Optical chopper based mechanically Q-switched ~3 μm Er:YAP single crystal laser

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We developed a compact and low-cost diode-pumped ~3 μm mechanically Q-switched Er:YAP laser with high-power using an optical chopper. At 2.4 W pumping and 7 kHz modulation frequency, a stable single-pulse repetitively Q-switched laser with wavelength of 2.796 μm has been observed. We recorded the pulse duration, the peak power, and the pulse energy of 264 ns, 22 W, and 5.9 μJ, respectively. As increasing pumping power to 7.4 W at frequency of 10 kHz, the lasing wavelength shifted to 2.921 μm and stable multiple-pulse laser was observed. The pulse with 75 ns duration and 34 μJ energy has been observed, corresponding to a peak power of 456 W. The peak power and the pulse energy are the highest value ever reported for an actively Q-switched mid-infrared (IR) Er:YAP laser. Thus, this laser has the potential to be utilized for industrial and science fields as high power mid-IR light source.

1. Introduction

Diode-pumped Er-doped solid-state lasers have attracted much attention owing to their ability to generate high-power laser emission in ~3 μm. These high power lasers are good light sources for material processing[1)] and sensing.[2)] In recent years, a lot of researches on Er-doped materials, such as Er-doped garnets[3,4)] (e.g., Er:YAG) and sesquioxides (e.g., Er:Y_2O_3 crystal/ceramics and Er:Lu_2O_3 crystal/ceramics),[5-11)] have been studied as diode-pumped 3 μm Er-doped laser gain media. In order to generate the high-power and high-efficiency 3 μm lasers, the Er-doped media with high thermal conductivity, good mechanical properties, and low phonon energy are required to oscillate the high power and high efficiency lasers. In this regard, yttrium aluminum perovskite (YAP) is a promising laser gain medium for developing high power and efficient lasers owing to its relatively higher thermal conductivity (~13.3$W\cdot m^{-1}\cdot K^{-1}$),[12)] good mechanical properties, higher thermal shock parameter (160 MPa),[13)] and lower phonon energy (550 cm^{-1})[14)] as compared with YAG, Y_2O_3, and Lu_2O_3. Additionally, according to our previous study[15)], the emission cross-section of Er:YAP in 3 μm is three times larger than that of Er:YAG. This feature is beneficial for developing an efficient laser. To date, diode-pumped 3 μm continuous-wave (CW) and Q-switched Er:YAP lasers have been reported. In 2018, C. Quan et al. demonstrated the first diode-pumped 3 μm CW Er:YAP laser, which exhibited a maximum output power of 739 mW, a slope efficiency of 12.1%, and dual-wavelength (2710 nm and 2728 nm) oscillations at room temperature operation.[16)] Recently, our group achieved efficient and high-power CW laser oscillation at 2.92 μm for the Er:YAP laser, which showed an output power of 6.9 W and a slope efficiency of 31%, and both of which are the highest values for the CW operation of an Er:YAP laser.[17)] In addition, we investigated the passively Q-switched Er:YAP laser with graphene at 2.9 μm with a peak power of 10 W and a pulse energy of 5.1 μJ.[18)] These results indicate that the Er:YAP crystal has the potential for efficient and high-power laser operation in the 3 μm region.

However, the repetition rate in passively Q-switched lasers is difficult to control because of the sensitivity to the pumping power. In contrast, the repetition rate in the active Q-switching operation can be controlled more flexibly by an externally driven Q-switch, which leads to a high pulse energy and a high peak power laser emission. To date, acousto–optic (AO), electro–optic (EO), and optical choppers have been used as the Q-switches for actively Q-switched lasers.[19-24)] Nevertheless, AO and EO Q-switches are typically expensive and optically narrow banded in the mid-IR wavelength region. Additionally, these switches make the laser bulky. On the other hand, a mechanical Q-switch, such as a rotating mirror and an optical chopper, is relatively cheaper, does not require a specific wavelength, and are small in size, which is beneficial for realizing a compact and low-cost cavity. In 2017, a mechanically Q-switched 2.7 μm $Er:Y_2O_3$ ceramic laser was demonstrated.[25)] This laser attained approximately 3 kW peak power and 80.8 μJ pulse energy. High peak power and high pulse energy can be expected by using a mechanical Q-switch owing to a larger modulation depth and slower frequency. The wavelength of Er:YAP laser—2.9 μm—is relatively closer to the absorption peak of polyethylene terephthalate (PET),[26)] which is a commonly used plastic material, than that of the other Er-doped solid-state lasers.[3-11)] Thus, a mechanically Q-switched 2.9 μm Er:YAP laser with high peak power can be a promising mid-IR light source for PET processing.

