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NON-REFLECTIVE INCIDENCE OF *P*-POLARIZED ELECTROMAGNETIC WAVES ON THE SOLID-STATE STRUCTURE "UNIAXIAL PLASMONIC METASURFACE — DIELECTRIC LAYER — METAL"

Subject and Purpose. *The solid-state structures involving metasurfaces can be used to effectively control some of the basic properties of electromagnetic waves, like amplitude, phase and polarization. The present work is aimed at analyzing the new effects that may appear during incidence of p-polarized electromagnetic waves upon a solid-state structure involving a uniaxial plasmonic metasurface, a dielectric interlayer, and a layer of metal.*

Methods and Methodology. *The conditions suitable for identifying the effects that result from the reflection of a p-polarized electromagnetic wave incident upon a solid-state structure of the above described type have been sought for via numerical simulation. That has allowed finding the magnitudes of the essential parameters, such as angles of incidence and frequencies of the electromagnetic waves, as well as thicknesses of the dielectric interlayer, that could stipulate appearance of novel electromagnetic effects.*

Results. *It has been shown that the solid-state structure involving a uniaxial plasmonic metasurface, a dielectric interlayer, and a layer of metal is capable, under certain conditions, to fully absorb an incident electromagnetic wave of p-polarization. Moreover, a new effect has been predicted, specifically that of full conversion of the incident p-polarized electromagnetic wave into a reflected wave of s-polarization. The necessary condition is that the plane of incidence of the electromagnetic wave were at an acute angle to the principal symmetry axis of the plasmonic metasurface.*

Conclusions. *The solid-state structures of the type involving a uniaxial plasmonic metasurface, a dielectric interlayer, and a layer of metal are characterized by unique reflective properties. They are capable of fully absorbing, under certain conditions, the p-polarized electromagnetic waves incident upon them. Such structures can be used for creating optical and nanoelectronic devices of new types.*

Keywords: *p-polarized electromagnetic waves, uniaxial plasmonic metasurface, polarization conversion, non-reflective incidence.*

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Цитування: Білецький М.М., Попович І.Д. Безвідбивне падіння *p*-поляризованих електромагнітних хвиль на твердотільну структуру типу «одновісна плазмонна метаповерхня — діелектричний прошарок — метал». *Радіофізика і радіоастрономія.* 2023. Т. 28. № 2. С. 166—173. https://doi.org/10.15407/rpra28.02.166

Introduction

Metamaterials and metasurfaces have of late been attracting ever more attention because of their special qualities [1—7].They permit effectively controlling all the basic properties of electro-magnetic waves, like amplitude, phase and polarization [3, 4], hence can be used for creating optical and nanoelectronic devices of novel types. Of particular interest are the effects accompanying electromagnetic wave reflection from metamaterials and metasurfaces. One of the most interesting among them concerns conversion of the electromagnetic wave's polarization for the wave incident upon a metamaterial overlying a metal substrate [3].

In the present work, we have studied the new effect of non-reflective incidence of p-polarized electromagnetic waves upon a solid-state structure composed of a uniaxial plasmonic metasurface, a dielectric interlayer, and a layer of metal. The effect owes to the destructive interference of direct and reverse electromagnetic waves superimposed in the solid-state structure. As has been shown, such behavior can only occur when the plane of incidence of the p-polarized electromagnetic wave is either parallel or perpendicular to the principal axis of the plasmonic metasurface. The specific wave frequencies and dielectric layer thicknesses have been identified, with which the non-reflective incidence effect can occur for p-polarized electromagnetic waves.

Moreover, we have predicted a new effect, namely that of full conversion of an incident p-polarized electromagnetic wave into a reflected wave of s-polarization. The effect has been shown to take place when the plane of incidence of the p-polarized wave makes an acute angle with the principal axis of the plasmonic metasurface. The conditions have been found that can ensure full conversion of the incident electromagnetic wave of p-polarization into an s-polarized reflected one.

1. Problem formulation

Consider the spatial domain $z < 0$ which is occupied by a dielectric material of permittivity ε_1. A dielectric interlayer of permittivity ε_2 (occupying the space $0 < z < d$) is placed on top of a perfectly conducting metal substrate (area $z > d$). The uniaxial plasmonic metasurface lying within the plane $z = 0$ is represented by a two-dimensional array of conductive ellipsoids (Fig. 1) [5—7].

