Transform-limited, achromatic injection-seeded terahertz-wave parametric generator

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Abstract. A review to our effort on developing the transform-limited, frequency-agile terahertz-wave parametric generator (TPG) is presented. A frequency-agile THz-wave generation is realized by introducing the injection-seeding method and the optical design for the stationary dispersion-compensation. The purity of the THz-wave frequency was dramatically improved to $\Delta\nu/\nu < 10^{-4}$. Simultaneously, the THz-wave output was several hundred times higher than that of a conventional TPG. In addition, a wide frequency tuning with fast tuning speed were realized. The THz-wave frequency can be set randomly or scanned continuously over a frequency range from 0.6 THz to 2.4 THz with narrow linewidth of sub 100 MHz. Furthermore, a tabletop, high-performance THz-wave gas spectrometer based on this achromatic injection-seeded TPG was developed. To demonstrate the potential of this system, we performed the measurement of the absorption line due to rotational transitions of the water molecules and determined their pressure-broadening coefficient.

1. Introduction

Frequency conversion in a nonlinear optical material is an effective method of achieving coherent THz-wave radiation due to its wide tunability and room-temperature operation. We have focused on the development of THz-wave parametric oscillator (TPO) and THz-wave parametric generator (TPG) based on the laser light scattering from the $A_1$-symmetry polariton mode of MgO:LiNbO$_3$ nonlinear crystal, which generated widely tunable, coherent THz-wave radiations with compact and room-temperature operation.

The difference between a TPO and a TPG is that the former has an idler cavity while the latter does not. The THz-wave linewidth of a conventional TPG exceeds 500 GHz and the output magnitude is much smaller than that from a TPO. The linewidth of a conventional TPO is about several tens GHz and is continuously tunable in the 100 to 300 $\mu$m (1 to 3 THz) range in a single operation. It can emit peak power of up to several tenths mW.

Injection-seeding by external narrow-band laser radiation at low power levels can considerably reduce the linewidth of an OPO down to the Fourier transform limit. Since the TPO and TPG are pumped by a nanosecond pump laser, a spectral linewidth of less than 100 MHz is possible under the Fourier-transform-limited condition.

The injection-seeded TPO (is-TPO) and the injection-seeded TPG (is-TPG) has been demonstrated to generate Fourier transform-limited THz-wave radiation. TPGs, as compared to TPOs, are especially preferred for external seeding by narrow linewidth light sources such as a CW tunable
SLM laser for two reasons. Firstly, a TPG has no cavity, therefore, there is no need to actively control the cavity length to match the frequency of the seeding laser. The closed-loop serving control for frequency tuning is also not necessary, which greatly simplifies the techniques for scanning the wavelength of the TPG. Secondly, since the TPG operated in a single-pass fashion, there is no feedback from the TPG back toward the external seeding laser. This is important for the CW SLM lasers, because even a small amount of feedback can disturb the SLM operation, and under certain circumstances can even damage the gain material. The no feedback is particularly important when using diode lasers as seeding sources. Therefore, for developing the sub-100MHz narrow linewidth THz-wave sources, we concentrated our efforts on the development of an injection-seeded TPG system. We developed an achromatical injection-seeded TPG (ais-TPG) that guarantees a fast and smooth frequency tuning. Furthermore, a tabletop, high-performance THz-wave gas spectrometer based on this ais-TPG was realized. Using the frequency-agile characteristics, such as narrow linewidth, wide tunability, and rapid frequency control in this spectrometer, high-resolution THz-wave gas sensing is demonstrated.

In this article, we summarize our results on developing the Transform-limited, achromatic is-TPG system.

2. The principle for THz-wave generation

The efficient parametric scattering of laser light via a polariton (stimulated polariton scattering) generates coherent THz waves. The scattering process involves both the second-order and the third-order nonlinear processes. LiNbO₃ is one of the most suitable materials for generating the THz waves efficiently because of its large nonlinear coefficient (d₃₃ = 25.2pm/V at λ = 1.064µm²⁰ and d₃₃ = 165pm/V at THz-wave region²¹) and its transparency over a wide wavelength range (0.4–5.5µm). LiNbO₃ has four infrared–active and Raman–active transverse optical (TO) phonon modes, called the A₁-symmetry modes. The lowest mode (ω₀ ≈ 250cm⁻¹) is useful for efficient tunable THz-wave generation. Figure 1 shows the dispersion relation of the polariton of the LiNbO₃ crystal. Polaritons exhibit phonon-like behavior in the resonant frequency region (near the TO-phonon frequency ω_TO). However, they behave like photons in the nonresonant low-frequency region, where a signal photon at THz frequency (ωₜ) and a near-infrared idler photon (ωᵢ) are created parametrically from a near-infrared pump photon (ωₚ), according to the energy conservation law ωₚ = ωₜ + ωᵢ (p: pump; T: THz; i: idler). In the stimulated scattering process, the momentum conservation law kₚ = kᵢ + kₜ (noncollinear
phase-matching condition; see the insets of Figure 1), also holds. This leads to the angle-dispersive characteristics of the idler and THz waves.