In this paper, we have studied a diode-pumped and an optical chopper based mechanically Q-switched Er:YAP laser operation at ~3 μm wavelength with a high peak power. At a modulating frequency of 7 kHz, a stable single Q-switched pulse was observed at 2.4 W of pumping power. A pulse duration of 264 ns, peak power of 22 W, and pulse energy of 5.9 μJ were achieved successfully. Further, with an increased pump power of 7.4 W at 10 kHz, a stable multiple-pulsed laser emitted at 2.921 μm. In this case, we obtained a pulse duration of 75 ns and pulse energy of up to 34 μJ. The corresponding peak power was 456 W, which represents the highest value achieved from a mechanically Q-switched Er:YAP laser. These results have exhibited that mechanical Q-switched Er:YAP laser can be a new candidate for the mid-IR light source to utilize in industrial and science fields.

2. Experimental methods

Figure 1 shows the experimental setup of the mechanically Q-switched Er:YAP laser. The setup had four parts: a pumping source, focusing lenses, an optical resonator, and detectors. The pumping source was a fiber-coupled laser diode (K976A02RN-9.00WN0N-10255I10ESM0, BWT Beijing) with a center wavelength (λ_{center}) of 976 nm, a core diameter of 105 μm, and a numerical aperture (NA) of 0.22. The pump source was firstly collimated and was thereafter focused into the Er:YAP with a diameter of ~400 μm by a pair of lens (20-mm and 75-mm focal length (f)). We constructed a plane–plane cavity with length of 17 mm, which was composed of a dichroic mirror (DM) with high transmittance for pumping wavelength (976 nm) and high reflectivity for the laser wavelength (~2.9 μm), and an output coupler (OC) with 5%, 10%, and 20% transmittance (T_{OC}) at approximately 2.9 μm. A 5 at.% Er:YAP single-crystal (Crytur Co., Ltd.) was used as the laser medium. This Er:YAP crystal was cut in a rectangular shape of 2 mm × 5 mm and a length (L) of 8 mm. Further, the end surface of the crystal was well-polished, but was not an anti-reflection coated. To achieve good heat dissipation, the crystal was mounted in a copper heatsink and was actively cooled by water at 16 °C. The optical chopper that was used for mechanical Q-switching had a thickness of 0.3 mm, as shown in the inset of Fig. 1. The slit width and the total number of slits were 1 mm and 100, respectively. In addition, the duty cycle was 50%. The rotation speed could be varied from 2 to 100 rps, corresponding to a modulating frequency range of 200 Hz–10 kHz. The optical chopper was placed between the crystal and OC. After passing through a 2.5–3.1 μm band pass filter, the laser output power and the temporal waveform were measured with a power meter (919p-003-10, Newport) and a photodetector (PVI-4TE-3-1, VIGO), respectively. The corresponding lasing spectra were measured using an optical spectrum analyzer (Model771, Bristol) with a wavelength resolution of 0.8 pm.

