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REFLECTIONLESS INCIDENCE OF THE *P*-POLARIZED ELECTROMAGNETIC WAVE THROUGH SOLID-STATE STRUCTURE "COATING-UNIAXIAL PLASMONIC METASURFACE-DIELECTRIC-METAL"

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In this work we studied the effects which occur during the incidence of *p*-polarized electromagnetic wave on the solid-state structure "coating-uniaxial plasmonic metasurface-dielectric-metal". The purpose of this work is researching how the coating influences the effect of reflectionless incidence of the *p*-polarized electromagnetic waves on the solid-state structure "uniaxial plasmonic metasurface-dielectric-metal". Numerical modelling was used to find the conditions that lead to reflectionless incidence of the *p*-polarized electromagnetic wave on the solid-state structure under consideration. Using this method we determined the parameters of the coating which are required to observe incidence of *p*-polarized waves with no reflection. It was found that dielectric coating of the solid state structure significantly changes the behavior of the effect. We showed that dielectric permittivity of the coating changes the frequencies at which reflectionless p-polarized waves occur. The dependency was established between permittivity and thickness of the coating which causes the effect of the reflectionless incidence of *p*-polarized waves. The conducted research has a great scientific and practical interest. The solid-state structure that was studied can be applied for designing conceptually new types of nanoelectronic and optical devices.
Keywords: *Dielectric coating; p-polarized electromagnetic waves; Uniaxial plasmonic metasurface; Reflectionless incidence*
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1. INTRODUCTION

The presence of two-dimensional material (metasurface) at the boundary of the dielectric layer causes some interesting and important effects to take place [1–6]. The articles [4–6] studied uniaxial plasmonic metasurfaces consisting of a periodical array of conductive ellipsoids. Such plasmonic metasurfaces can be described using a two-dimensional non-diagonal conductivity tensor, which depends on the frequency and the angle of electromagnetic wave propagation relative to the principal axis of the ellipsoids. Of particular interests are the effects based on the *p*-polarized electromagnetic waves that incident on the metasurface placed on top of the dielectric layer [4–6]. One of these effects is reflectionless propagation of *p*-polarized electromagnetic waves through the metasurface. Such behavior can be observed in case the symmetry axis of plasmonic metasurface is in fact the plane of incidence of the electromagnetic wave [4, 6]. Another interesting observation is full transformation of the *p*-polarized electromagnetic wave into the s-polarized one [5, 6], which occurs when the plane of incidence forms an acute angle with the great symmetry axis of the metasurface. It's important to note that both aforementioned effects take place in case coating of the dielectric layer is either metal or dielectric itself. In addition, in [4-6] the conditions were established which lead to reflectionless incidence and full transformation and how they depend on the frequency of *p*-polarized wave and the angle of incidence on the plasmonic metasurface.

In this paper, we are proceeding further with theoretical research of the described in [4, 6] effect of *p*-polarized electromagnetic wave incidence through solid-state structure with no reflection [6] assuming, that plasmonic metasurface has protective dielectric layer. Here, we studied how this new dielectric layer impacts the conditions of reflectionless incidence.

2. PROBLEM STATEMENT

The geometry of the problem is shown in Figure 1. Let the area $z < 0$ be a dielectric with permittivity ε_1. The first layer (area $0 < z < d_1$) – dielectric layer with permittivity ε_2 covers uniaxial plasmonic metasurface $(z = d_1)$, which is located on top of the second dielectric layer (scope between $d_1 < z < d_1 + d_2$) that has permittivity ε_3. Perfectly conductive metal substrate occupies the area $z > d_1 + d_2$. Uniaxial plasmonic metasurface was regarded as two-dimensional (2D) array of conductive ellipsoids [4-6].

We assumed that an electric field of the *p*-polarized electromagnetic wave lies in a plane which makes an angle φ with the major symmetry axis of the plasmonic metasurface. Moreover, let electromagnetic wave with frequency ω fall on the dielectric structure with angle θ.

As in [4–6] to describe electromagnetic properties of the plasmonic metasurface within the solid-state structure under consideration, we incorporated two-dimensional effective conductivity tensor.

