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Passively Q-switched Ho:YLF laser pumped by Tm^{3+}-doped fiber laser

Chao Yang [a], Youlun Ju [a], Baoquan Yao [a], Tongyu Dai [a,*], Xiaoming Duan [a], Jiang Li [b], Yu Ding [a], Wei Liu [a], Yubai Pan [b], Chaoyu Li [b]

[a] National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150080, China
[b] Key Laboratory of Transparent and Opto-functional Advanced Inorganic Materials, CAS, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 200050, China

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ABSTRACT

We demonstrate a compact and efficient passively Q-switched (PQS) Ho:YLF laser pumped by a self-made all-fiber laser. Firstly, we design and make an all-fiber laser operating at 1940 nm with a slope efficiency of 40.6%. Then, the all-fiber laser was used to pump Ho:YLF laser directly. In the CW (continues-wave) operation Ho:YLF laser, the maximum output power was 7.79 W, corresponding to the slope efficiency of 55.2%. Using Cr^{2+}:ZnS as the saturable absorber, the average power of 6.03 W was achieved with the slope efficiency of 45.9%. The shortest pulse duration was 15.6 ns and the pulse repetition frequency was 2.3 kHz at the pump power of 20.4 W. The pulse energy was a constant as 2.7 mJ when the pump power exceeded 15 W. The beam quality factor of M^2 was 1.05, indicating nearly diffraction limited beam propagation.

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1. Introduction

Pulsed solid-state lasers operating at 2 μm eye-safe spectral range have become one of the most explored regions. Based on the advantages as high energy, short pulse and "atmospheric window", 2 μm laser were broadly used in remote sensing [1], wind LIDAR [2], medicine [3,4] and pumping the optical parametric oscillators(OPOs) [5]. The pulse lasers commonly adopt the Q-switched technologies as actively Q-switched and passively Q-switched. It is much easier and more cost-effective for passively Q-switched lasers to achieve compact operations without the need for expensive and bulky acousto-optic or electro-optic modulators [6]. Besides, a suitable saturable absorber (SA) is crucially important for efficient PQS laser. It has been applied to several Tm-doped laser materials such as $KY(WO_4)_2$ [7], YAG [8], and YAP [9], using Cr^{2+}-doped ZnSe and ZnS crystals, PbS quantum dots, and InGaAs/GaAs semiconductor-based SAs. Compared with other SAs, Cr^{2+}:ZnS media have a series of excellent characteristics, such as the high optical damage threshold of 1.5 J/cm^2 [10] and the thermal conductivity in the cubic phase of 27 W/mK [11], which lead to a weaker thermal lens effect.

At present, the main 2 μm passively Q-switched laser media are Tm^{3+}-doped, Ho^{3+}-doped, and Tm^{3+},Ho^{3+}-codoped crystals. Compared with Tm^{3+}-doped media, Ho^{3+}-doped media have larger emitting cross section and longer upper laser level lifetime [12,13]. Tm,Ho co-doped media need to be operated under liquid N_2 temperature. Compared with Tm^{3+},Ho^{3+}-codoped media, the energy transition upconversion loss and reabsorption loss in Ho^{3+}-doped media were significantly decreased because there is no requirement of the sensitizing ions. So, better laser output characteristics in Ho^{3+}-doped laser can be obtained at room temperature.

Based on the effect of host material on thermology, mechanics and spectrum characteristics, the optical properties of Ho^{3+}-doped crystals crucially depend on the host materials. The host materials usually used in Ho^{3+}-doped crystals are oxide crystals (like YAP [14], YAG [15–17]) and fluoride crystals (like YLF [18], LuLF [19]). Compared with oxide crystals, the phonon energy of fluoride crystals is much lower and the related upper level lifetime is much longer, which helps to realize high energy storage and reach the laser operation condition. Ho:YLF is just a typical representation of fluoride crystal, which belongs to tetragonal system. In 2004, D. Y. Shen et al. used a tunable Tm-doped fiber laser operating at 1942 nm pumping a Ho:YLF laser. 4.8 W CW output power at 2.07 μm was obtained by 9.4 W pump power with a slope efficiency of 51% [20]. In 2006, Y. X. Bai et al. reported an efficiently Ho:YLF laser pumped by a fiber laser operating at 1941 nm. The maximum CW output power of 19 W at 2051 nm was obtained, corresponding to a slope efficiency of 64.7% [21]. In 2011, H. J. Strauss et al. realized a 330 mJ single frequency laser output pumping by a Tm:YLF laser at 1890 nm with π polarization

* Corresponding author.
E-mail addresses: daitongyu2006@126.com (T. Dai), lijiang@mail.sic.ac.cn (J. Li).

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direction (E//c-axis) [22]. However, the output performance of passively *Q*-switched Ho:YLF laser is seldom reported. Until the year of 2011, Dergachev A. reported a passively *Q*-switched Ho:YLF single-frequency laser by ring-cavity with Cr^{2+}:ZnSe SAs and the single pulse energy could reach to 0.42 mJ [23].

In this paper, we first report a Tm^{3+}-doped fiber laser directly pumping passively *Q*-switched Ho:YLF laser. The self-made Tm^{3+}-doped fiber laser was an unpolarized CW laser at 1940 nm with the slope efficiency of 40.6%. In CW Ho:YLF laser operation, output power was 7.79 W. In PQS Ho:YLF laser operation, a maximum average output power was 6.03 W. And the pulse width was 15.6 ns corresponding to the pulse repetition frequency of 2.3 kHz when the pump power at 20.4 W. The single pulse energy fluctuated around 2.7 mJ when the pump exceeded 15 W. The beam quality factor of M^2 was measured of 1.05 which was near-diffraction-limited.

