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Nonreciprocal Magneto-Plasmonic Waveguide with Compact Metal-Sandwiched Structure *

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A magneto-optical (MO) metal-sandwiched multilayered structure composed of metal, MO medium and dielectric buffer layers is presented and investigated by finite-element-method-based-mode solver and perturbation theory. The results show that this structure exhibits large nonreciprocal phase shift, strong mode confinement in the narrow buffer layers as well as very low propagation loss. The propagation length with 1 dB loss is much longer than the required length of $\pi/2$ nonreciprocal phase shifts in this structure. The modal area is smaller than half of the conventional MO waveguides. This phenomenon can be used to achieve a compact plasmonic isolator based on the Mach–Zehnder interferometer.

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Surface plasmon polariton (SPP) waveguides are essential elements in photonic integration circuits owing to their subwavelength confinement and potential applications in ultrasensitive optical measurements. Developing active components, such as the ones that exist in the conventional integrated optics as switches, modulators or isolators, has a substantial reality. Magneto-optical isolators, which are widely used to protect optical devices from unwanted reflections, play an important role in establishing stable high speed optical network systems. Magneto-optical (MO) waveguides with nonreciprocal phase shift (NRPS) play critical roles in applications of optical isolators.[1−4] Of the most interest is the Mach–Zehnder interferometer (MZI) isolator based on NRPS.[5−7] However, most of them are commonly dielectric waveguides which are not easily compatible with the SPP waveguides. Therefore, the work concerning the study of the MO properties of SPPs is indispensable. How to optimize a plasmonic MO waveguide structure which is more compatible than the full-dielectric MO waveguides with plasmonic nanophotonic circuits is an interesting topic. It is well known that plasmonic excitations can be sensitive to dielectric properties of the metal and the surrounding medium. Just considering the enhancement of the MO effect, the MO(+)/Cu/MO(-) structure waveguide based on short-range SPPs will really challenge conventional MO waveguides.[8] However, it is meaningless when the loss problem is still very serious in practical use. The structures reported in Refs. [9,10] based on long-range SPPs have large NRPS and low loss when the thickness of metal layer is moderate, but the effective width is very large because the SPPs spreads out into both top and bottom MO layers. Some hybrid plasmonic waveguides with different structures have a relatively long propagation distance and a nano-scale light confinement.[11−15] It is meaningful to study the MO properties of the hybrid magneto-plasmonic waveguide with improved structure.

In this Letter, we present a symmetrical SiO_2/MO(+)/SiO_2/Ag/SiO_2/MO(−)/SiO_2 structure which has large NRPS, low propagation loss and small modal area. By utilizing the coupling between the dielectric waveguide and plasmonic modes, the long-range SPPs can achieve a pretty long propagation distance. The proposed structure takes the advantage of the SPPs which are sensitive to MO material properties, and two buffer layers with low refractive index that confine the field strongly. The results show that the NRPS is large, and the mode is strongly confined with low propagation loss.

The proposed structure containing Ag, MO material, SiO_2 and Si substrate is shown in Fig. 1. The SPP modes propagate along the z direction, while the entire waveguide is magnetized in the x direction. Set the incident light wavelength λ_0=1.55 μm, and the dielectric constant of silver is $\varepsilon_{\rm m} = -125.8 + 3.33i$. The buffer cladding material is SiO_2 with $n_{SiO_2} = 1.45$ and the MO material is crystallized yttrium iron garnet (YIG) with $n_{\rm MO} = 2.22$. A crystallized YIG film grown on a cerium substrate can achieve a Faraday rotation as large as −4800 deg/cm at a wavelength of 1.55 μm.[16,17] With the magnetization, the dielectric constant tensor of YIG can be given as

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{\rm m} & 0 & 0 \\ 0 & \varepsilon_{\rm m} & i\gamma \\ 0 & -i\gamma & \varepsilon_{\rm m} \end{pmatrix}. \quad (1)$$

