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Near field evidence of backward surface plasmon polaritons on negative index material boundaries

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ABSTRACT

We present a detailed analysis about the electromagnetic response of a metamaterial surface with a localized defect. The excitation of electromagnetic surface waves leads to a near-field distribution showing a periodic dependence along the metamaterial surface. We find that this periodic pattern provides a direct demonstration of the forward or backward surface wave propagation.

1. Introduction

A property of conventional materials that exhibit a real negative electric permittivity — such as metals — is their capacity to guide surface plasmon polaritons (SPPs) along their boundary [1]. SPPs are waves trapped at the interface whose electromagnetic fields decay exponentially into both media. On a single plane interface, the electromagnetic wave is backward inside the metal, i.e., the direction of the energy flux parallel to the interface is opposite to the direction of the wave propagation, but forward on the vacuum side, that is, the direction of the energy flux is the same as the direction of the wave propagation, where the larger fraction of the energy flows. Thus, the net behavior of the SPP in a single metallic surface is always a forward wave for which the total energy flux is in the same direction as the phase velocity [2].

Continuous advances in the realization of negative index materials (NIMs) [3] (artificial media with electric permittivity and magnetic permeability simultaneously negative in the same frequency range), have stimulated a revived interest in the electromagnetic properties of SPPs, and novel characteristics that do not exist in conventional media, such as backward behavior — with a total energy flux, parallel to the interface, that is opposed to the phase velocity — have been reported in Ref. [4]. When the flat boundary of a NIM medium is perturbed with a periodic corrugation, novel SPP radiation characteristics together with new SPP–photon coupling effects, not present in the metallic case, appear [5]. On the other hand, the scattering of light from a topological defect on a metallic surface is currently being investigated, since it provides a convenient way to generate locally SPPs from the incident light [6–8]. One way of characterizing the SPP generation efficiency is by scanning the field near the defect, since its distribution is strongly characterized by the generated SPPs [7,9]. The purpose of this letter is to show that, when a flat boundary is perturbed with a single defect, the near field distribution is related to the forward or backward character of the SPPs excited. In particular, we report near field evidence of backward SPPs, not present in the metallic case, that appear under certain particular conditions on a NIM interface. Within this framework, by using a rigorous method based on Green's second identity [10] for modeling the scattering process, we study the electromagnetic response of an isolated protuberance when illuminated by an electromagnetic, linearly polarized wave. To avoid diffraction effects at the edge of the surface, which must be of finite length in the numeri-

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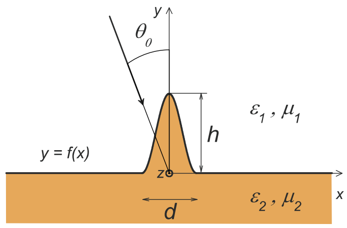

Fig. 1. (Color online.) Schematic illustration of the protuberance and the geometrical parameters.

cal treatment, as in Ref. [10] we assume the incident field to be a beam of finite width.

2. Scattering problem

In Fig. 1, we present schematically a single protuberance showing the geometrical parameters defining the structure and the coordinate axes used. The conventional material is vacuum ($\epsilon_1 = \mu_1 = 1$) and the boundary is a single sinusoidally corrugated as follows: $f(x) = h/2\ [1 + \cos(2\pi/d)]\,\mathrm{rec}(x/d)$ where $\mathrm{rec}(u)$ is the rectangular function centered at the origin with unit width and height. In all the examples presented here, the illumination is accomplished by a Gaussian beam, $\varphi_i(x, y) = e^{-(x\,\cos\theta_0 + y\,\sin\theta_0)^2/w^2}\ e^{i\frac{\omega}{c}(x\,\sin\theta_0 - y\,\cos\theta_0)}$, where $\varphi_i(x, y)$ is the z-directed component of the total magnetic field (p polarization) or the total electric field (s polarization), w is half of the beam width at the waist, ω is the angular frequency and c is the speed of light in vacuum. The angle of incidence θ_0 of the beam is defined with respect to the y axis. It is known (see Ref. [11], and references therein) that outside the corrugated region ($y > \max f(x)$ or $y < \min f(x)$), the fields can be rigorously represented by superpositions of plane waves,

$$\varphi_1(x, y) = \varphi_i(x, y) + \int_{-\infty}^{+\infty} R(\alpha)\, e^{i(\alpha\, x + \beta^{(1)}(\alpha)\, y)}\, d\alpha, \tag{1}$$

for $y > \max f(x)$ and

$$\varphi_2(x, y) = \int_{-\infty}^{+\infty} T(\alpha) e^{i(\alpha\, x - \beta^{(2)}(\alpha)\, y)}\, d\alpha, \tag{2}$$

