Terahertz Filters by Using Tapered Parallel-Plate Waveguides

Eui Su Lee[1], Young Bin Ji[1], Sun-Goo Lee[2], Chul-Sik Kee[2], and [#]Tae-In Jeon[1]
[1]Division of Electrical and Electronics Engineering, Korea Maritime University
Busan 606-791 Korea, jeon@hhu.ac.kr
[2]Nanophotonics Laboratory, Advanced Photonics Research Institute, GIST
Gwangju 500-712 Korea

Abstract

We present experimental and finite-difference time-domain simulation studies on high pass filter (HPF) based on transverse electric (TE) mode, low pass filter based (LPF) on multiple slits, and tunable notch-filter based on single slit. The LPF and notch filter are carried out by using the metal slits positioned at the center of the air gaps in tapered parallel-plate waveguides (TPPWG).

Keywords : Terahertz Notch Filter Low Pass Filter High Pass Filter Slit Waveguides

1. Introduction

Recently, Bragg and non-Bragg stop bands have been studied using metal slit arrays positioned at the center of the air gaps in TPPWG [1]. An easily installable notch filter satisfying the conditions such as transverse electromagnetic (TEM) mode, high Q factors, high signal-to-noise ratios, and tunable notch filters was implemented in this study using the characteristics of the non-Bragg stop band. A LPF, which cuts off high frequency regions using metal slit arrays having multiple Bragg stop bands, was also implemented. Together with a HPF using TE mode with a two-cylinder waveguide [2], the LPF can be applicable in many research areas.

2. Experimental Setup

The experimental apparatus is illustrated schematically in Fig. 1 (a) for HPF. The PPWG is located between the two reflectors at the conventional THz time-domain spectroscopy system. The incoming THz beam is vertically polarized and focused into the gap of the parallel plates by using the tapered part of the PPWG. The incoming THz beam was guided by the tapered structure and naturally formed a line focus to the air gap, as did the plano cylindrical silicon lens.

In order to have notch filter, a TPPWG is used to couple the air traveling THz pulses to the stainless steel sheet (slit) which is located between the two aluminum TPPWG blocks. Identical metal spacers are used to make same upper and lower air gaps (g). Such a structure confines the THz beam to the two equal-width air gaps on opposite sides of the steel sheet. When dealing with slit is located in the center of the air gap, the THz wave can propagate along the upper and lower surfaces of the sample because of the two tapered structures of the waveguide. The protruded length of the stainless steel sheet in the tapered part can separate the incoming THz beam into two parts. Although the stainless steel sheet is located at the vertical center of the incoming THz beam, the measured spectrum has no distortion. This is because of the thin metal sheet and because the THz beam is not fully focused at the beginning of the protruded sheet. A vertically polarized (y direction) THz beam, which is perpendicular to the tapered surface ($x \times z$ surface) of the waveguide, generates a TM mode.

(a)

(b)

Figure 1. Experimental setup. (a) HPF (b) notch filter.

3. High Pass Filter

The incoming THz beam is vertically polarized and focused into the gap of the parallel plates which have vertically located as shown in Fig. 1 (a). Based on the well-known wave equations, Maxwell's equations and the boundary conditions, only TE modes can exist in the TPPWG. Because of the high group-velocity dispersion near the cutoff frequency, the time domain pulse is stretched and expanded [3]. The lower frequencies travel slower than the higher frequencies as shown in Fig. 2 (a). The low frequency is truncated until 1.23 THz, which is the first cutoff frequency to show up as shown in Fig. 2(b). The spectrum then extends up to 4.5 THz. Below the cutoff frequency shows stop band characteristics and above the cutoff frequency shows pass band characteristics. The spectrum of TE mode shows characteristics of HPF. The cutoff frequencies of the TE modes are given by fc = mc/2d, where m is the number of high-order modes, c is the speed of light and d is the gap between the parallel plates where we used d = 122 μm in the measurement. When the TPPWG is removed in the THz beam path, the measured THz pulse is as shown in the upper inset of Fig. 2 (a). Lower inset shows Extension of the oscillation of TE_1-mode from 5 ps to 20 ps. The reference THz pulse propagates only air. The relative amplitude spectrum of the reference is shown in black line in Fig. 2 (b).

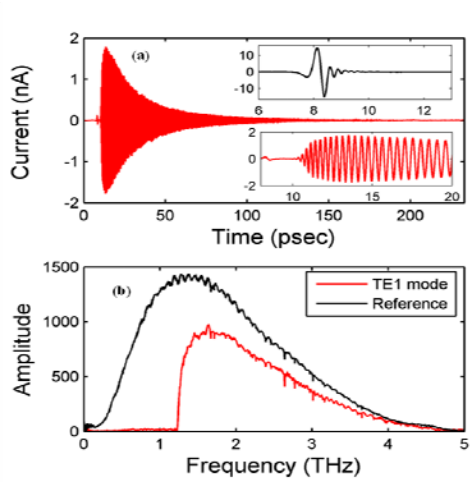

Figure 2. (a) Measured TE_1-mode THz pulse transmitted through a TPPWG with a plate separation of 122 μm when the polarized direction of the input electric field is parallel to the plates. Upper inset: Measured TM_0-mode THz pulse when the polarization direction of the input electric field is normal to the plate. Lower inset: Extension of the oscillation from 5 ps to 20 ps. (b) Relative amplitude spectrum of the TE_1-mode (red) and TE_0-mode (black).

