Wide-angle broadband absorber based on one-dimensional metasurface in the visible region

Minhui Luo\textsuperscript{1,2}, Yun Zhou\textsuperscript{1,2*}, Shangliang Wu\textsuperscript{1,2}, and Linsen Chen\textsuperscript{1,2*}

\textsuperscript{1}College of Physics, Optoelectronics and Energy and Collaborative Innovation Center of Suzhou Nano Science and Technology, Soochow University, Suzhou 215006, China
\textsuperscript{2}Key Lab of Advanced Optical Manufacturing Technologies of Jiangsu Province and Key Lab of Modern Optical Technologies of Education Ministry of China, Soochow University, Suzhou 215006, China

Received July 4, 2017; accepted August 8, 2017; published online August 30, 2017

A broadband absorber based on a one-dimensional metasurface is designed and characterized numerically. In this absorber, the lossless dielectric in non-noble metal nickel (Ni) grating grooves is essential, which supports strongly the localized electromagnetic modes concentrated in the nanocavity formed between two metallic walls. A high absorbance from 380 to 760 nm for either TM or TE polarization is attained. In particular, a nearly perfect absorbance (over 99\%) is achieved at $\lambda = 450$ nm for TE polarization. Furthermore, the absorption in the visible region remains above 60\% at incident angles up to 45\° for the two polarizations. © 2017 The Japan Society of Applied Physics

Electromagnetic wave absorbers are of great interest for the communities of both material science and physics for many decades and have many applications including solar cells, plasmonic sensors, photodetectors, and thermal emitters. Since the first publication of near 100\% absorption in the terahertz region in 2008, near-perfect absorbers have also been demonstrated from frequencies in the gigahertz and terahertz regions down to the near-perfect absorbers have also been demonstrated from frequencies in the gigahertz and terahertz regions down to the frequencies of visible light. Various materials and structures have been developed to realize near-perfect absorption, including metasurfaces, multilayer structures, pyramids, and nanoparticles. In recent years, metasurface absorbers have attracted considerable interest. Under suitable conditions, absorption can be enhanced by the intrinsic electronic and magnetic resonances at a single band frequency, including surface plasmon resonance (SPR), cavity-mode resonance (CMR), magnetic resonance (MR) or hybrid resonance. However, in these absorbers, large amounts of incident light within a broad frequency range are reflected, thus limiting their applications. For instance, in solar cells, broadband absorption is necessary to harvest more energy. Many device architectures have been proposed to broaden the absorption band, for example, by mixing multiple resonators with resonances at different frequencies, exciting phase resonances to divide the absorption band into multiple subbands, or employing a tapered anisotropic metamaterial waveguide to stimulate light slowly. Mulla and Sabah have proposed a multiband metamaterial absorber based on plasmonic resonances with 98.2\% absorption at 445.85 THz and 99.4\% absorption between 624 and 658.3 THz. Lin et al. have reported three-layered structures consisting of a lossy dielectric grating on top of a low-loss dielectric layer and a substrate of the same lossy dielectric placed at the bottom, which lead to enhanced absorption over a broad frequency range for both TE and TM polarizations. To obtain a polarization-independent absorber, two-dimensional (2D) periodic structures, which always exhibit a fourfold rotational symmetry about the propagation axis, are proposed. Recently, a polarization-independent broadband absorber incorporating a one-dimensional (1D) metasurface has been demonstrated. Abass et al. proposed a complex dual-interface grating system to enhance absorption efficiency in thin-film silicon solar cells. Roszkiewicz presented an analysis of phenomena leading to high and broadband absorption by a structure composed of three elements: two 1D metal and dielectric diffraction gratings and a thick metal layer.

