

Frequency stabilization of a mode-locked external cavity diode laser to a high-finesse cavity

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Abstract. A 17.84-cm-long Littrow external cavity diode laser at 823 nm is mode-locked by actively modulating the current at a 840.843-MHz fundamental harmonic frequency. This mode-locked external cavity diode laser has an overall spectral width of 0.16 nm (or 71 GHz), roughly corresponding to 84 longitudinal modes, a temporal pulse width of 63 ps, and an average power of 1 mW. Using the Pound-Drever-Hall technique with both fast and slow servo corrections, this mode-locked laser is then frequency-stabilized to a 17.84-cm-long sealed optical cavity with a finesse of 6000. To the author's knowledge, this is the first frequency stabilization of a mode-locked diode laser with such a high-finesse cavity. © 2007 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.2738982]

Subject terms: mode-locked external cavity diode laser; high finesse cavity; Pound-Drever-Hall technique; free spectral range.

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The motivations for frequency locking a mode-locked laser include applications as varied as laser metrology,¹ laser spectroscopy,² and nonlinear optics.^{3,4} Frequency locking a CW laser requires a stabilization scheme that locks the laser frequency to a stable reference, which can be a molecular absorption line or a reference cavity. But for mode-locked lasers, we need to simultaneously frequency lock each component of the frequency comb from the mode-locked laser to a stable reference. This requires that the stable reference also be composed of a frequency comb. In our case, this reference is a high-finesse Fabry-Perot cavity with a free spectral range (FSR) equal to the mode spacing of the frequency comb. With current coating technology, the reflectivity of mirrors can exceed 0.99995, giving a finesse of the optical cavity that exceeds 10,000. With this high-finesse cavity (HFC) enhancement, the laser's frequency can be stabilized to a narrow cavity resonance that is of interest, while in other cases the high intra-cavity power^{3,4} or the long effective path length can be built up between the mirrors opening the door for nonlinear optical processes to occur. Once the mode-locked diode laser⁵ is locked to HFC, the intra-cavity peak power will be much higher than in the CW case, which can assist in the study of nonlinear optical processes. In this case with active media filled inside a sealed HFC, many interesting nonlinear optical process can be studied with inexpensive and compact diode lasers.

Most work on frequency stabilization has been done with CW lasers. For frequency stabilization of mode-locked lasers, most reports are based on solid-state lasers or dye lasers.⁶ Jones and Diels presented the basic theory of frequency locking a mode-locked laser to an HFC to produce a frequency standard. They also experimentally stabilize a femtosecond Ti:S mode-locked laser to a reference cavity

made of ultra-low-expansion quartz (ULE).⁷ The first work related to frequency stabilization of a mode-locked diode laser to an optical cavity was done by T. Yilmaz in 2003. He achieved optical frequency comb stabilization of a hybridly mode-locked diode laser to a reference cavity with a finesse of 214.⁸ In his case, the FSR of reference cavity was about 10 GHz, with a finesse of 214, and the cavity linewidth was about 47 MHz, which is relatively large and relatively easy to frequency lock the laser mode within the 47 MHz. In our case, the HFC has mirrors with 50-cm radius of curvature and a reflectivity of approximately 0.9995 on both sides of the cavity, making the finesse about 6000. With this high finesse and the 840-MHz FSR, we need to lock all the laser longitudinal modes within 140 KHz simultaneously or about 10 KHz to ensure stable transmitted power. Note that this resonance is about three orders of magnitude narrower than in the previous work on stabilizing an ML-ECDL to a cavity. In this case, extra efforts on coupling all the longitudinal modes from ML-ECDL into HFC need to occur. In this paper, we provide the details on how to stabilize a mode-locked diode laser to such a high-finesse cavity.

Figure 1 illustrates the experimental setup. The ML-ECDL⁵ is in the classic Littrow configuration with an AR-coated 820-nm semiconductor diode laser at one end and a grating and a turning mirror at the other end. The typical reflectivity of a diode laser's back facet is 95% and the grating provides 40% feedback to laser diode, which makes the finesse of this external laser cavity as low as 6. The grating has 600 G/mm, and the center wavelength of the ECDL can be tuned 25 nm by tilting the grating. Mode locking is achieved by running the laser near threshold for the DC current and also modulating the laser current near the fundamental harmonic of the external cavity with a 23-dBm RF signal at 840.843 MHz, which is near the FSR associated with the 17.84-cm cavity. To operate the mode-locked laser, the modulation frequency does not have to