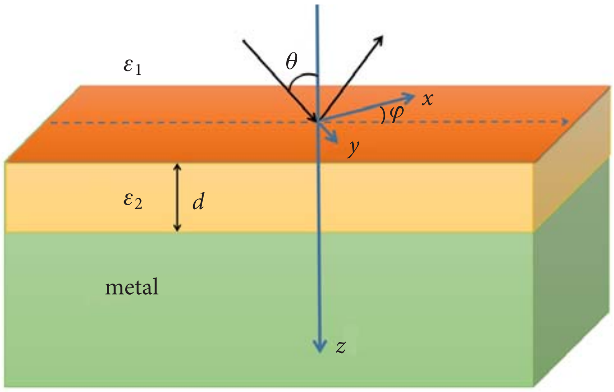

Fig. 1. Geometry of the problem

We will assume the electric field vector of the p-polarized electromagnetic wave to lie within the plane making an angle φ with the principal symmetry axis of the plasmonic metasurface. The electromagnetic wave of frequency ω is incident upon the metasurface at an angle θ.

The electromagnetic properties of the solid-state structure under consideration will be described in terms of the effective conductivity tensor of the uniaxial plasmonic metasurface [5—7]. The diagonal components of the tensor, normalized by $c / 4\pi$ where c is the speed of light, are of the form

$$\sigma_{\|,\perp} = \sigma^{\infty}_{\|,\perp} + i\frac{\omega A_{\|,\perp}}{\omega^2 - \Omega^2_{\|,\perp} + i\omega\gamma_{\|,\perp}} = \sigma'_{\|,\perp} + i\sigma''_{\|,\perp}.$$

The indices "$\|$" and "$\perp$" here relate to the directions along and across the principal axis of the plasmonic metasurface; $\Omega_{\|,\perp}$ and $\gamma_{\|,\perp}$ are, respectively, the resonant frequencies and half-widths of the resonance lines; $A_{\|,\perp}$ stand for oscillator strengths, and $\sigma^{\infty}_{\|,\perp}$ are background conductivities. Finally, $\sigma'_{\|,\perp}$ and $\sigma''_{\|,\perp}$ denote the real and the imaginary parts, respectively, of the corresponding conductivity tensor components. To carry out the calculations, we have assumed $\sigma^{\infty}_{\|,\perp} = 0.2i$; $A_{\|,\perp} = 0.2$; $\gamma_{\|,\perp} = 0.02$; $\gamma_{\|,\perp} = 0.02$, and $\Omega_{\perp} = 1.2$ [5].

Within the reference frame which is rotated by an angle φ with respect to the principal axis of the plasmonic metasurface (note the plane of incidence of the electromagnetic wave to be XZ), the conductivity tensor of the metasurface can be written as [5—7]

$$\sigma_{\varphi} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix}.$$

Where

$$\sigma_{xx} = \sigma_{\|} \cos^2 \varphi + \sigma_{\perp} \sin^2 \varphi \,,$$

$$\sigma_{yy} = \sigma_{\|} \sin^2 \varphi + \sigma_{\perp} \cos^2 \varphi \,, \text{ and}$$

$$\sigma_{xy} = \sigma_{yx} = \left(\sigma_{\perp} - \sigma_{\|} \right) \sin\varphi \cos\varphi \,.$$

Note that the presence at $\varphi \neq 0°$ and $\varphi \neq 90°$ of the non-zero off-diagonal conductivity tensor components σ_{xy} and σ_{yx} results in the appearance of reflected electromagnetic waves of s-polarization. Hence, upon incidence on the uniaxial plasmonic metasurface of a p-polarized electromagnetic wave, the reflected wave obtains all the field components, and generally is characterized by an elliptical polarization. In the coordinate system selected, the electromagnetic field of the p-polarized electromagnetic wave has the components as follows: $\vec{E}_p = \left\{ E_x, 0, E_z \right\}$, and $\vec{H}_p = \left\{ 0, H_y, 0 \right\}$. In the case of the s-polarized wave we have $\vec{E}_s = \left\{ 0, E_y, 0 \right\}$, and $\vec{H}_s = \left\{ H_x, 0, H_z \right\}$.

Within each of the media the wave vectors of the electromagnetic waves have the components as follows: $\vec{k}_j = (k_x, 0, k_{zj})$, with $j = 1, 2$. The longitudinal wavenumber is $k_x = \frac{\omega}{c}\sqrt{\varepsilon_1}\sin\theta$, hence the transverse wavenumbers can be represented as $k_{zj} = \sqrt{\frac{\omega^2}{c^2}\varepsilon_j - k_x^2}$.

