

Four-band near-perfect absorption of hyperbolic metamaterials

JIAO Li-na, LIU Qi, WU Wan-chun, XU Hua*

(Faculty of Science, Ningbo University, Ningbo 315211, China)

Abstract: Multi-layer stacking or multi-sized array is generally employed to realize multi-band near-perfect absorption, from which the complexities arise in preparation. In this work, a four-band absorber with narrow bands and absorptance over 0.99 at infrared wavelengths is proposed based on theory, which presents a single-sized array with a metallic and a dielectric layer on a metal substrate. The origin of the four-band near-perfect absorption is explained by studying the dispersion relation of hyperbolic metamaterials in combination with the waveguide theory. It is found that the multi-band near-perfect absorption with high quality factors is sensitive to variation of surrounding environments, which projects potential applications as a biosensor.

Key words: near-perfect absorption; narrow bands; hyperbolic metamaterials; waveguide; refractive index sensing

CLC number: O43

Document code: A

Article ID: 1001-5132 (2019) 01-0093-05

1 Introduction

Metamaterials are artificial composite materials that exhibit unusual optical properties, such as negative refractive index^[1-2], invisibility cloaking^[3], superlensing^[4], and near-perfect absorption^[5-14]. Since Landy et al^[5] first reported the perfect metamaterial absorber in the microwave region, tremendous interests in near-perfect absorbers working from microwave to visible frequencies have been aroused^[6-9].

In order to achieve near-perfect absorption, reflection is suppressed through matching the effective impedance of metamaterials to that of incident media, while transmission is, in general, eliminated by introducing a metallic plate as a substrate. Following the principle, various broad- or narrow-band absorbers have been proposed, which show single or multiple absorption peaks. For example, Liu et al^[10] experimentally

demonstrated a single-band absorber with a gold disk array structure in the infrared region. The dual-band absorbers have also been studied by Li^[11] and Bai et al^[12] in the frame of a ring disk and an L-shaped structure, respectively. Wang et al^[13] reported a triple-band absorber using a patterned asymmetric metallic cross. Yu et al^[14] presented a multi-band absorber by stacking the four identical triangular spiral-shape complementary wire structures. It was noted that the multi-layer stacking or multi-sized array is generally employed to realize multi-band near-perfect absorption. In fact, such means brings about the complexities in theoretical design and experimental preparation. Thus, single-sized arrays with less layers are favorable while preserving the multi-band near-perfect absorption.

In this work, we proposed a four band near-perfect absorber composed of rectangular arrays, which are composed of the single-sized two-layer stacking of Al and Ge on an Al substrate. The origin of the four-band

收稿日期: 2018-09-03.

宁波大学学报(理工版)网址: <http://journallg.nbu.edu.cn/>

基金项目: 浙江省自然科学基金 (LY17A040004) .

第一作者: 焦丽娜 (1991—), 女, 陕西咸阳人, 在读硕士研究生, 主要研究方向: 超构材料. E-mail: 939252946@qq.com

*通信作者: 徐华 (1979—), 女, 江苏无锡人, 副教授, 主要研究方向: 超构材料. E-mail: xuhua@nbu.edu.cn

absorption was studied analytically and numerically according to the hyperbolic waveguide theory^[15-16]. Thanks to the high quality factors of the absorption bands, they are sensitive to the change of environmental refractive index and the sensitivity was investigated for potential applications as a biosensor.

2 Single-sized four-band near-perfect absorber

The schematic of the proposed four-band near-perfect absorber is illustrated in Fig. 1(a). The absorber is a single-sized rectangular array with a metallic (Al) and a dielectric (Ge) layer on an Al substrate. Its cross-sectional structure is shown in Fig. 1(b). The thicknesses of Al, Ge layers, and Al substrate are $d_m=0.03$ and $d_d=0.209$, and 0.1 μm , respectively. The periodicity p and the patch width b are 1.92 and 1.817 μm , respectively. The simulations were performed using a commercial software COMSOL Multiphysics based on a finite element method. Firstly, both 2D and 3D calculations were carried out for comparison of absorption spectra. For simplicity, only the 2D array was considered with a periodic boundary condition and Floquet ports in the following calculations. A transverse-magnetic (TM) polarized light is normally incident along the z -direction, as shown in Fig. 1(a). The permittivity of Al was modeled by a Drude formula: $\varepsilon(\omega) = 1 - \omega_p^2 / (\omega(\omega + i\gamma_p))$, where the plasma frequency ω_p and the collision frequency γ_p are 2.24×10^{16} and 1.22×10^{14} $\text{rad} \cdot \text{s}^{-1}$, respectively, and the permittivity of Ge is 16.

