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Injection-seeded terahertz-wave parametric generator with wide tunability

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We report on the development of a widely tunable (frequency: 0.7–2.4 THz and wavelength: 125–430 μm), injection-seeded THz-wave parametric generator (IS-TPG), which operates at room temperature. The spectral resolution (<100 MHz and 0.003 cm^{-1}) is the Fourier transform limit of the nanosecond THz-wave pulse. The continuous scanning and narrow spectral bandwidth of the IS-TPG were verified in the absorption spectrum of low-pressure water vapor. The high peak power (>200 mW) of the output wave and the small beam divergence are suited to a variety of applications. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1429299]

The THz-wave (very far-infrared) region has attracted significant interest in recent years. Generation of THz radiation by optical rectification or photoconductive switching has been studied extensively using femtosecond laser pulses.[1–4] Applied research, such as time domain spectroscopy, makes use of the high time resolution and the ultrabroad bandwidth, which extends from the MHz to the THz region.

In contrast, our research focuses on the development of widely tunable THz-wave sources with narrow linewidth. Widely tunable sources already exist in the sub-THz (several hundreds of GHz)/ frequency region, such as a backward-wave-oscillator (BWO). However, a widely tunable THz-wave source has long been desired in the frequency region above 1 THz, where the tuning range of a BWO rapidly decreases. Several potential designs for a THz-wave source have been reported,[5–8] although they suffered from one or more of the following undesirable features: (a) large scale, (b) difficulties in operation, (c) narrow tuning range in one operation, (d) the use of liquid He, and (e) unreliability. Therefore, a compact, user-friendly source would be preferable in a variety of laboratory and diagnostic applications.

We have previously reported[9] on a transform-limited, narrow linewidth, injection-seeded THz-wave parametric generator (IS-TPG) based on laser light scattering from the A_1-symmetry polariton mode[10,11] of a MgO:$LiNbO_3$ crystal. In that experiment,[9] the tunability was not obtained because the injection seeder used was a Yb-fiber laser with fixed frequency (1.07 μm). In this letter, wide tunability from 0.7 to 2.4 THz (wavelength: 125 to 430 μm) was observed using an external cavity diode laser as an injection seeder. The continuous scanning and narrow spectral bandwidth of the IS-TPG were verified in the absorption spectrum of low-pressure water vapor. This report also showed the improved input–output characteristics, locking range, and other properties of the IS-TPG.

Figure 1 (upper) shows the experimental setup of the widely tunable IS-TPG used. The TPG gain media consisted of two serial nonlinear crystals (5 mol % MgO:$LiNbO_3$ (Ref. 12), 60 mm long). An array of seven Si-prism couplers was

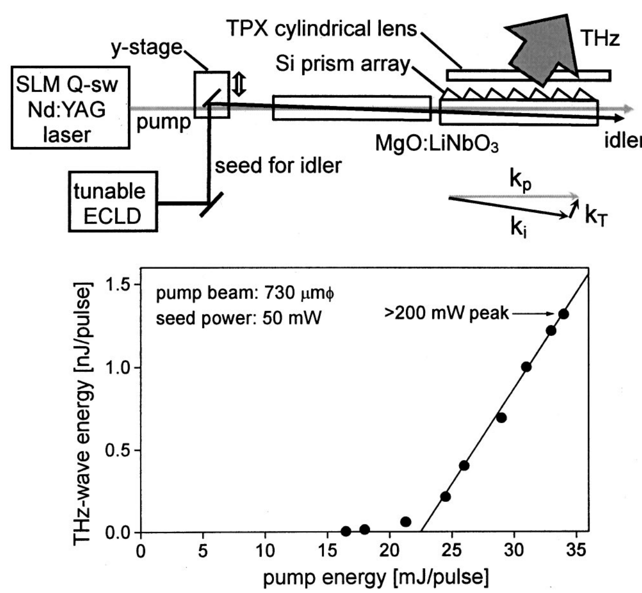

FIG. 1. (Upper) experimental setup for an IS-TPG. The pump was a Q-switched Nd:YAG laser (1.064 μm), and the seed for the idler was a continuous-wave tunable laser diode (1.066–1074 μm). (Lower) the input–output characteristics of the IS-TPG using two MgO:$LiNbO_3$ crystals in series.

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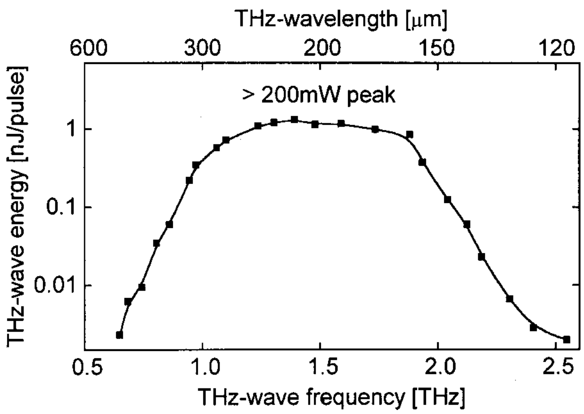

FIG. 2. The wide tunability of an IS-TPG. Dots indicate the experimental results.

