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Single-frequency, injection-seeded Er : YAG laser based on a bow-tie ring slave resonator

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Abstract. **A diode pumped, injection-seeded *Q*-switched Er : YAG laser at 1645.2 nm is demonstrated. A single frequency Er : YAG monolithic nonplanar ring oscillator (NPRO) laser emitting at 1645.24 nm with a maximum output power of 500 mW is used as a seed laser. The seed laser output is injected into a bow-tie slave laser, obtaining stable single-frequency *Q*-switched operation of the Er : YAG laser. The maximum single-frequency *Q*-switched Er : YAG laser output energy is 2.9 mJ at 100 Hz with a pulse duration of 160 ns.**

Keywords: *diode pumping, Er : YAG laser, injection seeding, single-frequency laser, Q switching.*

Laser sources emitting in the eye-safe region are useful for a variety of scientific and technical applications, including coherent Doppler lidars, differential absorption lidars, etc., which require high-energy and narrow linewidth pulsed operation. Furthermore, Doppler-based coherent systems need long enough pulse duration to achieve high measurement accuracy [1]. To meet these requirements, one needs a high-power *Q*-switched laser (slave laser) seeded by a single-frequency master oscillator (master oscillator) [2–4]. The injection locking requires either a strong injected signal or an injection laser whose wavelength is very close to that of the free-running oscillator (slave laser) to be locked [5]. A 2-μm injection-seeded laser has been extensively investigated. In 2009, Bai et al. [6] described high repetition rate operation of an injection-seeded Ho : YLF laser. In 2011, a 1.91-μm pumped, injection-seeded *Q*-switched Ho : YAG laser operating at room temperature was reported, achieving an output energy of 7.6 mJ and pulse duration of 132 ns at a repetition rate of 100 Hz [7]. Compared to 2-μm lasers, the damage threshold against human eyes is ten times higher when use is made of 1.6 μm lasers. The probes and other devices of a 1.6-μm laser are compatible with the 1.5-μm communication band, ensuring better practicability and commercial value.

A 1532-nm laser diode is a promising pump scheme in order to improve the overall optical efficiency and reduce the device volume. In 2005, Stoneman [8] reported an injection-seeded laser at 1645 nm. Recently, Wang [9] has reported a 1645-nm, resonantly pumped, injection-seeded, single frequency *Q*-switched Er : YAG laser. An U-shaped cavity was applied in the slave laser, leading to a large volume of the device and difficulty in the injection experiment. Therefore, a ring laser cavity seems more promising for such the experiments, because its length can be much less than the volume and it can provide two outputs for convenient injection seeding. Stoneman et al. [10] reported a single-frequency Er : YAG laser transmitter at 1617 nm, using a rectangular cavity as a slave laser. Another rectangular cavity was employed in a 1645-nm injection-seeded laser pumped by a laser diode [11].

In this paper we report a diode-pumped, single-frequency, *Q*-switched injection-seeded Er : YAG laser with a bow-tie ring resonator configuration at room temperature. Compared with the rectangular cavity, the bow-tie ring cavity is more compact and more stable. To decrease the thermal lensing effect, instead of a rod crystal we used a slab Er : YAG crystal to obtain a stable bow-tie design. A diode-pumped Er : YAG NPRO laser was used as a seed laser. To ensure successful injection seeding and avoid interference of the environment, the 'ramp-hold-and-fire' technique was utilised [12], which allowed us to design a 1645-nm single-frequency *Q*-switched Er : YAG laser with a pulse energy of 2.9 mJ and a pulse duration of 160 ns at a repetition rate of 100 Hz.

The schematic diagram of the injection-seeded Er : YAG laser is shown in Fig. 1. It consists of three parts: a continuous wave (cw) seed laser (master oscillator), a *Q*-switched slave laser and an electronic servo system for injection seeding.

The seed laser was a diode-pumped Er : YAG NPRO laser. The maximum single-frequency laser output power from the seed laser was 500 mW, corresponding to a slope efficiency of 18.2 %. The p-polarised laser operated on a single longitudinal mode which emitted at the centre wavelength of 1645.24 nm.

