Metasurface optical antireflection coating

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Light reflection at the boundary of two different media is one of the fundamental phenomena in optics, and reduction of reflection is highly desirable in many optical systems. Traditionally, optical antireflection has been accomplished using single- or multiple-layer dielectric films and graded index surface structures in various wavelength ranges. However, these approaches either impose strict requirements on the refractive index matching and film thickness, or involve complicated fabrication processes and non-planar surfaces that are challenging for device integration. Here, we demonstrate an antireflection coating strategy, both experimentally and numerically, by using metasurfaces with designer optical properties in the mid-wave infrared. Our results show that the metasurface antireflection is capable of eliminating reflection and enhancing transmission over a broad spectral band and a wide incidence angle range. The demonstrated antireflection technique has no requirement on the choice of materials and is scalable to other wavelengths.

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Optical antireflection is highly desirable in many optical systems such as cameras, telescopes, displays, and solar cells. Traditionally, optical antireflection has been accomplished using single- or multiple-layer dielectric film coatings1 with certain required refractive indices and appropriate thickness profiles. For high refraction index substrates, index-matched transparent materials that are suitable for coating become rare and, for long wavelengths, the coating thickness scales up with the wavelength, resulting in stress buildup and thermal expansion mismatch. Alternatively, graded index surface relief structures2 have been investigated in various wavelength ranges. However, surface relief structures involve complicated fabrication processes and impose challenges for device integration.

Metamaterials have enabled many exotic electromagnetic properties and optical phenomena not available in naturally existing materials.3 Recently, a vast amount of works in metamaterials are focused on ultrathin layer metamaterials for tailored resonance and dispersion.4 This class of metamaterials, i.e., metasurfaces, has attracted further interest because of their designer surface properties5–11 for polarization conversion and arbitrary wave-front shaping. Recently, a metamaterial antireflection coating was reported in the terahertz regime using a bi-layer patterned metal metasurface structure consisting of a subwavelength metal mesh and an array of metal resonators separated by a dielectric spacing layer.12,13 Essentially, this metasurface antireflection coating is a reduced size Fabry-Pérot cavity where the multi-wave reflection results in destructive interference in the reflection region.

In this work, we report an ultra-thin single-layer metamaterial surface structure (i.e., metasurface) together with a thin dielectric layer to achieve antireflection in the mid-wave infrared range for a high refractive index substrate. The metasurface antireflection is similar to the traditional quarter-wave antireflection, but with two advantages—it does not require refractive index matching of the dielectric layers and the overall antireflection coating thickness can be thinner. The latter is very significant for potentially providing better angular performance for optical antireflection.

Figure 1(a) shows the schematic of our metasurface antireflection structure on a germanium (n3 = 4) wafer, which has a high refractive index causing much reflection loss but is otherwise a widely used infrared optical material because of its optical transparency at wavelengths from 2 μm to 14 μm. The metasurface antireflection consists of a transparent dielectric layer of magnesium fluoride (MgF2, n2 = 1.32) with a thickness d = 520 nm and an array of gold cross-resonators with a thickness t = 60 nm on the top of the MgF2 layer. The MgF2 layer by itself cannot be used, for instance, as quarter-wave antireflection for germanium because of its index mismatch. The effect of the ultrathin cross-resonator array at the air/MgF2 boundary can be characterized by the complex optical transmission and reflection coefficients, which become strongly dispersive due to the resonant response and are dramatically contrast to a bare air/MgF2 interface. In virtue of the tailored dispersion, it facilitates destructive/constructive interference for the multiple reflections/transmissions with the presence of the MgF2/Ge interface, schematically shown in Fig. 1(c), where the required magnitude and phase conditions are largely attributed to the metasurface rather than the material index matching and the propagation phase of the coating materials.
Full-wave numerical simulations were first carried out to demonstrate the proposed concept of metasurface antireflection, by using commercial package of CST Microwave Studio. In the simulations, we varied the dimensions of the cross-resonators while fixing the MgF$_2$ thickness $d = 520$ nm and gold thickness $t = 60$ nm, consistent with the experiments. We use the Drude model for the complex electric permittivity function of gold$^{14}$ and the permittivity values of MgF$_2$ are obtained from reference$^{15}$ The simulated optical reflectance and transmittance are shown in Fig. 1(d) for a metasurface-coated germanium surface with $P = 1.2$ $\mu$m, $L = 0.9$ $\mu$m, and $w = 0.4$ $\mu$m. It can be clearly seen that the reflectance is reduced from 36% for a bare air/germanium interface to a minimum of $\sim 3\%$ at the wavelength of $\lambda = 5.35$ $\mu$m for the metasurface-coated surface. Correspondingly, the transmittance is enhanced from 64% to a maximum of 97%. Also shown in Fig. 1(d) are the semi-analytically calculated reflectance and transmittance using the optical wave interference model,$^{12}$ which an exhibit excellent agreement. As we will show later, it is possible to tune the resonator geometrical dimensions and the spacer thickness so that zero reflectance can be accomplished at any wavelength of interest.

