Study on the generation of Efficient Terahertz from cavity phase matching optical parametric oscillator with a GaAs Crystal sheet by CO_2 laser

Zhi-Ming Rao [1, a*], Hui-Hui Xu [1, b] and Fang-Sen Xie[1,c]

[1]School of Physics, Communication and Electronics, Jiangxi Normal University, nanchang, Jiangxi, 330022, CHINA

[a] raozm24@163.com, [b]506610113@qq.com, [c]121425353@qq.com

* corresponding author : raozm24@163.com

Keywords: terahertz, cavity phase matching, optical parametric oscillator, GaAs crystal sheet.
Abstract. We study on the generation of efficient terahertz (THz) wave. This scheme applying cavity phase matching (CPM) optical parametric oscillator (OPO) with a GaAs crystal sheet by CO_2 laser is proposed. The THz wave is emitted the nonlinear crystal. We calculated the optimized cavity length in a GaAs crystal sheet at the range of 100-1000 μm. The result is shown that CPM-OPO scheme is efficient to obtain efficient THz wave.

Introduction

Terahertz (THz) sources can be used in many applications in environment detections, security inspections, biomedical diagnostics, and so on [1-3]. Among the variety of nonlinear crystals, GaAs meet the requirements for high transparency in both 10 μm band and relatively high transparency in the THz region. A lot of work has been carried out enhancing THz power [[4-7]. We demonstrate a tunable THz source based on the collinear DFG in GaSe crystal with a dual-wavelength CO_2 laser [7]. A peak power of 182 mW was detected, which peak power corresponds to be external power conversion efficiency only about 1×10^{-5}%. Optical parametric oscillation(OPO) is one of the effective ways to produce high-power, narrow-band coherent THz sources in nonlinear crystals[4]. Optical parametric oscillation(OPO) was designed to satisfy the wave vector phase matching condition in nonlinear crystal. The scheme of cavity phase matching using has been proposed [8, 9] and demonstrated [10] to solve nonlinear optical crystals high absorption coefficients. In this scheme, the THz wave is generated in cavity phase matching. CPM-OPO makes it possible to avoid THz wave strongly absorbing crystals decay.

Theory of scheme and discussion

GaAs crystal has a large nonlinear coefficient, a widely transparency range, and a high damage threshold. According to the Manley-Rowe relation, the maximum conversion efficiency can be improved by one order of magnitude when using mid-infrared laser with longer wavelength running at 10 μm. Taking into account the maturity of mid-infrared laser technology and the development of technology of periodically-inverted crystals, it will be an effective way to generate THz wave based on CPM-OPO. However, the theory generation of the efficient THz wave in a crystal sheet cavity phase matching pumped by wavelength running at 10μm laser has not been detail reported.

In this letter, explore the terahertz (THz) wave generation based on cavity phase matching (CPM) Optical parametric oscillation in a GaAs crystal sheet. It is found that the Zinc blende semiconductor GaAs is an efficient THz frequency generator owing to its large second-order nonlinear coefficient (d_{36} (10.6 μm) =83pm/V) [11]. Our scheme is cavity phase matching (CPM). The optimized cavity length in a GaAs crystal sheet were calculated in this paper.

The geometry principle of phase matching is as shown . Here we assume that the wave propagation of the pump wave (at frequency w_P, wavelength l_P) is perpendicular to the domain wall of the nonlinear crystal. The THz wave (at frequency w_T, wavelength l_T) is emitted the nonlinear crystal. The damping of the THz wave is minimized due to the short pass length in the nonlinear crystal. The optimized cavity length in a GaAs crystal sheet *L* can be calculated by using the vector phase matching condition and energy conservation:

$$k_P = k_S + k_T + \frac{p}{\Lambda} \quad , \qquad (1)$$

$$\frac{1}{l_P} = \frac{1}{l_T} + \frac{1}{l_S} \quad , \qquad (2)$$

where, $k_i = 2\pi n_i / l_i$ and n_i (i=P,S,T) denote pump wave, singal wave and THz wave vector and refractive indices, respectively. The grating period *L* can be deduced from equations (1) and (2)

$$\Lambda = \frac{l_P l_T}{2(n_P l_T - n_T l_P - l_T n_S + l_P n_S)} \quad , \qquad (3)$$

