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Effects of gain saturation on terahertz radiation via optical difference frequency generation

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ABSTRACT

Numerical studies on stability of terahertz (THz) radiation generation based on difference frequency generation in nonlinear crystals are reported. When the gain saturation is achieved at a wavelength that corresponds to an optimal crystal length, the maximal output of THz radiation could be obtained. As a result of crystal absorption, the gain saturation region of THz radiation is unstable region for output. The stability of THz radiation is determined by the stability of pump in the stable region where behind of the gain saturation.

1. Introduction

Terahertz (THz) radiation also known as T-rays, is the part of the electromagnetic spectrum between microwaves and infrared in a frequency interval from 0.1 up to 10 THz (as wavelength: 3000–30 μm). In recent years, the THz wave has a large number of theoretical and experimental reported and providing people with new possibility for applications. THz wave generation technology is currently the key to develop high-power (high energy), high efficiency, and stable operation at room temperature for the miniaturization of THz radiation sources. THz radiation technique based on difference frequency generation (DFG) can achieve high peak power, room temperature operation, compact structure, easy-to-use all-solid-state, etc., which will become one of the primary instruments to obtain THz wave [1–5].

At present, most of the previous research has concentrated on extending the THz spectrum range and increasing the efficiency and power of THz wave generation, but little attention has been paid to the improvement of THz output stability which is super key for practical applications. For example, $LiNbO_3$ [6], GaSe [7,8], $ZnGaP_2$ (ZGP) [9,10] and GaP [11] crystals was recently used to generate THz waves that are tunable from 66.5 to 5664 μm, with the highest output power of 389 W at a wavelength of 203 μm [12].

In this paper, numerical studies of THz generation stability based on DFG in GaSe and ZGP crystal are reported. As a result, the THz wave output stability is depended on the balance of several factors such as pump intensity, crystal length, and signal intensity and so on. Based on our numerical simulation and analysis, we present a practical method to realize excellent stability of THz radiation based on DFG and high-power output, both of which are important to the technology of THz radiation.

2. Simulation and analysis

Whereas analytical solution to the coupled equations governing the three-wave parametric interaction can be contributed to the cases where pump depletion is small, the possible phenomena under the saturation region cannot be described [14]. For example, the optimal crystal length cannot be achieved with such calculation. According to the previous theoretical investigations, three-wave coupled equations can be written in the form by introducing the amplitude of traveling wave component where crystal absorption is considered α_i ($i = s, T, p$) [15]:

$$\frac{dA_s}{dl} = -\frac{1}{2}\alpha_s A_s - igA_T^* A_p e^{-i(\Delta k)l} \quad (1)$$

$$\frac{dA_T^*}{dl} = -\frac{1}{2}\alpha_T A_T^* + igA_s A_p^* e^{i(\Delta k)l} \quad (2)$$

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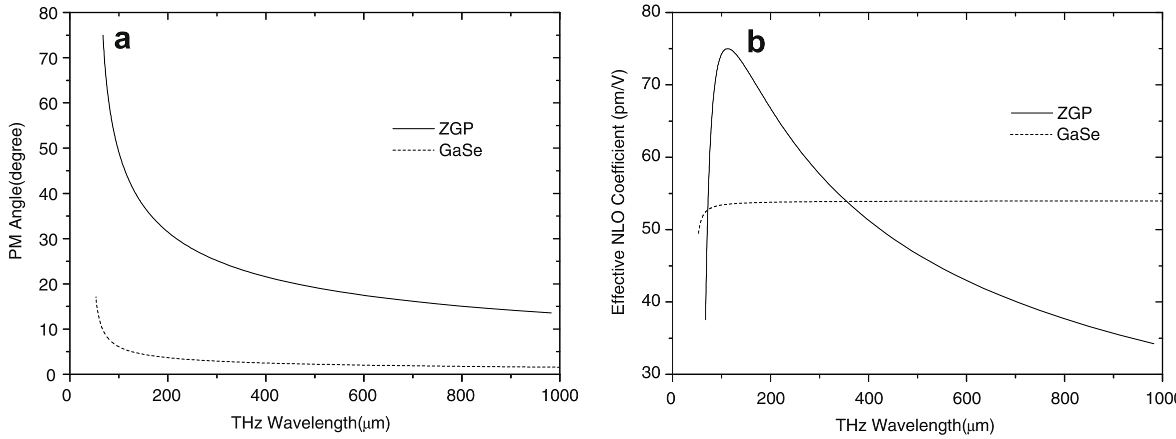

