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| 著者 | TANEBE Tadao, Nishizawa Jun-Ichi, Suto Ken, Saito Kyosuke, Kimura Tomoyuki, Oyama Yutaka |
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# THz Generation From GaP Rod-Type Waveguides

Jun-Ichi Nishizawa, *Life Fellow, IEEE*, Ken Suto, *Member, IEEE*, Tadao Tanabe, Kyosuke Saito, Tomoyuki Kimura, and Yutaka Oyama

***Abstract*—Terahertz (THz) generation was demonstrated from GaP rod-type waveguides via difference-frequency-mixing of near-infrared light using a collinear phase-matching condition. THz output peaks were observed, and appeared at frequencies corresponding to the fundamental and high-order waveguide modes. Interestingly, the position of the fundamental mode shifted to a higher frequency for a smaller waveguide cross-section, which is attributed to the waveguide confinement of the THz wave. The conversion efficiency was enhanced in the waveguide with a cross section of 200 $\mu$m $\times$ 160 $\mu$m as compared to that in bulk GaP crystals.**

***Index Terms*—Collinear phase matching, GaP, optical waveguide, phonon-polariton, terahertz (THz)-wave.**

## I. Introduction

THE terahertz (THz) region lies between the radio and infrared (IR) frequencies of the electromagnetic spectrum, and has garnered a great deal of attention lately due to a number of important potential applications [1], [2]. Recently, a tremendous amount of work has been devoted to developing a variety of THz sources. Ultimately, most sources are based upon photoconductive antenna [3]–[5], quantum cascade lasers [6], or nonlinear optical effects such as difference-frequency-mixing (DFM) [7]–[14], optical parametric oscillation [15], and optical rectification [16], [17]. The DFM technique is particularly attractive because it possesses many of the desired features for THz generation, such as high power, single frequency generation, frequency tunability, and room-temperature operation.

In the DFM process, a GaP crystal [7]–[10], [12]–[14] is utilized for THz generation because of its transparent properties in the IR and THz regions of the spectrum, while maintaining a relatively high efficiency for conversion due to phonon-polariton excitations [7]–[10], [14], [18]. In addition, previous work by our group successfully demonstrated the generation of THz waves with bulk GaP crystals when a small-angle noncollinear phase-matched DFM scheme was employed [7]–[9]. As a result of this work, a frequency-tunable THz spectrometer was constructed based on a GaP Raman THz wave generator, and the THz spectra of a variety of important biomolecules (e.g., sugars, nucleosides, nucleotides, and amino acids) were analyzed [19]–[21]. Indeed, for waveguides whose size is on the order of the THz wavelength itself, it is possible to generate THz frequencies using a collinear $\chi^{(2)}$ phase-matching configuration, in addition to developing simple THz generation optical systems. Semiconductor Raman lasers and amplifiers have also been demonstrated by exploiting the waveguide effect, and allow for a sizeable decrease in the threshold pump power (as low as 50 mW) and a Raman gain of $g = 12.3 \times 10^{-8}$ W $\cdot$ cm$^{-1}$ via the confinement of the phonon mode restricted within the GaP waveguides [22], [23]. In this letter, we demonstrate THz generation using a collinear phase-matched DFM optical scheme from GaP waveguides.