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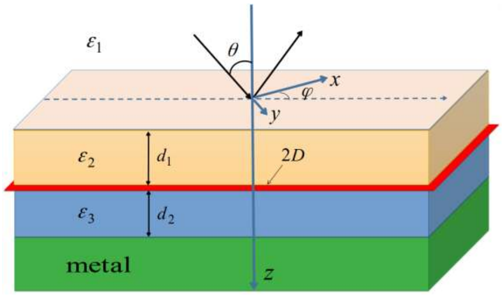

Figure 1. Geometry of the problem

In the coordinate frame making an angle φ with the principle axis of the plasmonic metasurface (assuming that the plane of incidence of the electromagnetic wave is identical to the XZ plane) effective conductivity tensor of the plasmonic metasurface takes the following form [4-6]:

$$\sigma_\varphi = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix}, \tag{1}$$

where

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

$$\sigma_{yy} = \sigma_\parallel \sin^2\varphi + \sigma_\perp \cos^2\varphi\,, \tag{3}$$

$$\sigma_{xy} = \sigma_{yx} = \left(\sigma_\perp - \sigma_\parallel\right)\sin\varphi\cos\varphi\,. \tag{4}$$

In the formulas (2–4) diagonal components of the effective conductivity tensor describing uniaxial plasmonic metasurface $\sigma_{\parallel,\perp}$, normalized by $c/4\pi$, can be expressed using (c is the speed of light):

$$\sigma_{\parallel,\perp} = \sigma^\infty_{\parallel,\perp} + i\frac{\omega A_{\parallel,\perp}}{\omega^2 - \Omega^2_{\parallel,\perp} + i\omega\gamma_{\parallel,\perp}} = \sigma'_{\parallel,\perp} + i\sigma''_{\parallel,\perp}\,. \tag{5}$$

The indices «$\parallel$» and «$\perp$» here correspond respectively to the along and across directions of the plasmonic metasurface principal symmetry axis, $\Omega_{\parallel,\perp}$ and $\gamma_{\parallel,\perp}$ are the resonant frequencies and half-widths of the lines, $A_{\parallel,\perp}$ are the oscillator forces magnitudes and $\sigma^\infty_{\parallel,\perp}$ are the background conductivities. In addition, $\sigma'_{\parallel,\perp}$ and $\sigma''_{\parallel,\perp}$ are the real and imaginary parts of the conductivity tensor for the corresponding components. We assumed that $\sigma^\infty_{\parallel,\perp} = 0.2i$, $A_{\parallel,\perp} = 0.2$, $\gamma_{\parallel,\perp} = 0.02$, $\Omega_\parallel = 1.0$, $\Omega_\perp = 1.2$ [4].

It should be noted that the presence of non-zero non-diagonal conductivity tensor components σ_{xy}, σ_{yx} in case $\varphi \neq 0$ and $\varphi \neq 90°$ cause reflective s-polarized electromagnetic waves to be created. As a result, when *p*-polarized wave propagates through uniaxial plasmonic metasurface reflected waves will have all the electromagnetic field components and will be elliptically polarized in the general case. In the chosen coordinate system, electromagnetic field of *p*-polarized waves has the following components: $\vec{E}_p = \{E_x, 0, E_z\}$, $\vec{H}_p = \{0, H_y, 0\}$. Similarly for the s-polarized electromagnetic waves we have: $\vec{E}_s = \{0, E_y, 0\}$, $\vec{H}_s = \{H_x, 0, H_z\}$.

The wave vectors for each layer have the following components $\vec{k}_j = (k_x, 0, k_{zj})$, $j = 1,2,3$. Moreover, the longitudinal wave number equals $k_x = \frac{\omega}{c}\sqrt{\varepsilon_1}\sin\theta$. For the transverse wave number the formula is $k_{zj} = \sqrt{\frac{\omega^2}{c^2}\varepsilon_j - k_x^2}$.

Let's write down non-zero tangential components of the electromagnetic field in each medium of the established above solid-state structure. We will omit multiplier $\exp(ik_x x - \omega t)$. In the equations below index «*p*» relates to the *p*-polarized waves, and «*s*» – to *s*-polarized ones.

Medium 1 (layer $z < 0$).

$$H^p_{y1}(z) = e^{ik_{z1}z} + r_{pp}e^{-ik_{z1}z}\,, \tag{6}$$

$$E^p_{x1}(z) = \frac{ck_{z1}}{\omega\varepsilon_1}(e^{ik_{z1}z} - r_{pp}e^{-ik_{z1}z}), \tag{7}$$

$$E^s_{y1}(z) = r_{ps}e^{-ik_{z1}z}, \tag{8}$$

$$H^s_{x1}(z) = \frac{ck_{z1}}{\omega}r_{ps}e^{-ik_{z1}z}. \tag{9}$$

Medium 2 (layer $0 < z < d_1$).

