A Numerical Investigation of Metamaterial Antireflection Coatings

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Abstract: Electromagnetic metamaterials have emerged as a new class of effective media where exotic properties are determined from structural geometry and dimensions of the basic building blocks, or meta-atoms. Through such a bottom-up approach, metamaterials have found applications in the construction of terahertz functional devices and components with unprecedented performance. In this paper, we numerically investigate planar metamaterials that function as antireflection coatings for dielectric surfaces, suppressing the reflection and enhancing the transmission. We show in detail how the metamaterial structures and losses affect the antireflection performance. We also show the angular dependence of metamaterial antireflection for both transverse electric and transverse magnetic polarizations, which reveals a tunable Brewster’s angle behavior.

Keywords: metamaterials, antireflection coatings, Terahertz, simulations

1. Introduction

Light reflection at a dielectric surface is undesirable in many situations, for example, causing insertion losses in photonic devices and optical components. This is a particularly severe issue in the far infrared or terahertz (THz) frequency range due to the generally low power available in many THz systems, and the fact that many THz devices and components are fabricated on substrates with high dielectric constant. Therefore, THz antireflection coatings are highly desirable to suppress the reflection and enhance the transmission. Antireflection coatings comprised of single or multiple layered dielectric thin films via vacuum depositions have long been the solution in the optical regime, however, this approach is quite technically challenging in the longer wavelength THz frequency range. The simplest antireflection approach, the quarter-wave antireflection coating, requires a refractive index matching, \( n_2 = \sqrt{n_1 n_3} \), and a coating thickness, \( d = \frac{\lambda}{4} \), where \( n_2 \) is the refractive index of the coating material, \( n_1 \) and \( n_3 \) are the refractive indices of two bounding dielectric media, and \( \lambda \) is the wavelength in the coating material [1]. It is therefore limited by the availability of natural materials, i.e., it might be difficult to find appropriate coating materials that satisfy the index-matching requirement and are also suitable for thick film coating ranging from tens to hundreds microns. The latter is necessary due to the long wavelength of THz radiation.

There have been a few efforts developing antireflection coatings at THz frequencies, though they are specific to certain substrates and/or coating materials. The first approach follows the conventional interference principle and creates the antireflection coating by various means: gluing thin wafers [2,3], vacuum deposition of silica [4], coating with polymers such as polyethylene [5], parylene [6], and polyimide [7], and plasma-enhanced chemical-vapor deposition of single layered silicon oxide [8] or multiple layered amorphous silicon and silicon oxide [9]. As pointed out, the antireflection coatings require an index matching of the coating materials, and they have to be quite thick, at least several tens of microns. The second antireflection approach is through fabricating artificial dielectric structures, or surface relief
structures, to achieve impedance matching with a gradient index [10-12], or to create an effective index value satisfying quarter-wave antireflection [13]. This approach, however, demands special high precision fabrication procedures, in addition to the fact that substrate surfaces are no longer flat or smooth, limiting their application to many photonic devices. The last approach is to coat substrate surfaces with thin metal films having very precisely controlled thickness [14-16]. It has the advantage of broadband performance, but suffers from high loss and therefore prevents any enhancement in the transmission.

Metamaterials with designed and controllable electromagnetic properties have enabled THz device applications with unprecedented performance, for instance, THz switches and modulators [17-23] using semiconductors as integrated parts of the metamaterial elements. It has also been demonstrated that metamaterials can match the free space impedance and result in perfect absorption of THz radiation [24,25]. A recent review of metamaterials in the THz regime can be found in Ref. [26]. Recently we have proposed and demonstrated that metamaterials can be used to achieve excellent antireflection performance and transmission enhancement over a wide range of incidence angle within a reasonably narrow bandwidth [27]. Its mechanism was elucidated when considering the metamaterial coatings as a thin slab, where the interfaces tune the reflection magnitude and impart large phase shifts satisfying the antireflection requirements [27]. The destructive and constructive interferences result in the suppression of reflectance and the enhancement of transmittance. This approach differs significantly from impedance matching to free space using metamaterials [28,29], i.e., we are using metamaterials to match impedances between two dielectric media. In this paper we provide a further numerical investigation of metamaterial antireflection, focusing on how the antireflection performance is affected by the spacer dielectric constant and thickness, as well as the dielectric and metal losses. We also show the angular dependent antireflection for transverse magnetic (TM) and transverse electric (TE) polarizations, which reveal a tunable “Brewster’s angle” for both polarizations.

