A 1 W injection locked cw titanium:sapphire laser

E. A. Cummings, M. S. Hicken, and S. D. Bergeson
Department of Physics and Astronomy, Brigham Young University, Provo, UT 84602

We report an injection-locked cw titanium:sapphire ring laser at 846 nm. It produces 1.00 W in a single frequency when pumped with 5.5 W. Single frequency operation requires only a few milliwatts of injected power.

Single frequency cw lasers are central to many experiments in spectroscopy, atomic physics, nonlinear optics, quantum optics, metrology, ranging, communications, and other fields. A number of tunable and fixed-frequency lasers are commercially available to cover the near ultraviolet, visible, and near infrared spectral regions. Dye lasers, Ti:sapphire lasers, optical parametric oscillators, Nd:YAG lasers, various gas lasers, diode lasers, and many others regularly find applications in these fields.

A few years ago, high-power single frequency diode lasers began to compete over selected wavelength ranges with moderate power Ti:sapphire lasers and dye lasers (see, for example, 1, 2, 3, 4, 5 and many others). These diode lasers were relatively inexpensive and could be frequency-stabilized, either by injection locking or by an external cavity, making them ideal for certain classes of experiments. However, many of these high-power single frequency diode lasers have become increasingly expensive and difficult to obtain at particular wavelengths.

In this paper we describe a moderate power, cw, tunable, single-frequency injection-locked Ti:sapphire laser. Injection-locking a high power laser with a low-power master laser reproduces the master laser at higher power with good fidelity 6, 7. Injection-locking has been demonstrated in a wide range of cw laser systems, including Nd:YAG 8, 9, 10, argon-ion 11, He-Ne 12, diode 13, and dye lasers 14. It has also been demonstrated for pulsed Ti:sapphire 15, 16 and dye lasers 17, 18. However, it has apparently not been demonstrated in cw Ti:sapphire lasers.

The injection laser determines the output wavelength and forces both single frequency and uni-directional operation. It eliminates birefringent filters and optical diodes in more traditional Ti:sapphire lasers 19, 20, 21, 22. The wavelength tunability of our system mirrors the tunability of the diode laser. While no single diode laser covers the entire tuning range of Ti:sapphire, diodes are available at many wavelengths from 0.66 to 1.1 µm. Furthermore, many kinds of experiments use only a limited wavelength range—some using only several GHz of tuning—and our laser is well-suited for those experiments.

Figure 1 shows a schematic diagram of our experiment. The master laser is an extended-cavity diode laser at 846 nm 23, amplified in a single pass through a tapered laser diode 24. It is optically isolated and coupled into a single-mode optical fiber. It delivers up to 30 mW to the Ti:sapphire laser cavity.

FIG. 1: A schematic diagram of the experimental layout. ECDL=extended cavity diode laser, PD=photodiode, PZT=piezoelectric transducer.

A pair of lenses mode-matches the collimated output from the fiber into the Ti:sapphire ring cavity. The coupling efficiency is typically 75% into the TEM00 Gaussian mode of the cavity, and higher order modes are about 1% or less than the Gaussian mode. The Ti:sapphire cavity is a four-mirror folded (bowtie) cavity around a Ti:sapphire crystal. The crystal is 10 mm long, 3 mm diameter, Brewster cut, with a low-power single-pass absorption coefficient of 2.1 at 532 nm. It is mounted in a water-cooled brass housing. The cavity’s flat output coupler reflectivity is 96.6%. The reflectivities of the other three mirrors are all > 99.5%. The radius of curvature for the curved mirrors is 100 mm. The short distance between the two curved mirrors, including the path through the crystal, is 114 mm. The long distance between the two curved mirrors is 1020 mm. The angle of incidence on the curved mirrors is 8º. These distances and angle of incidence are chosen to compensate for the astigmatism introduced by the Brewster-cut crystal 25. The “cold-cavity” finesse, measured without pumping the crystal, is 110.

Up to 5.5 W from the 532 nm pump laser is focused into the middle of the Ti:sapphire pump laser. Not shown in the Figure is a telescope in the green laser beam, with one lens mounted on a micrometer stage, to optimize the focus of the green laser beam into the crystal.
The diode current in the master laser is modulated at 37.15 MHz. This produces the frequency sidebands necessary to lock the master laser to the Ti:sapphire cavity using the Pound-Drever-Hall technique \[26\]. The electronic feedback circuit is a two-stage integrator, with fast feedback to the master laser current, and slow feedback to the master laser cavity length. One of the Ti:sapphire cavity mirrors is mounted on a piezo-electric crystal, allowing approximately 8 GHz of continuous frequency tuning. To achieve a particular wavelength from the Ti:sapphire laser, it is necessary to first set the approximate wavelength of the diode laser before injection-locking the Ti:sapphire laser. Fine wavelength tuning is achieved by scanning the Ti:sapphire cavity after engaging the lock. The optical signal used for the feedback circuit comes from a weak reflection from an uncoated quartz optical flat in the high power output from the Ti:sapphire laser. This reflected beam is attenuated to prevent saturation in the feedback photodiode. All of the power measurements reported here are made after the quartz flat, as shown in Figure 1.

