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Abstract

We demonstrate a terahertz-wave parametric oscillator (TPO) with a corner-cube resonator consisting of a corner-cube prism (CCP) and a flat mirror. By using the cavity configuration proposed in this Letter, the generation of tunable monochromatic terahertz (THz) waves can be achieved just by rotating the flat mirror instead of rotating the TPO cavity relative to the pump beam. The THz-wave output intensity and pulse width can be controlled periodically by rotating the CCP around the cavity axis. The TPO stability against cavity misalignment is significantly improved by at least 1 to 2 orders of magnitude compared with the conventional plane–parallel resonator configuration.

Keywords

terahertz, misalignment, oscillator, parametic, cavity, tuning, wave, resistant

Disciplines

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Terahertz-wave parametric oscillator with a misalignment-resistant tuning cavity

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We demonstrate a terahertz-wave parametric oscillator (TPO) with a corner-cube resonator consisting of a corner-cube prism (CCP) and a flat mirror. By using the cavity configuration proposed in this Letter, the generation of tunable monochromatic terahertz (THz) waves can be achieved just by rotating the flat mirror instead of rotating the TPO cavity relative to the pump beam. The THz-wave output intensity and pulse width can be controlled periodically by rotating the CCP around the cavity axis. The TPO stability against cavity misalignment is significantly improved by at least 1 to 2 orders of magnitude compared with the conventional plane–parallel resonator configuration. © 2011 Optical Society of America

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Terahertz-wave parametric oscillators (TPOs) based on simulated polariton scattering have proven to be one of the most effective and promising techniques to generate tunable monochromatic and coherent terahertz (THz) waves. Over the past few years, numerous research efforts have been carried out to effectively improve the operation performance of TPOs [1–6]. However, a conventional TPO employing a plane–parallel resonator (PPR) easily suffers cavity instability introduced by mirror misalignment due to external disturbances such as vibrations and temperature variations. The mechanical movement of the whole TPO cavity for the frequency tuning with the so-called angle tuning method has some negative effects on the reliability and rapid frequency tunability of a TPO system [5]. These unfavorable factors seriously hinder the further applications of this potential THz-wave source in harsh environments.

In this Letter, we demonstrate experimentally an output-mirror-tuning, highly misalignment-resistant TPO with a corner-cube resonator (CCR) configuration. Because CCRs offer a number of advantages, such as low misalignment sensitivity, ease of construction, and spatial gain homogenization, they have been widely applied to various lasers [7–9]. Here, the introduction of a CCR configuration into a TPO not only increases the misalignment-resistant stability of the TPO significantly, but also provides a novel frequency-tuning method. Besides, the THz-wave output characteristics can be readily varied through rotating the corner-cube prism (CCP) around the resonator axis.

An experimental setup of the TPO with a CCR configuration (CCR-TPO) is illustrated schematically in Fig. 1. The pump source was a Q-switched Nd: YAG laser (Spectra-Physics, Lab-170) operating at 1064 nm (pulse width, about 24 ns; repetition rate, 10 Hz). The pump beam diameter was compressed to about 2.5 mm using a telescope system (TS). The polarization direction of the pump beam was parallel to the c axis direction. A 5 mol.% MgO-doped $LiNbO_3$ crystal [60 mm (a) × 10 mm (b) × 5 mm (c)] was used as the nonlinear material. The a surfaces at both ends were polished and AR coated at 1064 nm. An array of six Si-prism couplers was used for efficient extraction of the THz waves. The CCR for the Stokes wave consisted mainly of a CCP and a flat mirror M2 (with a transmission of 5% at 1070 nm) as an output mirror that could be angle tuned as desired. A CCP, made up of three roof surfaces and one flat circular hypotenuse surface, has such a property that any light incident on its aperture will emerge antiparallelly to the direction of incidence based on total internal reflection, regardless of the corner-cube orientation. The front surface of the CCP with an 8 mm diameter effective aperture was AR coated for 1070 nm. The oscillating Stokes beam was incident onto the apex of the CCP as symmetrically as possible. Because the angle θ_{ext} between the pump beam and the cavity axis was very small, the TPO cavity was folded using a reflecting mirror M1 to spatially separate the pump and Stokes beams at the CCP. The total TPO cavity length was about 22 cm. The whole TPO cavity was mounted on a rotating stage.