## II. Experimental Section

Rectangular semi-insulating GaP crystals (5 mm long) cut in the $\langle 110 \rangle$ direction were used. The width of the crystals was varied from 1 mm to 200 $\mu$m for each thickness of 330 or 160 $\mu$m, respectively. A $Q$-switched Nd : YAG laser (1064 nm, 11-ns pulsewidth, and 10-Hz repetition rate) was used as the signal beam, while a $\beta$-$BaB_2O_4$ (BBO)-based optical parametric oscillator (OPO) was used as the pump beam (6-ns pulsewidth) in the DFM experiment. The OPO was tuned throughout the 1048–1063-nm range. The details of our experimental setup for the DFM optical scheme are shown elsewhere [7], [9]. The YAG and OPO input beams were carefully attenuated to 1.0 and 0.5 mJ, respectively. In addition, the input beams were collimated to 1-mm diameter and directed along the $\langle 110 \rangle$ direction of the GaP waveguide. The E-field polarization of the signal and pump beams was adjusted parallel to the $\langle 110 \rangle$ and $\langle 001 \rangle$ directions, respectively (TE and TM, respectively). The THz wave generated was detected by a liquid helium cooled Si bolometer (Infrared Laboratories, Inc. USA) that had a typical response time of 100 $\mu$s and a sensitivity of $2.57 \times 10^5$ V/W. The bolometer signal was collected and measured with a digital oscilloscope.

## III. Results and Discussion

The THz wave generation was carried out using collinear phase-matched DFM in GaP rod-type waveguides. Figs. 1 and 2 display the output characteristics of the THz wave generated in GaP waveguides of thicknesses 330 and 160 $\mu$m, respectively, and with widths of (a) 1 mm, (b) 500 $\mu$m, and (c) 200 $\mu$m. In those instances where the frequency of the OPO was varied against the fixed-frequency of the YAG source, two THz output peaks were observed, at $\sim$1.3 and 1.8 THz, respectively, and are collected in Fig. 1(a). The peak power of the wave generated at 1.3 THz was 40 $\mu$W (0.24 pJ/pulse). An interesting result was observed when the width of the waveguide was decreased to 200 $\mu$m. Displayed in Fig. 1(c), the peak position observed at 1.3 THz in Fig. 1(a) (width $=$ 1 mm) shifted to $\sim$1.5 THz, and the output power decreased to 7 $\mu$W (0.04 pJ/pulse). Note that the diameter of the incident IR beams was fixed at 1 mm, which, in all cases, was larger than the waveguide cross section. The decrease in the measured output power can be attributed

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J.-I. Nishizawa, K. Suto, and T. Kimura are with the Semiconductor Research Institute, Aoba-ku, Sendai 980-0845, Japan.

T. Tanabe, K. Saito, and Y. Oyama are with the Department of Materials Science, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan (e-mail: tanabet@material.tohoku.ac.jp).

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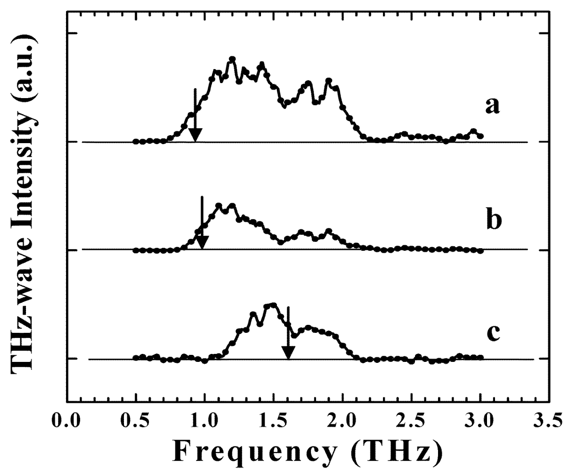


Fig. 1. Frequency dependence of the THz output power for a 330-mm-thick GaP rod-type waveguide with widths of (a) 1 mm, (b) 500 $\mu$m, and (c) 200 $\mu$m. The calculated fundamental mode frequency is shown with an arrow.

