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THz Wave Generation by Difference Frequency Mixing in Photonic Crystal Cavity

Masahiko Tani, Ping Gu, Kiyomi Sakai, Hideaki Kitahara, Masanori Suenaga, and Mitsuo Wada Takeda

Abstract **– It is known that a defect mode within a photonic band gap is localized in the photonic crystal. This suggests that a high-Q and loss-less cavity for an electromagnetic wave can be realized, and that it is possible to make an efficient and compact oscillator using such a photonic crystal cavity. In this paper we report observation of defect modes in a pseudo-simple-cubic lattice (d=0.4 mm) generated by excitation of a nonlinear crystal (defect layer) embedded in the photonic crystal with femtosecond pulses. The observed defect modes show different magnitudes and frequencies for defect layers with different thickness, suggesting a layer-thickness dependence of the defect modes. For the purpose of an efficient generation of narrow band THz radiation by difference frequency mixing (DFM) in the photonic crystal cavity, an experimental scheme using a chirped pulse beating is proposed.**

I. INTRODUCTION

The periodic dielectric structures, so-called as photonic crystals, are attracting much attention because of their peculiar optical properties [1-4]. The most striking one is the photonic band gap (PBG), where no propagating electro-magnetic mode exists. When a defect is introduced in a photonic crystal, local electromagnetic modes can occur within the forbidden band gap. The photonic crystal acts as a high-Q cavity for such local modes. In terahertz (THz) frequency range, a high-Q cavity has been difficult to realize due to a serious loss/absorption in the cavity. However, it is now feasible to achieve unprecedentedly high-Q cavity in the THz frequency range by using defect modes in a photonic crystal. Such a high-Q cavity can be used, for example, in a parametric or solid-state oscillator, a frequency filter for THz radiation, etc.

In this report we investigate defect modes in square-air-rod pseudo-simple-cubic lattice [5] formed in Si by using the THz time-domain spectroscopy (TDS). The defect modes were introduced by inserting a dielectric layer between the two photonic crystals. Nonlinear crystal (<110>-cut ZnTe crystal) substrates with different thickness were used as the dielectric defect layers so that THz radiation can be generated by the difference frequency mixing (DFM) within the defect layer. Firstly, we measure the transmission spectra of the photonic crystal with a defect layer by a standard THz TDS measurement. It revealed the existence of several defect modes within the PBG region. Secondly, we excited the nonlinear crystal with femtosecond laser pulses and generated THz radiation within the photonic crystal. By detecting THz radiation emitted from the photonic crystal, we can investigate dynamics of the defect modes and the effect of photonic crystal on the nonlinear process of the difference frequency mixing.

II. PHOTONIC CRYSTAL STRUCTURE

Fig.1 shows the structure of the pseudo-simple-cubic photonic crystal made with Si (ε_d =11.4). The lattice constant is 0.4 mm, and the filling factor is about 0.82. The detailed fabrication process and dimension of the lattice was described in the previous paper of this

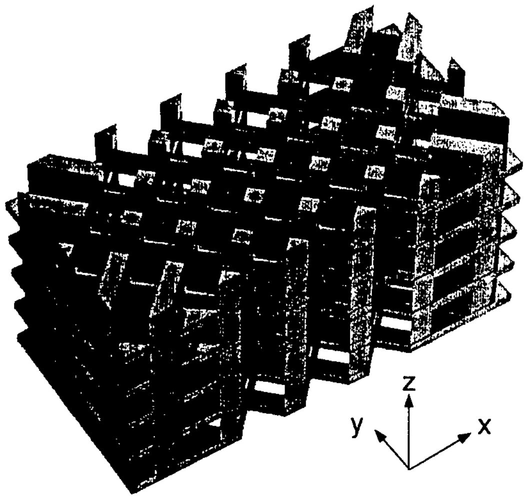

Fig. 1: Structure of the pseudo-simple-cubic lattice structure. The lattice constant is 0.4mm.

