High-energy, continuously tunable intracavity terahertz-wave parametric oscillator

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Abstract: This paper demonstrates an intracavity pumped by a THz optical oscillator from a diode-side-pumped Q-switched Nd:YAG laser. Based on a non-collinear phase matching geometry in the nonlinear crystal $MgO:LiNbO_3$, high-energy, low-threshold, coherent tunable Stokes light is obtained by changing the angles between the resonated idler wave and the pump wave, which means that the widely tunable, high-energy, coherent THz radiation can be generated. The tuning range for Stokes wave is from 1069.4 to 1073.4 *nm*, corresponding to the THz frequency range of 1.4-2.5 *THz*. Furthermore, the phenomenon of the coherent tunable second-order Stokes light scattering is also observed.

Key Words: Terahertz generation, nonlinear optics, parametric oscillators and amplifiers, frequency conversion, lasers, diode-pumped

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1. Introduction

The terahertz (THz) wave, located at the boundary between the microwave and optical bands, is of great interest for various applications in basic and applied physics. In recent years, compact THz light sources have been realized by optical methods. One such method is the ultrashort-pulse terahertz-wave generation, using high-speed photo conducting antennas or electro-optical materials, semiconductor, and superconductor materials pumped with a femto-second laser [1-4]. They have utilized ultra-broad-bandwidth characteristics of femto-second optical pulses, so that the generated THz waves posses high temporal characteristics with the sacrifice of their temporal coherence. In contrast to these methods, the tunable narrowband THz-wave sources with high temporal and spatial coherence have been developed by using nonlinear tuning techniques of difference frequency generation [5] or parametric oscillation [6-11]. This kind of THz wave can be applied to fast data sampling in frequency-resolved experiments for many applications, such as spectroscopy, imaging of biological and other materials, gas sensing and medical diagnosis.

Terahertz-wave parametric oscillator (TPO) source has the merits of good coherence, high output, room temperature operation, and a simple design. It has been reported and studied by some researchers recently. Typically such a system consists of a separate pulsed pump laser and a nonlinear crystal in an external-cavity. The threshold of this configuration is very high (usually more than 20-30 *mJ*) and the conversion efficiency is low. Moreover, the pump laser needs to be focused tightly into the nonlinear crystal to achieve the oscillator threshold, which increases the damage to nonlinear medium and optical coatings. The intracavity pumping technology that allows the nonlinear medium to be placed within the cavity of the pump laser has many advantages. First it can take advantage of high fundamental power density within the oscillator to realize a low threshold and high efficiency. Moreover, the intracavity configuration increases the effective interaction length due to many round trips of the pump laser in idler cavity. The wider spectral coverage associated with angle tuning can be obtained due to circulating intracavity field. In addition, it is easier to realize structure compactness than its external counterpart.

THz radiation sources based on intracavity non-collinear phase matched parametric oscillator have been investigated experimentally with the diode-end-pumped configuration [9, 10]. Although the end-pumped laser system has some advantages of high efficiency and high beam quality, some disadvantages of the thermal stress inducing fractures of the laser crystal, limit the output power scaling. On the contrary, the side-pumped configuration is useful for the purpose of power scaling because in this configuration, longer laser crystal rod can be used and more of diode lasers can be accommodated by placing them side-by-side.

In this paper, we present a diode-side-pumped Q-switched Nd:YAG laser as the pumping laser of intracavity TPO. Based on a non-collinear phase match geometry in the nonlinear crystal $MgO{:}LiNbO_3$, high-energy, low-threshold, coherent tunable Stokes light was obtained by changing the angles between the resonated idler wave and the pump wave, which means that the widely tunable, high-power, coherent THz radiation can be generated. Besides, the phenomenon of the coherent tunable second-order Stokes light scattering is also observed in our experiments.