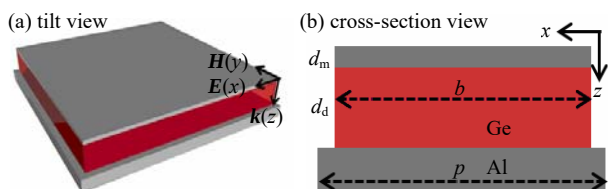


Fig. 1 Views of the proposed four-band absorber

As shown in Fig. 2, the black dotted line represents the 2D calculation of the absorption spectrum wavelengths from 2 to 18 μm , as compared with the 3D calculation. Similar curves were observed in both cases

except that the 3D calculation showed some weak absorption peaks as well as a minor blue shift. The discrepancies between the 2D and the 3D calculation results could be ascribed to the assumption that the 2D structure was infinite along the y direction, while it was not the case in the 3D. The detailed information about 2D absorption spectra is shown in Table 1. The four narrow-band peaks with the absorptance over 0.99 are located at $\lambda_1=16.27$, $\lambda_2=5.42$, $\lambda_3=3.27$ and $\lambda_4=2.37$ μm . Their corresponding resonant band widths, defined as FWHM (full-width at half-maximum), are 2230, 262, 100 and 54 nm, respectively; the quality factors Q , defined as $Q = \lambda_c / \Delta\lambda$, are 7.3, 20.7, 32.7 and 43.9, respectively, where λ_c and $\Delta\lambda$ are the central resonance wavelength and FWHM.

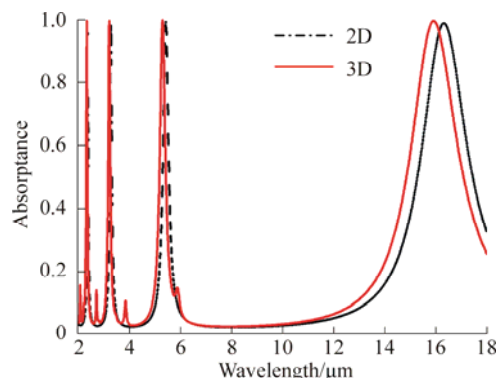


Fig. 2 Theoretical absorption spectra of the four-band absorber considering 2D and 3D models

Table 1 Detailed information about 2D absorption spectra

Wavelength/ μm	Absorptance	Q factor
$\lambda_1 = 16.27$	0.99	7.3
$\lambda_2 = 5.42$	0.99	20.7
$\lambda_3 = 3.27$	0.99	32.7
$\lambda_4 = 2.37$	0.99	43.9

3 Origin of four-band absorption

According to the effective medium theory^[17], the permittivity tensor of the proposed absorber could be calculated as: $\varepsilon_{xx} = \varepsilon_{yy} = f\varepsilon_{\text{Al}} + (1-f)\varepsilon_{\text{Ge}}$, $1/\varepsilon_{zz} = f/\varepsilon_{\text{Al}} + (1-f)/\varepsilon_{\text{Ge}}$, where f , the thickness filling ratio of the metal layer, is defined as $f = d_m / (d_m + d_d)$. The anisotropic effective permittivities were plotted in Fig. 3,

where the real parts of perpendicular and parallel components of the permittivity tensor are opposite in sign (i.e., $\varepsilon_{xx} = \varepsilon_{yy} < 0$ and $\varepsilon_{zz} > 0$), in accordance with the characteristic of HMMs (hyperbolic metamaterials)^[18]. Considering the HMMs as a waveguide, the waveguide modes were investigated by solving an eigenequation^[19]. As shown in the inset of Fig. 4, an HMMs waveguide is composed of a dielectric cladding ($\varepsilon_1 = 1$) and an anisotropic core layer ($\varepsilon_{xx} = -61 + 0.13i$, and $\varepsilon_{zz} = 18.37 + 0.009i$ at a wavelength of $3.8 \mu\text{m}$). The propagation constant β of even and odd TM modes can be obtained by solving the eigenequation, Eq. (1), as follows,

$$\varepsilon_{zz}\gamma_1 / (\varepsilon_1\gamma_2) = \tan(\gamma_2 w / 2), \text{ even modes}, \quad (1a)$$

$$\varepsilon_{zz}\gamma_1 / (\varepsilon_1\gamma_2) = -\cot(\gamma_2 w / 2), \text{ odd modes}, \quad (1b)$$