3. Results and discussion

Figure 2 shows the average output power ($P_{\text{out,avg}}$) as a function of the absorbed pump power in the Q-switched operation at T_{OC} of 5%, 10%, and 20%. The absorbed pump power was defined by as the value of absorbed LD power in Er:YAP. In our first experiment, the modulation frequency was set to 10 kHz. The laser output threshold was increased as increasing T_{OC}. A pumping-limited average output power of 773 mW was obtained with T_{OC} = 5% at a pumping power of 7.4 W, and the slope efficiency (η) was 15%. The laser mode diameter was calculated by the ABCD matrix analysis taking account of the thermal lens effect produced by temperature gradient. From Eq. (1)[27]. the thermally induced focal lengths (f_{th}) of Er:YAP at pump power of 2.4 W and 7.4 W were estimated to be 86 mm and 30 mm, respectively.

$$f_{th} = \frac{2\pi K_{\text{c}}{\omega_{\text{p}}}^2}{\xi P_{\text{abs}}(dn/dT)} \tag{1}$$

Here, thermal conductivity (K_{c}), pump beam radius at Er:YAP (ω_{p}), absorbed pump power (P_{abs}), and temperature coefficient of refractive index (dn/dT) were 13.3Wm^{-1} K^{-1},[12] 200 μm, and 8×10^{-6} K^{-1},[12] respectively. Additionally, the ξ means the fractional thermal loading in the material defined by $1 - (P_{\text{out,avg}}/P_{\text{abs}})$. The ξ at pump power of 2.4 W and 7.4 W were 0.98 and 0.90, respectively. Then, the calculated laser mode diameters at chopper corresponded to approximately 350 μm and 260 μm, which were smaller than the slit width.

Figure 3(a)–3(f) show the typical temporal measurement results under different pumping powers at a modulation frequency of 10 kHz. At 2.4 W pumping power, we obtained a stable single-pulse Q-switched laser, as shown in Fig. 3(a)–3(b). The corresponding average output power, pulse duration, pulse energy, and peak power were 47 mW, 296 ns, 4.7 μJ, and 16 W, respectively. For a higher pumping power, multiple pulses were observed, as shown in Fig. 3(c) and 3(d). The number of pulses also increase with the increased pumping power. Finally, for 7.4 W pumping, a pulse duration of 75 ns was achieved. The corresponding pulse energy was confirmed to be 34 μJ by the waveform integral within one modulation cycle. Thereafter, the peak power was calculated to be 456 W. The duration between the main pulse and the secondary pulses were several microseconds which was much shorter than the opening time of the chopper (50 μs). The occurrence of multiple pulses has been reported in previous papers.[28-30] This phenomenon can be explained by a slow Q-switching model[31] because mechanical Q-switching produces one of the slowly Q-switched lasers. The observation of multiple pulses suggests that the first Q-switched pulse was emitted at a relatively high cavity loss state before the Q-switch was opened perfectly. After emitting the first pulse, a fraction of the inversed population was depleted; however, the remaining inversed population was high enough to generate a secondary pulse. As the cavity loss continues to increase, the population inversion is recovered and the gain exceeds the loss again, leading to the emission of secondary Q-switched pulses. In addition, multiple pulses occur when the pumping power is increased.[30] The gain increases in direct proportion to the increasing pumping power. Therefore, the laser gain at a higher pumping power can easily exceed the cavity loss as compared to the gain at a lower pumping power. This resulted in the occurrence of multiple pulses with the increasing pumping power.

Figure 4(a) shows the average output power and pulse duration as a function of the modulation frequency at a pumping power of 2.4 W. When we changed the frequency from 10 kHz to 7 kHz, a stable Q-switched single laser pulse was observed. With a reduction in the frequency from 10 kHz to 7 kHz, the average output power and the pulse duration decreased from 47 mW to 41 mW and from 296 ns to 264 ns, respectively. Figure 4(b) shows the pulse energy and the peak power dependence on the modulation frequency. The pulse energy and the peak power increases with the decreasing frequency. At 7 kHz, the 5.9 μJ pulse energy and the 22 W peak power were achieved. To the best of our knowledge, the pulse energy and the peak power are the highest compared to those of the other 3 μm Q-switched Er:YAP lasers.[18,32] At a frequency less than 7 kHz, secondary pulses were observed that followed the initial pulse, an observation reported by other authors as well.[33] This phenomenon occurs even when the modulation frequency is reduced because the gain increases as the frequency decreases.