2. Metamaterial antireflection design and numerical simulation methods

The metamaterial antireflection coating consists of a square array of metallic electric split-ring resonators (SRRs) [30] and a metallic mesh [31], which are separated by a dielectric spacer layer, on a substrate surface. The unit cell is schematically shown in Fig. 1, where we assume lossless

![Fig. 1 Schematic of the metamaterial antireflection coating on a dielectric surface. The metamaterial coating consists of a mesh and an electric split-ring resonator array separated by a dielectric spacer layer.](image-url)
substrates with a dielectric constant of $\varepsilon_s = 12.0$, a value that is typical for many THz substrates. The SRRs have outer dimensions of 36 $\mu$m, a gap width of 4 $\mu$m, and a periodicity of 46 $\mu$m, and the width of metal lines is 4 $\mu$m. Finite-element numerical simulations in the frequency domain are carried out using the commercial available package CST Studio Suite [32]. A periodic boundary condition and hexahedral mesh are applied when metal and dielectric losses are neglected; otherwise perfect electric conducting and perfect magnetic conducting boundaries and tetrahedral mesh are used. A pair of waveguide ports is applied on the front surface of vacuum space and on the back surface of the substrate. The simulations result in complex S-parameters, from which we obtain the frequency dependent reflectance $R = |S_{11}|^2$ and transmittance $T = |S_{21}|^2$. Under normal incidence, we vary the spacer dielectric constant and thickness, as well as the dielectric and metal losses, to observe their effects on the reflection suppression and transmission enhancement. We also vary the incident angle to observe the reflectance for both TM and TE polarizations with different spacer thicknesses, where no loss has been assumed.

3. Dependence on the spacer dielectric and metal properties

First we investigate the THz reflection and transmission under normal incidence. A periodic boundary condition is applied assuming lossless metal and dielectric spacer. The spacer dielectric constant can be arbitrary assumed, and here we take two extreme values, $\varepsilon_s = 2.0$, which is quite small, and $\varepsilon_s = 14.0$, which is larger than that of the substrate. It should be noted that the spacer materials with these dielectric constants couldn’t be used for the quarter-wave antireflection purpose. The reflectance and transmittance as a function of spacer thickness are shown in Fig. 2.

![Fig. 2 Reflectance and transmittance spectra as a function of spacer thickness at the metamaterial-coated substrate surface under normal incidence, with the spacer dielectric constant (a) $\varepsilon_s = 2.0$ and (b) $\varepsilon_s = 14.0$. The legend units are microns.](image)

For all the spacer thicknesses simulated here, there are reduced reflectance and enhanced transmittance over a frequency band as compared to a bare substrate surface. When the spacer thickness is small, there still remains a certain amount of reflection, and it continuously decreases and shifts to lower frequencies as the spacer thickness increases. The simulations show that for any spacer dielectric constant, there is always an optimized spacer thickness, which is 8 $\mu$m for $\varepsilon_s = 2.0$ and 12 $\mu$m for $\varepsilon_s = 14.0$, with which reflectance of 0% and transmittance of 100% can be
achieved. Further increasing the spacer thickness, however, will degrade the antireflection performance. These metamaterial coatings are much thinner than those in quarter-wave antireflection coatings operating at the same frequencies, and also require no index matching. The results in Fig. 2 reveal that the antireflection performance is less sensitive to the spacer thickness when the spacer dielectric constant is smaller, and also has a broader bandwidth.

Losses have to be included in real metamaterial antireflection coatings, and arise from the finite conductivity of metal and the dielectric loss in the spacer layer. In Fig. 3 we show the thickness dependent reflectance and transmittance which are compared between two cases: i) considering metal as perfect electrical conductor (PEC) and using lossless spacer with $\varepsilon_s = 4.0$; and ii) using lossy gold with default conductivity ($4.5 \times 10^7$ S/m) and the spacer with $\varepsilon_s = 4.0$ and loss tangent of 0.02. The latter closely simulates the real metamaterial coatings using low loss polymers such as polyimide [25,33] as the dielectric spacer. When there is no loss from the metal and dielectric spacer, perfect antireflection is achieved at about 1.0 THz with the spacer thickness of 10 μm, i.e., 0% reflectance and 100% transmittance. After considering both the metal and dielectric losses, zero reflectance is still observed at 0.95 THz with the spacer thickness of 12 μm (the reflectance at 1.0 THz with 10 μm spacer thickness remains small), and 89% transmittance is achieved as compared to an expected transmittance value of 70% for the bare substrate surface, which is consistent with our experimental observations [27]. These results reveal that near zero reflectance can always be achieved. The losses mainly cause the reduction in transmittance, which is still fairly high due to the advantageous off-resonance operation of the metamaterial antireflection.