Now, let us write down the non-zero tangential components of the electromagnetic fields for each medium of the solid-state structure in question. The multiplier $\exp(ik_x x - \omega t)$ will be omitted; the subscript "p" relates to p-polarized, and subscript "s" to s-polarized waves.

Medium1 (area $z < 0$):

$$H_{y1}^{p}(z) = e^{ik_{z1}z} + r_{pp} e^{-ik_{z1}z} \,,$$

$$E_{x1}^{p}(z) = \frac{ck_{z1}}{\omega\varepsilon_1}\left(e^{ik_{z1}z} - r_{pp} e^{-ik_{z1}z} \right),$$

$$E_{y1}^{s}(z) = r_{ps} e^{-ik_{z1}z} \,,$$

$$H_{x1}^{s}(z) = \frac{ck_{z1}}{\omega} r_{ps} e^{-ik_{z1}z} \,.$$

Medium 2 (area $0 < z < d$):

$$H_{y2}^{p}(z) = H_{p2}^{+} e^{ik_{z2}z} + H_{p2}^{-} e^{-ik_{z2}z} \,,$$

$$E_{x2}^{p}(z) = \frac{ck_{z2}}{\omega\varepsilon_2}\left(H_{p2}^{+} e^{ik_{z2}z} - H_{p2}^{-} e^{-ik_{z2}z} \right),$$

$$E_{y2}^{s}(z) = E_{s2}^{+} e^{ik_{z2}z} + E_{s2}^{-} e^{-ik_{z2}z} \,,$$

$$H_{x2}^{s}(z) = -\frac{ck_{z2}}{\omega}\left(E_{s2}^{+} e^{ik_{z2}z} - E_{s2}^{-} e^{-ik_{z2}z} \right).$$

Here r_{pp} and r_{ps} are the amplitudes of the p- and s-polarized waves, respectively, which are reflected from the uniaxial plasmonic metasurface. The values H_{p2}^{+} and E_{s2}^{+}, and H_{p2}^{-} and E_{s2}^{-} stand for the amplitudes of the direct (+) and reverse (–) p- or s-polarized waves in the layer of dielectric permittivity ε_2.

To determine the r_{pp} and r_{ps} it is necessary to use the boundary conditions at $z = 0$ and $z = d$. At $z = 0$ we have

$$E_{x1}^{p}(0) = E_{x2}^{p}(0) = E_x(0) \,,$$

$$E_{y1}^{s}(0) = E_{y2}^{s}(0) = E_y(0) \,,$$

$$H_{y2}^{p}(0) - H_{y1}^{p}(0) = -\frac{4\pi}{c}(\sigma_{xx}E_x(0) + \sigma_{xy}E_y(0)), \text{ and}$$

$$H_{x2}^{s}(0) - H_{x1}^{s}(0) = \frac{4\pi}{c}(\sigma_{yx}E_x(0) + \sigma_{yy}E_y(0)).$$

At the metallic boundary, $z = d$, tangential components of the electric fields are equal to zero. The reflection coefficient of the p-polarized electromagnetic wave reflected from the plasmonic metasurface can be calculated as a sum of $|\, r_{pp} \,|^2$ and $|\, r_{ps} \,|^2$,

$$R_p = |\, r_{pp} \,|^2 + |\, r_{ps} \,|^2 \,,$$

where

$$r_{pp} = \frac{P_{-}S + Q}{P_{+}S + Q}, \tag{1}$$

$$r_{ps} = 2\sigma_{yx}\frac{\sin^2(k_2\delta)}{P_{+}S - Q}, \tag{2}$$

$$P_{\pm} = \frac{\varepsilon_2}{k_2}\cos(k_2\delta) - i(\pm\frac{\varepsilon_1}{k_1} + \sigma_{xx})\sin(k_2\delta),$$

$$S = k_2\cos(k_2\delta) - i(k_1 + \sigma_{yy})\sin(k_2\delta), \text{ and}$$

$$Q = \sigma_{xy}^2 \sin^2(k_2\delta).$$

We have introduced here dimensionless magnitudes as follows, $k_j = ck_{zj}/\omega$ and $\delta = d\omega/c$.

