High-finesse cavity external optical feedback DFB laser with hertz relative linewidth

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Received August 20, 2012; revised October 4, 2012; accepted October 15, 2012;
posted October 15, 2012 (Doc. ID 174417); published November 14, 2012

We report hertz level relative linewidth distributed feedback diode lasers with external optical feedback from a high finesse F-P cavity, and demonstrate the efficient phase noise suppression and laser linewidth reduction of the optical feedback technique. The laser phase noise is dramatically suppressed throughout the measurement frequency range. Especially at the Fourier frequency of 17 kHz, approximately the linewidth of the F-P reference cavity, the laser phase noise is significantly suppressed by more than 92 dB. Above this Fourier frequency, the noise maintains a white phase noise plateau as low as –124.4 dBc/Hz. The laser's FWHM linewidth is reduced from 7 MHz to 4.4 Hz, and its instantaneous linewidth is 220 mHz in the Lorentzian fitting.

OCIS codes: 140.2020, 140.3410, 140.3425, 140.4780.

External optical feedback is widely employed to suppress a semiconductor laser's phase and frequency noise for improving its spectral purity and reducing its linewidth. By optical feedback from solely a grating (Littrow configuration) or a combination of simple mirror and a grating (Littman configuration), the external cavity diode laser is common with a laser linewidth of several hundred kilohertz. For further reducing the laser linewidth, the optical feedback from a resonant cavity is utilized. References [1] and [2] have theoretically proved that the external optical feedback from a resonant cavity can effectively reduce laser linewidth and its phase/frequency noise, owing to the better spectrum characteristics of the cavity transmission and the intrinsic high-frequency sensitivity of the diode lasers to the injection light. Benefiting from this technique, the laser linewidth has been reduced to around some kilohertz [3–7], even to several hundred hertz [8–10]. However, no experiment has achieved a laser linewidth narrower than 10 hertz by using optical feedback only. In particular, there is no convincing experimental result to verify its excellent noise suppression capability at high Fourier frequency.

In this Letter, we not only present the property of the hertz linewidth optical feedback laser, but also prove that the optical feedback technique can efficiently suppress laser noise and reduce laser linewidth to a level comparative to what has been achieved with electrical feedback technique.

We employ two identical distributed feedback (DFB) InGaAsP diode lasers (Mitsubishi Electric, ML925B11F) at a wavelength of 1550 nm. Thanks to its high side longitudinal mode suppression ratio, a DFB diode laser could operate mode-hop freely in optical feedback [11]. The experiment is based on an approach of locking two lasers to the adjacent axial modes of a resonator cavity [12,13]. It can effectively reject the common mode noises and comprehensively present the characteristics of the optical feedback laser. In order to avoid disturbing each other, the two DFB lasers are operated in orthogonal polarizations.

Figure 1 shows the schematic of the two external optical feedback laser systems. The F-P cavity is in the typical V-shaped configuration, with a folded angle of 24°. The cavity mirrors are made of fused quartz and coated with an ultra-low loss coating (ATFilms, custom products). The plane mirror Mc1 is the couple mirror with an incident angle of 12°. The nonzero incident angle of the couple mirror leads to the result that two polarizations have different reflectivity of 99.99875% (s polarization) and 99.99823% (p polarization). The two normal incident mirrors are a plane mirror (Mc2) and a curved mirror with a radius curvature of 500 mm (Mc3), respectively. They are both coated with a reflectivity of 99.999% at 0°. The cavity's spacer, made of ultralow expansion glass, constitutes an optical cavity length of 160 mm. Through the ring-down technique, the finesse for the $s(p)$ polarization is measured to be 78,000 (66,000) and consequently the cavity linewidth of 12.8 kHz (15.2 kHz). As the F-P cavities are not evacuated, the finesses for both polarizations are slightly smaller than their reflectivity-based calculation values, which do not take the intracavity broadband losses by air [14] into account. Different from the one employed in [3], the F-P cavity in our experiment is with the non-confocal cavity configuration, and the folded mirror is a plane mirror instead of a curved mirror. All of them help to achieve lower optical aberrations loss and hence higher cavity finesse. By the expression $\Delta\nu \propto 1/F_c^2$ [2] (where $\Delta\nu$ is the linewidth of the optical feedback laser and F_c is the finesse of the F-P cavity), it is evident that the higher the cavity's finesse, the narrower laser linewidth.

