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Comparative study of diode-pumping self-injection and injection-locking Tm:YAG lasers

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Abstract

A comparative study of the laser characteristics of self-injection and injection-locking Tm:YAG lasers is given in this paper. At a pump energy of 145 mJ and Q-switched repetition rate of 100 Hz, an output energy of 2.39 mJ was obtained for an injection-locking Tm:YAG laser, with a pulse width of 403.2 ns and a pulse building-up time of 2.12 μs. Under the same conditions, the output energy, pulse width and pulse build-up time for a self-injection Tm:YAG laser were 2.21 mJ, 407.0 ns and 3.95 μs, respectively. The threshold of the Q-switched injection-locking Tm:YAG laser was much lower than that of the self-injection laser, and the pulse width was narrower and the pulse build-up time shorter. Additionally, the output spectrum was much purer for the injection-locking laser.

(Some figures may appear in colour only in the online journal)

1. Introduction

Diode-pumping all-solid-state lasers operating at 2 μm are useful for coherent Doppler LIDAR and differential absorption LIDAR. In a LIDAR system, a pulsed laser with high spectral purity and narrow line width is required. Injection-seeding is an effective method to achieve a high power Q-switched laser with a pure spectrum [1–3]. In 1998, a flash-lamp-pumping, injection-seeded, Q-switched, eye-safe 1.552 μm Er:glass laser was reported by McGrath [4]. The output energy and pulse width was 1 mJ and 400 ns, respectively. Tm-doped lasers operated at room temperature are suitable for Q-switched operation as their long fluorescence lifetime (8–16 ms) is favorable for realizing a wider pulse width [5]. Nowadays, Tm:YAG, Tm:LuAG and Tm:LuYAG are the most often used Tm-doped laser crystals [6]. Because of the advantages of high mechanical strength and high heat conductivity (0.13 W (cm K)$^{-1}$), with Tm:YAG it is possible to obtain a high power laser output without thermal fracture [7]. In 2011, an injection-seeded Tm:YAG laser was demonstrated by our group, and a nearly transform-limited pulsed single-frequency of 2013 nm with an output energy of 2.0 mJ and a pulse width of 356.2 ns was achieved at a repetition rate of 15 Hz [8].

In this paper, a comparative study of self-injection and injection-locking Tm:YAG lasers was carried out experimentally. At a pump energy of 145 mJ and Q-switched repetition of 100 Hz, an output energy of 2.39 mJ, pulse width of 403.2 ns and pulse build-up time of 2.12 μs were achieved for the injection-locking laser. Under the same conditions, output energy, pulse width and pulse build-up time for the self-injection laser was 2.21 mJ, 407.0 ns and 3.95 μs,

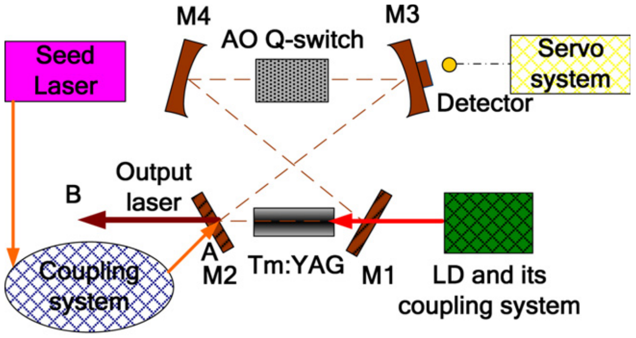

Figure 1. Schematic of the Tm:YAG laser and injection seeding system.

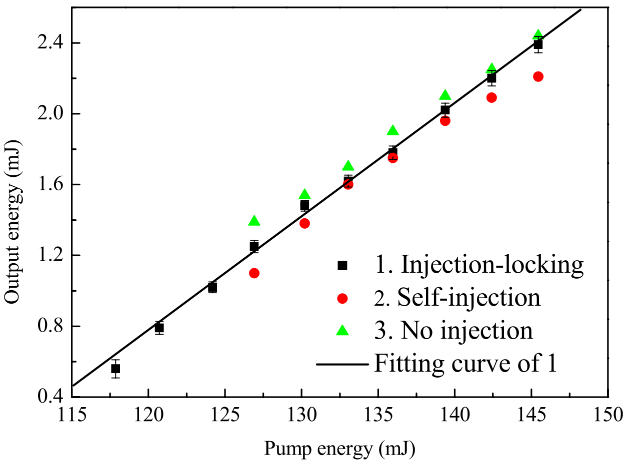

Figure 2. Output energy versus pump energy.

respectively. The results also showed that the spectrum for the injection-locking laser was much purer.

