Injection-seeded titanium-doped-sapphire laser

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We demonstrate injection seeding of a pulsed, laser-pumped, titanium-doped-sapphire ring laser by both continuous-wave dye and diode lasers. As little as 100 μW of seed light is required to produce 4 mJ of 30-nsec TEM_{00} output having a bandwidth of less than 25 MHz FWHM. Using an atomic resonance filter we find that more than 99.9% of the energy is at the 780-nm seed wavelength. We discuss the spatial and longitudinal mode-matching requirements for successful seeding.

The wide tuning range of titanium-doped sapphire (Ti:S) makes this solid-state laser medium useful for a number of chemical sensing applications. As noted by Brockman *et al.*,[1] Ti:S lasers are candidates for remote differential absorption lidar (DIAL) measurements of water-vapor concentration and atmospheric temperature and pressure. A measurement accuracy of a few percent requires intense light in a narrow bandwidth with precise frequency control. For resonant absorption measurements, no more than 0.1% of the energy should lie at frequencies outside the absorption bandwidth. An efficient means of obtaining such performance is to injection seed a slave oscillator with light from a low-power, narrow-bandwidth seed laser. This permits precise frequency control and efficient operation of the high-power slave oscillator.

Injection control of a Ti:S oscillator was first reported[1] with a pulsed dye laser as the seed source. While efficient energy extraction was demonstrated in that study, the linewidth obtained using the multimode pulsed seed source was too broad for use in DIAL measurements. Injection control of a Ti:S oscillator with a cw diode laser was later reported by Bair *et al.*,[2] but the spectral purity of the slave oscillator was insufficient for DIAL measurements. Rhines and Moulton[3] recently demonstrated single-longitudinal-mode (SLM) operation of a pulsed, unstable Ti:S resonator by injection seeding with a cw Ti:S SLM laser. In those experiments 150 mW of seed-laser light was used to obtain SLM operation. Minimization of the seed power and the complexity of the seed source are of concern in compact, field-deployable laser systems. Our research is motivated by the desire to use compact diode lasers as seed lasers for oscillators appropriate for DIAL measurements.

In this Letter we investigate the seed-laser requirements for a simple three-mirror Ti:S ring laser that contains no unidirectional or spectral-control elements. Using a narrow-linewidth cw dye laser as the seed source, we find that as little as 100 μW of the seed light can produce 4 mJ of SLM output from the Ti:S slave oscillator. We find that the seeding range, i.e., the range of detuning between the seed frequency and the slave-cavity resonance over which injection seeding effectively occurs, increases with both seed power and slave-laser gain. The output of the seeded oscillator shows a frequency shift of approximately −7 MHz relative to the unpumped slave-cavity resonance with no observable frequency chirp. The shift is attributed to pump-induced changes in the index of refraction[4] of the Ti:S crystal. Finally, we demonstrate injection seeding with a SLM diode laser.

Figure 1 illustrates our experimental layout. We use a ring configuration for the slave oscillator to minimize spatial hole-burning effects in the anisotropic Ti:S crystal. Three flat mirrors make up the 75-cm-long slave cavity. Output coupling and injection seeding are accomplished through a 45° mirror with 85% reflectivity at 780 nm for *p*-polarized light. The final mirror in the cavity is a 0° high reflector mounted on a piezoelectric transducer (PZT) to permit fine adjustment of the cavity length. The odd number of reflections in this cavity reduces the effect of pump-beam inhomogeneity in the plane of the ring.

The Ti:S crystal is 5 mm in diameter and 20 mm long, with an absorption coefficient of 2 cm^{-1} at 532 nm and with uncoated end faces polished at Brewster's angle. The *c* axis of the crystal is orthogonal to the rod axis and lies in the plane defined by the rod axis and the end-face normals. The pump laser and slave laser are both linearly polarized along the *c* axis to maximize the pump absorption and laser gain. The pump laser, a frequency-doubled, doughnut-mode 10-

