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Titanium resonators based ultra-broadband perfect light absorber

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ABSTRACT

We propose a new approach for achieving ultra-broadband perfect absorber by using titanium (Ti) resonators. Near-unity absorption with a high average absorptivity of 91.4% is achieved through the whole spectral range from 0.4 μm to 2 μm for the double-period lattice of Ti resonators array on the top of a silica layer coated on the opaque Ti substrate. In contrast to the common metal-insulator-metal (MIM) absorbers only with tens of nanometers absorption bandwidth, the Ti based ultra-broadband perfect absorber (T-UPA) can show a perfect absorption window (*i.e.*, the absorptivity exceeding 90%) with the spectral bandwidth over 1007 nm from visible to near-infrared region (*i.e.*, from 0.485 μm to 1.492 μm). The cooperative effects of the propagating surface plasmons and the corresponding localized plasmonic resonances of Ti resonators contribute to the broadband absorption response. Moreover, the ultra-broadband perfect absorption is polarization-independent and angle-insensitive, which hold the proposed T-UPA with strong practicality and high tolerance in the complex electromagnetic environment (*i.e.* sun radiation). Furthermore, the absorption window for this T-UPA can be greatly broadened via using a thin anti-reflection coating film, which shows a perfect absorption with the bandwidth of 1555 nm in the visible and near-infrared range. The numerically demonstrated thin-film absorber configuration facilitates the scalability to optoelectronics applications such as thermal photovoltaics and hot-electron devices.

1. Introduction

Plasmonic perfect absorbers [1–3] have attracted significant interest due to their unique capability on light trapping at the sub-wavelength range and potential applications in solar energy harvesting and other optoelectronics such as photovoltaics and thermo-photovoltaics, thermal emitters and photo-detectors. Plasmonic meta-material absorbers formed by the metal-insulator-metal (MIM) triple-layer structure usually produced single resonant absorption peak according to the size scale [3,4]. Nevertheless, it is desired to achieve broadband perfect absorption for these potential applications. To date, numerous strategies have been proposed and demonstrated for the broadband absorption with metallic nanostructures. One of the typical ways is to combine two or more metallic sub-resonators in the resonant unit cell [5–8], which can therefore provide multiple resonant absorption peaks in the spectrum and eventually broaden the absorption bandwidth. The other main approach is to build the planar film stacks consisting of alternating metal-dielectric layers [9–12]. But the number of the blended resonators in the unit cell is limited due to the competition of the neighboring resonances. Especially, these broadband absorber schemes are with great difficult to control in fabrication.

Moreover, as for the previous perfect absorbers, noble metals such as Au and Ag were used as the plasmonic materials. These noble metals can produce strong plasmonic resonances but also introduce Joule heating during the perfect light absorption. The photo-thermal effect has been experimentally demonstrated for geometry reconfiguration [13]. That is, the conventional plasmonic absorbers formed by the common metals are with weak thermal stability, suggesting the low capability for high-power treatment process such as the nonlinear optics and all-optical switching.

Titanium (Ti) is the tenth for the elements with their geological reserves in earth. The reserve of Ti is even 61 times than that of the Cu. Otherwise, owing to its high mechanical stability and the relative low mass density, Ti has been widely used in aeronautics and astronautics fields as the cosmic and space metal. Moreover, Ti is an impressive refractory material, its melting point is up to 1668 °C. At the room temperature, Ti can be very stable even if the surrounding is filled by the strong acid and alkali or the chloroazotic acid. Currently, Ti and its composite materials have been explored with strong plasmonic resonant behaviors due to the large loss due to the imaginary part of the permittivity [14–16]. These features hold the Ti as a suitable material for plasmonic metal with the ability on high thermal and high-power operating process.

In this work, we choose the Ti to replace the common noble metals

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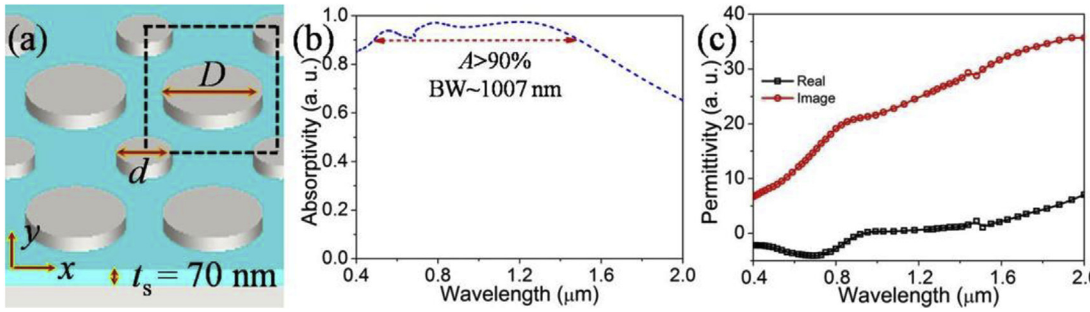

Fig. 1. (A) Schematic of the T-UPA, the middle dielectric film is with the thickness of 70 nm. (b) Spectrum of the T-UPA with a broadband absorption window with the bandwidth up to 1007 nm in the visible-near-infrared range. The dimensions are P = 400 nm, D = 300 nm, d = 170 nm, respectively. The thickness of the Ti disk t_d and the silica film thickness t_s are equal to 60 nm and 70 nm, respectively. (c) Dielectric permittivity for the Ti material in the wavelength range from 0.4 μm to 2 μm.

in the MIM absorbers by using its intrinsic plasmonic resonant features. With the design of two different Ti resonators in the unit cell, the absorption window is up to 1007 nm with the minimal absorptivity above 90% from the visible to near-infrared range. The maximal absorptivity reaches 97.5% for this 230-nm-thick Ti based ultra-broadband perfect absorber (T-UPA). In comparison with the obtained tens of nanometers for the absorption bandwidth for the common metal absorbers [3,4,17], the ultra-broadband absorption suggests a greatly broadened absorption bandwidth by this Ti resonators based absorber. The cooperative effects of the propagating surface plasmons and the localized plasmon resonances by the high loss Ti are the main contributions for the achieved ultra-broadband absorption.