2. Experimental setup

We utilized a double-cladding Tm^{3+}-doped all-fiber laser as a pump source for Ho:YLF crystal to generate 2.05 μm laser. The structure of fiber laser was depicted in Fig. 1(a). Two 793 nm Laser Diodes (LD) were employed as the pump source of the fiber laser. The laser cavity was composed of two Fiber Bragg gratings (FBGs). One of the FBGs was high reflective (HR, $R>99.0\%$) with the central wavelength of 1940.02 nm, and the other one was partial reflective (PR, $R=10.1\%$) with a central wavelength of 1940.00 nm. Both of the two FBGs are chirped, and the related wider spectral FWHM (full width at half maximum) of HR FBG is 2.00 nm and PR FBG is 1.00 nm at room temperature. The double-cladding Tm^{3+}-doped silica fiber (Nufern Co.) was considered as gain medium, which diameter is 25 μm and the core Numerical Aperture (NA) is 0.09. The diameter of the pure-silica inner cladding is 400 μm with 0.46 cladding NA, which is coated with a low-index polymer. The cladding absorption coefficient of the Tm^{3+}-doped fiber at 793 nm was 1.8 dB/m. A cladding stripper was designed and used to strip the light in inner cladding. The fiber output end was cleaved to 8° to eliminate the Fresnel reflection on the end facet of fiber laser. Compared with traditional 1940 nm Tm:YAP solid-state lasers [24], fiber lasers have many excellent optical characteristics, such as simplicity, tenability and compact structure

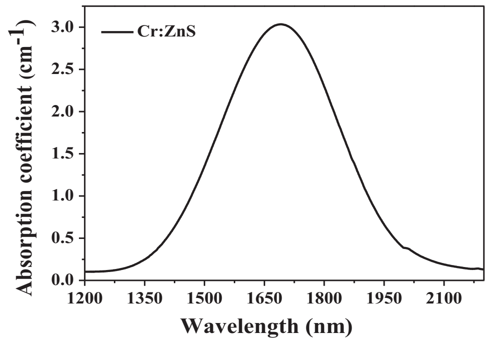

Fig. 2. The relationship between absorption coefficient of Cr^{2+}:ZnS and wavelength.

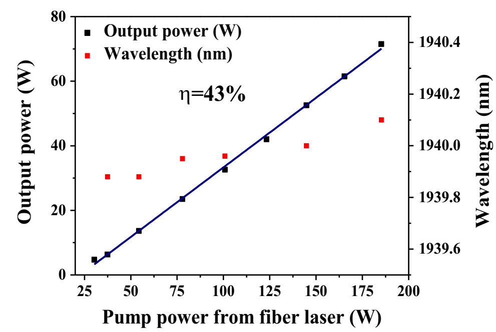

Fig. 3. The slope efficiency and wave length vs. pump power..

and have better beam quality.

The full unpolarized pump beam from the Tm^{3+}-doped fiber laser was used to pump the solid-state oscillator crystal. The structure of passively *Q*-switched Ho:YLF laser pumped by Tm^{3+}-doped fiber laser was shown in Fig. 1(b). The Ho:YLF crystal was 50 mm in length, 5×5 mm^2 in cross section, corresponding to the doping concentration of 1.5 at%. Ho^{3+} is the gain medium which is a quasi-two level system at room temperature. The transition from $^5I_7$–$^5I_8$ can generate laser wavelength around 2 μm. A Cr^{2+}:ZnS saturable absorber produced by a post-growth diffusion method was cut into 9×10 mm^2 cross section and 3 mm thickness with small-signal transmission of about 83%. The Cr^{2+} ions were uniformly-doped with a concentration of 1.9×10^{19} at/cm^3. The

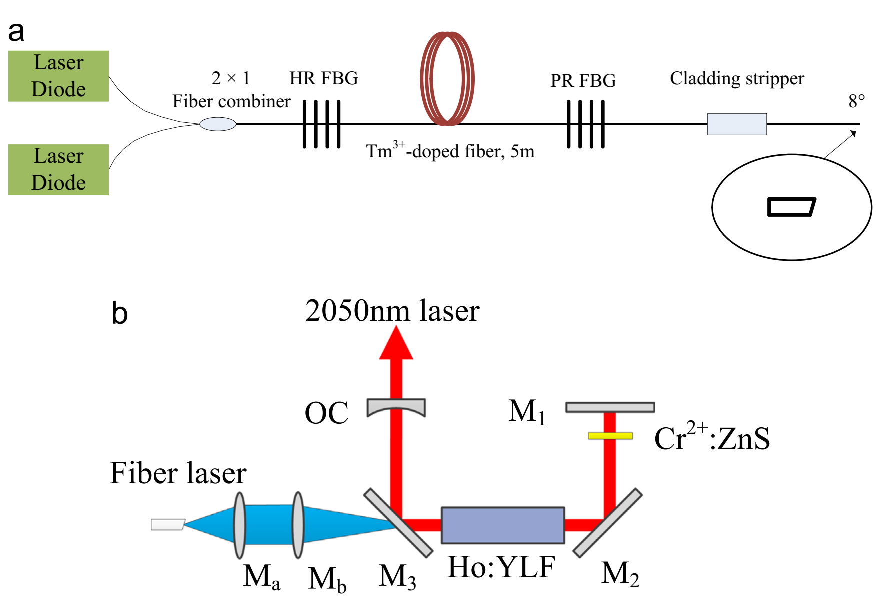

Fig.1. (a) The structure of Tm^{3+}-doped fiber laser and (b) passively *Q*-switched Ho:YLF laser.

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