

Analysis of Efficient Terahertz cavity phase matching Difference Frequency Generation in a GaAs Crystal sheet

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Abstract. In this paper explore the terahertz (THz) wave generation based on cavity phase matching (CPM) difference frequency generation (DFG) in a GaAs crystal sheet. This scheme applying cavity phase matching (CPM) is proposed. The wave propagation of the higher frequency pump wave is parallel to the wave propagation of the lower frequency pump wave, and both of them are perpendicular to the cavity length in a GaAs crystal sheet. 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 μ m (0.3-3THz). Our estimates illustrate that THz wave output corresponds to the power conversion efficiency of 50 times in CPM-DFG for in DFG. The result is shown that this scheme is efficient to obtain THz wave.

Introduction

Terahertz (THz) sources can be used in many applications in environment detections, security inspections, biomedical diagnostics, and so on [1-4]. Difference frequency generation (DFG) was designed to satisfy the wave vector phase matching condition in nonlinear crystal, and DFG is one of the effective ways to produce high-power, narrow-band coherent THz sources in nonlinear crystals, such as periodically poled MgO: LiNbO₃ [5], periodically poled LiNbO₃ (PPLN) [6], and periodically-inverted GaAs [7]. The conversion efficiency is dependent on the signal and pump beam overlap, focusing conditions, crystal temperature, crystal length, and crystal absorption coefficients in the THz wave region. However, nonlinear optical crystals have high absorption coefficients in the THz wave region, which limited the interaction length in crystals and lowered the output THz wave power. 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-DFG makes it possible to avoid THz wave strongly absorbing crystals decay and pump wave achieves 10 times in a GaAs crystal sheet.

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 μ m. 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-DFG. However, the theory generation of the efficient THz wave in a crystal sheet cavity phase matching pumped by wavelength running at 10 μ m laser has not been detail reported.

In this letter, explore the terahertz (THz) wave generation based on cavity phase matching (CPM) difference frequency generation (DFG) 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 ($d_{36}(10.6\mu\text{m})=83\text{pm/V}$) [11]. Our scheme is cavity phase matching (CPM). The optimized cavity length in a GaAs crystal sheet and the power conversion efficiency were calculated in this paper.

The geometry principle of phase matching is as shown . Here we assume that the wave propagation of the higher frequency pump wave (at frequency w_1 , wavelength I_1) is parallel to the wave propagation of the lower frequency pump wave (at frequency w_2 , wavelength I_2), and both of them are perpendicular to the domain wall of the nonlinear crystal. The THz wave (at frequency w_T , wavelength I_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:

$$k_1 - k_2 - k_T = \frac{p}{\Lambda} , \quad (1)$$

$$\frac{1}{I_T} = \frac{1}{I_1} - \frac{1}{I_2} , \quad (2)$$

where, $k_i = 2\pi n_i / I_i$ and n_i ($i=1,2,T$) denote high frequency pump, low frequency pump and THz wave vector and refractive indices, respectively. The grating period L can be deduced from equations (1) and (2)

$$\Lambda = \frac{I_1 I_T}{2(n_1 I_T - n_T I_1 - I_T n_2 + I_1 n_2)} , \quad (3)$$

This scheme can produce THz wave. For $I_1 = 9.552 \mu\text{m}$, 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

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

where, I is the pump or Thz laser wavelength, $b = 5.372514$, $b_1(\mu\text{m}) = 0.4431307 + 0.000050564DT$, $b_2(\mu\text{m}) = 0.8746453 + 0.0001913DT - 4.882 \times 10^{-7}DT^2$, $b_3(\mu\text{m}) = 36.9166 - 0.011622DT$, DT is the deviation from the reference room temperature 22°C , $g_1 = 27.83972$, $g_2 = 0.031764 + 4.350 \times 10^{-5}DT + 4.664 \times 10^{-7}DT^2$, 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 1000 μm 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.

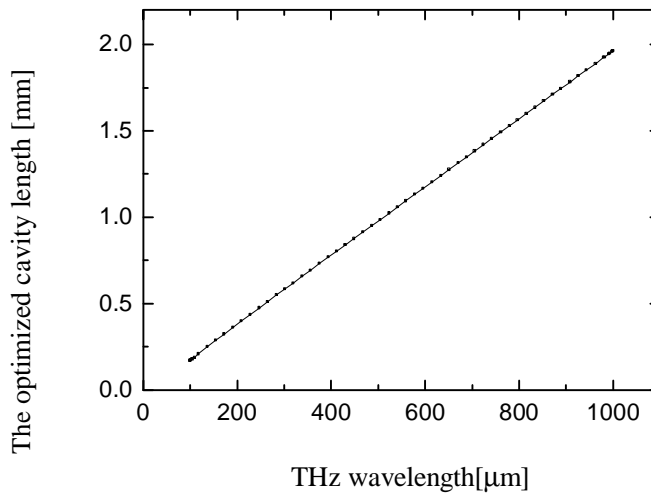


Fig.1. The optimized cavity length versus the generated THz wavelength with a GaAs crystal sheet

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

$$h = \frac{P_T}{P_1} = \frac{8p^2 d_{eff}^2 L^2 P_2}{e_0 c n_1 n_2 n_T I_T^2 A} e^{-\alpha_T L}, \quad (5)$$

where, L is the crystal length 0.058 cm, the pump intensity $P_2=10\text{MW}$, dielectric constant of vacuum $\epsilon_0=8.854187817 \times 10^{-12} \text{ F/m}$, light speed of vacuum $c=3 \times 10^8 \text{ m/s}$, and the pump area $A=0.1 \text{ mm}^2$. Zinc blende semiconductor GaAs THz absorption coefficient α_T is $0.5\text{-}4.5 \text{ cm}^{-1}$ at 1-3THz [7]. For DFG process, when THz-wave $I_T=300 \text{ } \mu\text{m}$ (1THz) from Eq. (5), which corresponds to the power conversion efficiency is of $\sim 0.000001\%$.

In this CPM-DFG 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

$$h = \frac{P_T}{P_1} = \frac{3200 d_{eff}^2 L^2 P_2}{e_0 c n_1 n_2 n_T I_T^2 A}, \quad (6)$$

where, $b=0.3 \text{ mm}$ is the crystal thickness, and the overlap factor $F=1$. For the CQPM scheme, at THz-wave $I_T=100 \mu\text{m}$ (3THz) from Eq.(6), which corresponds to the power conversion efficiency of $\sim 0.00005\%$. However, the power conversion efficiency of THz-wave at 3 THz is only 0.000001% in DFG. In CPM-DEG, the power conversion efficiency of THz-wave is far more than that of in DFG, which is due to the CPM-DEG 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 $10 \mu\text{m}$, and scheme of phase matching is CPM pattern. Using CPM-DEG 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 $1000 \mu\text{m}$ (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-DEG.

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