Continuous-Wave Frequency-Tunable Terahertz-Wave Generation From GaP

Jun-ichi Nishizawa, *Life Fellow, IEEE*, Tadao Tanabe, Ken Suto, *Member, IEEE*, Yusuke Watanabe, Tetsuo Sasaki, and Yutaka Oyama

***Abstract*—Continuous-wave (CW) single-frequency terahertz (THz) waves were generated using difference-frequency generation via excitation of phonon–polaritons in GaP. The two pump sources were an external cavity laser diode (LD) and an LD-pumped Nd : YAG laser. The power density of the latter beam was enhanced by using a ytterbium-doped fiber amplifier. The two incident beams were focused to near the wavelength of THz waves. This optical alignment enabled us to generate frequency-tunable CW THz waves in the 0.69–2.74 THz range. With a fixed angle between the pump beams, we obtained a frequency bandwidth as large as 600 GHz.**

***Index Terms*—Continuous-wave (CW), frequency-tunable, GaP, phase matching, phonon–polariton, terahertz (THz)-wave.**

I. Introduction

MANY terahertz (THz)-wave sources have been recently developed [1]–[10], and THz technologies have increased in many fields [11]–[13]. Nevertheless, most THz waves are generated by pumping with Q-switched or femtosecond laser pulses. However, pulsed THz waves have limited applications. Until now, the developments of continuous-wave (CW) THz waves generation have been limited [14]–[22], in which quantum cascade lasers have reached better performance [19]–[22]. The CW THz waves can be used for carriers and modulators in telecommunications, and CW THz waves pumped using semiconductor lasers have such a narrow linewidth, of a megahertz (MHz) order, that we can obtain high-resolution THz spectra rapidly. Also, a narrow linewidth is an essential requirement for multichannel telecommunication. Semiconductor lasers are stable at light intensities, and spectrometers using CW THz waves do not need prolonged measurements with much repetition. Imaging using CW THz waves will enable *in situ* security screening techniques.

In 1963, Nishizawa proposed THz-wave generation from compound crystals via the excitation of phonons or molecular vibrations [1], [2]. An electromagnetic wave with a frequency of 12.1 THz was generated from a GaP Raman laser, at a power of 3 W [5], [6]. Recently, wide-frequency-tunable high-power THz waves have been generated from GaP, by pumping with a Q-switched YAG laser and an optical parametric oscillator [23]–[25]. THz waves were generated using difference frequency generation via the excitation of phonon–polaritons in GaP, which converts energy very efficiently, and the THz wave had a pulsed energy of 9 nJ/pulse (peak power of 1.5 W) [26].

On this basis, frequency-tunable CW THz-wave generation from GaP should be possible by enhancing the power density of incident beams from semiconductor lasers. While the beam power is limited, the THz-wave output power (P_{THz}) can be increased in inverse proportion to the beam spot size S based on the following equation:

$$P_{\mathrm{THz}} = \frac{A}{S} \cdot P_1 \cdot P_2 \quad (1)$$

where A is the coefficient for generating THz waves from GaP at 1 μm pumped under noncollinear phase-matching conditions. A is estimated to be 0.4×10^{-13} $\mathrm{W}^{-1} \cdot \mathrm{cm}^2$ from the results of pulse pumping [23]–[25], S is the spatial overlap of the cross-sectional areas of the pump and signal beams, and P_1 and P_2 are the effective powers of the pump and signal beams, respectively. The enhancement of the beam power densities by decreasing the sizes of the beams could be applied on a collinear phase-matching [27], [28]. However, in the collinear phase-matched DFG, the near-infrared (IR) radiations have to be filtered out enough to detect THz waves. In sweeping the THz-wave frequency, each wavelength of the two near-IR lights has to be separately tuned.

This report describes the generation of widely tunable CW single-frequency THz waves from GaP based on laser diode (LD) pumping, in which the incident beams were focused to spot sizes near the wavelength of THz waves to enhance the power densities.

