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A Compact and Robust Regenerative Amplifier Pump Source for High Repetition Rate Terahertz Parametric Amplifier

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Abstract In this paper we report a compact and robust regenerative amplifier developed as the pump laser for a high repetition rate terahertz parametric amplifier. With properly chosen pump source and carefully designed cavity, Nd∶YVO_4 crystal, and laser beam collimator, a maximum output pulse energy of 480 μJ has been achieved at the repetition rate of 10 kHz. The output laser has a nearly Gaussian transverse profile and a narrow bandwidth of 0.2 nm. Long-term monitoring shows an root mean square power fluctuation of about 1%. These characteristics satisfy all requirements for high repetition rate terahertz parametric amplifier.

Key words regenerative amplifier; terahertz parametric amplifiers; thermal lens

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1 Introduction

In recent years, terahertz (THz) radiation sources and their applications have been undergoing a rapid development[1-5], among which high repetition rate, high power THz sources are becoming an attractive research topic[6-8]. THz parametric amplifiers (TPA, also called injection seeded THz-wave parametric generators, or is-TPGs for short, in some literatures[9-12]), which are based on stimulated polaron scattering (SPS) by the transverse optical phonon modes in some polar crystals[2], provide the possibility to generate high repetition rate, high power THz radiation with a broad frequency tuning range and at low cost. So far, most TPAs operate at a repetition rate of 1–100 Hz[9-12], and there are only a few studies on high repetition rate TPAs. In 2018, Moriguchi *et al.*[13] built a TPA with a repetition rate of 100 kHz, a pulse width of 73 ps and an average power of 30 μW. In 2021, Minamide *et al.*[14] built a compact TPA with a pulse width of 200 ps, an average power of 20 μW, and a maximum repetition rate of 70 kHz. At Peking University, we have been devoted to the research and development of high repetition rate, high average power TPA since 2017. In 2019, we built a tunable (4.2–6 THz) TPA with a repetition rate of 10 kHz, a pulse width of 5.4 ps and an average power of 89 μW using a $KTiOPO_4$ (KTP) crystal[15]. A $LiNbO_3$ (LN) crystal was then used to expand the frequency tuning range to 1.18–3.85 THz[16].

For efficient THz radiation output, the pump lasers of TPA need to have a high peak power, which is usually obtained with a master oscillator power amplifier (MOPA) configuration. As a core part of pump lasers, the amplifiers play a dominant role in determining the maximum achievable power and the stability of output THz radiation. In our previous work, the pump lasers for KTP-TPA and LN-TPA were delivered by a prototype regenerative amplifier (RA) operated at 1064.4 nm, which amplifies the laser pulse energy from 1 nJ to about 250 μJ[15-16]. To improve the performance of the TPAs, a compact and robust RA module has been developed recently.

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Several measures have been taken to assure a highly stable output at a higher pulse energy level. First, an 879 nm fiber laser was used instead as a pump source for the RA, at which wavelength the RA crystal (Nd: YVO_4) has a low absorption coefficient and therefore thermal effect in the crystal is significantly reduced. Second, the crystal length was increased, allowing to disperse the heat load into a larger volume. As a consequence, temperature rise, thermal stress, and thermal lens effect in the crystal are minimized. Third, a compact RA cavity was designed with improved performance. The laser spot size in the RA crystal now changes very slowly against the variation of focal length of the thermal lens, which helps to evaluate the RA performance more accurately in advance. Finally, a self-designed crystal frame integrated with collimation function was employed. This allows for a better overlap between the seed and the resonant laser. With these measures, an average power of 4.8 W has been achieved at the repetition rate of 10 kHz and the root mean square (RMS) power fluctuation is about 1% within 8 h.

