Multi-Band Light-Matter Interaction in hBN-Based Metasurface Absorber

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***Abstract*—This paper presents a multi-band metamaterial-based absorber using phononic two-dimensional (2D) material. The structure consists of a top hexagonal boron nitride (hBN) layer on an aluminum nanograting structure deposited on a dielectric slab waveguide and a thick metallic reflector forming an MIM (metal-insulator-metal) configuration. The proposed absorber exhibits a hyperbolic phonon polariton (HPPs) in hBN, surface plasmon (SP) modes in the spacer (ZnTe: zinc telluride), and Fabry-Perot resonances in the MIM configuration, resulting in five sharp, high absorption peaks in the mid-infrared (MIR) spectral range. The proposed multi-band absorber can be utilized in various applications, ranging from optical detection devices to multispectral thermoelectric volt.**

***Index Terms*—Multi-band perfect absorbers, metasurfaces, plasmon-phonon polaritons, polar materials.**

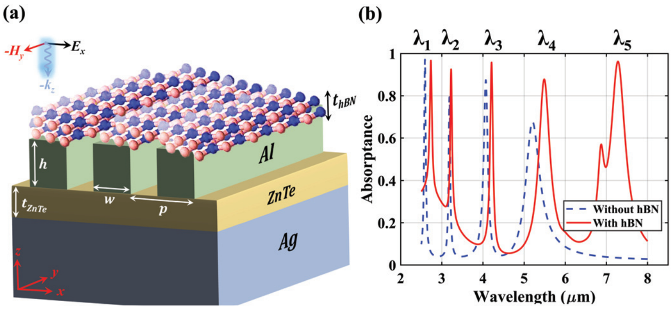

Fig. 1. (a) Schematic illustration of the proposed multi-band hBN-based metasurface absorber. (b) Spectral absorption responses of the proposed multi-band absorber with and without hBN topmost layer.

I. Introduction

Over the years, metamaterial-based designs have received considerable attention due to their advantages of controlling the propagation of electromagnetic (EM) waves. In the meantime, the development of tunable, multi-band, and broadband metamaterial-based absorbers within infrared (IR) wavelength ranges is crucial in various areas such as spectroscopy, thermal emitter, thermal cloaking, infrared detection, and sensor technologies [1]–[3]. Multi-band perfect metamaterial-based absorbers (PMA) are particularly promising as they are capable of achieving highly selective absorption at different resonance wavelengths. To obtain multi-band absorbers, different designs have been proposed in the literature. For example, by vertically stacking multi-layer subwavelength metal structures [4] or by combining resonators of different sizes or shapes [5], the multi-band characteristic is achieved at the cost of fabrication complexity. In contrast, other examples of multi-band absorbers with excellent absorption performance have been demonstrated using grating-based Fabry-Perot structure [6], utilizing two-dimensional plasmonic metasurface [7] coupled with an optical cavity [8], and coupling between localized plasmon modes in nanowire pairs with resonator modes of a microcavity, [9]. In addition, different perfect absorbers can be developed based on surface plasmon-polaritons (SPPs) or surface phonon-polaritons (SPhPs) resonances in gratings, magnetic polaritons (MPs) in MIM structures and deep metal gratings, and localized surface plasmon polaritons (LSPPs) in nanoparticles and nanoantennas. Recently, hybrid structures consisting of phononic two-dimensional (2D) materials and metasurfaces (2D form of metamaterials) have been widely used to create perfect absorption or multi-band absorption responses. Hexagonal boron nitride (hBN) is one of the phononic 2D materials having a very smooth surface and unique dielectric constant by two Reststrahlen bands with natural hyperbolic responses [10]. In [11], by coupling MPs in metal gratings with HPPs in hBN create hybrid hyperbolic phonon-plasmon polaritons which result perfect or near-perfect MIR absorption. To enhance interaction of optical phonon modes in hBN with plasmonic modes including the lattice and cavity modes a structure composed of gold (Au)-grating arrays fabricated onto a Fabry-Perot cavity (consist of hBN, Germanium, and Au back-reflector layer) is investigated in [12].

This paper proposes a multi-band absorber made of a polar material, hBN, on a MIM configuration (ZnTe sandwiched between top aluminum (Al) nanograting structur and bottom silver (Ag) layer). To the best of the authors' knowledge, the proposed multi-band absorber, which can provide five perfect or nearly perfect absorption by phononic 2D material, has not been reported before.

II. Design Procedure and Simulation Results

The geometric arrangement of the proposed multi-band absorber is shown in Fig. 1(a). The unit cell of the absorber consists of top hBN film on an Al grating deposited on top of a ZnTe spacer and Ag substrate. The dispersion of phonon polaritons in hBN due to optical phonon vibrations can exhibit the natural hyperbolic dispersion over the two mid-infrared (MIR) Reststrahlen bands, which makes the hBN films support multiple orders of low-loss HPP waveguide modes, and therefore, can be utilized to achieve perfect absorption [13]. Moreover, HPP waveguide modes in the hBN cannot be directly excited by the propagating waves from free-space since the transversal wavenumber of these modes is much larger than the photon wavenumber in free-space. A conventional way to match the wavevectors required by HPP resonance is placing the hBN film onto the deep metal grating, which supports a particular type of localized polariton resonance known as magnetic polaritons. The commercial Lumerical finite-difference time-domain (FDTD) software package is utilized to evaluate the optical performance of the proposed structure. These simulations are carried out in a two-dimensional (2D) environment when the structure is

