

# Modulatable narrow-linewidth semiconductor lasers

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We find that using the technique of optical feedback locking, to narrow semiconductor linewidths, does not sacrifice the ability to modulate the laser's frequency via the injection current. The frequency of a laser is stabilized to a separate Fabry-Perot reference cavity using resonant optical feedback and can be modulated efficiently at frequencies related by rational fractions to the free-spectral range of the reference cavity. This system can provide an array of narrow-linewidth, frequency-stable laser lines and shows promise for applications in frequency-division-multiplexed coherent communications, as well as laser frequency control and precision measurement systems.

Optical feedback locking of semiconductor lasers provides a powerful means for stabilizing the frequency and narrowing the linewidth of diode lasers.<sup>1-3</sup> This optical technique can reduce laser linewidths by more than a factor of 1000, thus achieving linewidths of a few kilohertz. We consider here the interesting and useful modulation characteristics of these optically stabilized semiconductor lasers (OSSL). Direct modulation of the injection current of these lasers can provide a high FM modulation index while the very narrow linewidth and frequency stabilization produced by the optical feedback lock is maintained.

The high-speed frequency and amplitude modulation capabilities of semiconductor lasers are important attributes of these lasers relative to other optical sources. Unfortunately, the FM capabilities are usually sacrificed when the laser linewidths are reduced by optical means.<sup>4</sup> With most frequency stabilization schemes there is a trade-off between the diode laser's linewidth and its FM modulation capabilities. Usually a one-to-one correspondence exists between these quantities; that is, if the laser linewidth is reduced by a factor of 10, its FM sensitivity to injection current (typically  $\sim 3$  GHz/mA) is also reduced by roughly this same factor of 10. In the case of the OSSL the modulation characteristics are definitely altered by the optical locking process, but we find that the modulation sensitivity is not necessarily reduced when the linewidth is narrow. In fact, we find that the modulation characteristics of the OSSL have a predictable resonant frequency dependence.

The concept behind the optical feedback locking technique is to establish weak resonant feedback from a high  $Q$  (relative to the  $Q$  of the diode laser cavity) optical resonator. Figure 1 is a diagram of a system which gives enhanced optical feedback when the laser frequency matches the cavity resonance and effectively zero-feedback off resonance. Here a beamsplitter picks off a small amount of the laser output ( $\sim 4\%$ ) and couples it off axis into a confocal optical resonator. This geometrical arrangement ensures that the laser sees positive optical feedback precisely when the laser frequency matches the cavity resonance frequency. The optical lock usually operates in the low feedback limit and typically requires an optical feedback power of about  $10^{-4}$  of the laser

output power.<sup>2</sup> At resonance the spectrally cleaned laser field which has built up in the reference cavity leaks back through the cavity input mirror and returns to the laser where it increases the laser gain at that frequency. This frequency-selective gain enhancement forces the laser to lock to the cavity resonance frequency. The result is that the semiconductor laser's frequency is stabilized to the cavity resonance, and its 20 MHz linewidth is reduced to less than 10 kHz. Related work has also been reported for semiconductor laser frequency control using optical feedback from optical waveguides<sup>5</sup> and fiber cavities.<sup>6</sup>

We have used a variety of optical geometries and reference cavities for these optical locking systems. The free-spectral ranges (FSR) of the reference cavities were between 7.5 GHz and 250 MHz with cavity resonance widths varying from 75 MHz to 20 kHz. The commercial lasers were single-mode AlGaAs lasers operating near 850 nm and were not modified in any way. For applications requiring higher spectral purity and low residual phase noise at high frequencies, it is useful to send all of the laser power into and through the high-efficiency reference cavity. The cavity then acts as a

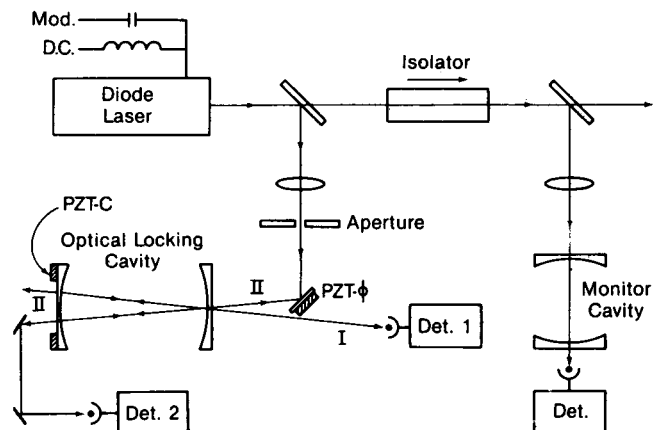


FIG. 1. Experimental diagram of an optically stabilized semiconductor laser (OSSL). Approximately 4% of the laser output power is coupled off-axis into the confocal optical locking cavity. In this geometry resonant optical feedback returns to the laser and automatically locks the laser frequency to the cavity resonance. Piezoelectric ceramics PZT-C and PZT- $\phi$  are used to control the cavity frequency and optimize the feedback phase, respectively. An additional monitor cavity is used for spectral analysis and is separated from the laser by an optical isolator. rf modulation is added to the dc injection current through the modulation port (mod.). Photodiode detectors (det.) monitor the transmission and reflection signals from the cavities.

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bandpass filter and removes the excess laser phase noise at very high frequencies. This scheme uses the reference cavity as a spectral and spatial filter as well as the frequency discriminator for the optical feedback lock using the weak reflection.