This scheme can produce THz wave. For l_P=9.552 μm, we calculated optimized cavity length in a GaAs crystal sheet *L* by using the Sellmeier equation of GaAs from Ref. [12] and Eq. (3). The Sellmeier equation of GaAs is given by

$$n^2(l) = b + \frac{g_1}{b_1^{-2} - l^{-2}} + \frac{g_2}{b_2^{-2} - l^{-2}} + \frac{g_3}{b_3^{-2} - l^{-2}} , \qquad (4)$$

where, *l* is the pump or Thz laser wavelength, b=5.372514, b_1(μm)=0.4431307+0.000050564*D*T, b_2(μm)=0.8746453+0.0001913*D*T-4.882×10^{-7}*D*T^2, b_3(μm) =36.9166-0.011622*D*T, *D*T is the deviation from the reference room temperature 22℃, g_1=27.83972, g_2=0.031764+4.350×10^{-5}*D*T+4.664×10^{-7}*D*T^2, and g_3=0.00143436.

The relation of the optimized cavity length in a GaAs crystal sheet *L* at room temperature and the THz wavelength are shown in Fig.1 from Eqs.(3) and (4). It can be seen that *L* is increased from 0.16 to 1.96 mm when THz wavelength is increased from 100 to 1000μm in the CPM scheme. Needing the optimized cavity length in a GaAs crystal sheet is a 0.58 mm in the CPM scheme to generate a frequency of 1 THz (300 μm) wave.

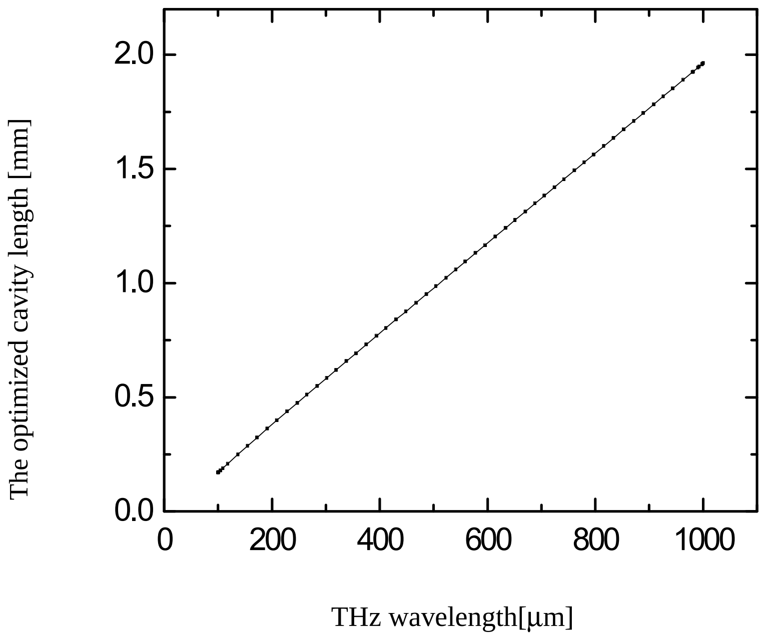

Fig.1. The optimized cavity length versus the generated THz wavelength with a GaAs crystal sheet

To evaluate the performances for using crystals as THz-wave converters, all the interactions can be phase matched in OPO, and THz power conversion efficiency *h* in the plane-wave fixed-field can be given by [13]

$$h = \frac{8p^{2} d_{eff}^{2} L^{2} P_{P}}{e_{0} c n_{1} n_{2} n_{T}\, l_{T}^{2} A} e^{-a_{T} L}, \qquad (5)$$

where, L is the crystal length 0.058 cm, the pump intensity P_P=10MW, dielectric constant of vacuum ε_0=8.854187817×10^{-12} F/m, light speed of vacuum c=3×10^{8} m/s, and the pump area A=0.1mm^2. Zinc blende semiconductor GaAs THz absorption coefficient α_T is 0.5-4.5cm^{-1} at 1-3THz [7]. For OPO process, when THz-wave l_T=300 μm (1THz) from Eq. (5), which corresponds to the power conversion efficiency is of ~0.000001%.

