Design, fabrication and transmitted properties of terahertz paper photonic crystals

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Abstract: The terahertz paper photonic crystals, including one-dimensional stacks, two-dimensional square and hexagonal lattices as well as three-dimensional body-centered cubic lattice, are designed and fabricated. Femtosecond laser direct writing is employed to process paper layers. The transmission properties of these photonic crystals in THz range are characterized using time-domain THz spectroscopy. The experimental results are in good agreement with the numerical simulations and well explained by the photonic band-structure calculated by the plane wave expansion method. Our results demonstrate that paper photonic crystals have a good performance on molding the flow of THz radiation. From another point of view, the fabrication method proposed in this work can be widely extended to manufacture different micro-structures on various materials.

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1. Introduction

The terahertz (THz) science and technology has been a significant research field during the past decades because of its promising applications in a wide range of areas, such as communication [1], imaging [2] and scientific study [3]. Therefore manipulating the propagation of terahertz wave becomes more and more important in such applications. It is known that electromagnetic waves with different frequencies propagating in photonic crystals (PCs) structure are scattered by periodic structures with periodic variation of the permittivity or permeability [4–6], resulting in the formation of a photonic stop band, in which no propagating mode exists. Furthermore, the break of the periodic structure in PCs is able to introduce defects, which can trap light. The specially designed PCs have been utilized as reflectors, waveguides [7], modulators [8] and filters [9].

As one of the commonest material, paper has recently attracted lots of interests on its highly promising application on lab-on-a-chip (LOC) devices [10]. In fact, paper-based bioanalysis started to research in early 20th century and now has wide applications in our lives, such as pH paper [11] and pregnancy test [12]. With the development of nanotechnology, researches on paper-based devices have made admired progresses, such as microfluidics devices with fluidic channels [13, 14] and foldable circuits with the resolution down to about 50 μm [15]. As a low-cost and environmentally friendly material, paper has also been used in terahertz (THz) devices. Metamaterials on paper substrates [16] and paper THz wave plates [17] have been developed recently.

The structural scale of a THz PC is comparable with the designed wavelength. Hence it is easy to fabricate even for three dimensional structures. In this work, we fabricate the THz paper photonic crystals, including one-dimensional (1D) stacks, two-dimensional (2D) square and hexagonal lattices as well as three-dimensional (3D) body-centered cubic (bcc) lattice. Paper PCs are processed using femtosecond laser direct writing (FsLDW) technique. We systematically study the THz transmission properties in these paper PCs. It is demonstrated that the defect modes shift is dependent on the defect thickness in 1D PC stacks. Moreover, a linear defect is introduced by removing a row of paper pillars in 2D hexagonal lattice, and the defect mode is observed in the stop band. All experimental results are found to be well reproduced by the numerical simulation by COMSOL Multiphysics and well explained by the photonic band-structure calculated with the plane wave expansion method.

2. Fabrication and experiment

All the PCs are fabricated with paper layer by layer using FsLDW and then optimally assembled. Different papers with different thickness (e.g. print paper, ivory board) are chosen for fabrications of different PCs. The specific pattern on each paper layer and the assembling method are determined by the structure of the designed PCs. Our samples have four types of structures (1D, 2D square, 2D hexagonal and 3D bcc). The 1D PC is constructed with pieces of 105 μm thick paper, which are separated by 105 μm thick air layers. The defect is introduced by placing two or more pieces of paper closely in it. For 2D square lattice PC, patterns on 260 μm thick paper layers are gratings whose period, slit width and length are 520 μm, 260 μm and 5.5 mm, respectively, as shown in Fig. 1(a). During stacking, the paper pillars of the \((n+1)\)th layer shift half period with respect to those of the \(n\)th layer, which produces a square lattice. In hexagonal lattice PC, thickness, grating period, width and length of the slits are 200 μm, 694 μm, 494 μm and 5.5 mm, respectively, as shown in Fig. 1(b). The patterns on layers of 3D bcc PC are arrays of square holes, whose periods on two orthogonal...
directions are both $600 \, \mu m$. The side length of square holes and the thickness of paper are $300 \, \mu m$ and $285 \, \mu m$, respectively. Holes on the $n$th layer align with the center of four holes on the $(n + 1)$th layer, which constitutes a bcc lattice, as shown in Fig. 1(c). Note that the thicknesses of paper used in the four types of PCs are different and appropriately chosen according to the theoretical calculation in order that the stop bands or dips of transmission spectra can be observed in the frequency range of our terahertz time domain spectroscopy (THz TDS).

