

Generalized transverse-electric Brewster effect and perfect absorption with reflectionless plasmonic metasurfaces

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The polarization of incident light may be tuned with the Brewster effect that is widely used in photography and optical coatings. The Brewster angle demonstrating zero reflection is usually observed for transverse-magnetic polarized light, but recent studies have discovered the generalized Brewster effect in transverse-electric polarization using nanostructures. In this work, we discover the way of the Brewster angle and perfect absorption control in transverse-electric polarization with two-dimensional plasmonic materials and nanostructures. We derive the analytical model of the reflectionless metasurface described by the surface conductivity within and beyond the total internal reflection state leading to the perfect absorption and generalized Brewster's angle, respectively. Then, we support our analytical results by the full-wave numerical simulation using the effective two-dimensional sheet obeying the Drude-Lorentz dispersion model and the real design of plasmonic anisotropic metasurface based on gold nanodisks. The results obtained open new opportunities for the planar polarization optics and related devices including polarization transformers, optical isolators, antireflection coatings, and biodetectors.

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I. INTRODUCTION

The fundamental principles of optical theory describing light propagation within the medium and at the interface between two media were established over two centuries ago [1]. One of these basic effects is the phenomenon of Brewster's angle (BA), at which light is perfectly transmitted from one transparent dielectric medium to another one, with no reflection for a specific polarization [2]. According to Maxwell's equations, there are two fundamental polarizations of the eigenmodes propagating within an isotropic homogeneous medium—transverse-electric (TE) and transverse-magnetic (TM) polarization states. It means that the electric and magnetic fields for TE- and TM-polarized eigenmodes, respectively, oscillate orthogonally (transversely) to the plane of wave propagation. Any polarization state may be considered as the superposition of TE and TM eigenstates. The Brewster angle in nonmagnetic media means a zero reflection of TM-polarized plane waves. In other words, the unpolarized light at BA becomes linearly TE-polarized in the reflection [3]. The applications of BA mainly include the polarization filters [4,5] and antireflection coatings [6,7]. However, more specific applications, such as microscopy of monolayers [8–10],

anomalous optical beam shifts [11–13] and optical biosensing [14–16], also actively utilize the BA.

The study of BA has been intensively expanded with randomly stratified dielectric media and surface roughness [17,18] and multilayers and gratings [19,20]. Even more interesting and efficient for BA control and tunability is the recent application of two-dimensional (2D) materials [21–23], dielectric nanostructures [24,25], and plasmonic [26,27] nanostructures. Ultrathin 2D materials and plasmonic metasurfaces, representing a subwavelength periodic array of metallic nanoparticles, demonstrate the ability to manipulate the reflection, refraction, absorption, and polarization of light. In particular, the Brewster angle can be shifted by several degrees using the voltage-tunable graphene [22] or by tens of degrees using the plasmonic metasurfaces [27] due to modifications in surface conductivity that alter the electromagnetic boundary conditions.

Another degree of polarization control is related to the discovery of BA in TE polarization. The obvious way is to use a metamaterial with resonant permeability as one of the media [28,29]. Another approach involves the engineering of the microwave metasurfaces adjusting to attain the impedance matching between two media [30,31]. It has recently been discovered that the BA in TE polarization at the specified angle may be achieved with completely nonmagnetic media using a nonmagnetic 2D conducting layer due to the compensation of reflection by absorption in the 2D layer, even at normal incidence [26]. However, the manipulation of the BA in TE polarization by the surface conductivity contribution of the 2D layer has not been properly evaluated or studied.

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One more important characteristic of the ultrathin devices is the polarization-dependent perfect absorption that refers to the complete and simultaneous suppression of reflection and transmission of incident electromagnetic waves. It may be achieved with the proper engineering of nano- and microstructures such as multilayers, gratings, engineered 2D materials, metasurfaces, arrays of nanoparticles, gyrotropic layers, etc. [32,33]. The main mechanisms of the perfect absorption include the impedance matching, critical coupling, resonant dissipation with eigenmodes, and interference effects [32,34]. Here, we extend the analysis of Brewster's law to the total internal reflection regime and derive the dual-functional metasurface acting as a Brewster-like polarizer or perfect absorber depending on the angle of incidence and the wavelength of the incident light.

In this work, we derive the analytical expressions connecting the zero-reflection angle in TE polarization and the surface conductivity of the two-dimensional sheet at the interface between two isotropic dielectric media. We reveal the condition of the zero-reflection angle existence in TE polarization for two regimes—beyond and within the total internal reflection. Using the developed analytical model, we study the emergence of the generalized Brewster angle and perfect absorption regimes caused by the presence of the 2D complex surface conductivity. Finally, we verify the analytical results by the full-wave numerical simulation via the field distributions and provide the real designs of plasmonic metasurfaces based on gold nanodisks at quartz substrate demonstrating the Brewster angle and perfect absorption in TE polarization. The results obtained complement the management of the BA in TM polarization creating a platform for the full polarization control with 2D materials and nanostructures and discovering new opportunities for flat optics and planar nanotechnologies.

II. THEORETICAL MODEL AND METHODS

A. Modified Fresnel equations for TE polarization

We consider a TE-polarized [$\mathbf{E} = (0, E_y, 0)$] plane wave propagating in the xz plane from medium 1 to medium 2, characterized by the refractive indices $n_1 = \sqrt{\varepsilon_1 \mu_1}$ and $n_2 = \sqrt{\varepsilon_2 \mu_2}$ (ε_i and μ_i are the corresponding permittivities and permeabilities), respectively, through the 2D interface described by the surface conductivity σ [Fig. 1(a)]. The tangential components of the wave vectors of the incident (i), reflected (r), and transmitted (t) waves are conserved and equal to $k_x = n_1 k_0 \sin \theta$, where θ is the angle of incidence, $k_0 = 2\pi/\lambda$ is the wave vector in vacuum at the wavelength λ , while their normal components are defined as $k_z^i = n_1 k_0 \cos \theta$, $k_z^r = -n_1 k_0 \cos \theta$, and $k_z^t = n_2 k_0 \sqrt{n^2 - \sin^2 \theta}$, $n = n_2/n_1$. Applying Maxwell's equations, Ohm's law, and the boundary conditions for the tangential components of electric and magnetic fields, we derive the modified Fresnel equations giving the complex reflection ($r = \mathbf{E}^r/\mathbf{E}^i$) and transmission ($t = \mathbf{E}^t/\mathbf{E}^i$) coefficients:

$$r = \frac{\frac{k_z^i}{\mu_1} - \frac{k_z^t}{\mu_2} - \sigma k_0}{\frac{k_z^i}{\mu_1} + \frac{k_z^t}{\mu_2} + \sigma k_0}, \quad t = \frac{2 \frac{k_z^i}{\mu_1}}{\frac{k_z^i}{\mu_1} + \frac{k_z^t}{\mu_2} + \sigma k_0}. \quad (1)$$