Fig. 1. (a) and (b), respectively, correspond to phase-matching angle and effective NLO coefficient versus THz output wavelength tuning curves for the type-I collinear THz DFG. Solid curves—ZGP; dash curves—GaSe.

$$\frac{dA_p}{dl} = -\frac{1}{2}\alpha_p A_p - igA_sA_Te^{i(\Delta k)l} \tag{3}$$

$$A_i = \sqrt{\frac{n_i}{\omega_i}}E_i \quad i = s, T, p$$

$$g = d_{eff}\sqrt{\left(\frac{\mu_0}{\varepsilon_0}\right)\frac{\omega_s\omega_T\omega_p}{n_sn_Tn_p}} \tag{4}$$

where α_s, α_T and α_p are the absorption coefficient of the signal, THz wave and pump waves; $\Delta k = \left|\vec{k_T} + \vec{k_s} - \vec{k_p}\right|$ refers to the corresponding mismatch of the three waves vectors; d_{eff} is the efficient nonlinear optical coupled coefficient.

The Runge–Kutta algorithm was employed to simulate the parametric interaction in two kinds of nonlinear crystal. According to Ref. [12] we take the negative uniaxial crystal GaSe and the positive uniaxial crystal ZGP as examples, where the phase-matching approach: $o = e + e$(GaSe) and $e = o + o$(ZGP) are taken place. We have chosen GaSe and ZGP crystal for calculation since their absorption coefficients in the THz domain are very low [16]. Such a low absorption coefficient is super important for coherent THz wave generation because the integral conversion efficiency is limited by the effective crystal absorption length. Furthermore, GaSe and ZGP crystals both have high second-order NLO coefficient (GaSe: d_{22} = 54 pm/V, ZGP: d_{36} = 75 pm/V) [17] and large figure of merit d_{eff}^2/n^3, are superior materials for efficient THz generation.

Precision crystal parameters such as phase-matching angle, walk-off angle and spectral tuning can be achieved with a sub-program. Fig. 1 shows the phase-matching angle tuning curves for the type-I collinear DFG on the two crystals. Important input parameters include the crystal length, and intensity and wavelength of each wave. A *Q*-switch Nd:YAG laser and an optical parametric pumped by the third harmonic of the same laser as a DFG pump and a signal (tunable source) sources are chosen for GaSe crystal. The different wavelengths of two CO_2 laser sources are chosen for ZGP crystal.

The simulation results of THz radiation based on DFG are shown in Fig. 2. Obviously, the similar trends generated in the two crystals, which is similar to the analytical solution [13] and indicate that crystal length is critical and must be chosen carefully once the parameters of pump and signal are set. In Fig. 2 a weak THz wave generation grows exponentially in the small gain region like the typical simulation results [14], but both signal and THz wave gradually decreases before the pump is fully depleted. What we could confirm is that either signal or idler energy cannot flow back

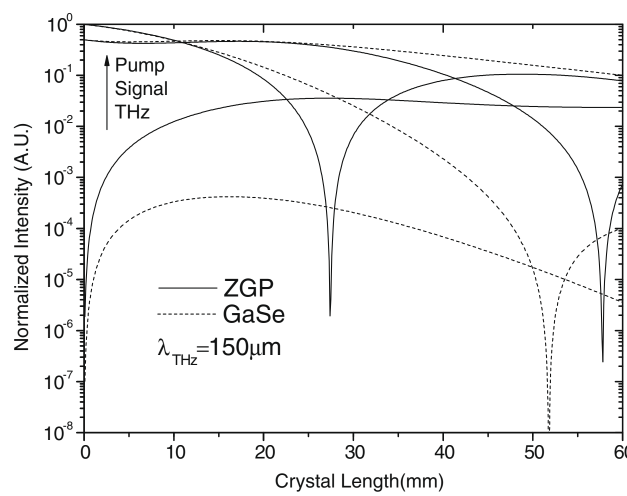

Fig. 2. Intensity curves of three waves at a THz wavelength of 150 μm. Solid curves—ZGP; dash curves—GaSe.

