Research article

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Simultaneous implementation of antireflection and antitransmission through multipolar interference in plasmonic metasurfaces and applications in optical absorbers and broadband polarizers

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Abstract: Metasurfaces have been widely used to control beam propagation e.g. transmission, reflection, and absorption on an interface through a thin layer of nano-antennas with the thickness smaller than the wavelength. However, previous study of metasurfaces typically focused on controlling only one form of these propagations. In this work, we propose and demonstrate a multipolar plasmonic metasurface that can simultaneously realize antireflection (AR) and antitransmission (AT) in the visible and near-infrared regions. The AR and AT arise from destructive multipolar interferences in the backward and forward directions, respectively, i.e., through the generalized Kerker effect. By engineering the multipolar interference, we show that the AR and AT can happen at different or similar wavelength ranges, which can be used for low-absorption spectral filters due to off-resonance operation or inversely strong optical absorbers through near-resonance operation, respectively. We also present a simple two-dimensional design of the multipolar metasurface that supports AT for one polarization and AR for another polarization over a broadband, which is applicable to broadband transmissive polarizers with efficiency over

90% and the extinction ratio over 18 dB. By tuning the dimension and thus the multipolar interference, the transmitted polarization and operation wavelength are both controllable.

Keywords: antireflection; antitransmission; generalized Kerker effect; multipolar metasurface; plasmonic metasurface.

1 Introduction

Metasurfaces consisting of two-dimensional arrangement of nanoantennas with subwavelength size, spacing, and thickness can manipulate the amplitude, phase, and polarization of light at will [1, 2]. In terms of the amplitude manipulation, metasurfaces can control the transmission (T), reflection (R), and thus absorption ($A = 1 - T - R$) of light through an interface. The amplitude control has been widely studied for realizing antireflection (AR) [3–9], antitransmission (AT) [10–15], and optical absorption (OA) [15–19] in various wavelength ranges. A fundamental and powerful approach to understand the underlying physics of this amplitude control is based on the multipolar expansion of the nanoantennas [20–28]. When a single nanoantenna or a nanoantenna array is irradiated by an external light field and multipole responses are excited in the nanoantennas, the reflection can be calculated by the interference between the radiation fields from multipoles in the backward direction, and the transmission can be calculated as the interference between the radiation fields from multipoles in the forward direction and the incident light. Therefore, the key idea to control the T , R , and A lies in engineering the multipolar interference, i.e., using the generalized Kerker effect [7, 29–32]. Many functionalities have been reported based on the generalized Kerker effect. For example, AR [5–9, 33] and AT [10–13] can be realized

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through destructive multipolar interferences in the backward and forward directions, respectively. OAs have also been reported based on multipole engineering in lossy nanoantennas by suppressing all the forward transmission and backward reflection [28, 33–37]. However, the nanoantennas used in previous work are relatively thick in order to excite the high-order multipoles and thus complicated in fabrication. Furthermore, in most cases, each design can realize only one functionality, e.g., AR, AT or OA.

Recently, we reported a multipolar plasmonic metasurface for transmission wavefront control in the visible and near-infrared (IR) region with high efficiency by tuning the multipolar interference approaching the generalized Kerker condition [38, 39]. The proposed metasurface is easy to fabricate and the multipole response can be easily tuned through the dimension change. In this work, we engineer multipole response in the multipolar plasmonic metasurface and demonstrate a metasurface that can simultaneously support AR and AT in the visible and IR ranges. More interestingly, the AR and AT wavelengths can be tuned to be either different or near each other, which can be used for spectral filters with low absorption due to off-resonance operation or inversely OA through near-resonance operation, respectively. In the first design, the transmission/reflection at the AR/AT wavelength $\sim 870/700$ nm reaches 75.7%/85.1% in simulation and 69.2%/82.4% in experiment. In the second design, the absorption is up to 94.1% in simulation and 92.8% in experiment at the wavelength ~ 695 nm. Furthermore, a two-dimensional subwavelength grating design is presented here for transmissive polarizers by tuning the multipolar interference to realize AR for one polarization and AT for another polarization at the same wavelength range. More importantly, we can choose which polarization is the transmitted one and apply it to different wavelength ranges by tuning the multipolar interferences. We present transmissive polarizers operating at two wavelength ranges around 800 and 1060 nm with the transmission efficiency over 90% and extinction ratio (ER) over 18 dB in broadband. This result indicates the possibility of applying plasmonic metasurfaces for certain optical functionalities with

