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Compact self-pulsed Tm:$GdScO_3$ laser with narrow pulse width

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A self-pulsed Tm:$GdScO_3$ laser was experimentally demonstrated by using a compact linear resonant cavity. When the pump power was 19.6 W, an average output power of 1771 mW was achieved from the self-pulsed Tm:$GdScO_3$ laser with a pulse width of 158.1 ns and a pulse repetition frequency of 112.8 kHz, corresponding to an optical-to-optical conversion efficiency of 9.0%. Moreover, a single pulse energy of 15.7 μJ and a pulse peak power of 99.3 W were acquired from the self-pulsed Tm:$GdScO_3$ laser. This is, as we know, the first time that the self-pulsed laser output at 2-μm waveband range was obtained by utilizing a Tm:$GdScO_3$ crystal so far.

Keywords: self-pulsed laser, Tm:$GdScO_3$ crystal, pulse width

PACS: 42.55.Xi, 42.60.Gd, 42.55.Rz

DOI: 10.1088/1674-1056/add4f9 **CSTR:** 32038.14.CPB.add4f9

1. Introduction

Solid lasers operating at 2-μm waveband range have attracted much attention for utilities in a variety of fields, including space communication, material processing, remote sensors, medicine, and nonlinear optical frequency conversion techniques.[1–4] Compared with continuous-wave solid lasers, pulsed solid lasers with higher peak power have greater potential in various applications.[5–7] Usually, the actively and passively *Q*-switched techniques are effective methods to obtain pulsed lasers at 2-μm waveband range.[8] For actively *Q*-switched (AQS) lasers, the actively modulators such as acousto-optic modulators or electro-optic modulators were normally placed in the resonant cavity.[9] For passively *Q*-switched (PQS) lasers, it is typically necessary to utilize a saturable absorber (SA) in the resonant cavity to obtain pulsed lasers.[10] However, whether AQS or PQS modulators, the design of lasers was largely limited by the complexity and insertion loss of the *Q*-switched modulators, which in turn affects the miniaturization and efficiency of the lasers.[11] With self-pulsed lasers, the laser systems require no additional modulators to excite and maintain the pulsed laser output.[12] Therefore, the self-pulsed lasers were considered an excellent method for realizing efficient pulsed laser output.[13] The investigation related to 2-μm waveband range lasers based on self-pulsed technology has therefore received widespread concentration.[14] The crystals that can achieve self-pulsed laser output play an important role in the research fields.[15,16]

Recently, a thulium-doped gadolinium scandidate (Tm:$GdScO_3$) crystal with an orthorhombic perovskite structure has been explored its potential as laser gain medium due to its low phonon energy and high thermal stability.[17,18] In 2022, Li *et al.* demonstrated a PQS Tm:$GdScO_3$ laser by using an SnS_2-based SA, and a pulse width of 460 ns and a pulse repetition frequency (PRF) of 88 kHz were achieved from the PQS Tm:$GdScO_3$ laser with a maximum average output power of 0.175 W and a pulse peak power of 4.32 W in the experiment.[19] In 2024, Qi *et al.* proved a PQS dual-wavelength Tm:$GdScO_3$ laser which was concurrently operated at 1982.3 nm and 1995.4 nm by utilizing an $SiTe_2$-based SA, and a shortest pulse width of 317 ns and an average output power of 622 mW were obtained with a PRF of 49.73 kHz.[20] However, to our knowledge, whether the Tm:$GdScO_3$ crystal can achieve self-pulsed laser output has not been experimentally demonstrated to this day.

In this work, we successfully demonstrated a self-pulsed laser at 2-μm region by using a Tm:$GdScO_3$ crystal. By selecting a compact flat-concave resonant cavity, the output characteristics of the self-pulsed Tm:$GdScO_3$ laser were investigated in detail, including the average output power, pulse width, PRF, single pulse energy, pulse peak power, output wavelength, and beam quality factor M^2 with the pump power increasing. The experimental results show that the Tm:$GdScO_3$ crystal can be used as promising laser gain medium for the development of all-solid-state self-pulsed lasers.

