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A Bilayer Plasmonic Metasurface for Polarization-Insensitive Bidirectional Perfect Absorption

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The implementation of perfect absorption of optical waves in artificial nanostructures has attracted tremendous attention among the scientific community. Traditional approaches based on metamaterials can only absorb optical waves in one direction while reflecting optical waves in the other direction. Here, a polarization-insensitive bidirectional perfect absorber that is composed of bilayer gold nano disks embedded into a silicon nitride substrate is demonstrated. The bidirectional perfect absorption in the proposed bilayer metasurface, which is irrelevant to the coherent of optical waves, is attributed to the multiple reflections and interference of optical waves in the bilayer structures. The proposed perfect absorber shall boost its applications in optical anti-counterfeiting, integrated photodetectors, and solar thermal applications.

Realizing the effective absorption of optical waves plays an important role in numerous modern photonics applications.[1–4] Traditional optical absorbers are always made of natural material with large intrinsic loss, which results in inherent disadvantages in volume, efficiency, and design flexibility.[4] Metasurfaces, planar arrays of artificial nanostructures, have emerged as an alternative method to overcome the drawbacks in traditional approaches and realize perfect absorption of optical waves in sub-wavelength scale. Since the first perfect absorber was demonstrated in metasurfaces,[5] perfect absorbers based on metasurfaces have attracted tremendous interest among the scientific community in past decade for their great importance in practical applications such as photodetectors, photovoltaics, imagers, thermal emitter, filters, and sensors.[6–11] Great efforts have been made to expand the working bandwidth of the perfect absorbers in recent years. Metasurfaces-based perfect absorbers with narrow band,[9,10] dual band,[12,13] multiband,[14,15] and broadband[16,17] optical responses have been proposed for different applications. Polarization-insensitive and wide-angle perfect absorption of optical waves have been further demonstrated in metasurfaces, which offers helpful insight and great potential for the commercialization of metasurfaces-based perfect absorbers.[17–19] However, these designs composed of metal–insulator–metal structures can only absorb optical waves in one direction while reflect optical waves in the other direction.[4] Predictably, the implementation of bidirectional perfect absorption of optical waves in metasurfaces will further expand the applications of metasurfaces-based perfect absorbers in nanophotonics.

Recently, a new approach named coherent perfect absorption has been used to realize the bidirectional perfect absorption of optical waves.[20–23] By utilizing two coherent beams with equal intensities illuminating from opposite directions, the absorption efficiency of metasurfaces-based absorbers can be dynamically manipulated by simply adjusting the phase difference between the two coherent beams.[23] Even though these approaches can realize the bidirectional perfect absorption of optical waves, the heavy dependence of absorption efficiency on the phase difference between the two coherent beams extremely limits the applications of metasurfaces-based bidirectional perfect absorbers. Recent advances in few-layer metasurfaces show some advantages to meet this challenge.[24–29] By involving a large phase gradient along the

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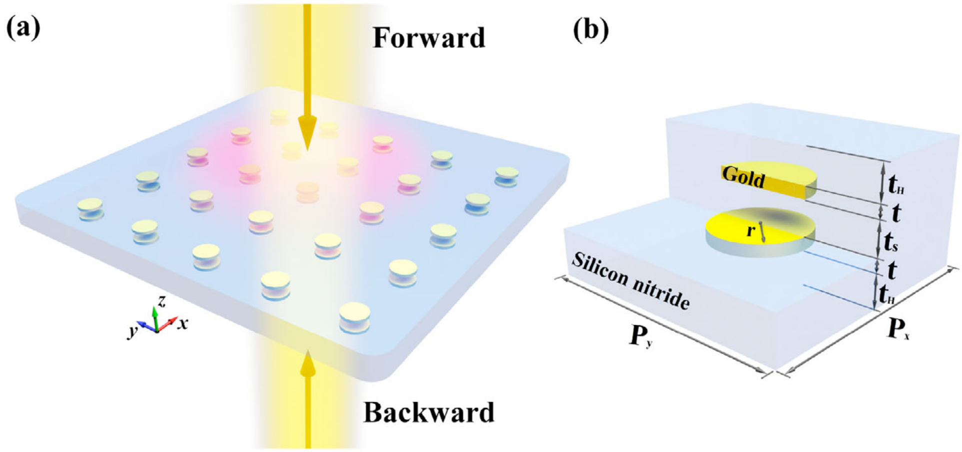

