Perfect electromagnetic absorbers from microwave to optical

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Metamaterials made of an electric resonator plus ground plane absorb light across four decades of frequency and may lead to novel applications such as compressive imaging and energy harvesting.

Metamaterials are fashioned from arrays of shaped conducting patterns and are able to exhibit great control over electromagnetic waves. This power stems from their ability to independently tailor both the electric and magnetic response and has led to many rapidly expanding areas of research, one of which is the metamaterial perfect absorber (MPA). MPAs are able to efficiently absorb electromagnetic radiation with negligible reflection and zero transmission. They are highly desired for frequencies above the microwave regime,1 and may lead to novel spatial light modulators.

Traditional absorbers, such as the Jaumann absorber and Salisbury screen, are comprised of one or more resistive sheets mounted one-quarter wavelength in front of a ground plane.2 However, this configuration leads to thick and heavy absorbers, especially for longer wavelengths. The first MPA was reported at microwave frequencies using a multilayer structure that sandwiched a thin layer of dielectric between an electric ring resonator and a cut wire.3 This MPA has a thickness 1/40th of the operating free space wavelength and is thus approximately an order of magnitude thinner than the conventional absorbers mentioned above. It realized an experimental absorption of 88%, even though simulation indicated near-unity absorption should be possible. More recently we have achieved an experimental absorption of 99.9% at 18GHz.4

Metamaterials scale with Maxwell’s equations, i.e., demonstrated designs at microwave frequencies are readily extended to higher frequencies (shorter wavelengths) by simply making them smaller. Thus in principle it should be trivial to scale MPAs to the terahertz (THz), IR, and optical regimes. However, several factors must be considered. The dielectric constant of materials may be quite different in the IR from that at lower frequencies. For example, IR phonons yield a strong frequency dispersion of the permittivity, and most organic materials have intrinsic absorption bands in the mid-IR range. In addition to variations in dielectric properties, metals have scattering frequencies of approximately 10THz, above which the conductivity falls off as one over the frequency squared. Perhaps most importantly, metals typically have plasma frequencies in the optical and UV, at which they become transparent. Many efforts have been made to push the operational range to higher frequencies.5–7 Together with collaborators, we have fabricated and characterized the absorption of several MPAs across the electromagnetic spectrum ranging from microwave to optical (see Figure 1).5–7

Figure 1. Experimental absorption of several MPAs that operate across a wide electromagnetic spectrum ranging from microwave to optical.

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Figure 2. Design and fabrication of the MPA. (a) Schematic of a MPA unit cell. (b) Scanning electron microscope (SEM) image of a periodically patterned array. (c) Simulated reflection, transmission and comparison between simulated and experimental absorption. The dashed gray curve for experimental absorption is replotted from Figure 1 (green curve).

Despite the differences in material properties across such a large range of the electromagnetic spectrum (four orders of magnitude in frequency), we used a similar design concept for each of the MPAs shown in Figure 1. For example, in order to obtain unity absorption, a condition of simultaneous zero reflection and zero transmission must be achieved. Impedance-matching to free space will result in zero reflection, while a ground plane thicker than the penetration depth guarantees no transmission. We have developed an MPA design which consists of three layers including a ‘cross’ resonator (gold), a ground plane (gold), and a layer of dielectric material (aluminum oxide, Al$_2$O$_3$) in between: see Figure 2(a). The cross resonator responds to the electric component of light, while interactions between the cross and ground plane permit coupling to the magnetic component. Thus the permittivity $\epsilon(\omega)$ and permeability $\mu(\omega)$ may be tuned independently to achieve an impedance-matching condition.

Figure 3. Experimental three-dimensional image of spatially dependent absorption of the MPA at a wavelength of 6$\mu$m.

We simulated the MPA structure presented in Figure 2(a) using a finite-difference time-domain program and obtained optimized dimensions of $a=2\mu$m, $l=1.7\mu$m, and $w=0.4\mu$m. The thickness of both gold layers is 100nm and the thickness of the Al$_2$O$_3$ layer is 185nm. We fabricated the sample using standard e-beam lithography and characterized it with an IR-microscope. A scanning electron microscope image of a periodically patterned array of the fabricated sample is shown in Figure 2(b). Our simulated reflection, transmission and absorption curves, and the measured absorption are shown in Figure 2(c). Our experimental results agree well with numerical simulations. The IR MPA (Figure 1, green curve) achieved an absorption of 97% at a wavelength of 6$\mu$m.

We used the IR MPA ($6\mu$m) to demonstrate the ability of metamaterials to act as spatial light modulators. We paired the MPA with another unit cell that achieved near-zero absorption to form a spatial pattern with the two letters ‘B’ and ‘C’. We acquired a hyperspectral image of the spatially modulated metamaterial absorber by taking frequency-dependent reflection and transmission spectra in small steps across the sample area and plotted the absorption as a function of spatial dimension at 6$\mu$m wavelength (see Figure 3). It is clear that the absorption is near unity for MPA unit cells and nearly zero elsewhere.
In summary, we have presented metamaterials that offer near unity absorption across four orders of magnitude in frequency. We have designed, fabricated, and characterized an infrared spatial- and frequency-selective MPA, which may lead to many potential applications, such as spatial light modulators for compressive imaging and data storage. The next step in our research involves using MPAs as structures for tailoring the emissivity of substances. This may find use in thermophotovoltaic devices for energy harvesting.

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Willie Padilla is an associate professor of physics at Boston College. Currently, his research interests involve the terahertz, infrared, and optical properties of metamaterials.

References