2. Experimental setup

Figure 1 shows a diagrammatic sketch of the self-pulsed Tm:$GdScO_3$ laser. In the experiment, a fiber-coupled laser

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diode (LD) was used as the pump source. The fiber had a core diameter of 200 μm and a numerical aperture (NA) of 0.16. To ensure the safe operation of the LD and facilitate efficient heat dissipation, a laser water cooling was employed, maintaining the temperature at 301.2 K to optimize the pump effect. When the pump power was 19.6 W, the central wavelength of the LD was measured to be stable at 791 nm. A system of collimating and focusing was consisted of a collimator lens (L1) and a focus lens (L2). The focal lengths of L1 and L2 were both 25 mm, and the pump light from the LD was focused into the gain medium by using the system of collimating and focusing. A compact linear resonant cavity with a physical length of 8 mm was consisted of a flat mirror (M1) and a flat-concave mirror (M2). The M1 was used as an input mirror, which was coated with a high transmittance material at 790 nm–810 nm on dual end faces and a high reflectivity material at 1.9 μm–2.1 μm on one end face. The M2 was employed as an output couple (OC) mirror with a radius of curvature of 150 mm and a transmittance (T) of 5%/7% at 1.9 μm–2.1 μm on concave face. An uncoated Tm:$GdScO_3$ crystal on both end faces was utilized to achieve the 2-μm waveband range laser radiation in the experiment. The Tm:$GdScO_3$ crystal had a Tm^{3+} doping concentration of 2 at.% and was cut along with its c-axis, whose cross-section and physical length were 3 mm×3 mm and 4 mm, respectively. The Tm:$GdScO_3$ crystal was mounted in a water-cooled copper block whose temperature was controlled to be 288 K by using a laser water cooler. To measure the output power of the self-pulsed Tm:$GdScO_3$ laser, a power detector (PD, S442C, Thorlabs) and a power meter (PM, PM100D, Thorlabs) were utilized in the experiment.

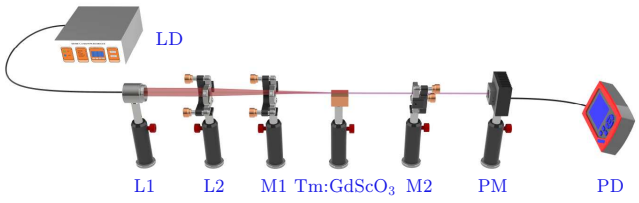


Fig. 1. The diagrammatic sketch of the self-pulsed Tm:$GdScO_3$ laser.

3. Experimental results and discussion

Figure 2 shows the average output power of the self-pulsed Tm:$GdScO_3$ laser. When an OC with $T = 5\%$ was used in the experiment, the Tm:$GdScO_3$ crystal began to generate laser radiation under the pump power of 1.2 W, and a maximum average output power of 1771 mW was gained from the self-pulsed Tm:$GdScO_3$ laser with the pump power of 19.6 W, corresponding to an optical-to-optical conversion efficiency of 9.0%. When an OC with $T = 7\%$ was employed, laser emission was also initiated with the pump power of 1.2 W, and a maximum average output power of 1723 mW was obtained under the pump power of 19.6 W, giving an optical-to-optical conversion efficiency of 8.8%. To avoid Tm:$GdScO_3$ crystal damage, the pump power was not increased further in the experiment. Compared with an OC of $T = 5\%$, using an OC of $T = 7\%$ leads to an increase of loss within the resonant cavity, which in turn leads to less energy storage within the resonant cavity, ultimately resulting in a slightly higher average output power with an OC of $T = 5\%$ than that with an OC of $T = 7\%$.[21]

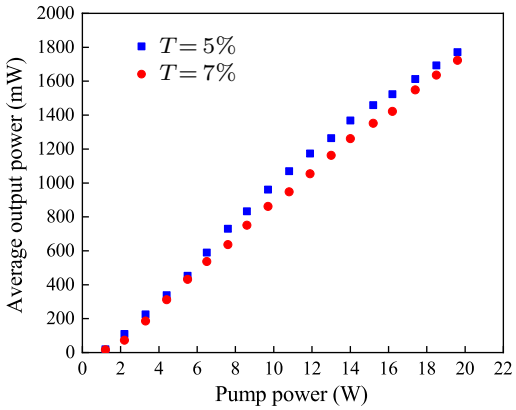


Fig. 2. The average output power of the self-pulsed Tm:$GdScO_3$ laser.