Two DFB lasers are both stabilized to room temperature and the stability is better than 10 mK. The output powers are roughly 5 mW with a driving current of 28 and 26.5 mA, respectively. After a half wave-plate (HWP1), the light from DFB1 is split by a polarizing beam splitter (PBS1). The reflection portion, which constitutes the output beam Output1 with a power of about 2 mW, is utilized for monitoring and beating with another laser. Different from the scheme in [6], in our experiment, the output is the beam before the resonant cavity instead of the transmission one. It represents the characteristics

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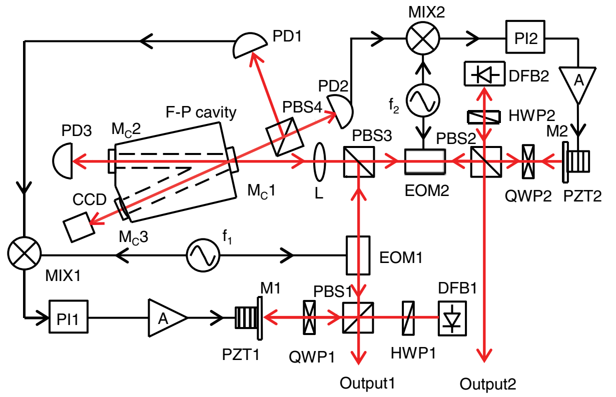

Fig. 1. (Color online) Scheme of the narrow linewidth optical feedback diode lasers setup. DFB, distributed feedback laser; HWP, half wave-plate; QWP, quarter wave-plate; PBS, polarizing beam splitter; M, reflecting mirror; L, lens; PD, photodetector; CCD, charge-coupled device camera; MIX, mixer; PZT, piezoelectric transducer; PI, proportional plus integral controller; A, high-voltage amplifier; EOM, electro-optic modulator. Two oscillators with the frequency of 20 MHz (f_1) and 27 MHz (f_2), respectively.

of laser noise and linewidth reduction by the optical feedback technique. Another advantage, specifically for the high finesse cavity optical feedback laser, is that the laser output power is not limited by the incident power of the resonant cavity. The transmitting portion from PBS1 is coupled into the F-P cavity. Its power is controlled by HWP1, and therefore the optical feedback ratio is optimized. Being similar to DFB1, the beam from DFB2 is split by PBS2, and the reflection portion is combined with DFB1's by PBS3. The combination beams are mode matched into the F-P cavity by lens L. The transmission beams from Mc1, which are collinear with the incident light but propagating in the opposite direction, are employed as feedback beams. They are split by PBS3 into orthogonal polarizations and fed back to the corresponding DFB laser diodes for optical feedback. By changing the temperature and current of the laser diodes, we shift their output frequencies to match the resonant frequencies of the cavity's adjacent axial modes. Finally, DFB1 (DFB2) is self-injected locked to the F-P cavity's $p(s)$ polarization resonance frequency. The frequency of the beat-note between two optical feedback lasers is 935.184 MHz. A photodetector PD3 and a CCD detect the transmission light from Mc2 and Mc3, respectively, in order to monitor the feedback beam mode.

Since the external feedback path (between the F-P cavity and the DFB laser diode) is sensitive to the environmental influence, the feedback phase is vulnerable. So we actively control the length of the external optical path by the Pound–Drever–Hall technique. PZT1 and PZT2 are feedback controlled by PI1 and PI2 respectively for maintaining optical locking. Following the F-P cavity resonant frequency, the laser frequency can be pulled in excess of 1.5 GHz, corresponding to the DFB laser current in roughly a 2 mA locking range. Both the large locking range and the wide linewidth of the solitary DFB laser are appropriate for the reliable optical self-locking, although the F-P cavity's resonant frequency drifts and jitters due to no temperature controls or vibration insulating mechanism, in addition to not being mounted inside a vacuum chamber.

