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Optimization of Figure of Merit in Magneto-Plasmonic Waveguides with Fe / Au Multilayer and Nonreciprocal Coupling on SOI substrate

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Abstract

We report on optimization of figure of merit in magneto-plasmonic waveguides with Fe / Au multilayer on Si on insulator (SOI) substrates. The thicknesses of the upper highly conductive metal Au, ferromagnetic metal Fe, and lower Au layers are optimized, so that sizable MO effect and low propagation loss coexist. Based on the optimized multilayer structure, we designed Si waveguide optical isolators based on nonreciprocal coupling by two dimensional finite difference time domain (FDTD) method. We estimated an isolation of 5.7 dB with forward insertion loss of 13.9 dB in a 34 μm-long nonreciprocal directional coupler.

1. Introduction

Surface plasmon polaritons (SPPs) are quasiparticles by collective electron oscillations coupled to light waves at the interface between a metal and a dielectric, which is applied to strong confinement of light for miniaturizing the optical waveguides or highly sensitive optical sensors. It has been reported that the propagation constant and losses of SPPs can be modified by the magneto-optic (MO) effect [1-3], which are called as Magneto-Plasmonics, and expected to realize waveguide optical isolators in short propagation length (< 100 μm) for protecting laser diodes from backward-reflected light in photonic integrated circuits (PICs). Owing to lower conductivity of ferromagnetic metals (Fe, Co) than that of noble metals (Au, Ag), loss of SPPs with ferromagnetic metal is much larger than that with noble metal. Combination of noble metals with ferromagnetic metals has been extensively studied, where the MO effect is implemented by the ferromagnetic metals whereas relatively lower losses of SPPs are realized by the noble metals [1,2].

In order to integrate optical isolators based on MO-SPPs with Si waveguides, we calculated the nonreciprocal effect by transverse MO Kerr effect; difference in the effective refractive index between the forward and backward propagating light, ΔN_{eff}, in magneto-plasmonic waveguides with Fe / Au multilayer on Si on insulator (SOI) substrates. We optimized the thickness of the Fe and Au layers to obtain the largest ΔN_{eff} for the designed propagation length. Furthermore, we designed Si waveguide optical isolators based on nonreciprocal coupling [4] by two dimensional finite difference time domain (FDTD) method, based on the optimized MO-SPPs on Si waveguides.

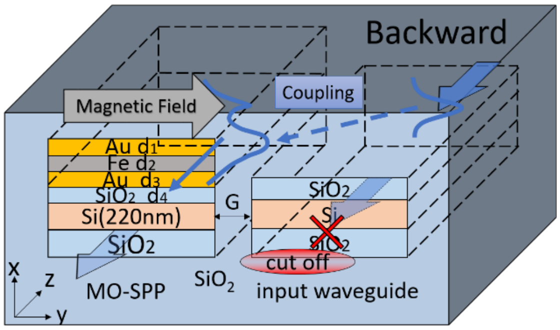

Fig. 1 A schematic figure of the optical isolator based on nonreciprocal coupling in magneto-plasmonic waveguides with Fe / Au multilayer on Si directional coupler.

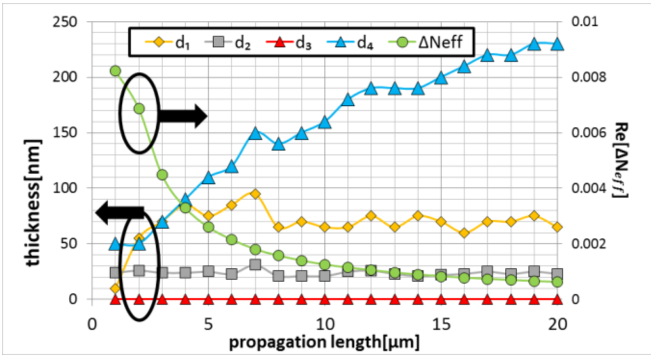

Fig. 2 Calculated sets (d_1, d_2, d_3, d_4 [nm]) of the layer thicknesses of the Fe, Au, and SiO_2 layers to obtain the largest Re[ΔN_{eff}] for the designed propagation lengths.

2. Structure of Magneto-Plasmonic Waveguides on SOI substrates, and Principle of Operation

We assumed magneto-plasmonic waveguides on SOI substrates for the wavelength of 1550 nm. The waveguides are composed of upper Au (thickness: d_1, refractive index: n_1 =0.559+9.81i) Fe (d_2, n_2=3.62+5.56i, off-diagonal component of permittivity $\varepsilon_{2,\,MO}$=3.12-1.80i), lower Au (d_3), SiO_2 (d_4, n_4=1.44) layers on an SOI substrate. The thickness of Si core layer was fixed at 220 nm. The upper and lower Au layers are added with Fe layer in order to reduce the loss by the ferromagnetic Fe layer. The SiO_2 layer is located between the metal multilayer and the Si core layer and works as a buffer layer. Ferromagnetic metal is magnetized parallel to the film and perpendicular to the propagation direction (Voigt configuration) providing transverse magneto-optic Kerr effect (TMOKE) to the propagating light.