2. Experimental setup

The experimental arrangement of the compact intracavity TPO is shown schematically in Fig. 1 The pump module is composed of three fifty-bar stacked diode arrays, emitting at 808 *nm* with a repetition rate of 10Hz. The maximum diode pumping peak power available is approximately 15000 *W*. We set the diode pulses as 200 μs long to match closely the upper laser level lifetime of 230 μs. The water faucet of the pump module can be connected to a water-cooled temperature controlling system. The Nd:YAG rod (5 *mm* in diameter, 115 *mm* in length) was plane-parallel polished and antireflection coated on both ends at 1064 *nm*. The overall pump wave cavity was 490 *mm* long and was formed by two flat mirrors, M_1 and M_2. The mirror M_1 was highly reflective at 1064 *nm* wavelength, and the M_2 mirror was 10% transmission at 1064 *nm*. The KD^*P and polarizer were used as Q-switch and mounted between the laser head and M_1 mirror. The OPO cavity (idler cavity) was formed by a pair of plane-parallel mirrors, M_3 and M_4. And they were placed in the pump light cavity to be consistent with the non-collinear phase matching geometry. M_3 was highly reflective at idler wavelength, and M_4 mirror was chosen to 16% transmission at idler wavelength in order to avoid optical damage to intracavity elements. The OPO cavity length was 190 *mm* long, as short as possible, in order to lower the oscillator threshold. However, its minimum length is limited by the need for completely separating the pump and idler beams at the idler cavity mirrors so as not to impede the pump wave. The dimensions of the 5mol% $MgO:LiNbO_3$ crystal used in the TPO were 5(z)×60(x)×10(y) mm^3. The x and y surfaces of the crystal were polished and uncoated. Since the absorption coefficient of LN crystal is quite large[11,12] in the THz frequency, the idler wave as well as the pump wave was aligned so as to pass through the crystal as close to the y surface as possible in order to minimize the absorption effect to the THz radiation. In addition, the Si prisms were placed against the y surface of the crystal for efficient coupling of the THz wave, which can avoid the total internal reflection of THz wave at the y surface of $MgO:LiNbO_3$ crystal.

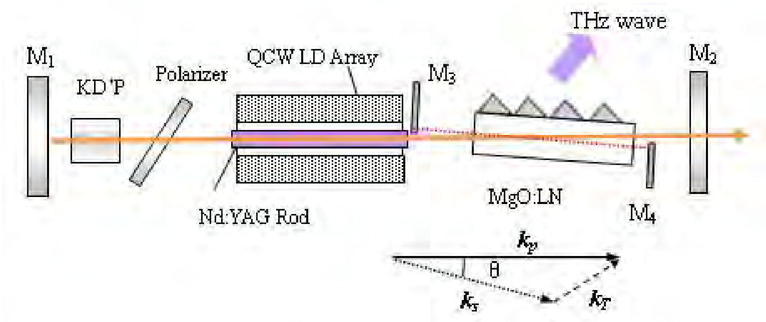


Fig. 1 Schematic diagram of the intracavity THz parametric oscillator

3. Results and discussion

The principle of TPO is based upon stimulated scattering from the long-wavelength side of the A1-symmetry soft mode in $LiNbO_3$ [13]. During the scattering process, both the energy conservation law ($\omega_p = \omega_i + \omega_T$) and the momentum conservation law ($\vec{k}_p = \vec{k}_i + \vec{k}_T$) hold. Through rotating the TPO cavity to vary the phase-matching angle θ between the pump and oscillated Stokes lights inside the crystal, coherent, tunable THz wave can be obtained. At the same time, continuous tunable idler light also can be detected.

To estimate the parameters of such an IOPO resonant, measurements of free-running operation without OPO elements and with them were carried out. The input-output characteristics of the intracavity TPO system are shown in Fig. 2. The horizontal axis represents the pump pulse output energy without OPO elements, whereas the vertical axis represents the Stokes pulse energy with OPO elements in the pump cavity. From Fig. 2, the oscillator threshold for the TPO cavity was observed corresponding to pump pulse energy of 29.64 *mJ*. The threshold pump power intensity in the cavity is about 26 MW/cm^2 with the pump radius of 1.4 *mm*, which is much lower than that of extracavity TPO (typically more than 40 MW/cm^2) [7]. Moreover, we consider the threshold can be further reduced with coated crystal and shorter cavity length due to the low loss in the cavity. The maximum Stokes-wave energy was 8.96 *mJ* with the pump pulse energy of 51.83 *mJ*. The optical-optical conversion efficiency is 17.3%. The energy of THz wave has not so far been directly measured, but on the basis of work by Edwards et al [9], it is anticipated that high energy THz-wave radiation is generated. The pulse durations (FWHM) for the pump wave and Stokes wave were 21.68 *ns* and 16.02 *ns*, respectively. It is estimated that the pulse duration of Stokes wave should be much smaller because of a certain mixture of pump wave. In addition, the shorter pulse duration of Stokes wave can be obtained with shorter OPO cavity. The pulse width of THz wave will be somewhat shorter than that of the idler wave based on the OPO buildup time.