It is assumed that the multiple-pulse will be suppressed by using a mechanical Q-switch with higher modulation frequency. For example, the rotating speed of a commercial optical chopper is around 110 kHz,[34] which is eleven times higher than the maximum frequency of the current one. Therefore, by replacing lower frequency mechanical Q-switch with higher frequency mechanical Q-switch, it can be expected to close quickly before generating a series of secondary pulses. This leads to increased pulse energy owing to concentration of energy of secondary pulses in initial pulse, and single pulse laser with higher peak power can be obtained at higher pumping power.

The typical mechanically Q-switched laser spectrum was measured with T_{OC} = 5%, as shown in Fig. 5. A lasing wavelength of 2.796 μm was recorded at 10 kHz modulation frequency for 2.4 W pumping. The wavelength remained constant at different modulation frequencies. At 4.7 W and 7.4 W pumping powers, an emission wavelength of 2.921 μm was observed at the same modulation frequency of 10 kHz. This red shift in the lasing wavelength has also been reported in our previous report on the graphene-based Q-switching operation.[18] A shorter wavelength is emitted at a lower pumping power because the lower Stark levels of the $^4I_{13/2}$ state remain unoccupied, which results in a short wavelength with large emission cross-section.[9] As the pumping power increases, the Stark levels in $^4I_{13/2}$ are populated, and reabsorption occurs owing to the relatively longer lifetime of the lower laser level.[10, 11] This process results in laser oscillations that are dominant at a longer wavelength.

4. Conclusions

We developed and demonstrated the compact and low cost ~3 μm mechanically Q-switched Er:YAP laser. A stable single laser pulse was observed at 2.796 μm with a pulse duration of 264 ns at 2.4 W pumping and 7 kHz modulation frequency. Further, the highest pulse energy of 5.9 μJ and the peak power of 22 W were successfully achieved. Conversely, at 7.4 W pumping power and 10 kHz modulation frequency, stable multiple laser pulses were recorded at 2.921 μm. The pulse duration and the pulse energy were 75 ns and 34 μJ, respectively, corresponding to a peak power of 456 W. Further, by using a mechanical Q-switch with higher rotational speed, a single-pulse operation of the laser with a higher peak power and a higher pulse energy at an increased pumping power is expected. These results indicate that a compact, low-cost ~3 μm mechanically Q-switched Er:YAP laser can emit a high peak power, which establishes its potential as a mid-IR laser source.

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Figure Captions

Fig. 1. Experimental setup of the diode-pumped mechanically Q-switched Er:YAP laser. Inset: Optical chopper as the Q-switch.

Fig. 2. Variation of the average output power of the Er:YAP laser with pumping power for the mechanical Q-switching operation using T_{OC} = 5%, 10%, and 20%.

Fig. 3. Temporal variations in the pulse train as a function of pumping power (P_{ab}) using T_{OC} = 5% at 10 kHz modulation frequency. (a), (c), and (e) Typical temporal waveforms. (b), (d), and (f) Temporal waveforms within one modulation cycle. Inset: Temporal waveform with the highest intensity within one modulation cycle.

Fig. 4. Modulation frequency dependent variation of: (a) average output power and pulse duration, and (b) pulse energy and peak power in the mechanically Q-switched Er:YAP laser operation using T_{OC} = 5% at a pumping power of 1.83 W.

Fig. 5. Lasing spectrum of the mechanically Q-switched Er:YAP laser at a frequency of 10 kHz and pumping power of 2.4 W and 7.4 W using T_{OC} = 5%.