By introducing injection-seed to the idler beam, the line width of THz-wave wave was narrowed to close to the linewidth of the pump beam. Simultaneously, the output was several tens times higher than that of a Terahertz-wave parametric generation without the injection-seed. In addition, wide tunability can be realized using a tunable seed by changing both the seed wavelength and the seed incident angle.

3. Injection-seeded THz-wave parametric generator (is-TPG)

Figure 2 shows the setup of our experimental is-TPG. The pump used was a single longitudinal mode Q-switched Nd:YAG laser (1.064µm), and the seed for the idler was a CW Yb-fibre laser (1.070µm). The THz-wave output and temporal waveform were measured with a 4K Si bolometer and a Schottky barrier diode detector, respectively.

Both of energies of the THz and idler waves were greatly enhancement by injection seeding. With increasing the seed power from 0 and 200mW, THz-wave and idler energy increased by factors of nearly 300 and 500, respectively. The maximum conversion efficiency was achieved when the pump and seed beams almost fully overlapped at the incident surface of the first MgO:LiNbO₃ crystal, as shown in Figure 2.

Figure 3 shows the measured THz-wave output energy from the is-TPG and a conventional TPG. The maximum THz-wave output of 900pJ/pulse (peak>100mW) was obtained with a pump of 45mJ/pulse and a seed power of 250mW. As the minimum sensitivity of the Si bolometer was almost
1fJ/pulse, the dynamic range of the injection-seeded TPG system was 900pJ to 1fJ–60dB, which is sufficient for most applications.

![Figure 3 Input–output characteristics of an is-TPG, showing THz-wave (190µm) energy enhancement by a factor of 300 hundreds with injection seeding.](image)

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Figure 4 shows the effect of injection seeding on idler spectrum narrowing. The dotted line indicates the idler spectrum of a conventional TPG without injection seeding and the solid line indicates the idler spectrum of an injection-seeded TPG. The resolution limit of the spectrum analyzer used was 0.2nm, so the idler spectrum in Figure 4 shows only the spectrometer resolution of the spectrum analyzer, the real idler spectrum was much narrower than that shown in this figure.

![Figure 4 Narrowing of the idler (1.07µm) spectrum by injection seeding. The dotted and solid lines indicate the idler spectrum of a conventional TPG and an is-TPG, respectively.](image)

Figure 4 Narrowing of the idler (1.07µm) spectrum by injection seeding. The dotted and solid lines indicate the idler spectrum of a conventional TPG and an is-TPG, respectively.

The linewidth of THz-wave should be close to the linewidth of the idler. It can be determined from a scanning Fabry–Perot etalon consisting of two Ni metal meshes or the absorption spectrum of low pressure water vapour. We will discuss it at the following context.

4. An achromatic is-TPG (ais-TPG) for frequency-agile THz-wave generation
Noncollinear phase-matching condition (the inset in Figure 1) must be satisfied in the stimulated scattering process for THz-wave generation in LiNbO$_3$. This leads to the angle-dispersive characteristics of the idler (seed) and THz waves. If we tune the incident angle as the wavelength of the seed is changed in Figure 2, we may realize a tunable THz-wave radiation. However, rapid tuning is difficult using this setup. An achromatic phase matching in the seed beam was introduced to automatically compensate for the dispersion in the LiNbO$_3$ crystals, we realized a frequency-agile THz-wave generator with tuning the wavelength of seed beam only.

