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CHARACTERISTICS OF THz-WAVE RADIATION USING A MONOLITHIC GRATING COUPLER ON A $LiNbO_3$ CRYSTAL

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Abstract

Wide tunable terahertz (THz) wave generation was successfully demonstrated utilizing a grating coupler fabricated on the surface of a $LiNbO_3$ crystal which was pumped by a Q-switched Nd:YAG laser. In this paper, we report the detailed characteristics of the oscillation and the radiation including tunability, spatial and temporal coherency, directivity, and efficiency. Oscillation using a $LiTaO_3$ crystal was also performed, in which experimental phasematching condition values agreed well with the calculated one.

Introduction

The development of coherent and tunable THz-wave radiation, based on the spectroscopic studies, has had a substantial impact on the basic physical understanding of this unexplored wavelength region , and opens new applications in the fields of material science, the life sciences and future high-speed optical communication. Tunable THz-wave generation, using nonlinear optical methods, had been widely reported where difference-frequency mixing between two laser sources was utilized, though the conversion efficiency observed was poor[1,2]. In contrast, higher conversion efficiency was obtained by simultaneous Raman and parametric oscillation, utilizing the polariton mode scattering of $LiNbO_3$ based on the 248 cm^{-1} A_1-symmetry soft mode [3-

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5]. This method used a single fixed optical source, and was performed at room temperature. The idler (in this paper, we ascribe this term to the higher energy wave of NIR) and signal (THz) waves were generated from the pump (NIR) wave in the direction consistent with the non-collinear phase-matching condition inside the $LiNbO_3$ crystal. The idler wavelength was longer by a few nanometers than the pump wavelength. A widely tunable coherent terahertz wave could easily be generated by slightly changing the incident angle of the pump beam. The nonlinearity arises from both the electronic and vibrational contributions of the material, and the tuning was accomplished by controlling the propagation constants. Although the interaction between waves was generated by stimulated oscillation, most of the generated THz wave was absorbed or totally reflected inside the crystal due to the material's large absorption coefficient and large refractive indices (5.2 at the THz range[6]). Therefore, it was rather difficult to couple out the THz radiation efficiently to the free space. In previously reported work[3-5], a specially prepared crystal was used, one corner of which was cut and polished at the proper angle to allow the signal radiation to emerge approximately normal to the exit surface, so that the problem of total internal reflection was avoided.

In the work reported here, a grating structure on the surface of $LiNbO_3$, to couple out the THz wave directly to the free air space with higher efficiency[7,8], was employed. As far as the authors are aware, the nonlinear optical generation of the tunable THz-wave has not been reported due to the alternative and successful use of submillimeter gas lasers. The authors thought it was worth reviving the coherent terahertz radiation by optical parametric oscillation (OPO) with a monolithic grating coupler as a convenient tunable THz-wave source.

Experimental Methods

Our experimental setup is shown in Fig.1. A 3.5mm-thick $LiNbO_3$ z-plate was cut to a dimension of 50(x)×10(y)×3.5(z) (mm^3). Two end-surfaces in the x-plane were cut parallel, polished and anti-reflection (AR) coated for operation at 1.07μm. The grating coupler was fabricated on the y-surface by the precise machining using DISCO cutter (DAC-2SP/86) as shown in Fig.2, and the grating pitch and length were 125μm and 10mm, respectively. Four different depths of grating, 20μm, 40μm, 60μm, and 100μm, were formed on the sample to investigate the coupling efficiency. The crystal was placed inside the cavity as shown in Fig.1, which was resonated by the idler wave using two high-reflection mirrors, M1 (f=∞) and M2 (f=10m). Both mirrors were half-area coated, so that only the idler wave could resonate and the pump beam propagate through the uncoated area without scattering. The mirrors and crystal were mounted on a rotating stage which was computer controlled. The pump source was a Q-switched Nd:YAG laser (SOLAR LF113, 1.064μm) whose electric field was along the z-axis. The pump power, pulse width, and repetition rate were 30mJ/pulse, 25nsec, 16.7Hz respectively. The pump beam entered X surface of the crystal and passed through the $LiNbO_3$ crystal close to the surface of the grating coupler. The THz-wave radiation was monitored with a 4K Si-bolometer (Infrared Lab.). A white polyethylene lens (f=60mm) was set in front of the bolometer to focus the THz-wave radiation.