transmission efficiency over 90% in the visible and IR regions, where the efficiency of plasmonic metasurfaces is typically too low to support practical applications and thus all-dielectric metasurfaces are more commonly used [40–42]. The record high transmission of plasmonic metasurfaces in this work is attributed to destructive multipolar interference in the backward direction and off-resonance operation of the multipole responses, which suppresses the reflection and reduces the absorption in the plasmonic nanoantennas, respectively. This multipolar plasmonic metasurface can find other applications in optical coatings, filters, and splitters.

2 Theory and principle

For a periodic array of nanoantennas with multipole responses, the multipole contributions of electric dipole (ED), magnetic dipole (MD), electric quadrupole (EQ), magnetic quadrupole (MQ), and electric octupole (EO) to the scattered fields are [25, 43]

$$\begin{aligned} E(p_{x,y}) &= \frac{ik_d}{2S\epsilon_0\epsilon_d} \cdot p_{x,y} \\ E(m_{x,y}) &= \frac{ik_d}{2S\epsilon_0\epsilon_d} \cdot \frac{1}{v_d} m_{x,y} \\ E(Q_{xz,yz}) &= \frac{ik_d}{2S\epsilon_0\epsilon_d} \cdot \frac{ik_d}{6} Q_{xz,yz} \\ E(M_{xz,yz}) &= \frac{ik_d}{2S\epsilon_0\epsilon_d} \cdot \frac{ik_d}{2v_d} M_{x,y} \\ E(O_{xzz,yzz}) &= \frac{ik_d}{2S\epsilon_0\epsilon_d} \cdot \frac{k_d^2}{6} O_{xzz,yzz} \end{aligned} \quad (1)$$

where p , m , Q , M , and O represent the complex ED, MD, EQ, MQ, and EO moments, respectively. S is the area of the unit nanoantenna. ϵ_d and k_d are the permittivity and wave number of the surrounding medium, respectively. ϵ_0 is the vacuum permittivity. When taking the substrate effect into consideration, the reflection and transmission coefficients can be calculated by [7, 25]

$$\begin{aligned} r_x &= \frac{(1 + r_0 e^{i2k_d z_0})[E(p_x) - E(M_{yz}) - E(O_{xzz})] - (1 - r_0 e^{i2k_d z_0})[E(m_y) - E(Q_{xz})]}{E_0} + r_0 e^{i2k_d z_0} \\ t_x &= \frac{E_0 + E(p_x) + E(m_y) - E(Q_{xz}) - E(M_{yz}) - E(O_{xzz})}{E_0} t_0 e^{ik_d z_0} \end{aligned} \quad (2)$$

for x-polarization input along the positive z direction, and by:

$$\begin{aligned} r_y &= \frac{(1 + r_0 e^{i2k_d z_0})[E(p_y) + E(M_{xz}) - E(O_{yzz})] + (1 - r_0 e^{i2k_d z_0})[E(m_x) + E(Q_{yz})]}{E_0} + r_0 e^{i2k_d z_0} \\ t_y &= \frac{E_0 + E(p_y) - E(m_x) - E(Q_{yz}) + E(M_{xz}) - E(O_{yzz})}{E_0} t_0 e^{ik_d z_0} \end{aligned} \quad (3)$$