Figure 1. a) An artistic rendering of the bidirectional perfect absorption of optical waves in the proposed bilayer metasurface. The incident wave propagation along the $-z$ (forward) or $+z$ (backward) direction can be completely absorbed in the working bandwidth. b) Schematic illustrating the structure parameters of a unit cell of the proposed bilayer metasurface.

metasurface interface, Li et al. proposed a bilayer metasurface that can transform the incident waves into evanescent waves, resulting in bidirectional perfect absorption of optical waves.[29] This new approach is irrelevant to the coherence of optical waves, and thus can realize perfect absorption of optical waves in two directions independently. However, this new design can only realize bidirectional perfect absorption of incident waves with a fixed linear polarization state and the performance of this design relies heavily on the degree of alignment between the structures in the two layers. Metasurface-based bidirectional perfect absorbers with advantages of being alignment-free, irrelevant to the coherence of optical waves and having a polarization-insensitive and wide-angle optical response, which are highly desirable, have not been explored yet.

Here, we present an alignment-free and polarization-insensitive bidirectional perfect absorber composed of bilayer gold nano disks embedded into a silicon nitride substrate. The simulated results indicate that the bidirectional perfect absorption in the proposed design is polarization-insensitive with over 99% absorptance within an incident angle up to 15°, and its working wavelength can be easily manipulated by adjusting the structure parameters of the bilayer metasurfaces. The experimental measurement further validates the bidirectional absorption of optical waves in the proposed design. By utilizing matrix theory of multilayer optics and multiple reflections and interference model, we reveal that the bidirectional perfect absorption in the proposed bilayer metasurface is attributed to the multiple reflections and interference of optical waves in the bilayer structures that result in a low requirement of alignment between the nano disks in the two layers. We also validate that the bidirectional perfect absorption in the proposed bilayer metasurface is irrelevant to the coherence of optical waves, and thus it can realize perfect absorption of optical waves in two opposite directions independently. With the advantages of having a polarization-insensitive, wide-angle, and bidirectional optical response, being alignment-free and irrelevant to the coherence of optical waves, the proposed perfect absorber shall boost its applications in optical anti-counterfeiting, integrated photodetectors, and solar thermal applications. We also believe that the proposed approach paves the way for the implementation of metasurfaces-based polarization-insensitive and omnidirectional perfect absorbers.

Figure 1a illustrates the artistic rendering of the proposed bidirectional perfect absorber composed of bilayer gold nano disks embedded into a silicon nitride substrate. Incident plane wave propagation along the $-z$ (forward) or $+z$ (backward) direction with arbitrary polarization can be completely absorbed in the working bandwidth, while it can partly transmit the metasurface in other wavelengths. The schematic illustrating the structure parameters of a unit cell of the proposed bilayer design is shown in Figure 1b. The periods of the unit cell in x and y directions are $P_x = P_y = 560$ nm. The radius of the gold nano disks is $r = 80$ nm, while the thickness of the gold nano disks is $t = 15$ nm. The thickness of the silicon nitride spacer between the bilayer gold nano disks (t_S) and the thickness of the silicon nitride spacer covered onto the gold nano disks (t_H) are both equal to 170 nm. Numerical simulations have been conducted to analyze the characterization of the proposed bilayer metasurface, which were carried out by using finite-differential time-domain method. In our simulations, the permittivity of the silicon nitride was taken as 4.00, and the dielectric function of gold was defined by Drude mode with plasmon frequency $\omega_p = 1.37 \times 10^{16} s^{-1}$ and damping constant $\gamma = 1.224 \times 10^{14} s^{-1}$.[30–32] The periodic boundary conditions were set in the x- and y-directions representing a periodical structure, and an open (perfectly matching layer) boundary was defined in the z-direction for light incidence and transmission while the excitation source was a linear-polarized plane wave.