2. Non-reflective incidence of the *p*-polarized electromagnetic wave on the uniaxial plasmonic metasurface

Let us identify the conditions which are necessary to make $R_p = 0$. As can be seen from Eq. (1), they are dependent on the magnitude of φ, with $\varphi = 0°$ or $\varphi = 90°$ we have $\sigma_{xy} = \sigma_{yx} = 0$ and $r_{ps} = 0$. Also, the reflected electromagnetic wave is p-polarized and $R_p = |r_{pp}|^2$. Let us consider the case in more detail. Eq. (1) implies that $r_{pp} = 0$ if $P_- = 0$. Since the latter value is a complex number, r_{pp} turns to zero when the conditions are met

$$\frac{\varepsilon_1}{k_1} - \sigma'_{\|,\perp} = 0, \text{ and} \tag{3}$$

$$\mathrm{tg}(k_2\delta) = -\frac{\varepsilon_2}{k_2\sigma''_{\|,\perp}}. \tag{4}$$

The roots of Eq. (3) define the frequencies at which the effect of non-reflective incidence of p-polarized electromagnetic waves on the uniaxial plasmonic metasurface is produced. The functions $\sigma'_{\|,\perp}(\omega)$ are symmetric, positively defined functions relative the resonant frequencies $\Omega_\|$ and $\Omega_\perp$. Accordingly, Eq. (3) demonstrates two roots, arranged symmetrically with respect to the frequencies $\Omega_\|$ and $\Omega_\perp$. Since the magnitude of k_1 decreases at higher values of θ, while the highest value of $\sigma'_{\|,\perp}(\omega)$ here is $\sigma'_{\|,\perp}(\Omega_{\|,\perp}) = 10$, it seems clear that there should be a maximum limiting value for $\theta_m = \arccos(0.1\sqrt{\varepsilon_1})$ still capable of providing for the effect of non-reflective incidence.

Equation (4) permits finding the thicknesses of the dielectric layer with which the incident p-polarized electromagnetic waves are not reflected. In case the inequalities $\Omega_{\|,\perp} >> \lambda_{\|,\perp}$ hold, the functions $\sigma''_{\|,\perp}(\omega)$ are asymmetric relative the resonant frequencies $\Omega_\|$ and $\Omega_\perp$. In the neighborhood of these, the conductivities $\sigma''_{\|,\perp}(\omega)$ demonstrate a similar behavior. As a result, the functions $\delta(\omega)$ behave in a similar way at $\varphi = 0°$ and $\varphi = 90°$.

Fig. 2 shows the θ-dependences of $\omega(\theta)$ (left-side vertical axis, solid lines) and $\delta(\omega)$ (right-side axis, dashed lines) for $R_p = 0$, with $\varepsilon_2 = 2.0$ and $\varphi = 0°$