In order to demonstrate this antireflection strategy, four metasurface coatings were fabricated on the front surface of a double-side polished germanium wafer through standard vacuum deposition of MgF$_2$, e-beam lithography, gold deposition, and a lift-off process for the gold cross-resonator arrays. The back surface of the germanium wafer was coated with a wideband multiple layer dielectric antireflective coating to eliminate the backside reflection for measuring the performance of the metasurface antireflective coatings on the front surface. The back side multi-layer antireflective coating has a reflectivity of less than 0.5% from 4.0 $\mu$m to 6.0 $\mu$m wavelength and less than 1.8% from 6.0 $\mu$m to 7.0 $\mu$m wavelength. For the four metasurface antireflection coating devices we fabricated, there are two periods which are 1.2 $\mu$m and 1.3 $\mu$m. For each period, we have two samples with slightly different gold cross-resonator dimensions. These dimensions of fabricated four samples are listed in Table I, and marked as A, B, C, and D. A representative scanning electron microscope (SEM) image of the fabricated devices is shown in Fig. 1(b), and the SEM images of the unit cell for individual samples are shown in the insets to Fig. 2.

Optical reflectance and transmittance were measured by using a microscope coupled Fourier transform infrared spectrometer (FTIR), where a broadband zinc selenide (ZnSe) refractive objective of numerical aperture NA = 0.08 was used to illuminate the samples and collect the reflection. The illumination spot size on the samples was varied from 50 $\mu$m to 100 $\mu$m, which however does not change the measurement results. The angle of incidence from the refractive objective is less than 5°, which is very close to normal incidence. The reflection spectra were normalized using a gold mirror as the reference, while the reference is air in transmission measurements. The experimental reflectance and transmittance are shown by the solid curves in Fig. 2, with the values of reflection minimum and transmission maximum summarized in Table I together with the corresponding center operational wavelength near 5 $\mu$m. We observe that the reflectance is less than 6% for all of the four metasurface-coated germanium surfaces (down to 4.5% in sample D), and the corresponding transmittance is higher than 92% (up to 94.9% in sample B).

The experimental results are then compared to full-wave numerical simulations which are also shown in Fig. 2. In the

| # | $P$ ($\mu$m) | $L$ ($\mu$m) | $w$ ($\mu$m) | $r_1$ ($\mu$m) | $r_2$ ($\mu$m) | $\lambda$ ($\mu$m) | $R_{\text{min}}$ (%) | $T_{\text{max}}$ (%) |
|---|---|---|---|---|---|---|---|---|
| A | 1.2 | 0.91 | 0.36 | 0.076 | 0.051 | 5.07 | 5.9 | 92.1 |
| B | 1.2 | 0.97 | 0.39 | 0.126 | 0.073 | 5.20 | 5.0 | 94.9 |
| C | 1.3 | 0.96 | 0.36 | 0.103 | 0.055 | 5.12 | 5.5 | 93.8 |
| D | 1.3 | 1.0 | 0.44 | 0.156 | 0.100 | 5.31 | 4.5 | 93.9 |
SEM images, we can observe that the dimensions of the metasurface (except for the periods) did not exactly follow our designs due to the fabrication uncertainty, as revealed particularly by the rounding corners of the cross-resonators. Therefore, in our numerical simulations we take the fabricated structure geometry and dimensions from the SEM images, which are also summarized in Table I. After taking these into account, the numerical simulations are in excellent agreement with the experimental results. We note that the simulated antireflection is slightly better than the experimentally obtained one for all four metasurface structures. The small discrepancy would be expected mainly due to (i) inhomogeneous resonator structures caused by the fabrication tolerance, (ii) there may be some small residual reflection at the (antireflection-coated) germanium back surface, and together with (iii) some other uncertainties of material properties and spacer thickness. We also note that in all four metasurface structures there is a small dip near $k = 6$ at the measured transmission spectra, which is caused by the absorption in the dielectric films coated on the other side of the germanium wafer.