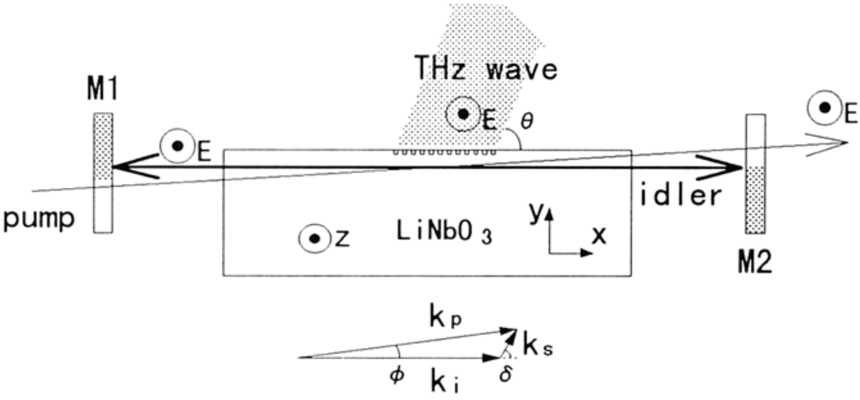

Fig.1 Experimental cavity arrangement for the THz-wave radiation utilizing a monolithic grating coupler on the y-surface of the $LiNbO_3$ crystal.

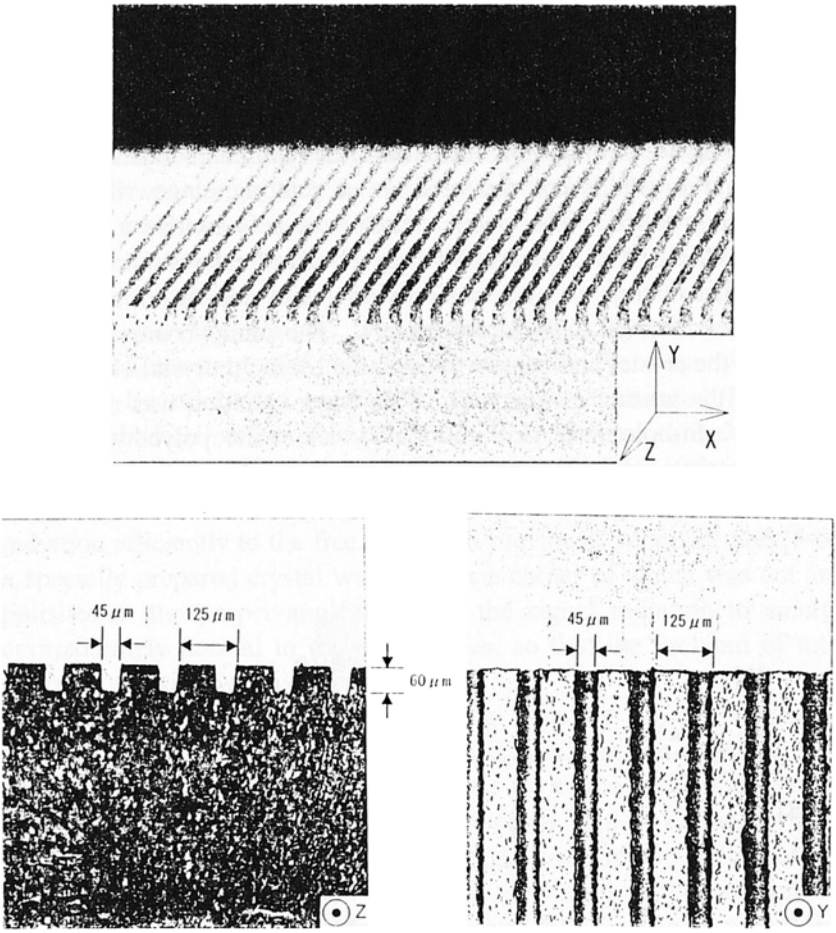

Fig.2 Magnified view of the grating coupler formed on the y-surface of $LiNbO_3$ crystal.

