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²³ ARTICLE INFO ABSTRACT ⁸⁹

²⁵ Article history: **Article history: Since the set of the present a detailed analysis about the electromagnetic response of a metamaterial surface with a ⁹¹** 26 92 localized defect. The excitation of electromagnetic surface waves leads to a near-field distribution showing 27 between the metamaterial surface. We find that this periodic pattern provides a 93 28 2010 2010 2016 2016 2016 2016 direct demonstration of the forward or backward surface wave propagation. Analished by Elsevier B.V. and the second of the secon 30 96 Communicated by V.A. Markel з на произведения с произведения с произведения с произведения с произведения с произведения с произведения пр
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1. Introduction

electric permittivity $-$ such as metals $-$ is their capacity to guide surface plasmon polaritons (SPPs) along their boundary [\[1\].](#page--1-0) 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 [\[2\].](#page--1-0)

Continuous advances in the realization of negative index ma-

³⁹ **1. Introduction exist in conventional media, such as backward behavior — with** 40 106 a total energy flux, parallel to the interface, that is opposed to ⁴¹ μ ⁴¹ A property of conventional materials that exhibit a real negative the phase velocity — have been reported in Ref. [4]. When the A property of conventional materials that exhibit a real negative the phase velocity $-$ have been reported in Ref. [\[4\].](#page--1-0) When the $\frac{108}{108}$ ⁴³ electric permittivity – such as metallic and the expactly to guide flat boundary of a NIM medium is perturbed with a periodic cor-
⁴³ 44 Surace plasmon polaritons (SPPS) along their boundary $[1]$. SPP regation, novel SPP radiation characteristics together with new $\frac{110}{110}$ ⁴⁵ also we use the line intervals whose electioning the subset of SPP–photon coupling effects, not present in the metallic case, ap-
described also the metallic case, ap-46 the algebra continuously into the scattering the scattering of light from a topo-
46 the algebra contribution in her hand incident the motel is the pear [\[5\].](#page--1-0) On the other hand, the scattering of light from a topo-47 discretion of the agency flux possible to the intention is currently and defect on a metallic surface is currently being investigated, 113 48 the direction of the way a proposation but forward on the vacuum since it provides a convenient way to generate locally SPPs from 114 ⁴⁹ side that is the direction of the energy flux is the same as the the incident light $[6-8]$. One way of characterizing the SPP gener- 50 direction of the wave propagation where the larger fraction of the ation efficiency is by scanning the field near the defect, since its 116 51 energy flows. Thus the net behavior of the SPP in a single metallic distribution is strongly characterized by the generated SPPs [\[7,9\].](#page--1-0) 117 52 surface is always a forward wave for which the total energy flux is The purpose of this letter is to show that, when a flat boundary 118 ⁵³ in the same direction as the phase velocity [2]. $\frac{158}{2}$ is perturbed with a single defect, the near field distribution is re-54 120 lated to the forward or backward character of the SPPs excited. ⁵⁵ terials (NIMs) [\[3\]](#page--1-0) (artificial media with electric permittivity and In particular, we report near field evidence of backward SPPs, not 56 122 magnetic permeability simultaneously negative in the same fre-57 quency range), have stimulated a revived interest in the electro-
- quency range), have stimulated a revived interest in the electro- conditions on a NIM interface. Within this framework, by using a ⁵⁸ 124
The magnetic properties of SPPs, and novel characteristics that do not
The property method based on Green's second identity [10] for model-tinagueuc properues of SPPs, and novel characteristics that do not the rigorous method based on Green's second identity [\[10\]](#page--1-0) for model-₆₀ 126 the scattering process, we study the electromagnetic response ₁₂₆ to the electromagnetic response ₁₂₆ 61 * Corresponding author at: Facultad de Ingeniería y Tecnología Informática, Uni-
23 metric linearly polarized wave. To avoid differentia effects at the second the second differential of the second 62 versidad de Belgrano, Villanueva 1324, C1426BMJ, Buenos Aires, Argentina. Nettic, ThealTy polafized Wave. To avoid diffraction effects at the 128 63 E-mail address: cuevas@df.uba.ar (M. Cuevas). The surface, which must be of finite length in the numeri-129 64 130 <http://dx.doi.org/10.1016/j.physleta.2016.10.013> 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 of an isolated protuberance when illuminated by an electromagnetic, linearly polarized wave. To avoid diffraction effects at the

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E-mail address: cuevas@df.uba.ar (M. Cuevas).