The *Q*-switched Er : YAG laser was used as a slave laser with a bow-tie ring resonator. Two fibre coupled laser diodes with a maximal output power of 20 W each were used as pump sources. To coincide with the absorption peak of the Er : YAG crystal, the wavelength was tuned to 1532 nm by changing temperature. The output of the LD was collected by a 20-mm focal length collimating lens and focused into the Er : YAG crystal using a lens with a 60-mm focal length. Then, the diameter of the pump beam waist was 600 μm, which was located at one third of the crystal from the entrance face. The resonator consisted of three plane mirrors and one curved mirror. Plane mirrors M1 and M2 were highly reflecting flat mirrors; a curved mirror (M3) with a 300-mm radius of curvatureM3 was mounted on a piezoelectric actuator (PZT). Mirror M4, which was an injection mirror and an output coupler of the ring laser, had a 85 % reflectivity at 1645 nm. The total resonator length was 350 mm. A 30-mm-long fused-silica acousto-optic *Q*-switch with low insertion

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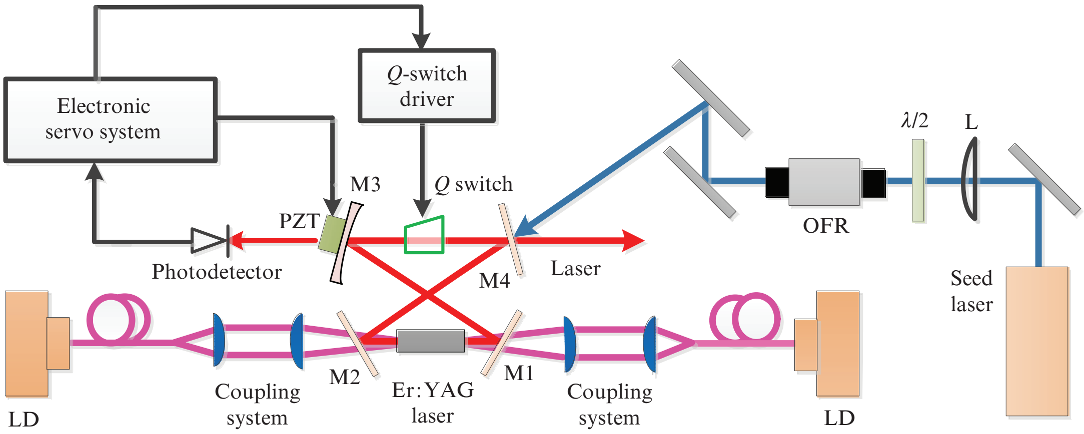


Figure 1. Scheme of the experimental setup: (LD) laser diode; (M1 – M4) mirrors; (PZT) piezoelectric actuator; (QS) *Q* switch; (L) lens; (OFR) optical Faraday rotator.

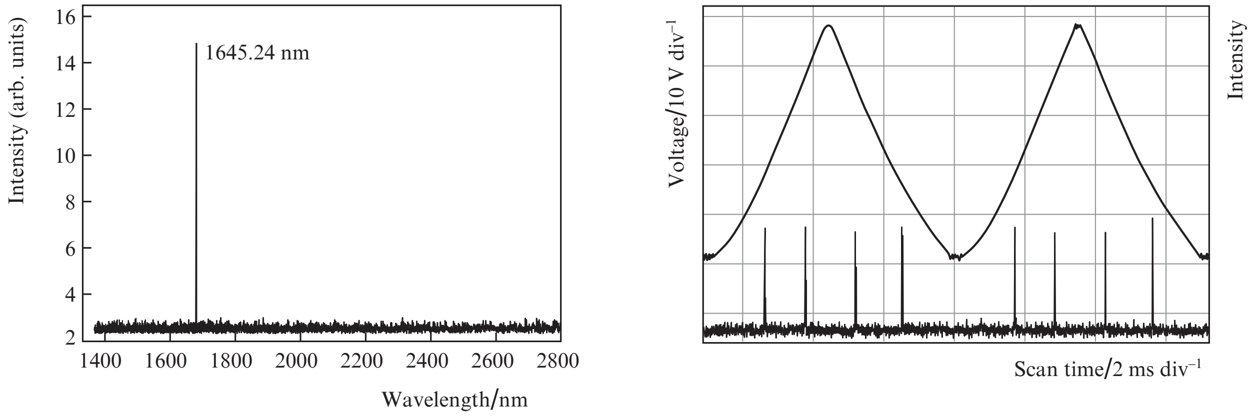
loss was used to ensure *Q*-switched operation. Its maximum RF power was 25 W and its intrinsic diffraction loss was 62.5 %, which was adequate to prevent lasing.

