Investigation of non-reciprocal magneto-plasmonic waveguides for compact integrated optical isolators on silicon

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Introduction

Creating compact on-chip non-reciprocal components is of fundamental interest in integrated optics at telecom wavelength of 1.55 µm. Today a lot of integrated functions are available commercially such as lasers, couplers, filters, modulators, but there is a lack of non-reciprocal integrated functions like optical isolators and circulators. Commercial optical isolators are expensive bulk components operating in the Faraday configuration (with a longitudinal external magnetic field) not suited for integration. They are based on garnet magneto-optical material which has very low absorption at telecom wavelength.

Integrated optical isolators based on Mach-Zehnder designs in the Kerr configuration (i.e. with a transverse external magnetic field with respect to the propagation direction) have been proposed using also garnet as magneto-optical material [1]. There have been a large number of demonstrations of stand-alone optical isolators and circulators based on iron garnet waveguides, but they have not become commercial devices due to their lack of compatibility with InP or Si-based photonic platforms. Up to now, the expensive technique of wafer bonding is necessary to combine garnets with InP- or Si-based semiconductor materials [2].

Another approach is the use a ferromagnetic material like FeCo which exhibits a much larger magneto-optical activity, thus leading to more compact devices. Moreover FeCo is fully compatible with InP or Silicon chips. Recently, FeCo has been used in an integrated laser system with direct isolation operating at 1.3 µm wavelength, demonstrating isolation ratio close to 100 dB/cm [3].

As a metal, FeCo can sustain surface plasmon polaritons. In this paper, we study so-called magneto-plasmonic waveguides combining both magneto-optical and plasmonic properties. We investigate numerically the non-reciprocal properties of such waveguides to assess their potential for optical isolators.

Results

We study compact SOI ridge waveguides with a FeCo capping layer of varying thickness on top. The waveguides have a typical width of 500 nm and a height of 220 nm and are embedded in a SiO_2 matrix. Finite element simulations were performed to analyze the modes supported by the waveguides as a function of the FeCo thickness. The refractive indices of Si and SiO2 were taken as $n_{Si} = 3.47$, $n_{SiO_2} = 1.44$ and the complex permittivity tensor of FeCo, with external magnetization applied along the *x* axis was taken as $\varepsilon_{FeCo} = \begin{pmatrix} -10+29i & 0 & 0 \\ 0 & -10+29i & -1.7+1.8i \\ 0 & 1.7-1.8i & -10+29i \end{pmatrix}$.

Without FeCo, the reference SOI waveguide supports two fundamental TE and TM photonic modes with an effective index of 2.43 and 1.84 respectively. For thin FeCo thickness on top of the waveguide, i.e. in the range 0-20 nm, both TE and TM modes show a smooth evolution of their effective index, as shown in Figure 1a. Above 20 nm of FeCo, plasmonic modes, with a maximum field intensity at the interface between FeCo and Si start to appear. These modes are typical of dielectric-loaded surface Plasmon polariton waveguides (DL-SPP) [4].

The non-reciprocity NR induced by the magneto-optical material FeCo is defined as the relative difference between the effective index of the forward and backward propagating modes under saturated magnetization with respect to the effective index under zero magnetization. The non-reciprocity therefore reads $NR = \frac{n_{eff}(+M) - n_{eff}(-M)}{n_{eff}(M=0)}$. For each mode, magnetization is applied in the Kerr configuration in order to avoid polarization conversion. For the TE mode, magnetization is applied along the *y* axis, whereas for the TM photonic and DL-SPP modes, magnetization is applied along the *x* axis. Results are presented in Figure 1b. For the TE and TM photonic modes, there is an optimal FeCo thickness for which the non-reciprocity is maximum. The optimal FeCo thickness is 25 nm for the TE photonic mode with a relative effective index variation of 0.4 10^{-3} and 15 nm for the TM photonic mode with a relative effective index variation of 3.6 10^{-3}. For the DL-SPP fundamental mode, the behaviour is different. The non-reciprocity increases exponentially and progressively reaches saturation. The relative effective index variation reaches 9 10^{-3} for a FeCo thickness of 50 nm. The corresponding Mach-Zehnder isolator devices defined by $L = \lambda_0 / 8\Delta n_{eff}$ are 215 µm for the TE photonic mode, 32 µm for the TM photonic mode and only 7 µm with the DL-SPP mode.

Conclusion and persepctives

We have studied numerically a magneto-plasmonic waveguide consisting of a classical silicon ridge waveguide with a magneto-plasmonic layer of FeCo on top. For a FeCo thickness above 20 nm, the waveguide supports a plasmonic guided mode, for which the relative non-reciprocal effective index variation between forward and backward propagation reaches 9 10^{-3}, allowing to reduce the size of optical isolator devices down to 7 µm. These waveguides can be fabricated on 300 mm wafers using standard microelectronic tools. Other more compact waveguide configurations like metallic slot waveguides can be envisioned in the future [5].

References

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Figures

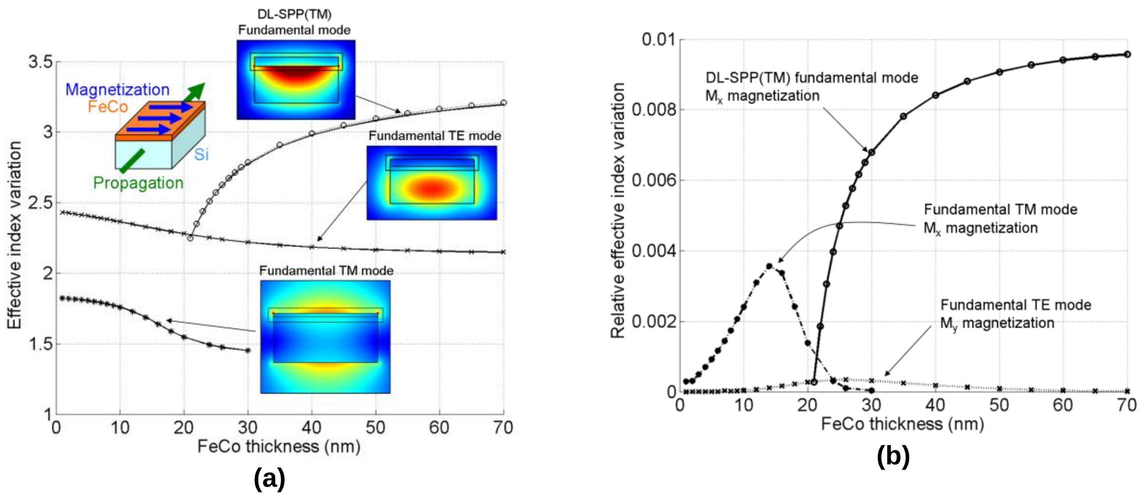

Figure 1: (a) Effective index of the modes supported by a silicon ridge waveguide with a FeCo layer of varying thickness on top. The associated electromagnetic field maps are represented as insets; (b) Relative effective index variation between forward and backward propagating modes illustrating the amount of non-reciprocity effect in the Si/FeCo magneto-plasmonic waveguide.