One-Way Extraordinary Optical Transmission and Nonreciprocal Spoof Plasmons

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We introduce a concept of a nonreciprocal spoof surface plasmon: an electromagnetic wave supported by a structured conductor embedded in an asymmetric magneto-optical medium and exhibiting a nonreciprocal dispersion. It is demonstrated analytically and by first-principles electromagnetic simulations that, by breaking the time-reversal symmetry, nonreciprocal spoof surface plasmons enable a dramatic optical response: one-way extraordinary optical transmission.

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Engineering dispersion and field confinement of surface plasmons through a specific design of structured metal surfaces and the recent achievements of nanofabrication paved the way to many fundamental and technological advances in the field of plasmonics [1]. In particular, it has been shown that a new type of so-called designer surface plasmonic modes, also referred to as spoof surface plasmons (SSPs), can be excited in many systems including structured perfect electric conductors (PECs) [1–8], thus expanding the universe of surface plasmon polaritons.

Surface plasmon polaritons are known to exhibit nonreciprocal properties in the presence of an external magnetic field [9]. However, the nonreciprocity observed is usually weak and/or requires very large magnetic fields. Nevertheless, several intriguing phenomena recently predicted for the systems supporting these surface modes revived the interest in nonreciprocity effects in plasmonic structures. In particular, it was shown that heterostructures composed of magnetized metal films and two-dimensional photonic crystals may support nonreciprocal surface modes exhibiting one-way behavior. In this case, there is a frequency range where such modes can propagate in only one direction along the surface while being stopped in the opposite direction by a band gap. Such unique dispersion characteristics were shown to have important consequences in the systems with defects, including the suppression of backscattering and avoided scattering [10–12].

A variety of traditional magneto-optical (MO) phenomena in the systems exhibiting extraordinary optical transmission has also been discussed recently. In particular, strong enhancement of the Faraday effect was predicted for the systems with an MO cladding [13] and MO material embedded into perforated metal [14]. Recently, plasmon-assisted giant MO orientational [15] and Kerr [16] effects have been discussed for one-dimensional metal gratings. Experimental studies of plasmonic MO heterostructures also confirmed the possibility of a significant enhancement of MO effects and tunability of optical responses of such structures [17,18].

In this Letter, we introduce a novel concept of engineered nonreciprocity of surface excitations such as SSPs, which mimics the nonreciprocity of conventional surface plasmons but reveals itself even in relatively weak magnetic fields. With a major motivation to supplement a variety of functional nonreciprocal plasmonic elements, we study SSPs at an interface between a two-dimensional structured PEC and a MO dielectric and demonstrate how to tailor their dispersion and engineer the nonreciprocal response of the structure.

Here we focus on the study of two geometries. The first geometry represents a single interface between a structured PEC and a semi-infinite MO material. This geometry corresponds to the case earlier considered in Refs. [2,3,7], but here we aim to study the properties of nonreciprocal spoof surface plasmons (NSSPs) in the presence of the MO material. The second geometry corresponds to the regime of extraordinary optical transmission (EOT) [19]. The corresponding structure consists of an optically thick perforated PEC film in an asymmetrically magnetized MO cladding (see Fig. 1). In the latter case we focus on NSSPs coupled to radiative modes of the vacuum giving rise to EOT. In both cases, the MO material is assumed to be Ce:BIG [20], which is homogeneously magnetized in the Voight geometry, and the permittivity tensor $\hat{\epsilon}$ has the following nonvanishing components: $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz} = \epsilon = 6.25$ and $\epsilon_{xz} = -\epsilon_{zx} = i\Delta$ with $|\Delta| = 0.06$. The holes' filler is a nonmagnetic dielectric with $\epsilon_h = 6.25$.

Nonreciprocal plasmonic modes.—Nonreciprocity can be found in the systems which do not possess time-reversal symmetry, such as MO systems, but it also requires removal of the mirror reflection symmetry [20,21]. Because the mirror reflection symmetry (σ_z in our case) is naturally violated at surfaces, we expect that nonreciprocity appears

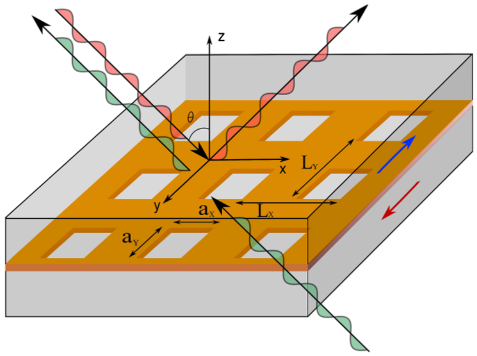

FIG. 1 (color online). Schematic of the layered structure supporting NSSPs and exhibiting one-way extraordinary optical transmission. Color arrows show the magnetization direction of the magnetic layers.