2. Experimental setup

A skeleton diagram of the experimental setup is shown in figure 1. The pump source is a pulsed fiber-coupled laser-diode (LD) with a peak power of 30 W. The output wavelength could be tuned to 785 nm by controlling the temperature of the LD, which coincides with the absorption peak of the Tm:YAG crystal. The diameter and numerical aperture of the fiber core were 400 μm and 0.22, respectively. The pumping laser beam was shaped and focused by a series of convex lenses, and it was focused into the Tm crystal with a beam diameter of about 1.2 mm. Mode matching between the pump laser and the oscillating laser was optimized by changing the waist radius of the pump beam and its location. The Tm:YAG crystal with dimensions of $\varnothing\ 3 \times 8$ mm^3 has a doping concentration of 3.5%. The faces are polished plane, parallel and antireflection coated near 785 nm ($R < 0.5\%$) and 2.01 μm ($R < 0.5\%$). To efficiently remove the waste heat generated in the crystal, it was wrapped with indium foil and held in a brass heat sink. The temperature of the heat sink was controlled at 290 K with a thermoelectric cooler. The oscillator was of the bowtie cavity type. The resonator consisted of two plane mirrors and two curved mirrors. M1 was a high-reflectivity flat mirror. The radius of curvature of high-reflectivity curved mirrors M3 and M4 was 5 m. The transmission of the flat output coupler M2 was 3.5% at 2.01 μm. The total resonator length was about 0.3 m. A 46 mm long fused-silica acousto-optical Q-switch was used to produce Q-switched operation. In this paper, the repetition rate of the Tm:YAG laser was set at 100 Hz. The thermal lens of the laser material was seen as a parabolic thin lens. The resonator was designed using ABCD matrices. When the thermal lens was longer than 80 mm, $\mathrm{d}\omega/\mathrm{d}f$ was approximately equal to 0, which means that the laser cavity was insensitive to the thermal lens and could be stably operated at a high pump power level. The bidirectional fashion of the bowtie oscillator was convenient for injection-seeding. For the self-injection system, the seed laser, which was fed back by a high reflection coated mirror at 2.01 μm, was one direction of output of the ring laser. For injection-locking, the seed laser was a continuous wave (cw) single-frequency Tm:YAG laser. The output wavelength of the single-frequency (measured by diagnostic air-gap scanning Fabry–Perot interferometer with a free spectral range of 3.75 GHz, a 9 V biased InGaAs detector and a digital oscilloscope) Tm:YAG laser was centered at 2013.9 nm (recorded by a Burleigh WA-650 spectrum analyzer combined with a WA-1500 wavemeter with resolution of 0.7 pm). The maximum output power of the seed laser was 60 mW (measured by LPE-1A power meter) and the output laser was linearly polarized with a degree of polarization over 30 dB (measured by a Glan–Taylor prism).

The seed laser was injected into the Tm:YAG laser cavity through its output coupler with a reflectivity of 96.5%, and the beam diameter of the seed laser at the Tm:YAG crystal was controlled about 0.8 mm by a coupling system. A critical point of the injection-locking system was used to adjust the length of the Q-switched Tm:YAG oscillator to stay in resonance with the seed laser. A technique called ‘ramp-and-fire’ was used for maintaining single-frequency operation of the injection-locking, Q-switched Tm:YAG laser. M3 was fixed on a piezoelectric transducer (PZT). The length of the Tm:YAG laser cavity was rapidly changed by the PZT until resonance with the seed laser, which was optically detected by the InGaAs detector placed behind M3. For the self-injection system, the seed laser was the output of one side of the ring laser and fed back by a high reflection coated mirror at 2.01 μm, therefore the injection-locking system cannot be operated then.

3. Experimental results and discussion

3.1. The output energy

The output energy of the Tm:YAG laser was measured by an energy meter and the result is shown in figure 2.

When there was no feedback, the output energy from two directions of the Tm:YAG laser was almost equal due to the

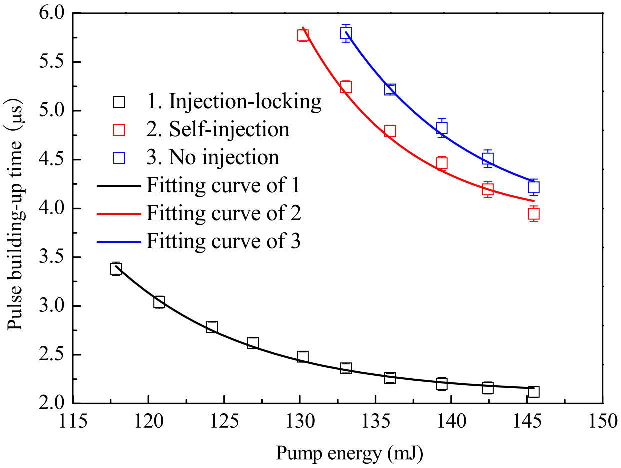

Figure 3. The pulse build-up time versus output energy.