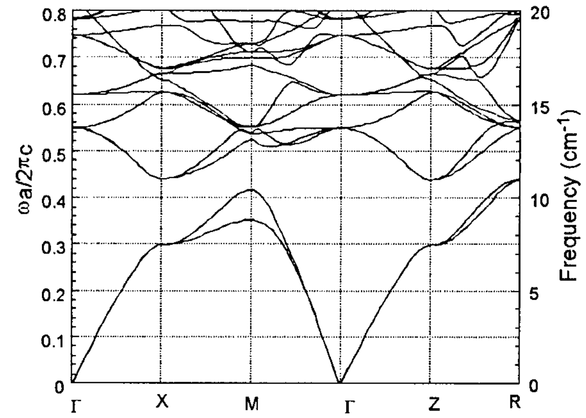

Fig. 2: Photonic band structure of a infinite, pseudo-simple –cubic lattice composed of parallel square air-rods formed in silicon(ε_d=11.4).

Masahiko Tani, Ping Gu, and Kiyomi Sakai are with Kansai Advanced Research Center, CRL, 588-2 Iwaoka, Kobe 651-2492, Japan
Hideaki Kitahara, Masanori Suenaga, and Mitsuo Wada Takeda are with Department of Physics, Faculty of Science, Shinshu University, Matsumoto 390-8621, Japan

Conference [6]. The band structure of the photonic crystal calculated by the plane-wave expansion method is illustrated in Fig. 2.

III. THZ TIME DOMAIN SPECTROSCOPY OF THE PHOTONIC CRYSTAL

In order to investigate spectroscopic characteristics of the photonic crystal, we carried out the THz TDS in a conventional scheme using low-temperature-grown (LTG) GaAs photoconductive antennas as the THz emitter and detector. The detailed description of the spectroscopic system is the same as that of in ref [6]. The measured transmission spectrum and phase shift for a ten-layer photonic crystal in Γ-Z direction are shown in Fig. 3 and the calculated ones (for eight layers) by using transfer matrix method are shown in Fig. 4, respectively. The experimental and calculated spectra show a good agreement between them. The experimental data shows a clear stop band from 6.5 to 10.2 cm^{-1} (1 cm^{-1} = 30 GHz), which is very close to the first PBG calculated as shown in Fig. 4. The phase shift also shows a close correspondence between the experimental data and the calculation. For the experimental phase shift in the second transmission band of Fig. 3 we included a π phase change across the PBG. The periodic spectral peaks observed both in the experiment and calculation originated from the Fabry-Perot effect in the finite size of the photonic crystal [6].

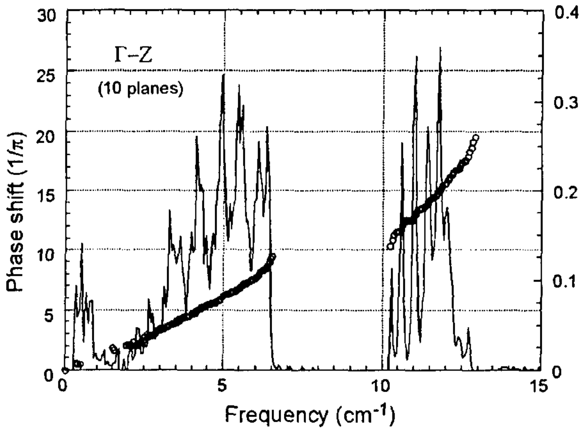

Fig. 3: Transmission amplitude (solid line) and phase shift (open circle) spectra of the pseudo-simple-cubic photonic crystal observed along the Γ-Z direction

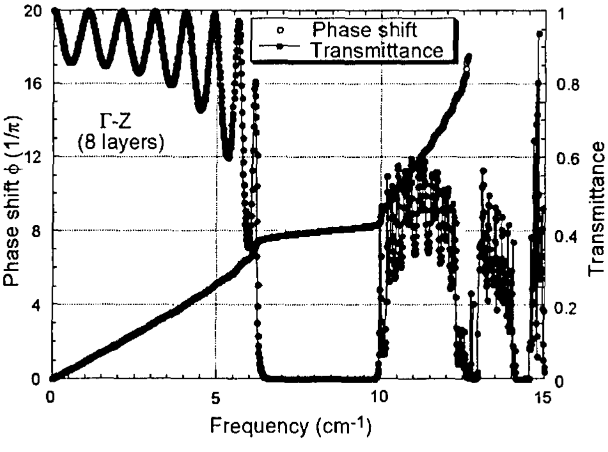

Fig. 4: Transmission (solid circle) and phase shift (open circle) spectra of the pseudo-simple-cubic photonic crystal calculated by the transfer matrix method along the Γ-Z direction for a sample with 8 layers.

