Polarization-sensitive perfect absorbers at near-infrared wavelengths

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Abstract: Three different types of polarization-sensitive perfect absorbers are designed and numerically investigated. The bottle-like and the cup-like absorbers are narrowband absorbers, which strongly absorb light of a specific polarization and reflect almost all light of another polarization. By varying the geometric parameters, their absorption peaks can be tuned from 1300 nm to 2300 nm and 700 nm to 1400 nm, respectively. The broadband absorber is polarization-sensitive as well, exhibiting an average absorption efficiency of 88% over a wide range of wavelength (700-2300 nm). The proposed absorbers may have potential applications in polarization detectors, polarizers etc.

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References and links
1. T. V. Teperik, F. J. Garcia de Abajo, A. G. Borisov, M. Abdelsalam, P. N. Bartlett, Y. Sugawara, and J. J. Baumberg, “Omnidirectional absorption in nanostructured metal surfaces,” Nat. Photonics 2(5), 299–301 (2008).
2. N. Liu, M. Mesch, T. Weiss, M. Hentschel, and H. Giessen, “Infrared perfect absorber and its application as plasmonic sensor,” Nano Lett. 10(7), 2342–2348 (2010).
3. K. Aydin, V. E. Ferry, R. M. Briggs, and H. A. Atwater, “Broadband polarization-independent resonant light absorption using ultrathin plasmonic super absorbers,” Nat Commun 2, 517 (2011).
4. V. G. Kravets, S. Neubeck, A. N. Grigorenko, and A. F. Kravets, “Plasmonic blackbody: strong absorption of light by metal nanoparticles embedded in a dielectric matrix,” Phys. Rev. B 81(16), 165401 (2010).
5. J. Hao, J. Wang, X. Liu, W. J. Padilla, L. Zhou, and M. Qiu, “High performance optical absorber based on a plasmonic metamaterial,” Appl. Phys. Lett. 96(25), 251104 (2010).
6. J. Wang, Y. Chen, J. Hao, M. Yan, and M. Qiu, “Shape-dependent absorption characteristics of three-layered metamaterial absorbers at near-infrared,” J. Appl. Phys. 109(7), 074510 (2011).
7. J. Wang, Y. Chen, X. Chen, J. Hao, M. Yan, and M. Qiu, “Photothermal reshaping of gold nanoparticles in a plasmonic absorber,” Opt. Express 19(15), 14726–14734 (2011).
8. X. Chen, Y. Chen, M. Yan, and M. Qiu, “Nanoscale photothermal effects in plasmonic nanostructures,” ACS Nano 6(3), 2550–2557 (2012).
9. A. Polyakov, S. Cabrini, S. Dhuey, B. Harteneck, P. J. Schuck, and H. A. Padmore, “Plasmonic light trapping in nanostructured metal surfaces,” Appl. Phys. Lett. 98(20), 203104 (2011).
10. V. G. Kravets, F. Schedin, and A. N. Grigorenko, “Plasmonic blackbody: almost complete absorption of light in nanostructured metallic coatings,” Phys. Rev. B 78(20), 205405 (2008).
11. J. Hao, Y. Yuan, L. Ran, T. Jiang, J. A. Kong, C. T. Chan, and L. Zhou, “Manipulating electromagnetic wave polarizations by anisotropic metamaterials,” Phys. Rev. Lett. 99(6), 063908 (2007).
12. H. Tao, C. M. Bingham, D. Pilon, K. B. Fan, A. C. Strikwerda, D. Shrekenhamer, W. J. Padilla, X. Zhang, and R. D. Averitt, “A dual band terahertz metamaterial absorber,” J. Phys. D Appl. Phys. 43(22), 225102 (2010).
13. Y. Ma, Q. Chen, J. Grant, S. C. Saha, A. Khalid, and D. R. S. Cumming, “A terahertz polarization insensitive dual band metamaterial absorber,” Opt. Lett. 36(6), 945–947 (2011).
14. M. K. Hedayati, M. Jahverirahim, B. Mozooni, R. Abdelaziz, A. Tavassolizadeh, V. S. K. Chakravadhanula, V. Zaporozhchenko, T. Strunkus, F. Faupel, and M. Elbahri, “Design of a perfect black absorber at visible frequencies using plasmonic metamaterials,” Adv. Mater. 23(45), 5410–5414 (2011).
15. K. Iwaszczuk, A. C. Strikwerda, K. Fan, X. Zhang, R. D. Averitt, and P. U. Jepsen, “Flexible metamaterial absorbers for stealth applications at terahertz frequencies,” Opt. Express 20(1), 635–643 (2012).
1. Introduction