MO-SPPs are excited for transverse magnetic (TM) mode,

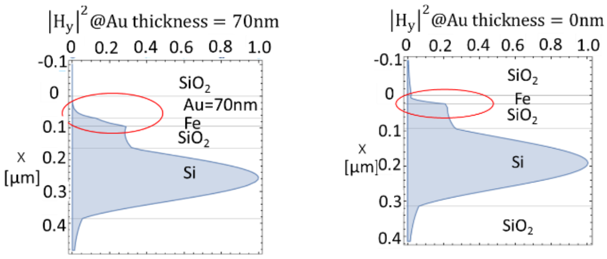

Fig. 3 Calculated $|H_y|^2$ profile of the propagating TM mode light for (a) optimized multilayer thicknesses, and (b) multilayer without upper Au layer (d_1 = 0 nm).

and N_{eff} differs by ΔN_{eff} between the propagation directions owing to TMOKE. Larger ΔN_{eff} brings larger difference of the waveguide coupling between the forward and backward propagating light in the directional coupler (nonreciprocal coupling) in Fig. 1. By utilizing the nonreciprocal coupling, backward propagating light is coupled to the MO-SPPs on SOI substrates more strongly than forward propagating light, leading to lower optical transmission for backward propagating light than that for forward propagating light. Therefore, optical isolator operation is realized.

3. Optimization of Figure of Merit in Magneto - Plasmonic Waveguides

We calculated N_{eff} and ΔN_{eff} in the waveguides with MO-SPPs as shown in Fig. 1. We optimized the thicknesses of the Fe, Au, and SiO_2 layers to obtain the largest Re[ΔN_{eff}] for the designed propagation lengths between 1 and 20 μm. The thicknesses of each layer; d_1, d_2, d_3, and d_4 are varied between 0-200, 0-50, 0-200, and 0-300 nm, respectively. Please note that it is important to maximize the difference of the real part of the effective refractive index Re[ΔN_{eff}] in order to increase the nonreciprocal coupling and optical isolation. Fig. 2 shows the calculated results of the optimized sets of the layer thicknesses and Re[ΔN_{eff}] for designed propagation length of 1-20 μm. When we set the propagation length to 3 μm, the optimized sets of the layer thicknesses (d_1, d_2, d_3, d_4 [nm]) is (70, 24, 0, 70 nm), and Re[ΔN_{eff}] is calculated to 0.00448. N_{eff} is calculated to $2.333 + 0.0411i$, and $2.337 + 0.0404i$ for forward and backward propagating light. The SiO_2 layer thickness d_4 is almost proportional to the propagation length and optimized lower Au layer thickness d_3 is 0 nm, meaning that the SiO_2 layer thickness determines the SPP loss. Insertion of the upper Au layer and optimized thickness d_2 of the Fe layer are effective to increase Re[ΔN_{eff}] for the same SiO_2 layer thickness and SPP loss, meaning that figure of merit in MO-SPPs is optimized by selecting the set of the thicknesses of the upper Au and ferromagnetic Fe layer (d_1 and d_2,).

Fig. 3 shows the calculated mode ($|H_y|^2$) profile of the propagating TM mode light for the (a) optimized multilayer thicknesses, and (b) multilayer without upper Au layer (d_1 = 0 nm). Moderate damping of the mode profiles is observed inside the Fe layer for (a), whereas sharp damping of the mode profile is observed inside the Fe layer for (b). By inserting conductive Au layer between the Fe and SiO_2 layer, ohmic loss at the interface was suppressed, leading to improved figure of merit.

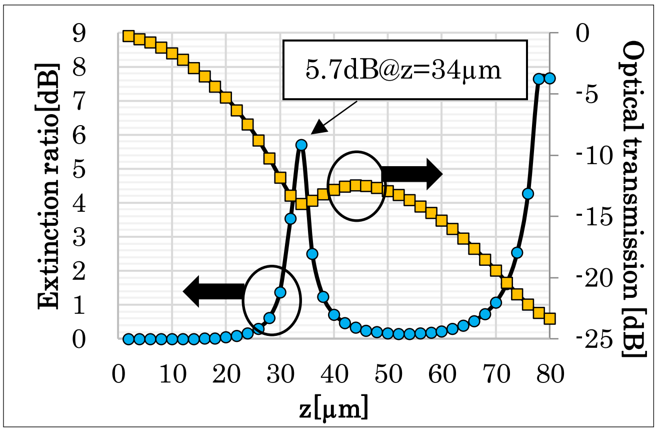

Fig. 4 Calculated extinction ratio and optical transmission (forward light) when SiO_2 gap width G = 0.45 μm.

4. Nonreciprocal Coupling in MO-SPPs on Si Waveguides with Directional Couplers

We estimated the nonreciprocal coupling in MO-SPPs on Si waveguides with directional couplers as shown in Fig. 1. One waveguide of the directional coupler is composed of a transparent Si wire waveguide having the effective refractive index of 2.333, which is the same as Re[N_{eff}] for the forward propagating light of the optimized MO-SPP waveguide in the previous section. The other waveguide is composed of the optimized MO-SPP waveguide. The width of the two waveguides, and wavelength are set to 400 nm, and 1550 nm. Two waveguides are surrounded with SiO_2 cladding layer. We estimated the optical transmission for the forward and backward TM mode light by two dimensional finite difference time domain (FDTD) method. Fig. 4 shows the calculated extinction ratio (optical isolation) and optical transmission for forward propagating light when the SiO_2 gap width is 450 nm. The extinction ratio of 5.7 dB was estimated with insertion loss (forward light) of 13.9 dB at the coupling length z = 34 μm. By optimizing the figure of merit in MO-SPPs on Si waveguides, sizable optical isolation was estimated. Although the loss is still large, the optimization of the propagation length of MO-SPPs in Fig. 2 and width of the waveguide improves the performance.

5. Conclusions

We designed optical isolators based on nonreciprocal coupling in magneto-plasmonic waveguides with Fe / Au multilayer on SOI substrate. We optimized the set of the layer thicknesses to obtain the largest fugure of merit in MO-SPP waveguides. Furthermore, we simulated nonreciprocal couping and estimated the extinction ratio of 5.7 dB with forward insertion loss of 13.9 dB.

Acknowledgements

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