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Frequency stabilization of semiconductor lasers by resonant optical feedback

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With simple optical geometries a separate resonant Fabry–Perot cavity can serve as an optical feedback element that forces a semiconductor laser automatically to lock its frequency optically to the cavity resonance. This method is used to stabilize laser frequencies and reduce linewidths by a factor of 1000 from 20 MHz to approximately 20 kHz.

The high sensitivity of diode lasers to optical feedback is a well-known phenomenon[1] that generally has a disruptive effect on the lasers' output frequency and amplitude stability. Under certain circumstances this sensitivity to feedback can be put to advantageous use. We have discovered an unconventional method that uses a low level of optical feedback to narrow semiconductor-laser linewidths substantially and also automatically to stabilize the laser's oscillation frequency. With the appropriate optical geometry the laser optically self-locks to the resonance of a separate Fabry-Perot reference cavity. The method relies on having optical feedback occur only at the resonance of a high-Q reference cavity. In this case the cavity serves two functions. It provides the optical feedback, which narrows the laser's spectral width, and it provides the center-frequency stabilization to the cavity resonance.

A growing need for lasers with high spectral purity has stimulated the development of a number of semiconductor-laser frequency-stabilization techniques. Methods have been developed based on the techniques of optical feedback,[2,3] external cavities,[4,5] injection locking,[6] and electronic servo control.[7,8] Another interesting and related system for diode-laser frequency stabilization is a hybrid method that uses electronic as well as optical feedback from a fiber-optic cavity.[9] Because of the spectral characteristics of semiconductor-laser frequency noise, the only systems that are able to achieve substantial linewidth reduction are those that incorporate some form of optical feedback or use very fast electronic servos[10,11] (typically requiring servo bandwidths ≥20 MHz).

Our laser locking system contrasts with the previous systems in that the laser sees optical feedback only when its frequency matches the resonant frequency of the reference cavity. We have tested a variety of optical locking geometries; Fig. 1 diagrams a particularly simple and effective version. As shown here, when the confocal reference cavity (mirror separation equal to mirror radius) is operated off axis, it should be viewed as a four-port device. It is important to note that the two ports on the input mirror side (labeled I and II) have different output characteristics. The output beam of type I is a combination of the reflected portion of the input beam with the transmitted portion of the resonant field inside the cavity. This beam has a power minimum when the laser frequency matches a cavity resonance. In contrast, the three outputs of type II contain only the transmitted portion of the cavity resonant field and hence have the desired characteristic of a power maximum on resonance. The geometry of Fig. 1 is one possible method of arranging to have the resonant optical feedback of type II (maximum feedback on resonance) while avoiding the complications inherent in the directly reflected beam contained in output I. For a wide range of feedback conditions this system tends to self-lock stably, thus forcing the laser frequency to match that of the cavity resonance.

Our experiments have been carried out using commercial, single-mode, 850-nm, GaAlAs lasers[12] without any special preparation of these devices. The free-running, unperturbed laser linewidths were measured to be approximately 20–50 MHz. A variety of reference cavities was used for the optical locking system. These had free spectral ranges varying from 250 MHz to 7.5 GHz and resonance widths ranging from 4 to 75 MHz. As an additional laser diagnostic we mon-

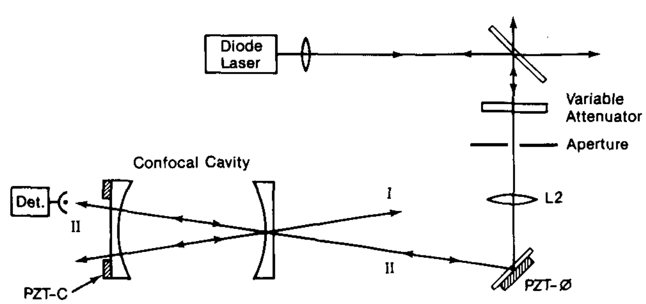

Fig. 1. Schematic of one version of the optical feedback locking system. Lens L2 is used to mode match the laser into the confocal reference cavity. The aperture blocks the unwanted feedback of type I while passing the desired feedback of type II. The variable attenuator is used to study the feedback power dependence of the locking process. The piezoelectric translator PZT-ϕ is used to optimize the feedback phase relative to the undisturbed laser. PZT-C is used to scan the reference cavity and in turn the optically locked laser frequency. A photodetector (Det.) monitors the transmitted power.