For analyzing the laser noise properties, the phase noise power spectral density (PSD) of the beat-note between the two DFB lasers is directly measured by a signal source analyzer (Agilent E5052B). As presented in Fig. 2, compared with the phase noise of the free running laser (Curve B), the optical feedback laser (Curve A) shows dramatic noise suppression throughout all measurements in the Fourier frequency range (with a measurement cut-off frequency as high as 100 MHz). Even more interesting is the phase noise corner appears clearly at a Fourier frequency of 17 kHz, where the noise is dramatically suppressed over 92 dB. The Fourier frequency of the phase noise corner agrees with the FWHM of the cavity linewidth. Above this corner frequency, it keeps white phase noise plateau as low as −124.4 dBc/Hz. In the experiment, it is the first time to prove that the optical feedback technique can efficiently suppress laser phase noise to the white phase noise plateau starting from the Fourier frequency in the order of the reference cavity linewidth, which strongly agrees with the theoretical model [1].

Because the F-P cavity is not under any vibration or acoustics insulation protections, or temperature control shield, its optical length is vulnerable to environmental fluctuations. These noises affect not only the cavity's resonant frequency, but also its free spectral range. As such, the frequency of the beat-note is not stable because both of the lasers are frequency locked to the adjacent axial modes of the F-P cavity [12]. Noncommon mode noises also affect the beat note leading to certain resonant noises in the low Fourier frequency, as displayed in Curve A. The resonances at the frequencies of 15.6, 47.2, and 50.7 kHz are probably contributed by the PZTs. The two peak noises at the frequency of 20 and 27 MHz correspond to the EOM modulation frequency in the corresponding lasers.

By the relationship to the phase noise [8], the beat-note linewidth between two optical feedback lasers is 5.6 Hz, according to the experimental data in Curve A. The corresponding single laser linewidth is 4 Hz.

To demonstrate the excellent linewidth reduction, we compare the beat-note power spectrums in free running

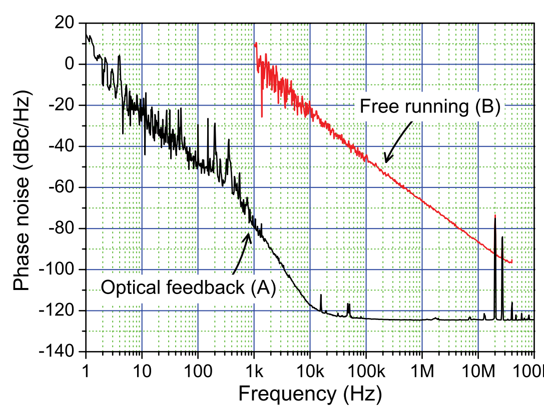

Fig. 2. (Color online) Phase noise PSD of the beat-note between the DFB lasers both in optical feedback (Curve A) and free running (Curve B). Curve B is measured in fast capture mode due to its frequency significant drift and wide linewidth in megahertz order.

