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Dielectric multilayer cavity coupled metamaterial

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Abstract. Dielectric multilayer stack metasurface is coupled with a gold mirror forming a hybrid metamaterial that targeting at multiband absorption. The resonant mechanisms responsible for each absorption band are explained in this study. Furthermore, a potential fabrication process has been proposed and demonstrated. This absorber exhibits flexibility in design and feasibility in fabrication, which makes it an excellent candidate for various applications, particularly in the field of sensing.

1 Introduction

Optical metamaterials (MMs) are artificial structures with unique optical properties that cannot be found in natural materials. Typically, MMs are constructed from sub-wavelength units, called "atoms", organized in a specific arrangement. By careful engineering, MMs can present unique properties such as negative refractive index, anomalous reflection/refraction, and super-resolution imaging across a wide range of wavelengths [1-4]. Due to the wide range of applications for optical MMs, the configuration and material selection for MMs can vary. Two of the families of MM are the metal-insulator-metal MMs (MIM-MM) and the all-dielectric MMs (DMM) with both advantages and inconvenient [5,6]. Therefore, combinations such as dielectric metasurface on metal [7] and dielectric film on metal mirror [8] are appealing to achieve more application functions. All-dielectric planar multilayer is a fundamental component to manipulate EM wave propagation. When alternating the layer property rather than using periodic structure, e.g., a planar microcavity, polariton splitting of intersubband transitions can be observed [9]. Moreover, when the top layer is truncated, optical surface modes (Bloch surface waves) can be excited, which later can be coupled into complex systems [10]. It enables wave and polarization manipulation with a minimum power absorption. In addition to the one-dimensional multilayer, metasurfaces are also demonstrated to exhibit extraordinary properties. They have been studied and applied in the field of nonlinear optics, ultrafast all-optical modulation, and scattering enhancement [11-13]. Integrating dielectric and plasmonic materials creates new opportunities for EM wave modulation [14].

In this study, we proposed a new approach to designing hybrid MM absorbers. Through rigorous three-dimensional finite element method (3D-FEM) simulation (performed with COMSOL Multiphysics) we unfold the behaviour and origin of its characteristic resonances. When excited, our proposed absorber can sustain three excitation modes dominated by electric or magnetic resonances. Moreover, a collective resonance within neighbouring DC blocks can be found. Due to such unique properties from the DC array, we demonstrate that each resonance can be tuned separately for more applications.

2 Results and Discussion

Fig. 1(a) is the 3D view of the absorber. The top active unit is a 5-layer all-dielectric cuboid cavity (DC) composed of a high refractive index material (titanium dioxide, TiO_2) and a low index material (silicon dioxide, SiO_2). The dielectric cavity array is coupled with a 150 nm-thick gold mirror by a 50 nm Al_2O_3 spacing layer. Fig.1(b) demonstrates the SEM image of the multilayer deposition, lithography, and etching process afterward. The selection of the materials in this study is optimized with our fabrication techniques. For example, the SiO_2, TiO_2 and Al_2O_3 can be deposited with identical conditions in our plasma-assist ALD system, which will avoid as much contamination as possible during the fabrication and reduce the fabrication time. Other than that, the SiO_2 and TiO_2 layers can be etched, again, with identical conditions in our plasma etching system. All processes are optimized so that the fabrication can be cost-effective and have consistence quality. Furthermore, all fabrication processes are compatible with large-scale manufacturing.

The optical responses of the MM absorber are shown in Figs. 1(c) and (d), and the input light is *s*-polarized normally incident from the top air-side. Three major resonances can be found at wavelengths λ_1=560 nm, λ_2=643 nm, and λ_3=718 nm. Most of the input power is dissipated in the Au layer since the imaginary permittivity of Au is larger than that of DC materials. It is also noticeable that at λ_3, the absorption is relatively low compared to the other situations. At the same time, the ratio between A_{Cavity} (absorption in cavities) and A_{Au}

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(absorption in the gold layer) is around 0.5 at λ_3. This is much higher than for the other two resonances. Fig.1(c) reveals the field mode at each eigenstate. Each resonance has its own distinct mode pattern where in λ_1 and λ_3, electric field confinement can be found in TiO_2 layers while the magnetic field is more profound in the cavity at λ_2. An intense electric field confinement in the gaps between adjacent cavities at λ_3, suggests a stronger collective effect contributing to the absorption than for the other cases. The three modes are coupled with the metal layer and the coupling is optimized by through the Al_2O_3 layer, making multiband absorption readily adjustable.

A key advantage of this all-dielectric metasurface configuration is its flexibility, which allows for the achievement of a wide range of optical functionalities by substituting different dielectric material pairs with varying refractive index contrasts. This enables the design of metasurfaces that can exhibit enhanced light absorption, efficient light coupling, and strong light-matter interactions. Furthermore, the geometrical parameters of the dielectric resonators can be easily adjusted to tune the spectral response of the absorber for specific applications, providing a simple and efficient way to achieve complex light-matter interactions. The inherent versatility of the all-dielectric metasurface allows the design of structures that can be integrated with other optical systems to expand its applications to optoelectronics, sensing, and information processing. Metasurfaces with multiple functionalities can enable devices tailored to specific applications, offering greater control over light-matter interactions. The impact of this approach could extend beyond the field of optics, with potential applications in fields such as nanotechnology and biomedicine.

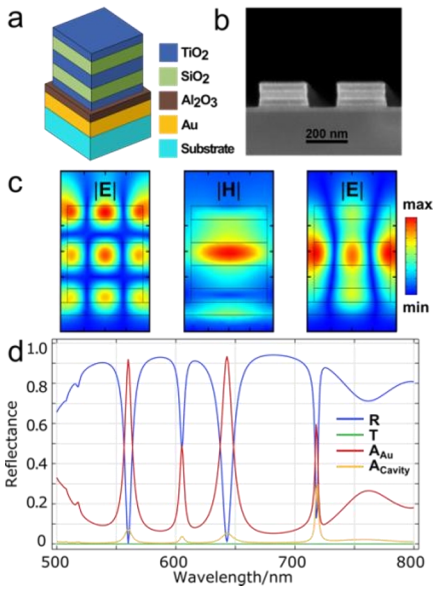

Fig. 1 (a) 3D view of the MM design, (b) SEM image of the etched structures, (c) major field distributions of the absorber at the three main resonant states (λ_1, λ_2, and λ_3), (d) reflection (*R*), transmission (*T*) and absorption (*A*) spectra.

The increasing need for integrated photonics components has led to research on combining different materials and structures to find suitable solutions for chip integration. Plasmonics has been seen as a key-enabling method, but its fabrication precision can be costly. In this work, we explore a hybrid solution that combines a flat metal surface with a dielectric cavity stack array, offering a promising way for better integration with relaxed fabrication. This unconventional approach has already demonstrated a wavelength-selective absorber and can be applied to numerous applications without increasing fabrication complexity. This concept bridges dielectric structures, such as photonic crystals, metallic structures, like plasmonics, and hybrid ones, such as metamaterials, without the limitations of patterning both metal and dielectric simultaneously.

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