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The element γ, which is related to the incident wavelength λ_0, the specific Faraday rotation θ_F and the YIG refractive index n_{MO}, is given by $\gamma = \lambda_0 \theta_F n_{MO}/\pi$. In order to enhance the NRPS, double YIG layers with opposite Faraday rotation and same thickness are used, as depicted in Fig. 1. This double-layer structure is achievable by modifying the chemical composition of the magneto-optical layer.[1–3,17]

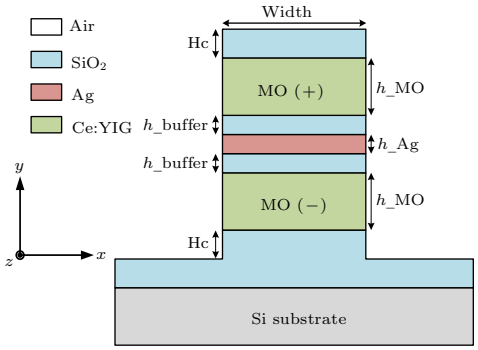


Fig. 1. Cross section of the proposed structure.

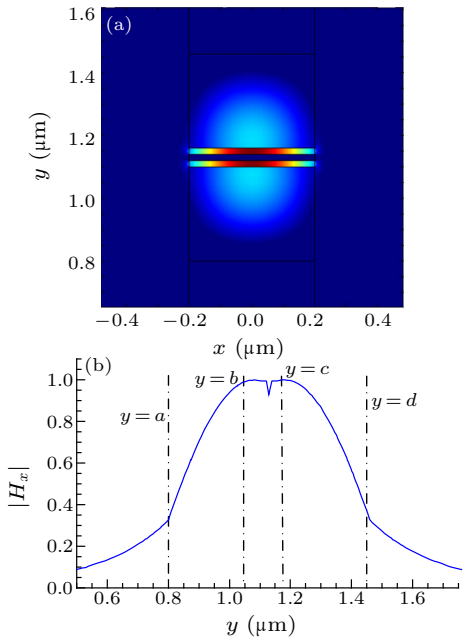


Fig. 2. (a) The distribution of the electromagnetic energy density without external magnetic field perturbation. Structure parameters are as follows: width=400 nm, h_{MO} = 300 nm, h_{Ag} = 20 nm, h_{buffer} = 20 nm. (b) The cross section of $|H_x|$ along the y direction at $x = 0$.

In this work, the unperturbed mode field distribution, the propagation constant and the propagation loss of the proposed structure are investigated by finite-element-method-based-mode (FEM) solver. The calculation region is sufficiently large. The cladding height H_c is set to be 800 nm to ensure it to be sufficiently high. For the proposed structure, there are two fundamental modes induced by the metal layer: a short-range mode and a long-range mode. Since the loss of the short-range mode is too high for practical isolating use, we would just focus on the long-range mode in the following discussion. It can be seen from Fig. 2(a) that the electromagnetic energy is strongly confined in the buffer layers with nanometric scale, which can be explained by the fact that a combination of plasmon and high-index contrast effects will give rise to a subwavelength mode confinement at the metal surface.[11–13]

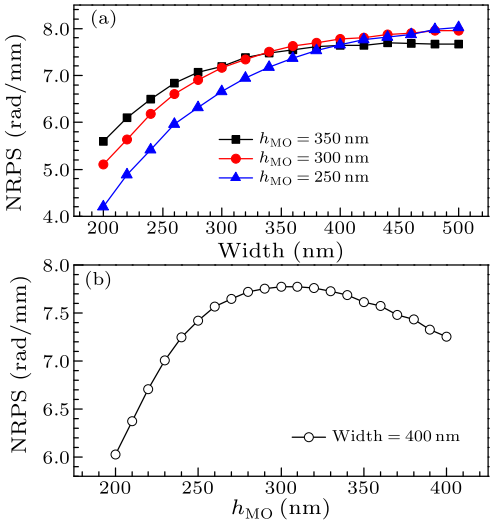


Fig. 3. (a) The NRPS with different waveguide widths. The structure parameters are h_{buffer} = 10 nm, h_{Ag} = 20 nm. (b) The NRPS with different thickness of MO layers. The structure parameters are width=400 nm, h_{buffer} = 10 nm, h_{Ag} = 20 nm. The value of γ is set to 0.0095.

