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Near-infrared six-band polarization-independent wide-angle absorber based on metal cavity arrays filled with GaAs

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Dear editor,
Since the first microwave metamaterial perfect absorber (MPA) was reported by Landy et al. [1], the study of metamaterial perfect absorbers has attracted attention because of their broad application prospects. Owing to the strong resonant nature of metamaterials, MPAs generally have a single narrow absorption band, which considerably affects their practical applications, particularly in infrared frequency-selective detection, imaging, and bolometric applications. To increase the number of absorption bands, there are currently two typical ways, namely, coplanar multiple substructures with different geometric dimensions in a unit cell [2,3], and vertically stacked multilayer metal/dielectric structures [4]. However, these designs are limited to triple-band and quadruple-band perfect absorption and five or more absorption bands are rarely involved. Therefore, the design of multiband (higher than five bands) infrared absorbers is still a challenge.

In this study, we propose an effective design approach to achieve a polarization-independent, wide-angle six-band near-infrared absorber by employing cross-shaped metal cavity arrays filled with a highly dielectric material. Compared to previously reported studies [1–4], our design yields at least three benefits. First, our design not only achieves a simple and compact structure but also avoids the problems of a large unit size and a complicated multilayer fabrication. Second, unlike the traditional MPAs, which consist of metal/dielectric/metal sandwich structures, our design utilizes subwavelength metal cavity arrays filled with a highly dielectric material, providing an alternative route to achieve a multiband perfect absorption. Third, and most importantly, the physical mechanism of the six-band perfect absorption is attributed to the combination of multiple cavity modes of the structure, which is different from the mechanism of previous MPAs.

Proposed near-infrared absorber with cross-shaped metal cavity structure. The proposed six-band near-infrared MPA is created with the help of a subwavelength cross-shaped metal cavity filled with gallium arsenide (GaAs), as exhibited in Figures 1(a)–(c). GaAs is selected as the filling material because it not only has a large refractive index but also has a wide number of applications in optoelectronic devices. The length (l), width (w) and depth (h) of the metal cavity are 270, 100, and 800 nm, respectively. The thickness (t) of the metal substrate is set at 200 nm, which is used to block light transmission. The period (p) of the array is set at 310 nm.

The optical properties of the proposed absorber

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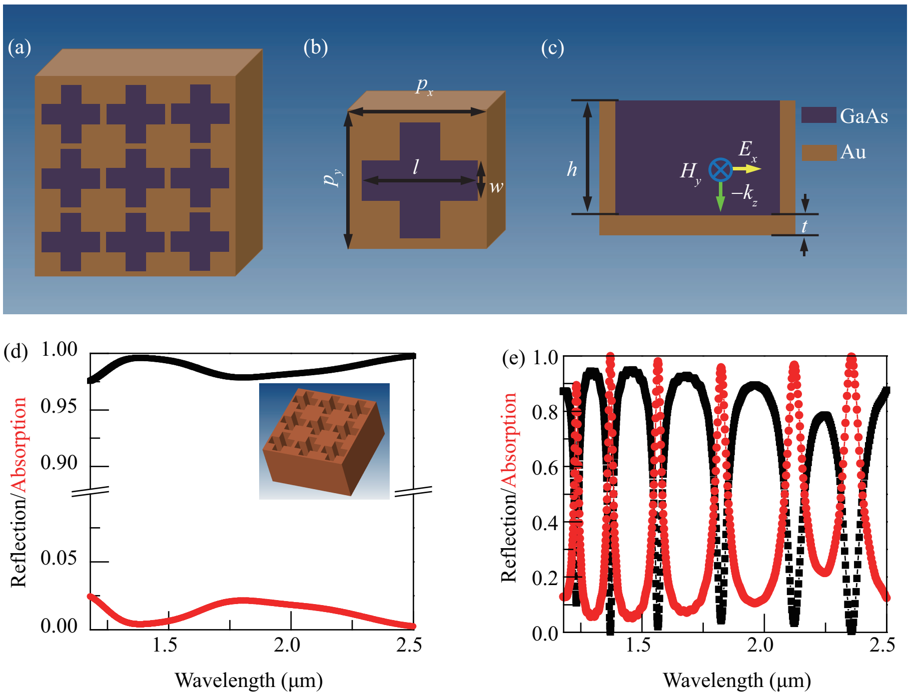

Figure 1 (Color online) (a) Three-dimensional view of the proposed absorber composed of cross-shaped metallic cavities filled with GaAs; (b) the perspective view and (c) the cross section of the unit cell; (d) the reflection and absorption spectra of the absorber based on Au-cavity arrays. The inset shows the schematic of the absorber; (e) the reflection and absorption spectra of the proposed absorber based on Au-cavity arrays filled with GaAs.