Figure 2a presents the simulated results of the absorption, reflection, and transmission spectra of the proposed bilayer metasurface under forward x-polarized normal incidence. The drops in the reflection and transmission curves can be observed around 1290 nm. Consequently, a distinct absorption peak with over 99% absorptance is obtained at 1290 nm. Moreover, the transmission curve rises when the wavelength is far from 1290 nm, which indicates that the proposed bilayer metasurface is partly transparent at other wavelengths. Ascribing to the totally structural symmetric of the proposed bilayer metasurface in forward and backward directions, the perfect absorption

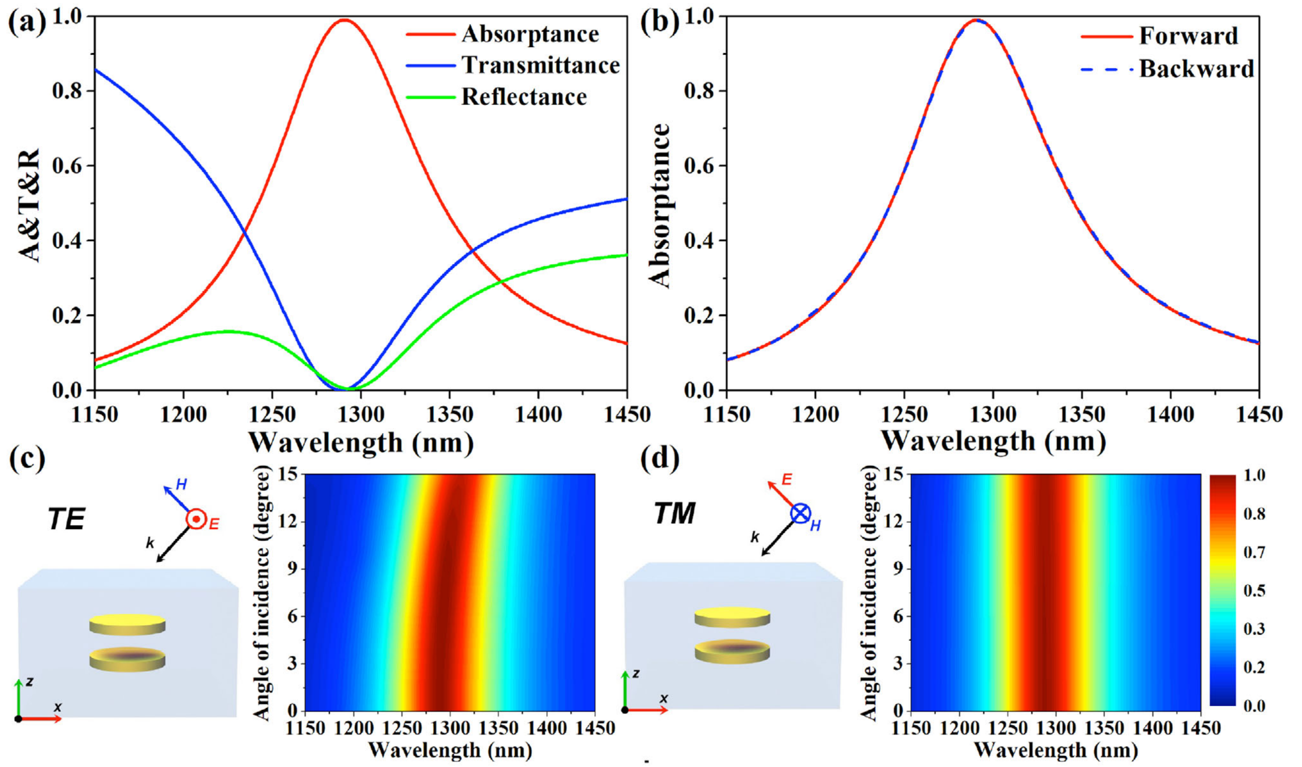

Figure 2. a) Simulated results of the absorption, reflection, and transmission spectra of the proposed bilayer metasurface under forward illumination. b) Simulated results of the absorption spectra of the proposed bilayer metasurface under forward and backward illumination. c,d) The absorption spectra of the proposed bilayer metasurface under forward TE (c) and TM (d) illumination with different incident angles.

of optical waves at 1290 nm should also be observed under backward x-polarized normal incidence, which is validated by the simulated results in Figure 2b. The absorption curves under forward and backward illumination are identical, validating the bidirectional perfect absorption of optical waves in the proposed bilayer metasurface. Moreover, the bidirectional perfect absorption of optical waves in the proposed bilayer metasurface is polarization-insensitive, which is attributed to the structural symmetry of the proposed metasurface in the plane perpendicular to the propagation direction. The influence of incident angle of the illumination on the perfect absorption has also been investigated. Simulated results of absorption spectra under forward x-polarized illumination with different angle of incidence are shown in Figure 2c,d. Results indicate that the absorptivity of the proposed bilayer metasurface remains constant within an incident angle up to 15 degrees for both TE and TM illumination.