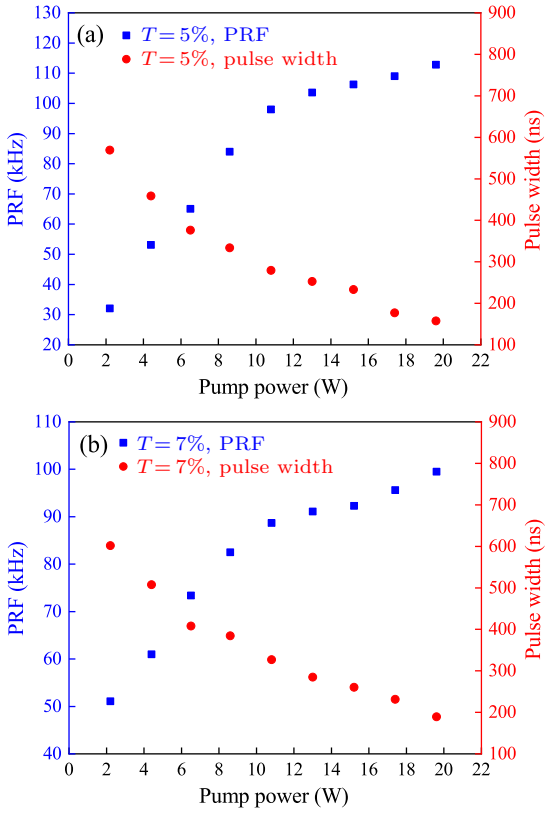


Fig. 3. The PRF and pulse width of the self-pulsed Tm:$GdScO_3$ laser.

Figure 3 shows the PRF and pulse width of the self-pulsed Tm:$GdScO_3$ laser, and these parameters were measured by using a photodetector (ET-5000, EOT) and an oscilloscope (MSO54B, Tektronix). With two kinds of OCs, the PRF of the self-pulsed Tm:$GdScO_3$ laser was increased and the pulse width was decreased as the pump power increasing.

As shown in Fig. 3(a), using an OC with $T = 5\%$, the PRF of the self-pulsed Tm:$GdScO_3$ laser was increased from 32.1 kHz to 112.8 kHz and the pulse width was decreased from 569.6 ns to 158.1 ns under the pump power increasing from 2.2 W to 19.6 W. Similarly, in Fig. 3(b), using an OC with $T = 7\%$, the PRF was increased from 51.1 kHz to 99.5 kHz, while the pulse width was reduced from 602.2 ns to 189.7 ns under the same pump power range.

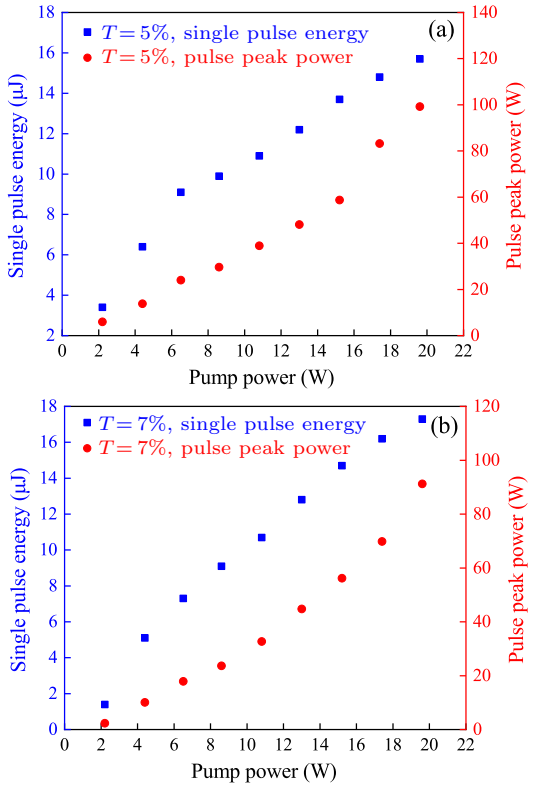


Fig. 4. The single pulse energy and pulse peak power of the self-pulsed Tm:$GdScO_3$ laser.