where $\gamma_1 = \sqrt{\beta^2 - k_0^2 \mu \varepsilon_1}$, $\gamma_2 = \sqrt{k_0^2 \mu \varepsilon_{zz} - \varepsilon_{zz} \beta^2 / \varepsilon_{xx}}$, with a vacuum wave vector $k_0 = 2\pi / \lambda$, the width of core layer w , and the permeability $\mu = 1$. Neglecting the imaginary part of the permittivity in solving Eq. (1) (i.e., $\varepsilon_{xx} = -61$, $\varepsilon_{zz} = 18.37$) for simplicity, the geometric dispersion curves of TM_0 , TM_1 , TM_2 , TM_3 , TM_4 , TM_5 and TM_6 modes were plotted, as shown in Fig. 4. The red dots that are tangent to the parallel lines to the y axis were considered as the degeneracy points^[20], where the group velocity is 0 and light is resonantly trapped in HMMs waveguides. For a certain of $w = 1.817 \mu\text{m}$, the resonant wavelengths of TM modes were determined to be 16.52 , 8.18 , 5.39 , 4.01 , 3.20 , 2.66 and $2.27 \mu\text{m}$. It was noted that the resonant wavelengths of the even modes, TM_0 , TM_2 , TM_4 and TM_6 , were in good agreement with those numerically simulated, as listed in Table 2, which suggested that the four-band near-perfect absorption originated from the excitation of the even TM modes. The cross-sectional electromagnetic field distributions at the four resonant wavelengths of near-perfect absorption are shown in Fig. 5. It was observed that the x -component of the electric field ($|\mathbf{E}_x|$) and the y -component of the magnetic field ($|\mathbf{H}_y|$) were mostly concentrated in the Ge layer with nodal distribution of alternating red and blue regions, which also verified that the origin of the four-band near-perfect absorption was due to the excitation of fundamental and

high orders of electromagnetic resonances. It was noted that the odd modes were not excited in the near-perfect absorber, which might result from the constraints from the structural symmetry. Once the symmetry was broken via amending the structure or incident angle, more resonances could be achieved.

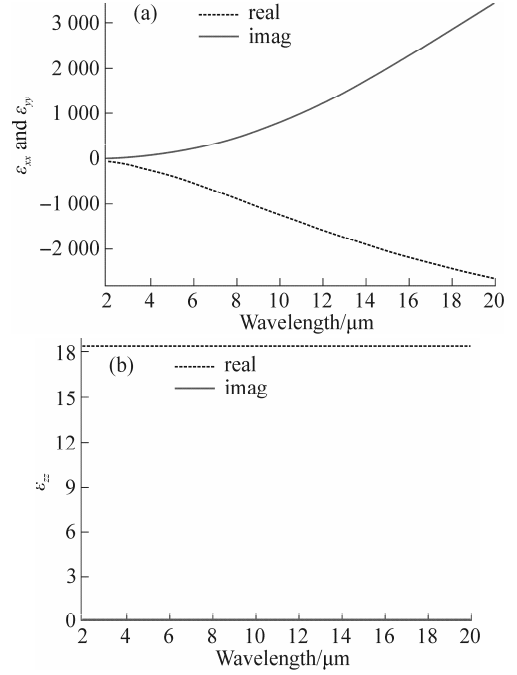


Fig.3 Effective permittivities of the Al and Ge stacking

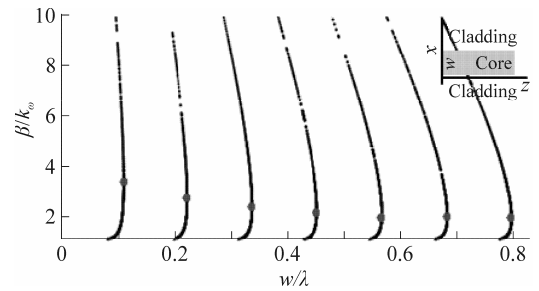


Fig. 4 Dependences of propagation constants of TM modes on the widths of anisotropic waveguides

Table 2 Comparison between the analytically and the numerically calculated resonant wavelengths

w/λ	$\lambda/\mu\text{m}$	Numerically simulated value/ μm
0.110	16.52	16.27
0.222	8.18	-
0.337	5.39	5.42
0.453	4.01	-
0.568	3.20	3.27
0.684	2.66	-
0.799	2.27	2.37