4.1. The optical design in seed beam for the stationary dispersion-compensation

An achromatic phase matching to compensate for the dispersion caused by the LiNbO$_3$ crystal is designed as shown in Figure 5. It consisted of a grating and two focus lenses that formed a 1:3 telescope device. The incident angle of the seed beam on the grating is $\alpha$, and the first-order diffraction angle $\beta(\lambda)$ is expressed by the grating equation $\beta = \sin^{-1} \left( \frac{\lambda}{d} \right)$ where $d$ is the spacing between grooves. The grating disperses wavelengths laterally ($\lambda_1 < \lambda_3$), and the lenses (focal lengths $f_1$ and $f_2$) form a telescope to expand the dispersion of the grating and to converge the dispersed seed beam onto the input surface of the LiNbO$_3$ crystal. The telescope magnifies the angular dispersion by $f_1/f_2$.

Figure 6 Calculated linear dispersion of the LiNbO$_3$ crystal (solid curve) and the 1200-groove/mm gratings followed by a telescope that magnifies the angular dispersion by $\frac{3[3\partial\theta_{IN}/\partial \lambda]}{\lambda}$ (dashed lines).

The solid curve in Figure 6 shows the calculated first-order coefficient $\partial\theta_{IN}/\partial \lambda$ of LiNbO$_3$ crystal with Sellmeier equations 23, 24 at the optical and THz frequency regions. The dashed lines in
The measured Half-Width at Half-Maximum (HWHM) external angle tolerance for THz-wave radiation without dispersion compensation was 0.16° at 1070 nm and corresponds to the full bandwidth of seed beam of 1.07 nm and a THz-wave frequency bandwidth of ~310 GHz.

Using the achromatic phase matching device, the first order dispersion $\partial \theta_{IN} / \partial \lambda$ can be compensated. The calculated full bandwidth of the second order dispersion in the frequency tuning range of the seed was 12 nm. (The second derivative, $\partial^2 \theta_{IN} / \partial \lambda^2$ is (~0.0093°/nm)/nm).

For THz-wave frequency tuning 0.6 to 2.7 THz at a pump wavelength of 1064 nm, the required seed wavelength tuning range is 1066–1075 nm (bandwidth: 9 nm). Therefore, matching the first derivative at an appropriate central wavelength is sufficient for the dispersion compensation of 9 nm bandwidth in the LiNbO$_3$ crystal.

4.2. Experimental setup for ais-TPG

Figure 7 shows the experimental setup of the ais-TPG. It included a pump source, a seed source, the optics for achromatic phase-matching and the nonlinear crystals. The pump source was a specially designed injection-seeded Q-switch YAG laser (developed by Megaopto Co., Ltd), which generated single-longitudinal-mode pulses at the wavelength of 1064 nm. Its pulse width, repetition rate and maximum output energy were 15 ns, 500 Hz and 21 mJ/pulse, respectively. The repetition rate was 50 times higher than that of the flash-lamp-pumped Nd:YAG laser that we used in the previous is-TPG. The seed source was a continuous-wave external cavity laser diode (ECLD) (NEW FOCUS, Inc) amplified up to 1 W by an Yb:fiber amplifier. The wavelength was coarsely tuned by DC motor drive screw from 1056 nm to 1083 nm without mode-hopping and finely tuned by a piezoelectric transducer over a range of approximately 20 GHz. The scan speed of the DC motor can be set to a value between 0.01~15.7 nm/sec, which is corresponding to the frequency between 3 GHz~47 THz/sec.

The TPG gain media is the MgO:LiNbO$_3$ crystal, same as that we have used in Figure 2. The seed from the Yb:fiber amplifier was collimated and expanded to 3.0 mm in diameter. The beam divergence was smaller than 0.3 mrad. Then, the seed beam was diffracted using a 1200-groove/mm grating with an angle of incidence of ~40° for 1071 nm. The diffracted seed beam was reflected by a pair of concave mirrors, CM$_1$ and CM$_2$, and injected into the MgO:LiNbO$_3$ crystal. The radius of curvature of the two mirrors was 1.5 m and 0.5 m, respectively. The pair of concave mirrors formed a telescope that expanded the dispersion of the grating and converged the dispersed seed beam onto the input surface of the MgO:LiNbO$_3$ crystal with a beam diameter of about 0.6 mm (FWHM). The center of rotation was fixed on the input surface of the first MgO:LiNbO$_3$ crystal. Owing to the design of the
stationary dispersion-compensated optical arrangement, the seed beam automatically can enter the MgO:LiNbO$_3$ crystal at the appropriate phase-matching angle, by changing the frequency of the seed beam alone.