The extracted THz wave was focused with a white polyethylene lens ($f = 60$ mm) and detected with a Golay detector (Tydex, Inc.). A 1 mm thick germanium (Ge) wafer was attached onto the detecting window of the Golay detector to filter out the scattered light of the pump and Stokes beams. The wavelengths of the Stokes waves were measured with an optical spectrum analyzer (OSA) (Agilent 86142B) to calculate the THz-wave frequencies using the energy conservation law. It should be noted that all of the measured THz-wave intensities in this Letter were characterized with the peak output

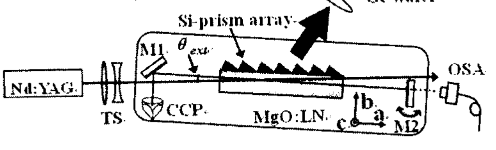

Fig. 1. (Color online) Experimental setup of the CCR-TPO.

voltage of the Golay detector, because no precise calibration data for this detector in the THz-frequency region were available.

For a conventional TPO using a PPR configuration (PPR-TPO), THz-wave frequency tuning is normally realized by rotating the TPO cavity relative to the pump beam to change the phase-matching angle between the pump and Stokes waves (defined here as the cavity-rotating tuning method). In our experiment, however, the change of the phase-matching angle was realized just by rotating the flat mirror M2 (defined as the output-mirror tuning method). In other words, the mirror M2 of the CCR-TPO acted as a frequency-selective element for the Stokes wave with the angular dispersion properties determined by the noncollinear phase-matching condition (see the inset of Fig. 1).

Initially, the angle θ_{ext} was set at a fixed value of about 1.45° by rotating the TPO cavity stage, where the generated THz wave at 1.46 THz possesses the highest parametric gain. Thus, the tunable monochromatic THz waves would be generated just through rotating the mirror M2 around the c axis in a small angle range. Figure 2 shows the tunability of the CCR-TPO under this tuning method. The measured tuning range from 1.1 to 2.6 THz was obtained at a pump energy of 73.5 mJ. Its frequency-tuning behaviors were closely similar to those of a TPO using the cavity-rotating tuning method under the same experimental conditions (indicated by the open circles). The measured tuning range was relatively narrower than that reported in other publications [1–3], which is mainly due to the low sensitivity of the Golay detector compared with a 4.2 K Si-bolometer, and the larger pump beam diameter used in our experiments. Compared with the conventional tuning method, this simple and unique tuning method showed some potential to increase frequency-tuning speed. Additionally, it had practical advantages in ease of handling and mechanical stability. It should be noted that under the CCR configuration, the linewidth of the Stokes beam measured at 1069.9 nm was only about 0.2 nm (see the inset of Fig. 2), similar to that of a PPR-TPO. It implied that a CCR-TPO could generate tunable THz waves with a narrow linewidth similar to that of a PPR-TPO. It should be pointed out that the following experimental results were carried out at a fixed frequency of 1.46 THz.

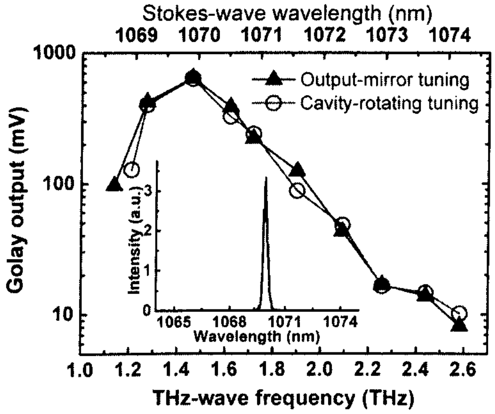

Fig. 2. (Color online) Measured tuning characteristics of the CCR-TPO under the output-mirror tuning (filled triangles) and cavity-rotating tuning (open circles) methods, respectively, at a pump energy of 73.5 mJ. The inset shows the spectrum of the Stokes wave at 1069.9 nm.