2. Design and structures of the T-UPA

The schematic of the T-UPA is depicted in Fig. 1(a). The absorber is composed of periodic Ti disk-shape resonators array and a continuous Ti film, separated by a silica (SiO_2) suffer layer. The topmost Ti resonators array is formed by combining two different sizes disks into the unit cell and periodically distributed in both the x- and y-directions with the period of 400 nm. The other parameters of the disk resonators are D = 300 nm, d = 170 nm and the thickness of the Ti disk t_d = 60 nm. The silica film thickness t_s is optimized to be 70 nm. A Ti film with the thickness of 100 nm is used as the reflector substrate, which is thick enough to block all the transmission in the investigated wavelength range. Ti is explored to be with high loss due to its large imaginary part of the permittivity in the visible and near-infrared range, which therefore can produce broadband and efficient light absorption based on the combination of the enhanced field dissipation at both magnetic or non-magnetic resonances. As for this design of the T-UPA, the total thickness of the triple layer is only 230 nm, which is only half value to the operation wavelength. Additionally, Ti based absorber can pave the way for high-power or high-temperature applications. Overall, the ultra-broadband perfect absorber formed by the Ti material provides alternative ways for achieving broadband absorption with ultra-thin film structure and also presents an outstanding candidate for efficient energy-harvesting and photo-thermal related applications.

3. Results and discussion

Fig. 1(b) presents the absorption for the T-UPA. Three-dimensional finite-difference time-domain method has been employed for calculation [18]. In the simulations, we only model a single unit cell by applying the periodic boundary conditions on the vertical sides of the cell along the x- and y-directions. The incident light is assumed to be a plane wave propagating normal to the surface with the polarized electric field along the x-axis. In this Ti-SiO_2-Ti configuration, the permittivity of the Ti is described by the experimental data by Palik [19], while the SiO_2 is considered to be lossless with a constant refractive index n of 1.45. The medium above the absorber is chosen to be air. Perfectly matched layers are used along z-directions to cancel the potential scattering. It is observed that a perfect absorption ($A > 90\%$) window is achieved with ultra-wide wavelength range from 0.485 μm to 1.492 μm. This result confirms the realizable for broadband absorber by the refractory material. The absorption window is with times or order of magnitude to that of the common noble metals based MIM absorbers [3,4,7] or the multiple resonators combined absorbers [5,8] in the optical frequency range. The maximal absorptivity is up to 97.5% and the whole absorption average value also reaches 91.4% in the visible and near-infrared range (0.4 μm–2 μm). As shown in Fig. 1(c), in the whole spectral range, a relatively large imaginary part of the permittivity is observed for the Ti material [19], which indicates the noticeable intrinsic absorption loss by the refractory metals, similar to that of the conventional metals in the UV–visible range.

Absorption behaviors of the single size Ti resonators are studied. As shown in Fig. 2, the absorber (S-A) formed by the small disk (d = 170 nm) shows a broadband absorption at the shorter wavelength range. The near-perfect absorption with A above 90% is observed in a wide range from 0.417 μm to 0.943 μm, suggesting a 526 nm high absorption window. For the absorber (L-A) formed by the large disk (D = 300 nm), a high absorption ($A > 90\%$) window with the spectral bandwidth of 681 nm is observed in the near-infrared range. Moreover, another absorption peak is obtained in the visible range.

To real the physical mechanism in the proposed absorbers, we calculate the electric (E_x) and magnetic field (H_y) at the absorption peaks (λ_1, λ_2) and (λ_3, λ_4) for the S-A and L-A, respectively. For the S-A, as shown in Fig. 3(a), the electric field is observed in the both sides of the disk along the polarization direction. Moreover, partial electric field is observed in the areas between the adjacent disks. The magnetic field for the absorption peak (λ_1 = 0.549 μm) is mainly observed in the buffer SiO_2 layer at the position away from the Ti disks (Fig. 3(b)). These features are the main result of the plasmonic lattice resonance by the periodic array [20] and the dipolar plasmon resonance of the disk. At

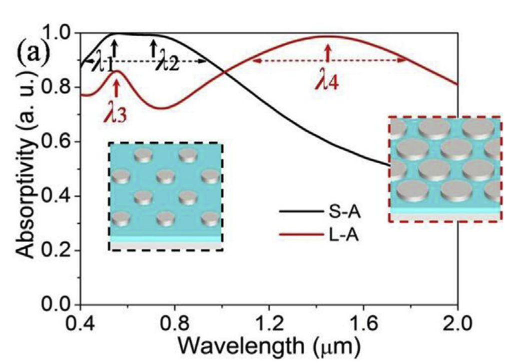

Fig. 2. Absorption curves for the single Ti resonators array.