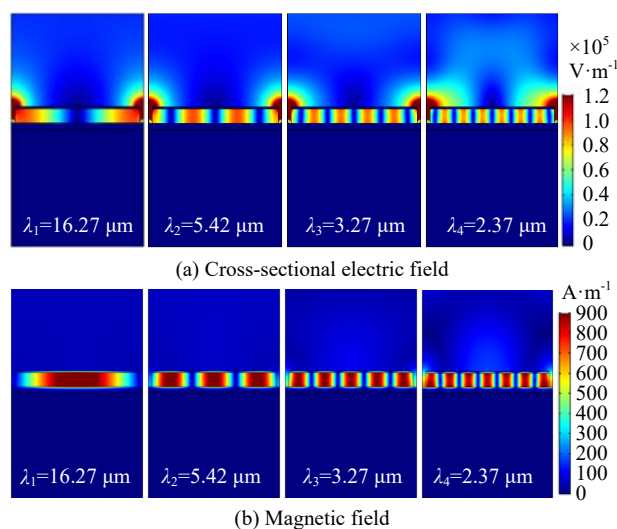


Fig. 5 Field distributions at the four resonant wavelengths of the near-perfect absorber

4 Sensing properties

Due to the high quality factors, the four-band near-perfect absorber would be sensitive to the change of environments. Accordingly, the sensitivity to the refractive index change was calculated, where the definition of sensitivity was $S = \Delta\lambda / \Delta n$. Herein, Δn is the refractive index change of analytes and $\Delta\lambda$ is the corresponding wavelength shift. The sensing properties are shown in Fig. 6, where the refractive index of analytes n increases from 1.0 to 1.8 at an interval of 0.1. The sensitivity at the resonant wavelengths of λ_1 , λ_2 , λ_3 are 3 119, 781, 512 nm per Refractive Index Unit, respectively.

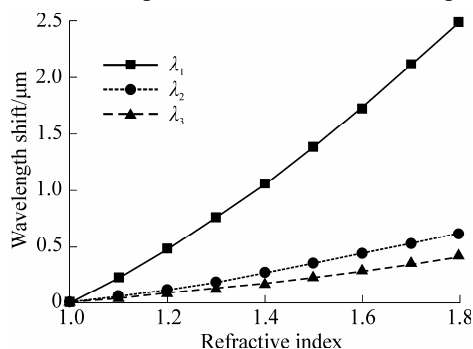


Fig. 6 Resonant wavelength shift as a function of environmental refractive indices at a fixed analyte thickness of 2 μm

Taking a certain environmental refractive index of $n=1.5$, the dependences of the resonant wavelengths on

thicknesses of analytes are shown in Fig. 7, where the wavelengths do not vary with the change of thicknesses at the studied range. It was noted that the highest order λ_4 was ruled out for sensing because it was susceptible to the appearance of analytes and the change of their thicknesses due to its adjacency to the diffraction wavelength.

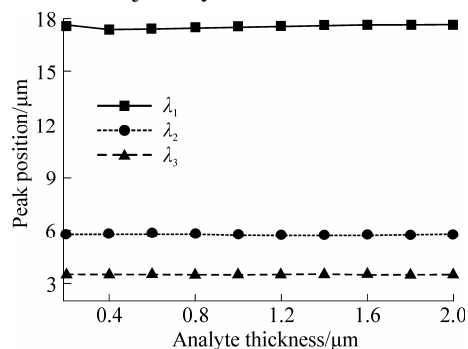


Fig. 7 Absorption peak position as a function of analyte thicknesses at a fixed refractive index of 1.5

5 Conclusions

In summary, a four-band near-perfect absorber was proposed without introducing multi-sized building blocks. Four absorption peaks, λ_1 , λ_2 , λ_3 and λ_4 , were located at 16.27, 5.42, 3.27 and 2.37 μm with the absorbance above 0.99. The origin of the four-band near-perfect was explained as a result of the excitation of even-order resonances in hyperbolic waveguides. Moreover, the absorber was sensitive to the change of environmental refractive index and showed the sensitivity of 3 119, 781 and 512 nm per Refractive Index Unit at λ_1 , λ_2 and λ_3 , respectively. The simple structure of the four-band near-perfect absorber suggested the ease and scalable fabrication, which would benefit the potential applications in sensing for not only the infrared, but also other electromagnetic wave region of interest.