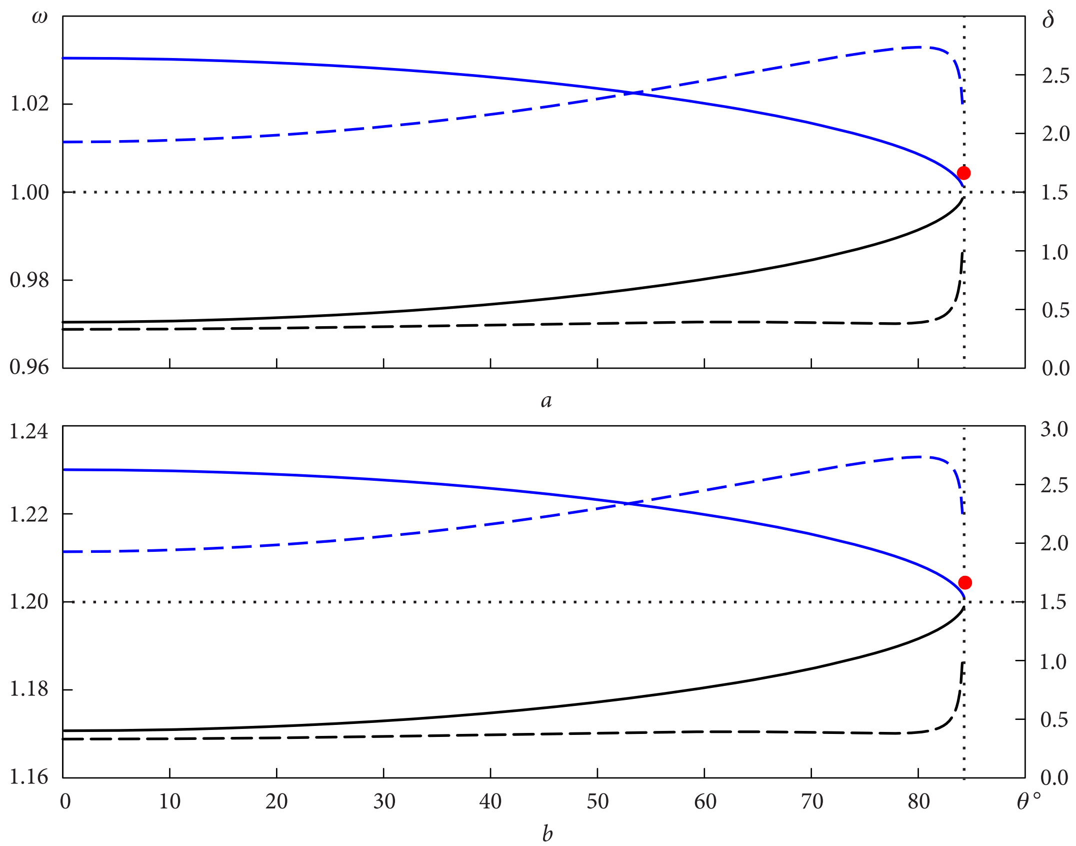

Fig. 2. The θ-dependences of $_{m<0}$ (left-side vertical axis, solid lines) and $\delta(\theta)$ (right-side vertical axis, dashed lines), presented for $R_p = 0$, with $\varepsilon_2 = 2.0$ (panel (*a*): $\varphi = 0°$, and panel (*b*): $\varphi = 90°$)

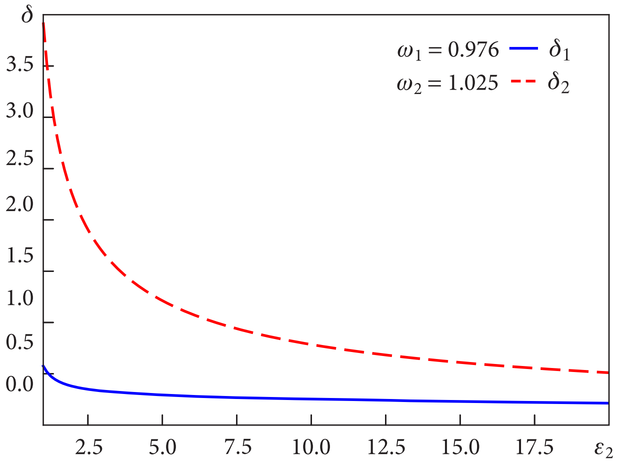

Fig. 3. The $\delta(\varepsilon_2)$ dependences corresponding to the condition $R_p = 0$ (with $\varphi = 0°$ and $\theta = 45°$)

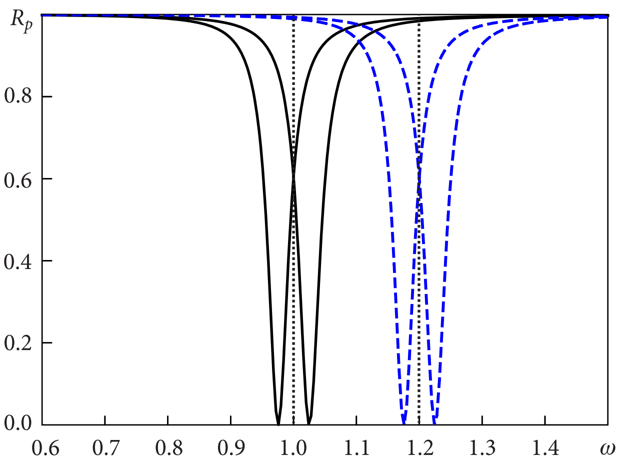

Fig. 4. The function $R_p(\omega)$ plotted for $\varepsilon_2 = 2.0$ and $\theta = 45°$: $\varphi = 0°$ (solid lines) and $\varphi = 90°$ (dashed lines)

(case *a*), and $\varphi = 90°$ (case *b*) point of the two $\delta(\theta)$ branches.

Another thing which can be concluded from Fig. 2 is that for every value of θ there are two values of frequency which follow from Eq. (3). Accordingly, there are two values of δ, obtainable from Eq. (4), that correspond to this pair of frequencies. The vertical dashed line in Fig. 2 relates to the case of $\theta = \theta_m$, and the circular sign marks the common. With account of $\mathrm{tg}(k_2\delta)$ being a periodic function, we have only sought for those dependences of $\delta(\theta)$ for which the magnitude of δ is the lowest.

It should be noted that the value of the dielectric permittivity ε_2 does not suggest any limitations on the non-reflective incidence effect for *p*-polarized electromagnetic waves at the uniaxial plasmonic metasurface.