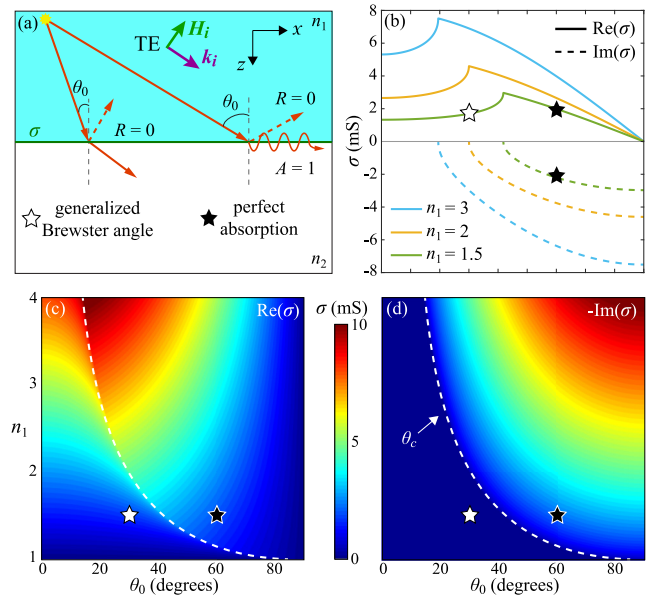


FIG. 1. (a) Schematic illustration of the generalized Brewster effect and the perfect absorption in TE polarization with 2D conducting layer described by the surface conductivity σ . (b) Dependence of the real (solid lines) and imaginary (dashed lines) parts of surface conductivity on the angle θ_0 corresponding to zero reflection for different refractive indices of the initial medium: $n_1 = 1.5$ (green lines), $n_1 = 2$ (yellow lines), and $n_1 = 3$ (light blue lines). (c), (d) The dependencies of (c) real and (d) imaginary parts of the surface conductivity on the zero-reflection angle and the refractive index of the initial medium. The white dashed line marks the critical angle of the total internal reflection. Here, the refractive index of the second medium is always $n_2 = 1$. The white and black stars mark the cases of the generalized TE Brewster angle and the perfect absorption cases, respectively, for $n_1 = 1.5$ and $n_2 = 1$.

Here, the surface conductivity σ is normalized per $c/(4\pi)$, where c is the speed of light. The intensity-related reflectance, transmittance, and absorptance are defined as $R = |r|^2$, $T = \text{Re}(\frac{k_z^t/\mu_2}{k_z^i/\mu_1})|t|^2$, and $A = 1 - R - T$, respectively. The derivation procedure in more details can be found in Refs. [21,26,27,35].

B. Surface conductivity

To analyze the spectral characteristics of the reflectionless resonant plasmonic metasurfaces, we consider the dispersion of the surface conductivity according to the Drude-Lorentz model [36]:

$$\sigma = \frac{i\sigma_0\omega^2}{\omega^2 - \Omega_0^2 + i\gamma\omega}, \quad (2)$$

where $\omega = 2\pi c/\lambda$ is the operational angular frequency, Ω_0 is the resonant angular frequency, γ is the bandwidth, and σ_0 is the conductivity-related amplitude. For the simplification, we switch to frequency-dimensionless quantities normalized to the resonant frequency, namely, $\tilde{\omega} = \omega/\Omega_0$ and $\tilde{\gamma} = \gamma/\Omega_0$.

It is important to note that in the lossless case ($\gamma = 0$), the surface conductivity is purely imaginary [$\text{Re}(\sigma) = 0$, $\text{Im}(\sigma) = \sigma_0\tilde{\omega}^2/(\tilde{\omega}^2 - 1)$], while at the resonant frequency

($\tilde{\omega} = 1$), the surface conductivity is purely real [$\text{Re}(\sigma) = \sigma_0/\tilde{\gamma}$, $\text{Im}(\sigma) = 0$].

C. Numerical simulation and determination of plasmonic metasurface design

We use the finite-element method in comsol multiphysics software to calculate the spatial field distribution for the 2D conducting layer and for the 3D meta-atom as well as to determine and to optimize the design of plasmonic metasurfaces. For the simulation of the 2D conducting layer, we consider a 2D model (xz plane) with applied boundary conditions along the x direction and the surface current describing the surface conductivity of a 2D layer (xy plane). For the simulation and optimization of the plasmonic metasurface, we consider a single unit cell with applied periodic boundary conditions along the x and y directions and perfectly matched layers along the z direction. The incident plane wave is excited by the periodic port. We fix the thickness of meta-atom as $h = 25$ nm that is approximately $\lambda/25$ for the designs of a metasurface under consideration, and we sweep the period of metasurface a and diameters of the nanodisks with elliptical cross sections d_x and d_y to determine a zero-reflection condition and the related wavelength $\lambda_0 = \lambda(R = 0)$ for the specified angles of incidence. The dispersion of gold for the thin films is taken from Ref. [37].

III. RESULTS AND DISCUSSION

By setting the numerator of r in Eq. (1) to 0, one can easily define the values of the surface conductivity σ necessary to achieve zero reflection at the specified angle θ_0 :

$$\sigma = \frac{n_1}{\mu_1} \left(\cos \theta_0 - \frac{\mu_1}{\mu_2} \sqrt{n^2 - \sin^2 \theta_0} \right). \quad (3)$$

Figures 1(b)–1(d) show the dependencies of the surface conductivity σ on the angle of zero reflection θ_0 for different combinations of the surrounding medium n_1 , while $n_2 = 1$. One can distinguish two regimes in the angular dependence of the surface conductivity separated by the critical angle of the total internal reflection (TIR) $\theta_c = \arcsin(n_2/n_1)$. The first regime is observed in the non-TIR angular range for the specified angles $\theta_0 < \theta_c$, where the surface conductivity is purely real [$\text{Re}(\sigma) > 0$, $\text{Im}(\sigma) = 0$]; see Fig. 1(b). The second regime is observed within the TIR for the specified angles $\theta_0 \geq \theta_c$, where the surface conductivity becomes complex [$\text{Re}(\sigma) > 0$, $\text{Im}(\sigma) < 0$]. The switching between these two regimes is characterized by the fracture of the real part and the emergence of the imaginary part of the surface conductivity [Fig. 1(b)]. The same discontinuity brought by the TIR, marked by the white dashed line, is observed in Figs. 1(c) and 1(d).