for y-polarization input along the positive z direction. E_0 is the electric field of the normally incident plane wave at the point of the multipole expansion center. z_0 is the distance between the expansion center and the substrate interface. $r_0 = (\sqrt{\epsilon_d} - \sqrt{\epsilon_s})/(\sqrt{\epsilon_d} + \sqrt{\epsilon_s})$ and $t_0 = 2\sqrt{\epsilon_d}/(\sqrt{\epsilon_d} + \sqrt{\epsilon_s})$ are the Fresnel reflection and transmission coefficients of a normally incident plane wave at the surrounding-substrate interface, respectively. ϵ_s is the permittivity of the substrate. Higher order of multipole moments such as magnetic octupole can also be included into the equations [24, 25]. The reflectance and transmittance of the periodic metasurface are

$$R_{x,y} = |r_{x,y}|^2, \quad T_{x,y} = \sqrt{\epsilon_s/\epsilon_d} |t_{x,y}|^2 \quad (4)$$

Clearly, based on Eqs. (2) and (3), one can realize AT by utilizing only one multipole response such as the ED, or realize AR with two multipole responses such as ED and MD which is essentially the design principle of high-transmission Huygens' metasurfaces [44–49]. However, Huygens' metasurfaces typically require overlap of the ED and MD resonances, which results in a narrow operational bandwidth [9]. Furthermore, both single-response and dual-response Huygens' metasurfaces require operation near the resonances of the multipolar responses, which is normally accompanied by high absorption and thus limited transmission, particularly for plasmonic metasurfaces in the optical wavelength range [44, 46]. On the other hand, through multipolar interference, it is possible to realize both AR and AT in multipolar metasurfaces even when all multipoles are off resonant, which can reduce the OA. Another advantage of the off-resonance operation lies in that the amplitude/phase variations of the multipolar responses over the spectrum are slower at wavelength ranges away from the resonance, which contributes to broader bandwidth. As we will show later, this is the main principle of the record high and broadband transmission for plasmonic metasurfaces demonstrated in this work. Lastly, we will show that OA can also be realized by

overlapping the multipolar resonances in a similar wavelength range.

3 Results and discussion

Figure 1a shows the schematic of the proposed unit nanoantenna which is comprised a rectangle shaped gold nanoaperture and a gold nanorod separated by a perforated dielectric resist layer with an etched hole. The nanorod is situated in the etched hole. The nanoaperture, nanorod, and etched hole have the same dimension which is a rectangle with length of l and width of w . The separation between the two gold layers is t_r . t_m is the gold thickness. P is the period of the array. The nanoantenna is located on a quartz substrate.

In the beginning, we show that this nanoantenna can simultaneously support AR and AT in the visible and IR region through the generalized Kerker effect. For this purpose, we propose a nanoantenna design with $P = 320$ nm, $t_m = 30$ nm, $t_s = 180$ nm, $l = 220$ nm, and $w = 75$ nm. Figure 1b shows the calculated transmission and reflection spectra of the nanoantenna array directly obtained from the power monitors in the simulation using Finite-Difference Time-Domain (FDTD) Lumerical. The input is normally incident from the nanoaperture side and linearly polarized along the width direction, that is the y direction. In the simulation, the dielectric constants for the gold and quartz were directly obtained by using the Gold–Johnson and Christy database and the SiO₂–Palik database in the software material's library, respectively. The resist is chosen as ZEP520 and the dielectric constants were obtained from ellipsometry data. We can see that AR is supported at 870 nm ($T = 75.7\%$, $R = 0$) and AT is supported at 700 nm ($T = 0$, $R = 85.1\%$). The AR and AT are realized through destructive multipolar interferences in the backward and forward directions, respectively. Figure 1c shows the multipole contributions to the transmission/reflection fields from ED, MD, EQ, MQ, and EO in this nanoantenna as

