Asymmetric transmission of surface plasmon polaritons

V. Kuzmiak[1] and A. A. Maradudin[2]

[1]*Institute of Photonics and Electronics, Czech Academy of Sciences, v.v.i., Chaberska 57, 182 51 Praha 8, Czech Republic*

[2] *Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA*

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We describe a surface structure that possesses a different transmissivity for a surface plasmon polariton incident on it from one side of it than it has for a surface plasmon polariton incident on it from the opposite side. This asymmetric transmission of a surface plasmon polariton does not require either electrical nonlinearity or the presence of a magnetic field but is a consequence solely of the geometry of the structure. This property of the structure is demonstrated by the results of computer simulation calculations.

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I. INTRODUCTION

It has been known for many years [1] that a surface electromagnetic wave propagating along the x_1 axis on the planar surface $x_3 = 0$ of a semi-infinite ($x_3 < 0$) metal or n-type semiconductor to which a static magnetic field has been applied in the x_2 direction (the Voigt configuration) is nonreciprocal. This means that the dispersion relation for the surface wave propagating in the x_1 direction is different from the dispersion relation for the surface wave propagating in the $-x_1$ direction. If the strength of the magnetic field is large enough, a narrow window of frequencies occurs within which the surface wave propagates only in the $+x_1$ direction. This result is the basis for the design of a waveguide in the form of a gap between a semi-infinite dielectric photonic crystal and a semi-infinite metal to which a static magnetic field is applied, in which electromagnetic waves can propagate in only one direction [2]. It was subsequently shown [3,4] that if the photonic crystal in this waveguide structure is fabricated from a transparent dielectric magneto-optic material, to which the magnetic field is applied, the window of the frequencies within which the waveguide displays one-way propagation can be achieved at much lower magnetic field strengths than are required for this purpose in the structure proposed in Ref. [2]. The application of a magnetic field to a structure to produce one-way propagation of the surface or guided waves it supports may not always be an option for some applications of those waves. This consideration stimulates searches for surface structures that produce one-way propagation of a surface or guided wave without the need of a magnetic field.

In this paper we describe a surface structure that has a different transmissivity for a surface plasmon polariton (SPP) incident on it from one direction than it does for a SPP incident on it from the opposite direction. This asymmetric transmission of a surface plasmon polariton does not require either electrical nonlinearity or the presence of a magnetic field, but is a consequence solely of the geometry of the structure. The latter was suggested to us by the structures used in recent studies of one-way diffraction gratings by Lockyear *et al*. [5], and of one-way propagation of acoustic waves by Li *et al*. [6].

II. THEORETICAL MODEL

The system we consider in this paper consists of vacuum in the region $x_3 > 0$ and a metal, characterized by a frequency-dependent dielectric function $\epsilon(\omega)$, in the region $x_3 < 0$. On the metal surface $x_3 = 0$ is deposited a square array of scatterers arranged in a triangular mesh with a lattice constant a_0 together with a diffraction structure with a period $4a_0$ in the x_2 direction to the left of the periodic array (Fig. 1). A surface plasmon polariton of frequency ω propagates along the x_1 axis on the structure from the region $x_1 < 0$ to the left of it, or from the region $x_1 > 0$ to the right of it. Using a two-dimensional elastic scattering model due to Bozhevolnyi and Coello [7] we describe the SPP by its electric field component parallel to the x_3 axis, evaluated on the surface $x_3 = 0$, $E_3^{(0)}(\mathbf{x}_{||}) = \exp(ik_{||}x_1)$ or $\exp(-ik_{||}x_1)$, respectively, where the wave number $k_{||} = (\omega/c)[\epsilon(\omega)/(\epsilon(\omega)+1)]^{1/2}$. In this model the scatterer located at the two-dimensional coordinate $\mathbf{R_j}$ is represented by an effective polarizability α that is the same for all $\mathbf{R_j}$. The total electric field $E_3(\mathbf{x}_{||})$ at a point $\mathbf{x}_{||}$ that does not coincide with the position $\mathbf{R_j}$ of any of the scatterers can be written as arising from the total fields $E_3(\mathbf{R_j})$ at the locations of the scatterers:

