Metasurface Perfect Absorber Based on Guided Resonance of Hypercrystal

You-Chia Chang[1,2], Alexander V. Kildishev[3], Evgenii E. Narimanov[3] and Theodore B Norris[1,4]
[1]Center for Photonics and Multiscale Nanomaterials, University of Michigan, 2200 Bonisteel Blvd., Ann Arbor, Michigan 48109
[2]Department of Physics, University of Michigan, 450 Church St., Ann Arbor, Michigan 48109
[3]School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907
[4]Department of Electrical Engineering and Computer Science, University of Michigan, 1301 Beal Avenue, Ann Arbor, Michigan 48109
Author e-mail address: youchia@umich.edu

Abstract: We report a perfect absorber utilizing the guided resonance of a hypercrystal. Because a hypercrystal confines light to a deeply subwavelength thickness, it operates as a metasurface, providing the required surface conductivity for unity absorption.

OCIS codes: (160.3918) Metamaterials; (350.4238) Nanophotonics and photonic crystals

1. Introduction

Ultrathin perfect absorbers are of great interest to detector, stealth, and thermal emitter technologies. Thanks to recent progress in metamaterials and metasurfaces, many new design concepts have been introduced [1]. Here we report a new design for a perfect absorber based on the guided resonance of a hypercrystal. We show that a hypercrystal slab is able to confine light to a thickness much thinner than a wavelength, and therefore it can be treated as a metasurface. By incorporating the hypercrystal with a dielectric spacer and a back reflector, our numerical simulation demonstrates that an absorber with absorption close to unity can be realized.

Subwavelength light confinement can be achieved in a hyperbolic metamaterial (HMM) because it supports high-k modes. A hypercrystal is a periodic structure that includes a HMM as the constituent element. It has a period much smaller than a wavelength but much larger than the metamaterial limit, and therefore exploits the unique dispersion of HMM as well as the band formation from the periodicity [2]. In our design, we utilize the guided resonance of a hypercrystal slab, similar to the guided resonance of a photonic crystal [3], but the light confinement is achieved within a much smaller thickness. As the thickness of the hypercrystal slab is much smaller than a wavelength, it can be modeled as a metasurface, and the design rule for a metasurface perfect absorber, which looks for the critical coupling condition [4], can be applied directly to our hypercrystal-based absorber.

Compared to other realization of metasurface perfect absorbers, our hypercrystal-based metasurface perfect absorber does not rely on extremely localized resonances, and therefore avoids hot spots with extremely strong field. It can be used for applications requiring higher damage or saturation thresholds.

2. Guided resonance in the hypercrystal slab

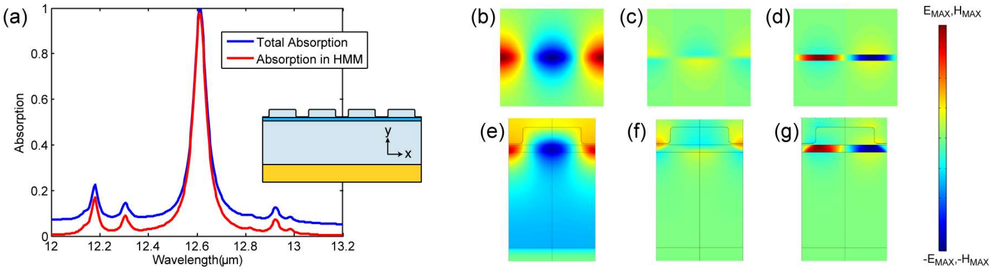

Fig. 1. (a) The absorption spectrum of the hypercrystal-based perfect absorber. The inset shows the geometry: the thickness of the HMM slab (light blue) is 50 nm. The dielectric grating (light grey) has a period of 590 nm and a duty cycle of 0.68. The heights of the dielectric grating is 120 nm (top of the grating to the dielectric/HMM interface) and 10 nm (valley to the dielectric/HMM interface). The thickness of the dielectric spacer (light grey) is 650 nm. (b-d) H_z, E_x and E_y of the counter-propagating TM_0 mode ($|b\rangle$ branch) in a waveguide of h-BN slab sandwiched by amorphous silicon at the wavelength of 12.61 μm [6]. (e-f) H_z, E_x and E_y of the hypercrystal-based perfect absorber simulated using FEM at the wavelength of 12.61 μm. In (b-g) E_x and E_y are plotted with a quarter cycle time delay relative to H_z.

The geometry of the hypercrystal-based perfect absorber is shown by the inset of Fig. 1(a). The perfect absorber consists of a hypercrystal slab that is formed by a subwavelength dielectric grating and a HMM slab, a dielectric spacer and a metallic back reflector. In this example, we choose the dielectric to be amorphous silicon (refractive index =3.74, lossless) for both the grating and the spacer. The HMM slab is made of hexagonal boron nitrite (h-BN), a natural type-I HMM at wavelengths between 12.1 and13.2μm [5]. The back reflector is made of Au. The dimensions are described in the figure caption. We use full-wave finite-element method (FEM) (COMSOL 5.1) to simulate this absorber. The absorption spectrum under TM excitation, demonstrated by Fig. 1 (a), clearly shows an total absorption of 99.6 % at 12.61 μm, and at resonance almost all the absorption is achieved within the very thin HMM slab (thickness ~ λ/252).