Figure 1: (a) Schematic of the unit nanoantenna of the multipolar plasmonic metasurface supporting simultaneous antireflection (AR) and antitransmission (AT) in the visible and near-infrared (IR) region. (b) Calculated transmission/reflection spectra through direct FDTD simulation for a nanoantenna array with $P = 320$ nm, $t_m = 30$ nm, $t_s = 180$ nm, $l = 220$ nm, and $w = 75$ nm. (c, d) Calculated multipole contributions (c) to the transmission/reflection fields and their interference induced transmission/reflection spectra (d) for the designed nanoantenna array. The input source is from the nanoaperture side and linearly polarized along the y direction.

a function of the wavelength calculated using Eq. (1). We can see that the nanoantenna supports multipole response. Especially, the ED and EQ, and the MD and MQ have relatively similar magnitude in the wavelength range of interest, which facilitates the multipolar interference and the realization of AR and AT. Figure 1d shows the transmission and reflection spectra calculated by the multipolar interference using Eqs. (3) and (4). The multipole calculation also indicates AR at ~ 870 nm and AT at ~ 700 nm, respectively, which shows agreement with the direct calculation in Figure 1b. The small discrepancy between the direct and multipole calculations might arise from the incompleteness of the multipole expansion methods we have used. It can be improved by including higher-order multipoles [26]. On the other hand, the substrate effect may be considered more precisely by considering the substrate-mediated inter-nanoantenna coupling and substrate-mediated self-coupling [50]. More discussion on this is provided in the Supplementary material.

To show the multipolar interferences more clearly, we calculate the complex fields contributed from each multipole and direct transmission/reflection at the AR and AT wavelengths, and plot the vector superposition of these fields in Figure 2. Figure 2a, b shows the result for the transmission and reflection fields, respectively, at the AR wavelength of 870 nm. Figure 2c, d shows the result for the reflection and transmission fields, respectively, at the AT wavelength of 700 nm. In the calculation, we have made a global phase shift of all fields so that the direct transmission has a zero phase and the direct reflection has a π phase. At the AR wavelength of 870 nm, the multipolar interference induced transmission field (amplitude:

0.8769, phase: 0.2954π) has a large amplitude (Figure 2a) while the reflection field (amplitude: 0.0544, phase: -0.7018π) is small (Figure 2b), which indicates constructive and destructive interferences, respectively. In contrast, at the AT wavelength of 700 nm, constructive and destructive multipolar interferences occur for the reflection (amplitude: 0.9167, phase: 0.1459π) (Figure 2c) and transmission (amplitude: 0.02, phase: 0.2691π) (Figure 2d), respectively. This result further confirms that the AR and AT of the proposed metasurface in Figure 1 are enabled by multipolar interferences, i.e., generalized Kerker effect. Here the overall phase of the transmission and reflection fields can be an arbitrary value in the range between 0 and 2π by tuning the multipolar interference. Therefore, it is also possible to use this multipolar metasurface to realize full phase control for both the reflection and transmission fields with a unit amplitude [51].

We then experimentally fabricate the above metasurface design by using electron beam lithography and electron beam evaporation. The detailed fabrication procedure has been discussed elsewhere in a study by Zhang et al. [38]. The T and R of the sample in a broadband were measured by an optical setup schematically shown in Figure 3a. A collimated beam from a broadband lamp source (Thorlabs: SLS301) was focused onto the metasurface sample, which was mounted on a three-dimensional moveable and rotatable stage. Before the focusing lens, a broadband Glan-Thompson polarizer (Melles Griot: 03 PTH 112/C) was utilized to select the polarization. For the transmission measurement, the beam was collected by an objective (10 $\times$, 0.25). For the reflection measurement, a small incident angle around 5° was used in order to collect

Figure 2: (a, b) Vector superposition of the calculated fields contributed from each multipole and direct transmission/reflection in the transmission (a) and reflection (b) directions at $\lambda = 870$ nm. (c, d) Vector superposition of the calculated fields contributed from each multipole and direct transmission/reflection in the reflection (c) and transmission (d) directions at $\lambda = 700$ nm.