2 Experimental setup

The experimental setup of the TPA pump laser is shown in Fig. 1. Since we want to obtain ps-scale THz pulses, its front-end source is a passively mode-locked picosecond fiber laser (using SESAM), which delivers a 1064.4 nm seed with an average power of 29 mW, a repetition rate of 29 MHz, and a pulse duration of about 7.5 ps. The output pulse energy is then doubled using a single-stage fiber amplifier, and the repetition rate is reduced to 10 kHz with a fiber acousto-optic modulator (AOM). Two thin-film polarizers (TFP1 and TFP2) together with a half-wave plate (HWP) and a Faraday rotator in between comprise the function unit for optic isolation and amplified pulse extraction. Between the AOM and TFP1 are two lenses (lens1 and lens2) with the focal length of 200 mm and 300 mm, respectively, which match the incident laser into RA cavity.

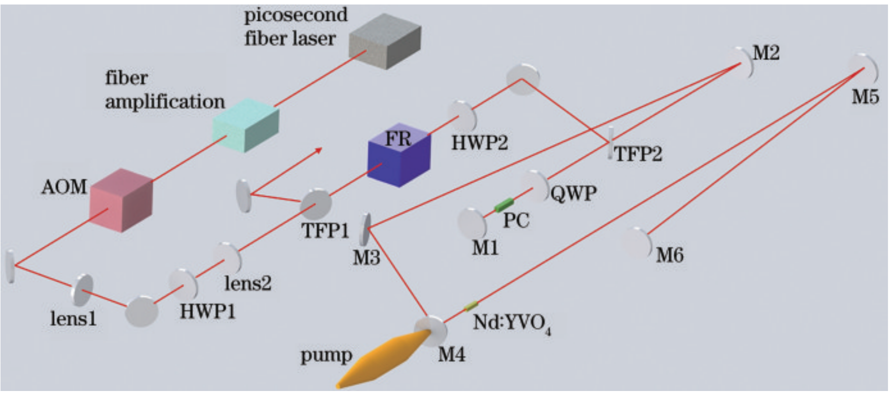

Fig. 1　Layout of the newly developed TPA pump system

The RA is composed of a Nd: YVO_4 crystal (gain medium), a thin-film polarizers (TFP2), a quarter-wave plate (QWP), a BBO Pockels cell (PC), and six mirrors (M1–M6). Among the mirrors, M2, M5, and M6 are high-reflectivity concave mirrors with the radius of curvature (ROC) of 2000 mm, 500 mm, and 500 mm, respectively, M1 and M3 are high-reflectivity plane mirrors, while M4 is a dichroic plane mirror with the coating transparent to the 879 nm pump source but reflective at 1064 nm. The Pockels cell (PCB4S-C-1064, EKSMA OPTICS) contains a 4 mm×4 mm×20 mm BBO crystal. Together with QWP and TFP2, it acts as an optical switch controlling the injection and extraction of laser pulses. The Nd: YVO_4 crystal, with the dimensions 3 mm×3 mm×12 mm, is doped at atomic fraction of 0.3%. In order to alleviate thermal lens effect, a 3 mm long undoped YVO_4 crystal is bonded onto its end surface on the pumping side. The whole crystal was wrapped with an indium foil and mounted into a copper frame cooled by recirculating water at 17 ℃. The 879 nm pump laser is focused into the Nd: YVO_4 crystal using two lenses with focal lengths of 60 mm. The single-pass measurements show that approximately 92% of the pump power was absorbed. The RA cavity has a length of 1.85 m, and the corresponding round-trip time is 12.3 ns. The 5-folded optical path makes the cavity very compact, which occupies an area of less than 0.2 m^2.

The copper frame for the Nd: YVO_4 crystal [17] is integrated with a collimator which has a length of 17 mm and a radius of 0.5 mm, as shown in Fig. 2. This collimator helps to align the seed laser to the resonant beam, which allows for a better overlap of the two beams.