Oscillation characteristics

The pump, the resonated idler, and the generated THz waves were directed in a manner consistent with the noncollinear phase-matching condition as shown in the insert of Fig.1. By varying the incident angle of the pump beam from 2 to 1 deg., the angle ϕ between the pump and idler inside the crystal was changed from approximately 1 to 0.5 deg. As the phase matching angle changed, the idler and the signal wavelength were tuned from 1.072-1.068μm and 140-290μm, respectively, as depicted in Fig.3. The angle δ between the signal and idler inside the crystal changed from 66 to 65 deg. We also found that $LiTaO_3$ was capable of oscillating in the same cavity. In the case of $LiTaO_3$, we needed to make the incident angle of the pump larger than that of $LiNbO_3$ as shown in Fig.3.

The signal wavelength and its linewidth were measured by a scanning Fabry-Perot etalon consisting of two metal mesh plates. Fig.4 shows an example of the measurement. The displacement of one of the metal mesh plates corresponds directly to a half of the wavelength. The free spectral range (FSR) of the etalon was about 83GHz, and the linewidth was measured to be less than 15GHz. It is expected that the linewidth will be dramatically narrowed introducing the quasi-phase-matching method using domain inverted structure[9].

Fig.5 summarizes the input-output characteristics of the oscillation. The signal output from a 10mm long grating coupler was measured to be 3mW with a pump power of 34.5mJ/pulse. Accordingly, we could obtain almost 15mW of output from the grating coupler on the whole Y surface of the crystal (50mm length). We also made an angled surface[6] at the end corner of the crystal, then we only got 5μW at best, under the same conditions. In comparison to the angled surface, the grating coupler had an efficiency of better than × 1000. Fig.6 shows the polarization characteristics analyzed by a wire grid polarizer, and it can bee seen that the THz-wave was linearly polarized along the z-axis .

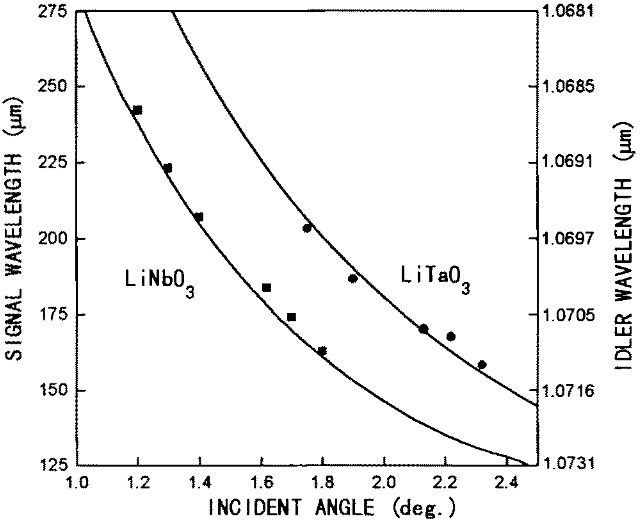

Fig.3 The tuning characteristic between the incident angle of the pump to the x-surface of the crystal normal, generated idler, and signal wavelength, for $LiNbO_3$ (square dots) and $LiTaO_3$ (circle dots). Solid curve indicates the calculated tuning curve.

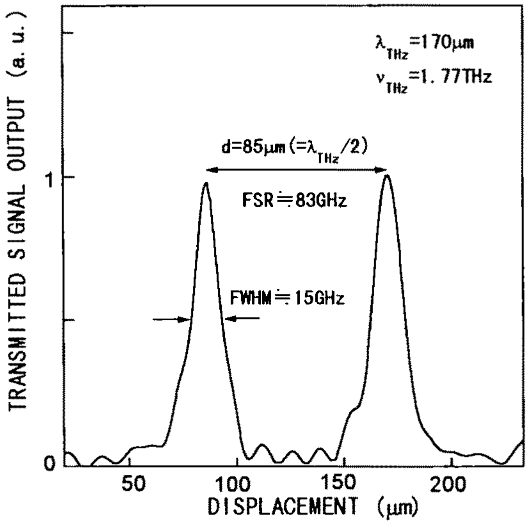

Fig.4 Example of the wavelength and line-width measurement using the scanning Fabry-Perot etalon consisting of metal mesh plates.