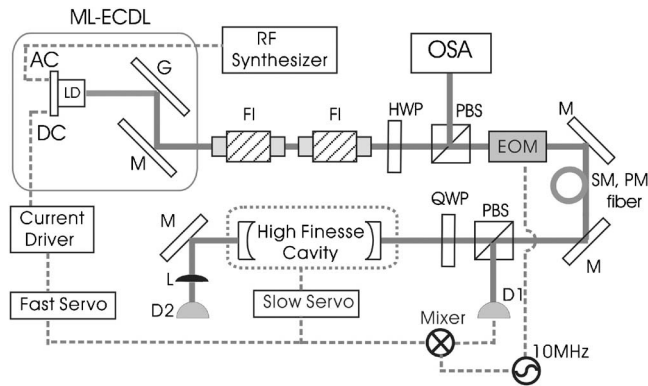


Fig. 1 Schematic of experimental setup. Frequency stabilization of actively mode-locked external cavity diode laser (ML-ECDL). (G—grating, M—mirror, FI—Faraday isolator, HWP—half-wave plate, PBS—polarizing beam splitter, SM—single mode, PM—polarization maintaining, OSA—optical spectrum analyzer, QWP—quarter-wave plate, EOM—electro-optic modulator, L—lens, D1—detector for error signal, D2—detector for cavity transmission.) The laser diode current is modulated near the laser cavity free-spectral range to achieve mode locking. The length of the HFC closely matches the laser cavity length to achieve stabilization of all the laser's modes to the HFC by the Pound-Drever-Hall locking scheme.

exactly equal the FSR or the fundamental harmonic of the laser external cavity because the laser cavity's finesse is so low and the mode-locked laser repetition rate is determined by the modulation frequency instead of the FSR of the laser's external cavity. This flexibility in the modulation frequency is extremely important when we proceed to couple this laser into the HFC. However, when the system is optimized for transmission through the HFC, the laser cavity's FSR will then closely match the modulation frequency.

Figure 2(a) shows the optical spectrum of the continuous-wave external cavity diode laser (CW-ECDL) (modulation off) and ML-ECDL (modulation on). The spectral width of ML-ECDL is, as expected, broader than the CW-ECDL. Its width is 0.16 nm or 71 GHz, which is determined by the depth of the modulation and the number of grooves illuminated on the grating. This width indicates that the ML-ECDL is supporting about 84 longitudinal modes, since the longitudinal modes are separated by 0.0019 nm. We have also measured the temporal pulse width of the mode-locked pulse using an autocorrelator. The autocorrelator is based on a Michelson interferometer with one arm fixed and the other scanned. Once the two pulses from the two paths overlap perfectly, they generate the highest power of the second harmonic in the KTP crystal. In Fig. 2(b), the bottom axis shows the conversion of scanning distance to delay time, taking into consideration the double pass of the arms of the autocorrelator and also the coefficient $\sqrt{2}$ due to the autocorrelator of a Gaussian pulse with itself. Thus, the temporal pulse width of the mode-locked pulses is 63 ps.

In order to couple all the longitudinal modes into the HFC well, three important steps are considered. First, the ML-ECDL noise level must be minimized. Next, the RF frequency driving the mode-locked laser must be close to the FSR of the HFC. Finally, the external cavity length must be finely tuned to the HFC length to optimize the whole system.

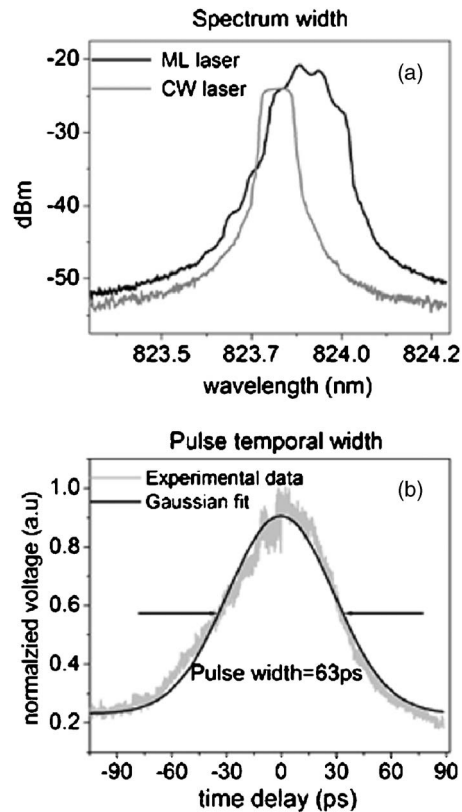


Fig. 2 Optical spectrum and pulse temporal width. (a) The spectrum broadens with mode locking. It is estimated that roughly 70 longitudinal modes are running during mode locking. (b) An autocorrelation curve of ML-ECDL that shows that the mode-locked pulses have a temporal width of 63 ps.

