Long-external-cavity distributed Bragg reflector laser with subkilohertz intrinsic linewidth

Qian Lin,[1] Mackenzie A. Van Camp,[1] Hao Zhang,[1] Branislav Jelenković,[2] and Vladan Vuletić[1,*]

[1]*Department of Physics, MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[2]*Institute of Physics, University of Belgrade, Serbia*
Corresponding author: vuletic@mit.edu

We report on a simple, compact, and robust 780 nm distributed Bragg reflector laser with subkilohertz intrinsic linewidth. An external cavity with optical path length of 3.6 m, implemented with an optical fiber, reduces the laser frequency noise by several orders of magnitude. At frequencies above 100 kHz the frequency noise spectral density is reduced by over 33 dB, resulting in an intrinsic Lorentzian linewidth of 300 Hz. The remaining low-frequency noise is easily removed by stabilization to an external reference cavity. We further characterize the influence of feedback power and current variation on the intrinsic linewidth. The system is suitable for experiments requiring a tunable laser with narrow linewidth and low high-frequency noise, such as coherent optical communication, optical clocks, and cavity QED experiments.   © 2012 Optical Society of America
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Highly stabilized and ultranarrow-linewidth lasers are important for applications in atomic physics, quantum measurement, and quantum information science. The traditional extended-cavity diode lasers (ECDLs) [1] and distributed Bragg reflector (DBR) lasers have typical linewidths of a few hundred kilohertz to a few ten megahertz, and specially fabricated DBR lasers have achieved an intrinsic linewidth of a few kilohertz [2,3]. Optical feedback from a resonator [4] is a common approach to reduce the linewidth of an ECDL, and recent systems [5–7] have demonstrated linewidth narrowing down to 7 kHz. Other linewidth narrowing schemes, such as active electronic stabilization to a high-finesse, ultrastable vertical cavity [8,9], or an all-fiber Michelson interferometer [10], have achieved subhertz linewidth. However, due to finite loop gain at high frequencies, the high-frequency noise is usually not substantially reduced using those active stabilization methods. This may be detrimental in some applications, such as cavity sideband cooling [11,12], cavity spin squeezing [13], and other cavity QED applications [14], as well as coherent optical communication [15].

In this Letter, we present a tunable, long-external-cavity DBR laser with a 3000-fold reduction of its intrinsic linewidth to 300 Hz. This is achieved by implementing a 3.6 m long external cavity using an optical fiber. The system exhibits noise suppression of over 33 dB at frequencies of 100 kHz and above. Low-frequency noise due to mechanical or thermal fluctuations in the feedback path can be controlled by stabilizing the laser to a reference cavity using an active servo loop. Feedback-induced mode instability [16] is avoided by operating within a 13 dB wide range of feedback power.

We use a 780 nm DBR laser (Photodigm PH780DBR120T8-S) with 120 mW maximum output power as our source. The laser diode has a front facet reflectivity close to 1%, effective gain region length of 1.8 mm, and DBR reflectivity of 60% (all values are nominal values provided by manufacturer). The diode is temperature stabilized to slightly below room temperature. Throughout our measurements, we operated the laser

at 100 mA (16 mW total output power). A beam splitter deflects 10% of the laser power into a 2 m long polarization-maintaining optical fiber that constitutes the feedback path (Fig. 1). An aperture is added before the angled fiber to block unwanted backreflection from the fiber tip. A mirror mounted on a piezoelectric transducer (PZT) reflects the light back into the fiber, and a quarter-wave plate in combination with a polarizing beam splitter is used to adjust the feedback power. A maximum −30 dB fractional power can be reflected back into the laser. (Henceforth we denote the fractional feedback power incident on the laser collimator as p, which may be less than the fractional power that is mode matched into the active region of the laser diode.) The external-cavity laser is set up on a $12'' \times 18''$ aluminum baseplate and enclosed by a plastic case to reduce environmental perturbations.

