Observation of wide-angle impedance matching in terahertz photonic crystals

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Abstract

Reflection due to impedance mismatch at interfaces of different materials is undesired in many THz applications including THz communication, spectroscopy and imaging. In this work, we theoretically and experimentally demonstrate a type of THz photonic crystals exhibiting wide-angle impedance matching property with free space. The reflection as well as the reflection-induced Fabry–Pérot resonances are efficiently suppressed in a relatively broad spectrum. A sample is fabricated using high-resistance silicon and polyethylene terephthalate films. By using THz time domain spectroscopy, we have clearly observed high transmittance and suppression of Fabry–Pérot resonances for a wide range of incident angles (0°–60°) and a relatively broad spectrum (0.26–0.55 THz) in both polarizations. Our work opens a general approach for improvement of transmission and imaging quality in THz spectroscopy.

1. Introduction

The terahertz (THz) regime including the frequency range 0.1–10 THz has attracted significant interest recently [1–12]. THz technology is vital to the further 6th generation wireless communication for higher data rates, larger network capacity, higher spectral efficiency, higher energy efficiency, and higher mobility. It is also very useful for imaging in both security and medical applications, because THz electromagnetic waves can penetrate through optical opaque materials and biological tissues. As a critical need for THz communication, spectroscopy and imaging applications, obtaining high efficiency of energy transmission or suppressing reflection and Fabry–Pérot resonances (i.e. the transmission dependence on the frequency and incidence angle) induced by impedance mismatch is very important. For example, although pure single crystalline silicon (Si) shows very low absorption at THz frequencies, the high refractive index of silicon (∼3.5) would cause a high reflection loss of round 30% which in turn results in a 30% increase of the noise temperature of the receiver [13].

The traditional method to suppress the reflection and Fabry–Pérot resonances is by using quarter-wave antireflection coatings (ARCs) [13] and ultrathin conductive ARCs [14–25]. However, for operation at THz frequencies, the quarter-wave ARCs would require multiple layers with total thickness as large as several millimeters, while the ultrathin conductive ARCs would lead to dramatic energy attenuation due to material loss [18].

An alternative way is based on impedance matching effect. Generally, the impedance matching only occurs at a particular angle, i.e. the Brewster angle, for transverse magnetic (TM) polarization at the interface of two difference dielectrics [26]. Interestingly, metamaterials and photonic crystals (PhCs) provide us a unique way to engineer frequency and spatial dispersions of effective permittivity/permeability, so that broadband and wide-angle impedance matching effect can be obtained [27–33]. Recently, Luo et al. [30] found that dielectric PhCs, the well-known band-gap materials, can possess omnidirectional impedance matching effect, allowing near 100%
transmission for all incident angles. This inspires a novel way to suppress reflection and Fabry–Pérot resonances in THz frequencies.

In this work, we experimentally demonstrate the wide-angle impedance matching effect in a one-dimensional THz PhC consisting of high-resistance Si and polyethylene terephthalate (PET) films. Although reflection occurs on the surfaces of a single Si or PET film due to impedance mismatch with free space, the overall reflection on the Si-PET PhC can be minimized. Moreover, we show that reflection and Fabry–Pérot resonances can be largely suppressed for a wide range of incident angles and a relatively broad spectrum for both transverse electric (TE) and TM polarizations. Such a THz PhC structure supports polarization-insensitive high transmission in the frequency range of 0.26–0.55 THz under all incident angles within 0°–60°.

2. Theory

To begin with, we consider a one-dimensional PhC composed of high-resistance Si and PET films that are periodically stacked along the x direction, as illustrate in figure 1(a). The unit cell with a lattice constant of 306 μm is arranged in a symmetric form, i.e. PET-Si-PET structure, in which the thickness of each PET (Si) film is 100 μm (106 μm). The relative permittivity of the PET (Si) is chosen as 3.3 (12.2). Figure 1(b) presents the band structures of the Si-PET PhC for TE (red lines, with electric fields polarized in the z direction) and TM (blue lines, with magnetic fields polarized in the z direction) modes based on finite element software COMSOL Multiphysics. The gray region denotes the working frequency range 0.25–0.6 THz, that covers the second and third bands.