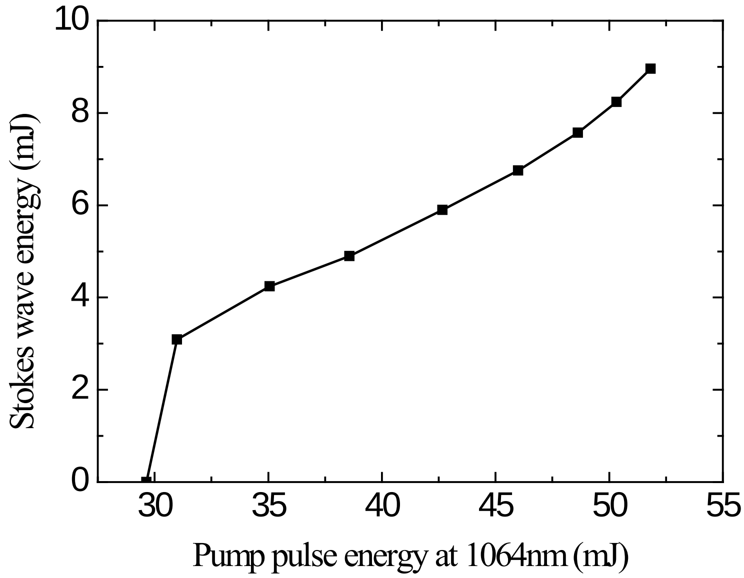
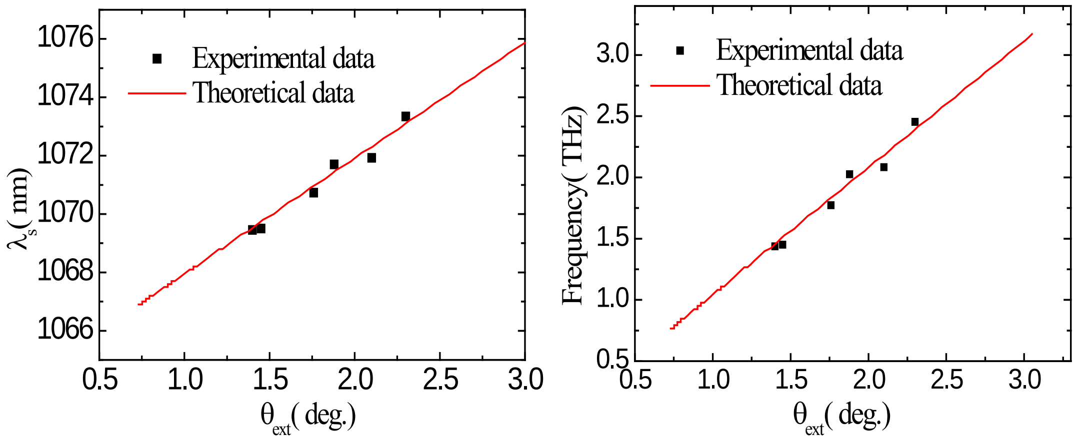