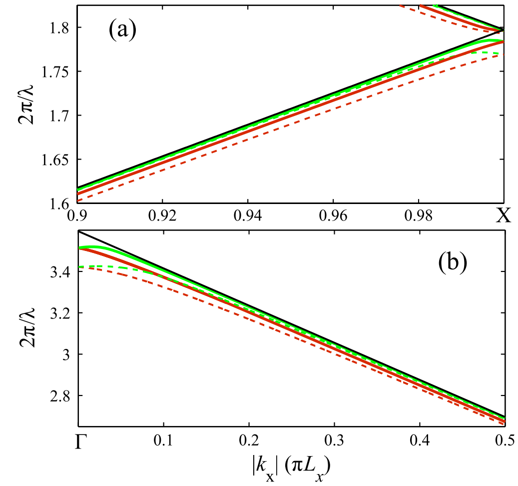

FIG. 2 (color online). Nonreciprocal dispersion of (a) transversely confined NSSPs and (b) NSSPs coupled to the far field calculated by the modal matching technique for parameters $L_x = L_y = 700$ nm, $a_x = a_y = 330$ nm, and $\Delta = 0.3$ to exaggerate the effect of nonreciprocity. The green and red lines show dispersion for forward ($k_x \geq 0$) and backward ($k_x \leq 0$) SSPs, respectively. The dashed curves are calculated with the use of the simplified model of Eq. (1). The black line in (a) and (b) shows the unfolded and folded light line, respectively.

in the single interface geometry in the presence of MO active materials [22].

The origin of nonreciprocity of NSSPs in perforated metal films with MO coating can be understood from the model suggested in Refs. [3,7], which represents an extension of the effective medium theory [2] used for explaining EOT [23]. It uses a modal matching technique consisting of two steps. First, due to periodicity of the surface indentations, the fields in the outer regions, the substrate, and the cladding are expressed by using the Rayleigh expansion. In the holes' region, the field is expanded in the basis of the waveguide modes. Second, by imposing a continuity condition of the tangential components of the electric and magnetic fields and using the orthogonality of the modes, a set of linear equations relating incident and scattered fields [7,23] is derived and expressed in the matrix form as $\mathbf{R} = \hat{S}\mathbf{I}$, where $\hat{S}(\mathbf{k}, \omega)$ is the scattering matrix.

The propagation bands $\omega_n(\mathbf{k})$ of the electromagnetic eigenmodes are found by solving the equation $\det[\hat{S}(\mathbf{k}, \omega)^{-1}] = 0$. Nonreciprocity of the optical response of the structure can be concluded from the form of $\hat{S}(\mathbf{k}, \omega)$ if, in general, $\hat{S}(\mathbf{k}, \omega) \neq \hat{S}(-\mathbf{k}, \omega)$. This property of the scattering matrix results in the nonreciprocity of the dispersion relation: $\omega_n(k_x) \neq \omega_n(-k_x)$. Figure 2 shows a dispersion diagram of NSSPs for positive and negative values of the propagation constant and confirms their nonreciprocity. Note that for these results (and other results below) obtained with the use of the described technique, the number of both diffraction and waveguide modes was taken to be sufficient to achieve convergence.

In general, the approach described above requires a numerical solution. However, a simple analytic dispersion relation can be obtained in the case when only the fundamental waveguide mode is taken into account and diffraction in the y direction is neglected. While such a model is rather approximate, its simplicity can provide a good physical insight and a qualitative description of the nonreciprocal behavior [23]. In this case, the expression for the NSSP dispersion takes the form

$$\frac{\beta_z^x}{2} + \frac{a_x a_y}{L_x L_y} \sum_m \frac{\epsilon {k_0}^2}{k_z^m - i(\Delta/\epsilon) k_x^m} S_m^2 = 0, \tag{1}$$

where $k_x^m = k_x + 2m\pi/L_x$, $k_z^m = [(n\omega/c)^2 - (k_x^m)^2 - k_y^2]^{1/2}$, $n = [\epsilon/(\epsilon^2 - \Delta^2)]^{-1/2}$, $S_m = 2/\pi \operatorname{sinc}(k_x^m a_x/2)$, and $\beta_z^x = [\epsilon_h {k_0}^2 - (\pi/a_y)^2]^{1/2}$. This form of the eigenvalue problem shows unambiguously the nonreciprocal contribution to the dispersion of SSPs due to the presence of the odd power of the SSP's propagation constant k_x in the denominator of the second term. As can be seen, the band diagrams calculated with the use of the simple equation (1) (shown in Fig. 2 by dashed lines) are in good qualitative agreement with the results of the exact technique.