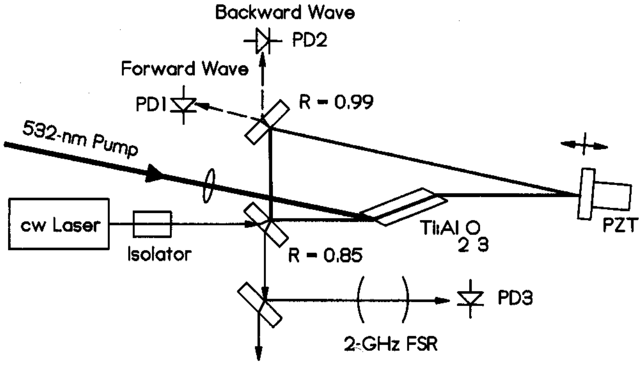

Fig. 1. Experimental layout illustrating the three-mirror slave cavity. Photodiodes PD1 and PD2 monitor the forward- and backward-propagating light in the laser cavity. A confocal étalon of 2-GHz free spectral range (FSR) is used to measure the laser linewidth and frequency relative to the seed laser.

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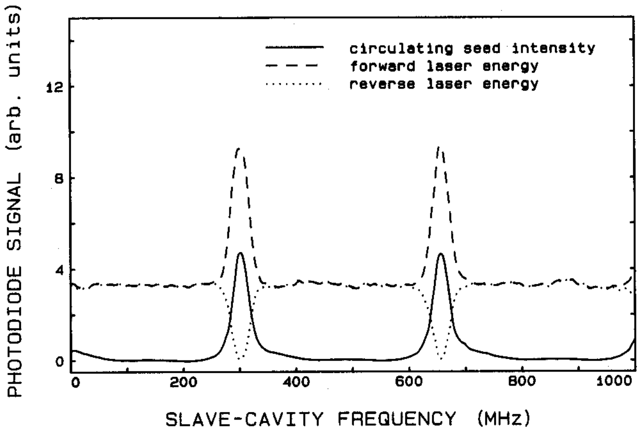

Fig. 2. Injection-seeding results with 0.1 mW of seed power while the slave oscillator is pumped at 1.5 times threshold. The slave-cavity length is slowly ramped while the intracavity seed intensity 500 nsec before the Ti:S rod is pumped (solid curve) is monitored. The maxima in the circulating seed intensity indicate cavity lengths for which the slave cavity is resonant with the seed-laser frequency. The forward- and backward-propagating output pulse energies from the slave oscillator are simultaneously monitored and plotted in arbitrary units as the dashed and dotted curves, respectively.

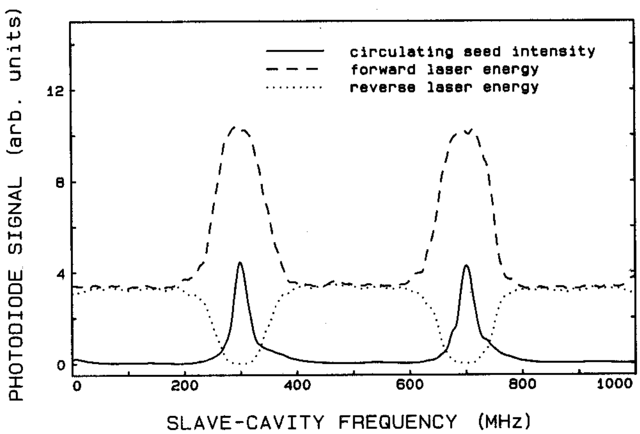

Fig. 3. Injection-seeding results with 10 mW of seed power while the slave oscillator is pumped at 1.5 times threshold. As expected, the seeding range increases with increased seed power.

Hz, Q-switched Nd:YAG laser, is focused to a spot approximately 2 mm in diameter to pump the crystal at fluences of as much as 4 J/cm^2. In spite of the nonuniform pump profile, TEM_{00} operation is ensured by the small Fresnel number (1.7) of the slave cavity. With 45 mJ of pump light (1.5 times threshold), the unseeded laser produces 2 mJ of output in each direction with a buildup time of 100 nsec and a pulse width of 30 nsec. The laser spectrum, apparently limited by the reflectance bandwidth of the cavity mirrors, extends from 765 to 795 nm.

Figures 2–4 show the laser performance when it is seeded with a SLM cw dye laser (Coherent 599) operating at 780 nm. The three traces are the intracavity seed intensity 500 nsec before laser pumping and the forward and the backward pulse energies as the voltage to the PZT is slowly ramped. The voltage has been converted to an approximate frequency scale based on the free spectral range of the slave cavity. The origins of the horizontal scales are arbitrary because of long-term drifts in the length of the slave cavity. The maxima in the circulating seed intensity in these figures indicate when the slave cavity is resonant with the seed frequency.

