【光电工程 / Optoelectronic Engineering】

Simulation and fabrication of one dimensional terahertz photonic filter

LI Ling†, LIAO Hui, HUANG Jing-zhen, and ZHAI Jian-pang

Shenzhen Key Laboratory of Laser Engineering, College of Electronic Science and Technology,
Key Laboratory of Advanced Optical Precision Manufacturing Technology of Guangdong Higher Education Institutes,
Shenzhen University, Shenzhen 518060, P. R. China

Abstract: The theoretical and experimental results of one dimensional (1D) terahertz (THz) filter were introduced based on photonic band gap structures. The periodic structures were fabricated by artificial stacking method. The polytetrafluoroethylene or polyethylene slices were used as high refractive index layers, and the alloy slices with hole in center were used as air layers. The transmission spectra were measured by a terahertz time domain spectroscopy. The measured frequency range was 0.1-0.9 THz. The measured results consisted well with the simulated data. Based on theoretical and experimental data, a band-stop filter with central frequency at 0.3 THz was designed and fabricated by polyethylene (PE). The duty cycle was 0.5, and the period was 400 μm. The 3 dB bandwidth was 0.08 THz, which was close to the simulated result (0.07 THz).

Key words: terahertz waves; photonic band gap; photonic crystals; bandstop filters; transmission spectra; polyethylene; high refractive index material; time domain spectroscopy

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一维太赫兹光滤波器的模拟与制作

李　玲，廖　晖，黄镜蓁，翟剑庞

深圳市激光工程重点实验室 深圳大学电子科学与技术学院
先进光学精密制造技术广东普通高校重点实验室，深圳 518060

摘　要：模拟并制作了基于光子带隙结构的一维太赫兹光滤波器. 通过人工叠加方式制作一维周期性结构，以聚乙烯或聚四氟乙烯作为高折射率材料，用钻有圆孔的合金片作为空气层，利用太赫兹时域光谱技术测量样品在 0.1 ~0.9 THz 波段的透射谱. 根据理论模拟结果，利用聚乙烯设计制作中心波长为 0.3 THz 的带阻滤波器，结构周期为 400 μm，占空比为 0.5. 测量的 3 dB 带宽为 0.08 THz，与模拟结果 0.07 THz 基本吻合.

关键词：太赫兹波；光子带隙；光子晶体；带阻滤波器；透射谱；聚乙烯；高折射率材料；时域光谱

In recent years, the interests in terahertz (THz) radiation have arisen extensively. The THz frequency band is from 0.1 THz to 10 THz, which lies between far-infrared wave to millimeter-wave[1-2]. It has the advantages of wide frequency band, good coherence, low energy and good penetrability and has been widely applied in medical diagnosis[3], astronomy[4], safety inspec-

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† **Corresponding author**: Professor LI Ling. E-mail: liling@szu.edu.cn
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tion[5-7], nondestructive testing[8-9], communication field[10] and so on. Interest in the use of THz radiation is extensive, thus being able to manipulate THz radiation with simple methods would be very attractive. The THz photonic devices designed based on photonic band gap (PBG) structures are the prior choices[11-12].

This paper presented a theoretical and experimental study of the fabrication parameters for one dimensional (1D) terahertz photonic filter. The simulation showed that by altering the material refractive index (n), period (d), and duty cycle (r/d, r is the thickness of the material layer), the position and width of each band gap would change obviously. We fabricated a series of 1D PBG structures by using an artificial stacking method and measured the transmission spectra of these samples in the range of 0.1-0.9 THz. The experimental results were consistent with the simulations. A band-stop filter with central frequency at 0.3 THz was designed and fabricated by polyethylene (PE). The duty cycle was 0.5 and the period was 400 μm. The measured band gap region of the filter was 0.27-0.35 THz, which was close to the simulated data (0.27-0.34 THz).

1 Simulation

Figure 1 shows the 1D PBG structure. It is made of several alternating stacking layers with two refractive indices. The white stripe indicates material with low n value, the gray stripe indicates material with high n value. In our simulations, polytetrafluoroethylene (PTFE, n = 1.35) or polyethylene (PE, n = 1.52) is used as high n material, and air layer is used as low n material. The photonic band gap structures of 1D photonic crystal are calculated using the plane wave expansion method. In 1D PBG structure, the position and the width of each band gap will change if the material refractive index, period, or duty cycle is changed.