The Er : YAG crystal with an Er doped concentration of 0.25 %, used in the slave laser, measured 1.5 × 6 × 50 mm. The heat produced in the slab crystal is easier to diffuse, providing a weaker thermal lensing effect than the rod. Both sides of the crystal were AR-coated at 1532 nm and 1645nm. The crystal was wrapped in indium foil and held in a copper heat sink at a constant 288 K by a TE-cooler to effectively remove the heat generated in the crystal. In addition, the dual-end pumped configuration facilitated the distribution of the thermal load. The coupling system contained two parts, coupling lens and optical isolation. The coupling lens was used to optimise the spatial mode matching. The beam diameter was controlled to be 0.2635 mm by a lens L with a focal length of 200 mm, which was almost the same as the beam diameter of the slave laser. An optical Faraday rotator and a half-wave plate were used to isolate the laser output for protecting the seed laser. We used the 'ramp-hold-and-fire' technique [12] to realise single-frequency, injection-seeded pulsed Er : YAG laser operation. An electronic servo system was applied to make the seed laser and the slave laser oscillate at the same frequency, which improved the spectral purity of the output laser. The *Q*-switched laser output energy should be relatively constant as a function of the *Q*-switch trigger delay time to minimise the energy fluctuation.

The spectrum of the seed laser was recorded by a 721 spectrum analyser (Bristol Company). The output wavelength was centred at 1645.24 nm (Fig. 2a). Figure 2b shows the output signal from the scanning Fabry – Perot interferometer (FPI) with a free spectral range of 3.75 GHz. No other transverse modes were observed in the scanning FPI spectrum. It can be seen clearly that the laser operated on a single longitudinal mode. A maximum single-longitudinal-mode laser output power of 500 mW was obtained in the seed laser.

At first, we recorded the wavelength of the slave laser for the cw operation and *Q*-switched operation. The output wavelength was centred at 1645.26 nm, almost the same as the seed laser, meaning good wavelength matching for both lasers. The output power for the cw regime of the slave laser as a function of the pump power P_p is shown in Fig. 3a. The measured slope efficiency was 11.58 %, corresponding to the lasing threshold of 19.55 W. The output energy and pulse duration for the *Q*-switched regime of the slave laser as a function of the pump power is shown in Fig. 3b. The pulse repetition rate of the laser was 100 Hz. The ring laser threshold was about 22 W. The maximum output energy of 3.55 mJ and a pulse duration of 128 ns were obtained at $P_p = 36.4$ W.

Figure 4a shows the dependences of output energy and pulse duration on the pump power in the injection-seeded



a

b

Figure 2. (a) Wavelength of the seed laser and (b) FPI spectrum of the seed laser.