Figure 4 shows the single pulse energy and pulse peak power of the self-pulsed Tm:$GdScO_3$ laser. With two kinds of OCs, the single pulse energy and pulse peak power exhibit an upward trend under the pump power increasing. As shown in Fig. 4(a), using an OC with $T = 5\%$, the single pulse energy of the self-pulsed Tm:$GdScO_3$ laser was increased from 3.4 μJ to 15.7 μJ and the pulse peak power was increased from 6.0 W to 99.3 W with the pump power increasing from 2.2 W to 19.6 W. Analogously, in Fig. 4(b), using an OC with $T = 7\%$, the single pulse energy was increased from 1.4 μJ to 17.3 μJ, and the pulse peak power was increased from 2.4 W to 91.3 W under the same pump power range.

Figure 5 shows the typical pulse trains and pulse profiles of the self-pulsed Tm:$GdScO_3$ laser. Under the pump power of 19.6 W, the typical pulse trains with an OC of $T = 5\%$ were illustrated in Figs. 5(a) and 5(b) at time scales of 4 ms and 100 μs, respectively. Meanwhile, the single pulse profile, exhibiting a pulse width of 158.1 ns, was displayed in Fig. 5(c) at a time scale of 1 μs. Likewise, at the same pump power of 19.6 W, the typical pulse trains with an OC of $T = 7\%$ were shown in Figs. 5(d) and 5(e) at time scales of 4 ms and 100 μs, respectively. The corresponding single pulse profile of 189.7 ns, was depicted in Fig. 5(f) at a time scale of 1 μs. In the experiment, the pulse stability was primarily influenced by two factors: thermal effects induced by the high pump power and fluctuations of pump power arising from the use of a non-stabilized power supply for the LD.[22] To enhance the pulse stability in future investigations, we will consider implementing a constant-current power supply for the LD and optimizing the thermal effects of the Tm:$GdScO_3$ crystal.