One-way extraordinary optical transmission.—It is well known that EOT in perforated films is inherently related to excitation of SSPs [19,23]; it can be explained as a result of evanescent coupling of leaky SSP modes existing at the opposite interfaces of the metal film. Thus, one can expect that the nonreciprocal character of the dispersion of SSPs should alter the phase-matching condition required for their excitation, and this could result in some specific, in particular, nonreciprocal, features in optical characteristics of such structures. From now on we consider a structure of finite thickness, composed of a perforated PEC film sandwiched between two oppositely magnetized 500 nm thick MO slabs (as shown in Fig. 1).

As already explained above, MO activity alone does not result in nonreciprocity, and reduction of spatial symmetries is required as well. In the single interface geometry discussed above, the mirror reflection symmetry σ_z was naturally violated, thereby ensuring the nonreciprocal properties of the structure. But it is not the case for the film geometry, which possesses a mirror plane across the center of the structure along the xy plane unless the symmetry is violated by other means. For this reason, if the substrate and cladding are magnetized in the same direction, the MO activity barely affects the optical response of the system, and it remains reciprocal. However, for the geometry shown in Fig. 1, the mirror symmetry is removed by asymmetrically magnetizing upper and lower MO slabs. This approach to reduce symmetry to induce nonreciprocity in magnetic photonic crystals was originally proposed in Ref. [20]. Note that this is only one of the possible ways to remove mirror reflection symmetry; the other possible solutions could be different upper and lower cladding dielectrics [21] or tilted holes.

As can be seen from Fig. 2(b), the dispersion of leaky SSPs above the light line is modified by the presence of the magnetic material in a similar way to the dispersion of confined SSPs below the light line [Fig. 2(a)], and they become nonreciprocal. This suggests that the optical response of the film can be nonreciprocal as well. In other words, the phase-matching condition dictating the spectral position of resonant coupling between incident radiation and leaky NSSPs will be satisfied at different frequencies for positive and negative values of the wave vector $\mathbf{k}$. Thus, the nonreciprocal character of NSSPs brings the directional dependence in the spectral position of EOT and may result in the most radical form of nonreciprocity known as one-way behavior. One-way behavior indicates frequency ranges where modes can be unidirectional, i.e., are allowed to propagate in only one direction—forward or backward—while propagation in the opposite direction is prohibited or significantly suppressed.

Conducting the modal matching described above at both interfaces of a metal film, we found the scattering matrix $\hat{S}(\mathbf{k}, \omega)$ of the whole structure (including MO slabs) and calculated amplitudes of the reflected and transmitted fields. The calculation results confirmed strong nonreciprocity of the transmittance and reflectance and revealed that the optical properties show a specific directional dependence, which is not observed in nonmagnetic structures. Figure 3 shows that in the proximity of EOT at the wavelength $\lambda = 1997$ nm the structure behaves as a one-way mirror transmitting light in the forward direction (green line) while reflecting light propagating in the backward direction (red line). Note that nonreciprocity was found to be significant across the whole Γ-X direction (i.e., for all possible angles of incidence) in the Brillouin zone and vanished only in the close proximities of Γ and X points, as dictated by vanishing of k_x [see dispersion relation (1)] and by the continuity of dispersion across the Brillouin zone edges [10]. However, we found that it was quite important to have a trade-off between bandwidth of the EOT peaks and nonreciprocity of NSSPs to get strong nonreciprocity in transmission spectra. The bandwidth of EOT peaks should be narrow enough, and optimally it

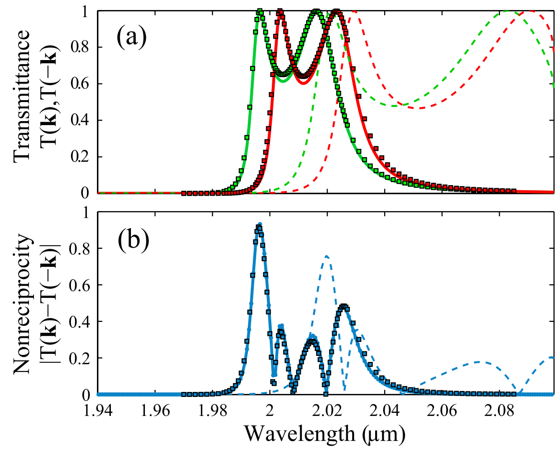

FIG. 3 (color online). (a) Nonreciprocal EOT at 30° incidence on a perforated 300 nm thick PEC film and (b) the corresponding differential transmission. The dashed curves are the results of the minimal model. The solid lines and squares are the results of the modal matching and FEM, respectively. The substrate and cladding are 500 nm thick and are magnetized in opposite directions (Fig. 1); $L_x = L_y = 700$ nm, $a_x = a_y = 330$ nm, and $|\Delta| = 0.06$.

should not exceed the value $\Delta\omega = |\omega(k_x) - \omega(-k_x)|$ characterizing nonreciprocity of SSPs. Simulations show that the bandwidth of EOT peaks gradually decreases with an increase of angle of incidence θ, but $\theta = 30°$ was sufficient to exceed 90% nonreciprocity in transmission. A further increase of θ resulted in a stronger nonreciprocity in transmission (up to 98%) but at the cost of the operational bandwidth of the structure.