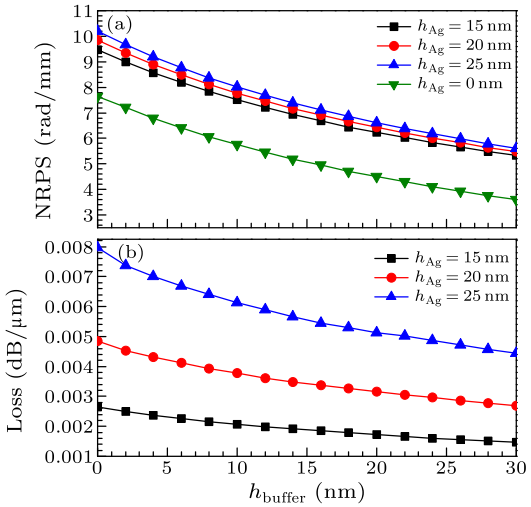


Fig. 4. The NRPS (a) and propagation loss (b) for increasing thickness of the buffer layers, with h_{MO} = 300 nm, width=400 nm.

From the perturbation theory, the NRPS for quasi-TM mode is written as[18]

$$\Delta\beta_{TM} = \frac{2\omega\varepsilon_0}{\beta_{TM} N} \iint \gamma E_y \partial_y E_y dxdy, \tag{2}$$

$$N = \iint [\boldsymbol{E} \times \boldsymbol{H}^* + \boldsymbol{E}^* \times \boldsymbol{H}]_z dxdy, \tag{3}$$

where $\beta_{\rm TM}$ is the propagation constant, N is the power flow in the z direction. Because of the piecewise continuity of γ in our structure and the relation $E_y = \beta_{\rm TM} H_x/\omega\varepsilon_0\varepsilon_{\rm m}$, Eq. (2) can be rewritten as[3]

$$\Delta\beta_{\rm TM} = \frac{\beta_{\rm TM}}{N\omega\varepsilon_0\varepsilon_{\rm m}^2}\Big\{ -\int_0^{\rm width} \gamma H_x^2|_{y=a}dx + \int_0^{\rm width} \gamma H_x^2|_{y=b}dx - \int_0^{\rm width} -\gamma H_x^2|_{y=c}dx + \int_0^{\rm width} -\gamma H_x^2|_{y=d}dx\Big\}, \quad (4)$$

which indicates that the high NRPS could result from the high H_x contrast (ΔH_x) between $y = b$ and $y = a$, and between $y = c$ and $y = d$ [see in Fig. 2(b)]. From Eq. (4), the NRPS is also related to the value of the width of this structure. It is obvious that increasing width will enhance NRPS. For clarity, the NRPS of the proposed structure on different waveguide widths is calculated, as shown in Fig. 3(a). Generally, the values of the NRPS increase very slowly after a given value of the waveguide width about 400 nm (the width is fixed at 400 nm in the following). The NRPS on different heights of MO material, $h_{\rm MO}$, is calculated as shown in Fig. 3(b). The largest NRPS appears at $h_{\rm MO} = 300$ nm. The result agrees well with the data in Ref. [3].

Figure 4(a) shows the NRPS on the thickness of buffer layers for different values of silver thickness. It is found that the NRPS becomes weaker with the increasing buffer layer thickness and with the decreasing silver thickness. The structure without the metal film has the lower NRPS than others with the metal film at the same $h_{\rm buffer}$. This can be explained by the fact that the field confinement in the buffer layers and the influence of the metal on the hybrid mode becomes weaker, which confirms the fact that the plasmonic excitations are sensitive to the dielectric properties of surrounding medium and the metal, and the plasmonic effect leads to enhanced NRPS. Figure 4(b) shows the propagation loss with different thickness of buffer layers. The propagation loss of the proposed structure becomes lower with the increasing buffer layer thickness, because the buffer layers with low refractive index pull the field out of the metal layer.