$$H^p_{y2}(z) = H^+_{p2}e^{ik_{z2}z} + H^-_{p2}e^{-ik_{z2}z}, \tag{10}$$

$$E^p_{x2}(z) = \frac{ck_{z2}}{\omega\varepsilon_2}(H^+_{p2}e^{ik_{z2}z} - H^-_{p2}e^{-ik_{z2}z}), \tag{11}$$

$$E^s_{y2}(z) = E^+_{s2}e^{ik_{z2}z} + E^-_{s2}e^{-ik_{z2}z}, \tag{12}$$

$$H^s_{x2}(z) = -\frac{ck_{z2}}{\omega}(E^+_{s2}e^{ik_{z2}z} - E^-_{s2}e^{-ik_{z2}z}). \tag{13}$$

Medium 3 (layer $d_1 < z < d_1 + d_2$).

$$H^p_{y3}(z) = H^+_{p3}e^{ik_{z3}z} + H^-_{p3}e^{-ik_{z3}z}, \tag{14}$$

$$E^p_{x3}(z) = \frac{ck_{z3}}{\omega\varepsilon_3}(H^+_{p3}e^{ik_{z3}z} - H^-_{p3}e^{-ik_{z3}z}), \tag{15}$$

$$E^s_{y3}(z) = E^+_{s3}e^{ik_{z3}z} + E^-_{s3}e^{-ik_{z3}z}, \tag{16}$$

$$H^s_{x3}(z) = -\frac{ck_{z3}}{\omega}(E^+_{s3}e^{ik_{z3}z} - E^-_{s3}e^{-ik_{z3}z}). \tag{17}$$

Here r_{pp} and r_{ps} are the amplitudes of *p*- and *s*-polarized waves, reflected from the uniaxial plasmonic metasurface. The magnitudes H^+_{p2}, E^+_{s2} and H^-_{p2}, E^-_{s2} are the amplitudes of the forward and backward *p*- and *s*-polarized waves in a medium with dielectric permittivity ε_2. Likewise, H^+_{p23} and E^+_{s3} are the amplitudes of the forward, while H^-_{p3} and E^-_{s3} – amplitudes of the backward *p*- and *s*-polarized waves within the layer characterized by permittivity ε_3.

To get both r_{pp} and r_{ps} we incorporated boundary conditions near the $z = 0$, $z = d_1$ and $z = d_1 + d_2$.

For $z = 0$ tangential components of the electric and magnetic fields in adjacent mediums are equal.

However, when $z = d_1$, tangential components of the electric fields are continuous, unlike tangential components of magnetic fields:

$$E^p_{x2}(d_1) = E^p_{x3}(d_1), \tag{18}$$

$$E^s_{y2}(d_1) = E^s_{y3}(d_1), \tag{19}$$

$$H^p_{y3}(d_1) - H^p_{y2}(d_1) = -\frac{4\pi}{c}(\sigma_{xx}E^p_{x2}(d_1) + \sigma_{xy}E^s_{y2}(d_1)), \tag{20}$$

$$H^s_{x3}(d_1) - H^s_{x2}(d_1) = \frac{4\pi}{c}(\sigma_{yx}E^p_{x2}(d_1) + \sigma_{yy}E^s_{y2}(d_1)). \tag{21}$$

On the metal boundary $z = d_1 + d_2$ tangential components of the electric fields equal to zero.

The reflection coefficient of the *p*-polarized electromagnetic wave from the plasmonic metasurface is a sum of $|r_{pp}|^2$ and $|r_{ps}|^2$:

$$R_p = |r_{pp}|^2 + |r_{ps}|^2, \tag{22}$$

where

$$r_{pp}=\frac{P_{-}S+Q_{-}}{P_{+}S+Q_{+}}, \tag{23}$$

$$r_{ps}=2\sigma_{yx}\frac{\sin^2(k_3\delta_2)}{P_{+}S+Q_{+}}, \tag{24}$$

$$P_{\pm}=\left(\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)-i\sigma_{xx}\sin(k_3\delta_2)\right)\left(\cos(k_2\delta_1)\mp i\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}\sin(k_2\delta_1)\right)- \\ -\sin(k_3\delta_2)\left(\frac{\varepsilon_2}{k_2}\sin(k_2\delta_1)\pm i\frac{\varepsilon_1}{k_1}\sin(k_2\delta_1)\right), \tag{25}$$

$$S=\left(k_3\cos(k_3\delta_2)-i\sigma_{yy}\sin(k_3\delta_2)\right)\left(\cos(k_2\delta_1)-i\frac{k_1}{k_2}\sin(k_2\delta_1)\right)- \\ -i\sin(k_3\delta_2)\left(k_1\cos(k_2\delta_1)-ik_2\sin(k_2\delta_1)\right), \tag{26}$$

$$Q_{\pm}=\sigma_{xy}^2\sin^2(k_3\delta_2)\left(\cos(k_2\delta_1)\mp i\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}\sin(k_2\delta_1)\right)\left(\cos(k_2\delta_1)-i\frac{k_1}{k_2}\sin(k_2\delta_1)\right). \tag{27}$$

Note that in equations above we used dimensionless quantities: $k_j=\frac{ck_{zj}}{\omega}$ $j=1,2,3$ and $\delta_{1,2}=\frac{d_{1,2}\omega}{c}$.