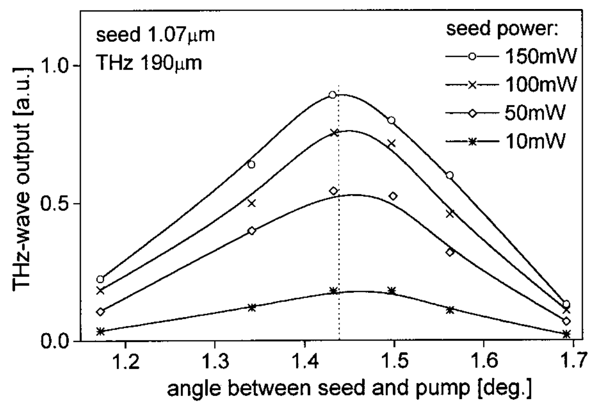

FIG. 3. The locking range of the IS-TPG. The THz and idler (seed) wavelengths were fixed, and the seed incident angle was varied. The seed incident angle shows significant tolerance. The vertical dotted line indicates the phase matching angle (1.43°).

placed on the y surface of the crystal for efficient coupling of the THz wave.[13] As depicted in the inset of Fig. 1 (upper), the idler and THz-waves were generated simultaneously in a direction that satisfied noncollinear phase-matching conditions. The pump used was a single longitudinal mode (SLM) Q-switched Nd:YAG laser (1.064 μm). A continuous-wave SLM-tunable diode laser (1.066–1.074 μm and 50 mW) was used as an injection seeder for the idler. The incident angle of seed was rotated, when necessary, by a mirror on a y stage. The single pass nature of the system makes it rugged and greatly simplifies wavelength tuning, inasmuch as no cavity-locking mechanisms are needed. The THz-wave output and temporal wave form were measured with a 4 K Si-bolometer and a Schottky barrier diode detector,[14] respectively. The typical pulse widths of the pump, idler, and THz waves were 15 ns, 4 ns, and 4 ns, respectively. The polarizations of the pump, seed, idler, and THz waves were all parallel to the z axis of the crystals. The THz-wave beam pattern was nearly Gaussian and had a diameter of 7 mmϕ at a distance of ~40 cm from the Si-prism array, which is suited to a variety of applications. Figure 1 (lower) shows the input–output characteristics of the system. The THz-wave output of 1.3 nJ/pulse (peak>200 mW) was obtained with a pump of 34.5 mJ/pulse and a seed of 50 mW, and is the highest output yet achieved in our research. The Si bolometer became saturated at about 5 pJ/pulse, so two cover glasses were used as an attenuator after calibration. As the minimum sensitivity of the Si bolometer was less than 1 fJ/pulse, the margin of detectivity was $1.3\,\mathrm{nJ}/1\,\mathrm{fJ}>10^6$, which is sufficient for most applications. The detectivity can be further improved by using a lock-in amplifier. A threshold of about 20 mJ/pulse was shown, proving that IS-TPG is not difference frequency generation.

It was possible to tune the THz wavelength using an external cavity laser diode as a tunable seeder. Wide tunability from 125 to 430 μm (frequency: 0.7 to 2.4 THz and wave number: 23 to 80 cm^{-1}) was observed, as shown in Fig. 2, by changing both the seed wavelength and the seed incident angle. The tuning range is limited by the TPG threshold, not by the detectivity of the Si bolometer; there is enough margin in the detectivity, even at the shortest or longest wavelength. In the case of THz-wave parametric oscillator (TPO), which uses a cavity for the idler, the longest wavelength ever observed during our study was 320 μm. In the wavelength region longer than 300 μm, the phase-matching angle between the pump and idler becomes less than 1°, making it difficult for the TPO to oscillate only the idler inside the cavity without scattering the pump.

Figure 3 shows the change in THz-wave output as a function of the seed incident angle. In this experiment, the seed wavelength (1.07 μm) and THz wavelength (190 μm) were fixed, and the calculated noncollinear phase-matched angle was 1.43°. Here, it is important to note that injection seeding was not overly sensitive to the seed incident angle. In addition, the Fourier transform limit linewidth was assured at any deviated incident angle. From this, we see that wavelength tuning for more than 10 μm is possible, simply by varying the seed wavelength, without having to adjust the incident angle. Tuning without mechanical movement will lead to stable, compact spectroscopic systems. Even when the incident angle must be varied for wide tuning, such as in Fig. 2, there is no requirement to precisely control the angle, due to this tolerance. As with the injection seeded TPO,[15] however, the incident angle must be precisely controlled so that it is always perpendicular to the cavity mirror.