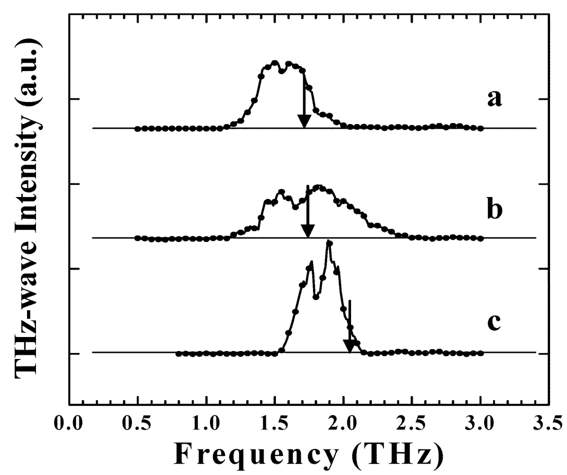


Fig. 2. Frequency dependence of the THz output power for a 160-$\mu$m-thick GaP rod-type waveguide with widths of (a) 1 mm, (b) 500 $\mu$m, and (c) 200 $\mu$m. The calculated fundamental mode frequency is shown with an arrow.

to a reduction of the effective power of the incident beams into the waveguide. Indeed, for the 160-$\mu$m-thick 1-mm wide waveguide in Fig. 2(a), only one peak was observed. Fig. 2 also reveals a shift in peak frequency from 1.6 to 1.9 THz when the waveguide width was reduced from 1 mm to 200 $\mu$m. In contrast to the 330-$\mu$m-thick waveguides, the output peak power of the THz wave increased to 70 $\mu$W (0.42 pJ/pulse) for the cross section of 200 $\mu$m $\times$ 160 $\mu$m, which was most likely due to the reduction of the waveguide width.

The large difference in the refractive index of the bulk GaP crystal between the near-IR and THz regions (i.e., $n_{\mathrm{IR}} < n_{\mathrm{THz}}$) makes it difficult to satisfy the phase-matching condition for DFM in bulk GaP crystals. Actually, $n_{\mathrm{THz}}$ ranges from 3.338 to 3.349 in the frequency from 1.0 to 2.0 THz, where the $n_{\mathrm{IR}}$ is 3.104 at 1064 nm [24]. One can satisfy the phase-matching condition by implementing a small angle between the two incident IR beams and following the phonon-polariton dispersion curve induced by the reststrahlen band of GaP in the THz region [13]. In the context of GaP rod-type waveguides, with cross section $(w \times t)$, the TE-mode effective index $n_{\mathrm{THz},lm}$ arises due to the modal dispersion, which is given by [25]

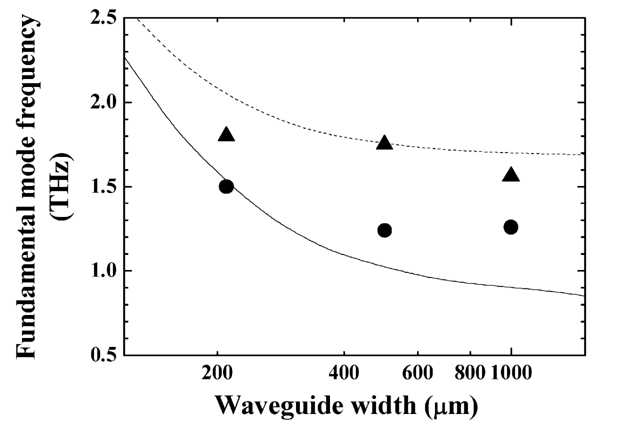


Fig. 3. Measured fundamental mode frequency as a function of waveguide size, 330 $\mu$m (●) and 160 mm (▲). Note, the calculated results for the 330-$\mu$m-thick and 160-$\mu$m-thick waveguides are shown as solid and dashed lines, respectively.