3. THE AFFECT OF THE COATING COVERING THE UNIAXIAL PLASMONIC METASURFACE ON THE REFLECTIONLESS INCIDENCE OF THE *P*-POLARIZED ELECTROMAGNETIC WAVE

We were trying to identify the conditions under which $R_p=0$ is the case. Let's consider either $\varphi=0°$ or $\varphi=90°$. Then $\sigma_{xy}=\sigma_{yx}=0$ and $r_{ps}=0$. It's clear, that under such circumstances the reflected electromagnetic wave becomes *p*-polarized and $R_p=|r_{pp}|^2$. Seeing that $Q_{\pm}=0$, from the expression (23) we can conclude that $r_{pp}=0$, when $P_{-}=0$. Since quantity P_{-} is a complex number, the equation $r_{pp}=0$ satisfied in case the following conditions are met simultaneously:

$$\left(\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)+\sigma''_{\parallel,\perp}\sin(k_3\delta_2)\right)\cos(k_2\delta_1)-\left(\frac{\varepsilon_2}{k_2}-\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}\sigma'_{\parallel,\perp}\right)\sin(k_2\delta_1)\sin(k_3\delta_2)=0, \tag{28}$$

$$\left(\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)+\sigma''_{\parallel,\perp}\sin(k_3\delta_2)\right)\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}\sin(k_2\delta_1)+\left(\frac{\varepsilon_1}{k1}-\sigma'_{\parallel,\perp}\right)\cos(k_2\delta_1)\sin(k_3\delta_2)=0, \tag{29}$$

From the equations (28), (29) we have:

$$\tan(k_2\delta_1)=\frac{\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)+\sigma''_{\parallel,\perp}\sin(k_3\delta_2)}{\left(\frac{\varepsilon_2}{k_2}-\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}\sigma'_{\parallel,\perp}\right)\sin(k_3\delta_2)}, \tag{30}$$

$$\tan(k_2\delta_1)=-\frac{\left(\frac{\varepsilon_1}{k_1}-\sigma'_{\parallel,\perp}\right)\sin(k_3\delta_2)}{\left(\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)+\sigma''_{\parallel,\perp}\sin(k_3\delta_2)\right)\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}}. \tag{31}$$

Comparing the right side of the equations (30) and (31) we obtain the following expression:

$$\frac{\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)+\sigma''_{\parallel,\perp}\sin(k_3\delta_2)}{\left(\frac{\varepsilon_2}{k_2}-\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}\sigma'_{\parallel,\perp}\right)\sin(k_3\delta_2)}+\frac{\left(\frac{\varepsilon_1}{k_1}-\sigma'_{\parallel,\perp}\right)\sin(k_3\delta_2)}{\left(\frac{\varepsilon_3}{k_3}\cos(k_3\delta_2)+\sigma''_{\parallel,\perp}\sin(k_3\delta_2)\right)\frac{\varepsilon_1 k_2}{\varepsilon_2 k_1}}=0. \quad (32)$$

With fixed values of ε_3 and δ_2 the equation (32) allows us to find the relation $\omega(\varepsilon_2)$, which causes the effect of reflectionless incidence of the *p*-polarized electromagnetic wave through composed solid-state structure. The relevant dependencies $\delta_1(\varepsilon_2)$ can be simply established from one of the equations (30) or (31).

It should be mentioned that for the solid-state structure uniaxial plasmonic metasurface – dielectric layer – metal ($\delta_1 = 0$) [6] the effect of propagation of the *p*-polarized electromagnetic waves with no reflection with the fixed angle of incidence θ can be observed at the two frequencies ω_1 and ω_2, that are symmetrically located relative to $\Omega_{\parallel}$ (for $\varphi = 0°$) and $\Omega_{\perp}$ ($\varphi = 90°$). These frequencies correspond to the different values of dielectric layer thickness δ_2. The reason is that for uniaxial plasmonic metasurface functions $\sigma'_{\parallel,\perp}(\omega)$ are symmetric, and $\sigma''_{\parallel,\perp}(\omega)$ are asymmetric relative to the resonant frequencies $\Omega_{\parallel}$ and $\Omega_{\perp}$.