References:

- [1] Veselago V G, Lebedev P N, Veselago V G. The electrodynamics of substances with simultaneously negative values of ϵ and μ [J]. Soviet Physics Uspekhi, 1968, 10(4): 509-514.
- [2] Shelby R A, Smith D R, Schultz S. Experimental

- verification of a negative index of refraction[J]. Science, 2001, 292(5514):77-79.
- [3] Schurig D, Mock J J, Justice B J, et al. Metamaterial electromagnetic cloak at microwave frequencies[J]. Science, 2006, 314(5801):977-980.
- [4] Pendry J B. Negative refraction makes a perfect lens[J]. Physical Review Letters, 2000, 85(18):3966-3969.
- [5] Landy N I, Sajuyigbe S, Mock J J. Perfect metamaterial absorber[J/OL]. Physical Review Letters, 2008, 100(20):207402 [2017-05-24]. <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.100.207402>.
- [6] Hao J, Wang J, Liu X, et al. High performance optical absorber based on a plasmonic metamaterial[J/OL]. Applied Physics Letters, 2010, 96(25):251104 [2017-09-17]. <https://doi.org/10.1063/1.3442904>.
- [7] Liu X, Starr T, Starr A F, et al. Infrared spatial and frequency selective metamaterial with near-unity absorbance [J/OL]. Physical Review Letters, 2010, 104(20):207403 [2017-05-24]. <https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.104.207403>.
- [8] Chen H T. Interference theory of metamaterial perfect absorbers[J]. Optics Express, 2012, 20(7):7165-7172.
- [9] Li W, Valentine J. Metamaterial perfect absorber based hot electron photodetection[J]. Nano Letters, 2012, 14(6):3510-3514.
- [10] Liu N, Mesch M, Weiss T, et al. Infrared perfect absorber and its application as plasmonic sensor[J]. Nano Letters, 2010, 10(7):2342-2348.
- [11] Li Z Z, Luo C Y, Yao G, et al. Design of a concise and dual-band tunable metamaterial absorber[J]. Chinese Optics Letters, 2016, 14(10):83-88.
- [12] Bai Y, Zhao L, Ju D, et al. Wide-angle, polarization-independent and dual-band infrared perfect absorber based on L-shaped metamaterial[J]. Optics Express, 2015, 23(7):8670-8680.
- [13] Wang B X, Wang G Z, Sang T. Simple design of novel triple-band terahertz metamaterial absorber for sensing application[J/OL]. Journal of Physics D: Applied Physics, 2016, 49(16):165307 [2017-08-09]. <http://iopscience.iop.org/article/10.1088/0022-3727/49/16/165307/pdf>.
- [14] Yu D, Liu P G, Dong Y F, et al. A sextuple-band ultra-thin metamaterial absorber with perfect absorption[J]. Optics Communications, 2017, 396:28-35.
- [15] Hu F F, Yi H X, Zhou Z P. Band-pass plasmonic slot filter with band selection and spectrally splitting capabilities[J]. Optics Express, 2011, 19(6):4848-4855.
- [16] Petschulat J, Helgert C, Steinert M, et al. Plasmonic modes of extreme subwavelength nanocavities[J]. Optics Letters, 2010, 35(16):2693-2695.
- [17] Choy T C, Effective Medium Theory: Principles and Applications[M]. Oxford: Oxford University Press, 1999: 148.
- [18] Narimanov E E, poddubny A, Iorsh I, et al. Hyperbolic metamaterials[J]. Nature Photonics, 2013, 7(12):948-957.
- [19] Hu H, Ji D, Zeng X, et al. Rainbow trapping in hyperbolic metamaterial waveguide[J/OL]. Scientific Reports, 2013, 3(2):1249 [2017-03-21]. <https://www.nature.com/articles/srep01249>.
- [20] Lu W T, Huang Y J, Casse B D F, et al. Storing light in active optical waveguides with single-negative materials [J/OL]. Applied Physics Letters, 2010, 96(21):211112 [2017-07-13]. <https://doi.org/10.1063/1.3431574>.

四带近完美吸收双曲超构材料

焦丽娜, 刘 琪, 吴万春, 徐 华*

(宁波大学 理学院, 浙江 宁波 315211)

摘要: 当前的多带近完美吸收通常是利用多层叠堆或多特征尺寸组合阵列结构来实现, 这给实验制备带来了一定的难度. 本文从理论上提出了吸收率高达 99% 的四窄带近完美吸收, 它是通过将单特征尺寸的金属和介电材料阵列置于金属衬底之上而构成. 其四带近完美吸收的机理可通过求解双曲超构材料的色散关系, 结合波导理论来解释. 此外, 由于这种多带近完美吸收具有高品质因子的特点, 对外界环境的变化较为敏感, 因而本文也就其在传感器方面的潜在应用进行了讨论.

关键词: 近完美吸收; 窄带; 双曲超构材料; 波导; 折射率传感

(责任编辑 韩 超)