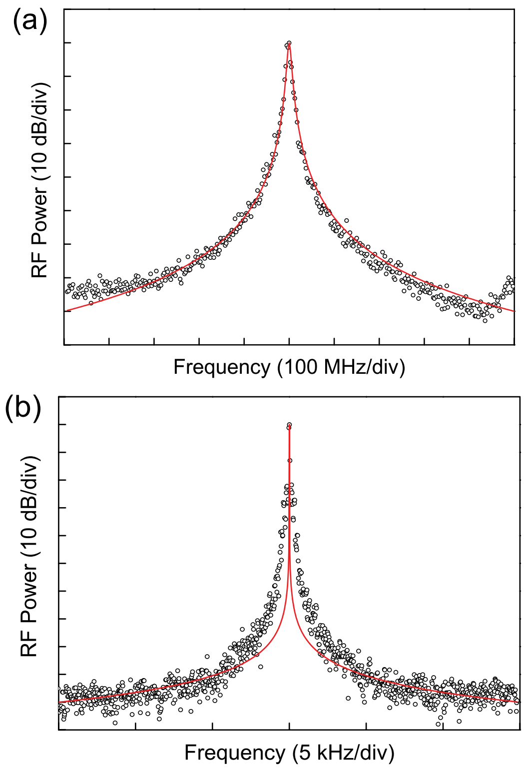

Fig. 3. (Color online) (a) Spectrum of the beat-note between the two DFB lasers in free running with a resolution bandwidth (RBW) of 2.5 MHz (black dot). The skirts of the line are fitted with a 10 MHz Lorentzian envelope (red line). (b) Beat-note of both DFB lasers in optical feedback with an RBW of 30 Hz (black dot) and fitted with a Lorentzian curve of 300 mHz FWHM (red line).

[Fig. 3(a)] and in optical feedback [Fig. 3(b)]. Fitted with a 10 MHz Lorentzian envelope in Fig. 3(a), the single laser linewidth in free running is wider than 7 MHz, which is consistent with the DFB specifications supplied by the manufacturer. We then fit the beat-note between the two optical feedback lasers by a Lorentzian curve of 300 mHz, the red line as shown in Fig. 3(b). The instantaneous linewidth of the individual laser is less than 220 mHz. It is broader than the fitting curve below the frequency detuning of 5 kHz due to the noises at the low Fourier frequency, which coincide with the resonant noises shown in Fig. 2.

Then the FWHM linewidth is obtained by measuring the beat-note in a linear scale. Shown in Fig. 4, the beat-note is averaged from 10 measurements with a resolution bandwidth (RBW) of 6 Hz. The drift of the beat-note frequency limits the measurement RBW not being allowed to be further reduced, so the beat note shown in Fig. 4 is with a FWHM linewidth of 6.2 Hz. It corresponds to an individual laser linewidth equal to or less than 4.4 Hz, which strongly agrees with the result calculated by the phase noise. And the linewidth suppression rate is higher than 10^6.

To conclude, this is the first time for the realization of hertz relative linewidth diode lasers by the external optical feedback technique. More importantly, we experimentally demonstrate that the optical feedback from a

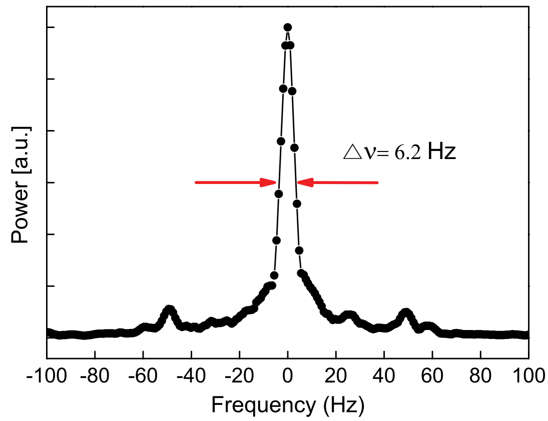

Fig. 4. (Color online) Beat-note between the two DFB lasers in optical feedback. It is averaged from 10 measurements with an RBW of 6 Hz. Its FWHM linewidth is 6.2 Hz.

resonant cavity can dramatically suppress laser phase noise along the entire measurement frequency band. In particular, it is reduced to a low white phase noise plateau from the Fourier frequency in the order of the FWHM linewidth of the optical feedback cavity. This result also exhibits the reliable results for the excellent property of the optical feedback diode laser at the high Fourier frequency, which is significantly better than the electrical feedback laser.

This work is supported by the National Basic Research Program of China (2005CB724501), the National Science & Technology Infrastructure Program of China (2006BAK03A20), and the National Major Research Program of China (2010CB922902).

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