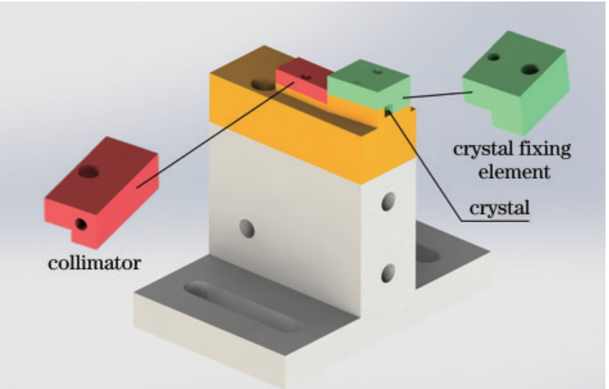

Fig. 2　Self-designed crystal mounting frame integrated with a collimator

3　Thermal effect analysis and beam propagation

$Nd:YVO_4$ crystals have a low thermal conductivity, therefore heat load and its effects need to be treated properly for highly stable operation of the RA. As mentioned above, several measures have been taken to minimize the thermal effect in our case. Our analysis was performed by using an imaginary thermal lens with an equivalent focal length f_T.[18] With the assumption of a flat-top pump laser, f_T can be evaluated as[19]

$$f_T = \frac{2\pi K_c \omega_p^2}{\left(\frac{dn}{dT}\right)\xi P_{in}\mu}, \tag{1}$$

where K_c, n, and T are the thermal conductivity, refractive index, and temperature of the crystal, respectively, ξ represents the proportion of absorbed pump energy dissipated as heat, P_{in} is the power of the pump laser at the crystal surface while w_p the effective radius in the crystal, and $\eta = 1 - \exp(-\alpha l)$ is the absorption rate with l the crystal length and α the absorption coefficient. Noting that thermally induced birefringence as well as the thermal expansion of $Nd:YVO_4$ crystal can be ignored herein, the focal length of the thermal lens is estimated to be 1000 mm when the pump power is 27.2 W. Fig. 3(a) illustrates the simulated propagation of the resonant beam in the RA under such a situation. We can see the beam has a slowly-varying radius around 710 μm between M1 and M2 where the Pockels cell is located. This fits the beam well into the BBO crystal while keeping the power density far below the damage threshold. Also note the beam radius is about 432 μm at the location of the $Nd:YVO_4$ crystal, which is about 1/7 of the crystal width.

Fig. 3(b) shows the simulated evolution of seed laser size with and without the matching lens (lens1 and lens2). For the matched case, the seed laser has a similar envelop as the resonant beam in the RA cavity. In experiments, we measured the seed beam radius at the location of M2 and M6, which are 800 μm and 350 μm, respectively. Both results indicate a high-quality matching of the seed laser into the cavity.

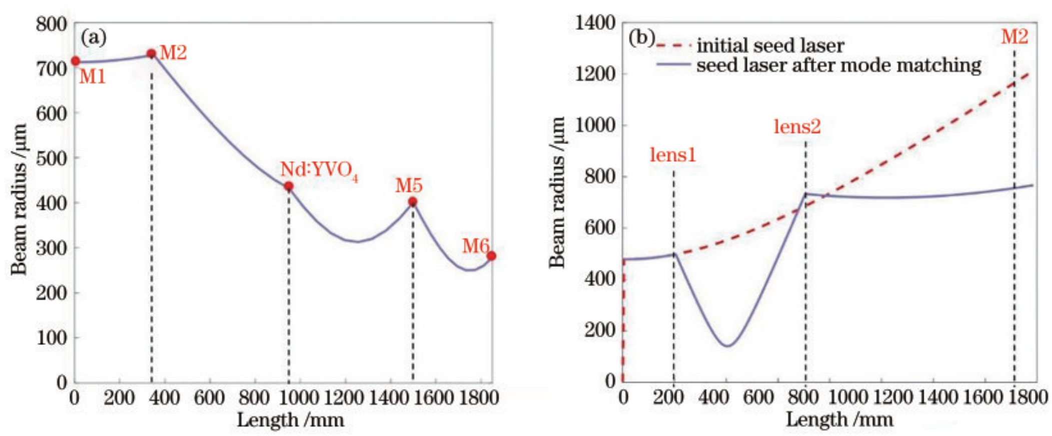

Fig. 3　Simulation results. (a) Simulated resonate beam propagation in the RA cavity; (b) seed laser matching into the cavity