4.3. Frequency-agile THz-wave generation

The threshold energy of the pump beam for generating THz-wave radiation was 13mJ/pulse with the waist of the pump beam of 0.7mm (FWHM) at the first facet of the MgO: LiNbO$_3$ crystal. THz-wave radiation was detected by a He-cooled Si bolometer. The THz-wave frequency was determined by the frequency difference between the pump beam and the idler beam based on the energy conservation of parametric processes in nonlinear optics. The voltage signal from the bolometer was sent to an analogue signal-processing circuit, which was the synchronized with the repetition frequency of the pump laser, including a peak-hold circuit and a delayed-sampling circuit. Peak intensity of every pulse envelope of the THz-wave signal can be capture with this device. The data from this signal-processing circuit was transferred to the computer. The frequency tuning and data acquisition were controlled by the computer using the Labview intermediate program.

Figure 8 shows the THz-wave output energy in the THz-wave frequency region of 0.6~2.4 THz obtained by smoothly tuning the seed beam wavelength from 1066.4 nm to 1073.3 nm. The pump energy and the seed beam power were 19 mJ/pulse and 250 mW, respectively. It takes about 1 minute for one scanning.

![Figure 8 THz-wave output energy in the tuning region of 0.6 to 2.4 THz with the pump input energy of 19 mJ/pulse and seed beam power of 250 mW.](image)

5. A frequency-agile high-resolution terahertz-wave spectrometer for gas sensing

The use of far-infrared or terahertz radiation for gas sensing is very much complementary to the well established microwave and mid-IR spectroscopy technique, and will greatly expand the number of gas species that can be detected. However, unlike gas sensing in both the microwave (<0.1 THz) and mid-infrared (>20 THz) frequency regions, far-infrared (IR) and terahertz sensing is relatively new, and its development has been hindered by a lack of suitable THz radiation sources and detectors. We have realized a narrow linewidth and tunable THz-wave generator, the establishment of a practical high resolution terahertz-wave spectrometer based on this ais-TPG is highly attractive for THz-wave gas-sensing.

5.1. Terahertz-wave spectrometer based on ais-TPG

Figure 9 shows the picture of the spectrometer. The spectrometer system is packaged into three chambers with a total volume of about 900 × 450 × 130 mm: the first chamber (I) contains the gas cells for THz-wave spectroscopy, the second (II) contains the nonlinear MgO:LiNbO$_3$ crystals for THz-wave generation, and the third (III) has the optics for steering both the seed beam (the thin white
line in the picture) and the pump beam (black line) to the nonlinear crystals. To eliminate atmospheric water vapor, the first two chambers were designed to operate under a flow of pure nitrogen gas. The THz-wave radiation (the thick white line in the picture) from the MgO:LiNbO₃ was collimated by a cylindrical lens and then steered into the chamber (I). A standing wire-grid beam splitter divided the THz-wave radiation into reference and signal beams. The signal beam was steered into a portable gas cell with two gas inlets controlled by ultra-high vacuum leak valves to facilitate sample processing, and controlling and monitoring its pressure. The cell was built with two quartz wedge windows for eliminating interference fluctuations due to parallel reflection surfaces. Pressure was measured with a capacitance manometer. A two-channel liquid He-cooled Si bolometer was used for dual-beam balance detection to cancel the noise in the THz-wave source. Both ports of the bolometer were connected to the chamber directly to prevent further corruption by ambient water over the optical path.

The frequency scanning rate of this spectrometer can be set from 3 to 47 GHz/s in intervals of 6–100 MHz. Each absorption profile consists of 20–100 resolution elements. The broader the line, the larger the chosen step. Spectral measurements for high-quality line shape fits were performed using the fine-tuning mode, which can cover a continuous tuning range up to 50 GHz.

![Figure 9](image)

**Figure 9** the picture of the tabletop THz-wave spectrometer.

5.2. Measuring the absorption spectroscopy of low pressure water vapor

![Figure 10](image)

**Figure 10** Accurate and rapid measurement of the water vapor spectrum in a wide frequency range from 0.8 to 2.1 THz with a 30MHz frequency step. The stick line shows the spectrum data from the NASA database.

