6 W, 1 kHz linewidth, tunable continuous-wave near-infrared laser

Sheng-wei Chiow,1 Sven Herrmann,1 Holger Müller,1,2,3 Steven Chu1,2,3

1 Department of Physics, Stanford University, Stanford, California 94305-4060, U.S.A.,
2 Department of Physics, University of California, 366 LeConte Hall, Berkeley, California 94720-7300, U.S.A.
3 Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, California 94720, U.S.A.

A modified Coherent 899-21 titanium sapphire laser is injection locked to produce 6-6.5 W of single-frequency light at 852 nm. After closed-loop amplitude control and frequency stabilization to a high-finesse cavity, it delivers 4-4.5 W with < 1 kHz linewidth at the output of a single-mode fiber. The laser is tunable from about 700-1000 nm; up to 8 W should be possible at 750-810 nm.

PACS numbers:

I. INTRODUCTION

The improvement of tunable, high-power, low linewidth lasers has been instrumental in advancing atomic physics. State-of-the-art titanium:sapphire (Ti:sapphire) lasers span wavelengths between 700-1000 nm or more. Typical commercial models use intracavity etalons for single-mode operation and achieve an output power around 1.5-2.5 W. Injection lock [1, 2, 3] allows for dispensing with the etalons and thus reaching a higher power of up to 5 W so far [4]. Diode lasers with tapered amplifiers, which are only available in few spectral regions, currently reach 1-2 W (up to 2.5 W in μs pulses [5]) at 780 nm and 0.5 W near 850 nm. Because of their lower beam quality and the need for an optical isolator, however, they rarely deliver more than 0.5 W into single-mode fibers. The linewidth of both commercial single frequency Ti:sapphire and extended-cavity diode lasers is on the order of a few 100 kHz. A reduction to the k Hz and even Hz level can be achieved by stabilization to high-finesse optical cavities. Here, we report an injection-locked Ti:sapphire laser system that achieves up to 6.5 W at 850 nm, up to 4.5 W after a single-mode, polarization maintaining (SM-PM) fiber, and < 1 kHz linewidth by stabilization to a high-finesse reference cavity.

II. DESCRIPTION

Figure 1 shows the setup. It can be roughly divided into the injection lock system shown on the left, the frequency stabilization in the upper right, and the amplitude control shown in the lower right part of the figure. The master laser (not shown) is a Coherent 899 with 1.2-1.3 W output power when pumped with 10 W from a Coherent Verdi V-10. It is frequency stabilized using the internal piezoelectric transducer (PZT) and Brewster plate as actuators. For this purpose, we modified the control box as described in Ref. [6]. As a frequency reference, we use an extended-cavity diode laser (ECDL) [1], which is in turn stabilized to a D2 transition in a cesium vapor cell. A detuning of 0 to ±20 GHz can be set by a microwave synthesizer.

The master passes an acousto-optic modulator, AOM 1 (Fig. 1), driven by voltage controlled oscillator VCO 1 at about 120 MHz. The light is then coupled to an SM-PM fiber, in order to decouple the alignments of the master and slave. About 0.8 W are typical after the fiber.

The slave laser is another Coherent 899. To increase the output power, we removed the thick and the thin etalon as well as the Brewster plate, as they are not required for injection locked operation [6] and replaced the output coupler by one having 10% transmission [4]. Pumped with 19 W from a Coherent Innova 400 argon-ion laser (not shown), we obtain 5.5 W output from the free-running slave.

For injection lock, the passive resonance frequency of the slave laser’s cavity must be stabilized to the master. For generating an error signal without adding sidebands to the radiation, we use the Hänisch-Couillaud method [10]. The master laser’s polarization has a small angle relative to the slave, set by a half-wave retardation plate. The small angle means that most of the electric field of the master can add to the slave’s field (at lower master power, an angle of 45° would be used to give a larger error signal). To generate the error signal, a small frac-
tion (25 mW) of the output beam is picked up and its polarization analyzed.

