Injection-seeded, single-frequency, Q-switched erbium:glass laser for remote sensing

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We have built and characterized an injection-seeded, Q-switched, flash-lamp-pumped, eye-safe Er:glass laser that is suitable for coherent remote sensing. The output of the device is a 400-ns, single-frequency, transform-limited pulse of 1 mJ at 1.552 µm. © 1998 Optical Society of America

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1. Introduction

Single-frequency, pulsed, eye-safe lasers are required for coherent detection in remote-sensing applications. Although it is well known that Er:glass lasers operate in the eye-safe wavelength band from 1530 to 1550 nm, these lasers have not been previously used for coherent detection. To the best of our knowledge, we report here the first successful demonstration of injection seeding of Er:glass (a quasi-three-level laser host), resulting in a transform-limited, single-frequency output pulse.

We are developing the laser as the coherent transmitter of a pulsed Doppler lidar for the measurement of wind velocities and wind shear. These measurements are not new, but have previously used CO_2 lasers at 10.6 µm[1,2] and more recently solid-state Nd:YAG,[3] Tm:YAG,[4] and Tm,Ho:YAG.[5] The neodymium systems are not eye safe at energies required for remote sensing, and although the 2-µm thulium and holmium lasers are eye safe, the Er:glass laser at 1.54 µm is considered eye safe at 10 times the energy of a 2-µm system.[6] This makes the Er:glass system attractive for some applications and partially offsets the limitations on the pulse repetition frequency that are due to thermal effects in this host. An Er:glass laser system is also attractive because it can make use of standard telecommunications components, including readily available diodes for laser pumping.

A requirement for a pulsed Doppler lidar system is a very narrow laser linewidth (≤1 MHz) to permit detection of the Doppler frequency shifts associated with backscatter from aerosols moving at typical wind speeds (approximately 1.3-MHz shift for 1-m/s velocity change at this wavelength). Pulsed erbium lasers have until now not been demonstrated to operate with a suitable bandwidth. We devised a technique for injection seeding a flash-lamp-pumped Er:glass laser so that it oscillates in a single longitudinal mode, producing coherent pulses of sufficient length for use in a pulsed Doppler lidar system.

2. System Description

The Er:glass laser system is shown in Fig. 1. Part of the output of the cw master oscillator (MO) is passed through an acousto-optic modulator (AOM) that shifts the frequency by 30 MHz. This frequency-shifted radiation is injected into the slave resonator through the Q-switch and is used to seed the laser pulse. The remainder of the MO output is used as the local oscillator (LO), resulting in a frequency difference of 30 MHz between the LO and the seed. In a pulsed Doppler lidar system, this 30-MHz difference allows detection of a heterodyne beat even from a stationary target, as well as providing direction sensing. It also allows verification of successful seeding of the slave by mixing the LO with a portion of the output pulse; a modulation of 30 MHz will be seen only when the seeding is successful.

The slave resonator regeneratively amplifies the seed radiation to produce a coherent laser pulse. The lasing medium is a Kigre QX/Er thermally strengthened, erbium-doped phosphate glass rod. The fluorescence spectrum[7] of this gain medium is shown in Fig. 2. The rod is 3 mm in diameter and 50

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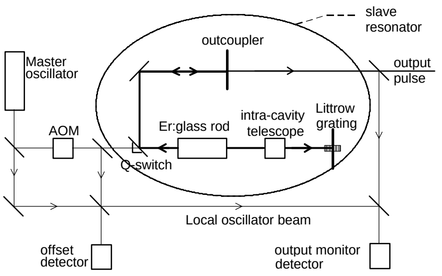

Fig. 1. Schematic of the injection-seeded laser system.

mm in length, with parallel antireflection-coated ends and is enclosed in a water-cooled Kigre flash-lamp-pumping chamber. It is pumped by a Kigre K-2113 flash lamp with 18-J electrical energy per flash, at a pulse repetition rate of 1 Hz. Inasmuch as the QX/Er rod is thermally strengthened, the power output could be increased to 15 Hz and 30 J/flash.[7]