In order to introduce defect modes in the photonic crystal, a <110>-cut ZnTe substrate was sandwiched by the photonic crystals with 4 layers. We prepared samples with different thickness of the defect layer: d = 0.3, 1.0, 1.3 mm. These samples were measured by the THz TDS. The results are shown in Fig. 5. In the PBG region non-zero transmission is observed for all the cases. We observe strong spectral peaks near 7 cm^{-1} for the defect layer thickness of 0.3 mm and 1.3 mm, while for the 1.0-mm thick defect the peak is not so distinct. There are also several sub-peaks in the band gap region (6.5-10.2 cm^{-1}). These peaks can be attributed to defect modes induced by the defect layer.

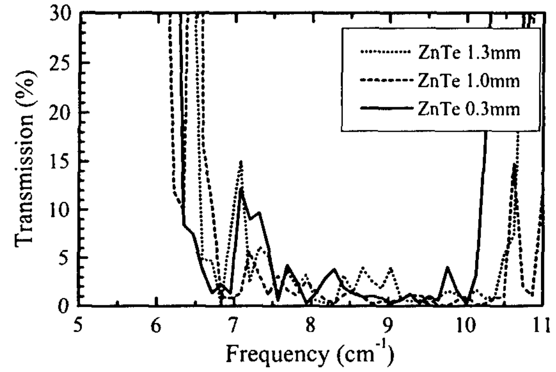

Fig. 5: The transmission spectra for photonic crystals with a defect layer inside. The thickness of the defect layers was 0.3 mm (solid line), 1.0 mm (dashed line) and 1.3 mm (dotted line), respectively.

IV. EXCITATION OF DEFECT MODE WITH FEMTOSECOND LASER PULSES

We tried to excite defect modes within the photonic crystals with a defect layer of thickness d=0.3 mm and 1.3 mm by excitation with femtosecond laser pulses. The defect layer is a <110>-cut ZnTe, which is known as an efficient emitter of THz radiation. The THz radiation is generated in the ZnTe crystal due to the optical rectification effect. This excitation process is also explained by the difference frequency mixing between different frequency components in the broad optical frequency spectrum of the femtosecond pulse.

The excitation pulses were delivered from a mode-locked Ti: sapphire laser, whose pulse width, repetition rate, and the center wavelength were 80 fs, 82 MHz, and 810 nm, respectively. The laser beam was focused by a lens (f=250 mm) to the defect layer through an air hole in the photonic crystal in direction of the z-axis. The radiation emitted from the opposite side of the sample was

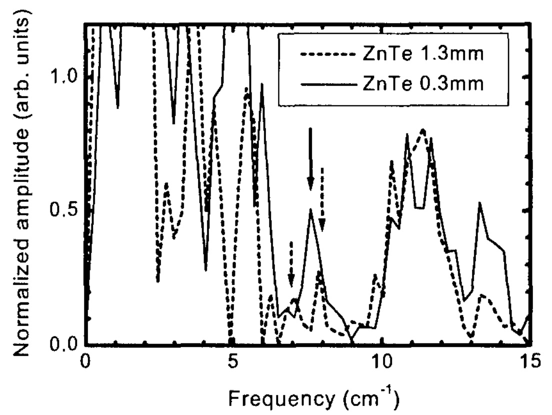

Fig. 6: Emission spectra from photonic crystals with defect layer of 0.3-mm thick (solid line) and 1.3-mm (dashed line) ZnTe. Defect modes observed are indicated by vertical arrows.