To confirm the predictions of the modal matching technique we also conducted fully vectorial 3D numerical simulations of the structure with the use of commercial finite element (FEM) solver COMSOL Multiphysics. As can be seen from Fig. 3, the obtained results shown by squares are in excellent quantitative agreement with those of the modal matching technique, which are shown by solid lines. Moreover, calculated field profiles allowed us to give a simple and instructive explanation of the discovered one-way character of EOT. Figure 4 shows the out-of-plane magnetic field distribution at the wavelength $\lambda = 1997$ nm where one-way behavior is most pronounced. The strong field enhancement near the structure surface is associated with the excitation of leaky NSSPs, but, for two cases corresponding to two opposite directions of incidence, modes excited at opposite surfaces of the film are coupled very differently. In fact, while for forward incidence coupling of NSSPs is perfect providing nearly complete transparency of the structure, in contrast, for backward incidence such coupling is almost completely suppressed, resulting in low transmission through the structure.

While until now we have been describing the metal as a PEC, the one-way behavior can also be observed for real metals. However, in this case, strong nonreciprocity can be

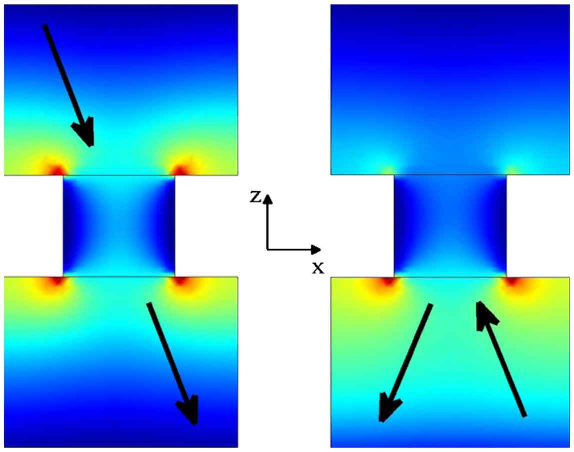

FIG. 4 (color online). Field profiles corresponding to two opposite directions of incidence (shown by arrows) on a PEC perforated film with asymmetrically magnetized cladding (Fig. 1). The structure is identical to that described in Fig. 3.

achieved only for moderate losses when broadening of the EOT resonance does not exceed the magnetization-induced spectral shift between the resonances for forward and backward propagation. To show that one-way behavior in the transmission can be quite robust to resistive losses, we employ FEM modeling of the structure with the geometry described above but with the PEC layer replaced with real gold. Figure 5 shows that, while losses suppress the transmission to some extent and give rise to spectral broadening of the resonances, the nonreciprocity is still large, and the difference between forward and backward transmittances can approach 43%, or nearly 72% of the transmitted light. Apparently, the mechanism behind the nonreciprocity in this system is the same as for PECs, and this fact was confirmed by the calculated field distributions (given as an inset in Fig. 5).

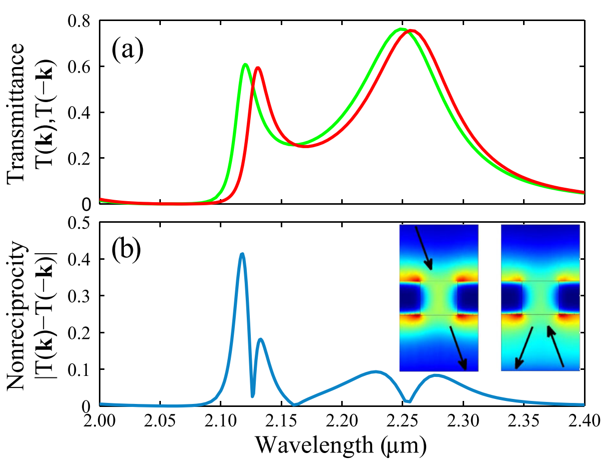

FIG. 5 (color online). (a) Nonreciprocal EOT at 30° incidence on a 300 nm thick gold film with asymmetrically magnetized cladding and (b) the corresponding differential transmission. The structure dimensions are identical to that described in Fig. 3.

In conclusion, we have studied surface plasmon modes and extraordinary optical transmission in structured metals embedded into a magneto-optical environment. We have found that this geometry exhibits nonreciprocal designer surface modes. In the film configuration, the nonreciprocity was shown to give rise to one-way extraordinary optical transmission, so that the structure behaves as a one-way mirror or an optical isolator. The plasmonic nature of the resonances responsible for this effect allows a composite structure to be as thin as the wavelength of light, thus suggesting a new generation of compact nonreciprocal elements vital for optical applications.

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