The requirement of precise alignment between the layers in previous few-layer metasurfaces makes enormous challenges in sample fabrication and cost, which prevent their further application and commercialization.[29,33] The influence of alignment between the bilayer gold nano disks in the proposed metasurface on the bidirectional perfect absorption is validated by designing several bilayer metasurfaces with different degrees of misalignment between the bilayer nano disks.[34] As shown in **Figure 3**a, three situations involving misalignment along x-axis (δ_x), y-axis (δ_y), and both x- and y-axis (δ_{xy}) are investigated. The simulated results of the absorption spectra of bilayer metasurfaces with different misalignment between the bilayer nano disks under forward x-polarized normal illumination are shown in Figure 3b–d. Results indicate that the absorptance keeps over 98% when the misalignment distance (δ_x, δ_y, and δ_{xy}) is no more than 30 nm, and the absorptance keep over 84% when δ_x and δ_{xy} no more than 80 nm (the radius of the nano disk) while the absorptance keep over 70% when δ_y is no more than 80 nm. The mini different influence of δ_x and δ_y on the absorption efficiency is ascribed to the polarization-dependent resonance in the bilayer nano disks. The influence of δ_x and δ_y on the absorption efficiency will inverse under y-polarized illumination. These results indicate that the implementation of the bidirectional perfect absorption in the proposed bilayer metasurface has a low requirement on the alignment of the bilayer nano disks, which significantly lowers the sample fabrication demand.

To experimentally validate the bidirectional absorption of optical waves in the proposed bilayer metasurface, we fabricated the designed bilayer metasurface and measured its optical spectrum. The scanning electron microscopy (SEM) image of the gold nano disks in the lower layer of a fabricated sample is shown in **Figure 4**a. The experimental measured results of the absorption spectra under forward and backward illumination are shown in Figure 4b. Results show that bidirectional absorption of optical waves with over 74% efficiency has been realized around 1540 nm, which are in reasonable agreement with the simulated results. The red shift of the working wavelength, the broaden bandwidth, and the decrease of the absorption efficiency can be mainly attributed to two reasons: 1) The radius of the gold nano disks in the fabricated bilayer metasurface is larger than the

