Laser diode pumped high-energy single-frequency Er:YAG laser with hundreds of nanoseconds pulse duration

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We demonstrated a high-energy single-frequency erbium-doped yttrium aluminum garnet (Er:YAG) laser. With 1470 nm laser diodes (LDs) as pumping sources, single-frequency laser pulses with energy of 28.6 mJ, 21.6 mJ, and 15.0 mJ are obtained at pulse repetition frequency of 200 Hz, 300 Hz, and 500 Hz, respectively. As far as we know, this is the highest single-frequency pulse energy with the Er:YAG gain medium. With the ring cavity design, pulse duration is maintained at hundreds of nanoseconds. This high-energy single-frequency laser with hundreds of nanoseconds pulse duration is a prospective laser source for light detection and ranging applications. Keywords: Er:YAG; injection-locking; single-frequency; high energy.

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A single-frequency erbium-doped yttrium aluminum garnet (Er:YAG) laser operating at an eye-safe wavelength has drawn much attention in various applications like plastics processing, laser medicine, and wind measurement light detection and ranging $(\text{Lidar})^{[1-5]}$. For coherent wind measurement Lidar, range and radial velocity of aerosols need to be measured at the same time. For long range detection, a high-energy single-frequency laser is required, and for accurate radial velocity detection, single-frequency laser pulses with longer pulse duration are required. So, in coherent wind measurement Lidar systems, laser pulses with duration of hundreds of nanoseconds are used [6.7]. There are plenty of works on such a kind of single-frequency laser system $\left[\frac{8-13}{2}\right]$. Most of the previous works on a single-frequency pulsed laser are based on a single gain medium, and the highest pulse energy with a single gain medium at 1645 nm is 16 mJ, with a pulse repetition frequency (PRF) of 250 Hz^{6} .

For higher energy, a double gain-medium configuration has been used in recent years^[14–17]. Single-frequency laser pulses with energies of 20.9 mJ^[15] and 21 mJ^[16] have been obtained at a PRF of 200 Hz and 500 Hz, with pulse duration of 110 ns and 93 ns, respectively.

These double gain-medium high-energy lasers produce laser pulses with duration around 100 ns, while wind Lidar application requires laser pulses with a duration of hundreds of nanoseconds. Furthermore, for longer detection range, a higher-energy laser pulse is needed and will lead to shorter pulse duration, which will deteriorate the Lidar performance.

Besides, these single-frequency Er:YAG lasers are completely or partially pumped by a 1532 nm fiber laser, with an extra power transfer stage from a laser diode (LD) to an Er,Yb co-doped fiber laser, resulting in lower electrical to optical efficiency and a complicated system. In this Letter, we demonstrate an LD pumped highenergy single-frequency Er:YAG laser at 1645 nm, with the pulse duration maintaining hundreds of nanoseconds. For high-energy laser pulses generation, we compared the common in-band pump source of a 1532 nm LD and 1470 nm LD theoretically. The analysis indicates that the 1470 nm LD outperforms the 1532 nm LD under highenergy operation. By using two 1470 nm LDs as pump sources and injection-locking technology, single-frequency laser pulses with pulse energy of 28.6 mJ, 21.6 mJ, and 15.0 mJ are obtained at PRFs of 200 Hz, 300 Hz, and 500 Hz. The pulse duration is maintained at 159 ns, 191 ns, and 263 ns, respectively, which satisfies the requirement of wind Lidar.

The center wavelengths of the in-band pump LD for the Er:YAG system are 1470 nm and 1532 nm, respectively. A simple model is used to compare the maximum upperstate density under different pumping wavelengths^[18]. The definitions of the parameters used in this Letter are listed in Table <u>1</u>.

 Table 1. Definition of the Parameters

Item	Definition	
ΔN	Inversion density	
f_2	Pump transition upper-state Boltzmann factor	
f_1	Pump transition lower-state Boltzmann factor	
N_2	Upper-state population density	
N_1	Lower-state population density	
N	Total dopant concentration	
β	Normalized upper-state density	

The inversion density of the pump transition is

$$\Delta N = f_2 N_2 - f_1 N_1. \tag{1}$$

In the pump transition process, the actual upper and lower states are N'_2 and N'_1 , with an inversion density of $\Delta N'$. For in-band pumping, the population transfers very fast from N'_2 and N'_1 to the laser state N_2 and N_1 through non-radiative transition, and thus the whole transition process can be treated as a two-level system. In this case, we can view N'_2 , N'_1 , $\Delta N'$ and N_2 , N_1 , ΔN as the same population density.