We are interested in the situation when the angle of incidence of the *p*-polarized waves on the structure under consideration equals $\theta = 45°$ and permittivity is $\varepsilon_3 = 2.0$. Assuming that there is no coating covering dielectric structure ($\delta_1 = 0$) and $\varphi = 0°$ the effect of the incidence with no reflection of the *p*-polarized waves arise at the frequency $\omega_1 \approx 0.976$ and the thickness $\delta_2 \approx 0.377$ as well as when $\omega_2 \approx 1.025$ and $\delta_2 \approx 2.224$. In case $\varphi = 90°$ reflectionless behavior can be observed for the following pairs of frequencies and thicknesses $\omega_1 \approx 1.176$, $\delta_2 \approx 0.377$ and $\omega_2 \approx 1.225$, $\delta_2 \approx 2.224$.

Let's now try to understand how the coating ($\delta_1 \neq 0$) affects the propagation behavior of the *p*-polarized electromagnetic waves in particular case when there is no reflection. We considered the following parameters $\varphi = 0°$, $\theta = 45°$ and $\varepsilon_3 = 2.0$. The general idea was to find how frequencies $\omega_{1,2}$ and thickness δ_1 depend on the dielectric layer permittivity ε_2.

Figure 2 shows relation $\omega_1(\varepsilon_2)$ (left-hand ordinate axis, solid line) and $\delta_1(\varepsilon_2)$ (right-hand ordinate axis, dashed line) in case $R_p = 0$ and $\varphi = 0°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 0.377$. From the Figure 2 we can observe that the function $\omega_1(\varepsilon_2)$ is monotonically increasing unlike $\delta_1(\varepsilon_2)$ which decreases in the same way. Horizontal dotted line from the Figure 2 corresponds to the quantity ω_1 when there is no coating covering the uniaxial plasmonic metasurface.

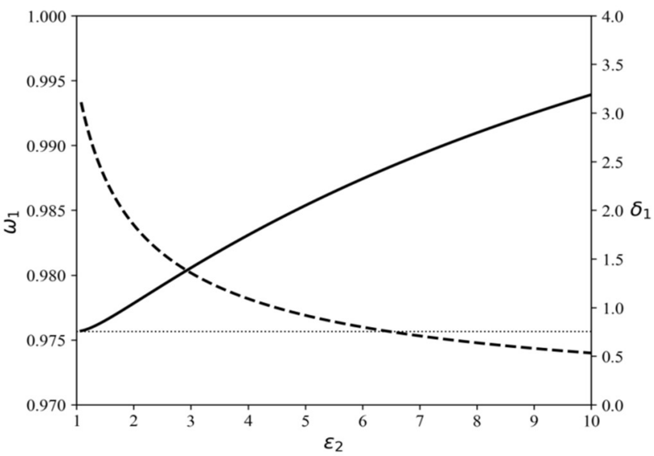

Figure 2. Dependencies $\omega_1(\varepsilon_2)$ (left-hand ordinate axis, solid line) and $\delta_1(\varepsilon_2)$ (right-hand ordinate axis, dashed line) corresponding to the situation $R_p = 0$ for $\phi = 0°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 0.377$

Therefore, when $\delta_1 \neq 0$ the frequency ω_1 shifts closer to resonant frequency $\Omega_{\parallel}$. The quantity of displacement is directly proportional to the permittivity value ε_2. We also can discover another dependency. The thickness value δ_1 that is necessary to observe the effect of electromagnetic wave reflectionless incidence propagation when ε_2 goes up.

The way that coating affects the reflection coefficient R_p of the *p*-polarized electromagnetic wave can be seen on the Figure 3. In this graph the solid line correspond to the dependency $R_p(\omega)$ for the situation when $\varphi = 0$, $\theta = 45°$, $\varepsilon_2 = 1.5$, $\varepsilon_3 = 2.0$, $\delta_1 = 2.329$, $\delta_2 = 0.377$. The figure also contains a dashed line showing the same dependency between the frequency and reflection coefficient for the solid-state structure with no coating ($\delta_1 = 0$).

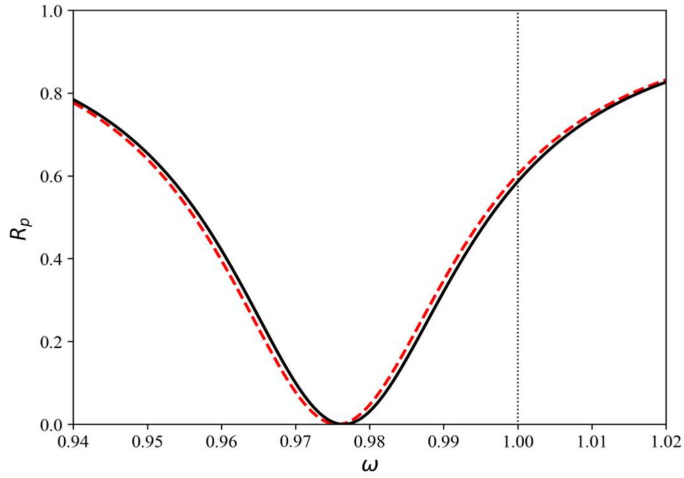

Figure 3. Dependency $R_p(\omega)$ for $\phi = 0°$, $\theta = 45°$, $\varepsilon_2 = 1.5$, $\varepsilon_3 = 2.0$, $\delta_2 = 0.377$ and $\delta_1 = 2.329$ (solid line), $\delta_1 = 0$ (dashed line)