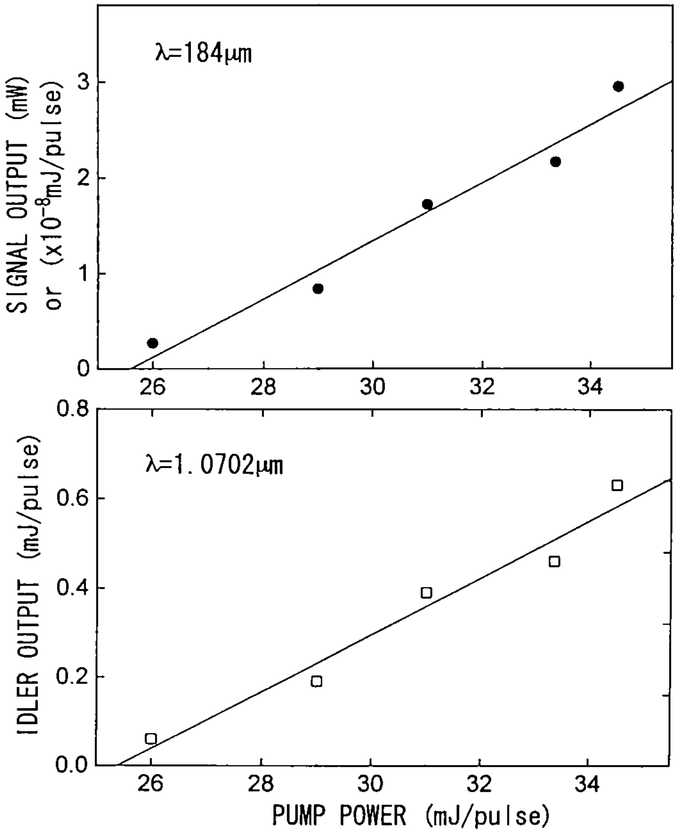

Fig.5 The input-output characteristic of the oscillator.

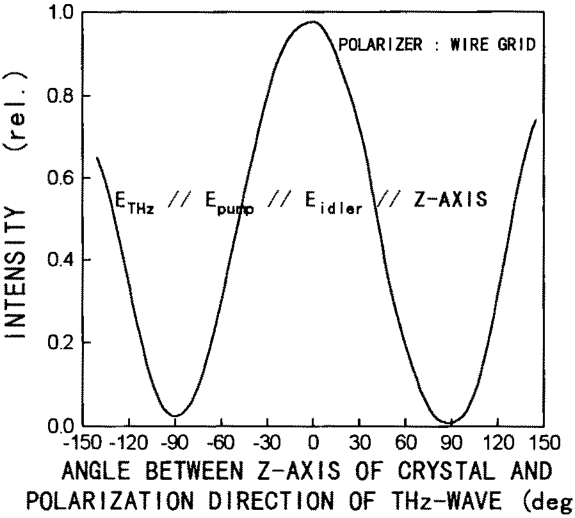

Fig.6 Measured polarization of the generated THz-wave using a wire grid polarizer.

Radiation characteristics of the grating coupler

Figure 7 shows the variation of the diffraction angle θ of THz-wave to the grating plane, with wavelength. The generated wavelengths ranged between 180μm to 270μm, while the radiated angles varied from 45 to 80 deg. This was in good agreement with our prior calculation[7]. The intensity distribution of the generated beam was Gaussian-like both along and perpendicular to the grating, as can be seen in Fig.8. FWHM spot sizes of 8 mm and 12 mm were observed along the grating direction (x) at the measured points of 150mm and 300mm from the grating, which corresponds to a beam divergence of 0.76 deg. While along z-axis, the divergence was determined by the pump spot size, and it was 1.5deg. These results are in good agreement with diffraction theory.