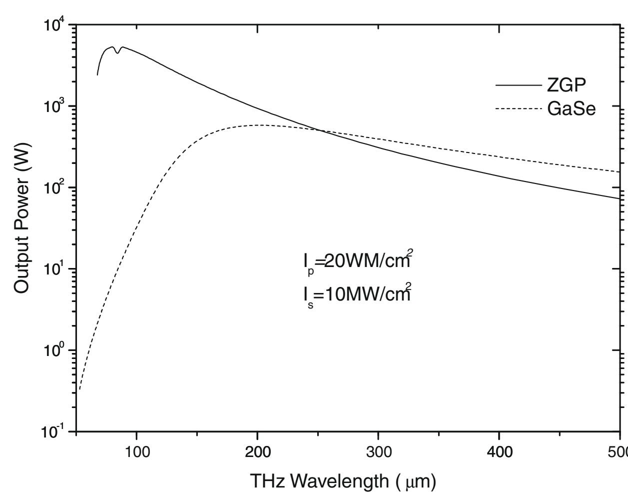

Fig. 3. THz output power versus the THz wavelength turning curve at a crystal length of 20 mm. I_s: input signal intensity and I_p: pump intensity. Solid curves—ZGP; dash curves—GaSe.

to the pump until the pump is fully depleted. Accordingly, the crystal absorption to the signal and THz wave inflect the location of

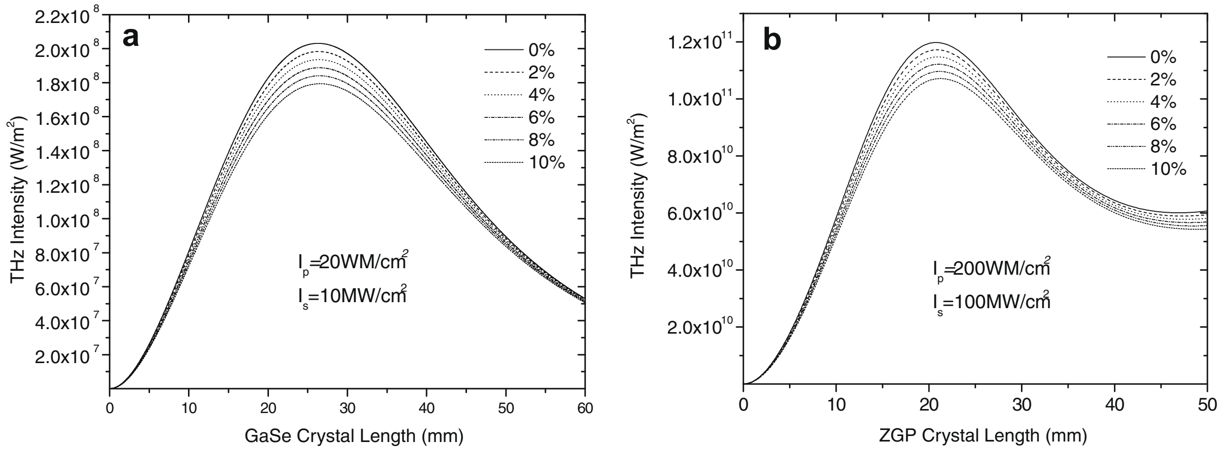

Fig. 4. Dependence of output stability on pump fluctuations. I_s: input signal intensity and I_p: pump intensity. (a) GaSe and (b) ZGP.