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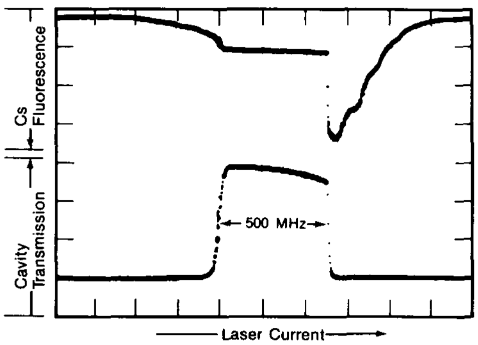

Fig. 2. The lower trace displays the power transmitted through the reference cavity as a function of the laser current. The upper trace, taken simultaneously, shows the fluorescence from a cesium cell as the laser scans from left to right across the 852-nm cesium resonance. The flat portion on the side of the fluorescence signal and on the peak of the cavity resonance occurs when the laser frequency locks to the cavity resonance and no longer scans with the laser current. The indicated locking range $\simeq$500 MHz corresponds to the frequency range that the laser would normally scan without the optical self-locking.

itor the resonance fluorescence from an atomic-cesium vapor cell.

With type II feedback if the laser frequency is far from matching a reference cavity resonance there is no optical feedback and the laser frequency scans as usual with changes in the injection current. However, as the laser frequency approaches a cavity resonance, resonant feedback occurs and the laser frequency locks to the cavity resonance, even if the laser current continues to scan. The actual frequency range over which the diode laser locks is a function of the feedback power level and the phase of the feedback light relative to that of the unperturbed laser. The optical locking of the laser frequency to the reference cavity resonance is observed directly with a photodiode, which monitors the power transmitted through the cavity as a function of the laser current. This signal is displayed as the lower trace in Fig. 2. Here we see an unusual Fabry–Perot transmission function, which has a flat top and a width approximately 10 times larger than the actual cavity resonance width of 50 MHz. This shape is a manifestation of the fact that the laser frequency is not scanning with the laser current but is locking to the frequency of peak transmission of the cavity resonance. The frequency locking is further demonstrated in the upper trace of Fig. 2, which shows a simultaneous record of the fluorescence from a cesium cell as the laser scans over the 852-nm cesium resonance line. This trace shows that when the laser frequency is far from the peak of the cavity resonance (shown in the lower trace) it scans smoothly over the cesium resonance as the laser current is varied. The self-locking, which stabilizes the laser frequency, is evidenced by the abrupt flattening in the scan of the fluorescence signal as well as the cavity transmission function. At the end of the 500-MHz locking range the laser abruptly drops out of lock and continues to scan over the cesium resonance.

For low levels of optical feedback the locking range depends on the feedback power ratio. This is the ratio of the external feedback power, coupled into the laser mode, to the power reflected internally by the output facet. Locking ranges of a few hundred megahertz were observed with feedback power ratios typically in the range of 10^{-4} to 10^{-5}, with a large uncertainty in the coupling efficiency of the feedback power into the laser mode.

In order to determine unambiguously the spectral characteristics of the optically locked semiconductor lasers, we measured the beat note between two lasers independently locked to separate reference cavities. Direct observation of the beat-note spectra avoids many of the uncertainties and errors that plague measurements of laser frequency stability and linewidth using delayed-self-heterodyne and electronic residual-error-signal techniques. Figure 3 shows the beat note detected with a fast photodiode and displayed on a rf spectrum analyzer. The upper trace shows the beat note when one of the lasers is free running without feedback while the other laser is optically locked. The sharply peaked trace is obtained when both of the lasers are optically locked to their independent reference cavities and indicates the dramatic linewidth reduction that is instantly achieved. In the locked case, the width of the displayed beat note is limited not by the laser linewidth but rather by the rf spectrum analyzer's resolution bandwidth of 300 kHz. Higher-resolution measurements show that the actual spectral width of the beat note can be less than 20 kHz (Fig. 4). This narrowing of the semiconductor linewdith by a factor of about 1000 (from 20 MHz to 20 kHz) is obtained by purely optical means without any electronic control.