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2 *M. Cuevas et al. / Physics Letters A* ••• *(*••••*)* •••*–*•••

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

13 cal treatment, as in Ref. [\[10\]](#page--1-0) we assume the incident field to be a set of the set of beam of finite width.

2. Scattering problem

18 In Fig. 1, we present schematically a single protuberance $30\sqrt{1-\frac{1}{12}}$ and $\frac{1}{12}$ and $\frac{$ 19 showing the geometrical parameters defining the structure and $28 - 28 + 4$ $\frac{1}{4}$ $\frac{$ 20 86 the coordinate axes used. The conventional material is vacuum ϵ_1 $(\epsilon_1 = \mu_1 = 1)$ and the boundary is a single sinusoidally cor-
 ϵ_2 ϵ_3 22 rugated as follows: $f(x) = h/2 [1 + \cos(2\pi/d)] \operatorname{rec}(x/d)$ where $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ as 23 $\text{rec}(u)$ is the rectangular function centered at the origin with $\begin{array}{ccc} & 22 \\ & & \end{array}$ $\begin{array}{ccc} & & \end{array}$ $\begin{array}{ccc} & & \end{array}$ 24 unit width and height. In all the examples presented here, the $\left|\mathbb{R}\right|^2 \frac{20 \neq \frac{1}{20 \times 10^{-10}} \frac{1}{100 \times 10^{-10}} \frac{1}{100 \times 10^{-10}}$ $_{25}$ illumination is accomplished by a Gaussian beam, $\varphi_i(x,y) =$ $_{2\perp}$ $_{2\perp}$ $_{3\perp}$ $e^{-(x \cos \theta_0 + y \sin \theta_0)^2/w^2} e^{i \frac{\omega}{c}(x \sin \theta_0 - y \cos \theta_0)}$, where $\varphi_i(x, y)$ is the **27** 2-directed component of the total magnetic field (p polarization) or the set of the set of the total magnetic field (p polarization) or the set of the set of the total magnetic field (p polarization) or the set of the 28 the total electric field (s polarization), *w* is half of the beam width $\| \cdot \|_2^2$ and $\| \cdot \|_2^2$ and 29 at the waist, ω is the angular frequency and *c* is the speed of $\mathcal{L}(\mathcal{L})$ and $\mathcal{L}(\mathcal{L})$ and $\mathcal{L}(\mathcal{L})$ is the speed of $\mathcal{L}(\mathcal{L})$ 30 light in vacuum. The angle of incidence θ_0 of the beam is defined $0 + \frac{1}{2}$ 31 97 with respect to the *y* axis. It is known (see Ref. [\[11\],](#page--1-0) and refer-32 ences therein) that outside the corrugated region ($y > max f(x)$ or $\qquad z$ and z and z and z and z and z or $\qquad z$ and z an 33 $y < \min f(x)$, the fields can be rigorously represented by super-
33 $y < \min f(x)$, the fields can be rigorously represented by superpositions of plane waves,

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

\n
$$
\varphi_2(x, y) = \varphi_i(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
$$
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$$
\varphi_3(x, y) = \varphi_1(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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$$
\varphi_1(x, y) = \varphi_1(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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\varphi_2(x, y) = \varphi_1(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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\varphi_3(x, y) = \varphi_2(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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\varphi_4(x, y) = \varphi_3(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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\varphi_5(x, y) = \varphi_6(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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\varphi_6(x, y) = \varphi_6(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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\varphi_7(x, y) = \varphi_7(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
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$$
\varphi_8(x, y) = \varphi_8(x, y) + \int_{-\infty}^{+\infty} R(\alpha) e^{i(\alpha x + \beta^{(1)}(\alpha) y)} d\alpha,
$$
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$$
\varphi_9(x, y) = \varphi_8(x, y) + \int_{-\infty}^{+\infty} R(\
$$

for $y > max f(x)$ and

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

for $y < \min f(x)$, where $R(\alpha)$ and $T(\alpha)$ are complex amplitudes

34 **positions of plane waves,** $h = 0.012 \lambda$ illuminated at normal incidence ($\theta_0 = 0$). Width (a) $d = 4\lambda$, p and s 35 **101** $\pm \infty$ **101** $\pm \infty$ **polarization, (b)** $d = 2\lambda$, 4/3 λ , λ , p polarization. The relative constitutive parame-**Fig. 2.** (Color online.) Curves of $|R(z)|^2$ for a sinusoidal protuberance with

