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Dynamically switchable polarization-independent and broadband metasurface perfect absorber in the visible and near-infrared spectra regime

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ABSTRACT

An electrically tunable absorber in the visible (Vis) and near-infrared (NIR) regime is theoretically investigated. The absorber is composed of aluminum (Al)-indium tin oxide (ITO) composite square pillars on top of thin dielectric layer and Al substrate. Significant tuning of absorption with modulation ratio of 86% can be achieved. The modulation ratio above 75% can be maintained from 1427 to 1795 nm and over 90% absorbance at the NIR regime from 1500 to 1800 nm can also be achieved. The symmetry of the absorber eliminates the polarization dependence and the near unity absorption efficiency can be maintained by incidence angles up to 70°. The presented method will enhance the functionality of absorber and has the potential for the applications that require active control over light absorption.

Introduction

Absorption of electromagnetic (EM) radiation in nanostructures has concentrated considerable attention and efforts [1,2]. EM absorbers made of metamaterials (MMs) can have lots of potential applications because of their unique optical properties [3–6]. MMs that exhibit unity absorption at different frequencies have become known as "perfect absorbers" (PAs) [1,7–10]. Over the past few years, the literature has witnessed great activity in the theoretical and experimental studies devoted to the understanding and design of PAs. The recent work on PAs has been mainly focused on the use of metasurfaces (MSs) [11–14], examples include studies of the structure composed of periodic subwavelength resonant patterns and multilayers.

Currently, there is a great interest in developing tunable MSs by employing electro-optical materials, such as graphene [15–23], phase change materials (PCMs) [24,25], and transparent conductive oxides (TCOs) [26–29]. Among TCOs, indium tin oxide (ITO) has emerged as a technologically relevant material for controlling the phase and amplitude of EM wave [30,31], owing to the switching properties that can be achieved across a wide spectral range and the compatibility with current semiconductor fabrication techniques [32–34]. ITO can be easily combined with passive metallic components to create active building blocks for optoelectronic devices [35,36].

In this work, we propose a hybrid MS absorber (MSA) consists Al-ITO square arrays on top of Al substrate with a sandwiched aluminum oxide (Al_2O_3) spacer. It is demonstrated that electrical control over light absorption can be achieved by introducing ITO into plasmonic cavities. In the Vis range, a 52.4 nm spectral shift can be attained by applying a reasonable bias voltage to effect the color change. While in the NIR range, particularly large changes in the absorptance with modulation ratio $\Delta A/A = 86\%$ can be achieved. The modulation ratio above 75% can be maintained from 1427 to 1795 nm. The predicted change in absorption spectrum, transforming the device from perfectly absorbing to highly reflective, should make this method attractive from the engineering point of view.

Model and method

The active MSA employs ITO to realize an electrical control over light absorption. Fig. 1(a) shows a schematic of the proposed device in which the top layer is an array of Al-ITO nano-pillars, which are periodically arranged in both the *x*- and *y*-directions, the intermediate layers are an ITO thin film of 10 nm and an Al_2O_3 thin film of 5 nm, and the bottom layer is a continuous Al film of 200 nm. Fig. 1(b) exhibits the cross-section view of the structure in the *x*-*z* plane. A weak Fabry-Perot (FP) cavity can be formed between the Al reflector and Al square

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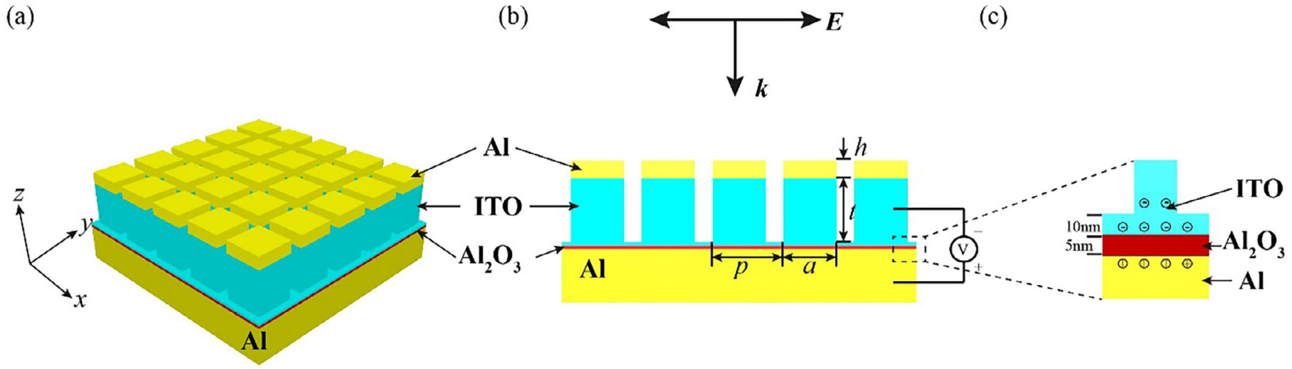

Fig. 1. (a) Schematic diagram and (b) cross-section view of the proposed PA. The height of Al arrays and ITO arrays are *h* and *t*, respectively. *a* represents the side length of ITO and Al array along both *x* and *y* directions. The period of array alone *x* and *y* direction both *p*. (c) Schematic diagram of ITO and Al_2O_3 substrate. The thickness of ITO and Al_2O_3 substrate is 5 nm, which between the ITO array and Al substrate.