The noise of the ML-ECDL plays a big role in our ability to couple all the longitudinal modes into the HFC. To see this noise, a New Focus 1554 12-GHz photoreceiver is placed after the laser external cavity and a Tektronix 2794 RF spectrum analyzer is used to monitor the noise. First, the translation stage under the grating is coarsely tuned to match the FSR of the external cavity close to RF modulation. It does not have to be a perfect match because, as stated earlier, the laser external cavity has low finesse; i.e., the modulation frequency determines the repetition rate of pulses, not the ECDL length. Then the piezoelectric transducer (PZT), which is placed after the grating, is adjusted. It is used to finely tune the grating alignment and also slightly tune the laser center frequency and the length of the external cavity. Figure 3(a) and 3(b) show the noise spectrum of this mode-locked laser at different PZT tuning voltages on the grating. The resolution bandwidth of the spectrum analyzer was set to 3 MHz with a full range of about 1.7 GHz for these measurements. Figure 3(a) shows the noise spectrum when the FSR of the ECDL and the repetition rate of the mode-locked laser are mismatched and the grating alignment is nonperfect. Before coupling this mode-locked laser into the HFC, the noise spectrum needs to be similar to Fig. 3(b); otherwise, not all the longitudinal modes can be coupled into the HFC simultaneously.

Next one needs to match the RF modulation frequency as closely as possible to the FSR of the HFC. This process

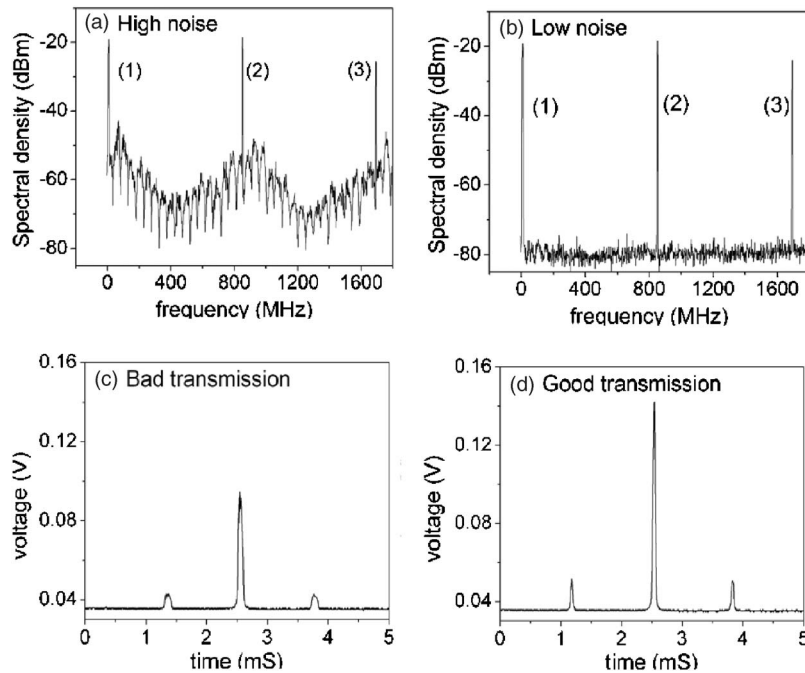


Fig. 3 The intermediate and final results of frequency locking on noise level and transmission mode when the HFC is being scanned (a) and (b). The noise spectrum of ML-ECDL at different PZT voltages: (1) DC; (2) 840.843-MHz component; (3) second harmonic component. The noise level of the laser needs to be as shown in (b) to achieve good coupling to the HFC. (c) The scanning transmission when FSR and RF do not match. (d) The scanning transmission when FSR and RF match.

is monitored by maximizing the height of the transmission peak while the cavity is being scanned at 10 Hz. By dividing the HFC's FSR by its finesse, we determined the HFC linewidth to be about 140 KHz. Since the linewidth divided by the number of longitudinal modes is 1.75 KHz, the RF synthesizer that modulates the laser current needs to have KHz resolution, consistent with our experimental observations.

To further increase the peak height of transmission, one can finely tune the ECDL length as well. Figure 3(d) shows the transmission when everything is maximized. Figure 3(c) shows the transmission at an intermediate step in this process. The sidebands in both Fig. 3(c) and 3(d) are due to modulation by an electro-optic modulator (EOM). When the system is optimized, all the laser longitudinal modes are transmitted from the HFC simultaneously, giving one sharp peak. When it is not optimized, the modes transmit at slightly different times, broadening the peaks and dropping the peak power, as seen in Fig. 3(c). During the entire process, the noise influence can guide us in the optimization of the system's alignment.