for $y < \min f(x)$, where $R(\alpha)$ and $T(\alpha)$ are complex amplitudes and $\beta^{(j)}(\alpha) = \sqrt{\frac{\omega^2}{c^2}\varepsilon_j \mu_j - \alpha^2}$. Note that the quantities $\beta^{(1)}(\alpha)$ are real or purely imaginary. In the first case, which occurs in the so-called radiative zone $|\alpha| < \omega/c$, the integrand in eq. (1) represents plane waves propagating away from the surface along a direction that forms a scattering angle θ_s [$\sin\theta_s = c\,\alpha/\omega$] with the $+y$ axis. In the second case, which occurs in the so-called non radiative zone $|\alpha| > \omega/c$, these fields represent evanescent waves that attenuate for $y \longrightarrow +\infty$. In the real case of lossy transmission media ($\mathrm{Im}\ \varepsilon_2 > 0$, $\mathrm{Im}\ \mu_2 > 0$), the quantities $\beta^{(2)}(\alpha)$ are always complex with a nonzero imaginary part, $\mathrm{Im}\ \beta^{(2)}(\alpha) > 0$, so that the fields in eq. (2) attenuate for $y \longrightarrow -\infty$. After imposing the boundary conditions, we arrive at the electromagnetic fields above and below the boundary $y = f(x)$. The calculations are obtained using an integral method based on Green's second identity [10] and incorporating the changes made in Ref. [11] in order to include media with negative indices of refraction. According to expression (1), the near field on the vacuum side is a superposition of propagating and evanescent waves, being $R(\alpha)$ the weight of each of them depending on whether $|\alpha| < \omega/c$ or $|\alpha| > \omega/c$, respectively. In order to clarify the role of these waves, we calculate the amplitude $R(\alpha)$.

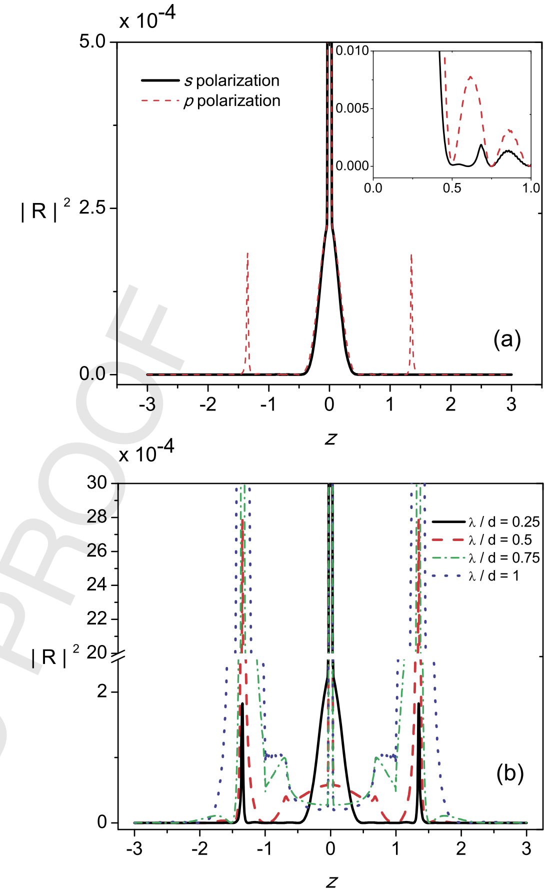

Fig. 2. (Color online.) Curves of $|R(z)|^2$ for a sinusoidal protuberance with $h = 0.012\,\lambda$ illuminated at normal incidence ($\theta_0 = 0$). Width (a) $d = 4\lambda$, p and s polarization, (b) $d = 2\lambda$, $4/3\,\lambda$, λ, p polarization. The relative constitutive parameters are $\epsilon = -1.3 + i0.01$ and $\mu = -0.35 + i0.01$.

First we consider the constitutive parameters $\epsilon = -1.3 + i0.01$ and $\mu = -0.35 + i0.01$ ($n = -0.674 + i0.012$), for which the flat interface supports a p-polarized forward SPP [4] with a complex dimensionless propagation constant $\kappa = c\,\alpha/\omega = 1.337 + i0.020$. We consider a protuberance with $h = 0.012\,\lambda$ and $d = 4\,\lambda$ ($h/d = 0.003$) where $\lambda = c/(2\pi\omega)$ is the wavelength in the vacuum. Fig. 2a shows the square modulus of the complex amplitude $R(z)$ as a function of the dimensionless wave vector $z = c/\omega\ \alpha$ for a normal beam wave incidence ($\theta_0 = 0$) and $w = 20\lambda$. In the radiative zone, $|z| < 1$, the curves are almost identical for both polarizations, with a principal peak whose spectral half width $\Delta z = c/\omega\,(2/w) = 0.1/(2\pi)$, centered at the value of the spectral variable $z = 0$. This peak represents the wave reflected by the flat surface, reaching a maximum value of 50000×10^{-4} [not shown in Fig. 2a]. The presence of the protuberance is manifested by non-zero values of $|R|^2$ in the non-specular direction, reaching a maximum value $\approx 2.5 \times 10^{-4}$ for $z = 0$ and two minima located at $z = \pm 0.5$ (see inset of Fig. 2a). We observe that only the values of $R(z)$ with z between these two minima significantly contribute to the scattered power. Unlike the radiative zone, the curve $|R(z)|^2$ shows a significant difference between the s and p polarizations beyond the radiative zone, as can be seen in Fig. 2a for $|z| > 1$. For p polarization, this curve shows two enhanced maxima at values of $z \approx \pm \mathrm{Re}\,\kappa$, indicating that two SPPs, one SPP propagating in $+x$ direction and the other one propagating in $-x$ direction, are excited by the p-polarized incident beam wave. However, there is no maximum for s polarization due to the fact that no SPPs with s polarization are supported by the surface. As we decrease the width of the protuberance d with respect to the

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