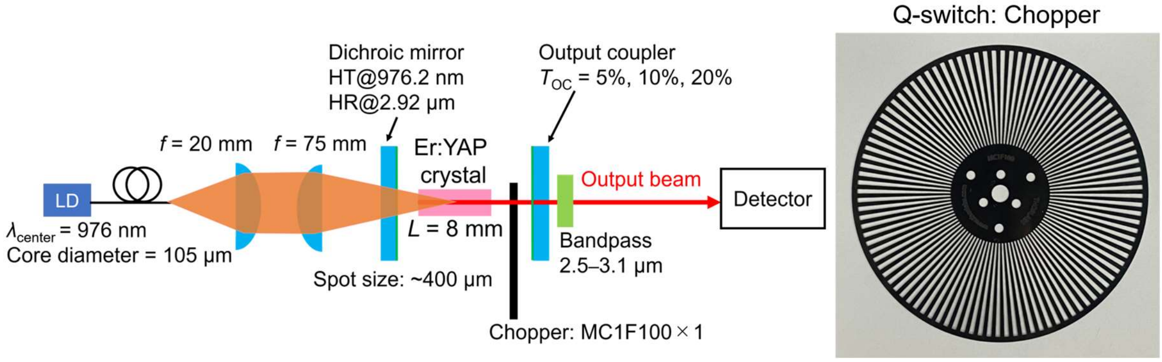

Q-switch: Chopper
Dichroic mirror
HT@976.2 nm
HR@2.92 μm
Output coupler
T_{OC} = 5%, 10%, 20%
f = 20 mm
f = 75 mm
Er:YAP
crystal
LD
Output beam
Detector
λ_{center} = 976 nm
Core diameter = 105 μm
L = 8 mm
Bandpass
2.5–3.1 μm
Spot size: ~400 μm
Chopper: MC1F100 × 1

Fig. 1.