![Fig. 1. Photo images of (a) 2D square lattice PC (b) 2D hexagonal lattice PC and (c) 3D bcc PC. Insets in (a), (b) and (c) show the structural parameters of paper PCs layers, respectively. (d) Schematic for femtosecond laser direct writing setup.](image)

FsLDW was employed on processing the layer patterns of 2D and 3D PCs. Femtosecond laser pulses, delivered from a Ti: sapphire regenerative amplifier (Spectra-Physics, Spitfire Pro.) with pulse duration of 120 fs at a center wavelength of 800 nm and repetition rate of 1 kHz, were focused onto the paper by a 20 × objective lens (N. A. = 0.3) to write the desired patterns. The paper was mounted on a computer controlled three dimensional stage. The laser power of 40 mW was focused on the upper surface of the paper. The focusing spot of laser beam was about 10 μm. The speed of writing was 160 μm/s and each pattern was scanned twice, which ensured the accuracy of the fabrication process. It spent 35–45 mins to process a patterned layer. The section of the obtained holes is trapezoidal, as shown in Fig. 1(d). The difference between top and bottom edges of the trapezoid increases with the thickness of paper. In current experiment, the largest deviation from the theoretical design value is less than 10 μm, which is permitted for the designed frequency range, 0.2–1 THz.

It is notable that the fabrication method proposed here is general. Many other materials, such as quartz, silicon and even metals, are also available to be processed by FsLDW. As mentioned above, easy processing and low-cost are the advantages of paper. Furthermore, the proposed method here can also be extended to fabricate other micro-structures, not only PCs. Compared with phototetching, it is more flexible and efficient for 3D micro-machining, especially in the submillimeter range.

To investigate the spectral properties of our paper PCs, a terahertz time domain spectroscopy in transmission configuration was used. The output of a mode-locked Ti:sapphire laser, with pulse duration of 100 fs, centered wavelength of 800 nm, and repetition rate of 80 MHz (Mai Tai HP-1020, Spectra-Physics), was used to generate and detect the THz transient. The emitter and detector of the THz wave were a pair of low-
temperature-grown GaAs photoconductive antennas. The bandwidth of the THz pulse was 1.5 THz, centered at 0.4 THz and the signal to noise ratio was 1000:1. The PCs were placed in a collimated terahertz beam. The THz pulses were measured over a time period of 60 ps in time domain, corresponding to a spectral resolution of 16.7 GHz. The electric field of THz pulse in time domain could be transformed into frequency domain with fast Fourier transform. The imaginary part of the complex refractive index of paper could lead to the decrease of transmission with increasing frequency. A number of pieces of unprocessed paper stacked together (paper stacks) acted as a paper-reference. The paper-reference was half as thick as the corresponding paper PC. In order to minimize the influence of imaginary part of complex refractive index on the transmission, we define the normalized transmission 

\[ T(\omega/2\pi) = \frac{T_{PC}(\omega/2\pi)}{T_{ref}(\omega/2\pi)} \]

where \( T_{PC}(\omega/2\pi) \) is the transmission of PC and \( T_{ref}(\omega/2\pi) \) is the transmission of paper-reference. Note that the normalized transmission obtained could be larger than 1.0.

3. Results and discussion

In order to design the structure of a PC and simulate the transmission spectra in THz frequency range, the refractive indices of these papers have been characterized according to the method described in [18]. By fitting the experimental data in the frequency range from 0.2 to 1.0 THz, we obtain the complex refractive indices (Table 1). The real parts are constant and the imaginary parts are linear functions of frequency, in which \( f \) denotes frequency in unit of THz. Papers with different thicknesses show a little difference in the refractive indices.

<table>
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<th>Table 1. The refractive indices of paper</th>
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<td>PC structure</td>
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<tr>
<td>1D</td>
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<tr>
<td>2D square</td>
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<td>2D hexagonal</td>
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<td>3D bcc</td>
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An electromagnetic wave with specific frequency propagates through a PC structure, the transmission spectrum, band structure and field pattern can be obtained by solving the following equation

\[ \nabla \times \left( \frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right) = \left( \frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}). \]  

(1)

This function is an eigenvalue problem for \( \mathbf{H}(\mathbf{r}) \) that describes the magnetic field distribution, in which \( \varepsilon \) and \( \omega \) denote permittivity and angular frequency, respectively. As an effective approach to solve Eq. (1), the plane wave expansion (PWE) method [19, 20] is employed to obtain the photonic band-structure of PCs. But it is difficult to use this method to treat loss, dispersion or metallic materials. For a better understanding and optimization of our paper PC structure, a commercial software, COMSOL Multiphysics, was employed to simulate the THz wave propagation in the paper with loss.
3.1 The THz spectra of 1D PC

Fig. 2. (a) Transmission spectra and (b) photonic band-structure calculated with PWE of 1D PC. In (a), ‘0’ and ‘1’ denote air and paper layers, respectively. The subscript ‘4’ and ‘10’ denote the number of repeat unit. The solid lines are calculated results based on numerical simulation and dash lines are experimental results. All curves are shifted vertically for clarity. In (b), the red region is stop bands, and the lines stand for photonic bands dispersion.

