# Contact grating device with Fabry-Perot resonator toward intense THz pulse generation by optical rectification

Masaaki Tsubouchi, Keisuke Nagashima, Fumiko Yoshida, Yoshihiro Ochi, and Momoko Tanaka
Japan Atomic Energy Agency, Kizugawa, Kyoto, 619-0215 Japan

***Abstract*— A novel design for a contact grating device with an incorporated Fabry–Perot resonator is proposed for high-power terahertz light (THz) generation. We deposited a multilayer consisting of $Ta_2O_5$ and $Al_2O_3$ on a magnesium-doped stoichiometric $LiNbO_3$ substrate and fabricated grating grooves on the outermost layer. The multilayer was designed such that conditions for a Fabry–Perot resonator were satisfied for light diffracted by the grating. Consequently, the diffraction efficiency was enhanced by the resonator. The diffraction efficiency of the fabricated device was 77%. THz light generation was also demonstrated with the contact grating device.**

## I. INTRODUCTION

INTENSE THz light is an indispensable tool for nonlinear THz spectroscopy. Presently, the optical rectification in a Mg-doped stoichiometric $LiNbO_3$ (LN) crystal with pulse-front control of the pump pulse is widely used as the most effective method for obtaining intense THz light [1]. To further increase intensity of the THz light with increasing intensity of the pump light, large-area excitation of the crystal is required to prevent damage to the crystal from the intense pump light. The commonly used setup in which the pump pulse front is tilted by a diffraction grating and imaged onto the LN prism, however, is unsuitable for large-area excitation, since any error in imaging of the pulse front increases for large-area excitation and limits the efficiency of THz light generation.

To overcome the problems accompanied with error in imaging, Pálfalvi and co-workers theoretically proposed a "contact grating setup" in which the diffraction grating is placed in contact with the input surface of the LN substrate [2]. The simplest design of the contact grating setup is to have a transmission grating directly fabricated onto the LN surface. However, the diffraction efficiency to obtain the pump light with the tilted pulse front is predicted to be < 20% by numerical calculation, which is too small to realize effective THz light generation [3].

In this paper, we propose the new design to realize a contact grating device with high diffraction efficiency and demonstrate THz light generation with this device [4]. Fig. 1(a) illustrates the concept of contact grating device proposed in this study. A dielectric multilayer is deposited on the LN substrate, and a diffraction grating is fabricated on its outermost layer. The near IR (NIR) pump light irradiates the grating layer at an incident angle $\theta_{in}$. The −1st-order diffraction light is trapped at Layer 1, since the grating layer and Layer 2 compose the Fabry–Perot resonator for the diffracted light. By precise design of the multilayer, we can enhance the transmittance of the diffracted light from the resonator to the LN substrate, which indicates high diffraction efficiency.

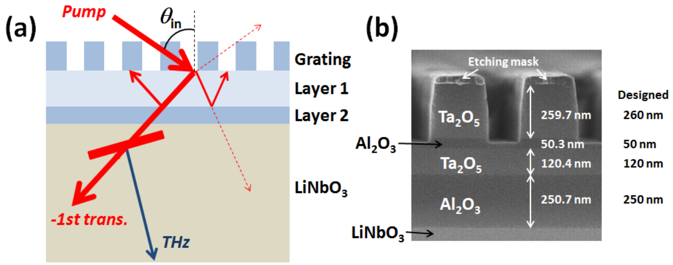

**Fig. 1.** (a) Details of the Fabry–Perot type contact grating device. The arrows show the wave vector of light. The thick bars indicate the pulse front. (b) SEM cross-section image of the fabricated Fabry–Perot type contact grating. This image was taken just before the final etching process in which the etching mask was removed.

## II. DESIGN OF THE CONTACT GRATING DEVICE

For effective THz light generation, we employed a pump light with a wavelength of 1030 nm and a picosecond pulse width generated by a Yb-doped YAG laser, which is preferable rather than a Ti:sapphire laser with 800 nm femtosecond light.

To realize the Fabry–Perot type contact grating device, there are several requirements for the thin layers. First, the refractive index of Layer 2 has to be lower than that of Layer 1 and the LN substrate, since the role of Layer 2 is partial reflector of the diffraction light. Second, the Fabry–Perot type device requires a higher damage threshold against NIR pump light irradiation than that for normal devices, since the pump light is trapped in Layer 1 with a sub-micrometer thickness. Third, there should be no diffusion of the metal atoms through the layers and LN substrate during the deposition process at high temperature. To satisfy these requirements, we selected $Ta_2O_5$ as the material for the grating layer and Layer 1, and $Al_2O_3$ for Layer 2, respectively.

## III. RESULTS AND DISCUSSION

The Fabry–Perot type contact grating device was fabricated on a 1.3 mol% Mg-sLN substrate with dimensions 16 mm (Z) × 20 mm (Y) × 0.5 mm (X). The grooves were etched parallel to the Z-axis with an effective area of 10 mm (Z) × 14 mm (Y). The SEM image, shown in Fig. 1(b), indicates that the multilayer was deposited according to the design with the optimized layer thickness. However, the ridge of the grating was slightly tapered, and the ridge width was measured to be 260–270 nm, which was slightly wider than the optimized value of 252 nm. This small error was produced in the etching process.

