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Tilt-tuned etalon locking for tunable laser stabilization

Bradley M. Gibson[1] and Benjamin J. McCall[2,*]

[1]Department of Chemistry, University of Illinois, 600 South Mathews Avenue, Urbana, Illinois 61801, USA
[2]Departments of Chemistry, Astronomy, and Physics, University of Illinois, Urbana, Illinois 61801, USA
*Corresponding author: bjmccall@illinois.edu

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Locking to a fringe of a tilt-tuned etalon provides a simple, inexpensive method for stabilizing tunable lasers. Here, we describe the use of such a system to stabilize an external-cavity quantum cascade laser; the locked laser has an Allan deviation of approximately 1 MHz over a one-second integration period, and has a single-scan tuning range of approximately 0.4 cm^{-1}. The system is robust, with minimal alignment requirements and automated lock acquisition, and can be easily adapted to different wavelength regions or more stringent stability requirements with minor alterations.

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Tilt-tuned etalons have been used as intra-cavity filters in lasers for decades [1] and continue to see use in modern laser designs [2]. Frequency locking of lasers to etalons outside of the resonator cavity is also a well-established technique [3]. It is common to see lasers locked to etalons that are length- [3] or index-tuned [4], but to the best of our knowledge there are no reports in the literature of locking to a tilt-tuned etalon to stabilize a tunable laser. Although length- or index-tuning are effective approaches, tilt-tuning can provide stability and tuning characteristics suitable for applications in molecular spectroscopy at lower cost and experimental complexity.

Here, we present a tilt-tuned etalon-locking system capable of maintaining MHz-level short-term stability over a single-scan tuning range of 0.4 cm^{-1} or more for an external-cavity quantum cascade laser (EC-QCL) centered near 1185 cm^{-1}. The system was constructed primarily from commercially available components at a cost of less than $5000 (USD), and could easily be adapted to work with tunable lasers of any wavelength for which suitable etalons and detectors are available. It is not our intent to demonstrate extremely high-frequency stability in this work; rather, we wish to show that a tunable laser with poor frequency stability can be made suitable for routine spectroscopy easily and at low cost using this technique. For more demanding applications, the frequency stability of the system could easily be increased through a number of simple modifications (e.g., balanced detectors, active temperature control, lower thermo-optic coefficient etalon, use of a full proportional-integral-derivative (PID) servo [5]).

In our technique, the locked laser is tuned by changing the free spectral range (FSR) of the etalon, which is given by the familiar formula

$$\mathrm{FSR} = \frac{c}{2nd\,\cos(\theta)}, \tag{1}$$

where c is the speed of light, n is the refractive index of the etalon, d is the etalon thickness, and θ is the angle of light propagation within the etalon relative to the etalon surface. The FSR can thus be tuned by altering n, d, or θ, with θ tuning providing a nonlinear response (see Fig. 1). Although a linear tuning profile would be preferable for calibration purposes, the nonlinear profile also offers an advantage by giving the user a means of controlling the ratio of angular to wavelength tuning. Changing the initial value of θ allows the user to optimize for maximum scanning range or minimum step size of wavelength tuning; this may be of use if the tilt mount used has a limited range of motion or can only be adjusted coarsely. The maximum allowed angle of incidence is limited by walk-off losses and the clear aperture of the etalon.

Once a laser has been locked to a given etalon fringe, tuning the FSR results in a proportional change in the fringe and laser frequencies. This also means that noise in the FSR will be mapped onto the laser frequency. Temperature fluctuations, which alter both the etalon length and refractive index, can be prevented by placing the etalon in a temperature-controlled oven; alternatively, simply enclosing the etalon to prevent air flow can slow temperature tuning enough to be handled through simple fitting procedures. Changes to the angle of incidence can be lessened through vibrational isolation and can also be mitigated somewhat by using an etalon material with a high refractive index.

The laser we have stabilized in this work is an EC-QCL based on designs by Wysocki *et al.* [6]. In its free-running state, the laser has a mode-hop-free tuning range of approximately 0.7 cm^{-1} and a short-term frequency jitter of 150 MHz, measured as the maximum peak-to-peak wavelength change while recording wavelength readings on a Bristol 621B wavemeter.

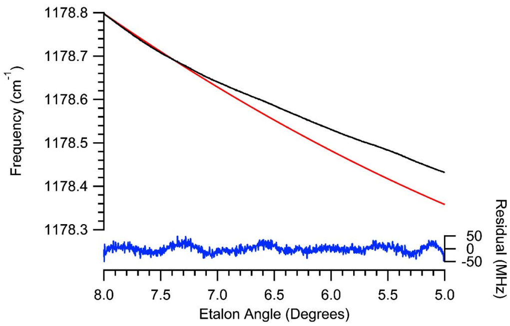

Fig. 1. Simulated and experimental tilt-tuning curves. The black top trace shows frequency readings for a typical locked-laser scan over an estimated 3° etalon slew. The red middle trace shows the simulated frequency shift of a given etalon fringe over the same angular tuning range. The measured frequency shift was also fit to a fifth-order polynomial of the etalon angle to assess the smoothness of the tuning. The fit line is indistinguishable from the experimental data at this scale; the blue bottom trace shows the residuals of the fit, with an expanded vertical scale.

