Compact self-Q-switched Tm:YLF laser at 1.91 μm

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We report self-Q-switching operation in a diode-pumped Tm:YLF bulk laser by exploiting saturable re-absorption under the quasi-three-level regime. Robust self-Q-switched pulse output at 1.91 μm in fundamental mode is demonstrated experimentally with 1.5 at.% doped Tm:YLF crystal. At maximum absorbed pump power of 4.5 W, the average output power and pulse energy are obtained as high as 610 mW and 29 μJ, respectively, with the corresponding slope efficiency of 22%. Pulse repetition rate is tunable in the range of 3–21 kHz with changing the pump power. The dynamics of self-Q-switching of Tm:YLF laser are discussed with the help of a rate equation model showing good agreement with the experiment. The compact self-Q-switched laser near 2 μm has potential application in laser radar systems for accurate wind velocity measurements.

1. Introduction

Thulium (Tm) doped solid-state lasers operating in the 2-μm eye-safe spectral range are of interest for applications in medicine, laser ranging and infrared lidar [1]. Q-switched 2-μm lasers are especially important for pumping optical parametric oscillators (OPO) for efficient conversion into the mid-infrared [2]. By using active or passive Q-switch elements, pulsed 2-μm laser sources have been widely obtained. Actively Q-switching operation can be obtained by introducing acousto-optical (AO) or electro-optical (EO) devices into laser cavity to provide optical shutters [3,4]. Passively Q-switching at 2 μm can be initiated by nonlinear saturable absorbers (SA), such as InGaAs/GaAs, Cr:ZnS and Cr:ZnSe crystals, graphene and carbon nanotube [5–7]. In comparison with the approaches of introducing AO/EO devices or SA elements, self-Q-switching as an available mechanism to generate pulse output is far simple and compact in laser architecture and low cost since no additional modulation components are needed [8].

Self-Q-switching was first performed in ruby lasers without additional Q-switch element [9]. Self-Q-switching operation at 1-μm spectral region has been widely achieved in Nd-doped, Cr, Nd-codoped, Yb-doped, and Cr,Yb-codoped lasers [10–14]. However, few studies has been reported on self-Q-switched solid-state lasers at 2-μm region. Razdobreev et al. demonstrated the self-Q-switching operation of monolithic Tm:YAP microlaser at 1.94 μm [15]. Stable self-pulsing output was obtained at high pump power beyond a certain threshold due to the phonon-assisted excited-state absorption (ESA) mechanism. Such self-pulsing regime is basically different from the relaxation oscillation instabilities observed in continuous wave (CW) Tm:YAP and Tm:YAG lasers [16]. Wu et al. presented a chaos analysis of self-pulsing output of Tm:YAP laser [17]. Nonlinear dynamical chaos regime was proposed to explain the self-Q-switching of Tm:YAP laser, but the physical parameters responsible for the chaotic behavior are unknown till now. Meanwhile, Cai et al. performed robust self-Q-switching operation in 5% doped Tm:YAP laser [18]. The time-dependent lens occurring inside the gain medium was believed responsible for self-Q-switching, which originates from refractive index changes induced by thermal lensing.

Compared with Tm:YAP, Tm:YLF crystal has been known as the excellent candidate to produce high power output at 2 μm region due to negative thermal lens, inherent linearly polarized output and high quantum yield [1,19]. With these favorable features, Tm:YLF lasers have been investigated by some workers with efforts to produce high power output towards the 100-W regime [19–23]. An optimized doping level of 2 at.% Tm:YLF with a slab geometry was shown experimentally to allow scaling of a single gain unit to output power of 70 and 148 W under single- and double-end-pumping schemes, respectively [21,22]. The actively and passively Q-switched Tm:YLF lasers has been studied to generate high energy pulses. With deploying the fused silica AO modulator as an active Q-switch, an end-pumped Tm:YLF laser was...
demonstrated to be capable of outputting up to 10-mJ pulse energy at 133 Hz repetition rate [24]. By using polycrystalline Cr\textsuperscript{2+}:ZnSe as a SA, stable passively Q-switching of Tm:YLF laser was obtained with highest pulse energy of 4.2 mJ at repetition rate of below 450 Hz [7]. Additionally, tunable CW operation of 1.5% Tm:YLF laser at 2.3 \( \mu \)m region has been demonstrated with maximum output power of 200 mW, showing the continuous tunability in the spectra from 2.20 to 2.46 \( \mu \)m [25]. By using Cr\textsuperscript{2+}:ZnSe SA, passively Q-switched operation of 2.3 \( \mu \)m Tm:YLF laser has been obtained with maximum output power of 27 mW and pulse energy of 13 \( \mu \)J under double-end-pumping [26]. However, stable self-Q-switching of Tm:YLF laser near 2 \( \mu \)m has not been reported yet.