The error signal is fed back to the piezoelectric transducer (PZT) that translates the lower fold mirror M3. We found the ~ 5 kHz bandwidth of this path to be sufficient for locking, but only just. Therefore, we add a fast (about 100 kHz bandwidth) feedback channel to VCO 1 (mini-circuits POS-150), in analogy to [2] (2). This makes the lock reliable, at the price of some broadening of the master laser’s linewidth. With up to 0.8 W from the master laser, there was no need to optimize for low master laser powers. We confirmed, however, that the slave can still be locked with about 200 mW from the master. Previous work used master laser powers of 1% to 1.5% of the slave, which would be in the range of 50-100 mW for our power level.

The combined power of master and slave (6 W typical with a slope efficiency of ~ 40%; 6.75 W have been achieved [13]) is deflected by AOM 2 (Crystal Technology 3080-122) and coupled into a short [12] SM-PM fiber (OFR). In our application, the AOM is usually driven by 100-µs pulses; nevertheless, we confirmed that cw operation for at least a few h is feasible without destroying the fiber. An adjustable OFR fiber port is used for the spatial mode-matching of the injection and the slave laser cavity: The mode matching is optimized so that the highest coupling efficiency of the combined light into the short fiber is obtained.

Since the injection lock leads to a fixed phase relationship between the master and the slave, given suitable alignment, the outputs of both lasers can be added coherently: we obtain 4 W typical (4.5 W best) after the fiber; this means that one of the AOM or the fiber is at least 81% efficient. This efficiency is similar to what we obtain with either the master or the slave alone, confirming that the outputs of the two lasers do indeed add coherently, so that the power of the combined lasers into the mode of the fiber is close to the sum of the individual ones.

The acoustical delay of the AOM is reduced to about 0.5 µs by moving the transducer close to the beam with a translation stage; this adjustment must be made with care, as the very strong Ti:sapphire beam instantly destroys the AOM if it ever hits the transducer.

The linewidth of the locked slave is about 500 kHz full width at half maximum. To reduce it, we split off a small sample, shift it by AOM 3 and stabilize it to a Fabry-Perot cavity with a linewidth of about 25 kHz (finesse 75,000). The error signal is generated by the Pound-Drever-Hall method. Phase modulation at 16 MHz is applied by an electro-optical modulator (EOM). The light reflected by the cavity is detected and down-converted to obtain the error signal. We feed back to AOM3’s frequency via VCO 2, with a loop bandwidth of about 300 kHz. VCO 2 also controls the main beam frequency by driving AOM 2. In effect, the main beam is stabilized to the cavity independent of the intensity setting of AOM 2. AOM 3 is positioned with a translation stage to match the delays of AOM 2 and AOM 3 so that the noise in the beat note measurement (will be described in the following paragraphs) is minimized. A slow (several 100 Hz bandwidth) servo (not shown) zeros the dc signal to the VCO by feeding back to the cavity via a PZT. This is used to take out the cavity drift and means that on long time scales, the slave is locked to the cesium spectroscopy.

To verify the linewidth of the system, a beat note measurement with an independent low-linewidth reference laser would be ideal. Such a laser was unfortunately not available to us. As the second best option, we use the transmitted light of the cavity as a reference. This method is as good as an independent laser for noise frequencies much higher than the cavity linewidth: Such noise components are filtered out by the cavity and are thus suppressed in its transmission. Regardless of frequency, the method measures the laser frequency relative to the cavity resonance. To minimize fluctuations of the cavity resonance itself, the cavity is held by viton rings inside a hermetically sealed (but not evacuated) stainless steel chamber to provide acoustic and thermal insulation.

For the beat note measurement, we overlap a sample of the power after the fiber with the transmitted light of the cavity on a photodetector. The measured spectrum (Fig. 2) reveals a linewidth of 1.3 kHz (full width at half maximum), limited by the 1 kHz resolution of our spectrum analyzer. Assuming that the linewidths add geometrically, we conclude that the laser linewidth is 800 Hz. Frequency modulation sidebands at 24 kHz are an effect of mechanical vibrations of the cavity. The wideband spectrum (Fig. 2, right) shows an about 800 kHz wide noise pedestal on the order of ~80 dBc/Hz, the residual of the free-running laser noise. At frequencies more than 400 kHz from the carrier, the noise drops rapidly.

The laser system as installed is tunable within 780-925 nm, and more than 700-1020 nm with the short or
long wavelength optics sets. Between 750-810 nm, the output power of Ti:sapphire lasers such as the Coherent 899 is typically about 30% higher than at 850 nm, so about 8 W are possible. We have, however, not ascertained that fiber coupling of this is feasible. If wide tunability is not required, a considerable cost reduction can be achieved by using a diode laser (possibly with a tapered amplifier) as the master laser.