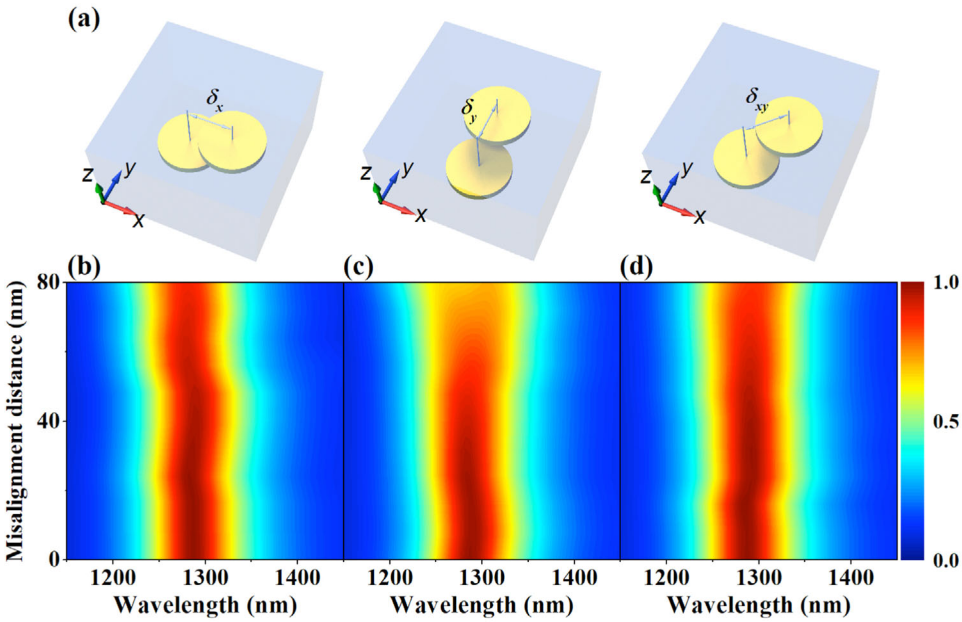

Figure 3. a) Schematic of the misalignment between the bilayer nano disks. δ_x and δ_y indicate the misalignment along x-axis and y-axis respectively, while δ_{xy} indicates the existence of equal misalignment in x and y direction. b–d) The simulated results of absorption spectra with different misalignment between the bilayer nano disks: b) δ_x, c) δ_y, and d) δ_{xy}.

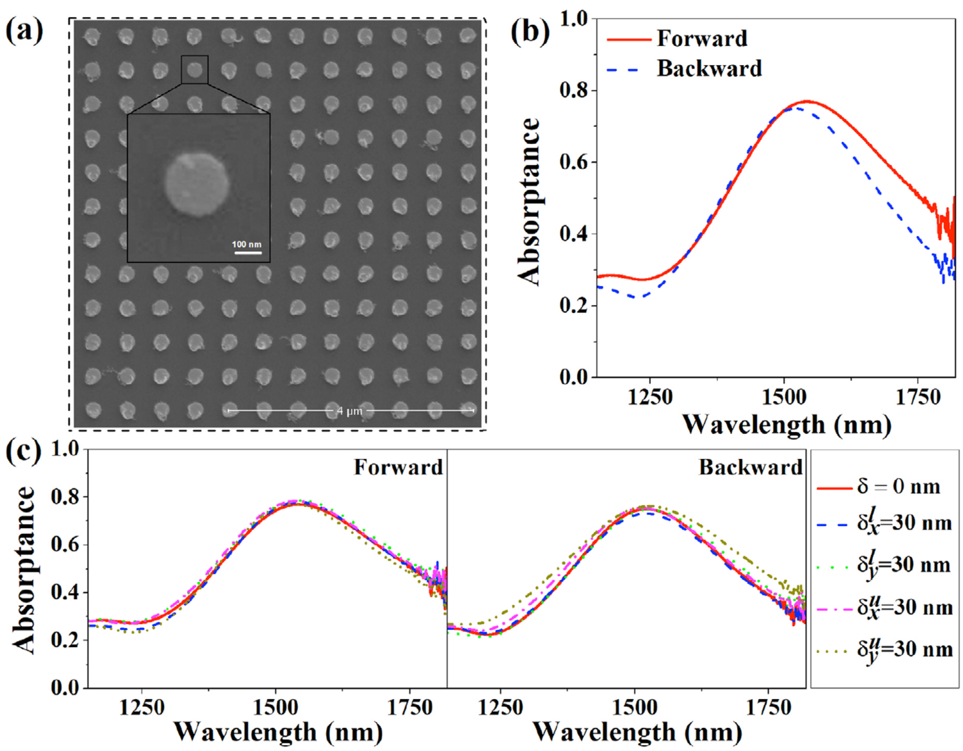

Figure 4. a) The SEM image of the fabricated gold nano disks in the lower layer, which was captured before the deposition of the middle silicon nitride layer. b) The experimental measured results of the absorption spectrum of the fabricated bilayer metasurface under forward and backward illumination respectively. c) The absorption spectra of the fabricated bilayer metasurfaces with different degree of misalignment along x- and y-axis, when under forward (left part) and backward (right part) illumination respectively. The superscript "u" and "l" indicate the upper layer and the lower layer, respectively.