Finally, we measured the absorption spectrum of low-pressure (<1 Torr) water vapor to demonstrate the continuous tunability of the IS-TPG. The absorption gas cell used was an 87 cm long stainless light pipe with TPX windows at both ends. Figure 4 shows an example of measurements at around 1.92 THz, where two neighboring lines exist. The tuning in Fig. 4 was produced without changing the seed incident angle. A resolution of less than 100 MHz (0.003 cm^{-1}) was clearly shown in Fig. 4. In fact, it is not easy for Fourier transform infrared spectrometers in the THz-wave region to demonstrate a resolution better than 0.003 cm^{-1} because of the instability of the scanning mirror for several meters. The system is capable of continuous tuning at high spectral resolution in 4 GHz segments anywhere in the 0.7 to 2.4 THz region. The range of continuous tuning is currently restricted by the mode hop of the tunable laser diode. Since there is no cavity to be slaved, continuous tuning is extendible, in principle, to the full tunability of the IS-TPG by using a mode-hop-free seeder, such as a Littman-type external cavity diode laser.

In conclusion, we demonstrated a widely tunable (125–430 μm, 0.7–2.4 THz, and 23–80 cm^{-1}) injection-seeded

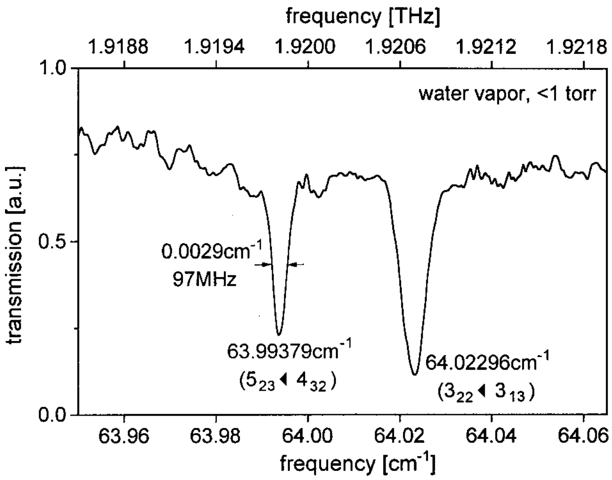

FIG. 4. An example of the absorption spectrum measurement of low-pressure (<1 Torr) water vapor at around 1.92 THz. Resolution of less than 100 MHz (0.003 cm^{-1}) is clearly shown.

THz-wave parametric generator using an external cavity diode laser as a seeder. An output of 1.3 nJ/pulse (peak >200 mW) was obtained using two MgO:$LiNbO_3$ crystals in series. Wider tunability than that of a THz-wave parametric oscillator was confirmed. Fine tuning with high spectral resolution (<100 MHz and 0.003 cm^{-1}) was demonstrated by THz spectroscopy of low-pressure water vapor. This compact system operates at room temperature, and promises to be an useful widely tunable THz-wave source.

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[1] P. R. Smith, D. H. Auston, and M. C. Nuss, IEEE J. Quantum Electron. **24**, 255 (1988).
[2] X.-C. Zhang, B. B. Hu, J. T. Darrow, and D. H. Auston, Appl. Phys. Lett. **56**, 1011 (1990).
[3] O. Morikawa, M. Yamashita, H. Saijo, M. Morimoto, M. Tonouchi, and M. Hangyo, Appl. Phys. Lett. **75**, 3387 (1999).
[4] N. Sarukura, H. Ohtake, S. Izumida, and Z. Liu, J. Appl. Phys. **84**, 654 (1998).
[5] *Free Electron Lasers and Other Advanced Sources of Light* (National Academy Press, Washington, DC, 1994), pp. 24–31.
[6] S. Komiyama, Phys. Rev. Lett. **48**, 271 (1982).
[7] E. Brundermann, A. M. Linhart, H. P. Roser, O. D. Dubon, W. L. Hansen, and E. E. Haller, Appl. Phys. Lett. **68**, 1359 (1996).
[8] E. R. Brown, K. A. McIntosh, K. B. Nichols, and C. L. Dennis, Appl. Phys. Lett. **66**, 285 (1995).
[9] K. Kawase, J. Shikata, K. Imai, and H. Ito, Appl. Phys. Lett. **78**, 2819 (2001).
[10] M. A. Piestrup, R. N. Fleming, and R. H. Pantell, Appl. Phys. Lett. **26**, 418 (1975).
[11] J. Nishizawa, Denki Kagaku **14**, 17 (1963) [in Japanese]; J. Nishizawa and K. Suto, J. Appl. Phys. **51**, 2429 (1980).
[12] J. Shikata, K. Kawase, K. Karino, T. Taniuchi, and H. Ito, IEEE Trans. Microwave Theory Tech. **48**, 653 (2000).
[13] K. Kawase, J. Shikata, H. Minamide, K. Imai, and H. Ito, Appl. Opt. **40**, 1423 (2001).
[14] T. Nozokido, J. J. Chang, C. M. Mann, T. Suzuki, and K. Mizuno, Int. J. Infrared Millim. Waves **15**, 1851 (1994).
[15] K. Imai, K. Kawase, J. Shikata, H. Minamide, and H. Ito, Appl. Phys. Lett. **78**, 1026 (2001).