The period of 1D PC is 210 μm and the thickness of paper and air layers are both 105 μm. The incident terahertz beam is normal to the PC surface. Figure 2(a) shows the transmission spectra of the 1D PCs with and without defect. The transmission stop band around 0.5~0.65 THz is observed in the transmission spectrum, in which the incident terahertz radiation is evanescent wave and cannot propagate in the 1D PC. Our experimental results are corresponding to the calculated photonic stop band, marked with red area in Fig. 2(b). The photonic band-structure of 1D PC structure is calculated with PWE.

The defect can be introduced by stacking paper closely in the 1D PC. In Fig. 2(a), it can be found that various defect modes appear in the transmission stop band. The stop bands with defect modes are slightly wider than that without defect modes, because the band structure is affected by the defect whose optical thickness is comparable with the designed wavelength. With the increase of the thickness of defect-layer, the frequency of defect modes shift and even multiple defect modes are observed in the photonic stop band. The experimental results are reproduced by the numerical simulation very well. The defect mode originates from the THz wave trapped by the defect and oscillating back and forth within it. The frequency of the defect mode is determined by the optical thickness of the defect. It decreases as the thickness of defect-layer increases, because the mode has more space to oscillate. Hence the frequency of the defect mode is controllable by modulating the optical thickness of the defect, such as changing the physical thickness or the refractive index. The transmission peak of the defect mode is expected to be as high as the edge of photonic stop band, if the imaginary part of refractive index is zero. However, in a loss media such as paper, optical loss for the defect mode is further increased due to the oscillations in the defective 1D PC. Therefore, the transmission peaks of the defect modes, as shown in Fig. 1(a), are much lower than the edge of stop band.
3.2 The THz spectra of 2D square lattice PC

Fig. 3. (a) Transmission spectra and (b) photonic band-structure of 2D square lattice PC. In (a), the black lines are the calculated results based on numerical simulation and the blue lines are experimental data. All curves are shifted vertically for clarity. Inset in (b) shows the first Brillouin zone and the direction of the incident THz wave.

For a 2D PC, the THz wave has two independent polarization states with respect to the pillar direction. One is the electric field of THz wave parallel with the pillars (E-polarization), and the other is the magnetic field of THz wave parallel with the pillars (M-polarization). In our experiment, the lattice constant of 2D square lattice PC is 367.7 μm and the side length of the pillar section is 260 μm. The normal incident THz beam travels along the Γ-M direction of the first Brillouin zone, as shown in the inset of Fig. 3(b).

In Fig. 3b, no stop band is observed in the photonic band-structure for M-polarization, however, a dip appears around 0.5 THz in the experimental and simulated transmission spectra. The dip is a low transmission range which is induced by the finite structure of PC. The photonic band-structure is calculated according to PWE method which assumes that PC has infinite periodic structure. This can explain the difference between experimental (numerical simulation) result and the PWE analysis. For E-polarization, a wide stop band is observed in both photonic band-structure and the transmission spectrum. There are some differences between the two stop bands. In fact, the transmitted wave shows oscillations in the transmission spectrum from 0.45 to 0.54 THz if the imaginary part of refractive index of paper is zero. In this frequency range, the THz wave is localized in the PC and its group velocity is low. The photon undergoes multiple reflections in the lattice and has a long optical path, which results in the significant decay in paper. That is the reason that the stop band obtained from THz transmission is significantly larger than that in the calculated band structure without considering the loss of paper. In another word, the absorption broadens the transmission stop band, which is probably an advantage when the PC is used as a polarizing device due to its polarization-dependent transmission in the range of 0.38 ~0.54 THz. It should be mentioned that the decay of localized wave often occurs near the edge of stop band.
3.3 THz spectra of 2D hexagonal lattice PCs

Fig. 4. (a) Incident-angle dependence of the transmission spectra and (b) photonic band-structure of 2D hexagonal lattice PC for E-polarization. In (a), the black lines are the calculated results based on numerical simulation and blue lines are experimental data. All curves are shifted vertically for clarity. Inset of (b) shows the first Brillouin zone and incident THz directions.