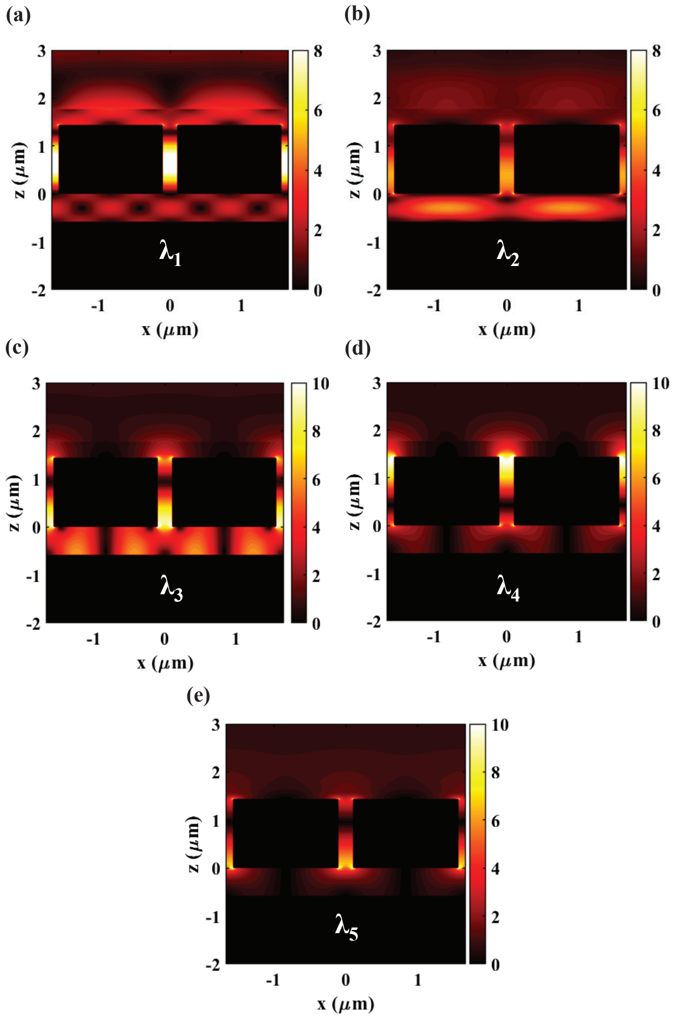

Fig. 2. Absolute values of the total electric-field distributions on the $x-z$ plane obtained for a two-unit cell at the resonance wavelengths of (a) $\lambda_1 = 2730$ nm, (b) $\lambda_2 = 3220$ nm, (c) $\lambda_3 = 4210$ nm, (d) $\lambda_4 = 5480$ nm and (e) $\lambda_5 = 7280$ nm.

normally illuminated by an $x-$ polarized uniform plane wave propagating along the $-z$ direction. The boundary conditions for the x and z directions are periodic and perfectly matched layers, respectively. In the simulations, the hBN permittivity is extracted from [12] and the permittivity of Ag and Al from the Johnson and Christy database [14]. The optimized parameters of the designed multi-band absorber are as follows: The Al grating period, height, and width are $p = 1660$ nm, $w = 1460$ nm, and $h = 1440$ nm. The thickness of the hBN layer is $t_{\text{hBN}} = 330$ nm, and the thickness of the ZnTe layer is set to be $t_{\text{ZnTe}} = 580$ nm. The spectral absorption responses of the absorber with respect to the wavelength with and without hBN are presented in Fig. 1 (b). This design shows five perfect or near-perfect absorptions at the resonance wavelengths of $\lambda_1 = 2730$ nm, $\lambda_2 = 3220$ nm, (c) $\lambda_3 = 4210$ nm, $\lambda_4 = 5480$ nm, and $\lambda_5 = 7280$ nm. It is observed that using hBN as a topmost layer strengthens the absorption of the fourth resonance while another resonance is excited (the fifth resonance). In order to provide insight into the resonating behavior of the proposed absorber, the absolute values of electric field distributions on the $x-z$ planes are extracted as shown in Fig. 2(a)–(e) at the resonance wavelengths. It can be seen from Fig. 2(a) that the electric-field distribution at the resonance wavelength of λ_1 is mostly concentrated within the groove and has characteristics similar to a Fabry-Perot resonance. From Figs. 2(b) and 2(c), it is observed that the electric-field distribution at the resonance wavelength of λ_2 and λ_3 are mostly concentrated within the spacer layer. The insulator layer of ZnTe between the top Al grating array and bottom silver layer makes the electromagnetic waves experience multiple reflections in the MIM structure and strengthen the absorptance at the plasmon resonance wavelengths when the phase-matching conditions are satisfied between the layers. The electric-field distribution of the fourth mode, λ_4, (Fig. 2(e)) shows simultaneous excitation of HPP mode in hBN and plasmon mode in Al-ZnTe interface. Therefore, the origin of λ_4 is due to the formation of both HPP and SP resonances. Finally, at the resonance wavelength of λ_5 (see Fig. 1(b)), the resonant phonon-polaritons in hBN contribute to the resonance phenomenon of the proposed structure.

III. Conclusion

In conclusion, we designed a hybrid structure and nearly perfect multi-band absorber based on phononic 2D material. Simultaneous excitation of HPPs, SP, and Fabry-Perot resonances lead to multi-band absorption characteristics in the MIR spectral range. In contrast to the other works, the proposed design is highly desirable in different types of optical detection equipment and has excellent absorption characteristics.

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