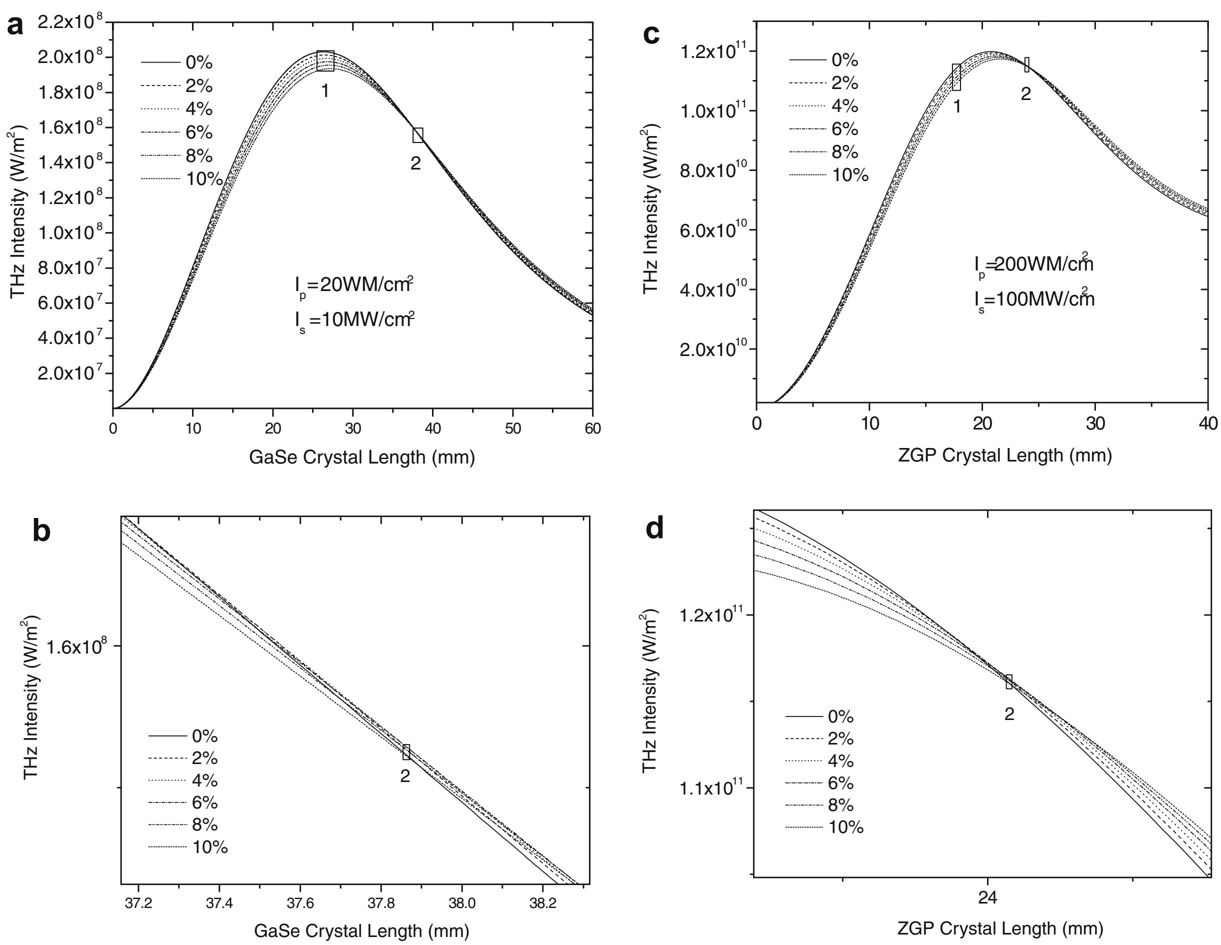

Fig. 5. Dependence of output stability on signal fluctuations: (b) is enlarged parts of (a); (d) is enlarged parts of (a). I_s: input signal intensity and I_p: pump intensity. (a) GaSe and (b) ZGP.

saturation region: the intensity of both signal and THz wave will increase when the gain is stronger than the absorption, or the intensity of both signal and THz wave will decrease. Therefore, the effective saturation region of THz radiation based on DFG is different to the typical saturation region, where high extraction efficiency and better stability can be achieved. We compare our simulation as shown in Fig. 3 with the results based on the analytical solution [7,18,19]. They show good agreement with each other. Decrease of the output power as the THz wavelength is increased because of Manley–Rowe relation. Fig. 3 also refers to that only the wavelength 227.5 μm could achieve the highest output power in GaSe crystal, but in ZGP crystal there are two peak points: 79.8 and 88.3 μm.