$$E_3(\mathbf{x}_{||}) = E_3^{(0)}(\mathbf{x}_{||}) + \alpha \sum_j G(\mathbf{x}_{||}|\mathbf{R_j})E_3(\mathbf{R_j}), \tag{1}$$

where

$$G(\mathbf{x}_{||}|\mathbf{x}'_{||}) = \frac{i}{4} H_0^{(1)}(k_{||}|\mathbf{x}_{||} - \mathbf{x}'_{||}) \tag{2}$$

and $H_0^{(1)}(x)$ is the Hankel function of the first kind and zero order. The total field at the positions of the scatterers can be determined by solving the Foldy-Lax equations,

$$E_3(\mathbf{R_k}) = E_3^{(0)}(\mathbf{R_k}) + \alpha \sum_{j(\neq k)} G(\mathbf{R_k}|\mathbf{R_j})E_3(\mathbf{R_j}). \tag{3}$$

We begin by studying the frequency dependence of the reflectivity and transmissivity of a SPP incident from $x_1 < 0$ on the square array of scatterers without the diffractive structure on its left side. The total electric field along the x_1 axis in the region $x_1 < 0$ is given by

$$E_3(\mathbf{x}_{||}) = E_3^{(0)}(\mathbf{x}_{||}) + E_3^{(r)}(\mathbf{x}_{||}) = e^{ik_{||}x_1} + r(\omega)e^{-ik_{||}x_1}, \tag{4}$$

where $r(\omega) = r_1(\omega) + ir_2(\omega)$ is the amplitude of the reflected field. The intensity of the total field in this region is then

$$|E_3(\mathbf{x}_{||})|^2 = 1 + |r|^2 + 2|r|\cos(2k_{||}x_1 - \alpha), \tag{5}$$

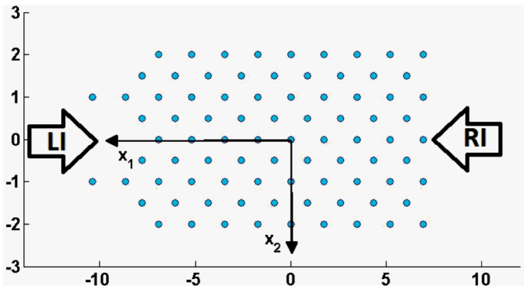

FIG. 1. (Color online) The surface structure studied in this paper.

where $\alpha = \tan^{-1}(r_2/r_1)$. The minimum and maximum values of the intensity are

$$|E_3(\mathbf{x}_{||})|^2_{\min} = (1 - |r|)^2, \tag{6a}$$

$$|E_3(\mathbf{x}_{||})|^2_{\max} = (1 + |r|)^2. \tag{6b}$$

Thus from the calculation of $|E_3(\mathbf{x}_{||})|^2$ as a function of x_1 in the region $x_1 < 0$ the value of $|r(\omega)|$ can be obtained, and hence the reflectivity $|r(\omega)|^2$, as a function of frequency.

The total electric field along the x_1 axis in the region $x_1 > 0$ is

$$E_3(\mathbf{x}_{||}) = E_3^{(0)}(\mathbf{x}_{||}) + E_3^{(t)}(\mathbf{x}_{||}) = e^{ik_{||}x_1} + t(\omega)e^{ik_{||}x_1}, \tag{7}$$

where the first term is the incident field, which is present in the absence of the scattering structure, while the second is given by the second term on the right-hand side of Eq. (1). The function $t(\omega) = t_1(\omega) + it_2(\omega)$ is the transmission amplitude of the SPP. The intensity of the total field in this region is then

$$|E_3(\mathbf{x}_{||})|^2 = |1 + t(\omega)|^2. \tag{8}$$

Therefore, from the calculation of $|E_3(\mathbf{x}_{||})|^2$ in the region $x_1 > 0$ the transmissivity of the SPP $|1 + t(\omega)|^2$ can be obtained as a function of frequency.