Figure 3: (a) Schematic of the optical setup for measuring the transmission/reflection spectra of the metasurface. (b, c) Scanning electron microscopy image (b) and measurement result (c) of the fabricated metasurface designed in Figure 1 for realizing antireflection (AR) and antitransmission (AT) simultaneously at different wavelengths in the visible and near-infrared (IR) region.

all the reflected beams without blocking. Two lenses were utilized for the beam collection. The beam is finally focused into the fiber collector of a spectrometer (Photon Control: SPM001). An iris was used to select the part of the light through the metasurface area. Transmittance of the metasurface was normalized to the transmittance of the quartz substrate. Reflectance of the metasurface was normalized to the reflectance from a 100 nm-thick gold thin film deposited on a quartz substrate. Figure 3b, c show the scanning electron microscopy image of the fabricated metasurface and the measurement result, respectively. In experiment, AT and AR are obtained at ~ 705.7 nm ($T = 0$ and $R = 82.4\%$) and at ~ 873.9 nm ($T = 69.2\%$ and $R = 1.3\%$), respectively. This result is close to the simulation in Figure 1. At the AR wavelength, the minimum R is not perfectly zero. This is due to the dimension difference in the fabrication and a small incident angle used in the measurement.

This above design indicates that the proposed metasurface can support AR and AT occurring at different wavelengths through multipolar interference. Next, we show that the AR and AT wavelengths are tunable by tuning the dimension. Especially, it is possible to tune them to an extreme case where the AR and AT wavelengths almost overlap with each other. In this case, the metasurface supports strong OA. The new design has $P = 320$ nm, $t_m = 30$ nm, $t_s = 180$ nm, $l = 122.5$ nm, and $w = 90$ nm. Figure 4a, b shows the calculated $T/R/A$ and multipole contributions of this design, respectively. We can see that the metasurface has T lower than 10% in a wavelength

range 645–708 nm with a minimum of 2.8% at 673 nm. With respect to the R , it is lower than 10% in a similar wavelength range 687–703 nm with a minimum of zero at 695 nm. The positions of the minimum wavelengths for T and R are close. As a result, strong absorption is supported in this wavelength range with $A > 90\%$ in 690–700 nm and a maximum value of 94.1% at 695 nm. In Figure 4b, all the multipoles have similar magnitude in the wavelength range near 695 nm, which causes AR and AT through multipolar interference. Meanwhile, all the multipoles support a local maximum in this wavelength range, which indicates resonances and thus strong absorption. Figure 4c shows the scanning electron microscopy image of the fabricated metasurfaces. The related transmission/reflection spectra of the metasurface are measured and shown in Figure 4d. In the experiment, T and R have minimum values of 3.8% at 711.2 nm and 2% at 692.4 nm, respectively. As a result, the maximum A is up to 92.8% at 692.8 nm, near-perfect absorption is demonstrated. This experimental result is broader than the simulation in Figure 4a. This is due to the surface roughness of the deposited metal film, which causes lower quality factor of the multipole resonances and thus broader absorption. Note that the plasmonic metasurfaces demonstrated here are thinner than most of previous multipolar metasurfaces demonstrated for AR, AT, and OA in the similar wavelength range, while the performance is comparable [9, 11, 35, 36, 47, 52, 53].

After utilizing the proposed multipolar metasurface to realize simultaneous AR and AT at one polarization,

Figure 4: (a, b) Calculated transmission/reflection/absorption spectra (a) and multipole contributions (b) for a nanoantenna array with $P = 320$ nm, $t_m = 30$ nm, $t_s = 180$ nm, $l = 122.5$ nm, and $w = 90$ nm, which is designed with overlapped antireflection (AR) and antitransmission (AT) wavelengths and thus strong absorption at a visible wavelength. (c, d) Scanning electron microscopy image (c) and measurement result (d) of the fabricated metasurface.