By deflecting mirror M2 around the b axis, the misalignment sensitivity concerning the output mirror of the TPO with a CCR versus a PPR was evaluated experimentally, as shown in Fig. 3. When the tilting angle approached 0.09°, the PPR-TPO was severely misaligned and THz-wave generation was almost unobtainable, while the CCR-TPO still operated normally with about 70% of the maximum output intensity. As mentioned above, tilting mirror M2 around the c axis would result in the variation of the THz-wave frequency. The misalignment characteristics of the CCP were also tested through deflecting the CCP, for example, around the c axis, as shown in the inset of Fig. 3. The normalized THz-wave output intensities only decreased by less than 30% when the titling angle of the CCP was as large as 1.36°. It follows that the CCR-TPO was highly insensitive to the tilt of the CCP. The misalignment-resistant characteristics of the CCP in other deflection directions were essentially similar because of the properties of its geometrical structure. Hence, we estimated that the use of a CCR could enhance the overall cavity stability of the TPO by at least 1 to 2 orders of magnitude compared with a PPR-TPO.

In the stimulated polariton scattering, the fact that the polarizations of pump, Stokes, and THz waves are all parallel to the c axis of the MgO:LiNbO$_3$ crystal will result in an efficient nonlinear interaction. As is well known, however, a CCP has an inherent depolarization effect, that is, when linearly polarized light is incident into a CCP, the retroreflected light is generally in a state of elliptical polarization, as described by the Jones matrix [10,11]. This effect has an obviously negative effect on the operation performance of the TPO with polarization-dependent gain. The polarization state of the oscillating Stokes wave inside the CCR would undoubtedly change with the rotation of the CCP around the cavity axis, and its variation was complicated. We defined that the polarizations of the S and P components of the Stokes wave were parallel to the c and b axes, respectively. Only the S wave could be resonantly amplified in the resonator and contribute to the efficient generation of THz waves, while the P wave could not.

Figure 4 indicates the measured variation of the output characteristics of the TPO as a function of the rotation angle of the CCP at a certain pump energy. It could be

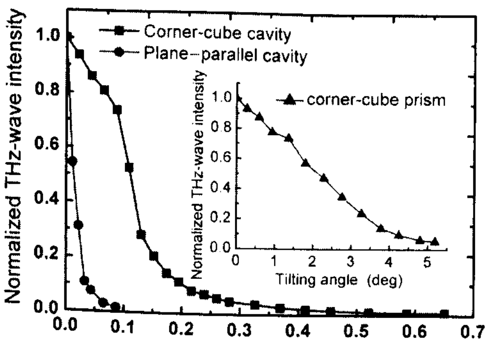

Fig. 3. (Color online) Normalized THz-wave output intensity versus the tilting angle of the output mirror under CCR and PPR, respectively. Inset, normalized THz-wave output intensity versus the tilting angle of the CCP.

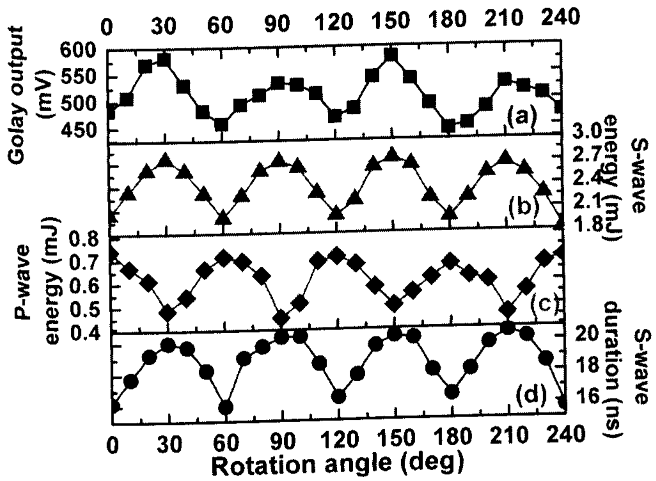

Fig. 4. (Color online) Variation of output characteristics of TPO as a function of the rotation angle of the CCP at a certain pump energy. (a) THz-wave intensity, (b) energy of the S wave, (c) energy of the P wave, and (d) pulse duration of the S wave.