We found that using a plane wave representation of the incident SPP is not suitable since the scattering structure considered in our paper is finite and the SPP diffraction by the corners of the structure affects the resulting transmissivity and reflectivity computed for a finite domain in front of the central part of the structure. To reduce this effect we use an incident beam with a Gaussian profile along the x_2 axis, which has in the case of left incidence the form

$$\mathbf{E}(\mathbf{x}_{||}|\omega)_{\text{inc}} = e^{ik_{||}(\omega)x_1 - \beta_0(\omega)x_3} e^{-\frac{x_2{}^2}{W^2}} \times \frac{c}{\omega}[-i\beta_0(\omega), 0, -k_{||}(\omega)], \tag{9}$$

where $\beta_0(\omega) = (\omega/c)\{-1/[\epsilon(\omega) + 1]\}^{\frac{1}{2}}$, and the parameter W is chosen to be order of, or smaller than, the lateral dimension of the array of point scatterers.

III. RESULTS

The reflectivity and transmissivity as functions of wavelength are plotted in Fig. 2 for a SPP incident along the x_1 axis on a 17×17 array of scatterers arranged in a triangular lattice on a gold surface. This is the ΓK orientation of the periodic structure with respect to the propagation of the incident SPP, in the terminology of Søndergaard and Bozhevolnyi [8].

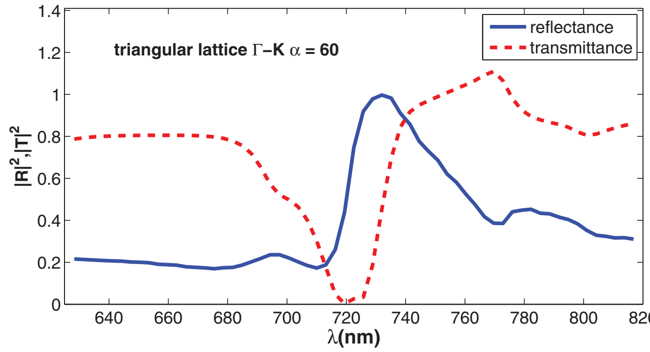

FIG. 2. (Color online) The reflectivity and transmissivity as functions of wavelength for a SPP beam incident along the x_1 axis on a 17×17 array of scatterers arranged in a triangular lattice on a gold surface.

In the calculations of the reflectivity and transmissivity for both the periodic and diffractive structures we used a Gaussian profile of the incident wave given by Eq. (9), where the profile width W was chosen to be $W = 9a_0$ and the vertical component of the electric field given by Eq. (9) is evaluated at $x_3 = 0$. The dielectric function of gold as a function of frequency was represented by the Drude form

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \tag{10}$$

where the plasma frequency ω_p and the electron scattering frequency γ were determined by fits to the data of Palik [9] in the frequency range 2.356×10^{15} rad/s to 4.712×10^{15} rad/s. The values obtained in this way are $\omega_p = 6.79 \times 10^{15}$ rad/s and $\gamma = 1.508 \times 10^{14}$/s. The lattice constant was chosen to be $a_0 = 400$ nm and the polarizability of each scatterer was $\alpha = 60$. The magnitude of the polarizability α is identical with the value used in simulations carried out by Bozhevolnyi and Volkov [10] that produced results close to those of experimentally measured distributions of the SPP intensity [11].

The peak in the reflectivity and the minimum in the transmissivity in the frequency dependence of these two functions presented in Fig. 2 are signatures of the presence of a band gap in the surface plasmon polaritonic band structure in the wavelength range 680 nm to 740 nm. Due to the finite size of the scattering structure the band gap is not as sharply defined by these results as it would be for an infinite structure.