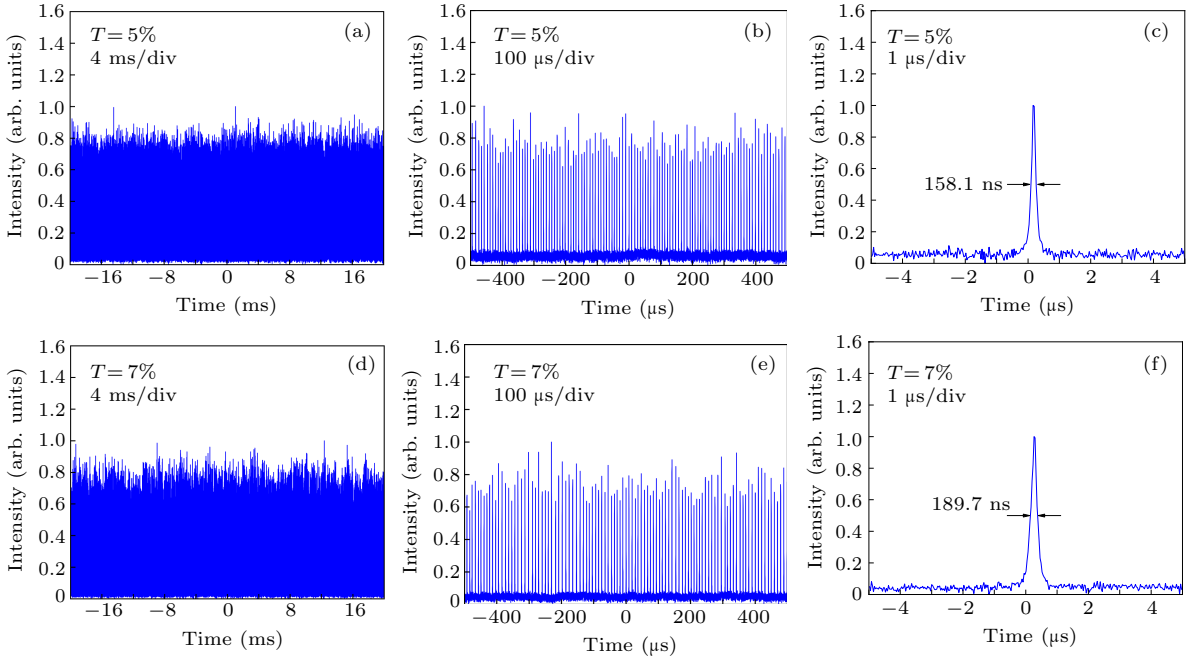


Fig. 5. The typical pulse trains and single pulse profiles of the self-pulsed Tm:$GdScO_3$ laser.

Figure 6 shows the output wavelengths of the self-pulsed Tm:$GdScO_3$ laser, and the output wavelengths were measured by using a laser spectrum analyzer (771B-IR, Bristol). When an OC with $T = 5\%$ was used in the experiment, a central wavelength of 1977.3 nm was obtained from the self-pulsed Tm:$GdScO_3$ laser under the pump power of 2.2 W, while the central wavelength was shifted to 1976.6 nm with the pump power of 19.6 W. Analogously, when an OC with $T = 7\%$ was used in the experiment, the central wavelength was measured at 1975.9 nm under the pump power of 2.2 W and further shifted to 1974.5 nm at the pump power of 19.6 W. As the pump power increasing, the number of emission peaks of output wavelengths shows an increasing trend with two kinds of OCs. The main reason for this phenomenon is that the pump power increasing not only enhances the laser output of the central wavelengths, but also allows to oscillate of the low-gain laser modes that were previously insufficient for population inversion to generate laser output, resulting in an increasing trend in the number of the emission peaks of output wavelengths.[23] Furthermore, when the pump power was increased, blue-shifts of the central wavelengths were observed with two kinds of OCs. This may be due to the thermal effect accumulated with the pump power increasing changing the inversion ratio in the quasi-three level laser system.[24] Compared with an OC of $T = 5\%$, there was also an obvious blue-shift of the central wavelength with an OC of $T = 7\%$ under the same pump power. Because of the higher cavity loss associated with an OC of $T = 7\%$, the changes in the gain–loss relation in the cavity result in shorter wavelengths with greater photon energy being more readily generated.[25]

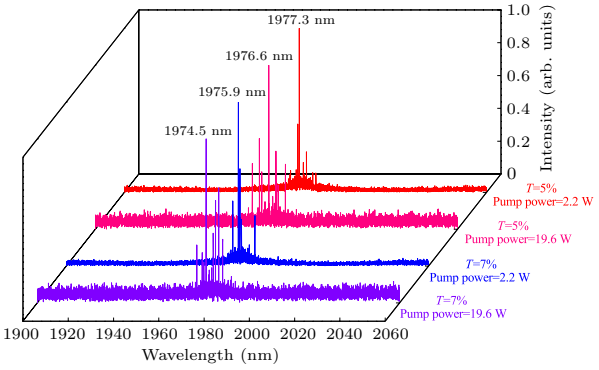


Fig. 6. The output wavelengths of the self-pulsed Tm:$GdScO_3$ laser.