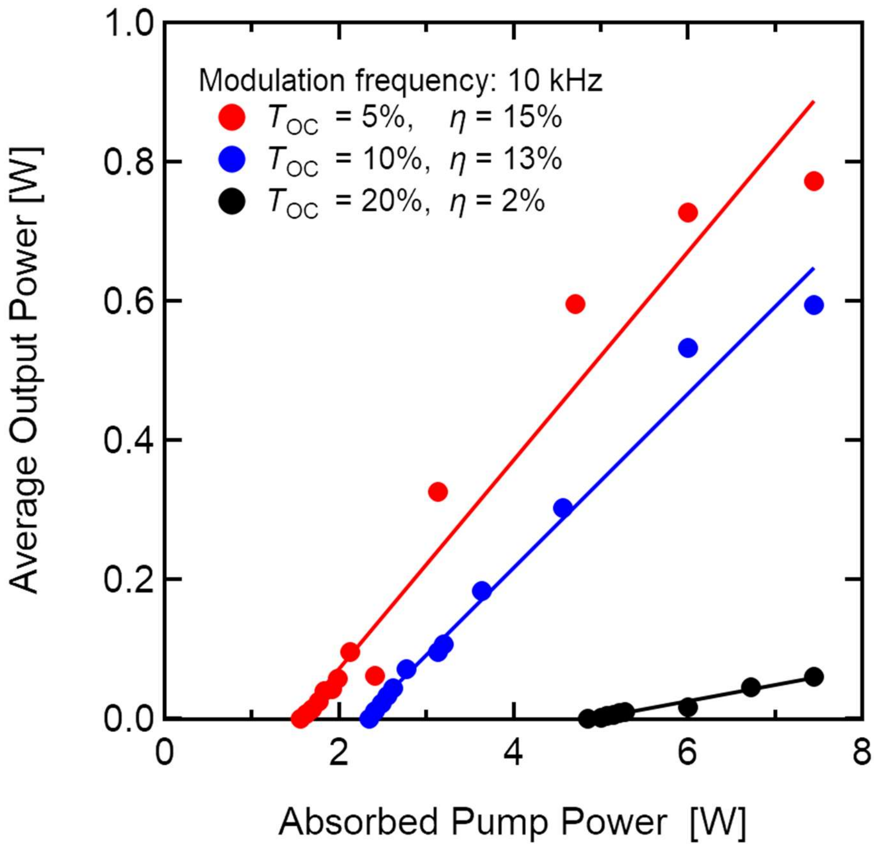
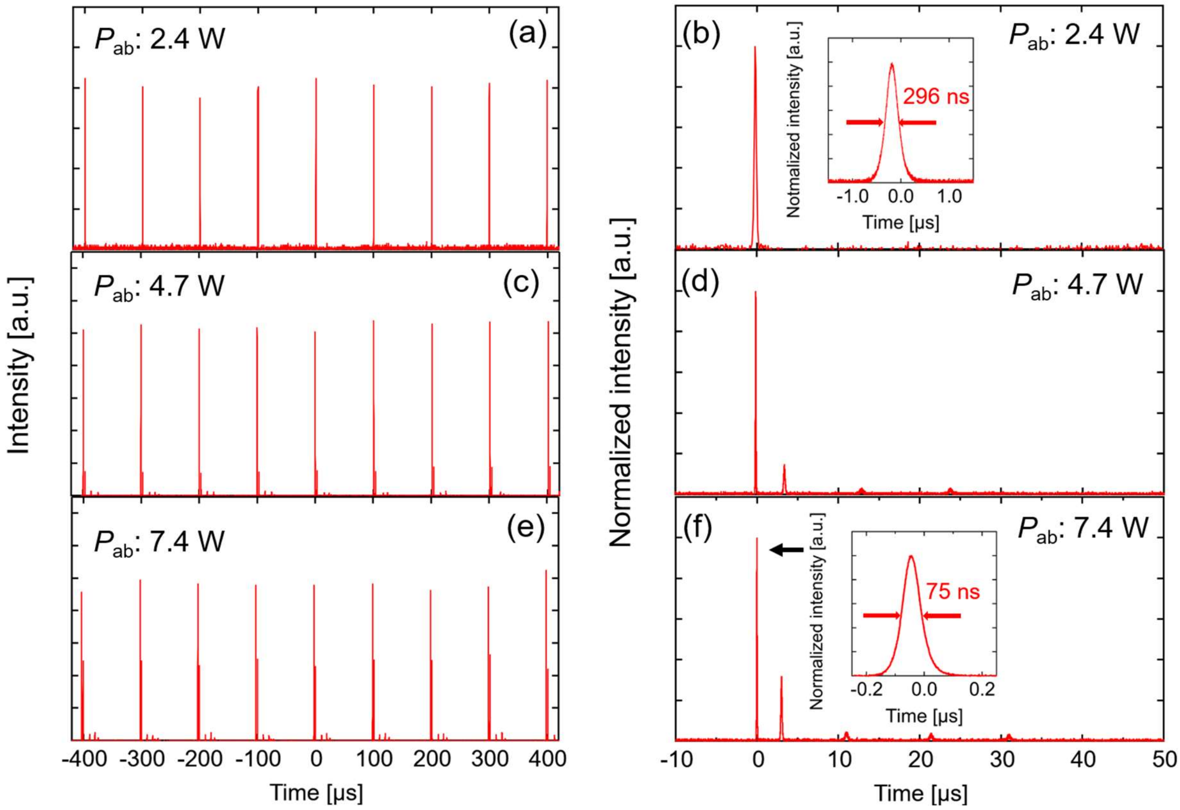
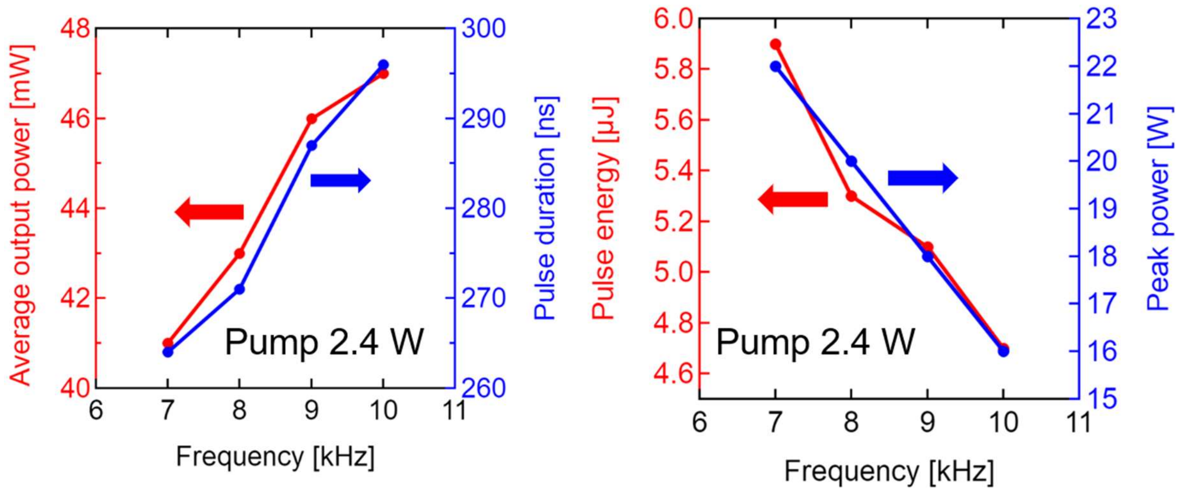