When the diffractive structure is added to the left side of the plasmonic crystal, the transmissivities of a SPP beam incident on the resulting structure from the left (left incidence, LI) and from the right (right incidence, RI) demonstrate asymmetric transmission when the frequency of the incident SPP is in the band gap of the plasmonic crystal; see Fig. 3. One can see that the difference in the RI and LI transmissivities of the diffractive structure occurs in the wavelength range 700 nm $< \lambda <$ 720 nm. Specifically, at the wavelength $\lambda = 703$ nm, the transmissivity for RI does not differ from that associated with the perfect plasmonic crystal, while the transmissivity for LI is reduced at this wavelength. This can be readily understood. In the case of right incidence (Fig. 3), because of the surface polaritonic band gap in the direction of propagation,

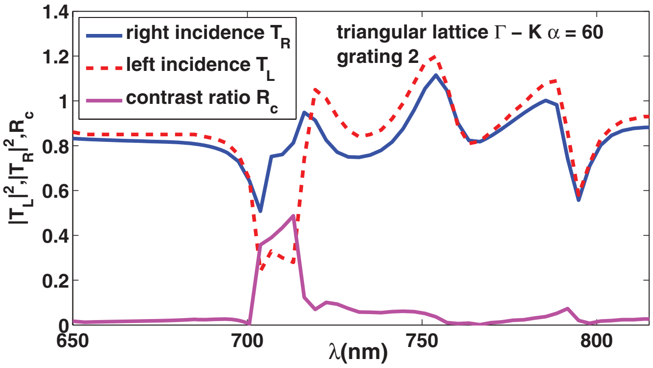

FIG. 3. (Color online) The transmissivities for a SPP incident along the x_1 axis on a plasmonic crystal with a diffractive structure shown in Fig. 1 from the right (T_R), from the left (T_L), and the contrast transmission ratio R_c as functions of wavelength.

the incident SPP is partially reflected at this wavelength. In the case of left incidence, because the period in the x_2 direction of the diffractive structure is larger than the wavelength of the incident SPP, several Bragg beams that are not parallel to the incident wave are excited and transmitted through it. In contrast, the zero-order beam, due to the existence of the band gap for propagation along the x_1 axis, is not transmitted through the polaritonic crystal. A qualitative measure of this asymmetry is provided by the contrast transmissivity ratio defined by [6]

$$R_c = \frac{T_L - T_R}{T_L + T_R}, \tag{11}$$

where T_L and T_R are the transmissivities for LI and RI, respectively. A plot of R_c as a function of wavelength is presented in Fig. 3. For the diffractive structure considered the contrast transmission ratio R_c is nonzero in the wavelength range 700 nm$< \lambda <$ 720 nm, increases as the wavelength is increased, and reaches a maximum at the upper bound of this wavelength range.

In Fig. 4 the spatial intensity distributions of the transmitted fields at the wavelength $\lambda = 703$ nm are depicted for both RI and LI. Both patterns reflect the difference in the RI and LI transmissivities observed at this wavelength (Fig. 3). Namely, while the field for RI, Fig. 4(a), in front of the surface without the diffractive structure remains almost unaffected, the field next to the opposite side of the plasmonic crystal in the case of LI reveals enhanced backscattering from the diffractive surface [Fig. 4(b)]. In Fig. 5 the spatial intensity distributions of the transmitted fields are plotted for both RI and LI at the wavelength $\lambda = 713$ nm. The field density associated with the wavelength $\lambda = 713$ nm in the case of RI, Fig. 5(a), reveals a significantly larger amplitude of the transmitted field in accord with the higher transmissivity at this wavelength than that at $\lambda = 703$ nm. In contrast, for LI, the field distribution of the transmitted field in the wavelength range 700 nm $< \lambda <$ 720 nm varies to a much smaller extent, as is shown in Fig. 5(b), and reflects a small variation of the transmissivity for LI in this range (Fig. 4). To achieve the highest possible