Fig. 2 Stokes wave and pump wave output character versus pumping energy

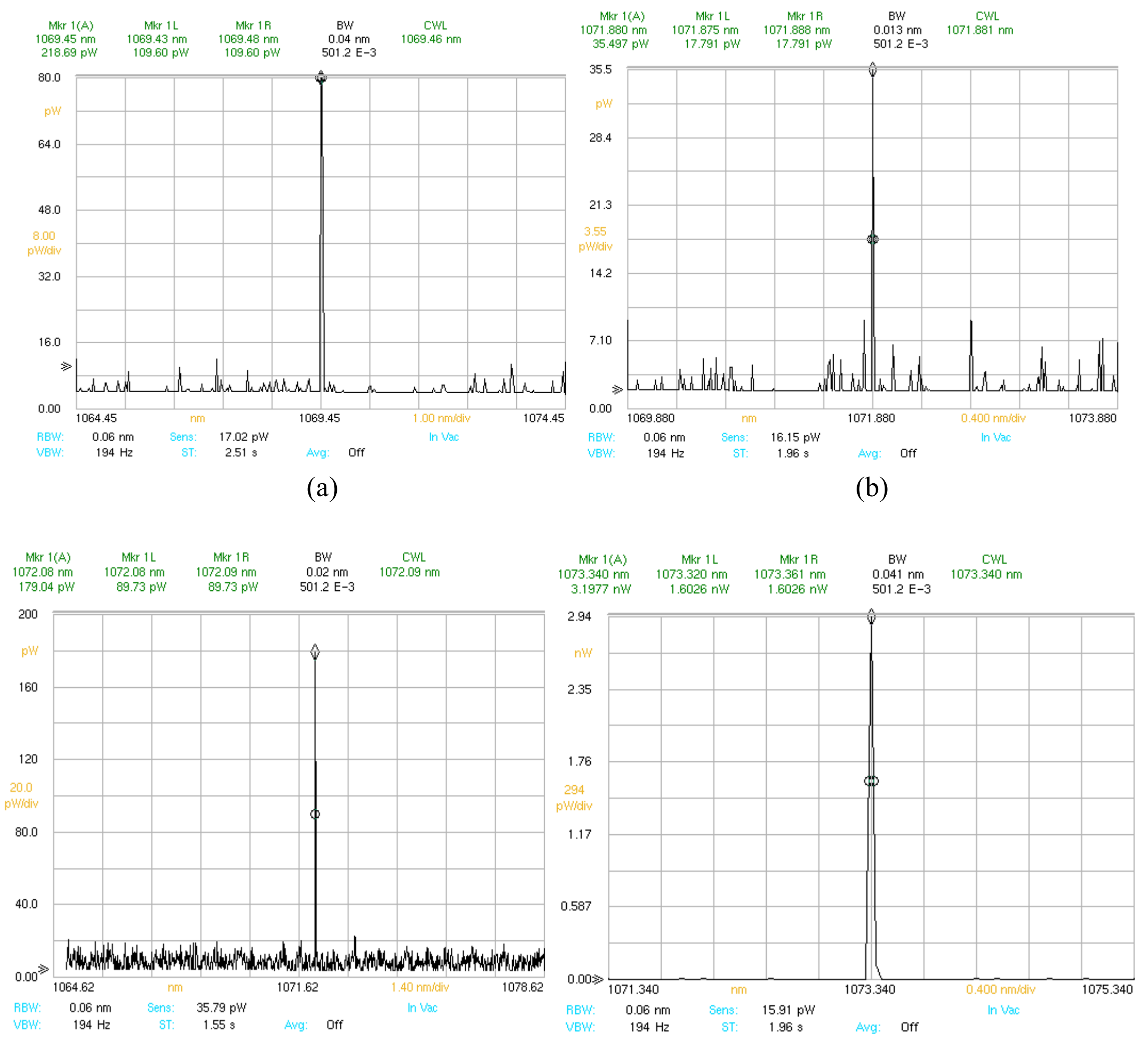
When rotating the TPO cavity for slight variation in the phase matching condition, the angle θ between the pump and oscillated Stokes lights outside the crystal varied between 1.4^o-2.3^o, and the detected idler wavelength varied between 1069.4-1073.4 *nm*, whereas the calculated wavelength of the THz wave varied between 209-122 *μm* (1.4-2.5 *THz*). Fig. 3 shows the wavelength/frequency of the idler light and THz light as a function of the external angle between the pump wave and idler wave. The solid line is a theoretical curve using the refractive index data for pump/idler waves from Sellmeier equations in reference [14], and for the THz wave with 5.2. The boxes values are our experimental data. It is seen that the experimental results is in good agreement with the theoretical calculation. When increasing the tuning angle, the idler wavelength and THz frequency will be increased. But the threshold is also increased due to decreasing the overlap between the pump wave and the idler wave. We didn't attempt to increase the angle in order to avoid optical damage to intracavity elements. The low frequency end of the tuning range is limited by the geometry of the device in that the idler cavity mirrors don't impede the pump wave.