From gigahertz to visible regime, metal surfaces are usually high efficient reflectors, which can be utilized as mirrors. However, micro or nanostructured surfaces may become high-efficiency absorbers. From gigahertz to visible regime, metal surfaces are usually high efficient reflectors, which can be utilized as mirrors. However, micro or nanostructured surfaces may become high-efficiency absorbers. Yet, the development of high-performance absorbers which can be realized in the near-infrared regime is still lacking. Here, we present a wide-angle perfect absorber based on a metal-dielectric-metal elliptical nanodisk array, which can absorb nearly all of the light within a wide angular range. The absorber is experimentally realized using a plasmonic metamaterial structure, and its performance is investigated using simulations and experiments. The results show that the absorber can achieve near-unity absorbance across a wide angular range, making it a promising candidate for applications such as solar energy conversion and thermal management.
around the near-infrared wavelength near 1550 nm [5,6]. Further, we studied the photothermal effects arising in the structures and considered utilizing it to reshape the gold nanoparticles [7, 8].

For polarization-sensitive absorption, A. Polyakov et al [9] experimentally demonstrated an array of rectangular trenches in gold to form a subwavelength grating, which can strongly concentrate the polarized incident light. The effect can be used for generation of laser harmonics or polarization switch. V. G. Kravets et al [10] designed and investigated composite deep metallic gratings, which strongly absorb the light with electric field perpendicular to the gratings, while behave as good reflectors for the other polarized light.

In this paper, three different types of metallic nanostructures are presented and numerically investigated. First, a bottle-like narrowband absorber is presented, originating from the gap plasmon resonance, whose resonant peak can be tuned from 1300 nm to 2300 nm. Then a cup-like narrowband absorber is discussed, which is simple to fabricate. Its resonant peak can also be varied through a broad spectral range from 700 nm to 1400 nm. Finally a broadband absorber is investigated, and numerical simulations show that the average absorption efficiency is over 88% from 700 nm to 2300 nm. All three absorbers are high-performance and polarization-sensitive at near-infrared range, so they can be used as polarization detectors or reflective polarizers to manipulate the polarization of electromagnetic wave [11].

2. Bottle-like narrowband absorber

A bottle-like absorber consists of an array of dielectric (SiO$_2$) strips embedded in gold, with small air gaps on the top of the dielectric strips, as illustrated in Fig. 1(a). Figure 1(b) shows the cross-section of a unit cell, where $a$ and $b$ represent, respectively, the width and the depth of the air gaps, $d$ and $c$ denote the width and the thickness of the dielectric strips, respectively, and $w$ is the period. In our numerical simulations using the commercial software COMSOL MULTIPHYSICS based on finite element method, the refractive index of the dielectric is 1.5, the permittivity of gold is given by the Drude Model $\epsilon_{\text{Au}} = 9 - \omega_p^2 / (\omega^2 + i \gamma \omega)$ with the plasmon frequency $\omega_p = 2\pi \times 2.175 \times 10^{15}$ s$^{-1}$ and the collision frequency $\gamma = 2\pi \times 1.5958 \times 10^{13}$ s$^{-1}$ [7]. All materials are assumed to be nonmagnetic ($\mu = \mu_0$).

Fig. 1. (a) Schematic of the bottle-like absorber, the yellow region is gold and blue regions are the dielectric. (b) Cross-section of a unit cell. The width and the depth of the air gap are represented by $a$ and $b$, respectively. $c$ and $d$ represent the thickness and the width of the dielectric strip, respectively, and $w$ is the period.
Gapped nanoparticles have been proved to be able to concentrate light and therefore cause electric field enhancement in the gap at resonant wavelength [29–31]. In our absorber, the thin layers of gold on the dielectric strips are structured to form small air gaps. Assume that a $p$-polarized (electric field perpendicular to the gap) plane wave illuminates the structure at normal incidence. Here an optimized set of parameters for a perfect absorber with resonant wavelength near 1600 nm is used as $a = 5 \text{ nm}$, $b = 10 \text{ nm}$, $c = 60 \text{ nm}$, $d = 60 \text{ nm}$, and $w = 600 \text{ nm}$. In the following simulations, if not particularly specified in the figure legends, the geometric parameters always keep constant. To investigate the relationship between the absorption spectra and the geometric parameters, the depth of the gap $b$, the width and the thickness of the dielectric strip $d$ and $c$ are, respectively, varied while the other parameters fixed. The results shown in Figs. 2(a)-2(c) demonstrate that resonant wavelength can be tuned over a very broad spectral range via varying the relevant parameters. The absorption is always above 97% for all different parameters. Figure 2(d) gives the absorbance for $s$-polarized normal incident light. Compared with the nearly total absorption under $p$-polarized light, the structure reflects almost all $s$-polarized light for the same wavelength range (average absorption is less than 1.8%), illustrating that it’s highly polarization-selective. Numerical simulations have also been carried out to extract the electric field distribution excited by the different polarized light radiation. We utilize a formula $EIF = \left| \frac{E}{E_{\text{inc}}} \right|^2$ to describe the electric intensity enhancement [32], where $E_{\text{inc}}$ is the electric field of the incident wave and $E$ is the total electric field. Under normal incidence at the resonant wavelength, comparison between the electric intensity enhancements under $p$- and $s$-polarized light radiations is shown in Fig. 3 to verify the effect. The values of electric intensity enhancements are plotted on log scale. Note
that the lack of obvious enhancement for the \( s \)-polarized light radiation is in sharp contrast to the situation for the \( p \)-polarized.