From the Figure 3 we can deduce that adding the coating ($\delta_1 \neq 0$) leads to the shifting of zero value of reflection coefficient R_p (displacement of ω_1) closer to the resonant frequency $\Omega_\parallel = 1.0$.

It is known that in the regular situation with no coating, the effect of the reflectionless incidence of the *p*-polarized electromagnetic waves takes place when the frequency value is either close to $\omega_1 \approx 0.976$ or $\omega_2 \approx 1.025$ [6]. The thickness value should be also shifted to $\delta_2 \approx 2.224$.

Let us now consider what happens with ω_2 after introducing the coating for the metasurface. The Figure 4 describes the relation $\omega_2(\varepsilon_2)$ (left-hand ordinate axis, solid lines) and $\delta_1(\varepsilon_2)$ (right-hand ordinate axis, dashed lines) that met $R_p = 0$ condition for $\varphi = 0°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 2.224$. It can be discovered from the graph that both $\omega_2(\varepsilon_2)$ and $\delta_1(\varepsilon_2)$ are monotonically decreasing functions. Horizontal dashed line on the Figure 4 corresponds to the value ω_2 when no coating covering metasurface. Thus, by increasing ε_2 the frequency value ω_2 at which reflectionless propagation of the *p*-polarized electromagnetic waves takes place is approaching to the resonant frequency $\Omega_\parallel = 1.0$.

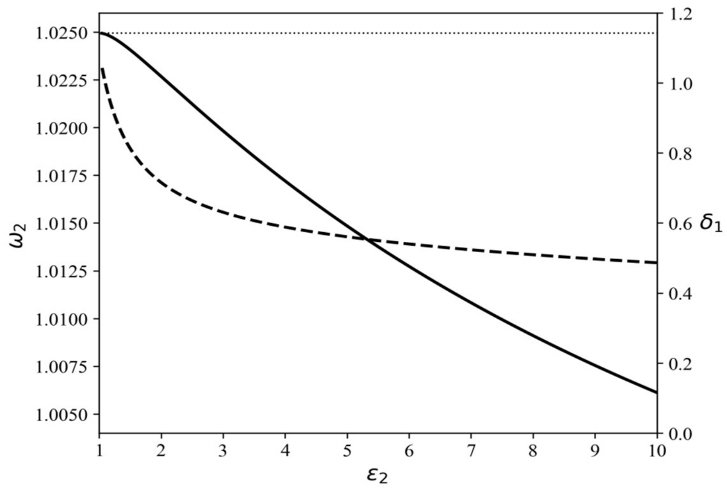

Figure 4. Dependencies $\omega_2(\varepsilon_2)$ (left-hand ordinate axis solid lines) and $\delta_1(\varepsilon_2)$ (right-hand ordinate axis, dashed lines) corresponding to $R_p = 0$ for $\phi = 0°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 2.224$

Figure 5 using a solid line describes dependency $R_p(\omega)$ for the particular situation when $\varphi = 0$, $\theta = 45°$, $\varepsilon_2 = 2.0$, $\varepsilon_3 = 2.0$, $\delta_1 \approx 0.716$, $\delta_2 \approx 2.224$. Similarly to the figures above, the graph also shows same dependency $R_p(\omega)$ for the case with no coating $\delta_1 = 0$.

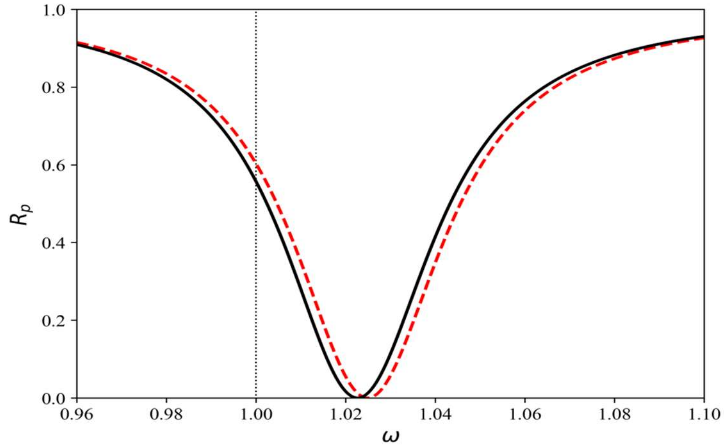

Figure 5. Dependency $R_p(\omega)$ for $\phi = 0°$, $\theta = 45°$, $\varepsilon_2 = 2.0$, $\varepsilon_3 = 2.0$, $\delta_2 = 2.224$ for $\delta_1 = 0.716$ (solid line) and $\delta_1 = 0$ (dashed line)