The physical origin of each peak can be identified. These peaks correspond to the guided resonances of the hypercrystal, and they are associated with the waveguide modes. The absorber is designed to achieve critical coupling for the TM_0 mode. Fig. 1 (b-d) show the analytic field distribution of a counter-propagating TM_0 mode of a waveguide of h-BN slab sandwiched by amorphous silicon [6]. Fig. 1 (e-g) show the FEM simulation results of electric and magnetic fields of the hypercrystal-based absorber at resonance. By comparing Fig. 1 (e-g) with (b-d), it is clear that the guided resonance of the hypercrystal slab originates from TM_0 waveguide mode in the HMM slab. It can be shown that other peaks in Fig. 1 (a) are associated with higher-order waveguide modes.

3. Design of the metasurface perfect absorber

Because the hypercrystal slab, formed by the dielectric grating and the HMM slab, has a thickness much smaller than the wavelength, it can be treated as a metasurface, and an effective surface conductivity can be defined for this metasurface. The effective surface conductivity can be extracted by performing simulations with the back reflector removed, and fitting the obtained reflection and transmission coefficients to the modified Fresnel equation $r_{12} = (n_1 - n_2 - \sigma Z_0)/(n_1 + n_2 + \sigma Z_0)$, $t_{12} = 2n_1/(n_1 + n_2 + \sigma Z_0)$, where n_1 and n_2 are the refractive indexes of air and amorphous silicon respectively [4]. σ is the effective surface conductivity of the metasurface. Z_0 is the vacuum impedance. Fig. 2 (a) shows the extracted effective surface conductivity, exhibiting a resonance behavior at 12.6μm.

The critical coupling condition for a metasurface absorber can be derived in the same way as calculating a Fabry-Perot resonator. The reflection coefficient of the whole absorber is given by [4]

$$r = \frac{r_{12}+(1+r_{12}+r_{21})r_{23}e^{i2\beta d}}{1-r_{21}r_{23}e^{i2\beta}}, \tag{1}$$

where r_{23} is the reflection coefficient of amorphous silicon/Au interface. β is the propagation constant in amorphous silicon. d is the thickness of the spacer. The critical coupling condition is satisfied when the numerator of Eq. (1) equals to zero. This condition can guide design the hypercrystal for providing the required surface conductivity.

We can verify that treating the hypercrystal slab as a metasurface is appropriate near resonance. Fig. 2 (b) shows the full-wave simulation of the absorption spectra for different spacer thicknesses. The absorption can also be calculated semi-analytically using the modified Fresnel equation and Eq. (1) together with the extracted effective surface conductivity shown in Fig. 2 (a). The semi-analytical calculation of the absorption is also plotted in Fig. 2 (b), which reproduces well the full-wave simulation. This verifies our understanding of the mechanism of the perfect absorber, in which the hypercrystal works as a metasurface to provide the appropriate surface conductivity for critical coupling.

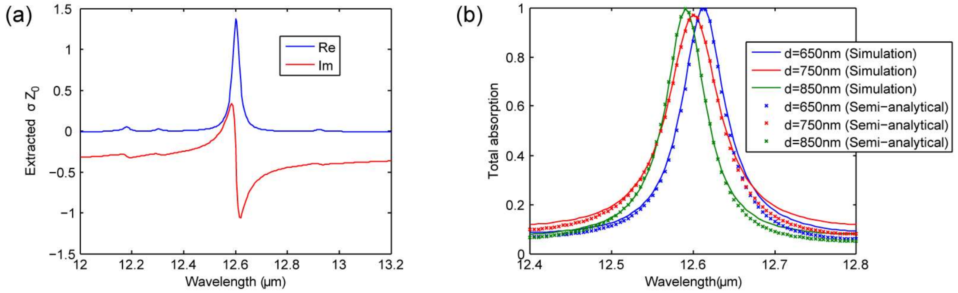

Fig. 2. (a) Real and imaginary parts of σZ_0 extracted from fitting the reflection and transmission coefficients obtained by FEM simulation. (b) The absorption spectra of the hypercrystal-based absorber for different spacer thicknesses. Both the results obtained from full-wave FEM simulation and semi-analytical calculation are plotted for comparison.

4. References

[1] Y. Ra'di, C. R. Simovski and S. A. Tretyakov, "Thin perfect absorbers for electromagnetic waves: theory, design, and realizations," Phys. Rev. Applied **3,** 037001 (2015).

[2] E. E. Narimanov, "Photonic hypercrystals," Phys. Rev. X **4,** 041014 (2014).

[3] J. Piper and S. Fan, “Total absorption in a graphene monolayer in the optical regime by critical coupling with a photonic crystal guided resonance,” ACS Photon. **1,** 347-353 (2014).

[4] Y. Yao, R..Shankar, M. A. Kats, Y. Song, J. Kong, M. Loncar and F. Capasso, "Electrically tunable metasurface perfect absorbers for ultrathin mid-infrared optical modulators," Nano Lett. **14,** 6526-6532 (2014).

[5] J. D. Caldwell *et al.* "Sub-diffractional volume-confined polaritons in the natural hyperbolic material hexagonal boron nitride," Nat. Commun. **5,** 5221 (2014).

[6] H. Hu, D. Ji, X. Zeng, K. Liu, and Q. Gan, “Rainbow trapping in hyperbolic metamaterial waveguide,” Sci. Rep. **3,** 1249 (2013).

The authors acknowledge financial support by the NSF Materials Research Science and Engineering Center (MRSEC) program (DMR 1120923) and the Air Force Office of Scientific Research MURI grant (FA9550-12-1-0389).