Figure 7 shows the beam quality factors M^2 and beam profiles of the self-pulsed Tm:$GdScO_3$ laser which were measured by using an M^2 measurement system (M2MS-BP209IR2, Thorlabs). The corresponding insets show the two-dimensional and three-dimensional beam profiles of the self-pulsed Tm:$GdScO_3$ laser. As shown in Fig. 7(a), the fitting curves indicate that with the pump power of 2.2 W and an OC of $T = 5\%$, the beam quality factors M^2 in the x and y directions were measured to be 1.14 and 1.19, respectively. In contrast, figure 7(b) shows that at the pump power of 19.6 W, the M^2 values increase to 1.55 and 1.54 in the x and y directions, respectively. Under the pump power of 2.2 W, the corresponding beam profiles present close to TEM_{00} Gaussian mode profiles. However, when the pump power was increased to 19.6 W, the beam quality factors exhibit an upward trend, while the corresponding beam profiles were distorted. This is mainly due to the thermal effect which was caused by the increasing of the pump power.[26]

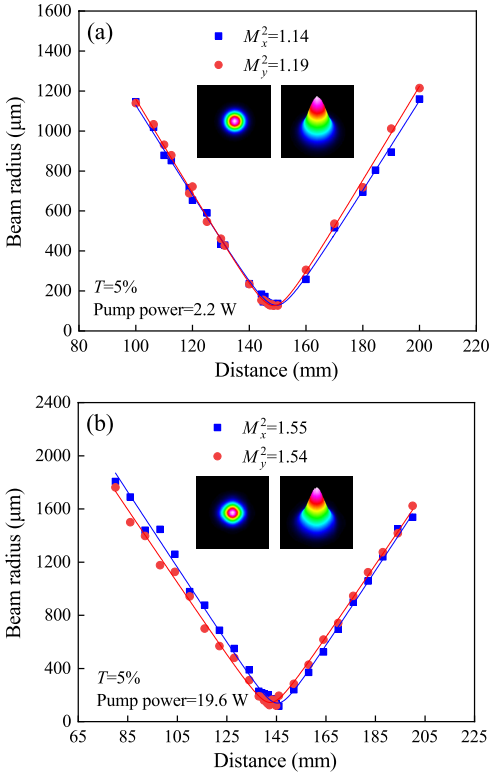


Fig. 7. The beam quality factors M^2 and beam profiles of the self-pulsed Tm:$GdScO_3$ laser.

Table 1. The output performances of the self-pulsed Tm^{3+}-doped solid-state lasers.

Crystal	λ (nm)	P_a (W)	f (kHz)	E (μJ)	τ (ns)	P_p (W)	Ref.
Tm:YAP	1988	1.7	65.2	25.7	1640.0	15.6	[27]
Tm:YLF	1910	0.6	21.0	29.0	1500.0	19.3	[28]
Tm:YAG	2006	0.9	69.9	12.4	2570.0	4.8	[29]
Tm:YAP	1946	2.8	86.3	32.1	2176.0	14.8	[30]
Tm:YAP	2028	6.6	28.0	235.1	540.1	435.3	[31]
Tm:YAP	1993	9.8	49.0	199.3	485.0	410.9	[32]
Tm:$GdScO_3$	1977	1.8	112.8	15.7	158.1	99.3	Now

The notations λ, P_a, f, E, τ, and P_p imply wavelength, average output power, pulse repetition frequency, single pulse energy, pulse width, and pulse peak power, respectively.

Table 1 provides a summary of the output performances achieved from self-pulsed Tm^{3+}-doped solid-state lasers utilizing various crystals, including Tm:YAP, Tm:YAG, Tm:YLF, and Tm:$GdScO_3$. Compared with other self-pulsed lasers, the parameter of the pulse width from our work has obvious advantage. A narrower pulse width typically indicates

higher measurement precision. The self-pulsed Tm:$GdScO_3$ laser we designed, with its compact structure and narrow pulse width, is expected to be significant in the field of measurement and beyond.

4. Conclusions

In conclusion, we reported a compact self-pulsed Tm:$GdScO_3$ laser at 1976.6 nm for the first time. Under the pump power of 19.6 W, a shortest pulse width of 158.1 ns was obtained from the self-pulsed Tm:$GdScO_3$ laser with a maximum average output power of 1771 mW and an optical-to-optical conversion efficiency of 9.0%. At 112.8 kHz, the single pulse energy and pulse peak power were calculated to be 15.7 μJ and 99.3 W, respectively. This work broadens the boundaries of self-pulsed lasers at 2-μm waveband range and informs further research on Tm:$GdScO_3$ crystals.

Acknowledgements

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