We steer the total THz-wave radiation into the gas sample cell, then detect the THz-wave
transmission spectroscopy using one of the two channels in Bolometer. Figure 10 shows the direct measured water vapor absorption spectrum from 0.8 THz to 2.1 THz. It takes only 3 minutes for scanning this wide frequency range with the frequency step 12 MHz. The pressure of water vapor in gas cell was 0.1 kPa. The absorption lines measured by this is-TPG spectrometer are in good agreement with the spectrum data from the NASA database\textsuperscript{25} showed in Figure 10 with a stick spectrum. The serious background noise was observed in Figure 10, which was arising from the amplitude fluctuation in THz-wave source and the interference fringe due to the quartz parallel windows in the gas cell. The balance detection and digital filter were employed for eliminating those background fluctuations.

Figure 11 shows the transmittance spectra of water vapor from 1.2 to 1.9 THz at 0.1 kPa using dual-channel balanced detection. It takes about 4 min for the continuous frequency scan of 700 GHz in 6-MHz frequency steps. A broader frequency step can be chosen for faster scans. Twelve purely rotational transitions were observed. The measured absorption lines agree well with the spectrum data from the NASA database, shown as a stick spectrum in Figure 11. Special attention to four transitions: $2_{21}-2_{12}$, $2_{12}-1_{01}$, $6_{34}-6_{15}$, and $7_{34}^r-7_{25}$ was given in Figure 11.

Because the balanced detection requires dividing the THz-wave into two paths, and the brightness of the signal beam decreases, the merit of the balanced detection for improving signal-to-noise ratio is lost at the low power region (0.6–1 THz and 2.0–2.4 THz). Single-channel direct detection offers the wider frequency region detection at the cost of a poorer signal-to-noise ratio.

Figure 11 Accurate, rapid measurements of the absorption spectrum of the 12 purely rotational transitions of water vapor. The stick line shows the spectral data from the NASA database for comparison.

5.3. Pressure broadening detection
We observed pressure broadening of the absorption lines using an inert buffer gas (pure N\textsubscript{2}). The atmosphere in the gas cell was pumped down to a pressure of 0.2 kPa, and then the N\textsubscript{2} gas was added until the desired final pressure was reached. No attempt was made to keep the pure water vapor in gas cell before the broadening gas was added. Any residual contribution to the total linewidth of water vapor due to the collision broadening from the 0.2 kPa atmosphere was mitigated by the fact that the foreign-gas collision-broadening coefficient is measured at a constant pressure atmosphere by varying the foreign gas pressure and computing the slope of the total linewidths as a function of this foreign-gas pressure. Further, the collision-broadening of a 0.2 kPa atmosphere is far narrower than the resolution of the THz-wave spectrometer; therefore, it can be ignored.

Absorption spectra of the $6_{34}-6_{15}$ and $7_{34}^r-7_{25}$ rotational transitions of water vapor were recorded while the pressure of the N\textsubscript{2} gas was varied between 0.2 and 10 kPa. The frequency interval between the $6_{34}-6_{15}$ and $7_{34}^r-7_{25}$ transitions is 2.4 GHz. Figure 12 shows the set of the two absorption lines under N\textsubscript{2} pressures of 0.4, 1.5, 2.5, 3.5, 4.5, 6, and 7 kPa (circles in Fig. 12). The nonlinear least-squares-fitted Voigt profiles were added to all the measured lines as solid lines in Figure 12. The spectral line
half width at half maximum (HWHM) at each foreign-gas pressure was obtained from a nonlinear least-squares analysis.

Figure 12 Set of absorption lines of the 6\_24-6\_15 and 7\_34-7\_25 rotational transitions of water vapor under N\_2 pressures of 0.4, 1.5, 2.5, 3.5, 4.5, 6, and 7 kPa (circles). The nonlinear least-squares-fitted Voigt profiles of all the measured lines were added in solid line. The frequency interval between the 6\_24-6\_15 and 7\_34-7\_25 transitions is 2.4 GHz.

Figure 13 shows the linewidth of the 6\_24-6\_15 transition as a function of the N\_2 pressure. The linear least-squares fit to the HWHM data above a pressure of 2.5 kPa is given by the straight line. The linear fit slopes give pressure-broadening coefficients of 32.66±0.52 MHz/kPa and 33.93±0.56 MHz/kPa at the 6\_24-6\_15 and 7\_34-7\_25 transitions, respectively.

Figure 13 The linewidth of the 6\_24-6\_15 transition as a function of N\_2 pressure. The straight line shows the linear least-squares fit to the HWHM data above a pressure of 2.5 kPa. The slope gives a pressure-broadening coefficient of 32.66±0.52 MHz/kPa.