Curves of THz wave output intensity dependence on the crystal length are given in Fig. 4, which are respected to different pump intensities stepwise decreasing by 0–10% of the first value, and

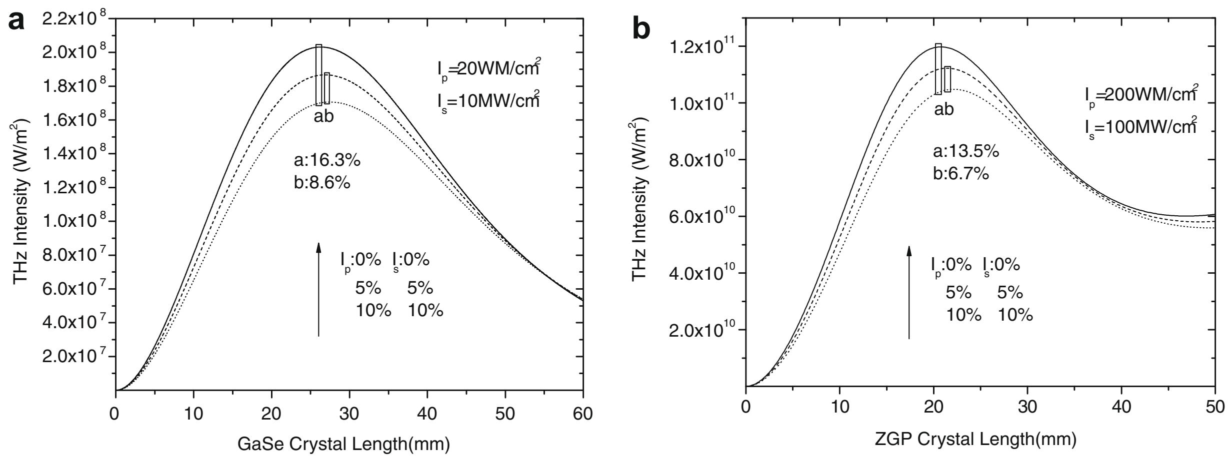

Fig. 6. Dependence of output stability on signal and pump fluctuations. I_s: input signal intensity and I_p: pump intensity. (a) GaSe and (b) ZGP.

all the curves start from the same input signal intensity. All curves tend to converge further behind the saturation peak, which is different to the typical statement [14]. Therefore, the THz wave output intensity is sensitive to the pump changes around the saturation peak point. Within 10% pump variation, both the maximal THz wave output changes are more than 11%. Curves of amplification dependence on the crystal length are given in Fig. 5(a) and (c), which is respected to different signal intensities stepwise decreasing by 0–10% of the first value with the same input pump intensity. Several curves tend to converge behind the saturation peak, which means a certain area exists where THz wave output intensity is less sensitive to the signal changes. Apparently, the saturation is reached earlier at higher signal intensity, while the peak intensity drops and moves towards longer crystal length as the signal intensity decreases, which inevitably induced to a cross-over of a certain number of intensity curves. This provides an interpretation for the good stability in the case of THz wave based on DFG by saturated amplification. Details can be clearly seen from Fig. 5(b) and (d). Within 10% signal variation, the maximal THz output changes are less than 0.1%. It could be as large as 4% and 4.3% in the unsaturated area indicated in Fig. 5(a) and (c), respectively. It is possible and necessary to choose an optimum stability. For example, once the pump and signal intensity is given, we can select the optimum crystal length obtained by the integration of Eq. (1).

Curves of THz output intensity versus crystal length are given in Fig. 6 where are respected to both pump and signal intensities decrease by 5% and 10%, respectively. Within 5% change by pump and signal, the maximal THz wave output changes are more than 8%, and 10% change by pump and signal, the maximal THz wave output change is more than 16%, which could be similar to linearly growth.

As is shown, the effective gain saturation region of THz wave cannot be stable as the gain saturation region in typical OPA [14] under the high output power at the wavelength of 79.8 and 88.3 μm in ZGP crystal and 227.5 μm in GaSe crystal. Taking the output intensity vibrating into consideration, which arises from the pump and signal intensity varying, we can obtain the stable THz wave output at a crystal length of 37.9 mm in GaSe crystal and 24 mm in ZGP crystal. Within 10% change by both pump and signal, the maximal THz wave output change is less than 1% throughout the stable region, where the THz wave output stability is primarily determined by the pump stability.

3. Conclusion

Based on the numerical simulation and analysis, we demonstrate an excellent region where exists for stable and high-power THz wave output. However the output variation is induced by the intensity changed by signal as well as pump, the optimal THz wave generation can be achieved by choosing the system parameters and making a balance between the power and the stability. This could be an effective and useful condition to obtain better THz wave output performance for widely applications.

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