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Terahertz antireflection coatings using metamaterials

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Abstract

We demonstrate terahertz metamaterial antireflection coatings (ARCs) that significantly reduce the reflection and enhance the transmission at an interface of dielectric media. They are able to operate over a wide range of incidence angles for both TM and TE polarizations. Experiments and finite-element simulations will be presented and discussed.

1. Introduction

When propagating electromagnetic waves encounter an interface of two dielectric media with different refractive indices, reflection and refraction coexist. In many applications, reflection is undesirable and causes, for example, insertion losses, and therefore antireflection coatings (ARCs) are required to eliminate or reduce the reflection. ARCs are of additional importance when considering the generally low power in many far infrared or terahertz (THz) systems. Single or multiple layered dielectric films have long been the solution in the optical regime. Single layered quarter-wave antireflection coatings require a coating refractive index matching and a quarter wavelength thickness. This approach is scalable over a wide spectral range, but it is limited by natural material properties. Additionally, it is often quite challenging to deposit the relatively thick films required for long wavelengths with high quality.

Metamaterials with independently tailored effective permittivity ϵ and permeability μ make it possible to match impedances of two different media and thereby to alleviate the non-availability of natural materials with the required index of refraction. But so far the general concept of metamaterials still suffers from high loss. Three-dimensional fabrication is another challenge. Here we present a novel approach of planar metamaterial ARCs on dielectric surfaces, which significantly reduce the reflection and enhance the transmission over a wide range of incidence angles at any specified wavelength from microwave to mid-infrared.

2. Experiments and results

The THz metamaterial ARCs consist of an array of gold electric split-ring resonators (SRRs) and a gold mesh patterned using conventional photolithography methods, and separated by a spacer layer of spin-coated and thermally cured $\sim$10 μm thick polyimide with dielectric constant $\sim$3.5 [1]. The 1 cm $\times$ 1 cm coating was fabricated on an intrinsic gallium arsenide (GaAs) substrate, with a unit cell schematically shown in Fig. 1(a), where the width of the metal lines is 4 μm, and the SRRs have outer dimensions of 36 μm, 4 μm gaps, and 46 μm periodicity. The metamaterial ARCs were characterized at various incidence angles through reflection and transmission measurements using a fiber-coupled THz time-domain spectrometer. Measurements were performed for both transverse magnetic (TM) and transverse electric (TE) incident waves.

Fig. 1(b) shows the experimental results of reflectance and transmittance under normal incidence to the metamaterial coated GaAs surface, which yield a reflectance minimum of 0.32% and a transmittance maximum of 90% near 1.2 THz, in contrast to 32% reflectance and 68% transmittance for a bare GaAs surface. Without any optimization yet the enhancement of transmission is already remarkable. It is also worthy of mention that no antireflection was observed when the positions of SRR and mesh were reversed. Figs. 1(c) and (d) show the measured reflectance with incident angles 20°, 40° and 60°, for TE and TM polarizations, respectively. For TE polarization, the reflectance monotonically increases from 0.5% at 20° to $\sim 10\%$ at 60° at the designed antireflection frequency; for TM polarization, it decreases first to zero reflectance and then increases with incident angles, with the reflectance less than 1% within the whole measured angle range. The angular dependent reflectance is shown in the inset to Fig. 1(d).

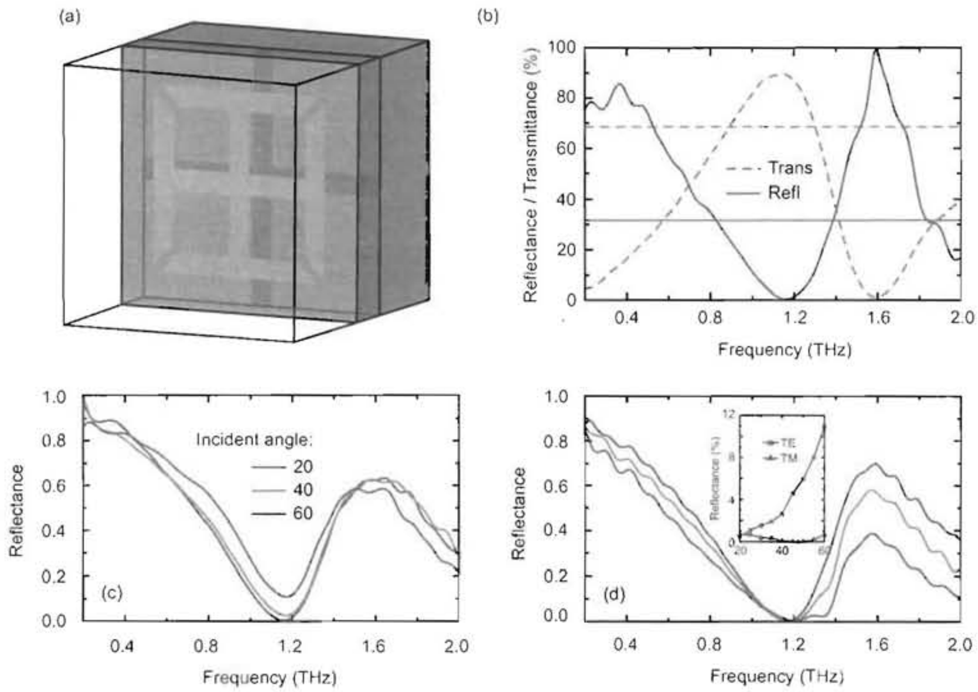

Fig. 1: (a) Unit cell schematic of the metamaterial antireflection coating. (b) Experimentally measured reflectance and transmittance with the gray lines for uncoated GaAs substrate. (c) and (d) Angular dependent reflectance for TE and TM polarizations, respectively. Inset to (d): reflectance as a function of incidence angle at antireflection frequency.

