1.2 A tunable injection-seeded terahertz-wave parametric generator using a compact, diode-pumped Nd:YAG laser.

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Abstract

We developed a compact (30 cm × 65 cm) tunable injection-seeded terahertz-wave parametric generator (is-TPG) with a diode-pumped Nd:YAG laser that was specially designed for pumping the is-TPG. The pump laser, which produced an output energy of 11 mJ in a single Q-switched pulse with a pulse width of 6 ns, was operated with MgO:LiNbO₃ crystals and a seed source for the idler wave. A narrow THz-wave linewidth of less than 33 GHz was achieved by injection seeding of the idler wave. The terahertz-wave energy was increased by a factor of 3 compared to the unseeded energy. Tunability of the terahertz frequency from 1.1 to 2.3 THz was obtained by varying the seeder frequency, and the tunable is-TPG was used to measure water vapor absorption.

1. Introduction

Terahertz-wave radiation sources are of considerable interest in biology, materials science, physics, electronics, imaging, etc. The ultrashort terahertz-wave pulse generated with a femtosecond-laser in a photoconductive device or a bulk-semiconductor emitter has been studied extensively as a broad-spectrum source for terahertz time-domain spectroscopy (THz-TDS) [1]. The practical use of the THz-TDS system in spectroscopic analyses is due to its room temperature operation, the miniaturization using femtosecond fiber lasers, and the high time resolution of the system [2, 3]. In contrast, tunable monochromatic terahertz-wave sources covering the region between 1 and 3 THz are limited to free electron lasers [4], harmonically multiplied backward wave oscillators [5], photo-mixers [6], and p-Ge lasers [7]. These conventional tunable sources have several problems, for example, large size, difficulty operating, liquid He requirement, and low output power.

We studied a THz-wave parametric oscillator (TPO) using noncollinear phase-matching conditions in a LiNbO₃ crystal, pumped with a Q-switched Nd:YAG laser [8]. Despite its simplicity, the TPO was able to operate over a wide frequency range at room temperature. The TPO simultaneously generates a signal wave in the terahertz frequency region and an infrared idler wave (∼1.070 µm) noncollinearly, and the idler wave is resonated in the TPO cavity to obtain narrow linewidth oscillation. Continuous tunability from 1 to 3 THz was obtained by slightly changing the angle between the pump and idler waves, and the typical linewidth of the TPO was approximately 50 GHz. In previous work, narrow linewidth operation (< 200 MHz) was accomplished with injection seeding of both the pump and idler waves [9]. In order to realize mode-hop-free tuning, however, the length of the idler-wave resonator had to be actively controlled using a piezoelectric actuator and a feedback circuit, and this complicated the system design. Therefore, an injection-seeded TPG (is-TPG) that has no resonator is a promising tunable source with a narrow

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Figure 1: Pump laser design for a TPG system. (a) Cross-section of the pump chamber. (b) Resonator configuration for a Q-switched Nd:YAG laser.

linewidth, because the absence of a longitudinal mode offers the potential advantage of mode-hop-free tuning. We achieved a Fourier-transform-limited narrow linewidth ($\sim 100$ MHz) and wide tunability (0.7 - 2.4 THz) by injection seeding both the pump and idler waves\cite{10}.

In spite of its excellent performance, the conventional is-TPG was unsuitable for practical use, since using a flashlamp-pumped Q-switched laser to pump the is-TPG resulted in a large system that required a high-voltage power supply and had a shorter operational lifetime. No one has attempted to produce a practical is-TPG system until now, although a compact, complete is-TPG system using a diode-pumped, solid-state laser (DPSSL) as a pump source is of great interest for future terahertz-wave research. Al-GaAs high-power laser-diodes (LDs) capable of generating a peak power exceeding 1 kW in a quasi-continuous-wave (QCW) mode, are now commercially available; consequently, a high-energy Q-switched DPSSL that is comparable to flashlamp-pumped lasers can now be realized. Recently, we developed a compact DPSSL for TPG pumping, and we have demonstrated a tabletop TPG system with a broad linewidth ($> 1$ THz) \cite{11}, although narrow-linewidth operation in a compact TPG system has not been achieved. Here, we describe the design and performance of a compact, is-TPG system. To our knowledge, this is the smallest complete TPG system to date.