Fig. 4 depicts the tunable Stokes light spectrums. The line widths for Stokes wave are all as narrow as several GHz, which indicates that THz wave is characterized by its coherence.



(a) (b)

Fig. 3 Stokes wavelength (a) and THz frequency (b) tuning characteristics for the intracavity TPO



(a) (b)

(c) (d)

Fig. 4 The measured tunable Stokes-spectrum

In addition to the pump and idler pulses, we also observed the tunable second-order Stokes lights at higher pump energy, as showed in Fig. 5. The intensity of second-order Stokes wave increases as the pumping energy enhances. It should interact with the pump light and make some effect on THz wave generation. The related analysis will be given in another paper.

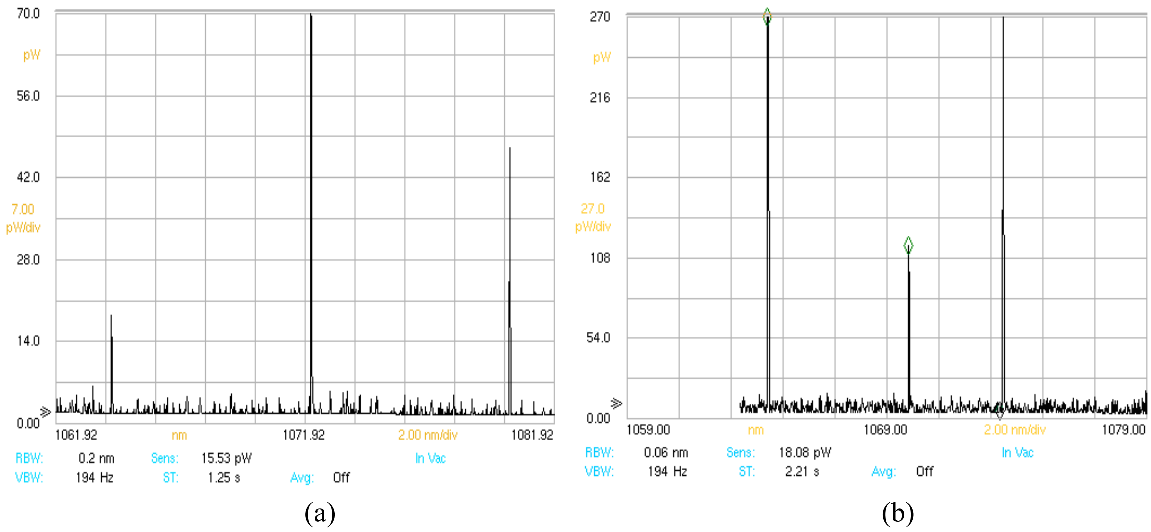


Fig. 5 The tunable spectrums of second-order Stokes light

4. Conclusions

In conclusion, we have demonstrated an intracavity THz optical oscillator pumped by a diode-side-pumped Q-switched Nd:YAG laser. Based on a non-collinear phase matching geometry in the nonlinear crystal $MgO:LiNbO_3$, high-energy, low-threshold, coherent tunable Stokes light was obtained by changing the angles between the resonated idler wave and the pump wave, which indicates that the high-energy, coherent, tunable THz radiation can also be generated. Currently operation has been limited by the long OPO cavity and the optical damage to the nonlinear crystal. We believe that low threshold, widely tunable THz radiation source can be obtained with improved cavity geometry, and the THz output energy will be further increased. Such high-energy, coherent THz wave source can find numerous applications in several areas, such as imaging, spectroscopic, and so on.

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