As we further demonstrate, the surface conductivity values of Eq. (3) in the non-TIR and TIR regimes correspond to the generalized Brewster ($R = 0$) and perfect absorption ($R = 0$, $T = 0$) effects, respectively (Fig. 1). The switching between these two regimes leads to the dual-functional coatings for polarization-controlled filtering and imaging.

A. Beyond total internal reflection: Transverse-electric generalized Brewster effect

In this case, the surface conductivity that corresponds to the resonant condition is purely real. It enables the absorption-mediated compensation mechanism for the reflection settings similar to the transverse-magnetic generalized Brewster effect with two-dimensional conducting materials and nanostructures [15,27]. The inverse task, i.e., the determination of the Brewster angle for the specified purely real surface conductivity, can be solved using the following relation for the nonmagnetic case ($\mu_1 = \mu_2 = 1$):

$$\theta_0 = \arccos \left(\frac{1 - n^2 + \tilde{\sigma}^2}{2\tilde{\sigma}} \right), \quad (4)$$

where $\tilde{\sigma} = \sigma/n_1$.

As an illustrative example, we define the surface conductivity for $\theta_0 = 30^\circ$, $n_1 = 1.5$, and $n_2 = 1$ as $\sigma_1 = 1.693$ mS from Fig. 1(b) and calculate the related reflectance, transmittance, and absorptance [Figs. 2(a) and 2(c)]. One can notice that the reflectance is purely zero ($R = 0$) at the specified angle in this case, while the transmittance and absorptance are approximately equal being about a half of the intensity of the incident light ($T \approx A \approx 0.5$). The spatial distributions of the reflected and transmitted normal components of the electric field support these derivations [Fig. 2(e)]. For comparison, we also show the spatial distribution of the electric field at $\theta = 60^\circ$ demonstrating nonzero reflectance within the TIR regime with $\sigma = \sigma_1$ [Fig. 2(f)].

B. Within total internal reflection: Perfect absorption

In this case, the condition $\sin \theta_0 > n$ leads to the emergence of the negative imaginary part of surface conductivity. The transmitted field in the second medium characterized by the refractive index n_2 is evanescent due to the TIR condition; i.e., the wave vector k_z^t is purely imaginary. Therefore, the zero-reflection condition for the nonmagnetic case according to Eq. (1) reads as

$$\begin{aligned} \text{Re}(\sigma) &= \frac{k_z^i}{k_0} = n_1 \cos \theta_0, \\ \text{Im}(\sigma) &= -\frac{\text{Im}(k_z^t)}{k_0} = -n_1 \sqrt{\sin^2 \theta_0 - n^2}. \end{aligned} \quad (5)$$

According to the energy law, zero transmission caused by the TIR regime and the zero-reflection condition due to the specific complex surface conductivity result in the perfect absorption ($A = 1$). The angle of the perfect absorption can then be defined according to Eq. (4) with the substitution of the surface conductivity (5).

As an illustrative example, we define the surface conductivity for $\theta_0 = 60^\circ$, $n_1 = 1.5$, and $n_2 = 1$ as $\sigma = 1.992 - 2.202i$ mS from Fig. 1(b) and calculate the related reflectance, transmittance, and absorptance [Figs. 2(b) and 2(d)]. The reflectance and transmittance are purely zero ($R = 0$, $T = 0$) at the specified angle in this case leading to the perfect absorption condition. The spatial distribution of the reflected and transmitted normal components of the electric field are shown in Fig. 2(h) demonstrating the concentration of the evanescent field in the vicinity of the 2D layer. For