In general, the effect of external cavity optical feedback depends on the feedback power, cavity length, and the phase of the feedback light, as summarized by Tkach
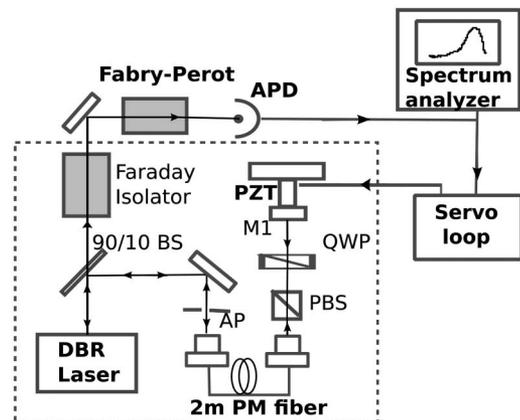
Fig. 1.   Schematic setup for the long-external-cavity laser and the frequency noise characterization. M, mirror; AP, aperture; PM fiber, polarization-maintaining fiber; QWP, quarter-wave plate; BS, beam splitter; PBS, polarization beam splitter; APD, avalanche photodiode; PZT, piezoelectric transducer.

and Chraplyvy [16]. Stable, narrow-linewidth operation of a DBR laser with optical feedback is only possible over a certain range of feedback power. At a fixed cavity length, three regimes of operation are observed as the fractional feedback power p is varied from −65 dB to −30 dB. The feedback phase is adjusted by moving the mirror M1 (Fig. 1) with the PZT.

• Significant line broadening is observed for $p < -64$ dB. For −64 dB $< p < -49$ dB and at certain feedback phases, the laser jumps at a rate over 1 kHz between two adjacent external cavity modes separated by 42 MHz.

• For −49 dB $< p < -40$ dB, stable single-mode operation is maintained for all feedback phases. −40 dB to −36 dB defines a transition between two regimes where multimode operation occurs occasionally but quickly converges to a single mode. Weak sidebands at adjacent external cavity modes with over 25 dB suppression from the carrier were observed.

• For −35 dB $< p < -31$ dB, intermittent multimode operation starts to appear as the feedback phase is varied, and bi-stable operation with the laser jumping slowly (<1 Hz) between nonadjacent external cavity modes separated by as much as 0.5 GHz is also observed. Nevertheless, it is still possible to maintain single-mode operation once the laser is frequency locked to some other reference, since the feedback phase is then stabilized. For $p > -31$ dB, multimode operation becomes dominant, and single-mode operation can only be achieved by increasing p from a lower level carefully while controlling the feedback phase.

To measure the laser's frequency noise spectrum, we locked the laser to the half-transmission of a Fabry–Perot cavity with a free spectral range of 1.5 GHz and linewidth of 4.0(2) MHz. The cavity transmission slope is used to convert power noise measured with a fast photodiode into frequency noise density $S_\nu(f)$. Stable locking achieved with a 15 kHz bandwidth feedback loop to the external-cavity PZT maintains a constant frequency-to-power conversion ratio. Since the lock bandwidth is low, the noise spectrum above a few ten kilohertz directly reflects the effect of optical feedback. At sufficiently high noise frequencies, $S_\nu(f)$ becomes independent of frequency with a level of S_0, corresponding to a laser emission spectrum with Lorentzian wings whose equivalent intrinsic linewidth $\Delta\nu$ can be calculated using [17]