The lattice constant of 2D hexagonal lattice PC is 400 μm and the side length of the pillar section is 200 μm. Figure 4(a) shows the incident-angle dependence of the transmission spectrum for E-polarization. It is seen that by changing the THz incident direction from Γ–K to Γ–M direction, as shown in the inset of Fig. 4(b), the stop band around 0.4 THz continuously becomes narrower and shifts to lower frequency. This tendency is also clearly observed in the calculated photonic band-structure, as shown in Fig. 4(b). Due to the high symmetry of the hexagonal lattice, the incident terahertz waves along the directions of Γ–M and Γ–N are supposed to undergo the same scattering condition, and then expectedly have the same transmission spectra. However, the slight difference between the second and third profiles in Fig. 4(a) is mainly caused by the square section pillars whose symmetry is lower than that of hexagonal lattice. By replacing the square pillar with the cylinder structure, these two transmission spectra are expected to be exactly coincident with each other.

By removing a row of pillars in the middle of the 2D hexagonal lattice PC, a linear defect is manually introduced. A defect mode is consequently observed in the transmission spectrum, as shown the red arrow in Fig. 4(a). The transmission peak of the defect mode is also quite low due to the long optical path of THz wave in the loss media, as discussed in the section of 1D PC. The terahertz wave in the frequency range of 0.38–0.4 THz is forbidden in the defective PC, while the waveguide mode is able to propagate along the defect. Therefore, the linear defect can act as a waveguide, which can be used to guide the propagation of THz radiation. It should be noted that the outgoing wave is nearly cylindrical and cannot be detected in the far field detection by our current experimental setup.
3.4 THz spectra of 3D BCC PC

Fig. 5. (a) Transmission spectra of 3D bcc PC. Dash lines are the calculated transmission of the absolutely symmetric bcc lattice. Solid lines are calculated transmission of our sample. The red line is the measured transmission spectrum in direction ‘z’. The blue and green lines are the measured transmission spectra in direction ‘x’ and ‘y’, respectively. All curves are shifted vertically for clarity. (b) Photonic band-structure of completely symmetrical 3D bcc PC with lattice constant of 600 μm. The inset shows the first brillouin zone.

In bcc lattice, because of its high symmetry, the transmissions are expected to be same in all three directions normal to the PC surface. Figure 5(b) shows the photonic band-structure in Γ–H direction of bcc PC whose lattice constant is 600 μm and the side length of the periodic air cube is 300 μm. No stop band is observed in the calculated band structure. However, at the edge of the first photonic band the THz wave in this frequency range is localized. If there is no absorption, it shows several oscillations in transmission spectrum. The field localization leads to significant absorption in paper and forms a stop-band-like frequency range in the transmission spectrum, as shown the dash lines in Fig. 5(a). For our sample, the structure is not absolutely symmetrical in the three orthogonal directions. The side length and period of air cube in the direction ‘z’ are 285 μm and 570 μm, respectively, 5% smaller than those in ‘x’ and ‘y’ directions. In current experiment, the incident terahertz beam is normal to the PC surfaces. The polarization of THz wave propagating along the ‘x’ or ‘y’ direction is in the ‘xy’ plane. Then the difference induced by the asymmetry in three directions has been characterized in the transmission spectra (Fig. 5(a)). It is seen that the transmission along ‘x’ direction is almost the same with that along ‘y’ direction. The stop bands in transmission spectra in the ‘x’ and ‘y’ direction shifts to high frequency, compared with that in the ‘z’ direction.

4. Summary

A series of paper PCs at terahertz range are designed and fabricated. The THz transmission properties of these paper PCs are studied with THz spectroscopy. We have investigated (i) the variation of defect modes in 1D PCs, (ii) the stop bands of E-polarization and M-polarization in 2D square lattice PC, (iii) the incident-angle dependence of the transmission spectra in 2D hexagonal lattice PCs with and without defect mode, and (iv) the transmission spectra of 3D bcc PC. The experimental data are in good agreement with the numerical simulation and PWE method. The major advantage of paper PCs is low-cost and easy to fabricate in the designed frequency range. By changing the structure and the parameters of paper PCs, the designed frequency of the photonic stop band, defect mode and guide mode can be tuned as required. Furthermore, the good agreement with the theoretical results indicates that the fabrication method proposed in present work is a promising approach to manufacture microstructure.
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