Whispering-gallery-mode-resonator-based ultranarrow linewidth external-cavity semiconductor laser

W. Liang, V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko,* D. Seidel, and L. Maleki

OEwaves Inc., 2555 E. Colorado Boulevard, Suite 400, Pasadena, California 91107, USA

**Corresponding author: andrey.matsko@oewaves.com*

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We demonstrate a miniature self-injection locked distributed-feedback laser using resonant optical feedback from a high-Q crystalline whispering-gallery-mode resonator. The linewidth reduction factor is greater than 10,000, with resultant instantaneous linewidth of less than 200 Hz. The minimal value of the Allan deviation for the laser-frequency stability is 3×10^{-12} at the integration time of 20 μs. The laser possesses excellent spectral purity and good long-term stability. © 2010 Optical Society of America

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Highly coherent, narrow linewidth lasers with long-term frequency stability have applications in many areas of optics, including spectroscopy, metrology, remote sensing, communications, and biochemical sensing. Semiconductor lasers stabilized with external cavities are readily available, but only in a few spectral intervals corresponding to optical communications bands. Modern semiconductor lasers allow coverage of nearly the entire optical spectrum, though their coherence properties are frequently inadequate for many applications. To improve the spectral properties and generate narrow linewidth light over a broad range of wavelengths, we use self-injection locking [1–3] with high-quality-factor (Q) whispering-gallery-mode (WGM) resonators.

WGM resonators are useful for laser stabilization, since they provide very high Q in a broad wavelength range. Self-injection locking [1–3] is one of the most efficient ways to lock a laser to a WGM. The method is based on resonant Rayleigh scattering in the resonator [4]: as a result of scattering, some amount of light reflects back into the laser when the frequency of the emitted light coincides with the frequency of the selected WGM. This provides very fast optical feedback and enables a significant reduction of laser linewidth. Several experiments on self-injection locking of various lasers to a WGM resonator have been previously reported [5–8].

Self-injection locking to a WGM is applicable to any laser emitting at the wavelength within the transparency window of the resonator host material. For instance, lasers emitting in the 150 nm–10 μm range can be stabilized using CaF_2 WGM resonators. This leads to a broad range of opportunities for realizing miniature narrow-line lasers suitable for any application where low optical phase and frequency noise is important. As the self-injection locking does not require any electronics, the laser can be very tightly packaged, which simplifies its thermal stabilization, and also reduces the influence of the acoustic noise on the laser frequency. The laser can be used as a master laser for pumping high-power lasers used for metrology and remote sensing.

This approach for self-injection locking also produces a tunable semiconductor laser. A widely tunable laser locked to a WGM resonator can be obtained with temperature tuning. The tuning speed, however, is comparably slow in this case and is determined by the thermal response of the resonator fixture, and the tuning rate is usually in the range of several gigahertz per degree. An agile frequency tuning of the laser can be achieved by other means. For instance, electro-optic resonators with voltage controlled spectra can be used to injection lock the laser. The tuning agility in such a system is determined by the ringdown time of the WGM mode, which can be shorter than a microsecond.

Here we describe results of our experiments on self-injection locking of distributed-feedback (DFB) diode lasers using crystalline WGM resonators. We have achieved instantaneous linewidths of less than 200 Hz in such lasers, with long frequency stability limited only by the thermal drift of the WGM frequency. While our investigations were performed with lasers at telecommunication wavelengths, they can be considered as a proof of principle for locking lasers at any wavelength where the WGM resonator has a high enough Q factor.