$$\Delta\nu = \pi S_0^2. \tag{1}$$

We measured the noise spectrum from 10 kHz to 1 MHz for the long-cavity laser as well as the DBR laser without optical feedback. As shown in Fig. 2, the white noise S_0 starts at 300–400 kHz for the bare DBR laser. For the long-cavity laser with cavity length $D = 3.6$ m, suppression of over 30 dB due to optical feedback was observed for both the Lorentzian and the non-Lorentzian parts of the spectrum. A minimum intrinsic linewidth $\Delta\nu = 0.29(5)$ kHz is achieved at $p = -31$ dB, exhibiting a 3000-fold reduction in intrinsic linewidth compared to the bare laser. To verify the expected inverse quadratic dependence of $\Delta\nu$ on the external cavity length [18], we
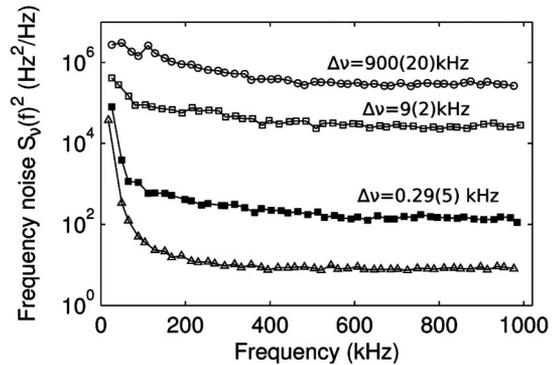
Fig. 2.   Laser frequency noise spectral density for different setups. From top to bottom: bare DBR laser, short-external-cavity laser, long-external-cavity laser, and measurement noise floor. The feedback power is −31 dB for both external cavities. The white-noise level S_0 at high frequency determines the intrinsic linewidth $\Delta\nu$ according to Eq. (1).

also set up a short-external-cavity laser using the same laser with cavity length $d = 16.5(5)$ cm and operated it at the same laser current and feedback power as the long-external-cavity laser. The linewidth ratio for the two cavity lasers of $\Delta\nu_d/\Delta\nu_D = 25(1)$ dB is very close to the predicted value [18] $(D/d)^2 = 26.8(1)$ dB.

The dependence of the intrinsic linewidth $\Delta\nu$ on the fractional feedback power p at fixed current, and on a variation in current at fixed feedback power is shown in Fig. 3. In general, a higher p produces better noise suppression but makes the laser more susceptible to operating multimode. We found that for $p = -36$ dB the noise density is only 3 dB higher than the minimum value (Fig. 3), but the laser remains stable, and frequency stabilization to an external reference can be easily achieved. At fixed p and external cavity length D, the current can be tuned over a limited range (≈250 μA) while the laser remains on the same mode. For $p = -39$ dB, it is observed that when decreasing the current, $\Delta\nu$ will increase gradually until the laser jumps to an adjacent external cavity mode. On the contrary, when increasing the laser current, a flat response in $\Delta\nu$ is followed by a sudden change into multimode oscillation. Thus, as long as one locks the laser close to the center of the flat response region, a ±50 μA current change can be tolerated without significant changes in $\Delta\nu$.

To tune the laser to a target frequency, one first changes the current at fixed cavity length, corresponding to the laser jumping over adjacent external cavity modes, until the mode closest to the target frequency is reached. Then the cavity length is tuned to change the laser
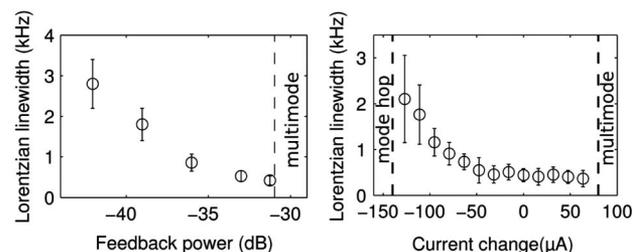
Fig. 3.   The dependence of intrinsic laser linewidth $\Delta\nu$ on fractional feedback power p (left) and on laser current near the operation point at $p = -39$ dB and $I_0 = 100$ mA (right).

frequency continuously to the exact target frequency. Finally, the laser current is fine adjusted to obtain optimal linewidth narrowing. Mode-hop free tuning over 700 MHz (more than 16 external cavity modes) can also be achieved by scanning the PZT and laser current simultaneously at an appropriate ratio. This tuning range was limited by the maximum stroke of our PZT. The optimal narrowing condition can generally be maintained during the scan, but may be limited by the nonlinearity of the PZT response.

