LA-UR- 10-00552

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Intended for: Photonic Metamaterials and Plasmonics (META) 2010

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A Novel Approach of Antireflection Coating Using Planar Metamaterials

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Abstract: We experimentally demonstrate a novel antireflection coating using planar metamaterials. It dramatically reduces the reflectance and enhances the transmittance over a wide range of incidence angles for both polarizations near the designed wavelength.

OCIS codes: (310.1210) Antireflection coatings; (310.1620) Interference coatings; (160.3918) Metamaterials; (300.6495) Spectroscopy, terahertz

1. Introduction

When propagating light encounters an interface of two dielectric media with different refractive indices, some portion of energy is reflected back and the rest transmits through. This well-known phenomenon is the basis of numerous optical technologies and is described by Snell's law and Fresnel equations. In many photonic applications however, reflection is undesirable and causes, for example, insertion losses or Fabry-Pérot fringes. Antireflection is of additional importance when considering the generally low power in many far infrared or terahertz (THz) systems. Antireflection coatings using single or multiple layered dielectric films have been long time the solution in the optical regime. Single layered quarter-wave antireflection coatings require a coating refractive index matching and a quarter wavelength thickness. Good performance is typically limited to a small range of incidence angles and a narrow bandwidth. This approach is scalable over a wide spectral range, but it is limited by natural material properties. For example, in the THz and microwave bands materials such as semiconductors and ferroelectrics often have large refractive indices, which make it difficult to find appropriate coating materials that satisfy the index-matching requirement. Furthermore, it is often quite challenging to fabricate 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 planar metamaterial antireflection coating on dielectric surfaces that dramatically reduces the reflectance and enhances the transmittance over a wide range of incidence angles at any specified wavelength from microwave to mid-infrared. The proof of concept is experimentally demonstrated in the THz frequency range.

2. Experiments

The THz metamaterial antireflection coating consists of an array of gold electric split-ring resonators (SRRs) [1] and a gold mesh [2] patterned using conventional photolithography methods, and separated by a spacer layer of spin-coated and thermally cured polyimide (dielectric constant ~3.5) [3,4]. The 1 cm × 1 cm coating was fabricated on an intrinsic gallium arsenide (GaAs) substrate, with a unit cell schematically shown in Fig. 1(a). The four-fold symmetric design makes it polarization insensitive under normal incidence. In this design, 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 polyimide spacer thickness is expected to be about 13 μm. The metamaterial antireflection coating was characterized at various incidence angles through reflection and transmission measurements using a fiber-coupled THz time-domain spectrometer [5]. Measurements were performed with both TM (transverse magnetic) and TE (transverse electric) incident waves.

3. Results and discussions

Since our THz system cannot directly measure the normal reflectance, it was determined by taking the advantage of echo pulses in the transmitted time-domain data. Echo pulses are generated by multiple reflections of the impulsive THz radiation between the two reflecting GaAs surfaces (with the front surface coated). As a result, the echoes measure the reflectance of THz radiation that is incident on the coating from the GaAs side. Figure 1(b) shows a reflectance minimum of 0.5% at 1.16 THz. The normal transmittance was also measured, from which we obtained a transmittance maximum of 84% as compared to 68% through a bare air-GaAs interface. It is worth mentioning that the antireflection frequency is not far from the resonance frequency of the split-ring resonators resulting in the appreciable loss of ~16%, caused by both the metal and dielectric dissipation. Although we cannot substantially address metal losses, alternative lower loss dielectric spacer materials and redesigned non-resonant metamaterial structures should be able to further reduce loss and improve the transmittance.

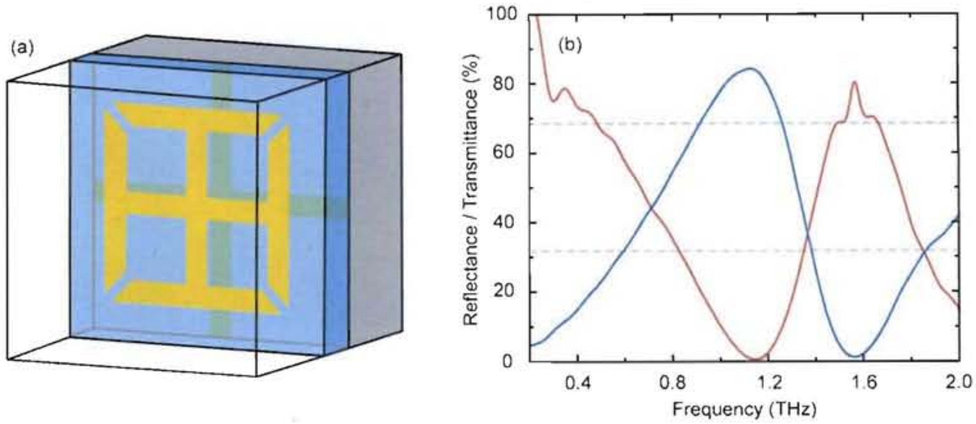

Fig. 1 (a) Schematic design of the metamaterial antireflection coating. From front to back: air, SRR, spacer, mesh, and substrate. (b) Experimental reflectance (red curve) and transmittance (blue curve) under normal incidence. The dashed gray lines are the expected THz reflectance and transmittance of a bare GaAs surface.