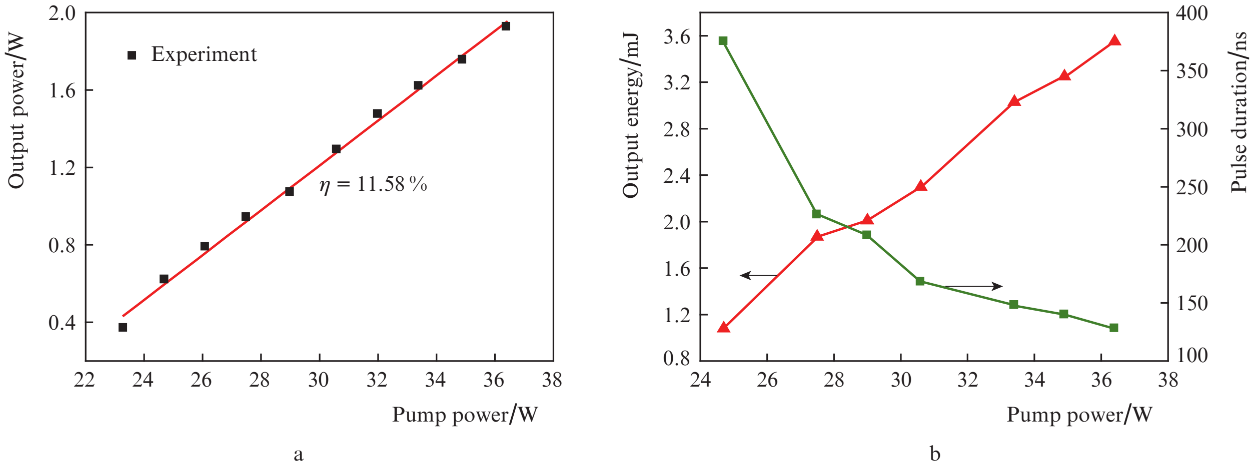


Figure 3. (a) Output power for the cw regime and (b) output energy and pulse duration for the Q-switched regime of the slave laser vs. pump power.

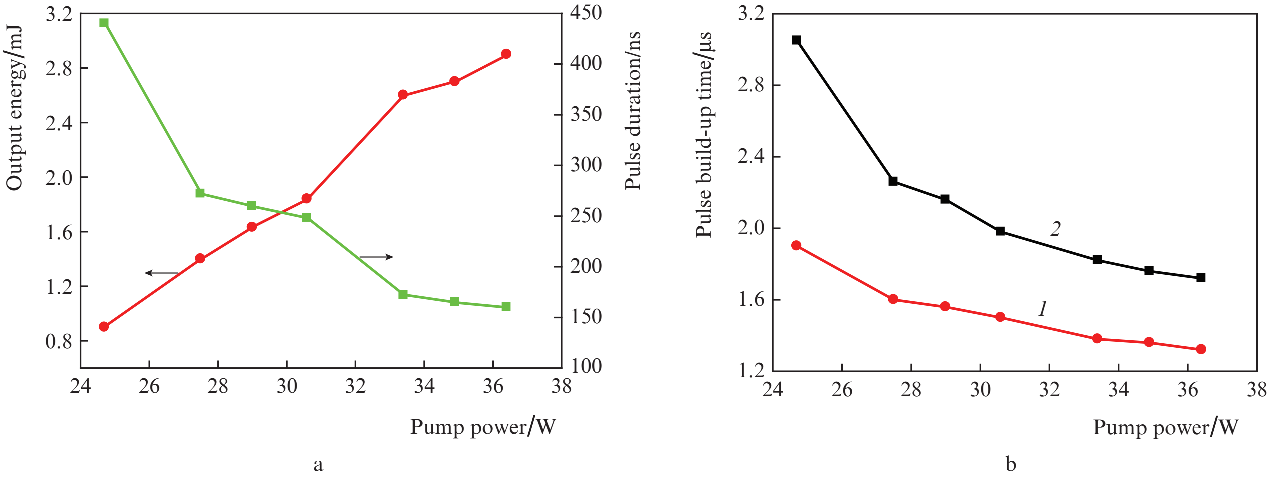


Figure 4. (a) Output energy and pulse duration for the injection-seeded regime and (b) laser pulse build-up time of the Er:YAG laser under (*1*) injection-seeding and (*2*) without it vs. pump power.