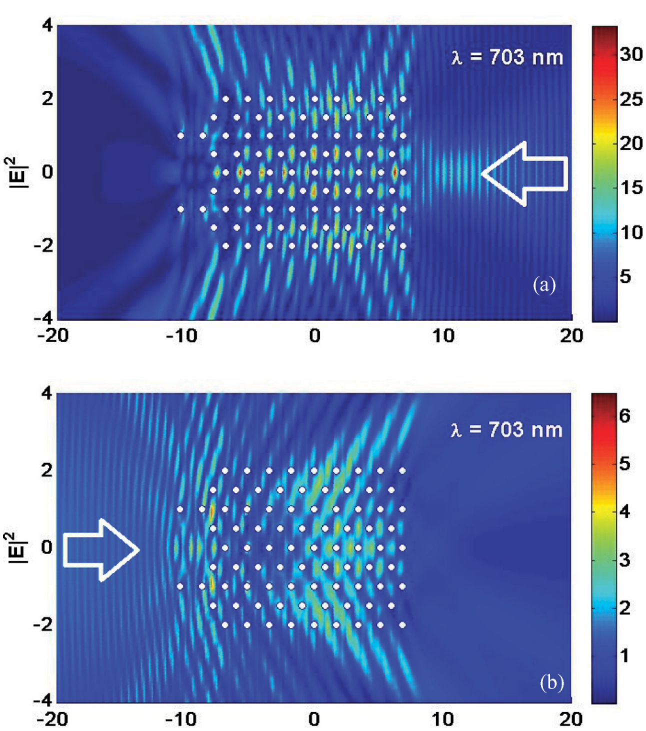

FIG. 4. (Color online) Spatial intensity distribution of the transmitted fields when a SPP with the wavelength $\lambda = 703$ nm is incident on the structure depicted in Fig. 1. (a) From the right side (RI); (b) from the left side (LI). Note different amplitudes used in colormaps in (a) and (b).

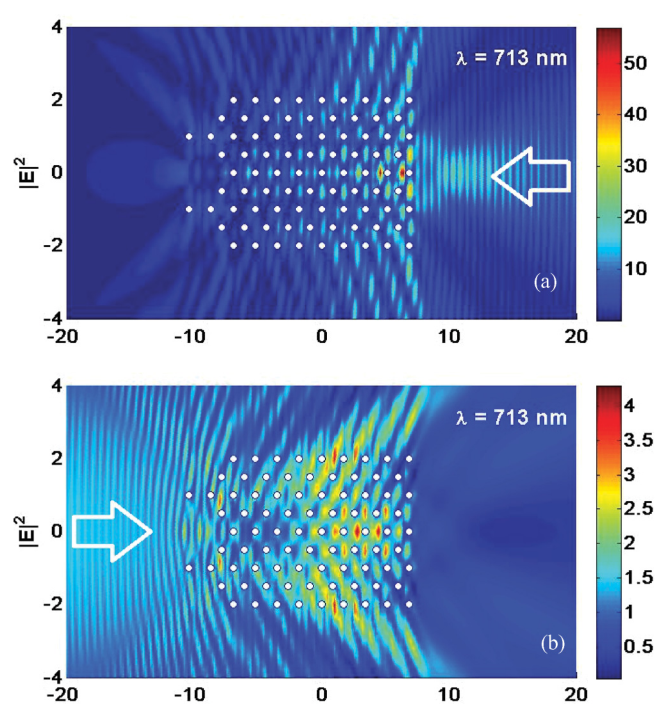

FIG. 5. (Color online) Spatial intensity distribution of the transmitted fields when a SPP with the wavelength $\lambda = 713$ nm is incident on the structure depicted in Fig. 1. (a) From the right side (RI); (b) from the left side (LI). Note different amplitudes used in colormaps in (a) and (b).

image contrast of the intensity distributions shown in Figs. 4 and 5 we employ the identical distribution of the colors while the amplitudes assigned to the colormaps reflect the differences in transmittances.

IV. CONCLUSION

We have demonstrated that the system consisting of a square array of scatterers deposited on a metal surface in a triangular mesh to which a diffractive structure is added to the left side of it reveals asymmetric transmission of SPP. The mechanism for this property is related to the higher Bragg modes that are excited due to the diffractive structure. By varying the material and geometrical parameters of the diffractive structure, one can control the contrast transmission that characterizes the degree of the asymmetry.

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