It has been pointed out in [30–32] that for frequencies in the second band, the PhC can be regarded as effective nonlinear media (i.e. the effective permittivity/permeability relies on wave vectors), because the corresponding equal frequency contours are almost ellipses centered at the X point. Such nonlocality can extend the impedance matching from one particular angle (i.e. the Brewster angle) to a wide range of angles and even all angles, which is absent in traditional dielectrics. Interestingly, here we notice that the elliptical equal frequency contours centered at the X point are not essential, the wide-angle impedance matching effect can still be obtained for frequencies within the third band (see figure 1(b)). In this situation, the working frequency band is almost doubled, as we shall demonstrate in the following.

In order to demonstrate the impedance matching effect, the effective parameters of the Si-PET PhC are calculated and plotted in figure 1(c). The effective relative permittivity and permeability are calculated as equations (1) and (2) [30, 34].
\[ \varepsilon_{\text{eff}} = -\frac{k_x}{\varepsilon_0 \omega} \langle H_{\parallel} \rangle, \]
\[ \mu_{\text{eff}} = -\frac{k_x}{\mu_0 \omega} \langle E_{\parallel} \rangle, \]

where \( E_{\parallel} \) and \( H_{\parallel} \) are the electric and magnetic field components along the \( y-z \) plane of the PhC unit cell. \( k_x \) is the \( x \)-component of Bloch wave vector, \( \omega \) is the angular frequency, \( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and permeability of free space, respectively. The effective parameters \( \varepsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) are calculated based on the eigenstates in the second and third bands along the \( I-X \) direction (i.e. \( k_y = 0 \)), showing that \( \varepsilon_{\text{eff}} \approx \mu_{\text{eff}} \) in a relatively broad spectrum (around 0.26–0.55 THz). This indicates that such a Si-PET PhC possesses the impedance matching effect with free space for modes in both the second and third bands, that can be used to minimize reflection and suppress Fabry–Pérot resonances.

For verification, we plot the energy transmittance through such a Si-PET PhC slab consisting of 5 unit cells under normal incidence in figure 1(d) (red solid lines). It is seen that the transmittance is very high (>0.95) within the frequency range 0.26–0.55 THz, except for a small dip around 0.39 THz caused by the mini band gap between the second and third bands (see the inset in figure 1(b)). Within this mini gap, the \( \varepsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) have opposite signs (i.e. \( \varepsilon_{\text{eff}} < 0 \) and \( \mu_{\text{eff}} > 0 \)), leading to decay of waves in the Si-PET PhC slab. For comparison, we remove all PET (or Si) films from the PhC slab, and compress all remaining Si (or PET) films together to construct a pure Si (or PET) slab. The energy transmittance through such a pure Si (or PET) slab is plotted as black dotted (dashed) lines in figure 1(d). Evidently, the transmittance strongly relies on the working frequency, manifesting the Fabry–Pérot resonance behaviors. Furthermore, we coat the pure Si slab with a quarter-wave dielectric ARC (relative permittivity ∼3.5, thickness ∼100 μm) on each surface of the Si slab, whose energy transmittance is shown by red dashed lines in figure 1(d). These results show that both the proposed PhC structure and ARCs can suppress the Fabry–Pérot resonances and greatly enhance energy transmittance. Interestingly, we find that the proposed PhC structure possesses the advantage of high transmission within a broader frequency band.

Furthermore, to investigate angular and polarization dependence, the energy transmittance through the PhC slab with 5 unit cells as functions of the incident angle and working frequency for TE and TM polarizations is plotted in figures 3(a) and (b), respectively. It is seen that the transmittance is quite high (>0.95) over a wide angle range (0°–60°) from 0.26 to 0.55 THz for both polarizations. Moreover, the Fabry–Pérot resonances are largely suppressed, demonstrating the impedance matching effect of the designed Si-PET PhC. In addition, we take material loss into account. Here, we assume the dielectric loss tangents of the Si and PET to be 0.002 and 0.02, respectively. The energy transmittance is recalculated and presented in figures 3(c) and (d) for the TE and TM polarizations, showing that the suppression of Fabry–Pérot resonances for both polarizations can still be obtained, though the transmission is reduced a bit due to the material loss.

