Visible ns-pulse laser oscillation in Pr-doped double-clad structured waterproof fluoride glass fibre with SESAM

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Abstract: A visible Q-switched pulse train at 639 nm was successfully generated in a Pr-doped double-clad structured waterproof fluoride glass fibre with a semiconductor saturable absorber mirror. The slope efficiency was calculated as 36.3%. The pulse duration and the radio frequency were measured as 270 ns and 107 kHz at 596 mW of absorbed power, respectively. The pulse energy and the pulse peak power were calculated as 1.32 µJ and 4.87 W, respectively.

1 Introduction

Many types of visible lasers have been developed so far, such as gas lasers, liquid dye lasers, and solid-state lasers, and they have many applications in science and technology, including medicine, laser processing, display, biology, metrology, and optical storage [1]. Nowadays, most lasers are solid state, in particular, the optical fibre laser. Fibre lasers have many advantages, including high beam quality, high efficiency, compactness, maintenance-free operation, efficient cooling, and reliability. Therefore, fibre lasers are commonly used in industrial applications [2]. Several works on primary visible fibre lasers have been carried out with ZBLAN glass fibre. Subsequently, Fujimoto *et al.* [1] reported another possibility of a primary visible fibre laser with Pr-doped waterproof fluoride glass fibre (Pr:WPFGF). The power of the Pr:WPFGF laser reached over 1 W, and therefore is considered one of the promising primary visible fibre lasers. The next goal is to get more a powerful and higher intensity laser with Q-switched pulse operation.

Some research works have been reported on primary visible Q-switched pulse lasers in Pr-doped gain media. In 2013, a Q-switched pulse Pr:YLF laser at 639 nm using a Cr:YAG crystal as a saturable absorber was reported [3]. Then, Q-switched pulses were observed in a Pr:ZBLAN laser with topological insulators [4] or transition-metal dichalcogenide [5] as a saturable absorber in the visible region. The semiconductor saturable absorber mirror (SESAM) is also well known as a high-performance saturable absorber with pico-second switching speed, and pico-second pulse generation in a Pr:YLF laser at 640 nm with a SESAM has already been demonstrated [6, 7]. We also already demonstrated ns-pulse generation in a multi-mode Pr:WPFGF with a graphene film as a saturable absorber at 603-nm wavelength [8]. In 2016, we reported a fabricated Pr-doped double-clad waterproof fluoride glass fibre (Pr:DC-WPFGF) and a laser demonstration in Pr:DC-WPFGF with single-mode operation [9]. It is considered that this single-mode operation will be helpful for achieving mode-locked operation in the visible-laser region.

In this paper, we show a visible Q-switched pulse generation in Pr:DC-WPFGF with SESAM as a saturable absorber at 639-nm wavelength by GaN-LD (laser diode) excitation.

2 Experiment

The experimental setup of a Q-switched pulse laser oscillator is shown in Fig. 1. The fibre's core diameter was 5.2 µm, inner-clad diameter was 14 µm, and NA of the core was 0.08. Since the V-number is calculated as 2.045, the fibre is in single mode. The Pr concentration of the fibre core is 3000 ppm. The fibre length was 100 mm. A GaN-LD (1.6 W; #NDB7875E, NICHIA Corp.) was used as a pump source. The LD was operated at 25°C by a Peltier device because the LD-emitting wavelength should be kept at the absorption peak at 442 nm of the Pr:DC-WPFGF. The laser cavity is composed of a direct dielectric multilayer coating on a fibre end surface as an output coupler ($T = 14\%$ at 639 nm) and a SESAM (RefleKron Ltd.) on an aluminium heat sink. The fibre's output beam was collimated by a collimation lens ($f = 7.5$ mm, $NA = 0.30$; #A375TM-B, THORLABS) and was focused on the SESAM by a focus lens ($f = 8.0$ mm, $NA = 0.50$; #C240TME-A, THORLABS). The best focus-beam diameter after focusing the lens was measured by the micro-beam profiler (#MBP-100-USB, Newport), and we recognised the beam diameter on the SESAM after optimisation of the cavity. The response time and the unsaturated reflection of the SESAM are 20 ps and <97%, respectively. The laser spectrum, output power, and laser pulses were measured with a fibre optic spectrometer (#HR2000, Ocean Optics), a power meter (#model 3A, OPHIR), and an oscilloscope (2.5 GHz; #TDS7254b, Tektronix) with a photodiode (2 GHz; #DET025A/M, THORLABS).