Fig. 3. Comparison between the electric intensity enhancements under (a) \( p \)-polarized light radiation and under (b) \( s \)-polarized light radiation at 1600 nm (plotted on log scale). Geometric parameters: \( a = 5 \) nm, \( b = 10 \) nm, \( c = 60 \) nm, \( d = 60 \) nm, and \( w = 600 \) nm.

In order to reveal the underlying physics of the relationship between the geometric parameters and the resonant wavelength, that is to answer why the resonant peaks can be tuned through varying the geometric parameters, further simulations were performed. Figure 4 shows the absorption efficiency and the electric intensity enhancement (plotted on log scale) in the center of the gap as functions of incident wavelength. It is clear that the resonant wavelength is achieved when the coupling strength is maximized. More numerical computations give similar results. Different sets of \( b \), \( c \), and \( d \) correspond to different resonant wavelength to maximize the electric field enhancement in the gap.

Fig. 4. Absorption and electric intensity enhancement (plotted on log scale) at the center of the air gap as functions of incident wavelengths under \( p \)-polarized light radiation. The geometric parameters are the same as those in Fig. 3.

We also utilized the effective medium theory to obtain the impedance \( Z \) and the refractive index \( n \) of the absorber [33]. As shown in Fig. 5, both \( Z \) and \( n \) are complex numbers. At 1.6 \( \mu \)m (as predicted by the vertical dashed line), \( Z = 0.84 + 0.02i \), which is close to that of the free
space. Therefore the reflection is very low, since \( R(\omega) = \left( \frac{Z(\omega) - 1}{Z(\omega) + 1} \right)^2 \) [34]. Meanwhile, since \( n = 0.52 + 8.15i \), the large imaginary part of refractive index gives rise to a high absorption.

Fig. 5. Retrieved impedance \( Z \) and refractive index \( n \). The geometric parameters are the same as those in Fig. 3.

Fig. 6. Absorbance as functions of wavelengths and incident angles. (a) \( E \perp S_{yz} \) (b) \( H \perp S_{yz} \) (c) \( E \perp S_{xz} \) (d) \( H \perp S_{xz} \).

The absorption effect of this type of absorber is robust and highly polarization selective even for non-normal incident radiation. As shown in Fig. 6, there is no obvious absorbance within the simulated wavelength region in the cases of \( E \perp S_{xz} \) and \( H \perp S_{yz} \). However, when the electric field is parallel to the \( xz \) plane, the structures strongly absorb the incident radiation at
resonant wavelengths regardless of the incident planes. In the E⊥Syz case (incident plane is the yz plane), even if the angle is up to 65°, the absorption remains 80%. It is similar to H⊥Sxz case (incident plane is the xz plane), in which the absorption efficiency remains high while the oblique incident angle becomes very large.

3. Cup-like narrowband absorber

Though the above type of structure possesses high performance and fine tunability, it’s fairly difficult to fabricate. Thus more simple structure is desirable in practice. For this purpose, another type of narrowband absorber is proposed.

As shown in Fig. 7(a), the absorber is composed of an array of nanoscale grooves with a layer of dielectric on it. Figure 7(b) is its cross-section of a unit cell. The width and the depth of the grooves are represented by $a$ and $H$, respectively. The thickness of the dielectric is denoted by $d$, and $w$ is the period. When carefully designed, it can provide nearly total absorption at resonant wavelength resulting from the destructive interference between light reflected from the top surface and light from the bottom of the grooves. Furthermore, it is found that by adjusting the thickness of the deposited dielectric, resonant peaks can also be tuned. Figure 8 shows the dependence of the absorption spectra on the groove depth $H$ and the thickness of the dielectric layer $d$ with $a = 20$ nm, $w = 600$ nm under $p$-polarized (electric field perpendicular to the grooves) normal light radiation.
As the depth of the grooves or the thickness of the dielectric layer increases, the absorption peaks are red-shifted. The structure still acts as a good reflector for \( s \)-polarized impinging light. Figure 9 shows the excited electric intensity enhancements under different polarized light radiation (plotted on log scale). In comparison with the significant field enhancement in the groove under \( p \)-polarized light, the structure can hardly concentrate \( s \)-polarized light. In the above simulations, the geometric parameters and the incident wavelength are the same as those corresponding to the first peak in Fig. 8(a). This type of absorber is also robust and highly polarization selective for non-normal radiation as well, which is verified by the Fig. 10, here \( H = 100 \text{ nm} \) and \( d = 90 \text{ nm} \). For either \( E \perp S_{yz} \) or \( H \perp S_{xz} \), the absorption remains over 85% when the incident angle is up to 50° at the main resonant wavelength around 1350 nm.
Fig. 10. Absorbance as functions of wavelengths and incident angles. (a) \( E \perp S_{yz} \) (b) \( H \perp S_{yz} \) (c) \( E \perp S_{xz} \) (d) \( H \perp S_{xz} \). Here \( H = 100 \text{ nm}, d = 90 \text{ nm} \).

