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Passive Q-switching of short-length Tm^{3+}-doped silica fiber lasers by polycrystalline Cr^{2+}:ZnSe microchips

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ABSTRACT

We demonstrate passive Q-switching of short-length double-clad Tm^{3+}-doped silica fiber lasers near 2 μm pumped by a laser diode array (LDA) at 790 nm. Polycrystalline Cr^{2+}:ZnSe microchips with thickness from 0.3 to 1 mm are adopted as the Q-switching elements. Pulse duration of 120 ns, pulse energy over 14 μJ and repetition rate of 53 kHz are obtained from a 5-cm long fiber laser. As high as 530 kHz repetition rate is achieved from a 50-cm long fiber laser at ~10-W pump power. The performance of the Q-switched fiber lasers as a function of fiber length is also analyzed.

1. Introduction

Thulium-doped fiber lasers operated around 2-μm wavelength have attracted particular interests for wide applications such as range finding, remote sensing, eye-safe LIDAR, ultra-low-loss long-span communications, and medicine [1]. In the eye-safe wavelength region (1.5–2 μm), the thulium ion-doped fiber laser is an excellent candidate due to its high quantum efficiency, broad fluorescence spectrum (over 400 nm) and strong absorption band near 790 nm compatible with commercially available AlGaAs laser diodes. High power CW operation of thulium-doped silica fiber lasers have arrived 100-W level recently [2–4]. Pulsed 2-μm fiber lasers have been demonstrated with various techniques, e.g., gain-switching, Q-switching, cavity dumping and mode-locking. Gain-switched Tm^{3+}-doped silica fiber lasers have generated high pulse energy over 10 mJ in several hundred nanosecond pulse duration [5,6], while Q-switched Tm^{3+}-doped silica double-clad fiber lasers have produced several-kilowatt peak power with the pulse durations around 100 ns [7,8]. Ultra-short 2-μm pulses have been achieved from mode-locked thulium-doped fiber lasers with the pulse durations as less as several hundred femto-seconds [9].

Passive Q-switching is an attractive approach to the simple, robust, and cost-efficient pulsed laser. Many saturable materials have been utilized as the modulation elements around 1-μm wavelength. However, only a few are suitable in the 2-μm spectral range, including Ho^{3+}:CaF_2, Co^{2+}:ZnSe, and Cr^{2+}:ZnSe crystals [10]. Tm^{3+}-doped silica fiber lasers near 2 μm passively Q-switched by a Cr^{2+}:ZnSe crystal have been demonstrated with the pulse duration of 330 ns and peak power of 15 W [10]. The fiber laser, pumped by a Nd:YAG laser, was as long as five meters, resulting in relatively broader pulse durations. Passive Q-switching Tm^{3+}-doped silica fiber lasers by a Ho^{3+}-doped silica fiber has also been investigated with the pulse width of ~1 μs [11].

In this work, we employed short-length Tm^{3+}-doped silica fibers (5–50 cm) pumped by a LDA at 790 nm to achieve short pulse durations. Polycrystalline Cr^{2+}:ZnSe microchips were used to passively Q-switch the short fiber lasers. Pulse width near 100 ns, and pulse energy over 10 μJ have been obtained. High pulse repetition rate of 530 kHz has also been achieved from a 50-cm long fiber laser.

2. Experimental setup

The polycrystalline Cr^{2+}:ZnSe, prepared by CVD technique and doped by thermal diffusion method, has a relaxation time of 5 μs [12], which is significantly shorter than the lifetime of the upper

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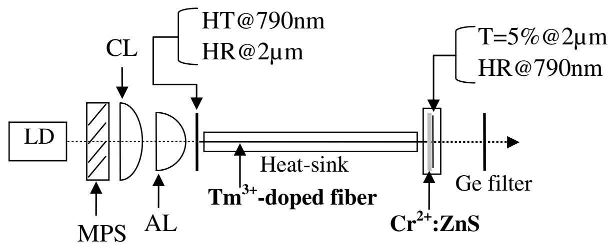

Fig. 1. Schematic of the experimental setup; LD: laser diode, MPS: micro prism stack, CL: cylindrical lens, AL: aspheric lens, HT: high transmission, HR: high reflection.

laser level of Tm^{3+} ions ($^3F_4 \rightarrow {}^3H_6$) of ~335 μs in silica [13]. The Cr^{2+} doping concentration of the polycrystalline is ~7×10^{18} cm^{-3}. Double-clad large-mode-area fibers (Fiberhome Tech. Corp. China) are used to increase the extractable energy from short-length fibers. The core, doped with approximate 2.5 wt.% Tm^{3+} ions, is 27.5 μm in the diameter and 0.20 of numerical aperture (NA). The pure silica inner cladding, coated with a low-index polymer, has a 400-μm diameter and NA of 0.46. Hexagonal cross section of the inner cladding is fabricated to improve pump absorption. The absorption coefficient at 790 nm is measured to be 13 dB/m.

Fig. 1 shows the experimental setup. A high-power LDA operating at 790 nm is used as the pump source. The pump beam is reshaped to a square beam pattern by a micro-prism stack, and then focused into the fiber using a cylindrical lens and an aspheric lens. The pump beam is launched into the fiber through a dichroic mirror with high reflectivity (>99.7%) at 2.0 μm and high transmission (>97%) at 790 nm. The output end of the fiber is butted directly to the polycrystalline Cr^{2+}:ZnSe. To avoid extra scattering loss between the butted mirror and fiber ends, both fiber ends are cleaved perpendicularly to the axis and polished carefully. Whole fiber is clamped in an air-cooled copper heat-sink. At the same time, the polycrystalline Cr^{2+}:ZnSe microchip is fixed separately on a water-cooled heat-sink to prevent it from thermal-induced fracture.

