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Optical design and enhanced output of a surface-emitted THz-wave parametric oscillator

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Abstract: High-power tunable terahertz wave (THz-wave) radiation was parametrically generated via a surface-emitted THz-wave parametric oscillator (TPO) pumped by a multi-longitudinal-mode Q-switched Nd:YAG laser. The effective parametric gain length under the condition of noncollinear phase matching was calculated to optimize the parameters of TPO. The THz-wave radiation from 0.77 to 2.83 THz was obtained. The maximum THz-wave output is 347.8 nJ/pulse at 1.78 THz when the pump power density is 222.3 MW/cm^2, corresponding to the energy conversion efficiency of 3.91×10^{-6}. The far-field divergence angle of THz-wave radiation is 0.020 4 rad at vertical direction and 0.006 8 rad at horizontal direction.

Key words: THz-wave; THz-wave parametric oscillator; noncollinear phase matching;
effective parametric gain length
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表面出射太赫兹波参量振荡器的设计与增强输出

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摘　要: 利用一台多纵模调 Q Nd:YAG 激光器泵浦的浅表垂直发射太赫兹波参量振荡器参量产生了高功率可调谐太赫兹波辐射。推导了非共线相位匹配条件下的有效参量增益长度以优化太赫兹波参量振荡器参数。实验测得太赫兹波的调谐范围为 0.77~2.83 THz。当泵浦功率密度为 222.3 MW/cm^2 时,在 1.78 THz 处太赫兹波的最大输出能量为 347.8 nJ/pulse,对应的能量转化效率为 3.91×10^{-6}。太赫兹波在垂直方向上的远场发散角为 0.020 4 rad,在水平方向上为 0.006 8 rad。

关键词: 太赫兹波;　太赫兹波参量振荡器;　非共线相位匹配;　有效参量增益长度

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0 Introduction

It is widely recognized that THz-wave offer a numerous variety of applications such as imaging, material detection, remote atmospheric sensing and monitoring, astronomy, life sciences, national defense security [1-3]. The selection of a method for generating THz pulses involving high-power output, tuning, compactness, coherence, room-temperature operation is of vital importance. In particular, THz-wave parametric oscillator (TPO) based on stimulated phonon-polariton scattering in a MgO-doped $LiNbO_3$ crystal exhibits multiple advantages such as compactness, narrow linewidth, coherent, wide tuning range, high-power output and room temperature operation [4]. In recent years, TPO has been developed rapidly. Sun et al.[5] demonstrated a TPO with a corner-cube resonator consisting of a corner-cube prism and a flat mirror. By using the cavity configuration proposed above, the TPO stability against cavity misalignment was significantly improved by at least 1 to 2 orders of magnitude compared with the conventional plane-parallel resonator configuration. Kiessling et al.[6] demonstrated a pump-enhanced optical parametric oscillator generating continuous wave tunable terahertz radiation. The tunability ranged from 1.2 to 2.9 THz at output power levels between 0.3 and 3.9 μW. Takida et al.[7] reported on a tunable picosecond THz-wave parametric oscillators by employing a noncollinear pump-enhanced signal-resonant cavity. The THz-wave peak frequency was continuously tunable from 0.9 to 3.3 THz, with the average output power of dozens of nanowatts.

In this letter, the effective parametric gain length under the condition of noncollinear phase matching is calculated. The TPO is designed based upon the particular parameters that are calculated from the expression of the effective parametric gain length. The THz-wave radiation is realized via a surface-emitted TPO which is composed of a Fabry-Perot cavity and a MgO:$LiNbO_3$ crystal. A widely tunable and high-power THz-wave radiation is realized. The experimental values of THz-wave frequency agree well with the theoretical curve calculated from the noncollinear phase matching condition. The far-field divergence angles of THz-wave are measured.

1 Optical design for TPO

The noncollinear phase matching configuration in TPO restricts the effective interaction volume among three mixing waves and increases the threshold power density, so the optimum design for TPO is necessary. Next the expression of effective parametric gain length under the noncollinear phase matching condition based on the theoretical model in Brosnan and Byer is deduced [8]. Here, the phase matching angle between pump wave and Stokes wave as a double refraction walkoff angle since the magnitude of both angles is approximately equal and the effect of both is identical. Assuming the three mixing waves have Gaussian profiles, the Stokes spot size is narrowed by the gain polarization and broadened by the diffraction simultaneously. The balance determines the final Stokes wave spot size. The relationship between pump wave radius w_p and Stokes wave radius w_s is given by

$$\left(\frac{\pi}{2L\lambda_s}\right)^2\left(\frac{w_p^2w_s^2}{w_p^2+2w_s^2}\right)^3+\frac{w_p^2w_s^2}{w_p^2+2w_s^2}-\frac{w_p^2}{2}=0 \tag{1}$$

where λ_s is the wavelength of Stokes wave and L is the optical cavity length, $L=L'+(n_s-1)l$, L' is the physical length of Stokes cavity and l is the crystal length. The walkoff length l_w is given by

$$l_w=\frac{\sqrt{\pi}}{2}\frac{w_p}{\theta_{in}}\sqrt{\frac{w_p^2+w_s^2}{w_p^2+w_s^2/2}} \tag{2}$$

where θ_{in} is the phase matching angle between pump wave and Stokes wave within MgO:$LiNbO_3$ crystal. Here θ_{in} is used as a substitute for the double refraction walkoff angle. The effective parametric gain length L_{eff} is given by

$$L_{eff}=l_\omega \mathrm{erf}\left(\frac{\sqrt{\pi}}{2}\frac{l}{l_\omega}\right) \tag{3}$$