4. Low Pass Filter

To design such an LPF, slits with equal width of 60 μm and 7 different periods of slit pattern were designed. Since each region has 10 identical slits, the total number of the slits is 70. A THz beam propagating along slits inside a TPPWG has a Bragg stop band with strong resonance. The bandwidth of the Bragg stop band broadens as the period gets narrower at the Bragg stop band positions in the high frequency range. Using such characteristics, if slits with different periods are arrayed in a line on a metal sheet, an LPF can be implemented to completely eliminate the high frequency component after cutoff frequency.

The spectra of the measured THz pulses are shown in Fig. 3 (a). The amplitude of the output spectrum (red) is cut off at 0.78 THz. As shown in the inserted figure, the magnitude response changes from pass band to stop band. The transition width is about 68 GHz. A power transmission, as shown in Fig. 3 (b), was obtained by using numerical modification of the reference amplitude, expressed as a dotted line in Fig. 3 (a). The power transmission in the cutoff region of the LPF is measured at about 35 dB, as shown by the red line. The experimental result is in good agreement with the FDTD simulation, which is represented with a black line in Fig 3 (b).

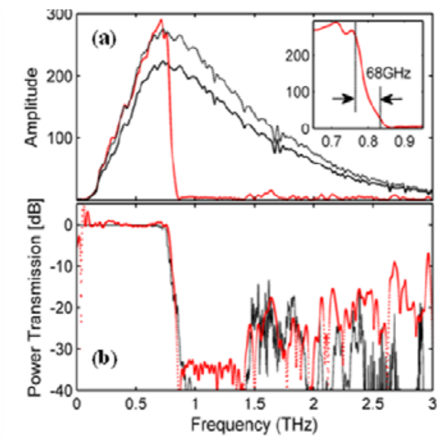

Figure 3. (a) The spectra of the reference (black) and output (red). The dashed spectrum indicates a numerically modified reference spectrum. The inset shows expended figure near the cutoff frequency. (b) Comparison of power Transmission in the measurement (red) and FDTD simulation (black).

5. Notch Filter

A single stainless steel slit was employed as a notch filter as shown in Fig. 1 (b). The slit has 30-μm thickness, 100-μm width, and 9-mm length. Unlike the Bragg resonance of the defect mode, the measured notch filter resonance can be explained by the canceling out of the THz beams due to the out-of-phase component between the straight THz beam and the THz beam passing through the slit. As the air gap had changed from 92 μm to 105 μm, the resonance frequency of the notch filter had also moved to a low frequency region by 0.168 THz (from 1.519 THz to 1.351 THz as shown in Fig. 4 (a) and (b)). The frequency tuning sensitivity (FTS) is given as $\Delta f / \Delta g$, where Δf is the resonance frequency shift and Δg is the air gap variation. Therefore, the FTS is 12.9 GHz/μm, which shows a tunable notch filter in the THz region. Figure 4 (c) and (d) show the absorbance of the resonance frequency; the arrows denote the FWHM of each absorbance, 11 GHz and 12 GHz, respectively. The calculated Q factors (resonance frequency divided by FWHM) are 138 and 113, respectively. The advantage of the notch filter used in this study is its tunable resonance frequency with high Q factor and high signal-to-noise ratio.

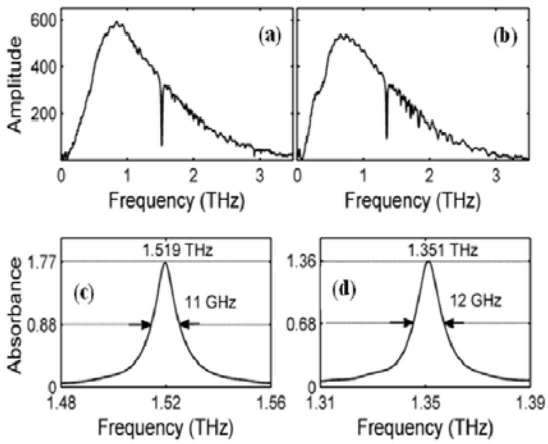

Figure 4. (a) and (b) Measured THz spectrum for a 92-μm and 105-μm air gap respectively. (c) and (d) Absorbance spectrum zoomed in on the resonance for a 92-μm and 105-μm air gap respectively.

6. Conclusions

When the polarization of THz field is parallel to the PPWG, only the TE mode can propagate at a plate separation. The THz signal can't detect below the cutoff frequency because the wave impedance only has reactive components that can be used for a HPF for a THz system. The non-Bragg and Bragg stop bands obtained from the slits embedded between the two surfaces of the TPPWG can be used as notch filters and LPFs. A tunable notch-filter with a good FTS and high Q factor with TM mode can be implemented by adjusting air gaps. Moreover, we performed the first LPF based on multiple Bragg stop bands using different slit width. The transition width of the cutoff is only 68 GHz and the cutoff region of power transmission is 35 dB.

References

[1] E. S. Lee, Y. B. Ji, and T.-I. Jeon, "Terahertz band gap properties by using metal slits in tapered parallel-plate waveguides," Appl. Phys. Lett., Vol. 97, no. 18, pp. 181112, 2010.

[2] M. Theuer, A. J. Shutler, S. Sree Harsha, R. Beigang, and D. Grischkowsky, "Terahertz two-cylinder waveguide coupler for transverse-magnetic and transverse-electric mode operation," Appl. Phys. Lett., Vol. 98, no. 7, pp. 071108, 2011.

[3] E. S. Lee, J. S. Jang, S. H. Kim, Y. B. Ji and T.-I. Jeon, "Propagation of Single-Mode and Multi-Mode Terahertz Radiation Through a Parallel-Plate Waveguide"J. Kor. Phys. Soc., Vol. 53, no. 4, pp. 1891, 2008.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No.2011-0001053 and No.2010-0009070), the Grant of the Korean Health Technology R&D Project; Ministry for Health, Welfare & Family Affairs of Korea (A101954).