The THz-wave absorption coefficient of $LiNbO_3$ at certain wavelengths was also measured. Keeping the angle condition between the pump and the idler constant, the signal (THz) intensity was measured as a function of crystal displacement d along the y-axis. Fig.9 indicates the relation between the distance d and the intensity of the THz-wave radiated from the grating coupler. Then the absorption coefficient was given by the slope to be α_e=21.2cm^{-1} for λ_{THz}=213μm, and α_e=51.9cm^{-1} for λ_{THz}=184μm in another measurement, both were in good agreement to the previously reported values[6].

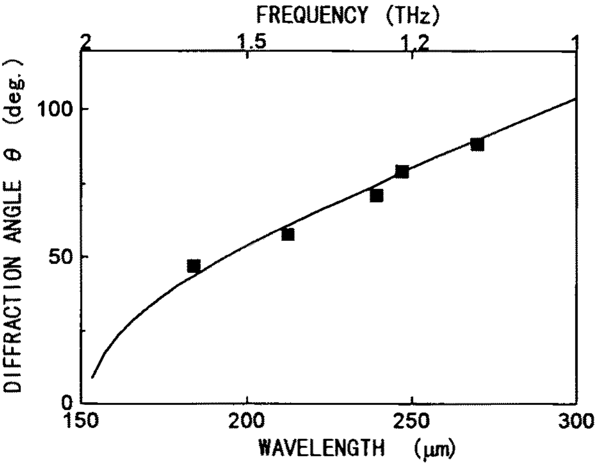

Fig.7 Diffracted angle θ of THz-wave to the grating plane. The solid line shows a calculated result.

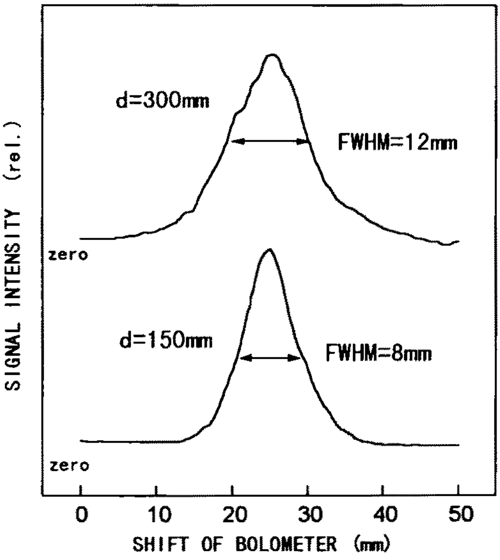

Fig.8 The intensity cross section for the horizontal direction at (upper curve) 300mm and at (lower curve) 150mm from the grating coupler.

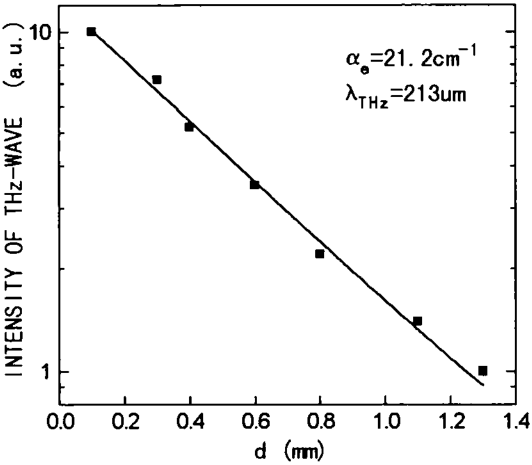

Fig.9 The plot of the output power from the grating coupler versus the distance d traveled by the THz-wave in $LiNbO_3$ before it reaches the grating plane.

Conclusion

We have demonstrated efficient $LiNbO_3$ OPO THz-wave generation from a monolithic grating coupler. Measurements on tunability, coherency, power, polarization, radiation angle, divergence, and absorption have been accomplished, proving this method to be suitable for many application fields. These include spectroscopy, communication, medical and biological applications, THz imaging, and so forth. For tunable THz-wave applications, the simplicity of the wave source is an essential requirement since cumbersome systems do not encourage new experimental thoughts and ideas. Compared with the available sources, the present parametric method has significant advantages in compactness, tunability, and ease of handling. Further study is required for higher efficiency, narrower linewidth and establishing a continuous operation utilizing quasi-phase-matching method with domain inverted structure[9].

Acknowledgment

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