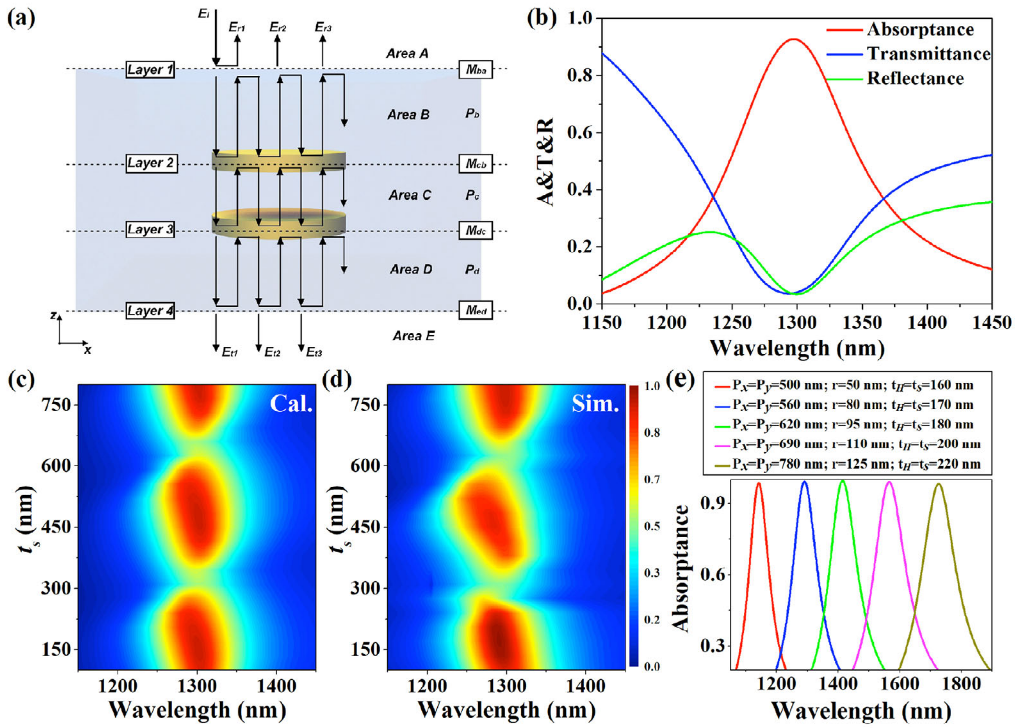

Figure 5. a) Schematic of the multiple reflections and interference model. b) Calculated results of the absorption, reflection, and transmission spectrum of the proposed bilayer metasurface under forward illumination by using the interference model. c) Calculated results and d) simulated results of the absorption spectra of the proposed bilayer metasurface under forward illumination for various t_s (the distance between the bilayer nano disks). e) The simulated results of the absorption spectra of the proposed bilayer metasurfaces with different structure parameters.

designed one, which can be observed from the SEM image. The increasing of the radius of the gold nano disks will directly induce a red shift of the working wavelength and a decrease of the absorption efficiency. And the tiny difference between the absorption spectra under forward and backward illumination is mainly attributed to the difference of the radius of gold nano disks between the two layers. 2) The thickness of the gold nano disks in the designed bilayer metasurfaces is 15 nm, thus the magnitude of the imaginary part of gold's permittivity in the proposed design is substantially larger than its bulk value. This will also induce some difference between the simulated and the measured results. We also experimentally investigated the affection of misalignment between the gold nano disks in the two layers on the performance of the bidirectional absorption, as shown in Figure 4c. Results indicate that the optical response of the proposed bilayer metasurface remains constant when there is a 30-nm misalignment along *x*- or *y*-axis between the gold nano disks in the two layers.

