Optical Stabilization of Semiconductor Lasers *

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The method of using resonant optical feedback to stabilize the frequency of semiconductor lasers has proved valuable for a number of applications [1-3]. It is one of a number of possible optical stabilization methods, as opposed to electronic stabilization methods, and contrasts from other optical methods in that the optical feedback comes from a high Q (quality factor) optical resonator. This technique for frequency stabilization uses commercially available lasers and Fabry-Perot cavities and can reduce diode laser linewidths to as low as 3 kHz. The resonance of the Fabry-Perot cavity serves as the frequency reference which stabilizes the lasers oscillation frequency and narrows its linewidth.

A specific optical feedback locking system is diagramed in Fig 1. This system uses a separated high Q (quality factor) Fabry-Perot resonator as the feedback element. Typically 10^{-2} of the laser output power is split off from the laser beam and is coupled off-axis into the Fabry-Perot resonator in such a way that the incident beam reflects off the cavity input mirror at an angle and does not return to the laser. On the other hand when the laser frequency is tuned to a cavity resonance, optical power is built up in the cavity, some of which leaks back through the input coupling mirror and returns to the laser. This type of resonant optical feedback is labeled type II and it has the characteristic that the feedback power is maximum when the laser frequency matches a cavity resonance. This type II feedback alters the characteristics of the diode laser resonator by coupling it optically to the higher-Q Fabry-Perot cavity. At a resonance of the Fabry-Perot the combined diode laser plus cavity system has lower loss. The laser then naturally oscillates at the point of minimum loss and hence "locks" to the Fabry-Perot cavity resonance. We note in Fig. 1 that the directly reflected type I beam, which has a power minimum at a cavity resonance, is deflected so that it does not return to the laser.

A characteristic of the optical lock is that the frequency of the laser is controlled as usual by the lasers injection current and temperature unless the oscillation frequency comes close to a resonance of the Fabry-Perot. In the latter case the laser frequency locks to the cavity resonance. The tuning range between the laser oscillation frequency and the cavity resonance frequency over which the

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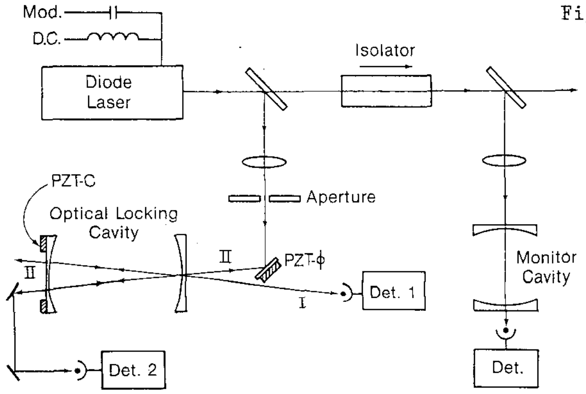

Fig 1. Optical feedback locking system diagram.

lock occurs is typically a few hundred megahertz. When the laser optically locks, its tuning sensitivity with respect to injection current is reduced by a factor of 100 or so. Both the locking range and the tuning sensitivity for injection current depends on the exact parameters of the lock including the cavity Q and feedback power level. P. Laurent and collaborators [2] have done an analysis of this optical locking method and they find good agreement between experiment and theory for most aspects of the lock.

Excellent performance can be achieved with this optical locking method in terms the spectral narrowing and center frequency stabilization of the diode laser. The commercial diode lasers we are using have free running 3 dB linewidths that are about 20 MHz, which can be narrowed with the optical lock to less than 5 kHz. This linewidth reduction represents an increase in the spectral density of the optical power and the laser's coherence length of more than a factor of 1000. Some care must be taken in evaluating the linewidth of semiconductor lasers because some of the common and popular methods are misleading and because the laser's lineshapes can be non-Lorentzian [2]. In fact, the optical lock narrows the linewidth by removing the frequency noise for low Fourier frequencies and out to a couple hundred megahertz. For semiconductor lasers this frequency range contains the most important contribution to the laser,s linewidth even though the frequency fluctuation spectrum extends out as far as the relaxation oscillation frequency at about 3 GHz.

Figure 2 shows the tremendous reduction in the laser linewidths that can be achieved using this optical feedback locking method. The figure shows the beat note generated on a fast photodiode between two independent diode lasers. The broad beat note displays the spectral width when one of the lasers is not optically stabilized whereas the narrow beat note is measured when both lasers are optically stabilized to independent cavities. The remaining width in the sharp beat note trace is due to the 300 kHz resolution bandwidth of the RF spectrum analyzer.