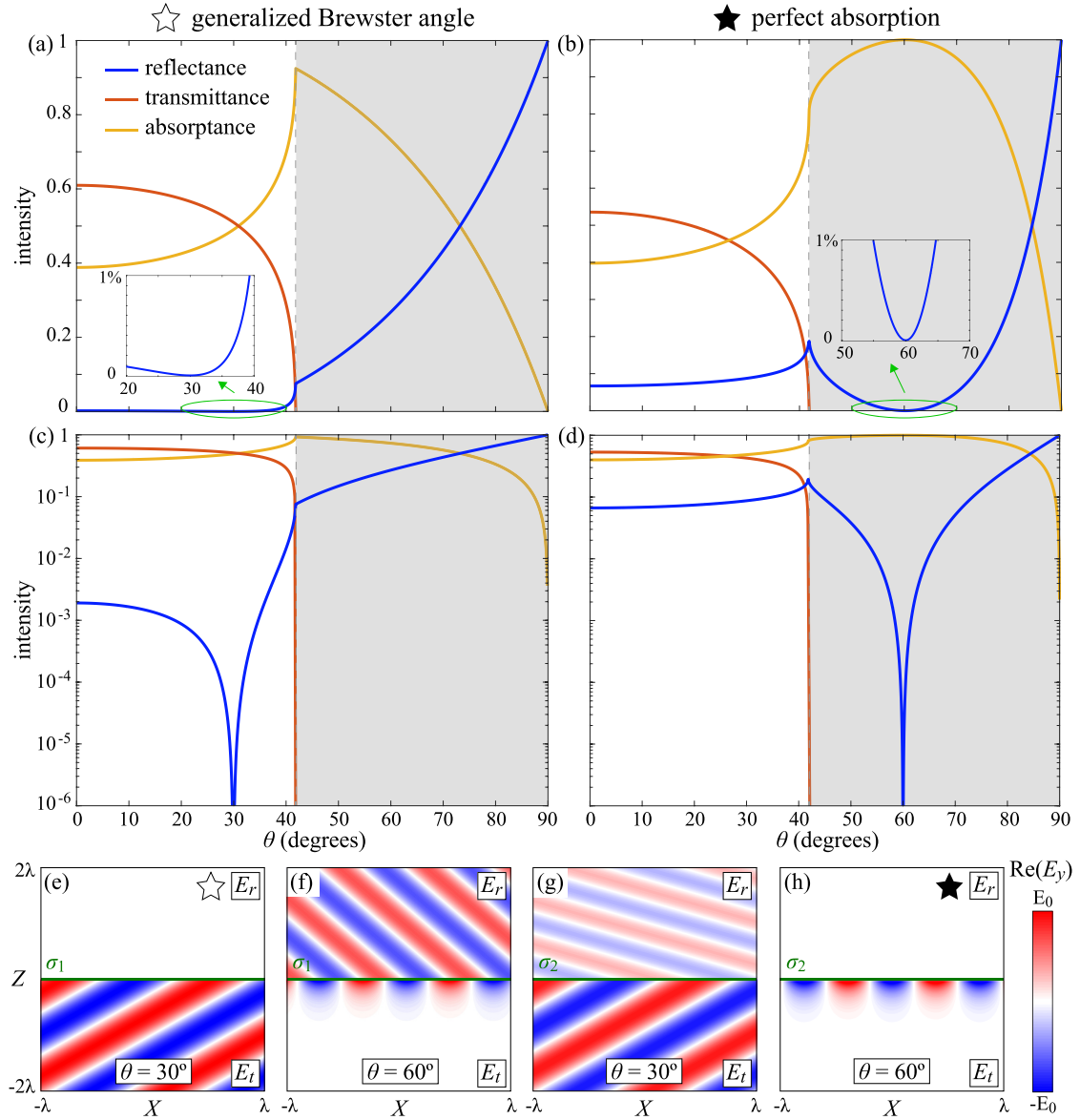


FIG. 2. (a)–(d) Dependencies of the reflectance R (blue line), transmittance T (red line), and absorptance A (yellow line) on the incident angle θ in (a), (b) linear and (c), (d) logarithmic scale for (a), (c) the generalized Brewster angle ($R = 0$) at $\theta = 30^\circ$ and (b), (d) the perfect absorption ($R = 0$, $T = 0$) at $\theta = 60^\circ$, respectively. The insets in panels (a) and (b) show the zooms of the zero-reflection condition. The gray regions in panels (a)–(d) correspond to the TIR regime. (e)–(h) Spatial distribution of the reflected (top half-plane) and transmitted (bottom half-plane) normal components of the electric field E_y at the incident angles (e), (g) $\theta = 30^\circ$ and (f), (h) $\theta = 60^\circ$ corresponding to (e) the generalized Brewster angle and (h) the perfect absorption. The refractive indices are $n_1 = 1.5$ and $n_2 = 1$, and the surface conductivities of the 2D layers are (a), (c), (e), (f) $\sigma_1 = 1.693$ mS and (b), (d), (g), (h) $\sigma_2 = 1.992$ – 2.202 mS.

comparison, we also show the spatial distribution of the electric field at $\theta = 30^\circ$ demonstrating nonzero reflectance and transmittance beyond the TIR regime with $\sigma = \sigma_2$ [Fig. 2(g)].

C. Spectral dependence of ideal 2D conducting sheet

Here, we consider the 2D conducting layer taking into account the dispersion obeying the Drude-Lorentz model according to Eq. (2). The typical dispersion of the real and imaginary parts of the surface conductivity for $\tilde{\gamma} = 0.3$ is shown in Fig. 3(a). Taking $\sigma_0 = 0.51$ mS and $\sigma_0 = 1.55$ mS for this case, we switch to the cases of the generalized

TE Brewster effect ($\sigma = \sigma_1$) and the perfect absorption ($\sigma = \sigma_2$) at the normalized frequencies $\tilde{\omega} = 1$ and $\tilde{\omega} = 0.85$, respectively.

Generally, the spectral width between the generalized Brewster angle and the perfect absorption regimes $\Delta\omega$ can be negligible in the vicinity of resonance of metasurface or, vice versa, can achieve the window compared with the resonant frequency Ω_0 for large absorption losses γ and angles of perfect absorption θ_0 [Figs. 3(b) and 3(c)]. Thus, the dual-mode regime of these metasurfaces could be ultranarrow or broadband depending on applications. The typical value of the surface conductivity amplitude, σ_0 in Eq. (2), is of the order of

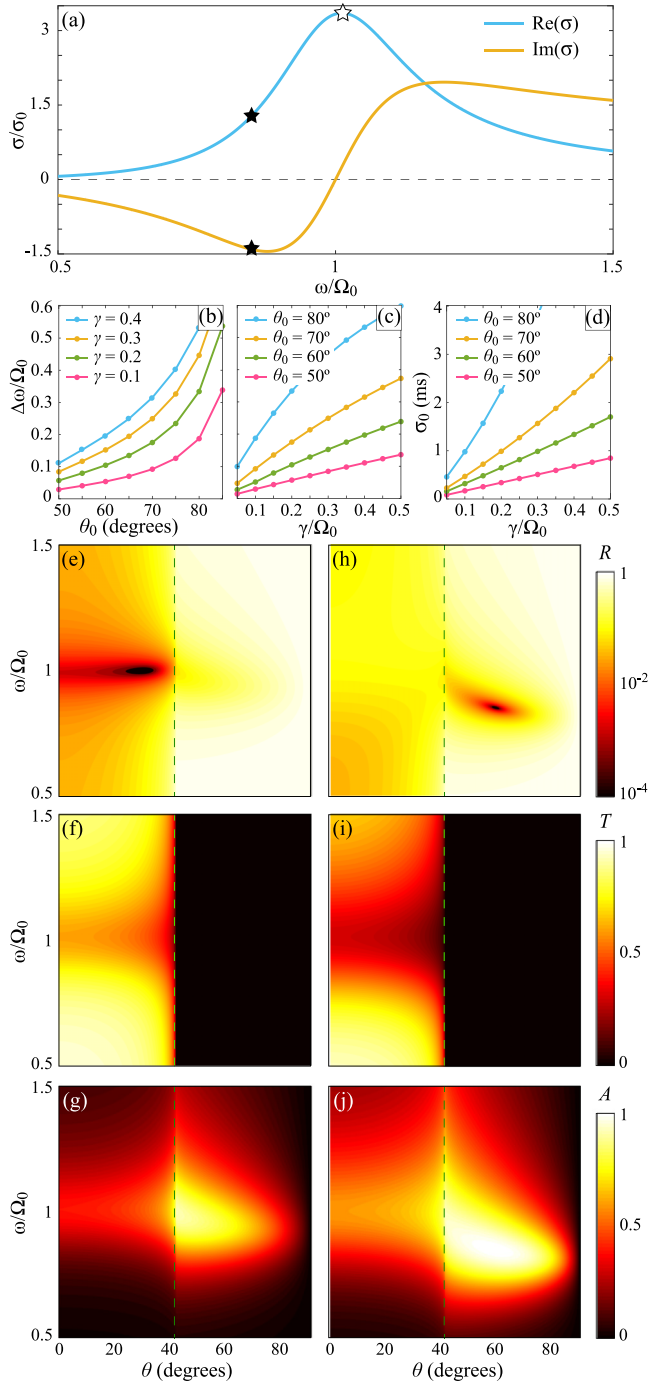


FIG. 3. (a) Dependence of the real (blue line) and imaginary (yellow line) parts of the normalized surface conductivity on the normalized angular frequency. (b), (c) Dependencies of spectral distance between resonant frequency and perfect absorption regime $\Delta\omega/\Omega_0$ (b) on the angle within TIR corresponding to the reflectionless condition θ_0 and (c) on the absorption losses γ/Ω_0 for different values of γ/Ω_0 and θ_0 , respectively. (d) Dependence of the conductivity amplitude σ_0 on absorption losses γ/Ω_0 for different values of θ_0 within TIR. (e), (j) The color maps showing the dependencies of (e), (h) reflectance, (f), (i) transmittance, and (g), (j) absorptance on the incident angle and the normalized angular frequency for (e)–(g) generalized Brewster's angle and (h)–(j) perfect absorption regimes.

a few millisiemens for the metasurfaces at the interface of air and quartz [Fig. 3(d)]. The expected values of surface conductivities could be achieved for different frequency ranges from microwaves to visible.