The implementation of bidirectional perfect absorption in the proposed bilayer metasurface with alignment-free feature is mainly attributed to the interference between the multiple reflections in the bilayer structures and the direct reflection. Matrix theory of multilayer optics and multiple reflections and interference model are utilized to reveal this underlying physical mechanism.[35–37] **Figure 5**a shows the schematic of the multiple reflections and interference model. For the thickness of the gold nano disks is much smaller than the distance between the bilayer nano disks (t_S) and the thickness of silicon nitride covered on the nano disks (t_H), the interface contains nano disks is treated as planar. For a planar interface between two media *i* and *j*, the forward and backward propagating waves can be related by utilizing a 4×4 wave-transfer Matrix $\mathbf{M}_{ji}$. For a homogeneous medium *i* with thickness of *d*, the forward and backward propagating waves can also be related by a 4×4 propagation matrix $\mathbf{P}_i$. The forward and backward propagating waves at the two ends of the proposed bilayer metasurface then can be related by the overall wave-transfer matrix **M** that can be treated as the matrix product of each part: $\mathbf{M} = \mathbf{M}_{ed}\mathbf{P}_d\mathbf{M}_{dc}\mathbf{P}_c\mathbf{M}_{cb}\mathbf{P}_b\mathbf{M}_{ba}$. In our calculation, the coefficients of the scattering matrix $\mathbf{S}_{ji}$ of each interface were obtained by simulation firstly, and then the corresponding wave-transfer matrix $\mathbf{M}_{ji}$ were calculated. Finally, we calculated the overall wave-transfer matrix **M** of the proposed bilayer metasurface, retrieved the coefficients of the overall scattering matrix **S** and calculated the transmission, reflection, and absorption spectra. The calculated results of the transmission, reflection, and absorption spectrum under forward *x*-polarized normal illumination by utilizing multiple reflections and interference model are shown in Figure 5b. The calculated results are in good agreement with the simulated one in Figure 2a. The slight difference is owing to the neglecting of the thickness of the nano disks that will introduce a tiny error in the calculation of overall transfer matrix **M**. We also calculated the variation of the absorption spectrum of the proposed bilayer metasurface when changing the distance between bilayer nano disks and make a comparison with the simulated one, as shown in Figure 5c,d. The calculated results in Figure 5c are in good agreement with the simulated results in Figure 5d.

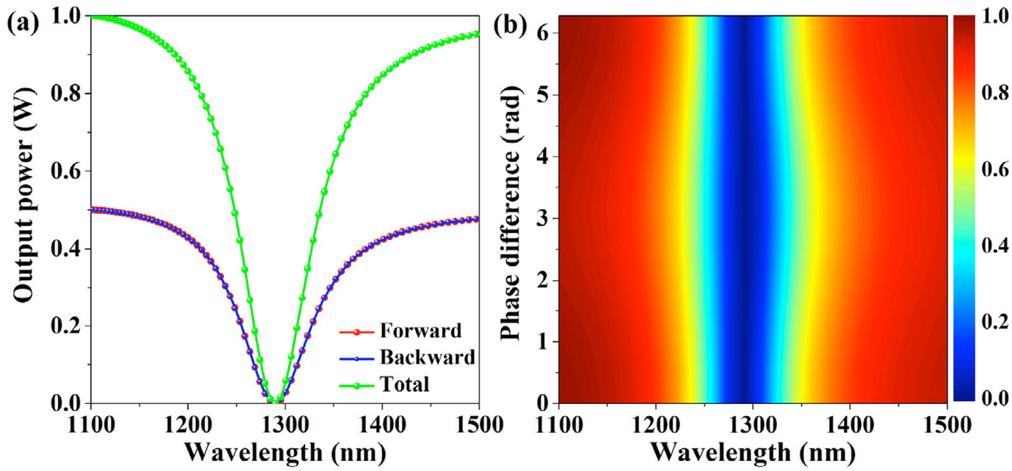

Figure 6. a) Simulated result of output power spectrum of the proposed metasurface when optical waves with a phase difference equal to zero illuminate from both forward and backward directions. b) Simulated results of total output power of the proposed metasurface when optical waves with various phase differences illuminate from both forward and backward directions.

The periodic variation of the absorption efficiency with the changing of the distance between the bilayer nano disks further reveals that the bidirectional perfect absorption in the proposed metasurface is mainly attributed to the interference between the multiple reflections in the bilayer structures and the direct reflection. Considering that the multiple reflections and interference model has been widely used in metasurfaces at different wavelengths, the bidirectional perfect absorption we proposed here can be further expanded to other wavelengths. Figure 5e shows the simulated results of the absorption spectra of the proposed bilayer metasurfaces with different structure parameters under forward x-polarized normal illumination. Results indicate that the working wavelength of the bidirectional perfect absorption in the proposed bilayer metasurfaces can be effectively manipulated in the near infrared regime by reasonably adjusting the structure parameters of the metasurfaces. Predictably, by utilizing other materials and structures, our approach can be further translated to mid-infrared, terahertz, and other frequency regimes. Because our approach is based on multiple reflections and interference model, it is worth mentioning that the broadband bidirectional perfect absorption of optical waves can be further realized based on our approach by stacking the proposed bilayer metasurfaces with different working wavelengths.[1]