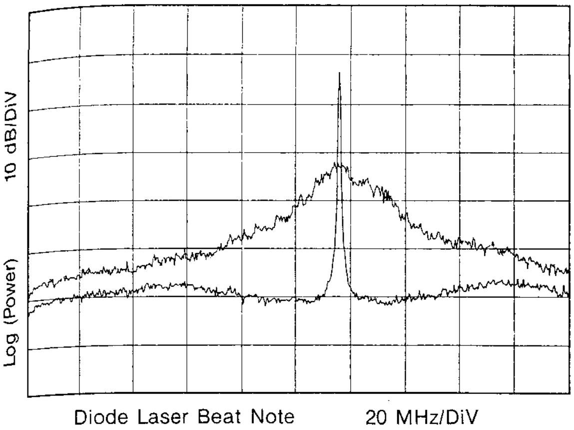

Fig 2. Diode laser beat not spectrum.

Higher resolution measurements have demonstrated beat notes with 3 dB bandwidths of as little as 3 kHz.

One of the many advantages of this frequency stabilization method is that the system is relatively simple to build and it does not require that the diode laser be modified with special coatings and one only needs access to one facet of the laser. In addition it is important to note that the system operates in the weak feedback limit, such that the total power feedback to the laser resonator is a small fraction of the laser's output power (usually 10^{-2} to 10^{-4}). This means that the usable laser output power is not significantly depleted and that the lock operates in a regime of optical feedback that is stable relative to small optical perturbations. The diode laser's linewidth decreases smoothly,from 20 MHz to a few kHz as the power of the resonant feedback is increased. If the feedback power is further increased the locking system becomes unstable.

It is interesting to note that even though the frequency modulation sensitivity of the laser to injection current is reduced for low frequencies (say less than 100 Mhz) it is still possible to modulate the laser at high frequencies using the injection current [4]. Modulation of the laser at high frequencies is compatible with the optical lock if either the modulation amplitude is small or if the modulation frequency is harmonically or rationally related to the free spectral range of the Fabry-Perot that is used for the lock. Experimental results are shown in Fig. 3 for strong FM modulation of a semiconductor laser at a frequency of 245 MHz which corresponds to the free-spectral-range of the locking Fabry-Perot cavity.

In this case the laser was biased at 97 ma injection current with 7 ma of additional RF modulation applied through the port labeled mod. in Fig 1. The optical lock with modulation thus provides an array of about 20 sidebands spaced at 245 MHz and each of which has a linewidth of less than 10 kHz. This sideband spectrum is detected using an optical spectrum analyzer as shown in Fig. 1.
The asymmetry in the spectrum is due to a combination of AM plus FM modulation as

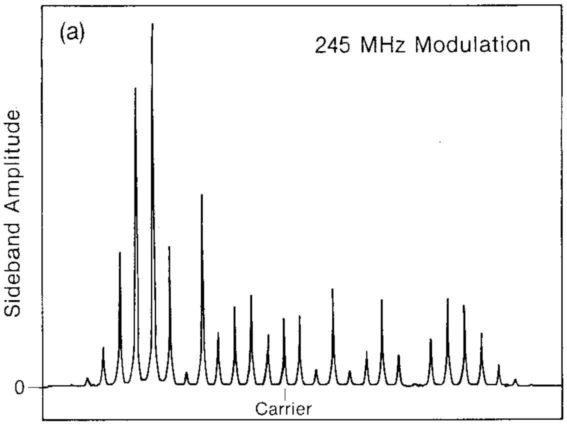

Fig. 3 RF modulation at 245 MHz optically locked diode laser.

well as harmonic distortion in the FM. The vertical scale is linear and the horizontal spacing between peaks is 245 MHz.

In addition to the advantages of this locking technique, it is also important note some of the challenges that must be faced in implementing the method. First of all, to optimize the lock it is necessary to have the proper phase of the light that is fedback to the laser. This is accomplished by adjusting the optical path length between the laser and the cavity using PZT-φ in Fig 1. In addition the laser frequency needs to be within an optical locking range of a cavity resonance. In order to tune and scan the frequency of the optically locked laser over frequency ranges larger than the optical locking range we need to simultaneously scan the Fabry-Perot cavity, the laser injection current and the feedback phase. All of these adjustments can be made automatically using simple electronic servo controls. We also note that there is some frequency pulling of the optically locked laser with variations in the feedback phase, but the pulling is small if the cavity has a high Q.

Lasers with high spectral purity are required in the fields of spectroscopy, precision measurements and for some communication systems applications. Additionally, in some cases the signal to noise ratio for spectroscopic detection is greatly enhanced when the lasers spectral width is reduced. For example laser induced fluorescence, or direct absorbtion spectroscopy of the cesium atom resonance line at 852 nm with diode lasers shows a significant amount of excess noise. This noise, though not well understood in the case of Cs, is typically reduced by a factor of about 100 when the diode lasers spectral width is narrowed by the optical lock. By reducing the laser's linewidth by a factor of 1000 and stabilizing the laser's center frequency this optical locking method can improve the performance characteristics of diode lasers such that new applications become possible.

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