3. Numerical simulations

Unit cell shown in Fig. 1(a) was used in the finite-element numerical simulations using CST Studio Suite with appropriate boundary conditions. We have assumed lossless substrates with a dielectric constant of $\epsilon_s = 12.7$. The simulations resulted in complex S-parameters, from which we obtain the frequency dependent reflectance $R = |S_{11}|^2$ and transmittance $T = |S_{21}|^2$. We observe the reflection and transmission properties by sweeping a few parameters including the spacer dielectric constant and loss tangent, spacer thickness, and incident angle for both TM and TE polarizations.

Fig.2(a) shows the simulated spacer thickness dependent reflectance and transmittance, with the spacer dielectric constant of 4.0, loss tangent of 0.02, and the default gold conductivity of 4.5×10^7 S/m. There is an optimized thickness where the reflectance reaches zero. It was also found that for any value of the spacer dielectric constant, even larger than that of the substrate, there is always a spacer thickness where zero reflectance can be achieved. Figs. 2(b) and (c) show the angular dependent reflectance for TM and TE polarizations, respectively, at the optimized spacer thickness. We found that the overall reflectance is different, however, at the designed antireflection frequency they have almost identical angular dependence shown in Fig. 2(d). When the spacer thickness is smaller than the optimized value, the antireflection performance at the designed frequency for TE and TM polarizations will be different and is shown in Fig. 2(e), which is consistent with our experimental results shown in the inset to Fig. 1(d), and indicates that the spacer thickness of our fabricated metamaterial ARC is a little too thin. For the spacer thicknesses larger than the optimized value, the behavior shown in Fig. 2(e) will be reversed for TE and TM polarizations.

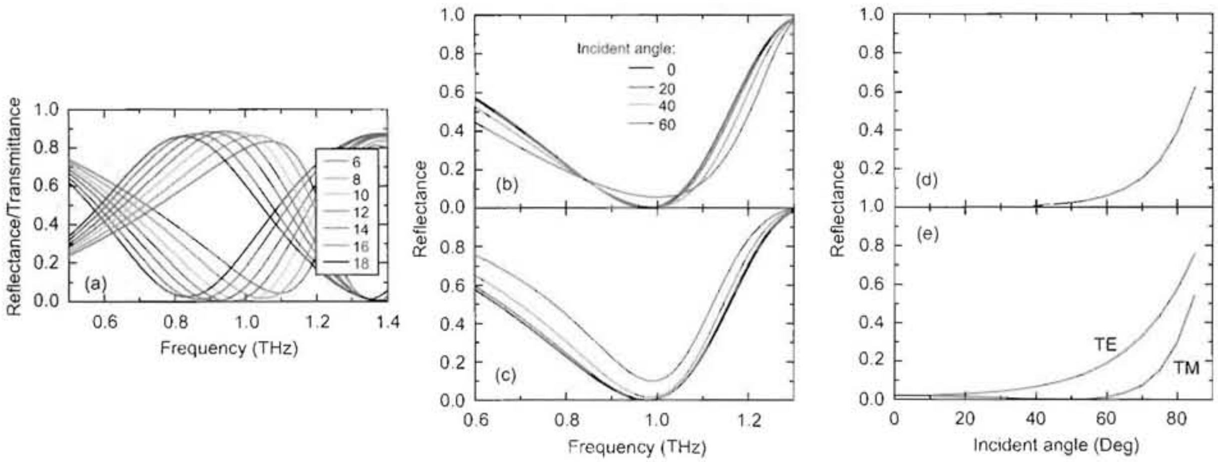

Fig. 2: (a) Simulated spacer thickness dependent reflectance and transmittance. Units for the spacer thickness: μm. (b) and (c) Angular dependent reflectance for TM and TE polarizations, respectively, at the optimized spacer thickness. (d) Identical antireflection behavior for TM and TE polarizations at the designed frequency when the spacer thickness is optimized. (e) Different antireflection behavior for TM and TE polarizations when the spacer thickness is less than the optimized value.

4. Conclusion

In summary, we have demonstrated a novel approach of antireflection coatings using planar metamaterials. The experimental results reveals extremely small reflectance and significantly enhanced transmittance for a coated high index substrate over a wide range of incident angles. This approach alleviates the strict requirements of coating materials and reduce the overall coating thickness. Numerical simulations show that the antireflection could be polarization independent when the spacer thickness is optimized. The antireflection coating can be explained by a simple model based on multiple reflection interference from the coating [2].

References

[1] H. Tao, N. I. Landy, C. M. Bingham, X. Zhang, R. D. Averitt, and W. J. Padilla, A metamaterial absorber for the terahertz regime: Design, fabrication and characterization, *Opt. Express*, vol. 16, p.7181, 2008.

[2] H.-T. Chen, J. Zhou, J. F. O'Hara, F. Chen, A. K. Azad, and A. J. Taylor, Antireflection coating using planar metamaterials, arXiv:1002.2305v1, 2010.