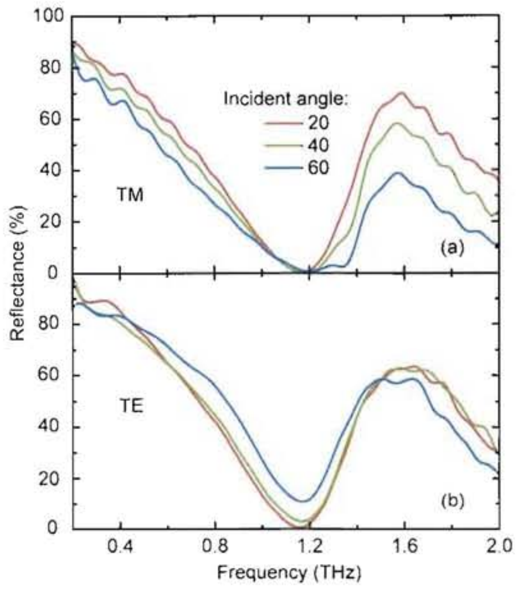

Fig. 2 Experimental results of reflectance from the metamaterial-coated GaAs surface with (a) TM and (b) TE polarized incident THz radiation, respectively, at various incidence angles.

The frequency dependent reflectance is shown in Fig. 2, where the THz radiation is incident on the coating from the air side. The measured incidence angles range from 20° to 60°, limited by the THz spectrometer and the sample and illumination spot sizes. Figure 2 (a) shows the reflectance spectra for TM polarization at three different incidence angles, 20°, 40°, and 60°, where the reflectance minima are 0.25%, 0.05%, and 0.64%, respectively. While for a bare GaAs surface, the reflectance values are 27.2%, 19.9%, and 8.7%, respectively. The lowest reflectance of 0.005% is achieved at the incidence angle of 47.5°. Figure 2(b) shows the reflectance for TE polarization at various incidence angles. The reflectance minimum is 0.46% at 20°, and it gradually increases to 10.9% at 60°. Although the reflectance for TE polarization is larger than for TM polarization, particularly at increasing angles, it significantly reduces the reflectance relative to the bare GaAs surface, which yields 34% and 56% at 20° and 60°, respectively, for TE polarization. By optimizing the spacer thickness, the TE reflectance is expected to be similar to the TM reflectance, a fact that has been verified through numerical simulations. The reflectance at small incidence angles is consistent with the results in Fig. 1(b). This indicates that the metamaterial antireflection coating is effective for both light propagating directions, in contrast to, for example, thin metal film coatings where the antireflection can be achieved only when THz radiation propagates from the optically dense to less optically dense media [6,7].

Numerical simulations using CST Microwave Studio are able to reproduce all the above experimental results. Importantly, simulation results suggest that the antireflection coating does not require any specific index of refraction for the dielectric spacer layer. With any refractive index of the spacer material, there is always a thickness that achieves near perfect antireflection. The spacer is much thinner than a conventional quarter-wave matching layer. They also reveal that losses in the metal and spacer material have a relatively small effect on the reflectance; instead it mainly affects the transmittance. Additionally, the antireflection performance is not sensitive to the alignment between the SRRs and mesh. Through further simulations we are able to elucidate the underlying mechanism responsible for the antireflection. The SRR and mesh structures can impart strong phase and amplitude shifts to the reflected and transmitted waves at the spacer boundaries. With the appropriate spacer thickness that adds additional propagation phase, antireflection conditions similar to the quarter-wave antireflection can be satisfied. Interestingly, the presumed magnetic response between the metal stripes of SRR and mesh does not play any significant role in the metamaterial antireflection coating. Finally, it is indicated that any metamaterial structure, including many subwavelength frequency selective surface elements, either resonant or non-resonant, may be employed in this antireflection coating approach. This may further simplify the metamaterial structure and enable integration with previously demonstrated metamaterial devices [8,9], achieving novel functionalities for many THz applications.

4. Summary

We have demonstrated a novel approach of antireflection using planar metamaterials in the THz frequency range, which can be easily extended to other frequency regimes as well. It dramatically reduces the reflection and enhances the transmission from dielectric surfaces. Unlike the conventional quarter-wave antireflection, this approach does not require any specific index of refraction for the spacer layer, and the total coating is much thinner. The metamaterial antireflection coating operates in a designed narrow frequency range and enables operation over a wide range of incidence angles for both TM and TE polarizations. Numerical simulations are able to reproduce all experimental results, and further elucidate the underlying mechanism responsible for the antireflection.

5. References

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