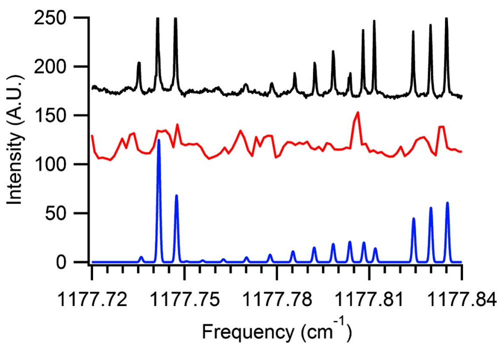

Fig. 2. Comparison of locked and unlocked laser performance for high-resolution spectroscopy. The spectra above show a Q-branch and several R-branch lines from the ν_{16} band of 1,3,5-trioxane. The black top trace was obtained with the locked laser, the red middle trace was obtained with the free-running laser, and the blue bottom trace shows a simulated spectrum produced with PGOPHER [7], using a Gaussian linewidth of 30 MHz. The scanning rate for the locked spectrum averaged 12 MHz/s. The locked spectrum clearly shows spectral structure that cannot be resolved in the free-running spectrum. A full discussion of the 1,3,5-trioxane spectrum, including the variation between experimental and simulated relative intensities, is available elsewhere [8].

This level of frequency jitter significantly impaired the laser's performance in high-resolution spectroscopy applications (Fig. 2).

To stabilize the EC-QCL, a side-of-fringe locking servo was built around a 2″ solid germanium etalon (Light Machinery) (Fig. 3). Light transmitted through the etalon was focused onto a PVM-10.6 MCZT detector (Boston Electronics), with the detector signal being passed to a home-built analog locking circuit. The difference between the detector level and a reference voltage was passed through an integral-only gain channel and applied to the three tuning elements of the EC-QCL (injection current and piezoelectric transducers controlling external cavity length and grating angle). The use of integral gain greatly simplifies lock maintenance during wavelength tuning, although

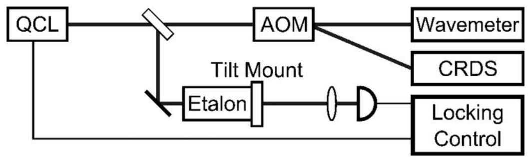

Fig. 3. Experimental layout. The tilt-tuned etalon locking system was integrated into our existing cavity ringdown spectrometer. A beamsplitter was placed before the acousto-optic modulator to direct a portion of the beam through a 2″ germanium etalon mounted in an AG-M100L piezo-driven optic tilt mount. Light transmitted through the etalon was focused onto a PVM-10.6 detector. The detector signal was fed into the locking electronics, which control the tuning mechanisms of the laser. Full details of the spectrometer are available elsewhere [8].

the inclusion of proportional and differential gain would have improved the high-frequency response of the circuit, this proved unnecessary for our application.

To allow tilt-tuning of the etalon and the locked laser, the etalon was mounted in an Agilis AG-M100L piezo-driven optic mount (Newport). The maximum angular tuning range and minimum step size of the mount were 4° and 0.2 arcseconds, respectively. The etalon was set to an initial angle of approximately 8°; during laser scanning, the etalon angle was decreased to approximately 5° in steps of 0.003°. This typically leads to a frequency slew of 0.4 cm^{-1} in steps averaging 12 MHz, but the tuning range can vary by ± 0.05 cm^{-1} depending upon slow etalon temperature drifts. Sub-MHz steps would be easily achievable with the minimum angular step size of the mount if needed. A simple cardboard enclosure was placed around the etalon to eliminate air currents and ensure that temperature drifts were slow relative to the angle tuning. It should be noted that using stepped-angle tuning rather than a constant slew necessitates a slight delay (<0.1 s) between stepping the etalon and recording data while the lock stabilizes.

Lock acquisition and tuning were automated using a Beaglebone Black development board and a custom Python script. To acquire a lock, the etalon angle is first swept over two fringes as detector voltages are recorded by an analog-to-digital converter. The median voltage is then selected as the setpoint for the lock, and the etalon is returned to its starting position. A small offset voltage is applied to the EC-QCL tuning elements before the integral gain channel is enabled; this procedure allows the laser to consistently lock to the side of the nearest fringe without user intervention. The etalon angle is then stepped whenever the scanning software sends a signal to slew the laser. Should the laser come unlocked during the scan, the lock will typically be reacquired immediately on a nearby fringe; the scan can then be continued without user intervention, although some additional work will be required during calibration to account for the frequency jump.