Fig. 3 shows the $\delta(\varepsilon_2)$ dependences for the case $R_p = 0$, with $\varphi = 0°$ and $\theta = 45°$. The dependences have been plotted for parameter values $\omega_1 \approx 0.976$ (solid curve) and $\omega_2 \approx 1.025$ (dashed curve). It can be seen from Fig. 3, that both branches of the $\delta(\varepsilon_2)$ dependency are monotonically decreasing functions.

Shown in Fig. 4 are $R_p(\omega)$ dependences for $\varepsilon_2 = 2.0$ and $\theta = 45°$, with $\varphi = 0°$ (solid lines) and $\varphi = 90°$ (dashed lines), wherefrom we can conclude that with every value of φ the magnitude of R_p becomes zero at two frequencies. However, the effect is observable at different thicknesses of the dielectric layer δ. Thus, the effect of reflectionless incidence of *p*-polarized electromagnetic waves takes place at two frequencies and with "properly" selected magnitudes of the dielectric layer thickness.

3. Full conversion of *p*-polarized into *s*-polarized electromagnetic waves

As can be seen from Eq. (2), the conditions $\varphi \neq 0°$ and $\varphi \neq 90°$ $(\sigma_{yx} \neq 0)$ provide for appearance of an *s*-polarized reflected electromagnetic wave $(r_{ps} \neq 0)$. So, the electromagnetic wave reflected from a uniaxial plasmonic metasurface is a sum of *p*-polarized and *s*-polarized components.

Meanwhile, it has been found that with some values of the wave frequency and thicknesses of the dielectric layer (dependent on ε_2, φ and θ) the reflected *p*-polarized waves may vanish. Accordingly, under such conditions we observe the case of full conversion of the incident *p*-polarized electromagnetic wave into an *s*-polarized one.

Fig. 5 shows the frequency dependences of $R_p(\omega)$ (solid lines), $|r_{pp}(\omega)|^2$ (dashed lines) and $|r_{ps}(\omega)|^2$ (dot-dash lines) with $\varphi = 60°$, $\theta = 45°$, and $\varepsilon_2 = 2.0$ for $\delta \approx 0.6$ (panel (*a*)) and $\delta \approx 2.1$ (panel (*b*)). It can be seen that at some frequencies (specifically, $\omega \approx 0.964$, see panel (*a*), and $\omega \approx 1.037$, panel (*b*)) the *p*-polarized wave is absent among the reflections ($|r_{pp}(\omega)|^2 = 0$). Note that with $\varphi = 30°$ the frequencies of a bright full conversion effect for the *p*-polarized electromagnetic wave are localized near the resonant frequency $\Omega_{\parallel} = 1.0$ Thus, an incident electromagnetic wave of *p*-polarization gets transformed into an *s*-polarized wave for two pairs of (ω, δ) magnitudes.