The dependencies of the reflectance, transmittance, and absorbance on the normalized frequency and the incident angle are shown in Figs. 3(e)–3(j). The zero reflectance can be observed in the vicinity of $\omega/\Omega_0 = 1$, $\theta = 30^\circ$ and $\omega/\Omega_0 = 0.85$, $\theta = 60^\circ$ in Figs. 3(e) and 3(h), respectively. The TIR is well observed in Figs. 3(f) and 3(i). The first case corresponds to the generalized Brewster effect with approximately equal transmittance and absorbance [Figs. 3(f) and 3(g)], while the second case demonstrates the perfect absorption within the TIR [Fig. 3(j)].

D. Designs of reflectionless plasmonic metasurfaces

Finally, we found the real designs of plasmonic reflectionless metasurface representing a square periodic array of gold nanodisks with an elliptical cross section at the quartz substrate ($n_1 = 1.5$). We optimized the parameters of metasurface supporting the generalized transverse-electric Brewster effect at $\theta = 30^\circ$ and the perfect absorption at $\theta = 60^\circ$, namely, the period of the structure and the axes of the elliptical cross section of nanodisks [Fig. 4(a)]. The proper methods of engineering the surface conductivity of anisotropic metasurface based on gold nanodisks and nanopatches have been recently discovered [38,39]. The specific procedure for designing the plasmonic anisotropic metasurface with the reflectionless states is outlined in Appendix A.

The intensity spectra and field distributions for a metasurface with a period of $a = 200$ nm, long axis of $d_x = 80$ nm and short axis of $d_y = 65$ nm of the elliptical cross section and the thickness $h = 25$ nm of nanodisks are shown in Fig. 4. As it is shown in Appendix B, the discussed effects remain stable for structural imperfections that result in deviations of up to 10% in metasurface parameters. First, we consider the incidence of the TE-polarized plane wave along the short axis of nanodisks and demonstrate the generalized Brewster angle at $\theta = 30^\circ$ [Fig. 4(a1)]. The reflectance, transmittance, and absorbance spectra demonstrate the zero reflection at $\lambda = 562$ nm [Figs. 4(b1) and 4(c1)]. This result is supported by the spatial distribution of the reflected and transmitted electric field in Fig. 4(d1). For the incident angle $\theta = 60^\circ$ (within TIR mode), there is no zero-reflection regime, so we observe $R > 0$ and $A > 0$ at any wavelength [Figs. 4(a2)–4(d2)]. Similarly, we consider the incidence of the TE-polarized plane wave along the long axis of nanodisks and demonstrate the perfect absorption at $\theta = 60^\circ$ [Fig. 4(a4)]. In this case, the zero-reflection regime is observed at $\lambda = 621$ nm [Figs. 4(b4) and 4(c4)], while at other incident angles the reflectance is nonzero [Figs. 4(b3) and 4(c3)]. These results are supported by the spatial field distributions in Figs. 4(d3) and 4(d4).

It is important to note a good coincidence between the spatial field distributions of both zero-reflection and other arbitrary regimes for the ideal 2D conducting sheet [Figs. 2(e)–2(h)] and the real design of the plasmonic nanodisk-based metasurface [Figs. 4(d1)–4(d4)]. One can