In the paper, self-Q-switched operation in a diode-pumped Tm:YLF bulk laser at 1.91 \( \mu \)m is demonstrated experimentally. The saturable re-absorption effect of Tm:YLF laser with quasi-three-level nature is exploited to initiate self-Q-switching. At maximum absorbed pump power of 4.5 W, the average output power and pulse energy are achieved as high as 610 mW and 29 \( \mu \)J, respectively, with the corresponding slope efficiency of 22% and repetition rate of 21 kHz. The self-Q-switching dynamics of Tm:YLF laser is discussed with the help of rate equation model showing good agreement with the experimental. It is of interest in understanding the origin of self-Q-switching of Tm-doped solid-state laser near 2 \( \mu \)m.

2. Experimental setup

Fig. 1 shows a schematic of the experimental setup used to obtain self-Q-switched operation of Tm:YLF laser. The pump source is a fiber-coupled diode laser with 10-W maximum CW power at 790 nm (spectral linewidth ~2 nm). The fiber core diameter is 400 \( \mu \)m, and the numerical aperture (NA) is 0.22. The pump beam is collimated and focused by a 1:1 coupling lens group into a pump spot radius of ~200 \( \mu \)m on the Tm:YLF crystal. In order to maximize the average output power, the pump spot on the crystal is optimized by slightly adjusting the focusing lens position during the experiment. The \( \alpha \)-cut 1.5% Tm:YLF crystal with dimensions of \( 3 \times 3 \times 10 \) mm\(^3\) was wrapped in Inconel foil and mounted in a water-cooled copper holder for heat dissipation. The circulating water temperature maintained at 286 K. Both end faces of Tm:YLF crystal were anti-reflection coated for high transmission (T > 99.5%) in the spectra of 1.9–2.1 \( \mu \)m and at 790 nm pump wavelength. The pump absorption at 790 nm by the crystal is about 74%. A compact linear resonator is adopted, with 145-mm cavity length. The dichroic input plane mirror (M1) is high reflection coated at 1.9–2.1 \( \mu \)m and anti-reflection coated at 780–800 nm. The output coupler (M2) is a plano-concave mirror with 150 mm curvature radius that is partially reflective with a 98% reflection coefficient at 1.9 \( \mu \)m band. By using ABCD matrix, the laser mode distribution in the cavity was simulated. The laser mode radius in the crystal is around 130 \( \mu \)m. The pump-to-mode ratio of 1.5 leads to optimal overlap efficiency, which is desirable to restrain random relaxation oscillations and fractional thermal loading [27,28].

The laser output was measured by a Coherent FieldMaxIII laser power meter and an InGaAs photodiode. The spectrum of the laser was monitored by a Zolix monochromator (Omni- \( \nu \), 3015, resolution of the spectrum is 0.1 nm). The pulse trains were recorded by a 300 MHz bandwidth digital oscilloscope (Tektronix TDS3032B) with a > 100 MHz bandwidth IR detector (Vigo PVM-10.6).

3. Results and discussion

Fig. 2 shows the average output power of self-Q-switched Tm:YLF laser with respect to the absorbed pump power. The threshold of pump absorption power is 1 W. At maximum absorbed pump power of 4.5 W, up to 610 mW of average power was obtained with the corresponding slope efficiency of 22%. No saturation of laser output was observed in experiment, which means that the higher power output can be achieved if more pump power is available. Beyond the pump threshold, a train of self-Q-switched pulses with full depth of modulation can be observed but the repetition rate varies with the pump power. The inset of Fig. 2 shows a typical pulse train at 3 W of absorbed pump power with the repetition rate...
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