In this paper, we propose a broadband absorber in the visible regime based on a metallic substrate and a 1D subwavelength metal-dielectric grating, where grooves are filled with a dielectric material (SiO$_2$). The broadband absorption effect of this absorber for a visible region is investigated. Structure parameters are optimized by the rigorous-coupled-wave analysis (RCWA) method. The absorber exhibits near-perfect absorption at multiple wavelengths, which result in a high absorbance from 380 to 760 nm for either TM or TE polarization. To gain physical understanding of such a broadband absorption behavior, the electric field distributions at the resonance wavelengths are investigated. The principle of such a broadband absorption effect is attributed to the magnetic polaritons (MPs) and CMR in the nanocavity for TM and TE polarizations, respectively. Note that the absorption capability remains high with the incident angle varying from 0 to 60°. Compared with those metamaterial absorbers with a 2D array structure and 1D complex structures, the proposed absorber is efficient for both TM and TE polarizations caused by the excitation of resonant performance at the nanocavity.

Figure 1(a) presents the schematic of the proposed absorber and the propagation configuration of the incident electromagnetic wave. This structure is characterized by the grating period $p$, the grating thickness $h$ (equal to the SiO$_2$ layer thickness), and the ridge width $w$. In this structure, the thickness of the metallic substrate is large enough (more than the skin depth) to block the transmission. In the simulation, it is set to be 200 nm. The metal Ni is employed owing to its high melting point (1455 °C) for specific applications (e.g., solar thermal absorbers). The dielectric constant of Ni is fitted by the Drude–Lorentz model and the refraction index of SiO$_2$ is set to be 1.5. The TM- and TE-polarized lights are projected on the structure from the top air side at an angle of $\theta$.

Figure 2 shows the absorption spectra of the absorber at normal incidence, where $p = 260$ nm, $w = 65$ nm, and $h =$
300 nm. The red curve represents the absorption for the TM-polarized light at normal incidence, where peak $A_1$ is 95.45% at 415 nm and peak $A_2$ is 96.37% at 695 nm. The blue curve represents the absorption for the TE-polarized light at normal incidence, where peak $B_1$ is 99.41% at 450 nm and peak $B_2$ is 97.81% at 610 nm. As can be seen from Fig. 2, the two peaks in the spectral range result in a wide absorption spectrum. A strong absorption is observed over the whole visible regime for both TE and TM polarizations. The absorbance exceeds 65% in the wavelength range for the TM-polarized light, while that exceeds 75% in the wavelength range for the TE-polarized light. The inset of Fig. 2 shows the absorption spectra of our absorber for different polarization angles ranging from 0° to 90° at normal incidence. As the polarization angle increases, the absorption remains very high over the whole visible regime and further increases owing to the absorption mechanism that changes from the MPs to the CMR. Although the proposed design is a 1D structure, this broadband absorber is very robust to the polarization angle.

In order to understand the physical mechanism that gives rise to the broadband absorption for TM polarization, the total magnetic field distributions at peaks of 415 and 695 nm are shown in Fig. 3. Obviously, the magnetic field is mainly localized in the nanocavity formed by the sidewalls of grating ridges filled with SiO$_2$. The peak absorption is due to the excitation of MPs, which results in the incident photons trapped in the nanocavity. As shown in Figs. 3(a) and 3(b), the magnetic field is almost trapped in the periodic cavities and a set of evanescent orders is closely confined in the vicinity of the metal grating surface. Multilevel MPs are controlled by the height and length of grating grooves. The absorption spectrum at normal incidence, where $w = 130$ nm, is depicted in Fig. 4, the inset of which shows the magnetic field at 740 nm corresponding to the absorption peak. Obviously, the magnetic field is enhanced by reducing the length of the grating grooves.
In order to gain qualitative physical understanding of such broadband absorption effects for the TE-polarized light, the total magnetic field distributions at peaks of 450 and 610 nm are shown in Fig. 5. It is obvious that the electronic filed distributions are trapped in the nanocavity, which is attributed to the excitation of cavity modes (CMs). The resonance wavelength corresponding to an ideal cavity under the TE-polarized light is given as