The system is frequency locked by the Pound-Drever-Hall^{9,10} technique for which the electronic locking servo system has a bandwidth of roughly 1 MHz. Thus, any laser fluctuation faster than \sim MHz will not be able to get corrected. The error signal obtained at the mixer output when the HFC length is scanned and the servo loop is open looks exactly the same as the error signal due to the single-mode laser.⁹ However, in the ML-ECDL case, the curve represents the summation of all the error signals from the different longitudinal modes. Since the modes are separated by the FSR of the HFC, this error signal is virtually

indistinguishable from the one due to the CW-ECDL. Figure 4 shows the transmission power when the system is locked and not locked. Since this is an HFC, the linewidth is about 140 KHz, while the linewidth of the ML-ECDL is about 71 GHz. When the system is not locked, almost no light can get through the high-finesse cavity. When the system is locked, with 400- μ W average input power before the HFC, or roughly 260- μ W coupled power by considering the window loss and nonperfect mode matching in the HFC, about 22 μ W is transmitted and the whole system can stay frequency-locked for hours. No temperature control servo is used for the HFC, and the system can remain locked in the lab environment with room temperature fluctuation.

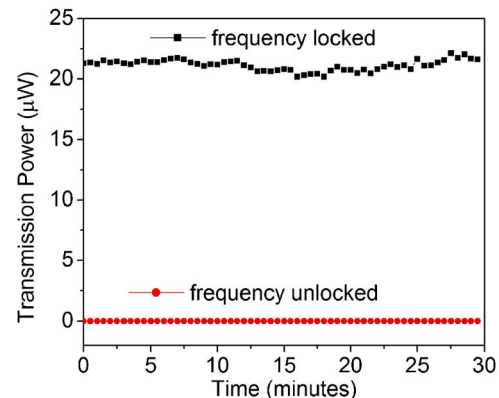


Fig. 4 Transmission power of the mode-locked diode laser when it is locked to the HFC.

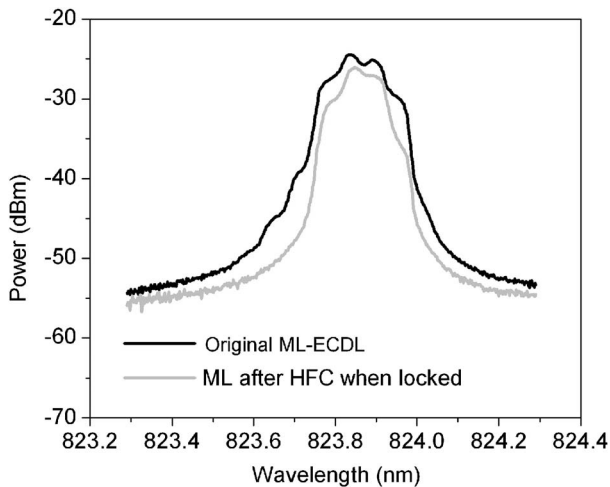


Fig. 5 Optical spectrum of original ML-ECDL and frequency-locked ML taken using the optical spectrum analyzer. This indicates that many longitudinal modes are being transmitted by the HFC as would be expected with good stabilization to the cavity.

tuations of $\pm 1-2^{\circ}\text{C}$. The vibration isolation was considered in the design of the HFC.^{11,12} The HFC is composed of two nested cylinders. The outer cylinder is sealed from the lab environment. The inner cylinder contains the high-finesse mirrors and is vibrationally and thermally isolated from the outer cylinder by means of some rubber padding. The system can maintain lock when the optical table is lightly tapped. The transmission rate is determined by squaring the ratio of transmission to absorption. In this case, the reflectivity is about 0.9995, the absorption is about 350 parts per million (350 ppm), and the transmission is about 150 parts per million (150 ppm). Mirrors with lower absorption losses are commercially available, by considering the impedance matching of the mirrors, relatively higher transmission power could be achieved. Figure 5 shows the optical spectrum of the ML-ECDL before and after the HFC. From the plot, we can tell that both measurements have similar optical spectra, which are broader than the single-mode spectrum shown earlier in Fig. 2(a). This indicates that, after frequency locking, the output ML laser still has a similar number of longitudinal modes compared to the input and that most of the input modes are frequency-locked to the HFC. As for the power, if the coupled average power is about $260\text{-}\mu\text{W}$, then the intra-cavity peak power will be about 30 W.

In the future, we plan to use a diode tapered amplifier¹³ after the ML-ECDL in order to increase the average power to the milliwatt range and then try to see ML-Stokes Raman emission from an HFC filled with hydrogen.^{3,4}

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