Tunable and coherent THz source using $ZnGeP_2$

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Abstract: Coherent THz and millimeter waves continuously tunable in the range of 83.1–1642 μm (3.61-0.18 THz) are efficiently generated by using $ZnGeP_2$ through collinear phase-matched difference-frequency generation. The maximum peak output power can reach 134 W.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (190.2620) Frequency conversion

1. Introduction

Parametric processes in nonlinear crystals can be used for efficient generation of THz and millimeter waves. Indeed, a $ZnGeP_2$ crystal was used to achieve THz waves by frequency-mixing two CO_2 laser emission lines [1]. Besides $ZnGeP_2$, $LiNbO_3$ [2], DAST [3], and GaSe [4] have also been used for THz generation. Among all the nonlinear crystals, GaSe has the lowest absorption coefficients in the THz while $ZnGeP_2$ has the absorption coefficients next to the lowest. The advantage of using $ZnGeP_2$ instead of GaSe lies in the fact that $ZnGeP_2$ can be easily polished and anti-reflection-coated. During this presentation, we report our result on efficient, tunable, and coherent THz radiation generated in $ZnGeP_2$, based on collinear type-I and type-II phase-matched difference-frequency generation (DFG). Although THz radiation was previously generated in $ZnGeP_2$ [1], the tuning range of the output wavelengths obtained in our experiments is much wider than that in Ref. [1]. Moreover, the highest output peak power is eight orders of magnitude higher than that obtained in Ref. [1]. Furthermore, type-II phase-matched DFG was not previously achieved. Our results demonstrate that $ZnGeP_2$ is indeed another promising nonlinear crystal for efficient THz generation.

2. Results and discussions

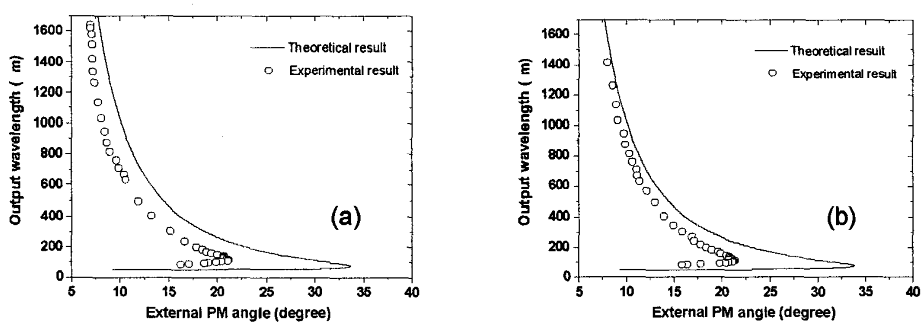

Fig. 1. Output wavelength vs. external phase-matching angle of (a) type-I (oee) and (b) Type-II (oeo) collinear phase-matched DFG.

In our DFG experiment, we used two pump beams one of which was the residual Nd:YAG laser beam at 1.064 μm while the second one was from the output of a master oscillator/power oscillator. The Nd:YAG laser pulses had a typical pulse duration of 10 ns and a repetition rate of 10 Hz. We used an annealed $ZnGeP_2$ crystal that has much lower absorption coefficients (~0.75 cm^{-1}) near 1.064 μm after a special annealing. As a result, we can use the laser lines near 1.064 μm as the pump beams. Following our simple design we chose a 0°-cut $ZnGeP_2$ crystal with a thickness of 20.6 mm along *c* axis, a cross-sectional area of 15 mm × 14 mm and no antireflection coatings. For type-I (oee) and type-II (oeo) collinear DFG in a $ZnGeP_2$ crystal, phase-matching conditions are given by