We note that the above calculations, including the band structures, effective parameters and energy transmittance, are performed by using software COMSOL Multiphysics based on finite element method. In the analysis of band structures, the eigenfrequency study is applied. A PET-Si-PET unit cell of the PhC is considered. Periodic boundaries are applied to the unit cell boundaries to set Bloch wave vectors, so as to compute eigenfrequencies and eigen-fields. Then, we substitute the obtained eigen-fields on unit cell boundaries into equations (1) and (2) to calculate the effective parameters. In the computation of energy transmittance through the PhC slab, the frequency domain study is applied. Port boundaries are utilized to generate incident waves and detect transmission waves, so as to calculate the energy transmittance.

3. Experiment

These theoretical predictions are verified by our THz experiments. We fabricated the Si-PET PhC composed of 5 unit cells, as illustrated in figure 3(a). The right inset show the photos of high-resistance Si and PET films we used. The thickness of each Si (PET) film is around 106 μm (100 μm). Figure 3(b) shows the block diagram of the THz time domain spectroscopy (TDS) system from Advantest. A rotating table is used to tune the orientation of the measured sample, so that the incident angle can be changed. TE (TM) polarized THz waves are realized by keeping the electric (magnetic) fields parallel to the Si/PET surfaces. Here, we use photoconductive antennas to generate and detect THz waves. Figure 3(c) shows the photo of measurement environment. The fabricated PhC sample is placed on the rotating table. Based on the Advantest THz-TDS system, amplitude, phase and power of transmitted THz waves through the PhC sample can be measured in the time domain and frequency domain.

In experiments, we first measured the energy transmittance through a pure Si structure (consisting of 5 Si films) and a pure PET structure (consisting of 10 PET films) for the TE polarization by the THz-TDS system, and the results are shown in figures 4(a) and (b), respectively. Oscillations of the transmittance as the increase of
working frequency are clearly seen in both cases, confirming the existence of Fabry–Pérot resonances inside the pure Si and PET structures. Interestingly, the measured energy transmittance through the fabricated Si–PET PhC slab for the TE polarization in figure 4(c) shows that the Fabry–Pérot resonances are largely suppressed over a wide angle range (around 0°–60°) from 0.26 to 0.55 THz. Moreover, we measured the transmission for the TM polarization, as presented in figure 4(d), also showing the wide-angle suppression of Fabry–Pérot resonances within a relatively broad spectrum. One may notice that the measured transmittance through the PhC slab is not...
quite high. It is because the dielectric loss tangent of the PET films is relatively large, as also can be seen in figure 4(b).

4. Discussions

Finally, it is worth noting that the design strategy can be extended to other materials besides the Si and PET. We can use two different dielectrics (e.g. low-index A and high-index B) to construct a one-dimensional PhC with impedance matching effect. In the designing process, a symmetric unit cell, i.e. ABA structure, is chosen to ensure the same transmission and reflection for incidence from either side. Such a ABA structure can generate appropriate electric and magnetic resonances in the central high-index B layer to tune the ratio of electric and magnetic fields. The low-index A layers on both sides can confine the dramatically changing fields in the B layer, and smooth the fields on unit cell boundaries, so as to match fields in free space. Then, through adjusting thicknesses of the A and B layers, the bandwidth of the impedance matching effect can be optimized.

In addition, we find that the frequencies for impedance matching are usually located in the second and third bands (electric and magnetic resonances in the first band are generally weak, while the fields on unit cell boundaries in higher bands vary too dramatically to hinder the field matching). Based on this point, we can adjust the working frequencies by engineering thicknesses of the components of the PhC to tune the band structures. In addition, tunable materials (e.g. liquid crystals, vanadium dioxide) can be utilized to tune the working frequencies, so that they can across the desired spectrum.

5. Conclusion

In summary, we propose a one-dimensional THz PhC composed of high-resistance Si and PET films that possesses the wide-angle impedance matching effect within a relatively broad spectrum. Simulation and experimental results demonstrate both high transmission and suppression of Fabry–Pérot resonances over a wide incident angle range (0°–60°) from 0.26 to 0.55 THz for both TE and TM polarizations. The proposed PhC provides a unique way to realize reflection-less THz materials and devices, which may find applications in THz communication, spectroscopy and imaging.
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