The laser setup is schematically shown in Fig. 1. Light emitted by a 1550 nm DFB laser mounted on a ceramic submount is collimated and sent into a CaF_2 WGM resonator using a coupling prism. The power at the output of the laser chip is 5 mW. The power at the exit of the prism is approximately 3 mW (the reason the power exiting the prism is less than that of the free-running laser is because of the absorption of the resonator when it is nearly

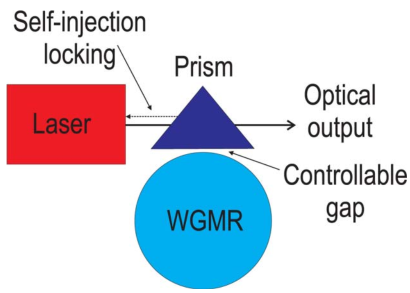

Fig. 1. (Color online) Schematic of the experimental setup. Light from the pump laser enters the WGMR through the prism. Part of the light is reflected back to the laser owing to Rayleigh scattering in the resonator. The light exiting the prism is collimated and sent to an optical spectrum analyzer.

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critically coupled). The free-running laser has 2 MHz instantaneous linewidth.

The resonator is 2 mm in diameter with an unloaded Q factor approaching 2×10^9. The prism coupler loads the mode until the Q approaches 1×10^9. Significant surface Rayleigh scattering [4], responsible for the self-injection locking, results in forming WGM doublets with frequency splitting of the order of 100 kHz.

A significant amount of light reflects back into the laser as a result of the scattering, leading to the lock of the laser frequency to the WGM. Following the WGM frequency, the laser frequency can be pulled in a excess of 4 GHz, leading to several milliamperes of locking range (in the laser current units). The laser and the resonator are mounted on a common thermal control element, and the thermal drift of the WGM (being of the order of a couple of megahertz) determines the long-term stability of the laser. Another source of drift is related to the heating of the resonator due to absorption of light. A drift of the frequency of the free-running laser moves the locking point, which changes the circulation power and, hence, the temperature of the resonator.

To characterize the phase and frequency noise of a laser operating far from threshold, we recall that the quantum noise limited linewidth is given by $\Delta\nu = 2\pi^2\hbar\nu_0(\Delta\nu_c)^2/P$, where $\Delta\nu_c$, an equivalent to the FWHM of the laser cavity, varies depending on the laser type and linewidth broadening factor α, ν_0 is the carrier frequency, and P is the output power. It is worth noting that the linewidth is the FWHM of the Lorentzian spectrum of the laser, and that $\Delta\nu$ is 2 times smaller as compared with the value of Schawlow–Townes linewidth. The phase diffusion associated with the linewidth is given by $\langle(\Delta\phi(\tau))^2\rangle = 2\pi\Delta\nu\tau$.

The single-side power density of the phase noise is $\mathcal{L}(f)[\mathrm{Hz}^{-1}] = \Delta\nu/(2\pi f^2)$, and the corresponding frequency noise is $S_\nu(f)[\mathrm{Hz}^2/\mathrm{Hz}] = 2f^2\mathcal{L}(f)(\Delta\nu = \pi S_\nu)$. The Allan variance of the frequency of an ideal laser is given by

$$\sigma^2(\tau) = 2\int_0^\infty \frac{S_\nu}{\nu_0^2}\frac{\sin^4(\pi f\tau)}{(\pi f\tau)^2}\mathrm{d}f = \frac{\Delta\nu}{\nu_0}\frac{1}{\nu_0\tau}. \tag{1}$$

The model is not applicable to a generic laser suffering from $1/f$ noise, so the following expression is used to determine an effective linewidth $\Delta\nu_{\mathrm{eff}}$ of the laser [9]:

$$\int_{\Delta\nu_{\mathrm{eff}}}^\infty \mathcal{L}(f)\mathrm{d}f = \frac{1}{2\pi}[\mathrm{rad}^2], \tag{2}$$

which gives $\Delta\nu_{\mathrm{eff}} = \Delta\nu$ in the case of an ideal laser.

We built two identical lasers and beat their emission on a fast photodiode to study the noise properties of the self-injection locked laser. By changing the temperature of one of the lasers, we shifted its frequency to be approximately 10 GHz away from the frequency of the second laser. The rf signal generated on the photodiode was used to analyze the spectral properties of the lasers.