collected and focused on to an LTG-GaAs photoconductive dipole antenna (50-μm long) by using a pair of off-axis parabolic mirrors. The THz emission spectra normalized by that without photonic crystals are shown in Fig. 6. For the defect layer with 1.3-mm ZnTe, we observe peak spectra at 7.0 cm^{-1} and 7.8 cm^{-1} (indicated by dashed vertical arrows). The former peak corresponds to the peak observed in the transmission spectrum at 7.0 cm^{-1}. The latter peak observed at 7.8 cm^{-1} also coincides well with a peak at 7.7 cm^{-1} observed in the transmission spectrum. For the defect layer with 0.3-mm thick ZnTe, a strong peak at 7.6 cm^{-1} (indicated by a solid vertical arrow) is observed. This mode is not clear in the transmission spectrum in Fig. 5. The reason why we observe a defect mode that is not observed in transmission measurement is not clear for present. One possibility is the difference of the symmetry for the transmission and excited modes: in the transmission spectrum we can only observe even modes regarding to the mirror symmetry for the z-y or z-x plane because the electromagnetic oscillations are symmetric for a plane, which is along z-axis and vertical to the polarization direction. On the other hand the electrical polarization generated by the optical rectification is not necessarily symmetric with respect to the z-axis, and thus can excite non-symmetric modes.

Although the femtosecond laser excitation is useful for investigation of defect modes generated in the photonic crystal, the enhancement of generation of THz emission due to the cavity effect is not strong because of the short coherence length of the femtosecond pulse (~30 μm in free space). To observe enhancement of THz radiation at defect modes, it is better to use an optical beat whose beat frequency is tuned to the defect mode frequency. However, in a completely continuous wave DFM, the peak intensity of the generated THz wave is expected to be week and thus it is difficult to achieve peak intensity needed for THz wave to interact with the strong pump beam. To obtain a strong peak intensity of the THz radiation we can use optical beating pulses or pulse trains by using chirped femtosecond laser pulses. An efficient way for generation of an optical beat and generation of narrow band THz radiation by the use of the chirped pulses was demonstrated by Weling *et al* [7], recently. The optical beat can be generated by superimposing two chirped femtosecond pulses with different time-delay. The difference frequency between the two chirped pulses is kept constant over the chirped pulse duration when the chirping rate is constant. Figure 7 shows the waveforms of THz radiation generated by excitation of a photoconductive antenna with such chirped beating pulses. By changing the delay-time between the two chirped pulses, the beat frequency can be tuned arbitrarily. Three waveforms excited with beat frequencies at around 150, 230 and 500 GHz are shown in Fig. 7(a). Figure 7(b) shows their corresponding FFT spectra. The spectral bandwidth of the radiation generated by the optical beat is about several tens GHz. The experiment to observe narrow band THz radiation from defect modes by excitation with the chirped optical beating pulses is now under way.

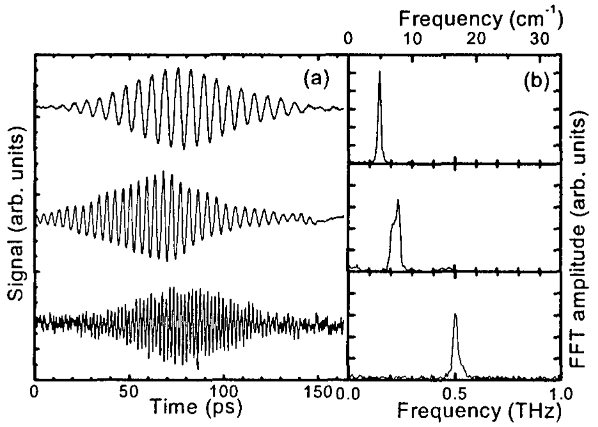

Fig. 7: (a) THz waveforms generated by excitation of a photoconductive antenna with chirped beating pulses, and (b) their FFT spectra.

V. CONCLUSION

We have demonstrated generation of THz radiation from defect modes in a pseudo-simple-cubic photonic crystal by excitation of the ZnTe defect layer with femtosecond laser pulses. Several defect modes were clearly observed, whose frequency and amplitude were depending on the thickness of the defect layer. This is the first observation of THz wave generation due to the defect modes of a photonic crystal.

Acknowledgement

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