Laser output power is measured with a pyroelectric power meter after the leaky pump light being blocked by a Ge filter ($T = 0.1\%$ at 790 nm). Laser spectra are examined by a mid-infrared spectrograph with a resolution of 0.2 nm and a TEC-cooled InAs detector (J12 series). An InAs PIN photodiode and a 500 MHz digital oscilloscope are used to measure the laser temporal characteristics.

3. Results and discussion

The bleaching experiment is carried out with an uncoated polycrystalline Cr^{2+}:ZnSe microchip with thickness of 1 mm. A 2-μm Tm-doped silica fiber laser with output power up to 3 W is used as the test source. The 2-μm laser was focused onto the crystal with an objective lens of 11-mm focal length and NA of 0.25. The beam diameter at the focus is measured to be 30 μm by using the knife edge method. Fig. 2 shows the power transmission for various laser intensities onto the crystal. The transmission nearly remains a constant ~0.6 as the incident intensity is above 164 kW/cm^2. The saturation intensity $I_s \sim 164$ kW/cm^2 is higher than that from Cr^{2+}:ZnSe crystal [10]. The higher saturation intensity is probably attributed to uncoated surfaces and additional scattering loss in the polycrystal. From the saturation intensity I_s and fiber diameter, the laser power to saturate the polycrystal is calculated to be ~1.3 W.

One surface of the polycrystalline microchip is precisely polished and the other one is coated with partial reflectivity ($R = 95\%$) at ~2 μm wavelength and high reflectivity ($R>99.8\%$) at 790 nm. To Q-switch the fiber laser, different thicknesses of polycrystalline Cr^{2+}:ZnSe microchips are chosen for various fiber lengths. The thickness is selected as follows. In the first place, CW operation of a 50-cm long fiber laser is constructed with the output coupling of 5%, and about 3.1 W CW output power is achieved. Based on the measured bleaching power of the polycrystalline Cr^{2+}:ZnSe, the microchip with thickness of 1 mm is sufficient to passively Q-switch the 50-cm long fiber laser. When the fiber length is reduced, the 1-mm thick crystal can not be fully bleached due to the reduction of gain. The polycrystalline microchip is then ground thinner to achieve pulse laser output at nearly the same pump threshold. The selected thickness of polycrystalline Cr^{2+}:ZnSe microchip for various fiber lengths is shown in Table 1.

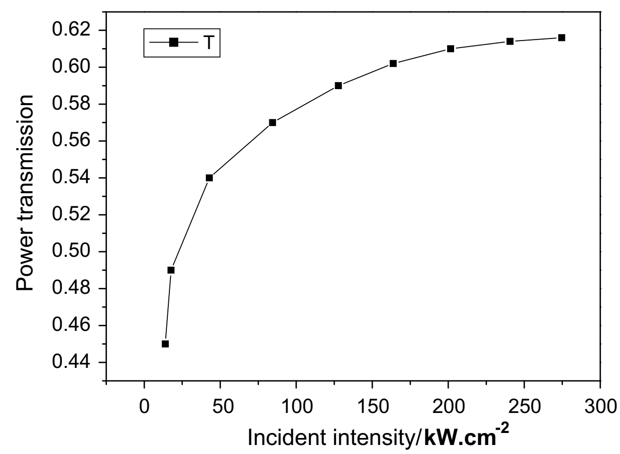

Fig. 2. Power transmission characteristics by 1 mm thick Cr^{2+}:ZnSe polycrystalline showing saturation intensity I_s = 164 kW/cm^2.

The characteristics of a 5-cm long Q-switched fiber laser are shown in Fig. 3 and 4. The fiber laser has a threshold pump power of ~3 W. Maximum average output power of around 50 mW is achieved, corresponding to a slope efficiency of ~0.5% with respect to ~10 W launched pump power. The output power increases nearly linearly with increasing launched pump power. When the pump power higher than 10.5 W, the dielectric film on the Cr^{2+}:ZnSe is damaged. The low output power and slope efficiency arise primarily from insufficient pump absorption in short fibers and reflection loss at the uncoated surface of the polycrystalline Cr^{2+}:ZnSe microchips. In the experiment, pre-lasing phenomenon is not observed due to low gain in the short-length fiber lasers.

When the polycrystalline Cr^{2+}:ZnSe microchips are replaced by a partially reflecting mirror, the short fiber lasers are operated in the CW regime. The performance of CW operation of short Tm^{3+}-doped fiber lasers has been described in the previous publication [14]. The maximum output power of a 5-cm long fiber laser is ~290 mW, corresponding to a slope efficiency of 2.9%. The Q-switched fiber lasers can extract about 17% of energy of the CW operation.

Pulse width of 120 ns is obtained from the 5-cm long fiber laser, which presents the shortest pulse duration achieved from passive Q-switched Tm^{3+}-doped fiber lasers. It is expected that sub-hundred-nanosecond pulses can be accessible by shortening the fiber length to ~1 cm. The pulse repetition rate increases linearly and reaches the maximum value of 53 kHz with the pump power of 10.3 W.

Table 1
Parameters of the fiber length and thickness of Cr^{2+}:ZnSe

Fiber length (cm)	5	10	20	50
Thickness of Cr^{2+}:ZnSe (mm)	0.3	0.4	0.5	1