II. Experiment

The experimental setup is shown in Fig. 1. The pump and signal lasers used for DFG in GaP were an external cavity laser diode (ECLD) and an LD-pumped Nd : YAG laser (1064 nm) with a ytterbium-doped fiber amplifier (FA), respectively. The wavelength of the ECLD can be varied between 1012 and 1080 nm, with a linewidth of 2 MHz. The power from the ECLD and from the FA was 0.24 and 3.6 W, respectively, before the beams struck the GaP crystal. The diameter of the amplified 1.064-μm beam was 5 mm, and it was focused to a spot about 300 μm in diameter using a lens with $f = 1200$ mm. The ECLD beam was elliptical in cross section (5×2.5 mm) before it was focused with a lens with $f = 600$ mm. The waist of the focused beam was also elliptical and measured 150×300 μm. Neglecting the noncollinear nature of the two beams, then $S = 3.5 \times 10^{-4}$ cm^2. The effective powers of

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J. Nishizawa, K. Suto, and T. Sasaki are with the Semiconductor Research Institute, Sendai 980-0845, Japan.

T. Tanabe, Y. Watanabe, 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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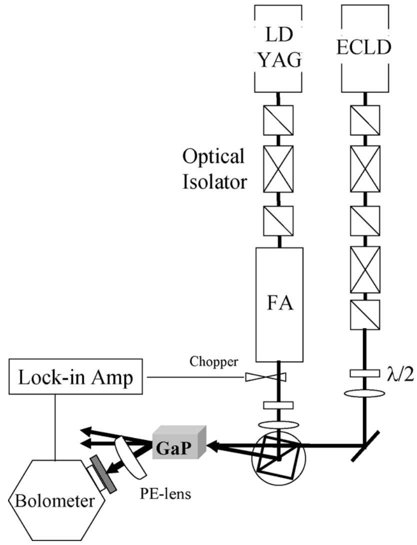

Fig. 1. Schematics of the experimental setup used to generate CW THz waves in GaP using ECLD and LD-pumped YAG lasers and a ytterbium-doped FA.

the pump and signal lights, P_1 and P_2, were 0.24 and 1.8 W, respectively. The expected THz power was 50 pW if the optical alignment were perfect.

A GaP crystal was cut into a rectangle measuring 10 mm in the $\langle 110 \rangle$ direction and 3 mm in the $\langle 001 \rangle$ direction. The pump beam from the ECLD was combined with the signal beam from the FA using a polarizing cube beam splitter. The incident beams were roughly parallel to the $\langle 110 \rangle$ crystal direction of the GaP. The THz-wave output power was collected using a polyethylene lens and detected with a liquid-helium-cooled Si bolometer. The Si bolometer was placed in the direction of the generated THz waves, which leave the GaP crystal output-face at 40 °–45° to the surface normal. Black polyethylene film and 0.8-mm-thick crystalline quartz with garnet powder were used to filter out near-IR radiation, which limited the detectable frequency below 3 THz. The bolometer signal was measured with a lock-in amplifier.

III. Results and Discussion

Fig. 2 shows the phase-matched angle ($\theta_{\rm in}^{\rm ext}$) dependence of the THz-wave output power at various THz frequencies in the 10-mm-long GaP crystal, where $\theta_{\rm in}^{\rm ext}$ is the external angle between the pump and signal beams outside the GaP crystal. THz waves were generated over the range from 0.69 to 2.74 THz, as $\theta_{\rm in}^{\rm ext}$ was varied from $7'$ to $35'$. The THz-wave output peak was experimentally 130 μV which is estimated to be 2 pW at 2.45 THz ($\theta_{\rm in}^{\rm ext} = 21'$), while the power expected from (1) is 50 pW, which can be obtained if beam alignment can be approximated as collinear.

In Fig. 3, the THz-wave output power is plotted as a function of the THz-wave frequency, for $\theta_{\rm in}^{\rm ext} = 12.6'$. The frequency bandwidth for half the maximum power was found to be 600 GHz for the fixed $\theta_{\rm in}^{\rm ext}$, indicating that a wide-frequency-tunable CW THz wave can be generated by sweeping the wavelength of the ECLD even if $\theta_{\rm in}^{\rm ext}$ is kept constant.