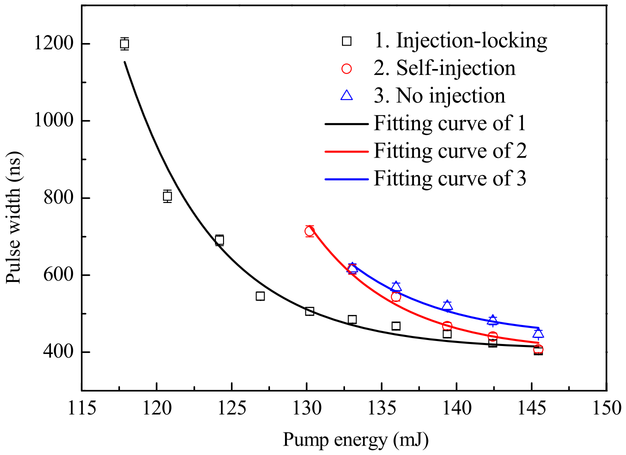

Figure 4. Pulse width versus pump energy.

cavity design. However, the output energy from direction B was close to the total energy, whether in the condition of self-injection or injection-locking. The threshold was the lowest when injection-locking appeared, and this phenomenon was not obviously under self-injection operation. Compared with the bidirectional output without injection-seeding, the energy stability was obviously improved after self-injection and injection-locking. The stability was best under injection-locking operation.

3.2. The pulse build-up time

The pulse build-up time was measured with a digital oscilloscope (Tektronix TDS3032B) and a room temperature mercury cadmium telluride photoconductive detector with a response time of 1 ns. The build-up time of the output pulse laser under no injection, self-injection and injection-locking versus pump energy is shown in figure 3. It can be seen that the build-up time of the output pulse was shortened when the pump energy was increased. At the same pump energy, compared with the no injection state, the build-up time of the pulse for the self-injection and injection-locking lasers was much shorter, especially around the threshold of the laser. Furthermore, the build-up time of the pulse for the injection-locking laser was shortest.

3.3. The output pulse width

The output pulse width was recorded by the digital oscilloscope and the room temperature mercury cadmium telluride photoconductive detector, as shown in figure 4. As the pump energy increased, the pulse width of the Tm:YAG laser under three states was decreased. The pulse width was the narrowest under injection-locking and the pulse width tended to a constant value, which was the cavity life of the oscillating light.

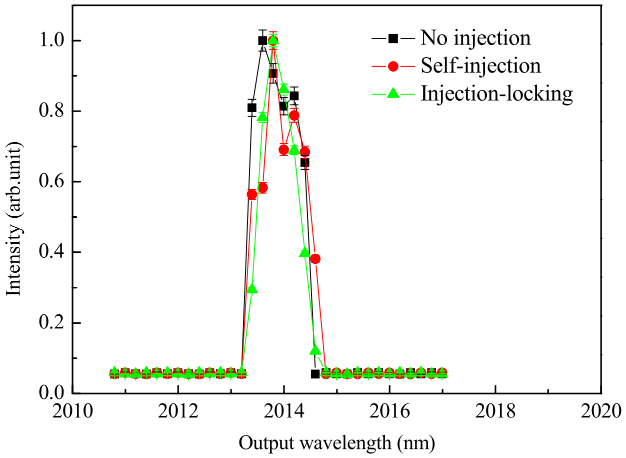

Figure 5. The output wavelength under three states.

3.4. The output wavelength

The output wavelengths of the pulse laser under three states were recorded with a monochromator (300 mm focal length, 300 lines mm^{-1} grating blazed at 2000 nm). The input laser was detected by an InGaAs detector connected to a digital oscilloscope (Tektronix TDS3032B). As shown in figure 5, when there was no injection signal, the output wavelength of the *Q*-switched laser had two peaks at 2013.6 and 2014.2 nm. For self-injection operation, two wavelength peaks also appeared at 2013.8 and 2014.2 nm, and the spectral purity was improved to some degree. Furthermore, the output spectrum was purest at the injection-locking state, and there was only one peak wavelength at 2013.9 nm, which coincided with the cw Tm:YAG seed laser.

4. Conclusion

In summary, this paper has given a comparative study of diode-pumping self-injection and injection-locking Tm:YAG lasers. Compared with self-injection, the threshold of the *Q*-switched Tm:YAG laser was much lower for the injection-locking state, and the pulse width was narrower and the pulse build-up time was shorter. It was shown that the characteristic of spectrum was determined by the seed laser in the injection-locking system, so the output spectrum was much purer. This meant that the self-injection technology without timing control could only improve the output performance to some degree. If there was no strict requirement on laser spectral purity, self-injection without precise timing control could be used to improve the output performance to some degree. However, for coherent Doppler LIDAR, a pulsed laser with high spectral purity and narrow line width was necessary and the injection-locking system was desired.

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