The propagation loss will be rapidly boosted, though NRPS will be enhanced by the increasing silver thickness ($h_{\rm Ag}$ fixed at 20 nm, as shown in Fig. 5). We show the result that the propagation length with 1 dB loss is much longer than the required length of $\pi/2$ phase shift in SPP waveguides with strong NRPS. A Mach–Zehnder interferometer (MZI) isolator of which two arms are made of the proposed structure with opposite magnetization could be realized just like the MZI configuration shown in Fig. 1 of Ref. [6]. Take $h_{\rm buffer} = 10$ nm as an example, the NRPS arm length $L\pi/2$ is 202 μm, and the propagation loss is 0.76 dB.

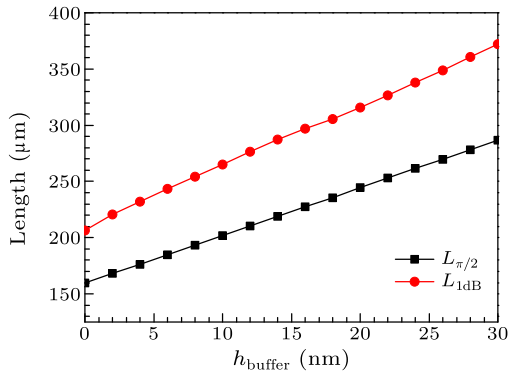


Fig. 5. The length $L_{\pi/2}$, $L_{\rm 1dB}$ with different thicknesses of buffer layers. The thickness of the silver film is fixed at 20 nm.

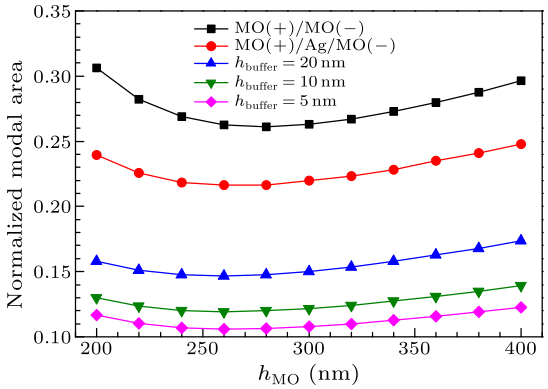


Fig. 6. Normalized modal area with different thickness of MO layers for different structures. Set the metal height to 20 nm except the DMMD structure.

In the above description, it has been shown that the proposed structure has large NRPS and low loss. To effectively evaluate the mode confinement, we also compare modal area of the proposed structure to the SiO/MO(+)/MO(-)/SiO_2 (DMMD) structure and the SiO_2/MO(+)/Ag/MO(-)/SiO_2 (DMAMD) structure [see Fig. 6]. The SiO_2 layer height is sufficiently large. The modal area $A_{\rm m}$ is defined as the total electromagnetic energy $W_{\rm m}$ and the peak of energy density $W(r)$ along the z direction:[13]

$$A_{\rm m} = \frac{W_{\rm m}}{\max[W(r)]} = \frac{1}{\max[W(r)]}\int\int_{-\infty}^{\infty} W(r)d^2r. \quad (5)$$

The normalized modal area is defined as $A_{\rm m}/A_0$, where A_0 is the diffraction-limited area in free space, $A_0 = \lambda^2/2$. We observe that the DMMD structure has the weakest mode confinement. It can be easily seen that the DMAMD structure has smaller modal area, which implies that the metal-induced plasmon effect will lead to much tighter field confinement. Take $h_{\rm MO} = 300$ nm and $h_{\rm buffer} = 10$ nm as an example, the normalized modal area is about 0.12, which is almost 0.55 times smaller than the DMAMD structure

and 0.45 times smaller than the DMMD structure. Therefore the proposed structure with buffer layers in our study has an advantage on tightly confined modal field, and it is more promising to develop the nanoscale optical waveguides.

In conclusion, the magneto-plasmonic effect in an MO metal-sandwiched structure based on long-range SPPs is investigated. It is shown that the proposed structure has large NRPS and small modal area, while the propagation loss is reduced down to cater to practical use. The optical properties of SPPs are effectively controlled by external magnetic field. Isolators based on such a waveguide structure have potential applications in nanoplasmonic optical circuits.

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