The proposed metasurface antireflection is capable of operating over a very wide incidence angle range. The numerically simulated incidence angle dependent reflection and transmission spectra are plotted in Fig. 3 for the metasurface structure B without losing generality. While near normal incidence the metasurface antireflection is polarization insensitive, increasing the incidence angle, the transverse electric (TE) and transverse magnetic (TM) polarizations behave differently, as shown in Fig. 3. For TE incidence, when the incidence angle increases, the reflection spectrum (also transmission spectrum that is not shown) exhibits a blue-shift and spectral narrowing, and the reflection minimum approaches zero near 50°, shown in Fig. 3(a). The spectral blue-shift is also observed for TM polarized incident light, shown in Fig. 3(b), however, there is a broadening in the antireflection spectrum, and the reflection minimum is reduced only slightly and then increases when the incidence angle further increases, though not significantly. The blue-shift of the antireflection wavelengths is due to the decrease of wave-vector component in the normal direction as the incidence angle increases. For both TE and TM polarizations, over the incidence angle range up to 50°, the reflectance is below 3.2% at the operational wavelength of 5.8 $\mu$m.
5.20 μm. Such an excellent wide angle antireflection is verified by additional experimental measurements of reflection when the unpolarized incident light has a cone with incidence angles ranging from 12° to 24°, where the reflection is actually the average of TE and TM polarizations. The reflection spectrum is compared with the one under near normal incidence, exhibiting an excellent overlapping in the inset to Fig. 3(b), which indicates operation over a wide incidence angle range.

In the above metasurface structures used for the validation of the antireflection concept, the minimal reflectance remains $R_{\text{min}} \sim 5\%$, not reaching zero yet in experiments. This is caused by the thick dielectric spacer layer being used in our metasurface antireflection structures. In the following, we show that zero reflection can be accomplished by tailoring the spacer thickness (or the metasurface structure). Using the metasurface structure B, the spacer thickness dependent reflectance is plotted in Fig. 4(a), where the MgF₂ layer thickness varies from 520 nm to 220 nm with an increment of 60 nm in numerical simulations. The reflection minimum experiences a blue-shift with reduced spacer thickness. More importantly, the minimal reflection decreases and approaches zero with reduced spacer thickness down to 340 nm, and then increases again with further decreasing spacer thickness. Further numerical simulations reveal that, for this particular metasurface structure B, the reflectance can be lower than 0.005% at $\lambda = 4.26 \mu m$ with a spacer thickness of 320 nm. Under this condition, we can also compare the antireflection bandwidth to the conventional quarter-wave antireflection by assuming a coating material with refractive index of 2 and thickness of 533 nm. The results are plotted in Fig. 4(b), where with a criterion of 5% reflectance we obtained a bandwidth of 31% for the metasurface antireflection and 41% for the quarter-wave antireflection. With the optimized spacer thickness, the incidence angle dependent reflection is shown in Fig. 4(c) for both the metasurface and quarter-wave antireflection with TE and TM polarized incident light. For TE polarization, the performance of quarter-wave reflection is slightly better; however, for TM polarization, the performance of metasurface antireflection is much superior to the quarter-wave antireflection approach. When averaged for both polarizations, it is obvious that, as shown in Fig. 4(d), our metasurface antireflection has quite equivalent incidence angle dependence from 0° to 50° compared to the traditional quarter-wave antireflection.

In summary, the design flexibility of the metasurfaces facilitates optical antireflection at mid-wave infrared wavelengths through tuning the metasurface structure dimensions and the underneath dielectric layer thickness. The broad bandwidth and wide incidence angle range achieved in our metasurface antireflection are comparable to a quarter-wave antireflection coating. Further increase of bandwidth is possible by using more complex metasurface structures in a super-unit-cell, a strategy which has been used for the realization of multi-band16–18 or broadband19–22 metamaterial perfect absorbers. This antireflection approach can be scaled to other wavelength ranges. It is particularly significant in longer wavelength ranges where the reduction of antireflection coating thickness is desirable because depositions of thick dielectric layers for antireflection in long wavelengths are difficult. Additionally, we like to point out that, although ultra-thin gold cross-resonator arrays were used in this work, other metasurface structures can also be used. The antireflection metallic metasurface structures can be used as near-perfect transparent electrodes23,24 for many optoelectronic devices such as optical switches, tunable filters, and photovoltaic solar cells.

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