2. Design of the TPG system

A TPG using a LiNbO$_3$ crystal typically requires a pump intensity greater than 100 MW/cm$^2$ to generate a THz-wave. The maximum pump intensity should be less than 500 MW/cm$^2$ in order to avoid optical damage to the LiNbO$_3$ crystal. A pump intensity of 300 MW/cm$^2$ is deemed practical, because it ensures reliable operation, even if other small problems occur, such as thermal lensing and self-focusing. A Q-switched Nd:YAG laser is suitable for pumping a TPG because of its efficiency and reliability. In addition to laser performance, a compact design is also important for a practical system. Therefore, we developed a diode-pumped, Q-switched Nd:YAG laser with a simple side-pumping geometry. Fig. 1 (a) shows a cross-section of the pump chamber, which consists of
a Nd:YAG rod, a fused-silica flow tube for water-cooling, two QCW-LDs mounted on copper heat-sinks, and a ceramic diffuse reflector with two slits for side pumping. Each LD was capable of operating with a 1-kW peak power at a center wavelength of 808 nm. They were operated at a pulse repetition frequency of 20 Hz, which was limited by the duty cycle of the LDs. The laser rod was 3 mm in diameter, 65 mm long, and encased in a fused-silica flow tube. The temperature of the cooling water was maintained at 20°C.

The optical resonator had a cavity length of 190 mm, and was folded using a polarizing beam splitter (PBS) in order to produce an output beam that was linearly polarized along the z-axis of the LiNbO₃ crystals. In Q-switched mode operation, a KD*P Pockels cell Q-switch was operated at a voltage of $\lambda/4$.

With the pump laser used in the previous TPG system, the Q-switched output energy was 12 mJ, and the pulse width was then 12 ns. Although the pump beam was collimated and focused onto the incident surface of the LiNbO₃ crystal using beam-shaping optics, the available pump intensity was at most 200 MW/cm² [11]. By contrast, the present pump laser produced an output energy of 11 mJ in a single Q-switched pulse with a pulse width of 6 ns. A relatively short pulse width is advantageous for reducing the threshold of TPG, since a high pump intensity leads to a high parametric gain. Using the knife-edge method, the $1/e^2$ radii of the laser beam in the horizontal and vertical directions were measured to be 680 and 620 µm, respectively. In addition, the beam quality factors ($M^2_x$ and $M^2_y$) in both directions were determined to be 2.5 and 2.1, respectively. Consequently, a pump intensity of up to 280 MW/cm² is available with the improved pump source, even without focusing optics. This means that we can expect enhanced THz-wave output in smaller and simpler TPG systems.

Figure 2 shows a schematic diagram of a compact TPG system with an injection seeder for the idler wave. The TPG system included the pump source, two nonlinear crystals, and a single-longitudinal-mode Yb-doped fiber laser operating at a wavelength of 1.070 µm. Sixty-five-mm-long LiNbO₃ and MgO:LiNbO₃ crystals were used as nonlinear crystals, and both ends of each crystal were antireflection-coated for a wavelength of 1.064 µm. These crystals were mounted in aluminum holders without cooling. We used a cascade arrangement of two crystals, since this was optimal for generating THz waves efficiently in preliminary experiments that examined several different arrangements. In this system,
the LiNbO$_3$ crystal was only used as an idler-wave generator; that is, THz waves were not extracted from this crystal. After the idler wave was generated from the LiNbO$_3$ crystal, it was incident to the MgO:LiNbO$_3$ crystal, and enhanced during propagation due to the higher gain in the LiNbO$_3$ crystal doped with an optimum MgO concentration (5 mol%). As a result, efficient THz-wave generation occurred, according to the noncollinear phase-matching condition. Since the MgO:LiNbO$_3$ crystal has a large absorption coefficient in the THz-frequency region (> 10 cm$^{-1}$), the pumped region in the crystal must be close to an output-side surface (y-surface). Hence, the distance between the y-surface and the center of the pump beam was precisely adjusted to obtain the maximum THz-wave output in our experiment. In addition, total internal reflection of the THz wave occurs at the y-surface, due to the large refractive index (n $\sim$ 5.2) in this frequency region. In order to achieve efficient THz-wave output-coupling without this problem, we used an arrayed Si-prism coupler (n $\sim$ 3.4) [12], which was placed on the output-side surface of the MgO:LiNbO$_3$ crystal. The y-surface of the MgO:LiNbO$_3$ crystal was polished over its entire length, since a polished surface allows minimization of the coupling gap at the interface with the arrayed Si-prism coupler. The unseeded TPG system is only 400 $\times$ 160 mm$^2$. When an idler seeder is added to the TPG system, the whole system is 400 $\times$ 250 mm$^2$. This is significantly smaller than conventional TPG systems pumped by a flashlamp-pumped Nd:YAG laser (1450 $\times$ 700 mm$^2$)[10].