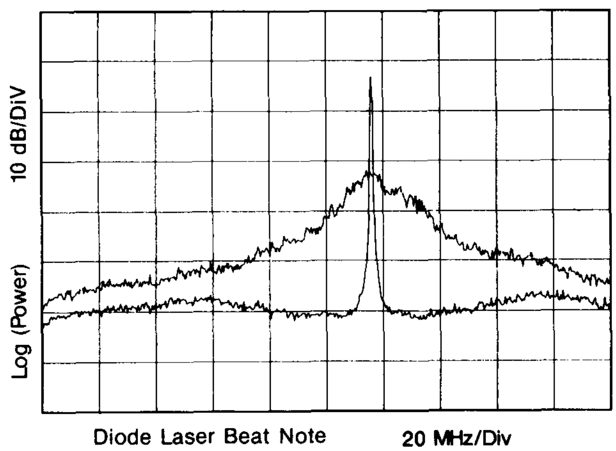

Fig. 3. The beat note between two semiconductor lasers is shown on a rf spectrum analyzer with a sensitivity of 10 dB/division vertically and 20 MHz/division horizontally and a resolution bandwidth of 300 kHz. The upper trace shows the broad beat-note peak that is observed when one of the two lasers is free running and unstabilized. The other, sharply peaked, trace shows the beat note when both of the lasers are optically self-locked to separate Fabry–Perot reference cavities. In the locked case the peak width is limited by the 300-kHz resolution of the spectrum analyzer.

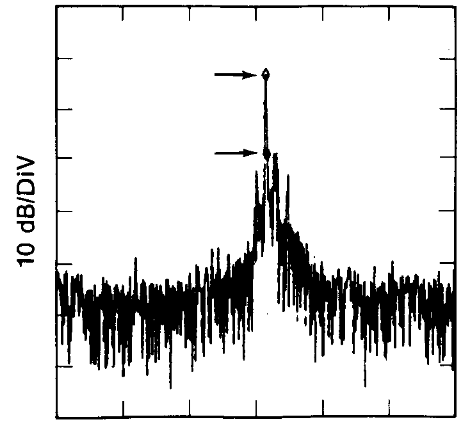

Fig. 4. Diode-laser beat note displayed with higher resolution now shows a very narrow width as measured on a rf spectrum analyzer. The approximately 20-kHz width is inferred from the two markers on the central peak (which are separated by −16 dB and 13 kHz), the spectrum-analyzer resolution of 10 kHz, the sweep rate of 30 msec/division, and the repeatability of the measurement.

One advantage of the optically self-locked laser system is that it shows some reduction in sensitivity to other sources of optical feedback. In addition, we find that the excess intensity noise ($\simeq$30 dB above the expected photodetection shot noise) that we measure on the light from the semiconductor laser is reduced by roughly 10 dB when the laser is optically locked to the cavity.

For many applications it is important to be able to scan the laser frequency as well as to have a stable long-term frequency lock. Continuous, narrow-linewidth scans of the laser frequency can be made by synchronizing the sweep of the laser current with that of the reference cavity length (PZT-C, Fig. 1) and the feedback phase (PZT-ϕ). With this synchronization we have made continuous scans of more than 4 GHz; these were limited only by the range of our present PZT-ϕ. We note that it is necessary to control the laser current only accurately enough that the free-running laser frequency is within the $\simeq$500-MHz optical-self-locking range. To avoid the inevitable drifts and to ensure long-term locking stability, it is useful to servo control the appropriate feedback phase and laser current relative to the reference cavity. Low-speed electronic feedback circuits are sufficient to accomplish this.

The actual physics that determines the spectral characteristics of semiconductor lasers is a topic of active research and is reviewed in Ref. 13. Initial theoretical analyis[14] of the self-locking process based on optical feedback theory[1,15–17] gives reasonable agreement with experimental results, at least in terms of linewidth reduction, locking range, and the phase dependence of the cavity locking.

The optical self-locking system described here has several advantages relative to conventional locking techniques. It is a relatively simple method that provides a vast improvement in the linewidth and direct control of the semiconductor-laser frequency. When the system is locked, the laser's linewidth is reduced dramatically, from 20 MHz to approximately 20 kHz, and the laser's oscillation frequency is stabilized to the cavity resonance frequency. Even narrower spectral widths could be expected with better-quality reference cavities. Long-term stability of the reference cavity resonance can be quite high.[18] We observe that the laser's intensity noise is reduced, as is its sensitivity to other sources of optical feedback. The system is also attractive because it does not require any modification of commercial laser diodes or any extremely fast electronic servo systems. With the increasing interest in semiconductor lasers with high spectral purity and precision optical measurements in general, this optical-self-locking method has the potential for numerous applications.

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