Define the normalized upper-state density as

$$\beta = N_2/N \tag{2}$$

and transition Boltzmann ratio as

$$f = f_1 / f_2.$$
 (3)

Then, inversion density could be expressed as

$$\Delta N = f_2 N[\beta - f(1 - \beta)]. \tag{4}$$

For a laser system, the inversion density of the pump transition should be no greater than zero (the gain medium should absorb rather than emit the photons at the pump wavelength):

$$\Delta N = f_2 N[\beta - f(1 - \beta)] < 0.$$
(5)

Then, β should have an upper bound:

$$\beta_{\max} = \frac{f}{1+f}.$$
 (6)

f is a wavelength-related function, and the calculation of f is described in Appendix <u>A</u>. The β_{max} for different wavelengths is shown in Fig. <u>1</u>.

As shown in Fig. <u>1</u>, the maximum upper-state population density decreases with the increasing pump wavelength. Thus, the 1470 nm pumping source could provide higher upper-state population density than the 1532 nm pumping source, implying more storage energy, which is conductive to high-energy laser operation.



Fig. 1. Maximum upper-state density versus different pump wavelengths.

Besides, the absorption bandwidth of Er:YAG at room temperature is about 10 nm at 1470 nm, while it is much narrower (less than ~ 1 nm) at 1532 nm^[19]. Thus, for the 1532 nm LD, additional spectral narrowing components such as volume Bragg grating (VBG) are required to improve the absorption efficiency, which brings additional cost and complexity.

Under the consideration above, we choose 1470 nm LDs as pump sources for our high-energy laser system.

The laser is an injection-locking system, consisting of a seed laser, a slave laser, and a control system. The laser system setup is shown in Fig. 2.

The slave laser is a ring resonator with double gain media, composed by M1–M7. The gain media are two $\Phi 4 \text{ mm} \times 60 \text{ mm} \text{ Er:YAG}$ ceramic rods, with Er^{3+} dopant concentration of 0.25% (atomic fraction). Both surfaces of the ceramics are anti-reflection (AR) coated from 1470 nm to 1645 nm. M1 is a curved output coupler with a radius of 1000 mm, which has a transmission of 20% at 1645 nm. M3 is a curved high-reflectivity (HR) mirror with a radius of 1000 mm; M2 is a flat mirror. M4–M7 are dichromatic mirrors; with HR at the lasing wavelength and high transmission (HT) at the pumping wavelength at the angle of 45°. The length of the whole cavity is extended to 2.4 m to generate pulses with long pulse duration. The beam radius of the laser in the two Er:YAG ceramic rods is 470 µm.

For the ring cavity laser, the large reflection angle of the tilted spherical mirrors will result in astigmatism^[16], leading to different beam waist positions in the meridian and sagittal directions. This effect increases the difficulty of beam shaping for the Lidar application. To reduce the



Fig. 2. Schematic diagram of laser setup. PD, photo detector; PBS, polarization beam splitter; HWP, half-wave plate; ISO, isolator; LD, laser diode; AOM, acousto-optic modulator; PZT, piezoelectric ceramic transducer.

astigmatism, spherical mirrors M1 and M3 are tilted by a very small reflection angle ($<8^\circ$).

The Er:YAG ceramics in the slave laser are pumped by two fiber-coupled 1470 nm LDs, delivering 40 W output with 10 nm linewidth, respectively.

The diverging output from the fiber (NA = 0.22, 200 µm core diameter) is a refocus module with a magnification of four, thereby resulting in a beam radius of 400 µm. The pump beam waist is slightly smaller than the laser radius for better beam quality. The acousto-optic modulator (AOM) with 40.68 MHz radio frequency is placed in the region with a moderate beam radius to avoid optical damage.

The seed laser is an LD pumped Er:YAG non-planar ring oscillator (NPRO), producing 150 mW stable continuous single-frequency output at 1645.22 nm, with a linewidth of less than 10 kHz. The seed laser beam is divided into two parts by a half-wave plate (HWP1) and a polarization beam splitter (PBS), for injection locking and heterodyne detection, respectively. The splitting ratio could be adjusted by HWP1. The s-polarized seed laser is rotated to be p-polarized and injected to the AOM at the first-order diffraction angle through M8. Lens 3 ensures the mode match between the injected master seed laser and the slave laser.

The injection locking is performed by the "Ramp-Fire" technique. Unfolded mirror M4 is mounted on a piezoelectric ceramic transducer (PZT), which is driven by the control system with a triangular wave. The leaked resonance signal is detected by the photo detector (PD1) behind M3. At the peak of the resonance signal, the cavity length meets the constructive interference condition of the seed laser frequency, and then the AOM is opened to build the laser pulses.

A small fraction of the output laser pulse is mixed with the seed laser for heterodyne detection, and the heterodyne signal is detected by PD2.

The Q-switch performance is tested without seed injection. As shown in Fig. <u>3</u>, laser pulses with energy of 28.7 mJ, 24.4 mJ, and 17.8 mJ, pulse width of 169 ns, 196 ns, and 261 ns at PRF of 200 Hz, 300 Hz, and



Fig. 3. Q-switched pulse energy and width without seed injection versus pump power.