The polarization of the pump and signal beams was adjusted to be in the $\langle 001 \rangle$ and $\langle 1\bar{1}0 \rangle$ directions, respectively. The inset

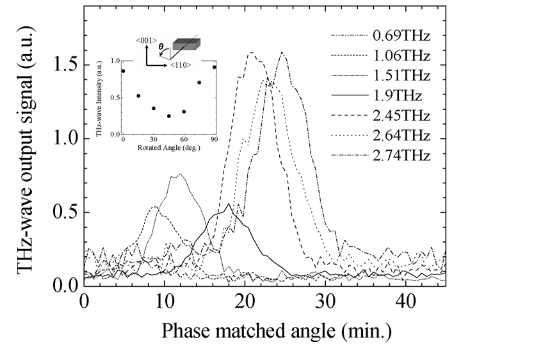

Fig. 2. Phase-matched angle dependence of the THz-wave output power at various THz frequencies in the 10-mm-long GaP crystal. Inset: The dependence of the output power on the angle of rotation of the GaP for 2.45 THz ($\theta_{\rm in}^{\rm ext}$ of $21'$), when the GaP was rotated around the axis of near-IR beams normal to the GaP(110) surface.

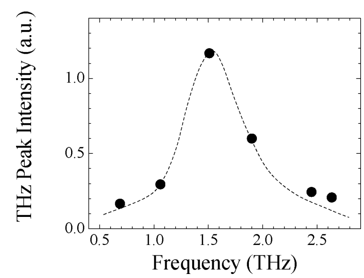

Fig. 3. THz-wave output power is plotted as a function of THz-wave frequency when $\theta_{\rm in}^{\rm ext}$ is fixed at $12.6'$. The dashed line is fitted to the experimental points.

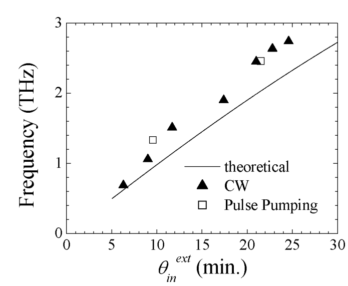

Fig. 4. Dependence of the peak angle position on the THz-wave frequency for the maximum THz-wave output power for each frequency. The symbol (□) represents the result of pulse pumping.

of Fig. 2 shows the dependence of the output power on the angle of rotation of the GaP for 2.45 THz and $\theta_{\rm in}^{\rm ext} = 21'$, when the GaP was rotated around the normal to the GaP (110) output surface. The result shows a clear sinusoidal dependence reflecting the Raman selection rule [29]. The highest output power was obtained at 0° and 90°, while the THz-wave output power decreased to a minimum at 45°.

When the THz wave was fixed at 1.51 THz, the maximum power appeared at $12'$. The width of the angle at half the maximum power was about $6.5'$ when the generated THz-wave frequency was fixed. When the frequency was changed to 2.45 THz, the THz-wave output power increased and the peak phase-matched angle shifted to $21'$. The peak angle position of the THz-wave output power for each frequency observed in Fig. 2 is plotted as a function of THz-wave frequency in Fig. 4, which corresponds to the dispersion curve of the phonon–polariton branch of GaP [30]. The slope of the plotted points is $0.15^\circ/\mathrm{THz} = 2.62$ mrad/THz, while the solid curve, with a slope of 2.91 mrad/THz, is the $\theta_{\rm in}^{\rm ext}$ curve calculated as a function of the THz-wave frequency for the phonon–polariton branch. Increasing $\theta_{\rm in}^{\rm ext}$ shifted the generated THz-wave frequencies slightly higher, similar to the result of pulse pumping [23]–[26].

IV. Conclusion

Widely frequency-tunable CW single-frequency THz waves were generated based on the DFG via excitation of phonon polaritons in GaP using pumping sources consisting of an ECLD and an LD-pumped Nd : YAG laser combined with an ytterbium-doped FA. By tuning the small angle between the two beam directions $\theta_{\rm in}^{\rm ext}$, a CW THz wave in the 0.69–2.74 THz range resulted, while the frequency bandwidth under a fixed $\theta_{\rm in}^{\rm ext}$ was 600 GHz. The frequency of the generated THz wave can be swept widely and easily with external cavity tuning and CW THz waves have very narrow linewidth of MHz. Although the THz power is of picowatt order, power on the order of μW will be available by decreasing the size of the beam overlap using a waveguide effect [31], [32] and by employing a longer GaP crystal [23]–[25], [33], with cooled GaP, which has a low carrier density. When the coherence length $\ell_{\rm coh}$ is sufficiently larger than the crystal length ℓ, the THz power is expected to be proportional to ℓ^2 [33]. In the experiment [23]–[25], the 20-mm-long sample gave the higher THz intensity, though it did not increase as much as expected from ℓ^2 dependence.

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