Modulation frequency: 10 kHz
T_{OC} = 5%, η = 15%
T_{OC} = 10%, η = 13%
T_{OC} = 20%, η = 2%
Average Output Power [W]
Absorbed Pump Power [W]
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8

Fig. 2.



Intensity [a.u.]
P_{ab}: 2.4 W
(a)
P_{ab}: 4.7 W
(c)
P_{ab}: 7.4 W
(e)
-400 -300 -200 -100 0 100 200 300 400
Time [μs]
Normalized intensity [a.u.]
(b)
P_{ab}: 2.4 W
Notmalized intensity [a.u.]
296 ns
-1.0 0.0 1.0
Time [μs]
(d)
P_{ab}: 4.7 W
(f)
P_{ab}: 7.4 W
Normalized intensity [a.u.]
75 ns
-0.2 0.0 0.2
Time [μs]
-10 0 10 20 30 40 50
Time [μs]

Fig. 3.


Average output power [mW]
Pulse duration [ns]
Pump 2.4 W
Frequency [kHz]
Pulse energy [μJ]
Peak power [W]
Pump 2.4 W
Frequency [kHz]

(a) (b)

Fig. 4.

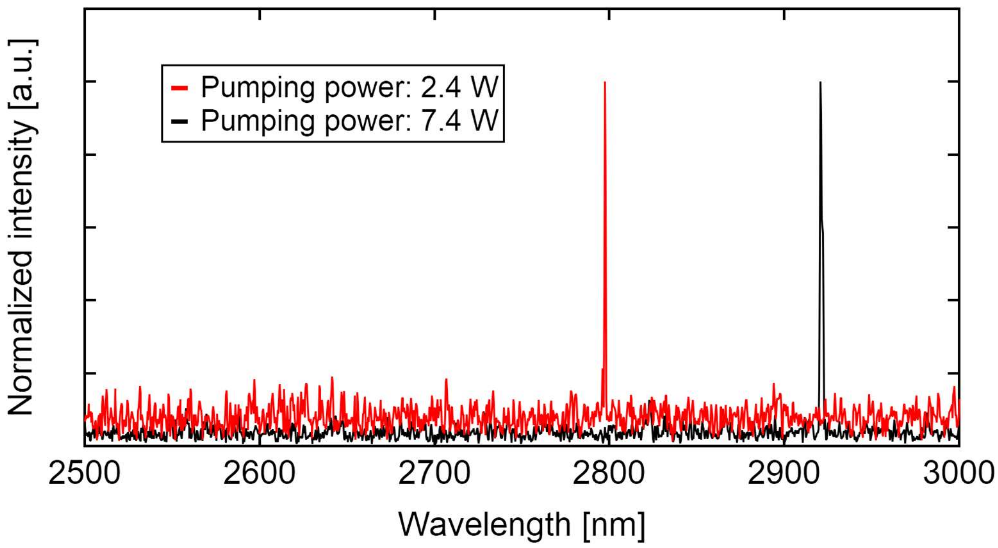

Pumping power: 2.4 W
Pumping power: 7.4 W
Normalized intensity [a.u.]
2500
2600
2700
2800
2900
3000
Wavelength [nm]

Fig. 5.