Table I compares our experimental measurements with theoretical predictions and other experimental results. The theoretical predictions are taken from the work of Gamache and Davies\textsuperscript{26}; the other experimental data in Table I are from Fourier-transform spectrophotometer (FTS) measurements taken by Townes et al\textsuperscript{27}. They measured 17 N\_2 broadened pure rotational transitions of water vapor using a commercial FTS in the spectral range of 0.75 to 3.3 THz with a gap in values
between 1.5 and 2.2 THz. They give a weighted average for the experimental N₂ broadening coefficient in the spectral range of 0.75 to 3.3 THz (shown in Table I). No experimental data measuring the same rotational transitions as we do using FTS are currently available. However, our data are in good agreement with this weighted average experimental data. Dr. Townes has argued that the theory may be biased toward the narrower linewidth transitions and therefore predicts smaller linewidth broadening coefficients than are observed experimentally.

Our experiment demonstrates the possibility of obtaining information on the pressure broadening in a broad frequency region with high resolution in the THz-wave region. This information is very important to the calculation of atmospheric transmission, where requires high quality spectral parameters for many thousands of water vapor transitions.

|               | 6_24–6_15 (MHz/kPa) | 7_34–7_25 (MHz/kPa) |
|---------------|---------------------|---------------------|
| This work     | 32.66±0.52          | 33.93±0.56          |
| FTS           | 32.25               | 29.93               |
| Theoretical   | 29.85               | 29.93               |

Table I. Comparison of our experimental measurements with theoretical predictions and the typical results from the commercial FTS.

5.4. The linewidth of THz-wave radiation

The typical pulse width of the THz wave was 3.4 ns measured by a Schottky barrier diode, and was almost identical to that of the idler, which was measured with a high-speed photodetector. The calculated Fourier transform-limited linewidth was 136 MHz. Theoretically, the linewidth of the THz-wave generated by is-TPG is Fourier transform-limited by the linewidth of the pump beam (in our case, the 17-ns single-longitudinal-mode pulse width means a 30-MHz linewidth). These facts go to confirm that the linewidth of the THz wave was possible to be narrowed to near the Fourier transform-limited. However, the THz-wave linewidth was still more than 10GHz when an injection-seeded TPG is pumped by a multi-frequency Nd:YAG laser. Thus, in order to obtain the transform-limited THz wave with a TPG, both the pump and seed must be SLM lasers.

The THz linewidth can be measured using a scanning Fabry–Perot etalon consisting of two Ni metal meshes. But it is not easy for such a narrow-linewidth THz source to demonstrate a resolution better than 100 MHz (0.003 cm⁻¹) because of the instability of the scanning mirror for several meters.

The absorption spectrum of the low-pressure (<1.5kPa) water vapour in Fig. 12 clearly revealed that the resolution of THz-wave was less than 100 MHz. As shown in Fig. 13, the measured pressure-broadening linewidth does not decrease linearly below 1.5 kPa; furthermore, the linear fit line offset (Lorentzian width at a pressure of 0 Torr) does not correspond to the Doppler linewidth (~2 MHz), but rather reaches a linewidth of 50 MHz (HWHM). The linewidth of the THz-wave source is responsible for the linear bias at low pressure (the calculated values of the pressure broadening are not affected by the bias). It demonstrates that the linewidth of THz-wave generated by this is-TPG was 50 MHz or so, nearly the Fourier transform-limited by the pulse width of the pump beam.

6. Conclusion

We reviewed the widely tunable injection-seeded THz-wave generator based on the optical parametric conversion in the nonlinear crystal MgO:LiNbO₃. In comparison with a conventional TPG without injection seeding, the output was increased around 300 times and the linewidth was decreased to near the Fourier-transform-limitation. The stationary dispersion-compensation optics design in the seeded beam made a rapid and easy THz-wave frequency tuning. We realized an achromatic injection-seeded THz-wave generator that can realize THz-wave frequency tuning from 1-3 THz by changing the frequency of the seed beam alone.

We developed a frequency-agile THz-wave spectrometer for high-resolution gas sensing using this achromatic injection-seeded THz-wave generator. This THz-wave spectrometer demonstrates the capability of obtaining THz-wave gas phase spectral information over a wide frequency region at very
fast data-acquisition times and high resolution. Its advantages include compactness, wide tunability, high resolution, rapid data acquisition, room-temperature operation, and ease of use.

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