By using the Figure 5 we can deduce that incorporating the coating causes shifting of zero value of R_p closer to the resonant frequency $\Omega_\parallel$. By increasing the dielectric permittivity of the ε_2 effect of non-reflective incidence of the *p*-polarized electromagnetic waves arise on the lower frequencies ω_2 and higher thicknesses δ_1 of the dielectric layer.

We also studied the changes introduced by adding coating for the case when the plane of incidence of the *p*-polarized electromagnetic waves makes the right angle with the principal axis of plasmonic metasurface ($\varphi = 90°$). Similarly to the previous cases we considered the following: $\theta = 45°$, $\varepsilon_3 = 2.0$. If $\delta_2 \approx 0.377$ and the coating is absent the effect of the reflectionless propagation of *p*-polarized electromagnetic waves takes place at the frequency $\omega_1 \approx 1.176$. Extending the solid-state structure with the coating leads to the change of ω_1. Figure 6 shows dependencies $\omega_1(\varepsilon_2)$ (left-hand ordinate axis, solid line) and $\delta_1(\varepsilon_2)$ (right-hand ordinate axis, dashed line) for $R_p = 0$ when $\varphi = 90°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 0.377$. It can be seen from the graph that the dependency $\omega_1(\varepsilon_2)$ is monotonically increasing function. However, $\delta_1(\varepsilon_2)$ monotonically decreases. Horizontal dashed line on the Figure 6 corresponds to the $\omega_1 \approx 1.176$, when there is no coating. It should be noted, that by increasing ε_2 the value ω_1 approached to the resonant frequency $\Omega_\perp = 1.2$, unlike δ_1 which is decreasing.

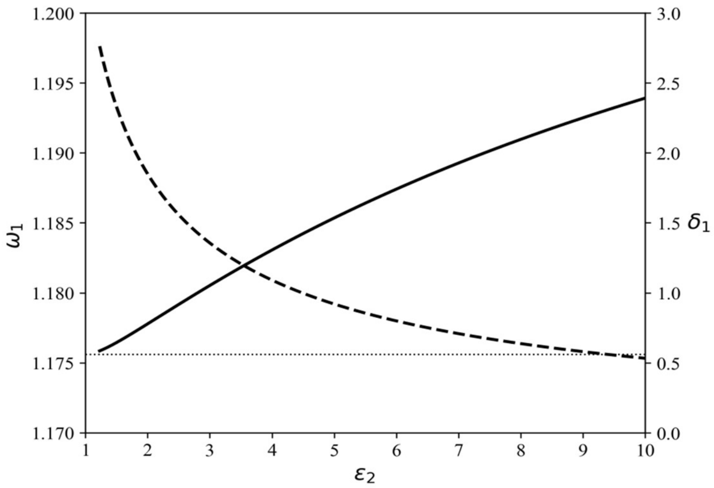

Figure 6. Dependencies $\omega_1(\varepsilon_2)$ (left-hand coordinate axis, solid lines) and $\delta_1(\varepsilon_2)$ (right-hand ordinate axis, dashed lines) corresponding to $R_p = 0$ for $\phi = 90°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 0.377$

Let's set $\delta_2 \approx 2.224$. Then for solid-state structure with no coating reflectionless incidence can be observed at the frequency $\omega_2 \approx 1.225$. Figure 7. shows the dependencies $\omega_2(\varepsilon_2)$ (left-handed ordinate axis, solid line) and $\delta_1(\varepsilon_2)$ (right-handed ordinate axis, dashed line). From the graph we can deduce that both dependencies $\omega_2(\varepsilon_2)$ and $\delta_1(\varepsilon_2)$ are monotonically decreasing functions. Also, it's possible to see that by increasing ε_2 the quantity of ω_2 advances to the resonant frequency $\Omega_\perp = 1.2$.