Figure 2 shows a plot of the power out of the injection-locked laser as a function of pump power. It also shows the free-running laser output power, when the injection laser is blocked. The injection-locked and free-running lasers have essentially the same maximum power output and slope efficiency. However, the injection-locked laser has a significantly lower threshold power. Without injection-locking, the laser does not oscillate until photons are spontaneously emitted into the cavity mode. However, the injection laser puts photons into the cavity mode, and the laser oscillates at pump powers below the non-injected threshold.

Our measured slope efficiency (23%) matches calculations based on a theoretical model \[2\]. However the threshold power (about 1.2 W) is considerably higher than the calculation (about 0.3 W). This implies that either the cavity waist or the pump laser waist (or both) are not as small as they should be. This is probably due to thermal lensing and to a mismatch between the confocal parameter for the pump laser beam and the crystal length.

When properly injected, the Ti:sapphire laser output is a single frequency. We monitor the frequency spectrum of the Ti:sapphire laser output with a scanning Fabry-Perot cavity (free spectral range = 2 GHz, finesse = 400). The optical spectrum of the injection laser beam is shown in Figure 3 (top trace). Also shown is the optical spectrum of the amplified beam (bottom trace). In both cases, the measured spectral width of the laser reflects the limit of resolution of the scanning Fabry-Perot cavity.

While the scanning Fabry-Perot does not have enough resolution to measure the spectral width of the laser, it can still give us an indication of the frequency content of the beam. Taking the Fabry-Perot cavity out of its sweeping-mode operation, we tune it into resonance with the Ti:sapphire laser. The signal output from the Fabry-Perot cavity is now a measure of the relative frequency of the cavity and the laser. The power spectrum of this measurement is shown in Figure 4. The upper trace in the Figure compares the cavity to the injection laser. The lower trace compares the cavity to the Ti:sapphire laser at an output power near 1 W. The two traces are essentially identical. They both fall rapidly in the first hundred Hz, more slowly to 5 kHz, and are flat at higher frequencies.

The minimum power required to maintain single frequency operation apparently depends critically on the feedback circuit. For our laser with a 1134 mm round trip cavity length, the minimum power, \(P_{\text{min}}\), for different pump powers is shown in Table I. As the injection power decreases, the amplitude noise in the output increases (indicating an improper feedback gain) long before the frequency noise increases. We also made smaller amplifier cavity, with 50 mm radius of curvature mirrors and an overall cavity length of 360 mm. The smaller
FIG. 4: Power spectrum of the relative optical frequency between the Fabry-Perot cavity and the laser. The top trace compares the cavity to the injection laser. The bottom trace compares the cavity to the amplified Ti:sapphire laser.

TABLE I: Minimum injection power, $P_{\text{min}}$, and output power, $P_{\text{out}}$, for different pump powers.

| Pump Power (W) | $P_{\text{min}}$ (mW) | $P_{\text{out}}$ (W) |
|---------------|-----------------|-----------------|
| 2.0           | 3               | 0.22            |
| 3.0           | 6               | 0.49            |
| 4.0           | 12              | 0.74            |
| 5.0           | 15              | 1.00            |

cavity, which has the same waist size, operates similarly to the system described in this paper in both threshold power and slope efficiency. However, the minimum power required to maintain single frequency operation is lower by a factor of 3.

We have demonstrated a single frequency cw injection-locked Ti:sapphire laser at 846 nm, continuously tunable over an 8 GHz range, with an output power of 1 W. The wavelength tuning range is determined by the tuning range of the laser diode used to inject the Ti:sapphire laser. A broad range of laser diodes are available that cover much of the Ti:sapphire gain region. At those wavelengths, an injection-locked Ti:sapphire laser will produce output powers in the 1 W range at relatively low cost.

This work is supported in part by grants from the Research Corporation and from the National Science Foundation under Grant No. PHY-9985027.