To characterize the locking performance, frequency readings were taken with a Bristol 621B wavemeter, and voltage readings were taken at the integral gain input with a Bitscope10 USB oscilloscope. Thirty-minute data sets at a constant etalon angle were taken for the unlocked laser, the locked laser without an enclosure and the locked laser with an enclosure. To demonstrate locked tuning, data were also obtained for the locked, enclosed laser as the etalon angle was stepped from 8° to 5°.

A comparison of wavelength stability between the locked and free-running laser shows a significant improvement in short-term stability, but a drastic increase in long-term drift [Figs. 4 and 5(A)]. This long-term drift appears to be a result of thermal tuning of the germanium etalon. This could be addressed through active temperature control of the etalon or by using a material with a lower thermo-optic coefficient, such as zinc selenide. However, enclosing the etalon to limit airflow appears to slow the thermal drift enough to allow effective fitting of the frequency tuning profile.

Limitations to the precision of our wavelength readings prevent adequate characterization of our short-term wavelength stability. To address this, voltage readings at the integral gain input were obtained and converted to frequency offsets from our lock point [Fig. 5(B)]. At short timescales, we see an improvement of more than an order of magnitude over the free-running laser, with Allan deviations on the order of 1 MHz for one-second integration times. As these measurements do not account for drifting of the lockpoint (e.g., through temperature tuning of the etalon), they do underestimate the long-term frequency jitter of the locked laser.

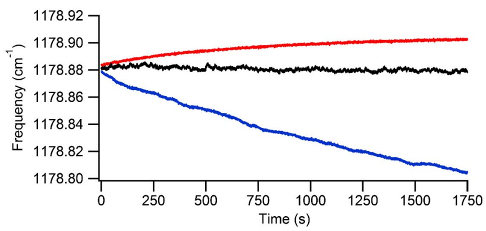

Fig. 4. Frequency stability comparison. The black middle trace shows the frequency stability of the free-running laser. The blue bottom trace shows the laser locked to an unenclosed etalon; although the short-term stability is clearly improved, significant long-term drift is introduced due to thermal drift in the etalon. The red top trace shows the laser locked to an enclosed etalon. By limiting airflow, thermal drift in the etalon is signficantly decreased.

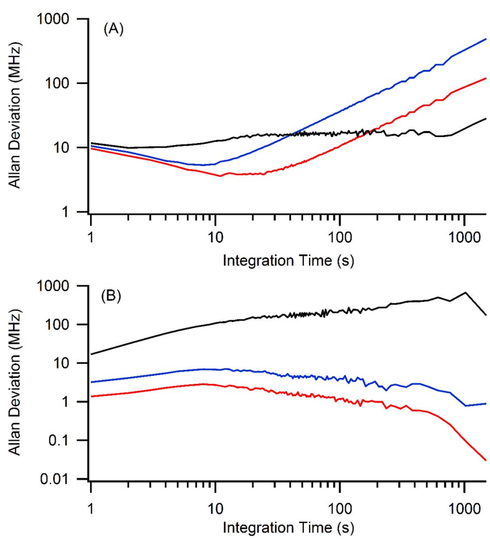

Fig. 5. Allan-Werle plots for the free-running and etalon-locked laser. The black top traces show the free-running laser, the blue middle traces show the laser locked to an unenclosed etalon, and the red bottom traces show the laser locked to an enclosed etalon. (A) Frequency readings were obtained using a Bristol 621B wavemeter, showing a clear increase in the long-term drift for the etalon-locked traces; the precision of the frequency readings (approximately ± 9 MHz over 1 s) limits comparisons at short (<10 s) timescales. (B) Error signal voltages from the locking circuit were converted to frequency offsets to provide more accurate stability data for short timescales. As these do not account for drift in the lock point, they are less reliable at long (>10 s) timescales.

Wavelength readings were also taken during a 3° scan of the etalon, which generally equates to a frequency tuning range of approximately 0.4 cm^{-1}, over 20 min; in this case, the temperature drift of the etalon decreased the tuning range slightly (Fig. 1). As can be seen in Fig. 1, the tuning profile varies somewhat from the expected $1/\cos(\theta)$ curve; this is partially the result of temperature drift and partially due to slight changes in alignment as the etalon angle was scanned. The scan can still be effectively calibrated through a simple polynomial fitting procedure.

In summary, we have developed a simple, low-cost frequency stabilization system for tunable lasers based on locking to a tilt-tuned etalon. The locking system improved the stability of our laser during scanning by more than an order of magnitude to approximately 1-MHz deviation over a one-second integration. A typical scan can cover 0.4 cm^{-1} with a 12-MHz step size, but both longer scanning ranges and smaller steps are easily achievable by altering the initial angle of the etalon. Likewise, for more demanding applications, the stability of the locked laser could easily be improved through active temperature stabilization, balanced detection, and optimized locking electronics. The same approach can be easily adapted to other laser types and wavelength regions.

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