Figure 2 is for 0.1 mW of seed power incident upon the output coupler and with the slave laser pumped at 1.5 times threshold (0.9 J/cm^2). As previously observed,[2] successful seeding is marked by a dramatic decrease in the backward pulse energy and an increase in the forward pulse energy. Indeed, when the slave cavity becomes resonant with the seed frequency, the ratio of forward energy to backward energy can exceed 1000:1.

Not surprisingly, increasing the seed power by a factor of 100, to 10 mW, substantially increases the seeding range (see Fig. 3). The more interesting effect of increased pump energy (laser gain) on the seeding range is shown in Fig. 4. With the same seed power as in Fig. 3, but with the pump energy increased from 1.5 to 2.5 times threshold, the seeding range increases. Similar behavior was predicted and observed by Park *et al.*[5] for an injection-seeded Nd:YAG laser. They found that increased laser gain decreases the seed intensity necessary to achieve injection seeding, or conversely, increased gain broadens the seeding range for a fixed seed intensity.

We obtained prolonged injection-seeded operation by electronically locking the slave-cavity resonance relative to the seed laser frequency with a simple offset-locking feedback circuit. By slightly detuning the slave-cavity resonance from the seed laser frequency, a signed error signal is derived by comparing the intracavity cw laser intensity with that incident upon the cavity through a simple dc light subtraction technique. This error signal is integrated, amplified, and applied to the PZT to maintain the relative frequency detuning. The sign of the feedback circuit determines the sign of the frequency offset between the seed light and the slave-cavity resonance.

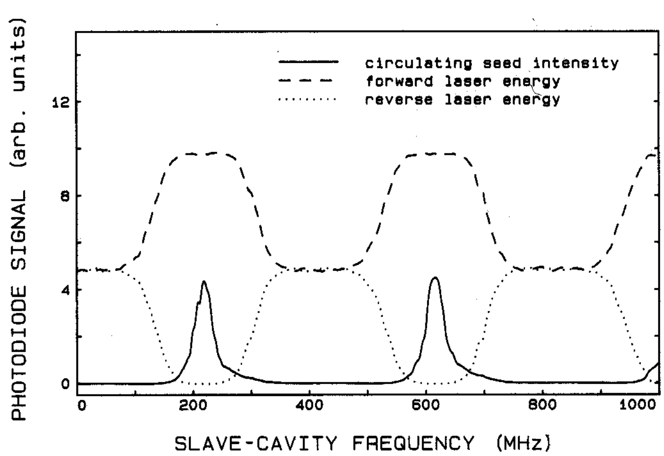

Fig. 4. Injection seeding results with 10 mW of seed power while the slave oscillator is pumped at 2.5 times threshold. Compared with that of Fig. 3, the seeding range clearly increases with increased pump energy.

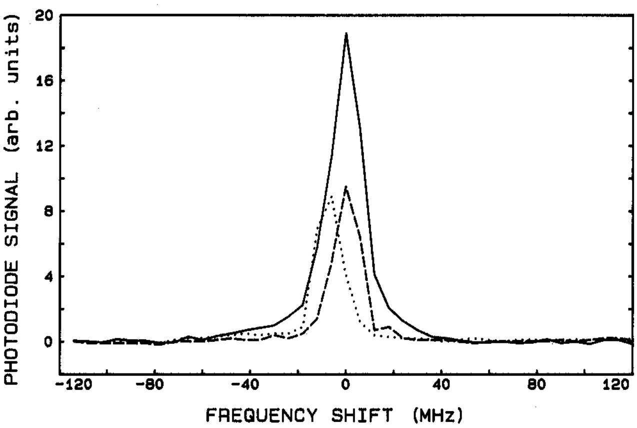

Fig. 5. Spectrum of the cw laser (solid curve) and pulsed output of the injection-seeded laser. The dotted (dashed) curve is obtained when the slave-cavity resonance is offset to the red (blue) of the seed frequency. The difference in frequency between the pulsed output beams is determined by the degree of offset between the master and slave oscillators. The mean of the pulsed output frequencies is slightly offset (−7 ± 5 MHz) with respect to the seed beam and is consistent with a pump-induced change in the index of refraction of the Ti:S.

