigation also found that the asymmetrization of the modes increases when the width w of the strip waveguide is increased. Therefore, in principle, by tapering the waveguide this effect can be exploited to achieve high asymmetry, especially when low gyrotropy materials are used.

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REFERENCES

- [1] Q. Cheng, M. Bahadori, Y.-H. Hung, Y. Huang, N. Abrams, and K. Bergman, "Scalable microring-based silicon crosstalk switch fabric with switch-and-select stages," *IEEE J. Sel. Topics Quantum Electron.*, vol. 25, no. 5, pp. 1–11, Sep. 2019.
- [2] A.S.Vorobev; G.V.;Bianco, G. Bruno, A. D'Orazio, L. O'Faolain, M. Grande, "Tuning of Graphene-Based Optical Devices Operating in the Near-Infrared". *Appl. Sci.* **2021**, 11, 8367.
- [3] A. Kazmierczak et al., "Highly integrated optical 4×4 crossbar in silicon-on-insulator technology," *J. Lightw. Technol.*, vol. 27, no. 6, pp. 3317–3323, Aug. 1, 2009
- [4] M.C. Falconi, D. Laneve, V. Portosi, S. Taccheo, F. Prudenzano, "Design of a Multi-Wavelength Fiber Laser Based on Tm:Er:Yb:Ho Co-Doped Germanate Glass", *Journal of Lightwave Technology*, 38 (8), art. no. 8961094, pp. 2406 – 2413
- [5] G. Calò, D. Alexandropoulos, V. Petruzzelli, "Active photonic band-gap switch based on GaInNAs multiquantum well", *IEEE Photonics Journal*, 4 (5), pp. 1936-1946.
- [6] G. Magno, A. Monmayrant, M. Grande, F. Lozes-Dupuy, O. Gauthier-Lafaye, G. Calò, V. Petruzzelli, "Stable planar mesoscopic photonic crystal cavities", *Optics Letters*, 39 (14), pp. 4223-4226.
- [7] A. Monmayrant, M. Grande, B. Ferrara, G. Calò, O. Gauthier-Lafaye, A. D'Orazio, B. Dagens, V. Petruzzelli, and G. Magno, "Full optical confinement in 1D mesoscopic photonic crystal-based microcavities: an experimental demonstration," *Opt. Express* 25, 28288-28294 (2017)
- [8] T. Mizumoto, Y. Shoji, R. Takei, "Direct Wafer Bonding and Its Application to Waveguide Optical Isolators". *Materials (Basel)*. 2012 May 24;5(5):985-1004.
- [9] W. Zaets, K. Ando "Optical waveguide isolator based on nonreciprocal loss/gain of amplifier covered by ferromagnetic layer", *IEEE Photonics Technology Letters*. 1999;11(8):1012-1014.
- [10] M. Fujita, R. M. Levy, L. Osgood, H. Wilkens, H. Dötsch, "Waveguide optical isolator based on Mach-Zehnder interferometer", *Appl. Phys. Lett.* 17 April 2000; 76 (16): 2158–2160.
- [11] L. Bi, J. Hu, P. Jiang, P. et al. "On-chip optical isolation in monolithically integrated non-reciprocal optical resonators", *Nature Photon* 5, 758–762 (2011)
- [12] P. Pintus, D. Huang, P.A. Morton, Y. Shoji, T. Mizumoto, J.E. Bowers, "Broadband TE optical isolators and circulators in silicon photonics through Ce: YIG bonding", *Journal of Lightwave Technology*, 2019, 37(5), 1463-1473.
- [13] S. Ghosh, S. Keyvaninia, W. Van Roy, T. Mizumoto, G. Roelkens, R. Baets, "Adhesively bonded Ce:YIG/SOI integrated optical circulator", *Opt. Lett.* 38, 965-967 (2013).
- [14] P. B. Johnson and R. W. Christy. "Optical constants of the noble metals", *Phys. Rev. B* 6, 4370-4379 (1972).
- [15] *Lumerical Solutions Inc.* Available online: <https://www.ansys.com/products/photonics>
- [16] S. Abadian, G. Magno, V. Yam, B. Dagens, "Broad-band plasmonic isolator compatible with low-gyrotropy magneto-optical material," *Opt. Express* 29, 4091-4104 (2021).
- [17] K. S. Ho, S. J. Im, J. S. Pae, C. S. Ri, Y. H. Han, J. Herrmann, "Switchable plasmonic routers controlled by external magnetic fields by using magneto-plasmonic waveguides", 2018 Scientific reports, 8(1), 10584.