Considering the uncertainty in evaluating the thermal lens focal length, we varied it alone and calculated the corresponding laser beam radius in the $Nd:YVO_4$ crystal. The results are plotted in Fig. 4. We can see from the figure that, as the focal length changes by ±200 mm, the variation of laser beam radius is within 1.4%, indicating the beam size is insensitive to the variation of thermal lens focal length. Also note that the pump laser is focused down to approximately 500 μm in the $Nd:YVO_4$ crystal, therefore the resonant beam can always be efficiently amplified.

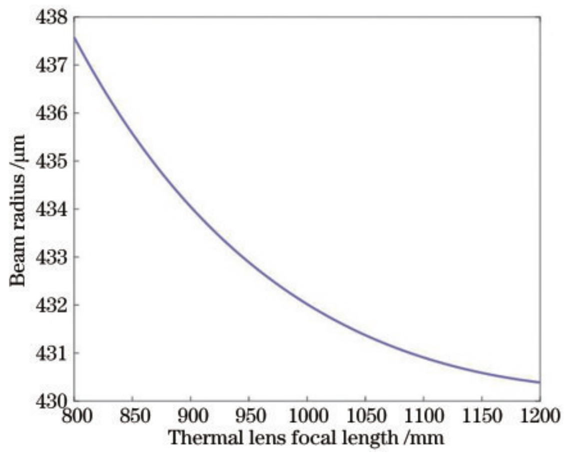

Fig. 4　Laser beam radius in the Nd : YVO_4 crystal with different focal length of thermal lens

4　Experimental results and discussion

We first tested the RA cavity without Pockels cell. As the pump power reached its maximum at 36.1 W, an output of 14.7 W was obtained, corresponding to an optical-to-optical conversion efficiency of 40.7% and a slope efficiency of 45.6%, which demonstrate the excellent performance of the cavity. We then installed the Pockels cell and delivered the mode-locked seed laser into the RA cavity. To investigate the power gain of the RA, we measured the maximum output power after different numbers of round trips for a series of pump powers, as shown in Fig. 5. We can see that as the pump power increases, the number of round trips required to obtain the highest output power gradually decreases. When the pump power was increased to 27.2 W (working point for the design), a maximum output of 4.8 W was achieved after 10 round trips. This corresponds to a pulse energy of 480 μJ and a power gain close to 0.5×10^6.

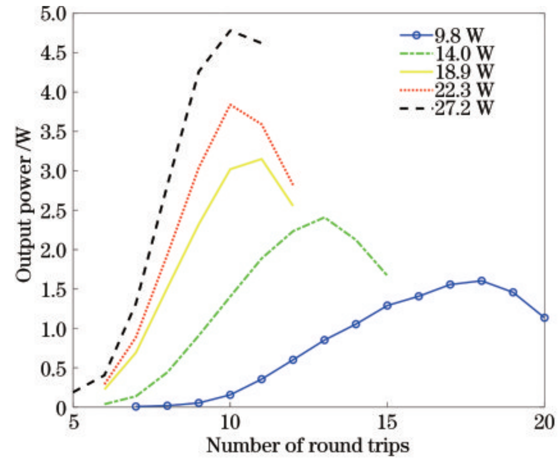

Fig. 5　Maximum output power after different numbers of round trips for a series of pump powers

To characterize the performance of the amplifier, we compared the output laser spectrum with the seeds. The measured spectrum is plotted in Fig. 6(a), from