[1] L. Goldberg, L. E. Busse, and D. Mehuys, “High power continuous wave blue light generation in KNbO3 using semiconductor amplifier seeded by a laser diode,” Appl. Phys. Lett. 63, 2237-2329 (1993).
[2] M. Praeger, V. Vuletic, T. Fischer, T. W. Hänsch, and C. Zimmermann, “A broad emitter diode laser system for lithium spectroscopy,” Appl. Phys. B 67 163-166 (1998).
[3] A. C. Wilson, J. C. Sharpe, C. R. McKenzie, P. J. Manson, and D. M. Warrington, “Narrow-linewidth master-oscillator power amplifier based on a semiconductor tapered amplifier,” Appl. Opt. 37, 4871-4875 (1998).
[4] G. Ferrari, M.-O. Mewes, F. Schreck, and C. Salomon, “High-power multiple-frequency narrow-linewidth laser source based on a semiconductor tapered amplifier,” Opt. Lett. 24, 151-153 (1999).
[5] C. W. Oates, F. Bondu, R. W. Fox, and L. Hollberg, “A diode-laser optical frequency standard based on laser-cooled Ca atoms: sub-kilohertz spectroscopy by optical shelving detection,” Eur. Phys. J. D 7, 449-460 (1999).
[6] A. Siegman, Lasers (University Science Books, Sausalito CA, 1986).
[7] A. D. Farinas, E. K. Gustafson, and R. L. Byer, “Injection locking of a 13-W cw Nd:YAG ring laser,” Opt. Lett. 21, 1189-1191, (1989).
[8] R. F. Teehan, J. C. Bienfang, and C. A. Denman, “Power-scaling and frequency stabilization of an injection-locked Nd:YAG rod laser,” Appl. Opt. 39, 3076-3084 (2000).
[9] C. N. Man and A. Brillet, “Injection locking of argon-ion lasers,” Opt. Lett. 84, 333-334 (1984).
[10] T. Urisu, T. Sugeta, Y. Mizushima, and K. Tsumenari, “Stabilized injection locking light amplification of a 1.15-µm He-Ne laser,” J. Appl. Phys. 52, 3154-3158 (1981).
[11] L. Goldberg and J. F. Weller, “Injection locking and single-mode fiber coupling of a 40-element laser diode array,” Appl. Phys. Lett. 50, 1713-1715 (1987).
[12] B. Couillaud, A. Ducasse, E. Freysz, and L. Sarger, “Experimental study of the injection-locked continuous-wave ring dye laser,” Opt. Lett. 9, 435-437 (1984).
[13] C. H. Bair, P. Brockman, R. V. Hess, and E. A. Meldin, “Demonstration of frequency control and cs diode laser injection control of a titanium-doped sapphire ring laser with no internal optical elements,” IEEE J. Quant. Electron. 24, 1045-1048 (1988).
[14] C.-K. Ni and A. H. Kung, “Amplified spontaneous emission reduction by use of the stimulated Brillouin scattering: 2-ns pulses from a Ti:Al2O3 amplifier chain,” Appl. Opt. 37, 530-535 (1998).
[15] K. S. E. Eikema, W. Ubachs, W. Vassen, and W. Hogervorst, “Lamb shift measurement in the 1 1S ground state
of helium,” Phys. Rev. A 55, 1866-1884 (1997).

[18] S. D. Bergeson, et al., “Measurement of the He ground state Lamb shift via the two-photon 1S-2S transition,” Phys. Rev. Lett. 80, 3475-3478 (1998).

[19] P. Albers, E. Stark, and G. Huber, “Continuous-wave laser operation and quantum efficiency of titanium doped sapphire,” J. Opt. Soc. Am. B. 3, 134-139 (1986).

[20] P. A. Schulz, “Single-frequency Ti:Al₂O₃ ring laser,” IEEE J. Quant. Electron. 24, 1039-1044 (1988).

[21] J. Harrison, A. Finch, D. M. Rines, G. A. Rines, and P. F. Moulton, “Low-threshold, cw, all-solid-stae Ti:Al₂O₃ laser,” Opt. Lett. 16, 581-583 (1991).

[22] C. Zimmermann, V. Vuletic, A. Hemmerich, L. Ricci, and T. W. Hänisch, “Design for a compact tunable Ti:sapphire laser,” Opt. Lett. 20, 297-299 (1995).

[23] Our extended cavity laser is a Vortex laser from New Focus Corp. (5215 Hellyer Ave., Suite 100, San Jose, CA 95138-1001).

[24] The tapered amplifier is a Model 8613 laser from SDL (80 Rose Orchard Way, San Jose, CA 95134-1365) with the rear cavity optics removed, configured as a single-pass amplifier.

[25] H. W. Kogelnik, E. P. Ippen, A. Dienes, and C. V. Shank, “Astigmatically compensated cavities for cw dye lasers,” IEEE J. Quant. Electron. QE-8, 373-379 (1972).

[26] R. W. P. Drever, J. L. Hall, F. B. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, “Laser phase and frequency stabilization using an optical resonator,” Appl. Phys. B. 31, 97-105 (1983).

[27] P. W. Milonni and J. H. Eberly, Lasers, (Wiley, NewYork, 1988), p. 292.