clearly seen that the output intensities of THz waves varied with a period of about 60° when the CCP was rotated, synchronized with those of the S wave because of the energy conservation law [see Figs. 4(a) and 4(b)]. The adjacent peak values of the THz wave were slightly different, while the corresponding values of the S wave were almost equal. The reason might be that the THz-wave traveling distance inside the crystal changed when the CCP was rotated, resulting possibly from the asymmetrical incidence of the Stokes wave onto the front surface and the apex of the CCP and its eigenmode distribution (approximately TEM_{03}) inside the CCR [12]. It is known that the THz-wave output intensities depend greatly on the propagation distance inside the crystal due to the large THz-wave absorption loss in the $MgO:LiNbO_3$ crystal. The output intensity variation of the S wave together with the P wave [see Fig. 4(c)] could reflect the polarization state of the Stokes waves inside the CCR. To clarify the complicated variation mechanism further under the polarization-dependent gain, a theoretical investigation is currently carried out. The periodic variation of the S-wave pulse width was also observed with a polarization beam splitter and an InGaAs-based photodiode [see Fig. 4(d)]. It could be deduced that the pulse width of the THz wave would also change synchronously based on the temporal characteristics of a three-wave parametric interaction.

We even tried to insert a polarizer into the CCR to make only S waves oscillate in the resonator and P waves reflect out of the cavity. However, the large insertion loss introduced by the polarizer resulted in lower THz-wave output intensities.

When the CCP was adjusted to reach THz-wave maximum output intensities, the oscillation threshold of the CCR-TPO was about 36 mJ, which was 24% higher than that of a PPR-TPO with a 16 cm long cavity under the same experimental conditions. The input–output performance of the CCR-TPO was also slightly unsatisfactory due mainly to a relatively large cavity loss resulting from the longer cavity length and the diffraction loss at the apex and three edges of the CCP with the depolarization effect. The poor pump beam quality and the eigenmode distribution of the Stokes beam inside the CCR were also possible factors. For more efficient performance, a CCP of high quality and an appropriate spot size incident into the CCP are necessary. On the other hand, the CCR had a distinctive property in spatial gain homogenization, which could overcome, to some extent, the adverse effect of the nonlinear crystal of poor quality on the conversion efficiency of THz waves.

In summary, we have proposed a TPO using a CCR configuration. Based on this resonator, the tunable THz waves can be generated using the output-mirror tuning method. The misalignment-resistant ability of the TPO is improved significantly by at least 1 to 2 orders of magnitude compared with a PPR-TPO. Besides, the THz-wave output characteristics (e.g., intensity and pulse width) can be easily varied through rotating the CCP around the cavity axis.

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References

1. D. H. Wu and T. Ikari, Appl. Phys. Lett. **95**, 141105 (2009).
2. T. Ikari, X. B. Zhang, H. Minamide, and H. Ito, Opt. Express **14**, 1604 (2006).
3. K. Imai, K. Kawase, J. I. Shikata, H. Minamide, and H. Ito, Appl. Phys. Lett. **78**, 1026 (2001).
4. R. X. Guo, K. Aklyama, H. Minamide, and H. Ito, Appl. Phys. Lett. **88**, 091120 (2006).
5. K. Kawase, J. I. Shikata, H. Minamide, K. Imai, and H. Ito, Appl. Opt. **40**, 1423 (2001).
6. T. J. Edwards, D. Walsh, M. B. Spurr, C. F. Rae, and M. H. Dunn, Opt. Express **14**, 1582 (2006).
7. G. M. Smith, D. V. Forbes, J. J. Coleman, and J. T. Verdeyen, IEEE Photon. Tech. Lett. **5**, 873 (1993).
8. W. Q. Gao, G. M. Yao, L. X. Xu, Y. Cheng, H. Ming, and J. P. Xie, Chin. Opt. Lett. **4**, 332 (2006).
9. H. Chu, Y. M. Jhon, S. S. Choi, and V. M. Plotnikov, Jpn. J. Appl. Phys. **36**, 6761 (1997).
10. J. Liu and R. M. Azzam, Appl. Opt. **36**, 1553 (1997).
11. C. C. Shih, J. Opt. Soc. Am. A **13**, 1378 (1996).
12. M. X. Shen, S. M. Wang, L. G. Hu, and D. M. Zhao, Appl. Opt. **43**, 4091 (2004).