For practical use, a thin $Al_2O_3$ layer was inserted between the grating layer and Layer 1 as a buffer layer. In our device, the groove depth of the grating had to be precisely controlled to obtain high diffraction efficiency. Since the $Al_2O_3$ layer was not easily etched by the etching process for $Ta_2O_5$, the $Al_2O_3$ layer acts as a barrier during grooving of the grating layer.

The properties of the fabricated device were evaluated by measurement of the diffraction efficiency with a Yb-doped fiber oscillator as the NIR light source with a wavelength of

1030 nm. The observed diffraction efficiency as a function of the incident angle $\theta_{in}$ is shown in Fig. 2 as the filled circles. The maximum diffraction efficiency was 77% at an incident angle of 44.0° ~ 44.5°, which was very close to the calculated value of 78% at 44.5° shown in the same figure as the solid curve.

THz light generation with the fabricated contact-grating device was performed using the following setup. A high-power Yb:YAG laser with 1030 nm wavelength and 1.3 ps pulse duration was employed as the NIR pump light source. The NIR light was collimated to 3.5 mm in diameter and was used for pumping the contact grating device to generate the THz light. Both the pump and THz light were s-polarized to the device. The THz light was separated from the pump light by a plastic plate with high-reflection coating for the NIR light and a black polypropylene film. The THz light irradiated from the device was collimated by an aspheric plastic lens with a focal length of 50 mm, and focused to the detection point by an off-axis parabolic gold-coated mirror with a focal length of 50 mm. At the detection point, the THz output power was measured by a thermopile detector, and the THz waveform was obtained by free-space electro-optic (EO) sampling in a 1-mm-thick CdTe crystal.

THz output energy as a function of the pump incident angle is shown in Fig. 2 as open squares. Pump energy of 3.0 mJ (18 GW/cm$^2$) was used in this measurement. A maximum THz output of 0.27 μJ was obtained at an incident angle of 43.0° ~ 43.5°. The efficiency of conversion to THz light was $9.0 \times 10^{-5}$ from the input light and $1.4 \times 10^{-4}$ from the diffraction light at an incident angle of 43°. The incident angle with maximum THz output was slightly different from the angle for the maximum diffraction and the phase matching, 44.5°. Figures 3(a) and (b) show the THz waveform and its Fourier-transformed spectrum measured by the EO sampling method, respectively. A monocycle THz electric field was successfully obtained. The spectrum had a center frequency of 0.3 THz and frequency range of 0.1–1.0 THz.

To optimize the conversion efficiency, we examined the thickness of the contact grating device. Since the absorption coefficients of our LN substrate was measured to be 7 cm$^{-1}$ at 0.3 THz, the optimized thickness was predicted to be 1 ~ 2 mm. When we fabricated the device on the LN substrate with the thickness of 2.2 mm, we obtained the THz output of 0.41 μJ with the pump energy of 2.7 mJ and the diffraction efficiency of 70%. The further optimization of the device thickness should be performed by experiments and calculations.

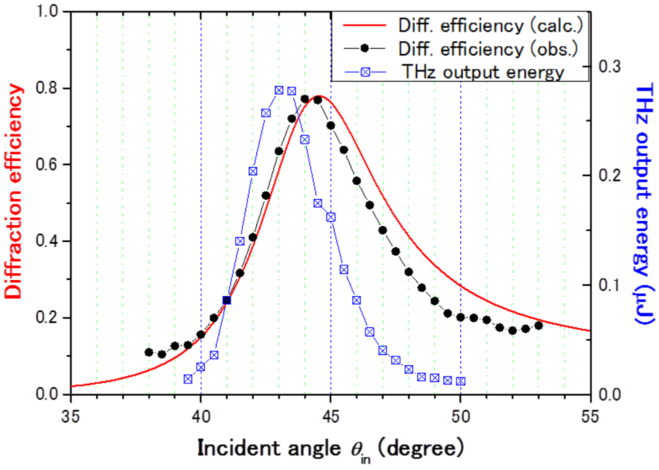

**Fig. 2.** Diffraction efficiency and THz output energy as a function of the pump incident angle. The solid line and filled circles show the calculated and experimental diffraction efficiencies, respectively. The open squares indicate the experimental THz output energy measured with pump energy of 3 mJ.

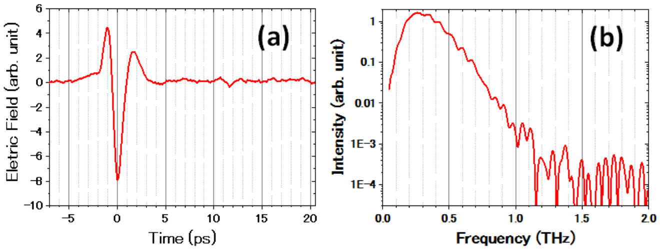

**Fig. 3.** (a) THz waveform and (b) its Fourier-transformed spectrum measured at a pump incident angle of 43.5° with pump energy of 3.0 mJ.

## IV. CONCLUSION

We realized a contact grating device with a Fabry–Perot resonator and demonstrated THz light generation with this device. The maximum diffraction efficiency and THz output were obtained to be 77% and 0.27 μJ, respectively. To further increase the THz output energy, we will design and fabricate a larger device that can be irradiated by a 100 mJ-class NIR pump laser which has been constructed in our laboratory

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