The slave resonator is approximately 0.7 m long, giving a free spectral range of 210 MHz. It is a two-mirror telescopic resonator employing flat end reflectors. The resonator is folded with two right-angled prisms to allow Q-switching by use of the frustrated total internal reflection technique[8,9] and to produce a compact laser. This Q-switching technique employs a small block of glass mounted on a piezoelectric translator, located close to the reflecting surface of one of the prisms (Fig. 3). The reflectivity of the prism is varied by adjusting the air gap between the prism's reflecting surface and this block of glass. A 45° flat on one corner of the Q-switch block forms an entry window allowing the seed radiation to be injected into the slave resonator through the Q-switch. With resonator end mirror reflectivities of 98.6% and 86%, the slave resonator produces a 30-mJ, 400-ns pulse at 1535 nm (Fig. 4), corresponding to the peak of the fluorescence spectrum (Fig. 2). This output energy produced by 18 J of pump energy is typical for an efficient, flash-lamp-pumped, Q-switched Er:glass laser.[7]

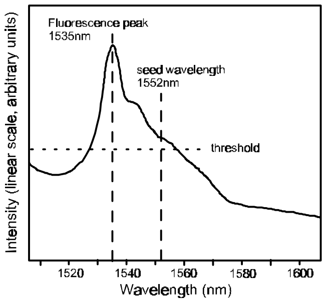

Fig. 2. Er:glass fluorescence spectrum indicating detuning required for seed laser used in this research (QX/Er Kigre data).

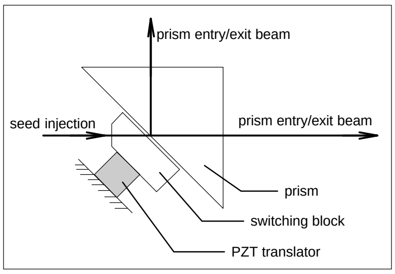

Fig. 3. Frustrated total internal reflection Q-switch design showing injection port and lasing axis. PZT, piezoelectric translator.

The MO is a commercial,[10] diode-pumped, single-frequency cw Er:glass laser producing 50 mW at 1552 nm. The wavelength of this particular MO (and hence the seed) is fixed and is a long way from the peak of the fluorescence curve, resulting in relatively little gain in the slave oscillator at that wavelength. To prevent oscillation at wavelengths near the line center at 1535 nm, it was necessary to replace one of the slave resonator mirrors with a diffraction grating in Littrow configuration. This method for controlling the frequency of an Er:glass laser was also used by Petrov and Fromzel,[11,12] who used a diffraction grating to scan the operating frequency of their laser, although without attempting to Q-switch or injection seed.

The grating is a high-efficiency, gold-coated holographic grating with 1200 lines/mm, blazed for Littrow configuration at 1550 nm.[13] In Littrow configuration, we measured a reflectivity of approximately 98% into the first order. The intracavity telescope, with a magnification of 1.5, not only provided transverse mode control, but also expanded the beam to reduce the power density on the grating to avoid damage. By adjusting the angle of the grating, we were able to scan the wavelength of the slave resonator and achieved lasing from 1528 to 1558 nm. The laser emitted 30 mJ at line center, but only 1-2 mJ at the seed wavelength of 1552 nm.

3. Results

The diffraction grating was aligned using the seed

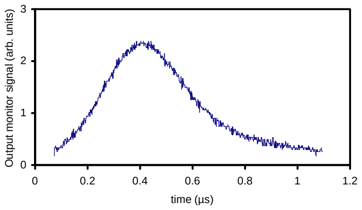

Fig. 4. Free-running , Q-switched slave output pulse, close to seed wavelength, as a function of time. Total energy is 2mJ.

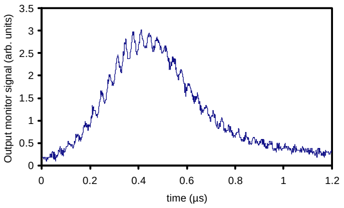

Fig. 5. Injection-seeded, Q-switched slave laser pulse showing 30-MHz heterodyne modulation with LO