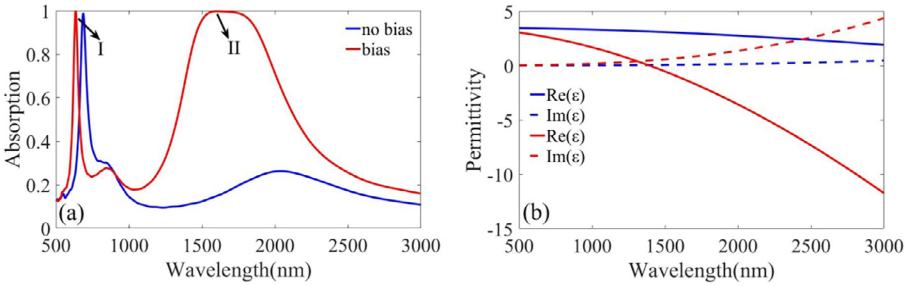

Fig. 2. (a). Total absorption at normal incidence for structure with and without bias. The geometrical parameters are chosen as t = 140 nm, h = 30 nm, a = 320 nm, and p = 400 nm. (b). Complex permittivity of ITO for the no-bias (blue line) and positive bias conditions (red line), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

arrays [37]. Al square pillar arrays cover the ITO square arrays and they have the same side length which marked as *a*. The height of Al and ITO pillar arrays are *h* and *t*, respectively. *p* represents the period of Al-ITO pillar array along both the *x* and *y* directions.

The interactions between the incident light and the designed MSA is investigated by utilizing the finite difference time domain (FDTD) method. The perfectly matched layer (PML) boundary condition is used for the boundary in *z*-direction, while periodic boundary condition (PBC) is employed along *x* and *y* directions. This option allows the periodic structure to be approximated to a single unit cell. In all simulations, the dimensions of mesh grids used are set as $\Delta x = \Delta y = \Delta z = 2\,\text{nm}$. The expected nanostructure is expected to be insensitive to light polarization due to the structural symmetry. Plane wave as a light source normally incidents to the array, while the electrical vector of plane wave is parallel to *x*-direction unless as otherwise noted.

The complex permittivity of ITO can be described by a Drude model, which is given by:

$$\epsilon = \epsilon_{inf} - \frac{\omega_p^2}{(\omega^2 + i\Gamma\omega)} \tag{1}$$

where $\omega_p = \sqrt{[ne/\epsilon_0\ m^*]}$, is a function of electron concentration *n*, we choose *n* as $7.5 \times 10^{19}\,\text{cm}^{-3}$, which is easy achieved by doping [38]. ϵ_{inf}, ω_p and Γ represent the permittivity at infinite frequency, plasma frequency and scattering frequency, respectively. *e* is the elementary charge, ϵ_0 defines the permittivity of free space. It is worth noting that the corresponding value of ω_p is 8.24×10^{14} rad/s and with this concentration, $\epsilon_{inf} = 3.49$ has been chosen in reasonable. The value of Γ is 1.8×10^{14} rad/s in order to effectively visualise the change of the mode index. m^* is the effective electron mass and equals $0.35\,m_0$, where m_0 is the electron mass in free space. The optical properties of Al are captured by a Drude model with $\varepsilon_{\text{inf}} = 2.1$, $\omega_{\text{p}} = 2.4 \times 10^{16}$ rad/s, and $\Gamma = 1.0 \times 10^{15}$ rad/s [39]. The dielectric permittivity value of Al_2O_3 from the experimental data by Palik [40] is used. As the bottom Al film is thicker than the penetration depth of the incident light, the incident light will be blocked and the transmission (*T*) of the structure is considered to be zero. Then absorbance $A(\omega)$ can be calculated by $A(\omega) = 1 - R(\omega)$, where $R(\omega)$ represents the reflectivity which can be obtained from the numerical calculation.

Results and discussions

One of the most inspiring aspects in developing active MSs is to realize the desired functions by configuring structures beyond their intrinsic properties [39]. Additional free electrons can be introduced in ITO pillar arrays to tune the total optical properties by shifting ω_{p}. An electrical bias is then applied between the ITO arrays and Al substrate to achieve this goal, as indicated in Fig. 1(b) and (c). ω_{p} is shifted to 2.55×10^{15} rad/s by increasing *n* to $7.1 \times 10^{20}\,\text{cm}^{-3}$ with a 3.5 V bias [40] that make ITO material optical property of permittivity close to zero, known as the epsilon-near-zero (ENZ) frequency, as show in Fig. 2(b). Since these structures are electrically separated by an insulating Al_2O_3 layer, additional free electrons are accumulated in ITO arrays and ITO substrate. This significant change in the optical properties of ITO paves the way for many potential applications in optoelectronic devices such as electrically tunable color filters and high resolution real-time displays [41]. The original geometrical parameters of the PA structure are assumed as $t = 140\,\text{nm}$, $h = 30\,\text{nm}$, $a = 320\,\text{nm}$, and $p = 400\,\text{nm}$. They will be used throughout the paper unless noted otherwise. Absorption spectra of the composite structure for no-bias (blue) and bias (red) cases is illustrated in Fig. 2(a). An obvious wavelength shift induced by voltage bias can be achieved. Dual absorption peaks can be observed under the condition of bias. One narrow absorption peak can be observed in the Vis range with the resonant wavelength of 635 nm, which marked as resonant mode I. The other broadband absorption peak is located in the NIR range, which marked as resonant mode II. It is amazing that over 97% absorption rate can be maintained within the wavelength range from 1500 to 1800 nm.

To reveal the underlying physical mechanism of the MSA, the electric field is quantitatively investigated. At the wavelength of