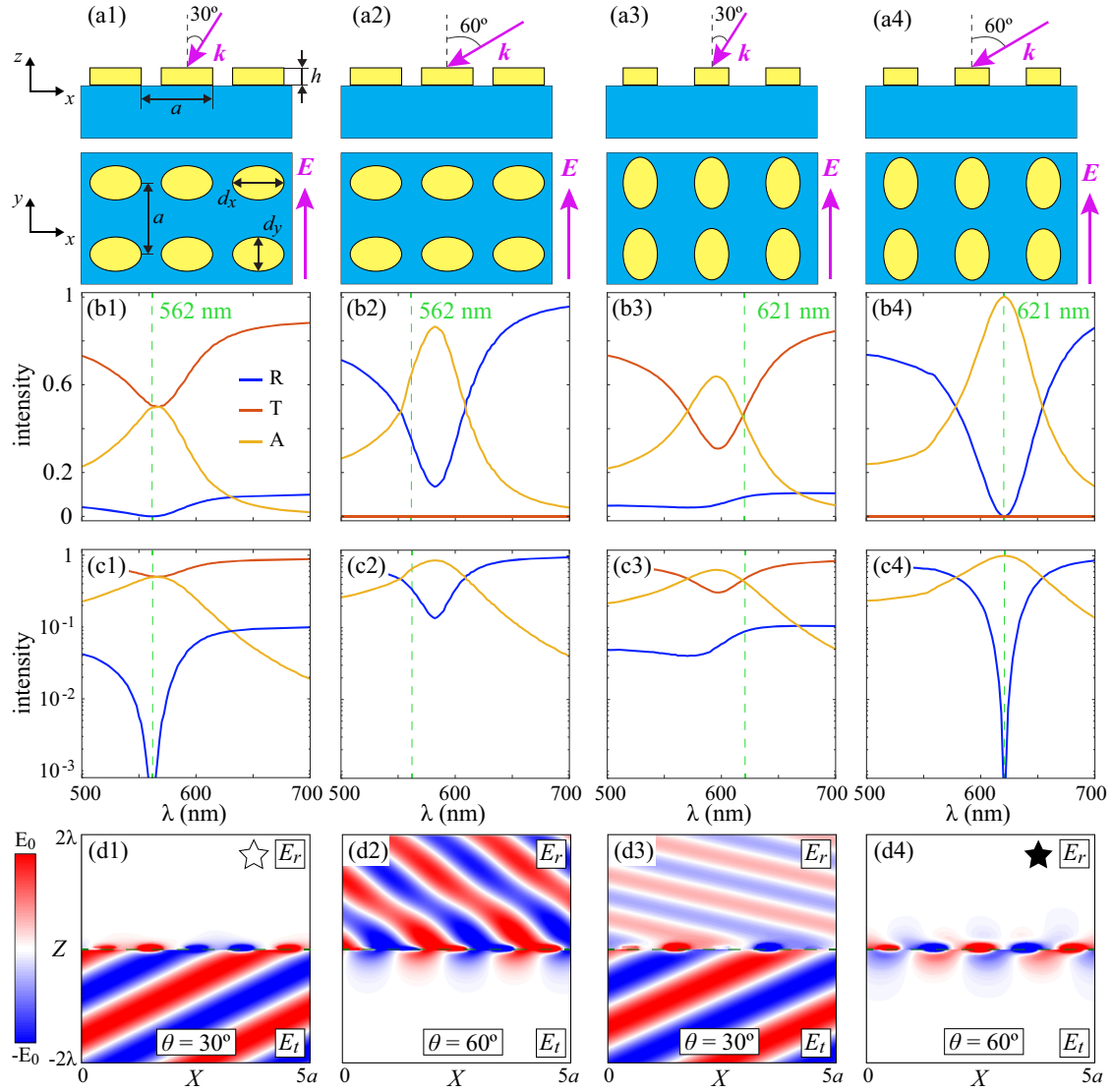


FIG. 4. (a) The schematic view of the different cases of the incidence field orientation with respect to the metasurface. Top line: Side view in the yz plane. Bottom line: Top view in the xy plane; magenta lines show the direction of $\mathbf{k}$ and $\mathbf{E}$ vectors. The metasurface is based on gold nanodisks with an elliptical cross section characterized by the period $a = 200$ nm and nanodisk sizes: thickness $h = 25$ nm, long $d_x = 80$ nm, and short $d_y = 65$ nm axes of the elliptical cross section. The quartz substrate is shown by blue rectangles. (b), (c) The spectral dependencies of the reflectance (blue line), transmittance (red line), and absorbance (yellow line) in (b) linear and (c) logarithmic scales for the cases under consideration. (d) Spatial distribution of the reflected (top half-plane) and transmitted (bottom half-plane) normal components of the electric field E_y in the xz plane at the wavelengths shown in panels (b) and (c) by a green dashed line. The cases under consideration: (a1)–(d1) $\theta = 30^\circ$, $\mathbf{E}$ is along the short axis; (a2)–(d2) $\theta = 60^\circ$, $\mathbf{E}$ is along the short axis; (a3)–(d3) $\theta = 30^\circ$, $\mathbf{E}$ is along the long axis; and (a4)–(d4) $\theta = 60^\circ$, $\mathbf{E}$ is along the long axis.

notice the near-field modulations in Figs. 4(d1)–4(d4) in the vicinity of the boundary between upper (quartz) and lower (air) media corresponding to the presence of a metasurface.

IV. CONCLUSIONS

In this work, we have introduced a theoretical and numerical framework to implement and control the generalized Brewster effect for transverse-electric polarization using two-dimensional plasmonic materials and structures. By deriving modified Fresnel equations and incorporating the complex surface conductivity of a 2D conducting layer,

we revealed the conditions under which zero reflection occurs both beyond and within the regime of total internal reflection. The latter leads to the perfect absorption for TE-polarized light. These regimes were analytically characterized and confirmed by full-wave numerical simulation. Furthermore, we analyzed the dispersive 2D conducting layer and real design of plasmonic metasurfaces based on gold elliptical nanodisks at quartz substrate to demonstrate the regimes of the generalized Brewster angle and perfect absorption in terms of the reflectance intensity spectra and spatial field distributions. Our results show that careful engineering of surface conductivity and metasurface design

enables precise control over polarization and absorption characteristics.

The results obtained could be extended to different materials and frequency ranges, from the visible spectrum to microwaves, as long as the two-dimensional layer is deeply subwavelength and sufficiently absorptive, and its surface conductivity varies from several to several tens of millisiemens. The possible implementations include the ultrathin metallic films, 2D materials, metasurfaces, and nano- and microstructures. These findings open new possibilities for the development of flat photonic devices, including polarization-selective components, optical isolators, ultrathin absorbers, and biosensors, where efficient and tunable control over polarized light is crucial.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: DESIGNING REFLECTIONLESS ANISOTROPIC PLASMONIC METASURFACE

First, we defined the optimum values of surface conductivities that led to the zero-reflection condition at $\theta = 60^\circ$ and

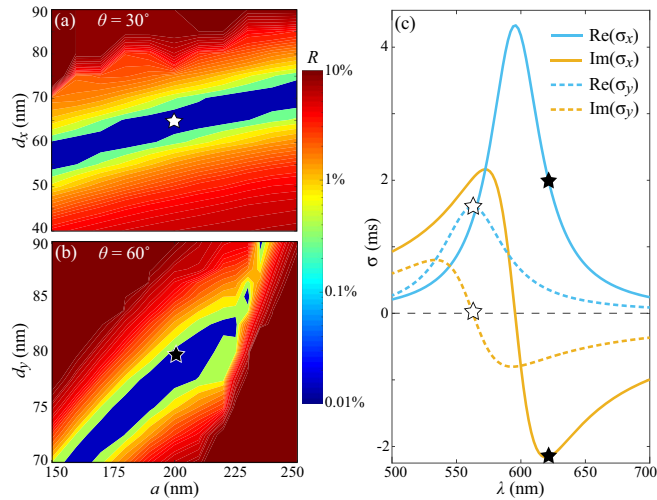


FIG. 5. (a), (b) The color maps showing the dependence of the reflectance on the period of metasurface and the diameter of the nanodisk (a) along the y axis at $\theta = 30^\circ$ and (b) along the x axis at $\theta = 60^\circ$. (c) Dependence of real (cyan lines) and imaginary (yellow lines) parts of the extracted surface conductivity on wavelength along the x axis (solid lines) and the y axis (dashed lines).