The effective parametric gain length versus the radius of pump wave and the length of MgO:LiNbO$_3$ crystal is shown in Fig.1, assuming the cavity physics length is 175 mm and the frequency of generated THz-wave is 1.5 THz. From the figure we find that the pump beam with a larger radius and the crystal with a longer length can increase the effective parametric gain length. The pump wave with a large beam radius can generate Stokes wave and THz-wave with a large beam radius simultaneously, resulting in a long effective parametric gain length. Actually for the maximum conversion efficiency, the pump beam diameter must be increased until the effective parametric gain length is equal to the crystal length. A long crystal can enlarge the effective parametric gain length until pump wave and Stokes wave are spatially separated within MgO:LiNbO$_3$ crystal.

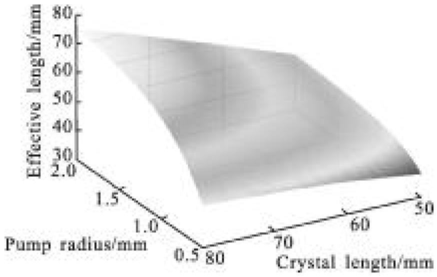

Fig.1 Effective parametric gain length versus the radius of pump wave and the length of MgO:LiNbO$_3$ crystal

2 Experimental setup

The experimental setup comprises a single-resonant optical parametric oscillator with a Fabry-Perot cavity pumped by a multi-longitudinal-mode Q-switched Nd:YAG laser at 1 064 nm, as is shown in Fig.2. The pulse width and the repetition rate of pump wave are 15 ns and 10 Hz, respectively. The pump beam is collimated by a lens pair to a diameter of about 2 mm. The nonlinear gain medium is a 5% MgO-doped congruent LiNbO$_3$ crystal. The pentagonal crystal is cut from a rectangular crystal, measuring 70(x)×46(y)×5(z) mm^3. The propagation length of Stokes wave within MgO:LiNbO$_3$ crystal at both sides of THz-wave exit point is 35 mm. All crystal surfaces are antireflection coated with a residual reflectivity smaller than 1% at Stokes wavelengths. All interacting waves are extraordinarily polarized. The TPO cavity for Stokes wave consists of two plane-parallel mirrors, M$_1$ and M$_2$. M$_1$ is highly reflecting(>99.8%) and M$_2$ is coated with a reflectivity of 95%. The cavity with a length of 160 mm is symmetric. The pump wave passes through the cavity at the edge of M$_1$ and M$_2$. The cavity mirrors and MgO:LiNbO$_3$ crystal are mounted on a rotating stage.

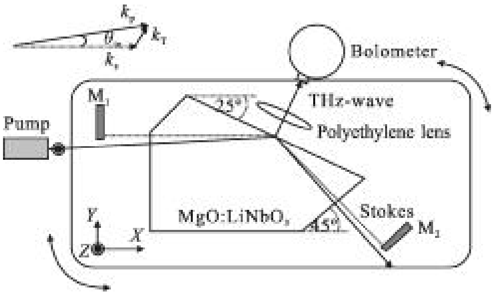

Fig.2 Experimental setup of MgO:LiNbO$_3$-TPO

3 Results and discussions

For the optical parametric oscillation, two requirements have to be fulfilled: the conservation of energy $\omega_p=\omega_s+\omega_T$, and the noncollinear phase matching condition $\bar{\mathbf{k}}_p=\bar{\mathbf{k}}_s+\bar{\mathbf{k}}_T$. Here, ω_p, ω_s and ω_T are the angular frequencies while $\bar{\mathbf{k}}_p$, $\bar{\mathbf{k}}_s$ and $\bar{\mathbf{k}}_T$ are the wavevectors of pump, Stokes and THz-wave, respectively. The noncolline ar phase matching condition can be rewritten as $\mathbf{k}_T^2=\mathbf{k}_p^2+\mathbf{k}_s^2-2\mathbf{k}_p\mathbf{k}_s\cos\theta_{in}$. Varying the angle θ_{in} continuously by rotating the stage on which the resonant cavity and MgO:LiNbO$_3$ crystal are fixed, the tuning THz-wave radiation can be obtained. The tuning characteristics of THz-wave are shown in Fig.3. θ_{ext} is the phase matching angle between Stokes wave and pump wave at the external side of the crystal. The solid curve indicates the values calculated from the noncollinear phase matching condition. The THz-wave frequency is figured out exactly by analyzing the spectra of Stokes waves and taking the frequency difference between pump wave and Stokes waves. The THz-wave radiation in the range from 0.77 to 2.83 THz is obtained. The experimental results agree well with the values calculated from the noncollinear phase matching condition.