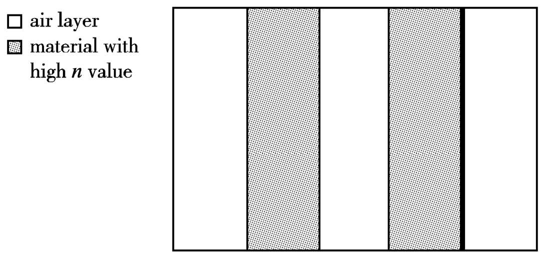

Fig. 1 The schematic structure of one dimensional terahertz photonic filter

图1 一维太赫兹光子滤波器结构

The effect of material refractive index on the PBG structure is firstly investigated. Table 1 shows the band gap (BG) regions and widths of PTFE and PE PBG samples. It can be seen that the band gap central frequency moves to lower frequency and the width of the band gap increases when n increases.

Table 1 The BG region and width of PBG structures made by PTFE or PE with duty cycle r/d = 0.5

表1 PTFE和PE构成的一维周期性结构的带隙位置和宽度,占空比为0.5

material	PTFE, n = 1.35	PE, n = 1.52
BG region and width	f_0 = 0.38-0.47 (Δf_0 = 0.09)	f_0 = 0.35-0.45 (Δf_0 = 0.10)
	f_0 = 0.83-0.87 (Δf_0 = 0.04)	f_0 = 0.76-0.83 (Δf_0 = 0.07)

In the simulations, the band gap is shown in the form of normalized frequency f_0. The actual measured frequency for each band gap f needs to be transformed using equation $f = f_0 c/d$. Here $c = 3 \times 10^8$ m/s is the velocity of light, d is the period of the structure. Since f is inversely proportional to the period d, the measured central frequency f of band gap should move to lower frequency as the period increases when the duty cycle is fixed.

The effect of duty cycle on BG region and width is shown in table 2. The PBG structures are constructed by alternating stacking PE and air layers with different duty cycles. The central frequency of each band gap moves toward lower frequency as the duty cycle increases.

Table 2 The BG region and width of samples made by PE with different duty cycles

表2 不同占空比PE构成的一维周期性结构的带隙位置与宽度

duty cycle	r/d = 0.3	r/d = 0.5	r/d = 0.7
BG region and width	f_0 = 0.38-0.49 (Δf_0 = 0.11)	f_0 = 0.35-0.45 (Δf_0 = 0.10)	f_0 = 0.33-0.40 (Δf_0 = 0.07)
	f_0 = 0.83-0.90 (Δf_0 = 0.07)	f_0 = 0.76-0.83 (Δf_0 = 0.07)	f_0 = 0.68-0.78 (Δf_0 = 0.10)

2 Experiment

The transmission spectra measurements have been carried out by a terahertz time domain spectroscopy (THz-TDS)[13-14]. As shown in figure 2, an Ti:sapphire femto-second laser beam is split into two beams in the pump-probe scheme. The THz source is generated by the strong pump beam on a biased GaAs wide aperture antenna. The PBG sample is put 11 mm away from the GaAs emitter surface, where the diameter of THz wave spot is about 2 mm. The transmitted THz wave is collected onto another GaAs detector by a couple of reflecting mirrors. The other weak beam from femto-second laser is a probe beam, which reaches the detector at the same time. By changing the delay line, the terahertz transmission signal of the sample in the time domain is amplified by the lock-in amplifier and recorded by the computer. By Fourier transform, the corresponding THz transmission spectra in the frequency domain can be obtained. The measuring frequency range is 0.1-0.9 THz.

According to the theoretical results, we fabricate the related PBG structures using PTFE or PE by artificial stacking method. The material slices with different thickness are prepared by mechanical machining. The slice area is 20 mm × 20 mm, and the thickness varies from 200 to 400 μm. The thickness deviation of the slices is less than 1% after precise polishing.

A series of metal alloy slices with different thickness are also prepared. There is a hole with diameter of 10 mm at the center of these slices. It can be used as air layers in the PBG structures. The 1D periodic structure was then formed with alternating stacking air layer and material layer, which is shown in the inset of figure 2.

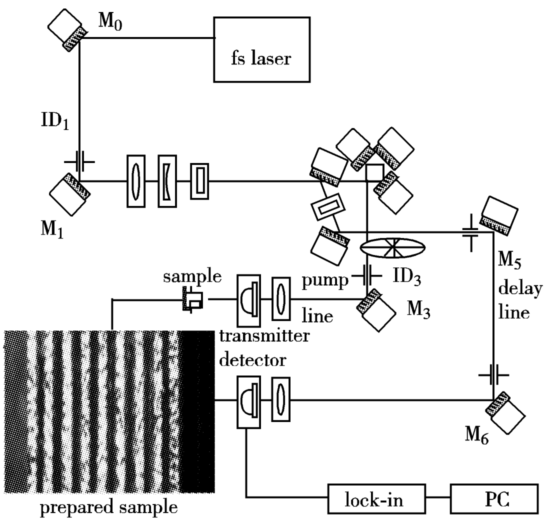

Fig. 2　Experimental setup of the THz transmission spectra

图 2　THz 透射光谱的测试装置

We firstly investigate the relationship between the output signal intensity and the period numbers (N), which is shown in figure 3. The material is PE. The output intensity I is normalized by the background signal without sample I_0. The intensity attenuation is defined as $10\lg(I/I_0)$, the unit is dB.