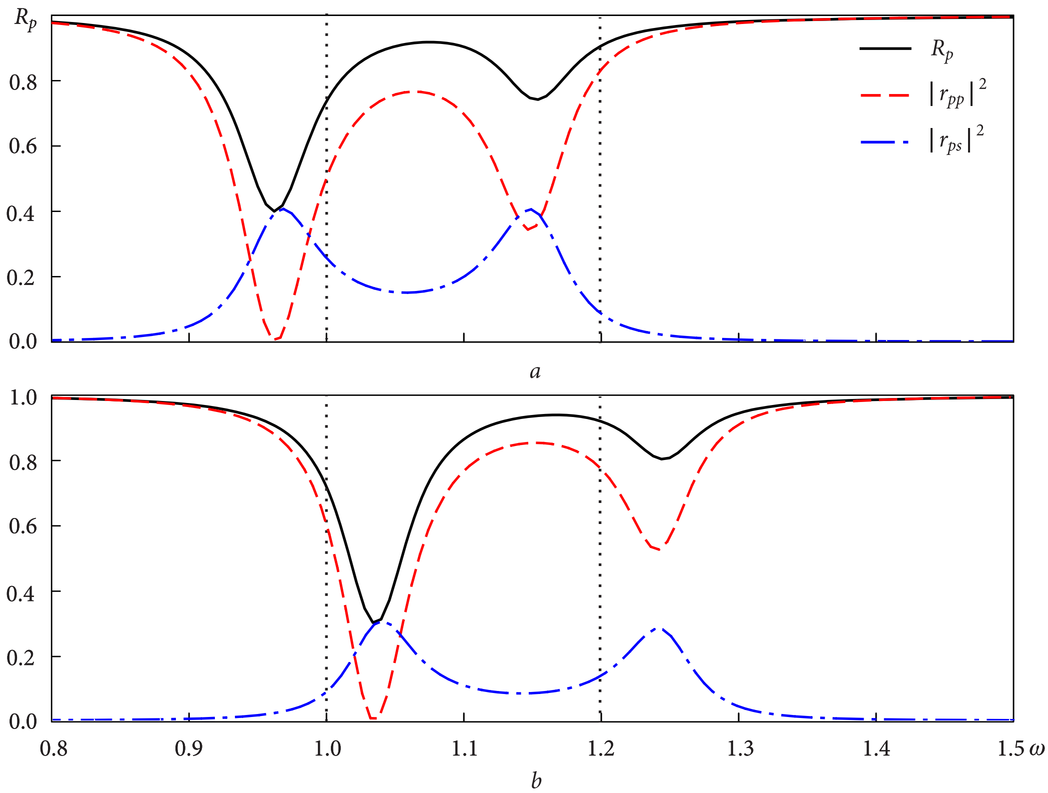

Fig. 5. Frequency dependences of $R_p(\omega)$(solid lines), $|r_{pp}(\omega)|^2$ (dashed lines) and $|r_{ps}(\omega)|^2$ (dot-dash lines) observed at $\varphi = 30°$, $\theta = 45°$, and $\varepsilon_2 = 2.0$ for $\delta \approx 0.6$ (panel (a)) and $\delta \approx 2.1$ (panel (b))

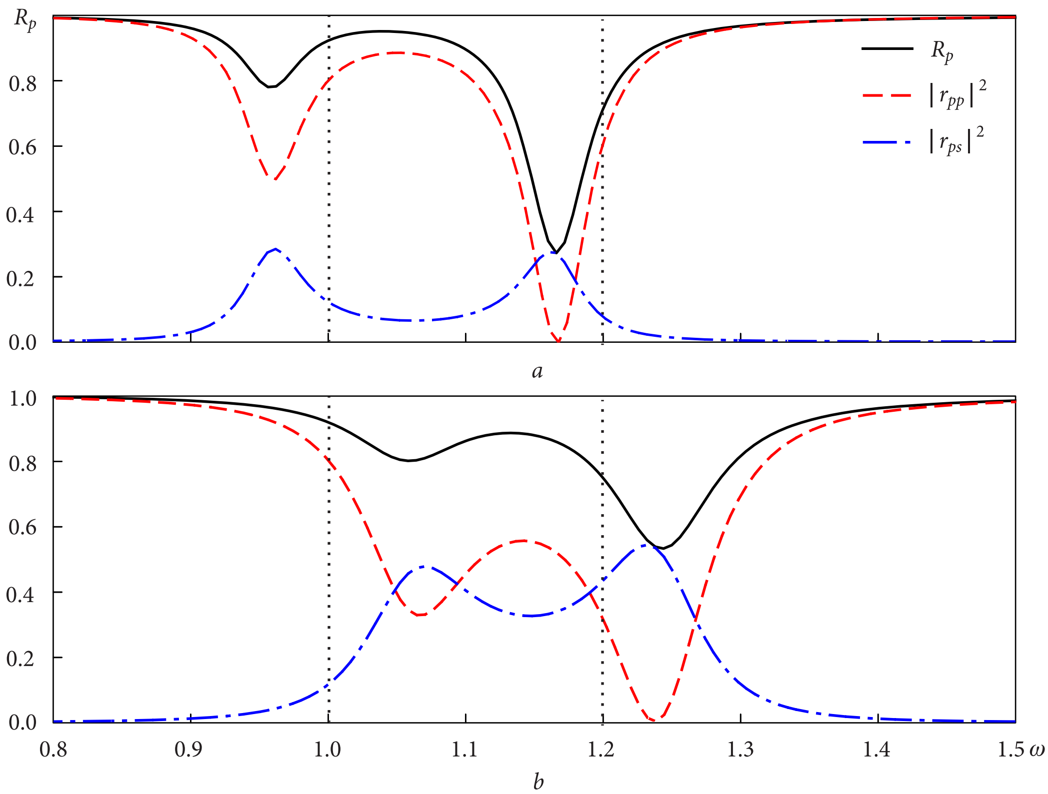

Fig. 6. Frequency dependences of $R_p(\omega)$ (solid lines), $|r_{pp}(\omega)|^2$ (dashed lines), and $|r_{ps}(\omega)|^2$ (dot-dash lines) observed at $\varphi = 60°$, $\theta = 45°$, and $\varepsilon_2 = 2.0$ for $\delta \approx 0.5$ (panel (a)) and $\delta \approx 2.0$ (panel (b))