3. Unseeded operation

The input-output characteristics of the unseeded TPG system were obtained under different pumping conditions. Fig. 3(a) shows the idler-wave energy as a function of the pump energy. Since the pump energy was changed using an attenuator consisting of a half-wave plate and a PBS, the pulse width was fixed during each experiment. After the second-harmonic output ( $\lambda$= 532 nm) from the MgO:LiNbO$_3$ crystals had been blocked using a green-cut filter, the net idler-wave energy was measured using a pyroelectric
Figure 4: (a) THz-wave energy of an injection-seeded TPG system as a function of seeder power for the idler wave. (b) Idler-wave spectra of unseeded and seeded TPGs.

detector. With 6-ns pulse pumping, the maximum idler-wave energy reached 1.4 mJ, which was 3.4 times higher than that with 12-ns pumping. Note that no optical elements were used to focus the pump beam in the case of 6-ns pumping, whereas the previous pumping system used beam-shaping optics, as mentioned above. In addition, the shorter cavity design of the Q-switched laser is also advantageous for constructing a compact TPG system.

THz-wave energies were measured under the same conditions as in Fig. 3(a). Fig. 3(b) compares the THz-wave energies for the two pumping conditions. A 4.2-K Si-bolometer was used to measure the THz-wave energy. With 6-ns pulse pumping, a THz-wave energy of 1.7 pJ was achieved with a pump energy of 11 mJ; the THz-wave energy increased by a factor of 5.7. The higher pump intensity increased the parametric gain for both the THz- and idler-waves, so the increases in both output energies were due to the higher gain with intense pumping. Moreover, the parametric gain for the THz wave in our method is approximately proportional to that for the idler wave. Therefore, we expected an improvement equivalent to that in Fig. 3(a), but the results of the experiments differed. The reason for the greater improvement in THz-wave energy might be that the distance between the pump beam path and the Si-prism coupler was optimally adjusted in this measurement. The pulse width of the idler wave, measured using a digitizing oscilloscope, was 4 ns (FWHM). Therefore, the peak THz-wave power was estimated to be 425 µW. No saturation of the idler-wave or THz-wave energy was observed during these experiments.

4. Seeded operation

Following the experiments with unseeded operations, the TPG system was injection
Figure 4 (a) shows the THz-wave energies from the injection-seeded TPG system as a function of seeder power for the idler wave. The seeder power was varied from 0 to 350 mW, and injection seeding was observed to affect the THz-wave energy, even when the seeder power was less than 2 mW. The THz-wave energy increased with seeder power, but there was only a slight increase for seeder powers greater than 20 mW. This can be explained as follows: since the injection seeder defines the idler wavelength, the gain bandwidth for the idler wave becomes narrower, leading to a higher parametric gain at that wavelength. Once the TPG system is completely injection seeded, however, an increase in the seeder power no longer enhances the output energy, since the injection seeder merely plays a role in narrowing the gain bandwidth. A maximum THz-wave energy of 5 pJ (peak power 1.25 mW) was achieved with a seeder power of 350 mW, and an idler-wave energy of 2 mJ was then obtained. These results are approximately 3 times greater than those with the unseeded TPG system. In this experiment, the laser beam of the seeder was not focused, in order to realize a simple, compact system; a focused beam will allow us to use an injection seeder with lower power, in the order of a few milliWatts.

Figure 4(b) shows the idler-wave spectra for various seeder powers. The upper horizontal axis in this figure is the corresponding THz wavelength, which was calculated using the energy conservation law with a pump wavelength of 1.064 µm and the idler wavelengths shown on the lower horizontal axis. The idler-wave spectrum was measured with an optical spectrum analyzer, which had a resolution of 0.2 nm. The pump energy was fixed at 11 mJ. In unseeded operation, the idler-wave spectrum was observed over the wavelength range of 1.0694 to 1.0723 µm, which corresponds to a THz-wavelength range of 134 to 212 m (1.4 to 2.2 THz). As the seeder power increased from 0 to 2 mW, the intensity of the idler wave near the wavelength of an emission peak decreased slightly, and a new peak near the seeder wavelength of 1.070 µm appeared in the idler-wave spectrum. For a maximum seeder power of 350 mW, THz-wave generation dominated at a wavelength of 1.070 µm, rather than at the peak wavelength of the unseeded TPG spectrum.
Figure 6: Schematic of a tunable injection-seeded terahertz-wave parametric generator. The pump laser is a diode-pumped Q-switched Nd:YAG laser. ECLD: an external cavity laser diode, operated at from 1.0685 to 1.073 µm. M₁: mirror for beam deflection.