beam to tune the slave resonator to the frequency of the MO by observing the return of the seed from the grating back through the open Q-switch (high resonator loss) to the MO. By partially closing the Q-switch, the other mirror (outcoupler) of the slave oscillator was aligned by observing the corresponding increase in intracavity power using a detector to detect the zeroth order beam outcoupled by the grating. This approach guaranteed that the slave resonator was aligned and tuned to the seed. We obtained injection seeding by scanning the length of the slave resonator while simultaneously observing the buildup time of the slave resonator pulse and the heterodyne beat between the output and the LO. The buildup time of power in the slave resonator was observed by use of the detector on the zeroth order beam from the grating. With an oscilloscope triggered by the Q-switch drive pulse, the extinction of the intracavity seed power could be observed as the Q-switch closed, followed later (typically 10 µs) by the rapid and sharp increase in power that was due to the Q-switched slave pulse. When the slave laser resonator length was correct for injection seeding, this buildup time was reduced to a few microseconds, and the initial rise of the pulse appeared less sharp. Coincident with this reduction in pulse buildup time, the heterodyne beat frequency changed from random values, typically including the 210-MHz beat note from adjacent longitudinal modes, to a single 30-MHz signal as shown in Fig. 5. This indicates that the mode competition usually occurring during pulse buildup was suppressed by the dominant seeded mode, and it remained so for the duration of the pulse. Note that the receiver bandwidth used was 500 MHz, and a 420-MHz signal was never observed. These observations show that no more than two longitudinal modes lased when free running and prove that the slave laser was operating on only a single frequency when injection seeded.

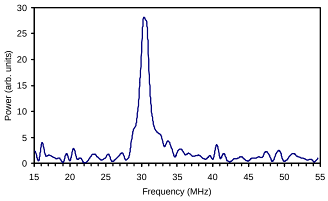

Fig. 6. Spectrum of seeded pulse. Shown is the Fourier transform of the pulse in Fig. 5, indicating a transform-limited output pulse. FWHH, full width at half height.

The shallow modulation depth in Fig. 5 is due to much more power in the sampled portion of the output pulse than in the LO. A spectral analysis of this signal shows the modulation frequency to be 30 MHz and transform limited (Fig. 6). Calculations show the Fourier transform bandwidth of a pulse of this shape to be 1.3 MHz, in good agreement with the measured value of 1.5 MHz.

In our present research, seeding occurred only intermittently because the length of the slave resonator was not actively controlled. In the future we plan to build a servo system that monitors the pulse buildup time and adjusts the slave resonator length, as described, for example, by Rahn.[14]

We found it necessary to include a 40-dB Faraday effect optical isolator between the AOM and the Q-switch. This prevented Q-switch leakage from propagating back through the AOM, where it would be frequency downshifted, reflected from the front of the MO into the LO beam and produce a spurious 30-MHz beat signal on the heterodyne detector for all slave oscillator pulses. With the isolator in place, the 30-MHz signal was observed only when both the output of the injection-seeded slave and the output of the MO were incident on the heterodyne detector.

In recent research we also determined that injection seeding can be accomplished by injecting the seed through the zeroth order beam path on the grating. This method worked and is advantageous because it can be implemented with a standard electro-optic Q-switch instead of the frustrated total internal reflection Q-switch. It has the additional advantage that the slave resonator can be tuned accurately to the seed by closing the Q-switch completely and observing the high finesse of the well-aligned slave resonator on a detector beyond the outcoupler. This signal could be used as an alternative method for a length-adjusting servo system. For this seeding approach, we tuned the grating to the MO wavelength by demanding that the first-order diffracted beam from the grating was accurately returned to the MO output aperture, and we subsequently aligned the slave to the zeroth order injected beam as before. This approach guarantees seed radiation in the slave oscillator at all times, also after the closure of the Q-switch, but it allows less power to enter the slave before the Q-switch closes. We observed the reduction in buildup time of the slave resonator to be consistently less (typically 3 μs) in this seeding arrangement, thus indicating that seeding was more readily achieved when injecting through the Q-switch.

4. Conclusions

We have demonstrated single-frequency operation of a pulsed Er:glass laser using injection seeding. This was achieved by matching the resonant frequency of the slave resonator to the frequency of the MO by use of a diffraction grating in Littrow configuration. The resultant injection-seeded laser produces pulses that are suitable for use in a pulsed Doppler lidar system for velocity and range sensing. The output energy was limited by the fixed wavelength of the MO. In a further development, we plan to acquire a new cw MO to permit operation close to the peak of the fluorescence curve to optimize laser efficiency and energy.

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