$\theta = 30^\circ$ as $\sigma_x = 1.992 - 2.202i$ mS and $\sigma_y = 1.693$ mS using Eqs. (3)–(5). Second, we used a metasurface representing a square periodic array with a 200-nm lattice constant of gold nanodisks, each with a diameter of 70 nm and a height of 25 nm, as a starting reference. Then, using Eq. (12) from Ref. [38], we defined the elongated and shortened axes of the elliptical nanodisk as $d_x = 80.5$ nm and $d_y = 61$ nm (stretching factor is 1.15) to adjust the corresponding resonances of surface conductivity in the vicinity of 600 and 560 nm, respectively. Further optimization was performed using comsol multiphysics to calculate the reflectance, transmittance, and absorptance spectra at specific angles of 30° and 60° via parametric sweep. The obtained reflectance spectra for

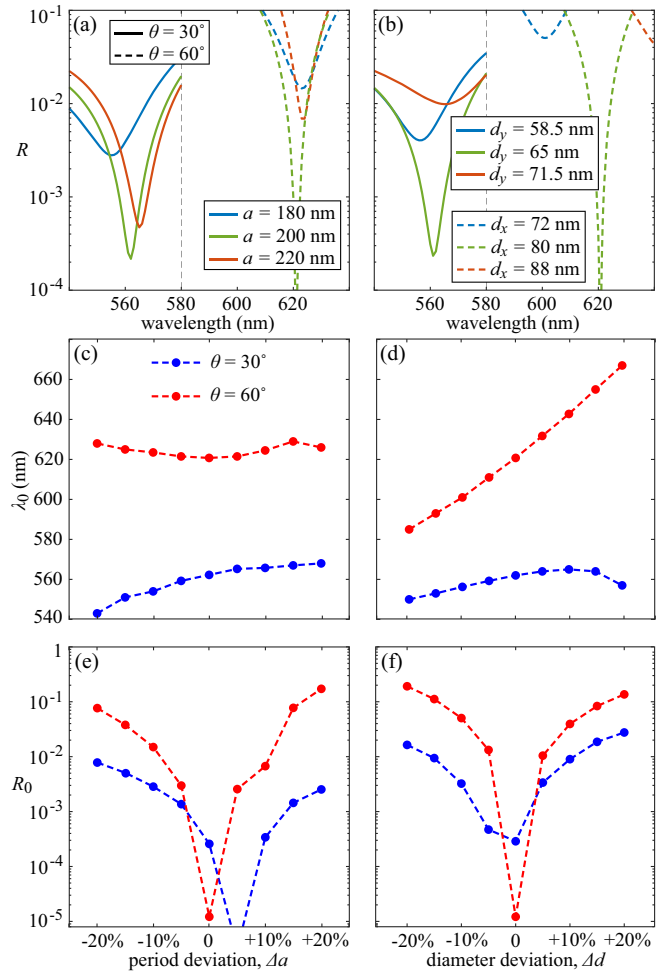


FIG. 6. (a), (b) The dependence of the reflectance on wavelength for the incident angles of $\theta = 30^\circ$ (solid lines) and $\theta = 60^\circ$ (dashed lines). The optimized metasurface shown in Fig. 4 is depicted by the green lines. The blue and red lines correspond to the deviations of -10% and $+10\%$, respectively, from the (a) period and (b) axes of the elliptical nanodisks. (c)–(f) The dependencies of the (c), (d) wavelengths and (e), (f) reflectances corresponding to zero-reflection condition on the deviations of (c), (e) period from $a = 200$ nm and (d), (f) axes of elliptical nanodisks from $d_x = 80$ nm ($\theta = 60^\circ$) and $d_y = 65$ nm ($\theta = 30^\circ$).

$\theta = 30^\circ$ and $\theta = 60^\circ$ are shown in Figs. 5(a) and 5(b), respectively. The optimized designs have been chosen as $d_x = 80$ nm and $d_y = 65$ nm with corresponding reflectionless states ($R < 0.03\%$) at 621 and 562 nm at the incident angles of 60° and 30° , respectively.

Applying the retrieval procedure from Refs. [36,38] we extract the surface conductivity along main axes of the metasurface [Fig. 5(c)]. The values of surface conductivities at the specified wavelengths of 562 and 621 nm differ from the optimal values by less than 2%. The extracted surface conductivity can be fitted by the Drude-Lorentz formula (2) with the parameters $\Omega_0 = 504$ and 533 THz, $\gamma = 40$ and 57 THz, and $\sigma_0 = 0.34$ and 0.17 mS for the x - and y -oriented electric fields, respectively.

APPENDIX B: DEPENDENCE OF ZERO-REFLECTION CONDITION ON STRUCTURAL IMPERFECTIONS

Surface conductivity depends on the lattice constant and meta-atom geometrical parameters; therefore, the Brewster angle and the perfect absorption regime may be shifted or even disappear. We analyze the stability of the zero-reflection condition on the structural imperfections such as the period of metasurface and the axes of the nanodisks. Figure 6 shows the dependence of the reflectionless Brewster-related state on the structural imperfections. One can notice that the discussed effects changed insignificantly for the period and diameter deviations up to $\pm 10\%$ from the optimized ones, while the deviations over 20% can break the phenomena under consideration.