Light from two lasers, each with power $P/2$ and carrier frequencies ν_1 and ν_2 ($\nu_{1,2} \approx \nu_0$) produces an rf signal with carrier frequency $|\nu_1 - \nu_2|$ on a fast photodiode. The signal is characterized with phase noise

$$\mathcal{L}_{\mathrm{beat}}(f) = \frac{4\pi\hbar\nu_0}{\eta a P}\left(1 + \eta a\frac{(\Delta\nu_c)^2}{f^2}\right) + \frac{Fk_BT\ ^2}{\rho\mathcal{R}a^2P^2} + \mathrm{RIN}, \tag{3}$$

in the case of lasers with quantum limited linewidth, where F is the noise figure of the rf circuit, k_B is the Boltzmann constant, T is the external temperature, η is the quantum efficiency of the photodiode, a is the attenuation factor, ρ and $\mathcal{R} = q\eta/2\pi\hbar\nu_0$ are the resistance and responsivity of the photodiode, respectively, q is the electron charge, and RIN is the relative intensity noise of the lasers. Naturally, the frequency-dependent term in Eq. (3) describes the laser linewidth, which is not influenced by the signal loss or the efficiency of the photodiode. In the case of beating two typical lasers on a photodiode, the phase noise of the rf signal, $\mathcal{L}_{\mathrm{beat}}(f)$, contains f^{-l} terms ($l = 1, \ldots, 4$). By substituting those terms into Eq. (2), we find $\Delta\nu_{\mathrm{eff}}$ for the linewidth of the beat note. In some cases, flicker noise of the photodiode may need to be taken into account.

An example of the phase noise of the laser beat note is shown in Fig. 2. The beat frequency was of the order of 7–10 GHz, depending on the temperature difference of the two resonators. The power of lasers on the photodiode were about 0 dBm each. A 20 GHz photodiode (Discovery DSC720) was utilized in the measurement. We used a commercial measurement system developed by OEwaves (OE8000) to measure the phase noise. We compared the measured noise with the fundamental thermodynamics-limited phase noise [10] and found that the system stability is restricted by the technical noise at a level 10 dB away from the fundamental noise.

It is reasonable to find the linewidth of the beat note in accordance with Eq. (2). To do this, we fitted the phase-noise dependence by using the decomposition over frequency and calculated the integral. The resultant linewidth is 1.2 kHz. Hence, a single laser has subkilohertz

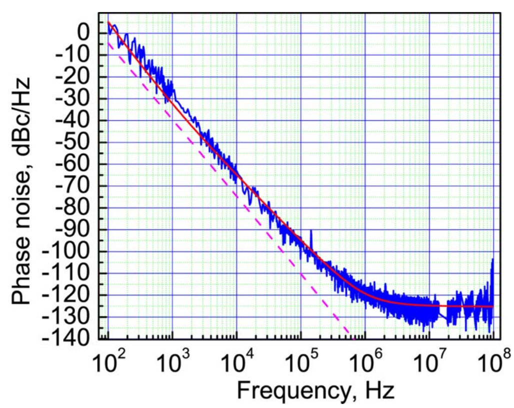

Fig. 2. (Color online) Single-sided phase-noise spectrum of the rf beat signal generated by two self-injection-locked DFB lasers on a fast photodiode. The solid curve is the fit of the noise using decomposition of terms f^{-l} ($l = 1, \ldots, 4$). The dashed curve is the fundamental limit of the phase noise determined by the thermodynamic fluctuation of the WGM frequencies. Interestingly, the low-frequency phase noise has $f^{-7/2}$ frequency dependence, similar to the theoretical limit.