500 Hz, respectively, are obtained. The pulse duration is maintained at hundreds of nanoseconds.

After injection locking, the laser produces stable singlefrequency pulses with slightly reduced pulse energy. The single-frequency laser output performance is shown in Fig. <u>4</u>; single-frequency laser pulses with energies of 28.6 mJ, 21.6 mJ, and 15.0 mJ are obtained at PRFs of 200 Hz, 300 Hz, and 500 Hz, with pulse widths of 159 ns, 191 ns, and 263 ns.

Figure 5 shows the build-up time of the laser pulses with and without injection at a PRF of 200 Hz. With seed injection, the laser pulses are built up from the injected seed laser, which is far stronger than spontaneous emission, and thus the build-up time is reduced. However, under high pump power, the gain in the cavity is sufficiently high, which ensures that the pulse is built up very fast, even without injection locking. In such case, the reduction of the pulse duration is negligible.

The heterodyne detection result of the maximum output energy at 200 Hz is shown in Fig. <u>6</u>. The fast Fourier transformation (FFT) result indicates that the laser pulse is single-frequency, with a linewidth of 3.4 MHz, which is 1.2 times the Fourier transformation limit for the 159 ns pulse width.



Fig. 4. Characteristics of single-frequency pulse energy and width versus pump power.



Fig. 5. Build-up time with and without seed injection at a PRF of 200 Hz.



Fig. 6. Heterodyne detection result and FFT result at the highest output energy.



Fig. 7. Central frequency stability of the beating signal.

As shown in Fig. 7, the central frequency stability of the beating signal is measured in 30 min, with a root mean square (RMS) less than 1.5 MHz.

The stability of pulse energy under the output energy of 28.6 mJ is also tested in 30 min, with an RMS less than 2.1%.

The beam profile is measured in different positions by a Pyrocam III-C-A camera (Spricon Inc.) at the highest output energy (Fig. 8). The M^2 factors are 1.37 and 1.09 in the x and y directions. The beam quality in meridian and



Fig. 8. Beam characterization at highest output energy.

sagittal planes are both diffraction limited, which is important for the long detection range in the wind measurement Lidar system.

In summary, an LD pumped, single-frequency highenergy Er:YAG laser system suitable for wind measurement Lidar is demonstrated. With the configuration of the double gain media pumped by 1470 nm LDs, up to 28.6 mJ single-frequency laser pulses with pulse duration of 159 ns at 1645 nm under a PRF of 200 Hz are obtained. The M^2 factors are 1.37 and 1.09 in the xand y directions, which indicates that the beam quality of the laser is diffraction limited. To the best of our knowledge, 28.6 mJ is the highest single-frequency pulse energy around 1645 nm, with hundreds of nanoseconds pulse duration. This single-frequency high-energy Er:YAG laser system is a suitable laser source for wind measurement Lidar.

Appendix A

The Boltzmann factors of the i^{th} lower state and the i^{th} upper state are f_{1i} and f_{2i} :

$$f_{1i} = \frac{\exp\left[-\frac{hc(E_{1i} - E_{11})}{kT}\right]}{Z_1},$$
 (A1)

$$f_{2i} = \frac{\exp\left[-\frac{hc(E_{2i} - E_{21})}{kT}\right]}{Z_2}.$$
 (A2)

h is the Planck constant, and *c* is the speed of light. *k* is the Boltzmann constant, and *T* is Kelvin temperature. E_{1i} and E_{2i} are lower-state and upper-state crystal energy levels of the laser system, and the units of them are the wavenumber in centimeters to the negative first power (cm⁻¹).

 Z_1 and Z_2 are the partition function of the lower state and upper state:

$$Z_1 = \sum_j \exp\left(-\frac{hcE_{1j}}{kT}\right),\tag{A3}$$

$$Z_1 = \sum_j \exp\left(-\frac{hcE_{1j}}{kT}\right). \tag{A4}$$

Table 2. Crystal Energy Levels at 300 K^{19}

i	$E_{1i}(\mathrm{cm}^{-1})$	$E_{2i}(\mathrm{cm}^{-1})$
1	0	6544
2	19	6596
3	57	6602
4	76	6779
5	411	6800
6	424	6818
7	523	6879
8	568	



Fig. 9. f versus the pump wavelength.

 Z_1 and Z_2 can be calculated according to Table 2. For a temperature of 300 K, Z_2/Z_1 is about 0.96.

The Boltzmann transition ratio should be

$$f = \frac{f_1}{f_2} = \left(\frac{Z_1}{Z_2}\right) \exp\left\{\frac{hc\left[\frac{1}{\lambda_p} - (E_{21} - E_{11})\right]}{kT}\right\}.$$
 (A5)

 λ_p is the pump wavelength.

The value of f versus wavelength is shown in Figure 9. Then, the β_{max} versus pump wavelength could be calculated.

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