In this CPM- OPO scheme, to evaluate the performances for using crystals as THz-wave converters, assume that the pump wave achieves 10 times in a GaAs crystal sheet. THz-wave power conversion efficiency *h* neglecting pump depletion in the plane-wave fixed-field can be given by

$$h = \frac{3200 d_{eff}^{2} L^{2} P_{P}}{e_{0} c n_{1} n_{2} n_{T}\, l_{T}^{2} A}, \qquad (6)$$

where, ***b=0.3*** mm is the crystal thickness, and the overlap factor F=1. For the CQPM scheme, at THz-wave l_T=100μm (3THz) from Eq.(6), which corresponds to the power conversion efficiency of ~0.00005%. However, the power conversion efficiency of THz-wave at 3 THz is only 0.000001% in DFG. In CPM- OPO, the power conversion efficiency of THz-wave is far more than that of in DFG, which is due to the CPM- OPO pump wave achieves 10 times in a GaAs crystal sheet.

Summary

In conclusion, we have investigated THz generation from the optimized cavity length in a GaAs crystal sheet with wavelength running at 10μm, and scheme of phase matching is CPM pattern. Using CPM- OPO the pump wave achieves 10 times in a GaAs crystal sheet, and the power conversion efficiency is 0.00005% at a frequency of 1 THz, since the pump beam is achieve 10 times in a GaAs crystal sheet. We calculated the optimized cavity length in a GaAs crystal sheet at THz wavelength from 100 to 1000μm (0.3-3THz). It is shown that the optimized cavity length in a GaAs crystal sheet is efficient to obtain high power conversion efficiency of THz wave generation with mid-infrared laser by using CPM- OPO.

Acknowledgements

This work was financially supported by the Natural Science Fundation of Jiangxi Province (20161BAB202052), by the Science Fundation of Jiangxi Province Office of Eduaction (150337), and by the Fundation of Jiangxi Normal University (7170).

References

[1] Y.M. Bahk, H.R. Park, K.J. Ahn, H.S. Kim, Y.H. Ahn, D.S. Kim, J. Bravo-Abad, L. Martin-Moreno, and F.J. Garcia-Vidal, *Phys. Rev. Lett.* Vol.106 (2011), 013902.

[2] M. B. Johnson, D.M. Whittaker, et al, Linfield: *Phys. Rev. B.* Vol. 65(2002), 165301.

[3] X. Xie, J. Dai, Zhang. X.C, *Phys. Rev. Lett.* Vol.96 (2006), 075505.

[4] Z.M. Rao, X.B. Wang and Y. Z. Lu, *Optics Communications,* Vol.284(2011),5472-5474.

[5] Z.M. Rao, X.B. Wang, Y. Z. Lu, et al, *Chinese Physics Letter*, Vol.28(2011), 074215·

[6] Z.M. Rao, W. Tao, Y. He, et al, *SPIE,* Vol.8330(2011), 83300Q.

[7] Y. Geng, X. Tan, X. Li, J. Yao, Compact and widely tunable terahertz source based on a dual-wavelength intracavity optical parametric oscillation, *Appl. Phys. B.* Vol. 99 (2010),181-185.
[8] Armstrong J A, Blombergen N, *Physics Review,* Vol.127(1962) , 1918-1939.
[9] Haidar R, Forget N, and Rosencher E,*Quantum Electron,* Vol.39 (2003) ,569-575.
[10] Xie Z D, Lv X J,Liu Y H, et al,Physical Review Letters, 106(2011):083901.
[11] D. N. Nikogosyan: Nonlinear Optical Crystals: A Complete Survey *(New York: Springer*) 2005, p208
[12] T. Skauli, P.S. Kuo, K.L. Vodopyanov, T.J. Pinguet, O. Levi, L.A. Eyres, J.S. Harris, B. Gerard, L. Becouarn, and E. Lallier: *J. Appl. Phys.*Vol.94**(**2003)**,** p.6447.
[13] V. G. Dmitriev: *Handbook of Nonlinear Optical Crystals* (Springer publications, Berlin 1999) p50