3 Results

The beam diameter on the SESAM was measured to be <3.6 µm by the micro-beam profiler. The input–output characteristics of red Q-switched pulse laser oscillation are shown in Fig. 2. The laser oscillation threshold power and the slope efficiency were calculated

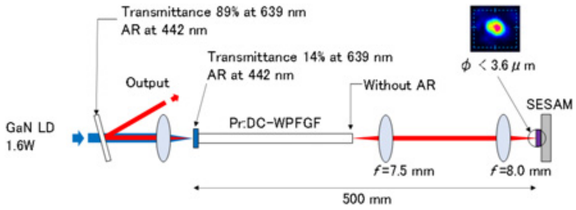

Fig. 1 *Experimental setup for Pr:DC-WPFGF visible pulse laser oscillator*

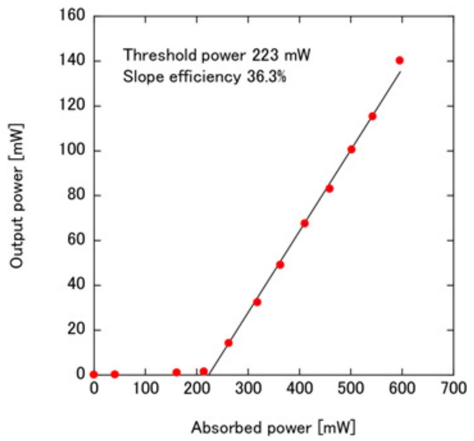

Fig. 2 *Input–output characteristics of red Q-switched pulse fibre laser as function of absorbed pump power*

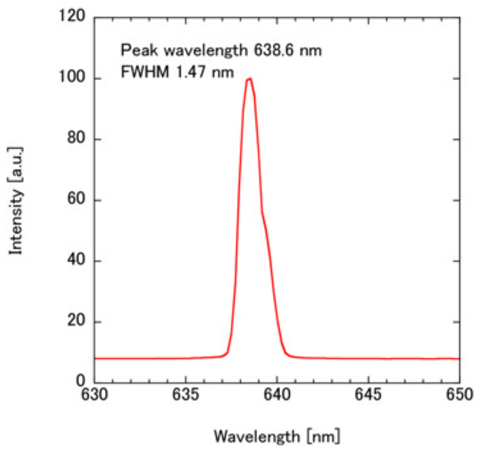

Fig. 3 *Spectrum of red Q-switched pulse fibre laser*

as 223 mW and 36.3%, respectively. The maximum average output power was measured as 140 mW at 596 mW of absorbed power. The measured spectrum of the red Q-switched pulse laser is shown in Fig. 3. The peak wavelength and the FWHM of spectrum width were obtained as 638.6 and 1.47 nm, respectively. The red Q-switched pulse laser train is illustrated in Fig. 4. The radio frequency and FWHM of the pulse duration were measured as 107 kHz and 270 ns, respectively. Thus, the pulse energy and the pulse peak power were calculated as 1.32 µJ and 4.87 W, respectively.

4 Discussion

For further progress, let's consider mode-locked operation. A Pr:YLF mode-locked laser was reported by Gaponenko *et al.* [6]. They also used a SESAM made by RefleKron Ltd., and reported that the required power density of the SESAM for achieving stable mode-locking was ~23 MW/cm^2 [7]. On the other hand, the maximum power density on the SESAM was estimated to be 344 MW/cm^2 in our experiment; therefore, it is considered that enough power density had been irradiated on the SESAM for mode-locking. The reasons we could not observe the mode-locking phenomenon in this experiment are thought to be a phase mismatch due to material dispersion in the fibre, optimisation of the cavity length, and ASE noise on the SESAM. When these parameters are optimised, we will be able to achieve a primary visible mode-locking fibre laser in the future.

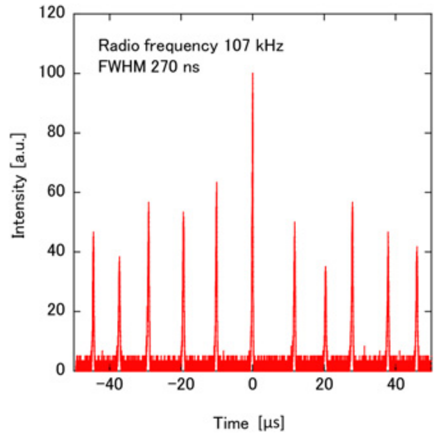

Fig. 4 *Pulse train of red Q-switched pulse fibre laser*

5 Conclusion

Visible Q-switched pulse fibre laser at 639 nm was successfully generated in Pr:DC-WPFGF using a SESAM as a saturable absorber. The radio frequency and FWHM of the pulse duration were measured as 107 kHz and 270 ns at 596 mW of absorbed power, respectively. The pulse energy and the pulse peak power were calculated as 1.32 µJ and 4.87 W, respectively. In the future, a primary visible ultra-short pulse laser with a mode-locking technique is expected to be demonstrated.

6 Acknowledgments

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7 References

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