It can be seen that when the period number increases, the intensity attenuation in the band gap region increases obviously,

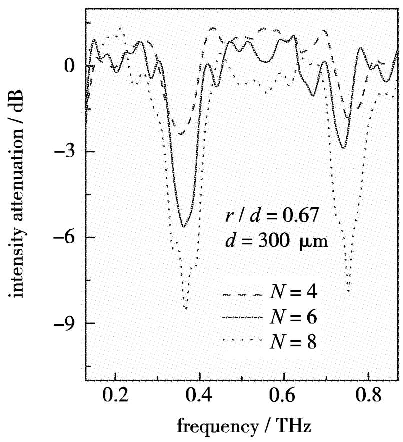

Fig. 3　Transmission spectra of PE samples with different period numbers

图 3　不同周期数 PE 样品的 THz 透射谱

but the center of the band gap varies little. For the photonic crystal with infinite period, the attenuation should be 100%. However, in practice, people often use 3 dB bandwidth to characterize the filtering property of the related filter. That is, the bandwidth in which the intensity attenuation is above 50% relative to the background intensity. According to the results in figure 3, we set the period number as eight in the following measurements, with which the intensity attenuation at the BG central frequencies can reach above 85%.

In order to study the actual effects of material refractive index on the PBG structure, the transmission spectra of PTFE (dash line) and PE (solid line) PBG samples have been measured, which are shown in figure 4. The duty cycle is 0.67, and the period is 300 μm. The experimental BG central frequencies for PE sample are 0.36 and 0.75 THz. The 3 dB bandwidths are 0.10 and 0.08 THz. As comparison, the measured BG central frequencies for PTFE sample are 0.37 and 0.81 THz with 3 dB bandwidths of 0.08 and 0.05 THz. This experimental result agrees well with the simulated result in table 1, in which the BG frequency increases and the width of the band gap decreases when n decreases.

As shown in figure 4, the PE sample behaves better than PTFE sample in the case of wave filtering since it has deeper intensity attenuation with the same duty cycle and period. Thus, in the following measurements, PE samples fabricated with different duty cycles and periods have been investigated.

The transmission spectra of PE samples with duty cycle of 0.5 (solid line) and 0.67 (dash line) are shown in figure 5. The period is 600 μm. The simulated and experimental results are list in table 3. The difference between measured results and simulated results is tiny. And the BG region moves to lower frequency side as the duty cycle increases.

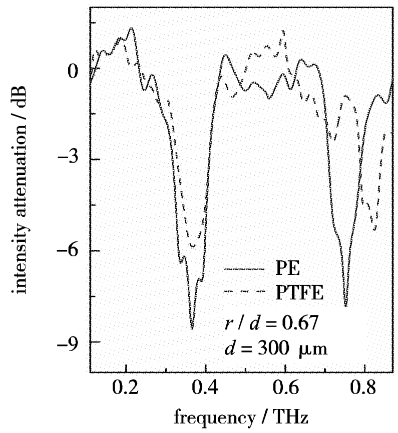

Fig. 4 Transmission spectra of PTFE and PE PBG samples

图4 PTFE 和 PE 样品的 THz 透射谱

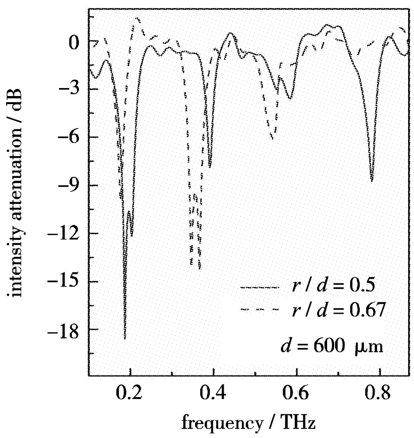

Fig. 5 Transmission spectra of PE samples with different duty cycle

图5 不同占空比时 PE 样品的 THz 透射谱

Table 3 The simulated BG regions and experimental results of PE samples with different duty cycles

表3 不同占空比时 PE 样品带隙位置的理论值与测量值

r/d		BG region / THz		
0.50	simul.	0.17-0.22	0.38-0.41	0.58-0.61
	expt.	0.16-0.22	0.38-0.40	0.56-0.59
0.67	simul.	0.17-0.20	0.35-0.40	0.54-0.57
	expt.	0.16-0.19	0.33-0.38	0.52-0.56

Figure 6 shows the transmission spectra of PE samples with different period. The solid line indicates the period is 300 μm, the dash line represents 450 μm, and the dot line represents 600 μm. The duty cycle is 0.67. The simulated BG regions and experimental results are list in table 4. The experimental results consist well with the simulated data.