$$\lambda_{\text{res}} = \frac{2\sqrt{\varepsilon}}{\sqrt{(m/a)^2 + (n/h)^2}},$$

where $\varepsilon$ is the dielectric constant of the nanocavity filler and $m$ and $n$ are both non-negative integers. In addition, $a$ and $h$ are the width and length of the nanocavity, respectively. Note that, since $a < h$ for the grating geometry, the first term on the right-hand side of Eq. (1) is the most relevant for the threshold to excite quasi-stationary states (standing waves). The electric field distribution in Fig. 5(a) is analogous to the CM with $m = n = 1$ and the estimated value of the TE$_{11}$-like mode is 473 nm, which is close to the simulated value of 450 nm. In addition, the electric field distribution in Fig. 5(b) is analogous to the CM with $m = 1$, $n = 0$, and the estimated value of the TE$_{10}$-like mode is 578 nm, which is close to the simulated value of 610 nm. Note that the slight error can result from the field penetrating into the side walls because the grating ridge width is smaller than the skin depth of Ni. The simulation results in Figs. 3 and 5 reveal that the absorption peaks of TM and TE polarizations are formed by the same parts of the 1D structure, and the high absorbance over a broad wavelength range results from the near-perfect absorption at multiple wavelengths.

The Poynting vector distributions at peaks $A_2$ and $B_1$ for TM and TE polarizations are shown in Figs. 6(a) and 6(b), respectively. The energy arrowhead indicated the direction of incident flow. As shown in Fig. 6(a), for the TM-polarized light, the fundamental TM mode guided between two metallic walls does not have a cutoff frequency, and the light can be squeezed into sizes much smaller than the wavelength, which is attributed to the excitation of MPs. Similarly, in Fig. 6(b), the enhanced energy is localized in the nanocavity; in this case, the CMR can be excited for high absorption. As we know, the bulk Ni layer can achieve broad absorption in the visible regime. Therefore, the roles of localized electromagnetic modes combined with the strongly attenuating properties of Ni lead to a strong absorption at these wavelengths.

The absorption spectra for the normally incident TM- and TE-polarized lights with different periods ($p$), duty cycles ($f$), and thicknesses ($h$) are shown in Fig. 7. For TM polarization, the MP resonance wavelength is almost not affected by the period ($p$) or duty cycle ($f$). When the thickness ($h$) is varied, multilevel MPs can be observed in Fig. 7(c), and their resonance wavelengths increase with $h$. For TE polarization, the bandwidth changes with increasing $p$ and $f$, as the position of the peak can be effectively adjusted by the width of the nanocavity. Multilevel CMs emerged when the thickness varies from 50 to 450 nm in Fig. 7(f). As the thickness ($h$) increases, the cavity mode inside the air nanocavity with different orders is excited. The larger the nanocavity height is, the higher order the cavity mode has.

In addition, the absorption spectra of the two polarizations versus the incident angle $\theta$ are shown in Fig. 8. The same geometric parameters as those in Fig. 2 are chosen. It is obvious that a high absorption capability can be maintained in the visible region with the incident angle varying from 0 to 45°. The absorption remains above 68% for TM polarization and above 60% for TE polarization at incident angles up to 45°. Thus, the absorber can work well within a wide incident angle for the two polarizations.

In conclusion, we have reported a wide-angle broadband absorber based on a 1D metasurface. Different strongly localized electromagnetic modes have been excited in an
identical nanocavity for two polarizations. High absorbances from 380 to 760 nm for both TM and TE polarizations are achieved. In particular, a nearly perfect absorbance (over 99%) is achieved at $\lambda = 450$ nm for TE polarization. The absorber still has a high absorption above 60% at incident angles up to 45° for the two polarizations. The absorber has great potential for harvesting solar energy as it can provide an excellent absorption capability in the visible regime. It is believed that the results may provide useful guidelines for the design of broadband absorbers with 1D metasurfaces.

Acknowledgments This work was supported by the National Natural Science Foundation of China (NSFC; Grant Nos. 61505134, 61575133, and 91023044), the NSFC Major Research Program on Nanomanufacturing (Grant No. 61575133), the Science and Technology Project of Suzhou (Grant Nos. ZXG201427 and ZXG2013040), and the project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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