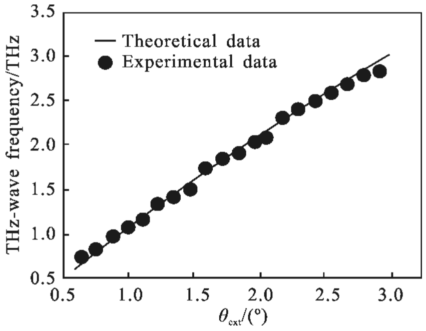

Fig.3 Tuning characteristics of THz-wave

Figure 4 shows the output characteristics of THz-wave under the pump power density of 156.4 MW/cm^2. The THz-wave radiation is detected using silicon bolometer operating at 4 K. Transmittance-calibrated black polyethylene filters is used as the low-pass filter, which only allows THz-wave to pass through. The tuning output of THz-wave from 0.88 to 2.68 THz is obtained, and the maximum output of THz-wave is 152.2 nJ/pulse at the frequency of 1.75 THz. The phase matching angle θ_{in} increases as THz-wave frequency locates in the high frequency band. The decrease of the effective parametric gain length due to the increase of phase matching angle θ_{in}, as shown in Eq.(2)-(3), restricts the enhancement of THz-wave radiation. Moreover, the absorption coefficient of MgO:LiNbO$_3$ crystal is large in high frequency band[9-10].

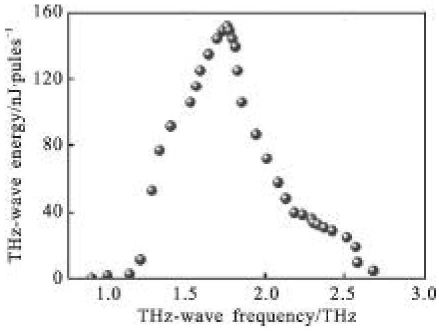

Fig.4 THz-wave output characteristics with the pump power density of 156.4 MW/cm^2

The output characteristics of THz-wave and Stokes wave at the frequency of 1.78 THz as a function of the pump power density is shown in Fig.5. From the figure we find that the threshold behavior and the good correlation between Stokes wave and THz-wave are obvious. The maximum output of THz-wave and Stokes wave is 347.8 nJ/pulse and 2.67 mJ/pulse respectively when the pump power density is 222.3 MW/cm^2, corresponding to THz wave energy conversion efficiency of 3.91×10^{-6}.

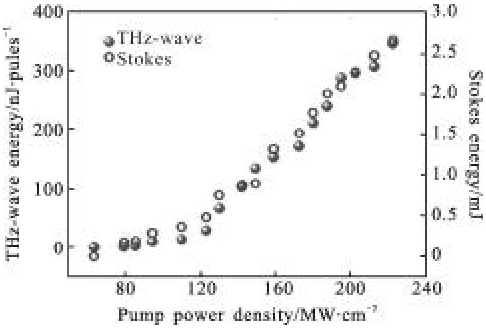

Fig.5 Output characteristics of THz-wave and Stokes wave as a function of the pump power density

The area where THz-wave emitted is not circular but elliptical due to the total reflection of pump wave and Stokes wave, which means that the cross section of THz-wave is not circular also. The far-field divergence angle of THz-wave is in inverse proportion to the diameter of the emitting area. The far-field divergence angle of THz-wave radiation in this experiment is 0.020 4 rad at vertical direction and 0.006 8 rad at horizontal direction.

4 Conclusion

The expression of effective parametric gain length under the condition of noncollinear phase matching is deduced. Based upon particular parameters calculated from the expression of the effective parametric gain length we design the surface-emitted TPO. The THz-wave radiation from 0.77 to 2.83 THz is realized. The maximum THz-wave output is 347.8 nJ/pulse at 1.78 THz when the pump power density is 222.3 MW/cm^2, corresponding to the energy conversion efficiency of 3.91×10^{-6}. The far-field divergence angle of THz-wave is 0.020 4 rad at vertical direction and 0.006 8 rad at horizontal direction.

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下期预览

太阳模拟器AM0型滤光片及其稳定性研究

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摘 要：太阳模拟器作为航天科技卫星空间环境模拟和太阳能电池检测与标定的必要模拟设备，越来越受到人们的关注。太阳模拟器滤光片作为模拟器的核心部件，通过对模拟器光源滤光，可以得到不同的太阳光谱辐照度。所研究的AM0滤光片通过对氙灯光源滤光，可以得到大气层表面的太阳光谱辐照度分布。根据标准AM0光谱辐照度曲线和标准氙灯辐照度曲线，得到AM0滤光片透过率曲线。在此基础上对滤光片进行膜系设计和镀制，得到了满足国标A类标准的AM0滤光片。对滤光片进行了紫外辐照实验和高温烘烤实验，研究了其光学稳定性，所镀制的滤光片光学稳定性优于目前使用的滤光片。