Optical feedback reduces the high-frequency noise, but servo feedback is necessary to suppress the low-frequency noise that is dominated by thermal and acoustic noise in the fiber. The free running laser exhibits a frequency stability of ≈600 kHz over 20 ms and ≈3 MHz over 1 s as measured relative to a reference laser locked to an ^{87}Rb atomic transition. To demonstrate frequency stabilization at the subkilohertz level, we locked the laser to a cavity with finesse $\mathcal{F} = 2.3(2) \times 10^4$ (linewidth $\delta\nu_c = 120(10)$ kHz) with 5 μW incident power and $p = -36$ dB using the Pound–Drever–Hall technique [19]. The feedback loop includes a low-bandwidth feedback path to the PZT and an ac coupled, high-bandwidth (2 MHz) path to the laser current. The sideband frequency is chosen at 59.2 MHz to prevent the up-converted modulation signal from triggering adjacent external cavity modes at integer multiples of 42 MHz. An rms frequency error of 0.65 (5) kHz relative to the reference cavity was calculated from the error signal in a 50 kHz bandwidth.

In conclusion, we have built a subkilohertz, tunable DBR laser in a compact long-external-cavity setup by fiber-coupling the feedback light. A 35 dB reduction in the high-frequency noise was demonstrated. Different regimes of operation under varied levels of feedback power were characterized and are in agreement with previous results [16]. We have investigated the linewidth and mode stability as a function of feedback power and laser current variation. Owing to its low cost, ease of alignment and robust performance, we believe the system can be used for a wide range of high-precision and ultra-low-noise experiments.

References

1. L. Ricci, M. Weidemuller, T. Esslinger, A. Hemmerich, C. Zimmermann, V. Vuletic, W. Konig, and T. W. Hänsch, Opt. Commun. **117**, 541 (1995).
2. S. Spießberger, M. Schiemangk, A. Wicht, H. Wenzel, G. Erbert, and G. Tränkle, Appl. Phys. B **104**, 813 (2011).
3. S. Spießberger, M. Schiemangk, A. Sahm, A. Wicht, H. Wenzel, A. Peters, G. Erbert, and G. Tränkle, Opt. Express **19**, 7077 (2011).
4. B. Dahmani, L. Hollberg, and R. Drullinger, Opt. Lett. **12**, 876 (1987).
5. J. Labaziewicz, P. Richerme, K. R. Brown, I. L. Chuang, and K. Hayasaka, Opt. Lett. **32**, 572 (2007).
6. Y. Zhao, Y. Peng, T. Yang, Y. Li, Q. Wang, F. Meng, J. Cao, Z. Fang, T. Li, and E. Zang, Opt. Lett. **36**, 34 (2011).
7. K. Hayasaka, Opt. Lett. **36**, 2188 (2011).
8. A. D. Ludlow, X. Huang, M. Notcutt, T. Zanon-Willette, S. M. Foreman, M. M. Boyd, S. Blatt, and J. Ye, Opt. Lett. **32**, 641 (2007).
9. J. Alnis, A. Matveev, N. Kolachevsky, T. Udem, and T. W. Hänsch, Phys. Rev. A **77**, 053809 (2008).
10. F. Kefelian, H. Jiang, P. Lemonde, and G. Santarelli, Opt. Lett. **34**, 914 (2009).
11. K. W. Murch, K. L. Moore, S. Gupta, and D. M. Stamper-Kurn, Nat. Phys. **4**, 561 (2008).
12. M. H. Schleier-Smith, I. D. Leroux, H. Zhang, M. A. V. Camp, and V. Vuletic, Phys. Rev. Lett. **107**, 143005 (2011).
13. M. H. Schleier-Smith, I. D. Leroux, and V. Vuletic, Phys. Rev. Lett. **104**, 073604 (2010).
14. P. R. Berman, ed., *Cavity Quantum Electrodynamics (Advances in Atomic, Molecular, and Optical Physics Supplement 2)* (Academic, 1994).
15. K. Kikuchi, Electron. Lett. **23**, 885 (1987).
16. R. W. Tkach and A. R. Chraplyvy, J. Lightwave Technol. **4**, 1655 (1986).
17. D. S. Elliott, R. Roy, and S. J. Smith, Phys. Rev. A **26**, 12 (1982).
18. C. H. Henry, J. Lightwave Technol. **4**, 298 (1986).
19. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B **31**, 97 (1983).