At higher values of φ the frequencies where the full conversion effect occurs for the p-polarized and s-polarized electromagnetic waves also get higher, shifting toward the other resonant frequency, i.e. $\Omega_{\perp} = 1.2$. This situation is illustrated in Fig. 6 for $\delta \approx 0.5$ (panel (a)) and $\delta \approx 2.0$ (panel (b)) with the parameters like $\varphi = 60°$, $\theta = 45°$, and $\varepsilon_2 = 2.0$. It can be concluded from this plot that at $\omega \approx 1.17$ (panel (a)) and $\omega \approx 1.24$ (panel (b)) the p-polarized electromagnetic wave is absent among the reflected. So, at these frequencies we observe a complete conversion of a p-polarized into an s-polarized electromagnetic wave.

Conclusions

It has been shown that the solid-state structure involving a uniaxial plasmonic metasurface, a dielectric interlayer, and a layer of metal is capable, under certain conditions, to fully absorb an incident electromagnetic wave of p-polarization. To achieve that, the plane of incidence of the p-polarized electromagnetic wave should be either parallel or perpendicular to the principal axis of the plasmonic metasurface. Then the effect of a non-reflective incidence of the p-polarized electromagnetic wave is observable at two frequencies, conditioned by a proper choice of the dielectric layer's thickness. As has been found, the effect of non-reflective incidence of p-polarized electromagnetic waves is not affected by any limitations associated with the value of the dielectric layer's permittivity.

Also, a new effect has been predicted, specifically that of complete conversion of the incident p-polarized electromagnetic wave into a reflected wave of s-polarization. The necessary condition is that the plane of incidence of the electromagnetic wave were at an acute angle to the principal symmetry axis of the plasmonic metasurface, ($\varphi \neq 0°$, $\varphi \neq 90°$). In addition, the wave frequencies and thicknesses of the dielectric layer, which the effect takes place for, have been found. The dependence upon the angle φ between the plane of wave's incidence and the principal symmetry axis of the plasmonic metasurface has also been studied with respect to its importance for the full conversion of a p-polarized electromagnetic wave into an s-polarized electromagnetic wave.

The new effects discovered can be used both for improving the characteristics of existing optical and nanoelectronic devices, and for creating new equipment with unique properties.

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БЕЗВІДБИВНЕ ПАДІННЯ *P*-ПОЛЯРИЗОВАНИХ
ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ НА ТВЕРДОТІЛЬНУ СТРУКТУРУ
ТИПУ «ОДНОВІСНА ПЛАЗМОННА МЕТАПОВЕРХНЯ –
ДІЕЛЕКТРИЧНИЙ ПРОШАРОК – МЕТАЛ»

Предмет і мета роботи. Твердотільні структури, що містять метаповерхні, можуть бути використаними для ефективного контролю істотних властивостей електромагнітних хвиль, як-от амплітуди, фази та поляризації. Метою роботи є дослідження нових ефектів, що виникають при падінні *p*-поляризованої електромагнітної хвилі на твердотільну структуру типу «одновісна плазмонна метаповерхня — діелектричний прошарок — метал».

Методи та методологія. Для знаходження умов для ідентифікації ефектів, що супроводжують відбиття *p*-поляризованої електромагнітної хвилі від твердотільних структур вказаного вище типу, було використано числове моделювання. За його допомогою визначено кути падіння електромагнітних хвиль, їхні частоти, а також товщини діелектричного прошарку, що обумовлюють появу нових електромагнітних ефектів.

Результати. Показано, що за певних умов твердотільна структура типу «одновісна плазмонна метаповерхня — діелектричний прошарок — метал» може повністю поглинати *p*-поляризовану електромагнітну хвилю, що падає на неї. Окрім цього, передбачено новий ефект, а саме повну трансформацію *p*-поляризованої хвилі у відбиту хвилю *s*-поляризації. Для цього є необхідним, аби площина падіння електромагнітних хвиль становила гострий кут з головною віссю симетрії плазмонної метаповерхні.

Висновки. Твердотільні структури типу «одновісна плазмонна метаповерхня — діелектричний прошарок — метал» характеризуються унікальними відбивними властивостями. За певних умов такі структури здатні повністю поглинати *p*-поляризовану електромагнітну хвилю при її падінні на структуру та можуть використовуватись для створення принципово нових оптичних приладів і пристроїв наноелектроніки.

Ключові слова: *p-поляризовані електромагнітні хвилі, одновісна плазмонна метаповерхня, перетворення поляризації, безвідбиткове падіння.*