in the end we show that this metasurface can also be used to control the transmission and reflection of light at different polarizations. Specifically, we propose to use the metasurface for high-efficiency transmissive polarizers which have high transmission for one polarization and low transmission for another polarization. For this purpose, we let the length of the rectangle design to be infinite, i.e., a two-dimensional sub-wavelength grating design is used, as shown in Figure 5a. The two-dimensional structure is periodic in the x direction and invariant in the y direction. We first present two polarizers with optimized performance for the wavelength range around 800 nm. The first

polarizer design, which has $P = 100$ nm, $w = 42.4$ nm, $t_s = 121.4$ nm and $t_m = 60$ nm, is a broadband polarizer that transmits the x -polarization and blocks the y -polarization. Its calculated transmission spectra of two polarizations and ER between two polarizations are shown in Figure 5b. T_y is less than 1% in a broadband 665–1600 nm, while T_x is over 72% in the same wavelength range with a peak value of 97% at 800 nm. The ER which is defined by $10 \times \log_{10}(T_x/T_y)$ is more than 18.2 dB. We note that similar structure has been reported before for polarizer in the visible range [54]. However, here we explain the underlying physics of the selective transmission of T_x through the generalized

Figure 5: (a) Schematic of the two-dimensional metasurface design for broadband polarizers. (b–c) Calculated $T_{x,y}$ and their extinction ratios of the polarizer designs optimized for transmission of x -polarization (b) and y -polarization (c) at a wavelength range ~800 nm. (d–e) Calculated $T_{x,y}$ and their extinction ratios of the polarizer designs for transmission of x -polarization (d) and y -polarization (e) at a wavelength range ~1060 nm.

Kerker effect. Because of this, we are able to tune the multipolar interference of the metasurface for selective transmission of the y -polarization, which has never been reported before in a similar structure. The result of such a polarizer design is shown in Figure 5c, which has $P = 400$ nm, $w = 240$ nm, $t_s = 200$ nm and $t_m = 15$ nm. In a broadband 730–900 nm, T_x is less than 1%, while T_y is over 72% with a peak value of 91% at 800 nm. The ER which is defined by $10 \times \log_{10}(T_y/T_x)$ exceeds 18 dB. Furthermore, we can also design the polarizer optimized for other wavelength range of interest based on the multipole tuning. For example, Figure 5d, e show the polarizers optimized for a wavelength range ~1060 nm for selective transmission of the x -polarization and y -polarization, respectively. The left design supports $T_x = 98.4\%$ and ER = 24 dB at 1150 nm. The right design supports $T_y = 90.3\%$ and ER = 26.6 dB at 1000 nm. The simulations of the multipole contributions of these four polarizer designs are provided in the Supplementary material, which show the off-resonance of the multipolar responses at the operation wavelength of each design for the transmitted polarization. Compared to previous plasmonic metasurfaces enabled polarizers in the similar wavelength range, this 2D plasmonic metasurface is simpler, while the performance is comparable or even better [54–56].

These above results fully and clearly show the flexibility of the proposed multipolar metasurface in its structure, functionality, and operation wavelength for controlling the amplitude of the light at different polarizations with high efficiency. The fabrication of this metasurface is simpler than previous metasurfaces as there is no need for lift-off or etching after the lithography.

4 Conclusion

In conclusion, we have designed and demonstrated a multipolar plasmonic metasurface that can control the transmission, reflection, and absorption of light in the visible and IR region through multipolar interference. The metasurface is subwavelength in thickness. AR and AT have been realized simultaneously at different wavelengths or at close wavelengths, which can be used for spectral filter and OA, respectively. A simple two-dimensional design is further presented for realizing broadband polarizers at two different wavelength ranges near 800 and 1060 nm. The polarizers support high transmission and ER with tunability on the transmitted polarization and operation wavelength. This metasurface will find applications in high-efficiency ultrathin optical coatings, filters, splitters, absorbers, and polarizers.

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- Supplementary material:** See the Supplementary material for expressions of the multipole moments, near-fields at two metallic layers, and the simulated multipole contributions of four polarizer designs in Figure 5.
- The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2020-0325>).