III. CONCLUSION

In summary, we have presented an injection locked laser system. The master and slave laser’s power add coherently to up to 6.75 W. The system produces power (up to 4.5 W) and frequency stabilized (linewidth below 1 kHz) and mode-filtered radiation at the output of a single-mode, polarization maintaining fiber. The optical frequency is locked to a Cs hyperfine transition with an offset between 0 and ±20 GHz; a high-finesse cavity is used for linewidth reduction. The amplitude stabilization with its 250 kHz loop bandwidth allows us to precisely shape light pulses of arbitrary form. This system is ideally suitable for demanding applications such as high-order Bragg diffraction [14] in atom interferometry, or as a basis for a powerful, tunable uv source by frequency multiplication [15].

A. Acknowledgments

H.M. and S.H. thank the Alexander von Humboldt Foundation. This material is based upon work supported by the National Science Foundation under Grant No. 0400866 and by the Air Force Office of Scientific Research under Award Number FA9550-04-1-0040.

[1] U. Tanaka, J. C. Bergquist, S. Bize, S. A. Diddams, R. E. Drullinger, L. Hollberg, W. M. Itano, C. E. Tanner, D. J. Wineland, “Optical frequency standards based on the Hg-199(+) ion,” IEEE Trans. Instrumentat. Meas. 52, 245-249 (2003).
[2] E.A. Cummings, M.S. Hicken, and S.D. Bergeson, “Demonstration of a 1-W injection-locked continuous-wave titanium:sapphire laser,” Appl. Opt. 41, 7983-7987 (2002).
[3] Y. H. Cha, Y. W. Lee, K. H. Ko, E. C. Jung, G. Lim, J. Kim, T. S. Kim, and D. Y. Jeong, “Development of a 756 nm, 3 W injection-locked cw Ti:sapphire laser,” Appl. Opt. 44, 7810-7813 (2005).
[4] Y. H. Cha, K. H. Ko, G. Lim, J. M. Han, H. M. Park, T. S. Kim, and D. Y. Jeong, “External-cavity frequency doubling of a 5-W 756-nm injection-locked Ti:sapphire laser,” Optics Express 16, 4866-4871 (2008).
[5] K. Takase, J. K. Stockton, and M. A. Kasevich, “High-power pulsed-current-mode operation of an overdriven tapered amplifier,” Opt. Lett. 32, 2617-2619 (2007).
[6] D. Haubrich and R. Wynands, “A modified commercial Ti:Sapphire laser with 4 kHz rms linewidth,” Opt. Commun. 123, 558-562 (1996).
[7] H. Müller, S.-w. Chiow, Q. Long, C. Vo, and S. Chu, “Extended-cavity diode lasers with tracked resonances,” Appl. Opt. 46, 7997-8001 (2007).
[8] We also tested removing the optical diode and the birefringent filter. We found, however, that this makes the laser exceedingly difficult to align and thus we achieve higher power with these elements in place.
[9] CVI part No. PR1-850-90-0537; both the original and a tested 20% output coupler resulted in lower power.
[10] T. W. Hänsch and B. Couillaud, “Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity,” Opt. Commun. 35, 441-444 (1980).
[11] It is important to limit the PZT volatge to below the maximum of 500 V (using Z-diodes, for example).
[12] Shorter than 1 m, to avoid stimulated Brillouin scattering.
[13] Increased pump power can increase the total power to a maximum of 7 W, but also results in instable operation. Eventually, at more than 22 W pump, the output power drops. We attribute this behavior to thermal lensing.
[14] H. Müller, S.-w. Chiow, Q. Long, S. Herrmann, S. Chu, “Atom interferometry with up to 24-photon-momentum-transfer beam splitters,” Phys. Rev. Lett. 100, 180405 (2008).
[15] J. Mes, E. J. van Duijn, R. Zinkstok, S. Witte, and W. Hogervorst, “Third-harmonic generation of a continuous-wave Ti:Sapphire laser in external resonant cavities,” Appl. Phys. Lett. 82, 4423-4425 (2003).