$$q_z = \frac{\omega}{c} n_{\mathrm{THz},lm} = \sqrt{\left(\frac{\omega}{c} n_{\mathrm{THz}}\right)^2 - \left(\frac{\pi}{w} l\right)^2 - \left(\frac{\pi}{t} m\right)^2} \quad (1)$$

where $q_z$ is the propagation constant along the waveguide direction, $l$ and $m$ are integers that correspond to the different orders of the waveguide modes, $\omega$ is the angular frequency, and $c$ is the speed of light. Note, (1) naturally implies a reduction in the refractive index $n_{\mathrm{THz}}$ to $n_{\mathrm{THz},lm}$ within the waveguide, for example, $n_{\mathrm{THz},lm}$ is 3.298 at 1.0 THz for the 330-$\mu$m-thick and 500-$\mu$m-wide GaP waveguide, while that of the bulk GaP, $n_{\mathrm{THz}}$ is 3.338. Thus, the phase-matching condition can be achieved using a collinear optical configuration. These results indicate that the observed THz output corresponded to the fundamental and high-order transverse electrical modes (TE-mode) in the waveguide thickness. The calculated frequency positions for the fundamental mode are designated by the arrows displayed in Figs. 1 and 2. The relationship between the fundamental mode frequency and waveguide size is displayed in Fig. 3. In order to supplement the experimental data, the calculated results obtained, taking into account modal dispersion for the rod-type waveguides (1), are displayed as solid and dashed lines in Fig. 3, where reported values for the refractive index of GaP are used [24]. When the size of the waveguide was reduced, a shift in the position of the fundamental towards a higher frequency was observed. This remarkable tendency is consistent with the calculated results in all cases except for the 330-$\mu$m-thick 1-mm-wide GaP waveguide.

The conversion efficiencies for THz wave generation from the rod-type waveguides were estimated from the results highlighted in this work, and are displayed in Fig. 4. The generated THz power $(P_3)$ is proportional to the power of the two incident beams ($P_1$ and $P_2$, respectively), and the conversion efficiency in the DFM scheme is given by

$$\eta = P_3/P_1P_2 \ (\text{in W}^{-1}). \quad (2)$$

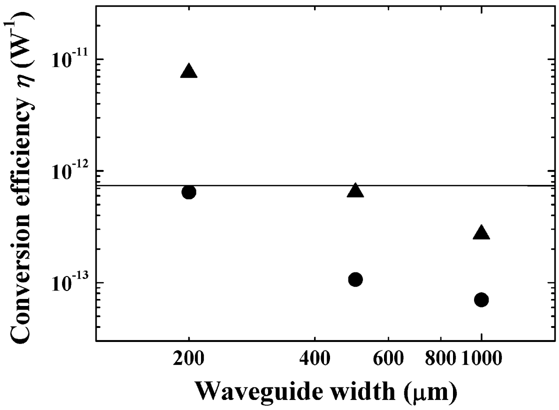


Fig. 4. Conversion efficiency for THz wave generation in the waveguides with thicknesses of 330 $\mu$m (●) and 160 mm (▲), respectively. The solid line represents the experimental results from the bulk GaP crystal [9].

Note, the effective input power was estimated by taking into account the incident beam diameter and waveguide cross section. In the context of the change in conversion efficiency observed, Fig. 4 reveals the inverse relationship that exists for smaller waveguide-sizes and higher conversion efficiencies. As a proof-of-principle example, the waveguide with cross section 200 $\mu$m $\times$ 160 $\mu$m led to a conversion efficiency of $7.6 \times 10^{-12}$ $W^{-1}$. Note, this value is approximately an order of magnitude greater when compared to the bulk 5 mm-length GaP crystal value ($7.4 \times 10^{-13}$ $W^{-1}$) [9].

## IV. Conclusion

THz generation using small GaP rod-type waveguides in a collinear phase-matched DFM optical scheme has been demonstrated. For waveguides whose size was on the order of the wavelength of the THz wave, the THz output peaks appeared at different frequency positions corresponding to the fundamental and high-order waveguide modes. The results emphasize how the measured fundamental mode shifts to a higher frequency when the waveguide cross section is reduced. As a result of the waveguide confinement of the THz wave, the conversion efficiency for THz generation improves for smaller waveguides. Although the peak power of the THz wave is pico-W order, the improvement of the THz power could be possible by using a longer GaP waveguide as well as a cooled GaP which has a lower absorption coefficient of THz wave.

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