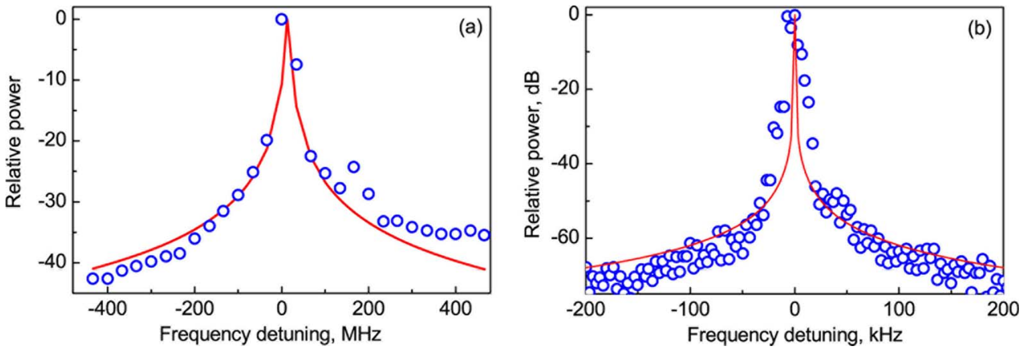

Fig. 3. (Color online) Frequency spectrum of the rf signal generated by beating two DFB lasers on a fast photodiode. (a) The lasers are free running. The skirts of the line are fitted with 8 MHz Lorentzian envelope. (b) The lasers are self-injection locked. The lineshape is taken with an 18 kHz resolution bandwidth. The line is inhomogeneously broadened due to the frequency drift. The skirts of the line are fitted with 160 Hz Lorentzian envelope.

linewidth. The phase noise of the beat note at low frequencies has a signature of thermal drift.

We studied the rf beat note using an rf spectrum analyzer to determine the instantaneous linewidth of each laser. Drift of the beat note did not allow us to reduce the resolution bandwidth significantly. We used 18 kHz resolution bandwidth and fitted the skirt of the line with a Lorentzian curve of 160 Hz FWHM, shown in Fig. 3(b). This indicates [5] that the instantaneous linewidth of the individual laser is less than 160 Hz. To compare the linewidth of the locked and unlocked lasers, we have measured the linewidth of the free-running lasers using the same technique and obtained 8 MHz FWHM value for the beat note [Fig. 3(a)], which corresponds to the laser specifications supplied by the manufacturer.

Finally, we measured the Allan deviation of the rf beat note directly using the frequency counter technique, and recalculated the data to obtain the Allan deviation of the optical signal. Results are shown in Fig. 4. The smallest value of the Allan deviation corresponds to 600 Hz, which has the same order of magnitude as the instantaneous linewidth. To verify the measurement, we took the fit of the phase-noise data (Fig. 2) and calculated the short-term Allan deviation using Eq. (1). The resultant curve agrees well with the measurement results.

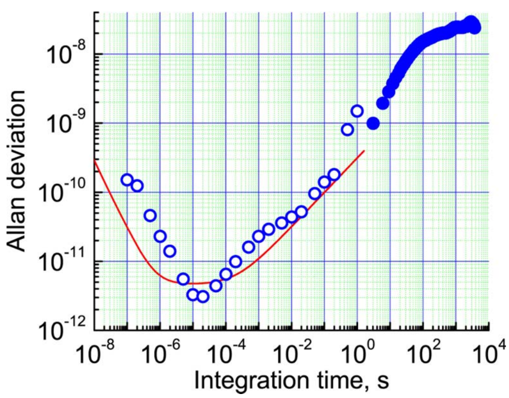

Fig. 4. (Color online) Allan deviation of the rf signal produced by beating two self-injection-locked DFB lasers on a fast photodiode. We used a signal analyzer to measure the short-term stability (open circles) and a frequency counter to measure the long-term stability (solid circles). The solid curve represents the curve calculated using the fitting curve in Fig. 2.

To conclude, we have demonstrated narrow linewidth DFB lasers self-injection locked by means of WGM resonators. While these first prototypes had dimensions of about 20 cm^3, the device can be realized in a package with 15 mm sides with a thickness of less than 3 mm. These lasers have good short- and long-term stability, with instantaneous linewidth smaller than 200 Hz; their long-term frequency drift is less than 10 MHz. Narrow linewidth and frequency stable semiconductor lasers of this type are important for various applications in sensing and metrology. Our experiments indirectly show that any DFB laser at any wavelength can be locked to a WGM resonator using the same principle, especially at wavelengths where lasers with narrow linewidths are currently not accessible. Other kinds of semiconductor lasers may also be used instead of the DFB structures.

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