38 **104** $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ First we consider the constitutive parameters $\epsilon = -1.3 + i0.01$ ¹⁰⁴ 39 $\mu = -0.35 + i0.01$ ($n = -0.674 + i0.012$), for which the flat ¹⁰⁵ 40 106 interface supports a p-polarized forward SPP [\[4\]](#page--1-0) with a com-41 $+\infty$ **plex dimensionless propagation constant** $\kappa = c\alpha/\omega = 1.337 + 107$ 42 108 *i*0*.*020. We consider a protuberance with *h* = 0*.*012 *λ* and *d* = 4 *λ* $\mu_2(\lambda, y) = \int_0^1 f(\alpha) \epsilon$ and $\mu_1(\alpha) = \int_0^1 f(\alpha) \epsilon$ (*h*/*d* = 0.003) where $\lambda = c/(2\pi \omega)$ is the wavelength in the vac- $-\infty$ 110 $-\infty$ 110 ⁴⁵ for $v \neq min f(x)$ where $R(\alpha)$ and $T(\alpha)$ are complex amplitudes $R(z)$ as a function of the dimensionless wave vector $z = c/\omega \alpha$ ¹¹¹ 46 112 for a normal beam wave incidence (*θ*⁰ = 0) and *w* = 20*λ*. In the and $\beta^{(j)}(\alpha) = \sqrt{\frac{\omega^2}{c^2} \epsilon_j \mu_j - \alpha^2}$. Note that the quantities $\beta^{(1)}(\alpha)$ are a radiative zone, $|z| < 1$, the curves are almost identical for both 113 ⁴⁸ real or purely imaginary. In the first case, which occurs in the so-
⁴⁸ real or purely imaginary. In the first case, which occurs in the so-
polarizations, with a principal peak whose spectral half t¹¹⁴ 49 called radiative zone $|\alpha| < \omega/c$, the integrand in eq. (1) represents $\Delta z = c/\omega (2/w) = 0.1/(2\pi)$, centered at the value of the spec-
¹¹⁵ ⁵⁰ plane waves propagating away from the surface along a direction tral variable $z=0$. This peak represents the wave reflected by ¹¹⁶ ⁵¹ that forms a scattering angle $θ_s$ [sin $θ_s = cα/ω$] with the +y axis. the flat surface, reaching a maximum value of 50000 × 10⁻⁴ [not 117] 52 In the second case, which occurs in the so-called non radiative shown in Fig. 2a]. The presence of the protuberance is manifested 118 53 zone $|α| > ω/c$, these fields represent evanescent waves that at-
by non-zero values of $|R|^2$ in the non-specular direction, reach-
¹¹⁹ 54 tenuate for *y* → +∞. In the real case of lossy transmission media ing a maximum value $\approx 2.5 \times 10^{-4}$ for $z = 0$ and two minima ¹²⁰ 55 (Im $ε$ ₂ > 0, Im $μ$ ₂ > 0), the quantities $β$ ⁽²⁾(α) are always complex located at $z = ±0.5$ (see inset of Fig. 2a). We observe that only ¹²¹ 56 with a nonzero imaginary part, Im $β$ ⁽²⁾(α) > 0, so that the fields the values of $R(z)$ with z between these two minima significantly 122 57 in eq. (2) attenuate for $y \rightarrow -\infty$. After imposing the boundary contribute to the scattered power. Unlike the radiative zone, the ¹²³ ⁵⁸ conditions, we arrive at the electromagnetic fields above and be-
 $\int |R(z)|^2$ shows a significant difference between the s and p 59 low the boundary $y = f(x)$. The calculations are obtained using an polarizations beyond the radiative zone, as can be seen in Fig. 2a 125 60 integral method based on Green's second identity [\[10\]](#page--1-0) and incor- for $|z|>1$. For p polarization, this curve shows two enhanced 126 ⁶¹ porating the changes made in Ref. [\[11\]](#page--1-0) in order to include media maxima at values of $z \approx \pm$ Re κ , indicating that two SPPs, one ¹²⁷ ⁶² with negative indices of refraction. According to expression (1), the SPP propagating in +x direction and the other one propagating in ¹²⁸ 63 near field on the vacuum side is a superposition of propagating $-x$ direction, are excited by the p-polarized incident beam wave. 129 64 and evanescent waves, being $R(\alpha)$ the weight of each of them de-
However, there is no maximum for spolarization due to the fact of the 65 131 pending on whether |*α*| *< ω/c* or |*α*| *> ω/c*, respectively. In order 66 to clarify the role of these waves, we calculate the amplitude $R(\alpha)$. We decrease the width of the protuberance d with respect to the 132 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 $z \approx \pm \text{Re } \kappa$, 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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