The THz-wave linewidth and wavelength were measured using a scanning Fabry-Perot interferometer, which consisted of two metal-mesh mirrors, placed between the Si-prism coupler and the Si-bolometer. The results are shown in Fig. 5. The mirror spacing was varied using a precise actuator. A THz wavelength of 190 µm was obtained from the displacement between the two periods. The two peaks in the inset of Fig. 7 are separated by a 69-GHz free spectral range. The THz-wave linewidth was measured to be less than 33 GHz, which was 1/24 times narrower than that in unseeded operation. At present, the THz-wave linewidth is limited by the linewidth of the pump laser, since the idler seeder has a sufficiently narrow linewidth (~1 MHz). Even transform-limited narrow-linewidth operation should be feasible using a single-longitudinal-mode Q-switched laser as a pump source.

5. Tunability

Figure 6 is a schematic of a tunable is-TPG. As a tunable seed source for the idler wave, an external cavity laser diode (ECLD) was used in place of the fixed frequency Yb-doped fiber laser. Part of the seeder beam was introduced into a wavemeter for terahertz frequency calibration. The angle of incidence of the ECLD beam was rotated using a mirror (M₁), and injected into the crystal after passing through a 3:2 telescope consisting of two lenses (f = 300 and 200 mm). The center of the beam’s rotation on the mirror was relayed onto the input surface of the MgO:LiNbO₃ crystal. We used two MgO:LiNbO₃ crystals (73 mm × 2) in order to reduce the pump energy required. To enhance the terahertz-wave output, the pump beam diameter was reduced using a telescope. The full width at half maxima on the input surface of the MgO:LiNbO₃ crystal in the horizontal and vertical directions were 0.66 and 0.52 mm, respectively. The overall size of the system was reduced to 30 × 65 cm, including the pump, seed source, and beam-scanning optics.

Figure 7 (a) shows the measured THz-wave tuning range of the is-TPG at a fixed pump energy of 10 mJ/pulse. The threshold of parametric generation was 5.5 mJ/pulse. The closed circles are the terahertz-wave output. Tunability from 1 to 2.3 THz was obtained.
Figure 7: (a) Measured output characteristics of the THz wave from a MgO:LiNbO$_3$ is-TPG at a fixed pump energy (10 mJ/pulse). The seed input power was 28 mW. (b) Absorption lines and relative intensities reported in [13]. (c) Water vapor absorption line measured between 1∼1.8 THz. (50-cm light tube, 1 atm, 22 °C, humidity 40%)

by varying the seeder wavelength from 1.0685 to 1.073 µm, respectively. We obtained the maximum THz-wave output of 40 pJ/pulse at 1.6 THz. The absorption loss inside the LiNbO$_3$ crystal is larger in the higher frequency region, which limited the upper frequency to 2.3 THz. In the low frequency region, the phase matching angle outside the crystal was too small to completely separate the pump and seeder beams at the mirror M$_2$. The small angle limited the lower frequency to ∼ 1 THz.

The terahertz-wave frequency was calibrated using the measured pump and seeder wavelengths. Figure 7 (c) shows the water vapor absorption line measured between 1 and 1.8 THz. The ECLD used in this experiment had frequent, large mode hops. The range of the continuous tuning was restricted by the mode hop of the tunable laser diode. Therefore, the wavelength of the ECLD was carefully varied though temperature and the piezo-actuator voltage in order to observe the several absorption lines. Moreover, the incidence angle of the seed beam was adjusted to satisfy the phase-matching conditions every time the wavelength of the ECLD was changed. The terahertz-wave output was detected with two Si-bolometers after passing through 50-cm light tubes with crystal quartz plates. One of the light tubes was evacuated <10Pa as the reference, and the other was open to the atmosphere (temperature 22 °C, humidity 40%). Although, the measured absorption linewidth was broadened to 50 GHz due to the linewidth of the unseeded Nd:YAG laser, the absorption frequency was in good agreement with the reported absorption line shown in Fig. 7 (b)[13].

6. Summary

We developed a compact, complete is-TPG system that included a diode-pumped, Q-switched Nd:YAG laser as the pump source, and a seed source for the idler wave. Using an
injection-seeding technique, the THz-wave energy was 3 times higher and the linewidth 
was 1/24 narrower (33 GHz) than those of an unseeded TPG. The overall size of the 
tunable is-TPG system was 30 cm × 65 cm, including the pump and seed source. It 
should be emphasized that the is-TPG system presented here is the smallest such system 
reported, and its performance remains excellent.

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