Though the refractive index of the dielectric above is chosen to be 1.5, further numerical simulations show that for both the bottle-like and cup-like absorbers, absorption spectrum will redshift when the value of refractive index is increased, but the high absorption is kept unchanged.

It’s worth noting that the bottle-like absorber exhibits the tunable resonant peak ranging from 1300 nm to 2300 nm, while the cup-like absorber exhibits the tunable resonant peak ranging from 700 nm to 1400 nm, which theoretically implies that any polarized electromagnetic wave with wavelength ranging from 700 nm to 2300 nm can be perfectly absorbed using the designed absorbers.

4. Broadband absorber

In addition to the narrowband absorber, broadband absorber with high performance is also of importance. Here a broadband absorber is demonstrated, and an average absorption efficiency of 88% is achieved over a wide range of wavelengths (700-2300 nm) for \( p \)-polarized light.

In the inset of Fig. 11, (a) shows the 3D schematic, and (b) is the cross-section of the half of a unit cell. Blue regions are the dielectric. For better performance, the refractive index is chosen to be 1.75. Yellow region is gold. \( a = 100 \text{ nm}, w = 80 \text{ nm}, \) and \( H = 50 \text{ nm} \). In the simulations, half a unit cell consists of 40 grooves, i.e., the width of half a unit is \( 40 \times a = 4000 \text{ nm} \) and the depth of the deepest groove is \( 40 \times H = 2000 \text{ nm} \). Note that, for visual convenience, we present only the simplified structure in the inset in Fig. 11, in which half of a unit cell consists of three grooves instead of 40 grooves. Figure 11 shows the absorption as a function of wavelengths under \( p \)-polarized light. An average absorption efficiency of 88% is achieved. It is highly polarization sensitive, reflecting more than 98% of incident \( s \)-polarized light.
Fig. 11. Absorption under $p$-polarized light. Average absorption efficiency is over 88%. Every half of a unit cell contains 40 grooves. In the Inset is the simplified structure. (a) is schematic of the broadband absorber, the yellow region is gold and blue regions are the dielectric. (b) is cross-section of half a unit cell. $a = 100$ nm, $w = 80$ nm, $H = 50$ nm.

Figure 12 shows the calculated impedance and refractive index using the effective medium theory. In the simulated wavelength range, $\text{Im}(n)$ is always large and $Z_{\text{average}} = 0.52 + 0.01i$. Using the formula $R(\omega) = \left(\frac{Z(\omega) - 1}{Z(\omega) + 1}\right)^2$ [34], we obtain that the average reflectivity $R(\omega)$ is 9.8%. Since the transmission here is very low, so the absorption is approximately $A(\omega) = 1 - R(\omega)$. The obtained average absorption is thus 91%, which agrees well with the numerical result (88%).
Figure 13 presents the absorbance as functions of wavelengths and incident angles. In sharp contrast to the good reflection to the incident light for the $H_{⊥yz}$ and $E_{⊥xz}$ cases, when electric field is parallel to the $xz$ plane i.e. perpendicular to the grooves, the structure strongly absorbs the incident light over a wide angle range. When the incident angle is up to 60°, for the $E_{⊥yz}$ case, the absorbance remains over 75%. For the $H_{⊥xz}$ case, a much higher absorption efficiency of 95% can be achieved.

5. Summary

In conclusion, we utilize the gap plasmon resonance to design the bottle-like absorber, where the resonant wavelength can be tuned over nearly one thousand nanometers via varying the embedded dielectric strip’s width, thickness or the depth of the gaps. Based on the destructive interference, we also propose the cup-like absorber, which is simple to fabricate. It’s found that just by depositing dielectrics with different thickness, the absorption peaks can be altered for a range of hundreds of nanometers. Finally, by combining grooves with different depths and carefully arranging its geometric and material parameters, a broadband absorber with an average absorption efficiency of 88% (700-2300 nm) is presented. All three structures are highly polarization selective, so they might have the potential to be used as polarization detectors or reflective polarizers at near-infrared wavelengths.

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