are investigated by employing the commercial software (Lumerical Solutions Inc.) based on the finite-difference time-domain (FDTD) method. A unit cell is selected as the simulation region. For the unit cell, the periodic boundary conditions are adopted for both the x- and y-directions, and the perfect matching layers are used for the z-direction. The complex refractive index dispersions for gold (Au) and GaAs are chosen as CRC [5] and Palik [6], respectively, from the default material database, respectively. A plane wave with electric field (E) parallel to the x-direction normally illuminates the top of the metallic cavity, and the reflection is obtained in the backscattered plane. The absorption (A) is calculated by $A(\lambda) = 1-T(\lambda)-R(\lambda)$, where $T(\lambda)$ and $R(\lambda)$ are the transmission and the reflection, respectively. The transmission $T(\lambda)$ is zero for the designed structure, because the bottom metal substrate ($t = 200$ nm) completely suppresses the light transmission. Thus, A is directly computed by $A(\lambda) = 1 - R(\lambda)$. The proposed MPA can be fabricated by a typical microfabrication technique [7].

Results and discussion. For the absorber composed exclusively of Au-cavity arrays, the light absorption response is exhibited in Figure 1(d). It is observed that a reflectivity of over 97.56% is obtained in the wavelength range of interest, which indicates that the absorber achieves an absorption of less than 2.44% in the absorption spectrum. Nevertheless, six distinctive reflection dips are obtained for the Au-cavity array filled with GaAs, as exhibited in Figure 1(e). According to these reflection dips, a six-band near-perfect light absorption is obtained. The six absorption peaks are located at 1.233 μm (λ_1), 1.372 μm (λ_2), 1.566 μm (λ_3), 1.824 μm (λ_4), 2.124 μm (λ_5), and 2.355 μm (λ_6), with absorptivities of 89.38%, 99.92%, 98.06%, 95.91%, 96.81%, and 99.70%, respectively. The corresponding absorption bandwidths, defined as full width at half maximum (FWHM), are 0.023, 0.025, 0.038, 0.066, 0.084, and 0.087 μm, respectively. The quality factors of the six absorption peaks are 55.3, 54.9, 41.2, 27.6, 25.3, and 27.1, respectively. Further, the details of the effective impedance are presented in Appendix A.

The electric field intensity distributions are presented to understand the physical origin of the six-band light absorption, as exhibited in Figure B1 (refer to Appendix B for details). The field distributions on the x-z plane demonstrate that the strong electric fields are mainly concentred on the central region of the cross-shaped cavity, displaying the Fabry-Perot (FP) cavity mode excitation with a perfect standing wave along the z-direction. For mode λ_1, a strong electric field with five nodes is localized in the cavity, demonstrating that the fifth-order cavity mode resonance is excited effectively [refer to Figure B1(a)] [2]. Similarly, the modes λ_2–λ_6 are respectively attributed to the fourth-order, third-order, second-order, first-order, and zeroth-order FP cavity mode resonances, as illustrated in Figures B1(b)–(f).

The FP cavity modes can be effectively excited by the plasmonic standing waves in the semi-closed metal cavity, and the resonant wavelengths of the metal cavity related to the depth of the cavity can be expressed by [8]

$$\phi_1 + \phi_2 + 2n_{\rm eff}k_0h = 2m\pi, \tag{1}$$

where ϕ_1 and ϕ_2 are the phases caused by the reflection at the two terminations of the cavity, $n_{\rm eff}$ is the effective refractive index of the plasmon wave in the cavity, which depends on the period, width, length, and depth of the cavity, k_0 is the vacuum wave vector, h is the depth of the cavity, and m is the order of the resonance.

We next investigate the sensitivities of the six-band light absorption to the polarization angles and oblique incidence angles, as exhibited in Figure C1 (refer to Appendix C for details). It can be observed from Figure C1(a) that the proposed six-band absorber is polarization-insensitive. Figures C1(b) and (c) exhibit the absorption characteristics of the six-band absorption under different oblique incidence angles with p-polarization and s-polarization waves, respectively. The six-band near-perfect absorption responses continue to maintain an absorption level of more than 80% for oblique incidence angles up to 50° under the p-polarization and s-polarization waves. Thus, a near-perfect, polarization-insensitive and wide-angle six-band light absorption is achieved via the absorber platform owing to the high symmetry of the patterned structure and the FP resonances of the cavity. These absorption properties are desirable for applications in the absorption filter and in optoelectronics because the absorption spectra are polarization-independent and have a large tolerance range for oblique incidence angles. In addition, we have also studied the influence of the basic structural parameters, metal, and filling materials on the absorption spectra. The detailed results and analysis are presented in Appendix C.

Conclusion. We propose a polarization-insensitive and wide-angle six-band near-infrared absorber consisting of cross-shaped Au-cavity arrays filled with GaAs. Six distinct absorption peaks with the maximal absorption rate of 99.92% can be obtained at normal incidence. Furthermore, the absorption coefficient and position of each absorption peak are unchanged for all polarization angles, and the absorption peaks continue to maintain an absorption level of more than 80% for oblique incidence angles up to 50° under the p-polarization and s-polarization waves. The proposed absorber has potential applications in the optoelectronic field, such as in thermal emitters, microbolometers, and photodetectors.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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