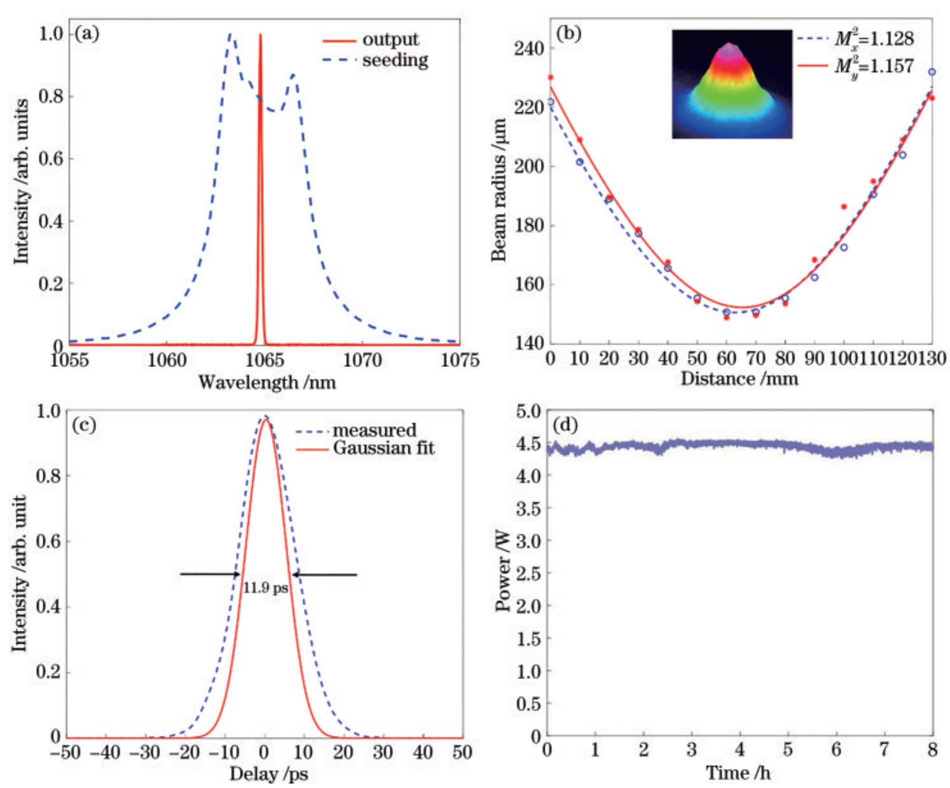

Fig. 6　Output laser performance of the RA. (a) Plots the spectrum together with the seed; (b) plots the transverse profile with fitted Gaussian curves in horizontal and vertical directions; (c) plots the autocorrelation signal and Gaussian fitting result of the RA; (d) plots an 8 h power monitoring of RA output

which we can see that the spectrum becomes narrower and clearer after amplification due to the narrow gain bandwidth of Nd∶YVO_4. The spectrum is centered at 1064.8 nm with a full width at half maxima bandwidth of 0.2 nm, as expected from our TPA study. We also measured the beam characteristics of the output laser, as shown in Fig. 6(b). The result gives a beam quality of $M_x^2=1.128, M_y^2=1.157$ in both directions perpendicular to the axis of propagation. The pulse duration of the RA was determined by the intensity autocorrelator to be 11.9 ps, as shown in Fig. 6(c). Finally, the output power was monitored for a long time. Fig. 6(d) shows the monitoring results for 8 hours, indicating that the RMS power fluctuation is about 1%.

5 Conclusions

In summary, a compact and robust RA has been built as the pump source for high repetition rate TPAs. A maximum output power of 4.8 W has been achieved at the repetition rate of 10 kHz, corresponding to a pulse energy of 480 μJ and a power gain close to 0.5×10^6. The output laser has good quality in terms of transverse distribution and spectrum. An 8 h monitoring shows an RMS power fluctuation of about 1%. During a few month's operation no re-calibration or maintenance was needed, indicating the robustness of the RA. Driven by this RA, the TPA performance is expected to be improved significantly.

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