![Fig. 3 Reflectance and transmittance spectra as a function of spacer thickness of the metamaterial-coated substrate surface under normal incidence. (a) Considering the metal as a perfect electric conductor and using a lossless spacer dielectrics with $\varepsilon_s = 4.0$. (b) Using lossy gold with the default conductivity in CST, and assuming the lossy spacer dielectrics $\varepsilon_s = 4.0$ and a loss tangent of 0.02. The legend units are microns.](image)

4. Angular and polarization dependence

Previously we have experimentally observed that the metamaterial antireflection coatings are able to operate over a wide range of incident angles, and they behave a little differently for TM and TE polarizations [27]. Here we simulate the angular dependence of reflectance for TM and TE polarizations, either at or deviating from the optimized spacer thickness. For simplicity, losses
are not included, and the spacer dielectric constant is $\varepsilon_s = 4.0$. Fig. 4(a) and 4(b) show the reflectance for TM and TE polarizations, respectively, at the optimized spacer thickness of 10 $\mu$m. At frequencies away from the operation frequency of 1 $THz$, we clearly observe a significantly different angular dependence. At the antireflection frequency of about 1 $THz$, however, they show the almost identical dependence on the incident angles, which are shown in Fig. 4(c) and 4(d). Under normal incidence, the reflectance is nearly zero. Increasing the incident angle will slowly increase the reflectance monotonically with $R < 1\%$ up to 35°. Further increasing the incident angle the reflectance will continue to increase but it is still less than 10% at incident angles up to 60°. The polarization insensitive property in metamaterial antireflection coatings is obviously advantageous over the conventional approaches such as quarter-wave antireflection.

Deviating from the optimized spacer thickness, even at the designed antireflection frequency, the TM and TE reflectance behaves differently. Fig. 5 shows the simulated angular dependence of the reflectance at the antireflection frequencies, with the spacer thickness of 6 $\mu$m and 16 $\mu$m, which are thinner and thicker, respectively, than the optimized spacer thickness of 10 $\mu$m. The antireflection frequency shifts as shown in Fig. 3, and the reflectance under normal incidence is still low, only 2–3%. In the case that the spacer thickness is less than the optimized value, TE reflectance increases monotonically with the incident angle, as shown in Fig. 5(a), while TM reflectance decreases first and than increases, with zero reflectance near 45°, which is similar to the Brewster’s angle. When the spacer thickness is larger than the optimized value, the angular
dependence is reversed for TM and TE polarizations, as shown in Fig. 5(b). Now the TM reflectance increases monotonically with the incident angle, while the TE reflectance decreases first then increases, showing a Brewster’s angle-like behavior. For a dielectric surface, this Brewster’s angle-like behavior for TE polarization is not possible unless utilizing materials where the magnetic permeability is not equal to unity.

5. Conclusions

We have numerically investigated a novel antireflection approach using metamaterials. The results are consistent with earlier experimental observations. The metamaterial antireflection coatings do not require materials having a matched refractive index, and they can also be much thinner than conventional antireflection (quarter-wave) coatings. The metal and dielectric losses have little effect on the reflectance. They reduce the transmittance, but ~90% transmittance should be still achievable. The metamaterial antireflection is polarization independent when the spacer thickness is optimized. As the spacer thickness deviates from the optimized value, the TM and TE reflections behave differently. Particularly, when the spacer thickness is larger, TE reflectance reveals a Brewster’s angle-like behavior, which cannot be observed for non-magnetic dielectric surfaces. The metamaterial antireflection will significantly suppress the insertion losses in many THz photonic devices and components, and it can be integrated to achieve many novel metamaterial functionalities.

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