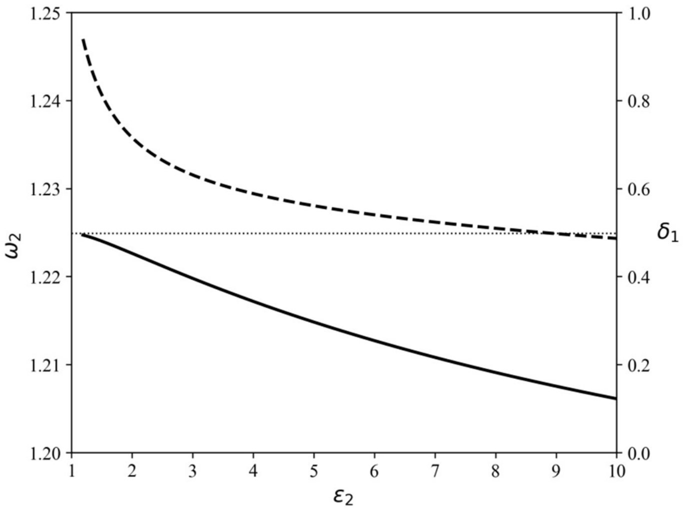

Figure 7. Dependencies $\omega_2(\varepsilon_2)$ (left-handed ordinate axis, solid line) and $\delta_1(\varepsilon_2)$ (right-handed ordinate axis dashed lines) corresponding to $R_p = 0$ for $\phi = 90°$, $\theta = 45°$, $\varepsilon_3 = 2.0$, $\delta_2 \approx 2.224$

4. CONCLUSIONS

It was shown that the dielectric coating of the solid-state structure uniaxial-plasmonic metasurface-dielectric-metal significantly influence the effect of reflectionless incidence of the *p*-polarized electromagnetic waves. The conditions were studied under which the effect of the non-reflective incidence of *p*-polarized wave can be observed depending on the dielectric permittivity of the coating. We established that increasing coating permittivity causes the frequency at which the effect arising to shift closer to the resonant frequency $\Omega_\parallel$ (for $\varphi = 0°$) or to the frequency $\Omega_\perp$ (for $\varphi = 90°$).

In addition, the thicknesses of the coating δ_1 were founded required for the reflectionless incidence of *p*-polarized wave. We also analysed dependency between δ_1 and dielectric permittivity of the coating ε_2. It was determined that by increasing the permittivity of the coating ε_2, we end up with lower thickness δ_1, that is required to observe the effect of non-reflective incidence. Moreover, we found that, this holds true not only for the case when the plane of incidence of the electromagnetic wave is parallel to the principal symmetry axis of plasmonic metasurface ($\varphi = 0°$), but also if the plane of incidence is perpendicular to the principal symmetry axis ($\varphi = 90°$).

Studied effects can be applied for designing conceptually new types of optical and nanoelectronic equipment with unique practical characteristics.

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ПАДІННЯ БЕЗ ВІДОБРАЖЕННЯ *p*-ПОЛЯРИЗОВАНОЇ ЕЛЕКТРОМАГНІТНОЇ ХВИЛІ НА ТВЕРДОТІЛЬНУ СТРУКТУРУ "ПОКРИТТЯ-ОДНОВІСНА-ПЛАЗМОННА МЕТАПОВЕРХНЯ-ДІЕЛЕКТРИК МЕТАЛ "

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У роботі досліджені ефекти, що виникають при падінні p-поляризованоі електромагнітної хвилі на твердотільну структуру "покриття-одновісна плазмонна метаповерхня-діелектрік-метал". Метою роботи є дослідження впливу покриття твердотільної структури "одновісна плазмонна метаповерхня-діелектрік-метал" на ефект падіння p-поляризованих електромагнітних хвиль без відображення. Для знаходження умов виникнення ефекту падіння без відображення p-поляризованої електромагнітної хвилі на структуру "покриття-одновісна плазмонна метаповерхня-діелектрік-метал" було використано чисельне моделювання. За допомогою цього методу було визначено параметри покриття, що дають змогу спостерігати ефект падіння без відображення p-поляризованих електромагнітних хвиль. Було знайдено, що діелектричне покриття твердотільної структури, яка розглядалася, має істотний вплив на ефект безвідбівного падіння p-поляризованих хвиль. Показано, що діелектрична проникність покриття змінює частоту спостереження цього ефекту. Визначена залежність між проникністю та товщиною покриття, яка необхідна для виникнення ефекту падіння без відображення p-поляризованих електромагнітних хвиль. Проведене в роботі дослідження має великий науковий та практичний інтерес. Досліджені в роботі структури можна використати для створення принципово нових пристроїв оптики та наноелектроніки.

Ключові слова: *діелектричне покриття; p-поляризовані електромагнітні хвилі; одновісна плазмонна метаповерхня; падіння без відображення*