- [1] M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light* (Elsevier, Amsterdam, 2013).
- [2] D. Brewster, On the laws which regulate the polarization of light by reflexion from transparent bodies, *Philos. Trans. R. Soc. London* **105**, 125–159 (1815).
- [3] A. Lakhtakia, Would Brewster recognize today's Brewster angle? *Opt. News* **15**, 14 (1989).
- [4] R. Magnusson, D. Shin, and Z. Liu, Guided-mode resonance Brewster filter, *Opt. Lett.* **23**, 612 (1998).
- [5] D. J. Dummer, S. G. Kaplan, L. M. Hanssen, A. S. Pine, and Y. Zong, High-quality Brewster's angle polarizer for broadband infrared application, *Appl. Opt.* **37**, 1194 (1998).
- [6] D. Shin, Z. Liu, and R. Magnusson, Resonant Brewster filters with absentee layers, *Opt. Lett.* **27**, 1288 (2002).
- [7] H. Fan, J. Li, Y. Lai, and J. Luo, Optical Brewster metasurfaces exhibiting ultrabroadband reflectionless absorption and extreme angular asymmetry, *Phys. Rev. Appl.* **16**, 044064 (2021).
- [8] D. Hoenig and D. Moebius, Direct visualization of monolayers at the air-water interface by Brewster angle microscopy, *J. Phys. Chem.* **95**, 4590 (1991).
- [9] S. Hénon and J. Meunier, Microscope at the Brewster angle: Direct observation of first-order phase transitions in monolayers, *Rev. Sci. Instrum.* **62**, 936 (1991).
- [10] R. Wang, S. He, S. Chen, and H. Luo, Brewster differential microscopy, *Appl. Phys. Lett.* **121**, 231103 (2022).
- [11] H. Lai and S. Chan, Large and negative Goos-Hänchen shift near the Brewster dip on reflection from weakly absorbing media, *Opt. Lett.* **27**, 680 (2002).
- [12] H. Luo, X. Zhou, W. Shu, S. Wen, and D. Fan, Enhanced and switchable spin Hall effect of light near the Brewster angle on reflection, *Phys. Rev. A* **84**, 043806 (2011).
- [13] J. B. Götte and M. R. Dennis, Limits to superweak amplification of beam shifts, *Opt. Lett.* **38**, 2295 (2013).
- [14] K. V. Sreekanth, P. Mahalakshmi, S. Han, M. S. Mani Rajan, P. K. Choudhury, and R. Singh, Brewster mode-enhanced sensing with hyperbolic metamaterial, *Adv. Opt. Mater.* **7**, 1900680 (2019).
- [15] K. V. Sreekanth, M. ElKabbash, R. Medwal, J. Zhang, T. Letsou, G. Strangi, M. Hinczewski, R. S. Rawat, C. Guo, and R. Singh, Generalized Brewster angle effect in thin-film optical absorbers and its application for graphene hydrogen sensing, *ACS Photonics* **6**, 1610 (2019).
- [16] W. Daeer, M. Mahadeo, and E. J. Prenner, Applications of Brewster angle microscopy from biological materials to biological systems, *Biochim. Biophys. Acta, Biomembr.* **1859**, 1749 (2017).
- [17] T. Kawanishi, The shift of Brewster's scattering angle, *Opt. Commun.* **186**, 251 (2000).
- [18] K. J. Lee and K. Kim, Universal shift of the Brewster angle and disorder-enhanced delocalization of p waves in stratified random media, *Opt. Express* **19**, 20817 (2011).
- [19] Z. Wang, T. Sang, J. Zhu, L. Wang, Y. Wu, and L. Chen, Double-layer resonant Brewster filters consisting of a homogeneous layer and a grating with equal refractive index, *Appl. Phys. Lett.* **89**, 241119 (2006).
- [20] X. Liu, S. Chen, W. Zang, and J. Tian, Triple-layer guided-mode resonance Brewster filter consisting of a homogenous layer and coupled gratings with equal refractive index, *Opt. Express* **19**, 8233 (2011).
- [21] B. Majerus, M. Cormann, N. Reckinger, M. Paillet, L. Henrard, P. Lambin, and M. Lobet, Modified Brewster angle on conducting 2D materials, *2D Mater.* **5**, 025007 (2018).
- [22] Z. Chen, X. Chen, L. Tao, K. Chen, M. Long, X. Liu, K. Yan, R. I. Stantchev, E. Pickwell-MacPherson, and J.-B. Xu, Graphene controlled Brewster angle device for ultra broadband terahertz modulation, *Nat. Commun.* **9**, 4909 (2018).
- [23] M. Oliva-Leyva and G. G. De la Cruz, Unveiling optical in-plane anisotropy of 2D materials from oblique incidence of light, *J. Phys.: Condens. Matter* **31**, 335701 (2019).
- [24] R. Paniagua-Domínguez, Y. F. Yu, A. E. Miroshnichenko, L. A. Krivitsky, Y. H. Fu, V. Valuckas, L. Gonzaga, Y. T. Toh, A. Y. S. Kay, B. Luk'yanchuk, and A. I. Kuznetsov, Generalized Brewster effect in dielectric metasurfaces, *Nat. Commun.* **7**, 10362 (2016).
- [25] D. R. Abujetas, J. A. Sanchez-Gil, and J. J. Sáenz, Generalized Brewster effect in high-refractive-index nanorod-based metasurfaces, *Opt. Express* **26**, 31523 (2018).
- [26] X. Lin, Y. Shen, I. Kaminer, H. Chen, and M. Soljačić, Transverse-electric Brewster effect enabled by nonmagnetic two-dimensional materials, *Phys. Rev. A* **94**, 023836 (2016).

- [27] O. Yermakov, Shift of Brewster's angle with two-dimensional materials and structures, *Phys. Rev. A* **109**, L031502 (2024).
- [28] Y. Tamayama, T. Nakanishi, K. Sugiyama, and M. Kitano, Observation of Brewster's effect for transverse-electric electromagnetic waves in metamaterials: Experiment and theory, *Phys. Rev. B* **73**, 193104 (2006).
- [29] S. Yin and J. Qi, Metagrating-enabled Brewster's angle for arbitrary polarized electromagnetic waves and its manipulation, *Opt. Express* **27**, 18113 (2019).
- [30] C. Wang, Z. Zhu, W. Cui, Y. Yang, L. Ran, and D. Ye, All-angle Brewster effect observed on a terahertz metasurface, *Appl. Phys. Lett.* **114**, 191902 (2019).
- [31] Q. Lv, C. Jin, B. Zhang, L. Yin, S. Liu, B. Tian, and T. J. Cui, Ultrawide-angle ultralow-reflection phenomenon for transverse electric mode in anisotropic metasurface, *Adv. Opt. Mater.* **10**, 2102400 (2022).
- [32] Y. Ra'di, C. R. Simovski, and S. A. Tretyakov, Thin perfect absorbers for electromagnetic waves: Theory, design, and realizations, *Phys. Rev. Appl.* **3**, 037001 (2015).
- [33] D. G. Baranov, A. Krasnok, T. Shegai, A. Alù, and Y. Chong, Coherent perfect absorbers: Linear control of light with light, *Nat. Rev. Mater.* **2**, 17064 (2017).
- [34] R. Alaei, M. Albooyeh, and C. Rockstuhl, Theory of metasurface based perfect absorbers, *J. Phys. D: Appl. Phys.* **50**, 503002 (2017).
- [35] R. Ud Din, Y. Zhou, R. Asgari, and G. Xianlong, Enhanced Brewster angle shift in doped graphene via the Fizeau drag effect, *J. Appl. Phys.* **138**, 014302 (2025).
- [36] O. Y. Yermakov, D. V. Permyakov, F. V. Porubaev, P. A. Dmitriev, A. K. Samusev, I. V. Iorsh, R. Malureanu, A. V. Lavrinenko, and A. A. Bogdanov, Effective surface conductivity of optical hyperbolic metasurfaces: From far-field characterization to surface wave analysis, *Sci. Rep.* **8**, 14135 (2018).
- [37] D. I. Yakubovsky, A. V. Arsenin, Y. V. Stebunov, D. Y. Fedyanin, and V. S. Volkov, Optical constants and structural properties of thin gold films, *Opt. Express* **25**, 25574 (2017).
- [38] A. Hrinchenko and O. Yermakov, Designing optical hyperbolic metasurfaces based on gold nanodisks, *J. Phys. D: Appl. Phys.* **56**, 465105 (2023).
- [39] A. Hrinchenko, S. Polevoy, O. Demianyk, and O. Yermakov, Engineering hyperbolicity and plasmon canalization for resonant plasmonic anisotropic nanopatch-based metasurfaces, *J. Appl. Phys.* **135**, 223102 (2024).