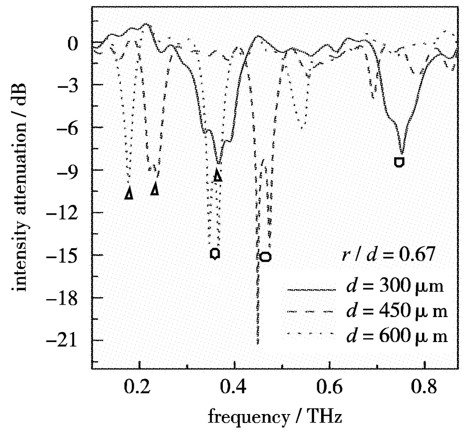

Fig. 6 Transmission spectra of PE samples with different periods

图6 不同周期时 PE 样品的 THz 透射谱

Table 4 The simulated BG regions and experimental results of PE samples with different periods

表4 不同周期下 PE 样品带隙位置的理论值与测量值

d/μm		BG region / THz		
300 μm	simul.	0.33-0.40	0.69-0.79	
	expt.	0.31-0.41	0.71-0.79	
450 μm	simul.	0.23-0.27	0.46-0.53	0.72-0.77
	expt.	0.21-0.26	0.43-0.49	0.68-0.70
600 μm	simul.	0.17-0.20	0.35-0.40	0.54-0.57
	expt.	0.16-0.19	0.33-0.38	0.52-0.56

Since the measured frequency f is inversely proportional to the period, the central frequency difference ($\Delta f_1 = f_{300} - f_{450}$) of 300 and 450 μm PBG structures should be two times larger than that ($\Delta f_2 = f_{450} - f_{600}$) of 600 and 450 μm samples ($\Delta f_1 = 2\Delta f_2$). In figure 6, for the first central frequency group (marked by open triangles), $\Delta f_1 = 0.12$ THz, and $\Delta f_2 = 0.06$ THz. For the second central frequency group (marked by open circles), $\Delta f_1 = 0.29$ THz, and $\Delta f_2 = 0.11$ THz. Both two groups of data confirm the inverse relationship between frequency and period.

According to the above theoretical and experimental investigations, we can design and fabricate 1D THz band-stop filter based on PBG structures in any designated wavelength. For example, we have fabricated a band-stop filter centered at 0.3 THz with alternating stacking PE and air layers, which is in our measurement range. The duty cycle is 0.5 and the period is 400 μm. The 3dB bandwidth is 0.08 THz, and the measured band gap region is 0.27-0.35 THz, as shown in figure 7. The measured result agrees well with the simulated result (0.27-0.34 THz).

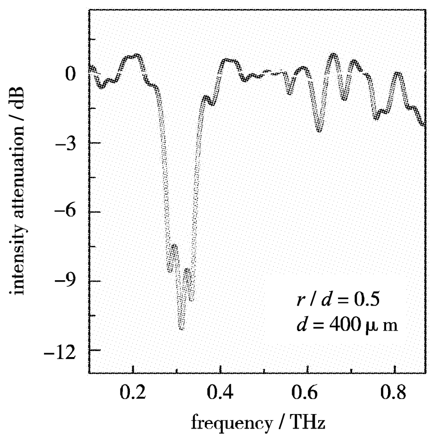

Fig. 7　Transmission spectra of 1D THz photonic filter
图 7　一维 THz 光子滤波器的透射谱

Conclusion

In conclusion, we fabricated the 1D periodic structures using an artificial stacking method and measured the transmission spectra of the samples in the range of 0.1-0.9 THz. The measurement were consistent with the simulations. Based on the theoretical and experimental results, a band-stop filter centered at 0.3 THz had been designed and fabricated. The duty cycle was 0.5 and the period was 400 μm. The measured band gap of the structure was 0.27-0.35 THz. The 3 dB bandwidth was 0.08 THz, which was close to the simulated result (0.07 THz). This work proposed a simple and low cost way to fabricate a band-stop filter in any designated THz frequency range, which could be useful in THz imaging technology.

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作者简介： 李　玲（1976-），女（汉族），湖北省嘉鱼县人，深圳大学教授、博士．E-mail：liling@szu.edu.cn
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