$\frac{n_o(\lambda_3)}{\lambda_3}-\frac{n_e(\lambda_2,\theta)}{\lambda_2}=\frac{n_e(\lambda_1,\theta)}{\lambda_1}$ and $\frac{n_o(\lambda_3)}{\lambda_3}-\frac{n_e(\lambda_2,\theta)}{\lambda_2}=\frac{n_o(\lambda_1)}{\lambda_1}$, respectively, where λ_3 and λ_2 are the wavelengths of the two pump beams, λ_1 is the wavelength of the output THz beam, and n's are the indices of refraction for the respective waves. For the two phase-matching configurations, the polarizations for the two pump beams remain the same while the THz beams correspond to extraordinary and ordinary beams for the type-I and type-II, respectively. The relative effective nonlinear coefficients depend on the phase-matching angle (θ) and azimuthal angle (φ) as $d_{eff}^{(I)}=d_{36}sin2\theta cos2\varphi$ and $d_{eff}^{(II)}=d_{36}sin\theta sin2\varphi$. Obviously $d_{eff}^{(I)}$ reaches an optimized value at $\varphi = 0°$. On the other hand, $d_{eff}^{(II)}$ reaches a maximum value at $\varphi = 45°$. As a result, by choosing different values for φ through crystal rotation we selected either the type-I or the type-II configuration. The generated THz and millimeter wave was detected by a bolometer. In Fig. 1 (a) and (b) the angle-tuning characteristics for the type-I and type-II phase-matched DFG are depicted. The open circles correspond to the experimental results at which the phase-matching condition is satisfied while the solid curves correspond to the calculations made by using the phase-matching conditions and the refractive-index dispersion relations of conventional $ZnGeP_2$ [5]. For each data point in Fig. 1 a phase-matching peak was obtained by maximizing the THz pulse energy through varying θ and one of the pump wavelengths. As a result, tunable and coherent output wavelengths in the range of 83.1−1642 μm (3.61-0.18 THz) for type-I and 80.2−1416 μm (3.74-0.21 THz) for type-II were obtained, respectively. From Fig. 1, one can see that the theoretical and experimental phase-matching curves significantly deviate from each other over the most output wavelengths. These discrepancies are due to the fact that the theoretical curves are calculated by using the Sellmeier equations for the conventional (i.e. before annealing) $ZnGeP_2$ crystal. Based on the measured absorption coefficients of the conventional and annealed $ZnGeP_2$ crystals, we conclude that the refractive indices for these two types of the crystals are quite different from each other especially in the near-IR range. Therefore, the Sellmeier equations obtained previously are not accurate enough for the annealed $ZnGeP_2$.

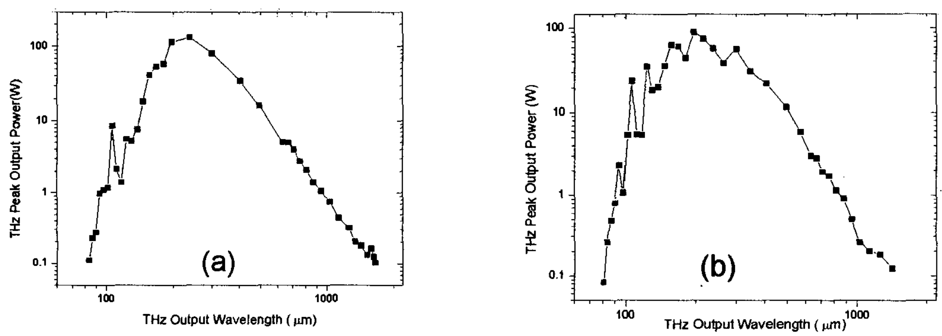

Fig. 2. Measured THz peak output power vs. output wavelength for (a) type-I and (b) type-II phase-matched DFG.

For the Nd:YAG pump intensity of 17 MW/cm^2 and OPO pump energy of 1-2 mJ, the output peak powers at different output wavelengths are also measured for the type-I and type-II configurations by using calibrated bolometer, see Fig. 2 (a) and (b). For the pump intensity of less than 20 MW/cm^2, there is no obvious surface damage for the annealed $ZnGeP_2$ crystal. The measured THz radiation has the pulse duration of 5 ns and a repetition rate of 10 Hz. The highest output peak power reaches 133.8 W at 237 μm (1.27 THz) for the type-I and 90 W at 196 μm (1.53 THz) for the type-II. These peak powers are about *eight orders of magnitude* higher than that obtained in Ref. [1]. In our experiments we have consistently observed two dips near 110 μm (see Fig. 2). We believe they are due to the presence of impurities in $ZnGeP_2$. This is consistent with the observation of a similar dip in the previous measurement of the absorption spectrum [5]. For the highest output peak powers mentioned above, the energy conversion efficiencies are measured to be 0.037% and 0.026% for the type-I and type-II, respectively. Based on these high conversion efficiencies $ZnGeP_2$ can be another promising nonlinear crystal for implementing a compact THz source.

3. Concluding remark

We have achieved efficient, tunable and coherent THz radiation based on the type-I and type-II phase-matched DFG in an annealed $ZnGeP_2$ crystal pumped by two near-IR laser beams. We have made dramatic improvement on the

tuning ranges and output peak powers of the THz waves over the previous result. Our results demonstrate that $ZnGeP_2$ is, indeed, another valuable nonlinear material for efficient and coherent generation of tunable THz waves.

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4. References

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