To validate that the bidirectional perfect absorption in the proposed bilayer metasurface is irrelevant to the coherent of optical waves, we simulated the output power spectrum of the proposed metasurface when two coherent beams are illuminated from opposite directions. **Figure 6**a shows the simulated results of output power spectrum of the proposed bilayer metasurface when optical waves with a phase difference equal to zero and identical intensities illuminate from both forward and backward direction. The power of incidence in forward and backward direction are both equal to 0.5 W. The simulated results validate the existence of the bidirectional perfect absorption in the proposed bilayer metasurface when optical waves with a phase difference equal to zero and identical intensities illuminate from both forward and backward directions, which is quite different from the coherent perfect absorption in previous works.[20–23] Figure 6b shows the simulated results of the total output power of the proposed bilayer metasurface when optical waves with various phase differences illuminate from both forward and backward directions. The results indicate that the bidirectional perfect absorption in the proposed bilayer metasurface is irrelevant to the coherent of optical waves, which shall significantly boost its real applications.

In conclusion, we have numerically, experimentally, and theoretically demonstrated the polarization-insensitive bidirectional perfect absorption of optical waves in a bilayer plasmonic metasurface composed of bilayer gold nano disks embedded in a silicon nitride substrate. Simulated results indicate that the proposed bilayer metasurface can realize polarization-insensitive bidirectional absorption of optical waves with over 99% absorptance within an incident angle up to 15° at 1290 nm, which is irrelevant to the coherence of optical waves. The bidirectional absorption in the proposed design has been further validated by experimental measurement. The measured results also indicate that the misalignment between the bilayer nano disks in the propose metasurface has limited affection on the efficiency of the bidirectional perfect absorption when the misalignment distance is no more than 30 nm, which significantly lowers the sample fabrication demand and quite benefits to real applications. By utilizing the Matrix theory of multilayer optics and involving the multiple reflections and interference model, we reveal that the implementation of bidirectional perfect absorption in the proposed bilayer metasurface with alignment-free feature is mainly attributed to the interference between the multiple reflections in the bilayer structures and the direct reflection. Moreover, the simulated results also validated that the working wavelength of the bidirectional perfect absorption in the proposed bilayer metasurface can be effectively manipulated by reasonably adjusting the structure parameters of the metasurface. Our approach paves the way for the implementation of metasurfaces-based polarization-insensitive and omnidirectional perfect absorbers, which opens new routes for intensity manipulation of optical waves and will have wide applications in optical anti-counterfeiting, integrated photodetectors and thermal emitter.

Experimental Section

Sample Fabrication: The proposed bilayer metasurface was fabricated by electron-beam lithography (EBL), electron beam deposition (EBD) of gold, and plasma-enhanced chemical vapor deposition (PECVD) of silicon nitride. A 70 nm thick silicon nitride was deposited onto a 100 nm thick self-supporting silicon nitride film (a silicon substrate with a window of silicon nitride film) first. After that, a 200 nm thick poly(methyl methacrylate) (PMMA) resist was subsequently spin-coated onto the sample, which was layer then subjected to bake out on a hotplate at 180 °C for 2 min. The pattern was exposed using an EBL system (Raith150, Raith GmbH, Germany). After the exposure, the sample was developed in methyl isobutyl ketone: isopropyl alcohol (MIBK:IPA) (1:3) for 40 s and IPA for 30 s and then blown dry with pure nitrogen. A 15 nm thick Au film was subsequently deposited by using EBD. After removing the PMMA resist with acetone, the gold nano disks in the lower layer were created. A 170 nm thick silicon nitride layer was subsequently deposited onto the sample by using PECVD. The gold nano disks on the upper layer were prepared by repeating the exposure, deposition, and resist-removal processes. Finally, a 170 nm thick silicon nitride layer was deposited on the top of the sample by using PECVD. Five samples were fabricated at one fabrication process with overlay exposure method while involving 30 nm displacement in the positive and negative *x*- and *y*-direction in the upper layer among four samples respectively.

Experimental Measurement: The transmission and reflection spectra were measured by using a Fourier transform infrared spectrometer (VERTEX 70, Bruker Optics, Germany), from which the absorption spectrum can be calculated. The spectral data, which were acquired with the OPUS 6.0 software, were recorded by averaging the data from 64 measurements. Air was used as the reference for measuring the transmittance while a gold mirror was used as the reference for measuring the reflectance.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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