regime. At P_p = 36.4 W, an output energy of 2.9 mJ with a pulse duration of 160 ns was obtained. In addition, it is clearly seen that the pulse duration decreases sharply with increasing pump power. We also investigated the dependence of the output energy of the Er:YAG laser under injection-seeding and without it on the pump power. For Q-switched operation without injection-seeding, the laser exhibited bidirectional output. However, after injection-locking the laser exhibited unidirectional output. Compared to the case when injection locking is absent, the output energy under injection seeding was barely a little lower at the same pump power. The laser build-up time of the Er:YAG laser under injection seeding and without injection seeding vs. pump power is shown in Fig. 4b. It can be noted that the build-up time of the output laser pulse was shortened when the pump power increased. Compared to the case when there was not injection-locking, the laser pulse build-up time for the frequency-locked laser was shorter at the same pump power.

We also studied the temporal behaviour of the all-solid-state, injection-seeded ring Er:YAG laser. The frequency-unlocked to frequency-locked pulse-jumping phenomenon is shown in Fig. 5. For frequency-locked regime, the build-up time of the pulse was about 1.5 μs, which was 480 ns shorter than that in frequency unlocked regime at a pulse energy of 1.84 mJ.

Thus, we have reported a diode pumped, injection-seeded Q-switched Er:YAG laser based on a bow-tie slave laser at room temperature. A diode-pumped, single frequency Er:YAG NPRO laser with the centre wavelength of 1645.24 nm and a maximum output power of 500 mW has been used as a seed laser. Single frequency, Q-switched operation of the Er:YAG laser has been obtained by injection seeding. The maximum output energy of the single-frequency Q-switched pulse is 2.9 mJ, corresponding to the pulse duration of 160 ns at a repetition rate of 100 Hz.

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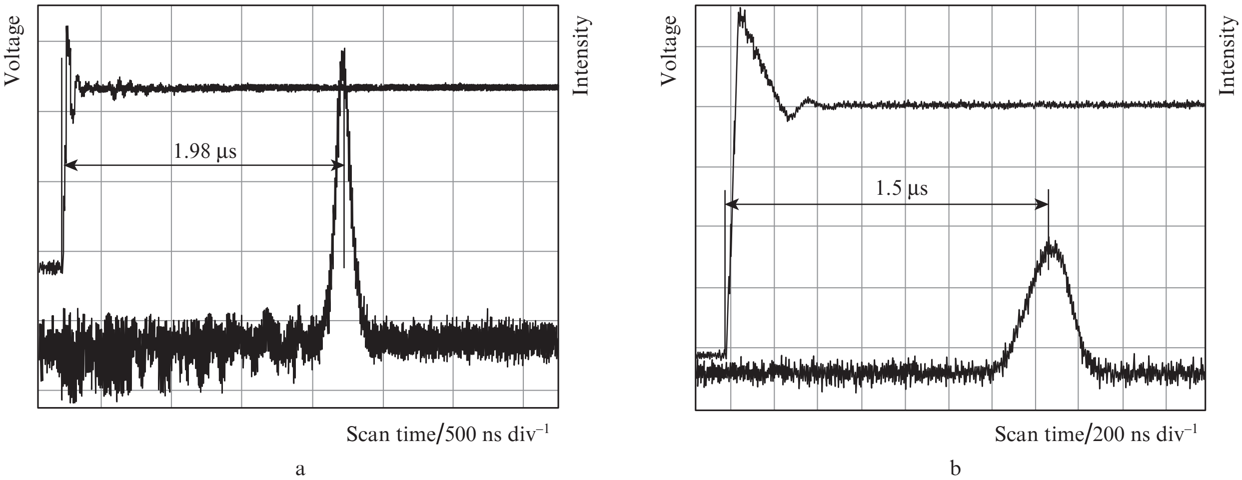

Figure 5. (a) Build-up time of the output laser pulse under injection-unlocked regime and (b) build-up time of the output laser pulse under injection-locked regime.

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