We measured the linewidth and frequency of the locked and seeded slave-laser light, relative to the seed light, using a 2-GHZ free-spectral-range confocal étalon. With the seed frequency fixed, the transmitted seed and slave light were monitored simultaneously as the étalon was tuned (see Fig. 5). As noted by Park *et al.*,[5] the output frequency of an injection-seeded oscillator is determined by the resonance frequency of the slave oscillator. The difference between the output and injected frequencies in this experiment is due in part to the offset-locking technique and in part to any frequency chirp or offset induced by the gain medium in the oscillator. We find that the pulsed output frequencies for red and blue offset locking are not symmetrically distributed about the seed frequency, as would be expected from our offset-locking technique, but instead show a net offset of −7 ± 5 MHz. Given our large experimental uncertainty, this offset is consistent with the quoted value[4] for the pump-induced nonresonant change in the index of refraction of Ti:S.

We tested the spectral purity of the laser output by measuring the transmission through an optically dense atomic potassium absorption cell having an absorption bandwidth of approximately 1 cm^{-1} FWHM. The dye laser was tuned to the $4s\ ^2S_{1/2}$ to $4p\ ^2P_{3/2}$ transition at 766.7 nm, and the slave-laser output was attenuated and expanded to prevent saturation of the absorption. Without injection seeding, the broadband slave-laser output was transmitted with negligible attenuation; however, with injection seeding, it was attenuated by a factor of more than 1000. This implies that the total energy in any residual broadband background is less than 0.1% of the energy at the seeded wavelength.

We have also demonstrated injection seeding with a predominantly SLM cw diode laser (Sharp LT024MD0) operating at 780 nm. The diode laser requires a high degree of optical isolation (>30 dB) from the slave laser to avoid optical damage to the diode output facet. We found it necessary to line narrow and stabilize the diode laser by passively locking it to an external cavity[6] in order to obtain good seeding. With a narrowed linewidth, <6 MHz, the seeded forward-to-backward energy ratio was typically approximately 1000:1. Without the line narrowing, the diode-laser linewidth was broadened by scatter from the isolators to approximately 150 MHz, and the seeded forward-to-backward ratio was only 100:1. Even when the diode laser is nominally SLM and line narrowed, numerous other longitudinal modes of the diode laser are present with intensities ~1% of that of the dominant mode. Consequently when the total seed power is >1 mW, there is always sufficient power in some of these modes to cause partial seeding even when the dominant mode is outside the seeding range. This leads to a nonresonant front-to-back energy ratio of 10:1. The slave laser operates only SLM when the dominant laser-diode mode is resonant with the slave cavity.

Efficient use of the seed light requires proper spatial mode matching to the transverse fundamental mode of the slave cavity. The dye-laser beam used in these experiments was filtered to produce a top-hat intensity distribution of 2-mm diameter with a divergence of less than 0.5 mrad. High-fidelity SLM output from the slave laser can be obtained reliably with approximately 300 μW of seed light. The diode laser has a relatively poor spatial beam, but at least 25% of the light can be coupled into the cavity, so a 10-mW laser supplies ample seed light for our slave oscillator. When spatially filtered and collimated, the diode laser yielded injection-seeding performance comparable with that of the dye laser.

In summary, we have investigated the requirements for injection seeding of a pulsed Ti:S oscillator with cw dye and diode lasers. We find that injection seeding is possible with as little as 100 μW of seed-laser light under proper spatial and longitudinal mode-matching conditions. A nearly pulse-width-limited bandwidth is obtained in 4-mJ, 30-nsec TEM_{00} pulses that have less than 0.1% broadband energy. The best injection-seeding performance with the diode laser was achieved when the diode laser was line narrowed and passively locked to an external cavity.

References

1. P. Brockman, C. H. Bair, J. C. Barnes, R. V. Hess, and E. V. Browell, Opt. Lett. **11**, 712 (1986).
2. C. H. Bair, P. Brockman, R. V. Hess, and E. A. Modlin, IEEE J. Quantum Electron. **24**, 1045 (1988).
3. G. A. Rhines and P. F. Moulton, Opt. Lett. **15**, 434 (1990).
4. K. F. Wall, R. L. Aggarwal, M. D. Sciacca, H. J. Zeiger, R. E. Fahey, and A. J. Strauss, Opt. Lett. **14**, 180 (1989).
5. Y. K. Park, G. Giuliani, and R. L. Byer, IEEE J. Quantum Electron. **QE-20**, 117 (1984).
6. B. Dahmani, L. Hollberg, and R. Drullinger, Opt. Lett. **12**, 876 (1987).