Modulation of the injection current of nonstabilized semiconductor lasers results in both amplitude and frequency modulation of the laser output. At least in the limit of low modulation index the temporal characteristics of the laser electric field can be represented by

$$E(t) = A [1 + m \cos(\omega_m t)] \sin[\omega t + \beta \cos(\omega_m t + \theta)]. \quad (1)$$

Here  $A$  is the field amplitude,  $\omega/(2\pi)$  is the laser carrier frequency,  $\omega_m/(2\pi)$  is the modulation frequency, and  $m$  and  $\beta$  represent the amplitude and frequency modulation indices, respectively.<sup>7,8</sup> The resulting frequency-domain spectra can be described by the usual sum of AM plus FM sidebands (with Bessel function amplitudes) except that the relative phase  $\theta$  between AM and FM is frequency dependent. When a diode laser is operating well above threshold, a small modulation of the injection current results in a modulation of the laser field that is predominantly FM with the ratio of  $\beta$  to  $m$  typically in the range of 10 to 20. However, when the modulation index is large ( $\beta > 2$ ), the situation can be considerably more complicated.

When the OSSL is modulated at low frequencies, typically  $\omega_m < 200$  MHz, the frequency modulation is suppressed by the optical lock relative to that of an unstabilized laser.<sup>9</sup> On the other hand, there are special modulation frequencies that strongly affect the frequency modulation characteristics of the OSSL. With certain modulation conditions some or all of the modulation sidebands can resonate with the reference cavity (with or without the carrier), in which case they return to the laser and reinforce the optical lock. In particular optical sidebands at frequencies that correspond to the FSR (or its harmonics) of the reference cavity are simultaneously resonant with the cavity and are fed back to the laser with the carrier. In this way it is possible to modulate the laser current with a high modulation index  $\beta$  and generate many sidebands without disrupting the frequency stabilization and linewidth narrowing provided by the optical feedback lock.

Figure 2 shows the resonances in the optical locking process that one observes as a function of the applied rf modulation frequency. The tallest, evenly spaced, sharp resonances in this figure occur when the modulation is at frequencies integrally related to the cavity FSR of 245 MHz. Good optical locking is observed at the modulation frequencies corresponding to these resonances. Also, the power transmitted through the cavity is maximized because the laser carrier and the sidebands match cavity resonances.

All of the cavity transmission resonances shown in Fig. 2 correspond to modulation frequencies that are related to the reference cavity FSR by rational numbers, that is, when the modulation frequency is

$$\omega_m/(2\pi) = (a/b)(\text{FSR}), \quad a, b = 1, 2, 3, \dots \quad (2)$$

The smaller resonances shown in Fig. 2 occur when the ratio ( $a/b$ ) is not an integer. This rational relationship between

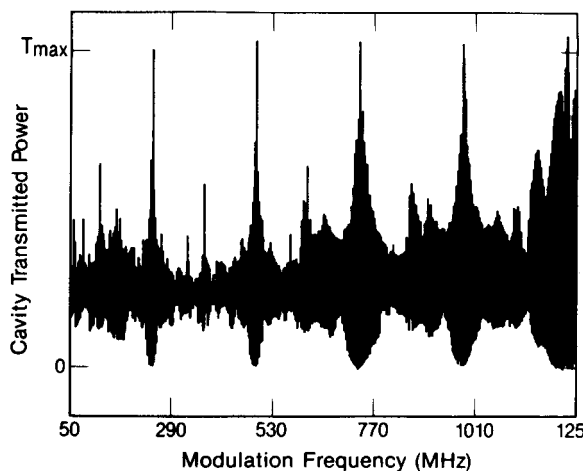


FIG. 2. Power transmitted through the optical locking cavity (FSR = 245 MHz, finesse = 10) as seen by detector 2 (Fig. 1) as a function of the frequency of the modulation applied to the injection current. The modulation frequency is swept slowly from 50 to 1250 MHz. Points of zero and maximum transmission are indicated on the vertical axis. The sharp peaks indicate the resonant nature of the stability of the optical lock as a function of modulation frequency. The large evenly spaced peaks correspond to modulation at the frequency of the cavity free-spectral range (245 MHz) and its harmonics. The smaller resonant peaks occur when the modulation frequency is related to the cavity FSR by a noninteger rational number. A modulation current of  $\sim 5$  mA was added to the dc current of 95 mA ( $\sim 1.7$  times threshold).

the modulation frequency and the cavity FSR for stable optical locking is easily understood: that is, under the conditions of Eq. (2) every  $b$ th sideband can resonate with every  $a$ th cavity mode. For example, modulation at 367 MHz corresponds to  $a/b = 3/2$  and means that when the carrier is resonant with a cavity mode, every other sideband will be simultaneously resonant with every third cavity mode. This situation gives stable optical locking with roughly half of the available power resonant with the cavity. We have observed these resonant enhancements in the optical lock for many modulation frequency to FSR ratios, including those with  $a = 1-9$  and  $b = 1-5$ . In principle, some optical locking occurs for any modulation frequency that is related to the cavity FSR by a rational number ( $a/b$ ), but in general as the denominator  $b$  gets larger, less and less of the available optical power is resonant with the cavity modes and hence the optical lock is less effective. The strength of a particular resonance depends on the number and size of the sidebands that are resonant with cavity modes and thus depends strongly on the modulation index  $\beta$  and the value of  $b$ .

The frequency domain power spectra of an optically locked laser that is modulated at one of the resonances [consistent with Eq. (2)] consist of an array of frequency stabilized, narrow-linewidth laser lines separated by the modulation frequency. Figure 3 shows sideband spectra of a modulated OSSL taken with an optical spectrum analyzer (see Fig. 1). The optical spectrum analyzer that is used to display the modulation sidebands is not capable of measuring the very narrow laser linewidth because of the limited resolving power when a large FSR (7.5 GHz) is required. In order to measure the laser linewidth we use heterodyne methods to detect the beat note between two OSSL's.<sup>2</sup> We find that the locked laser linewidths are less than 10 kHz and

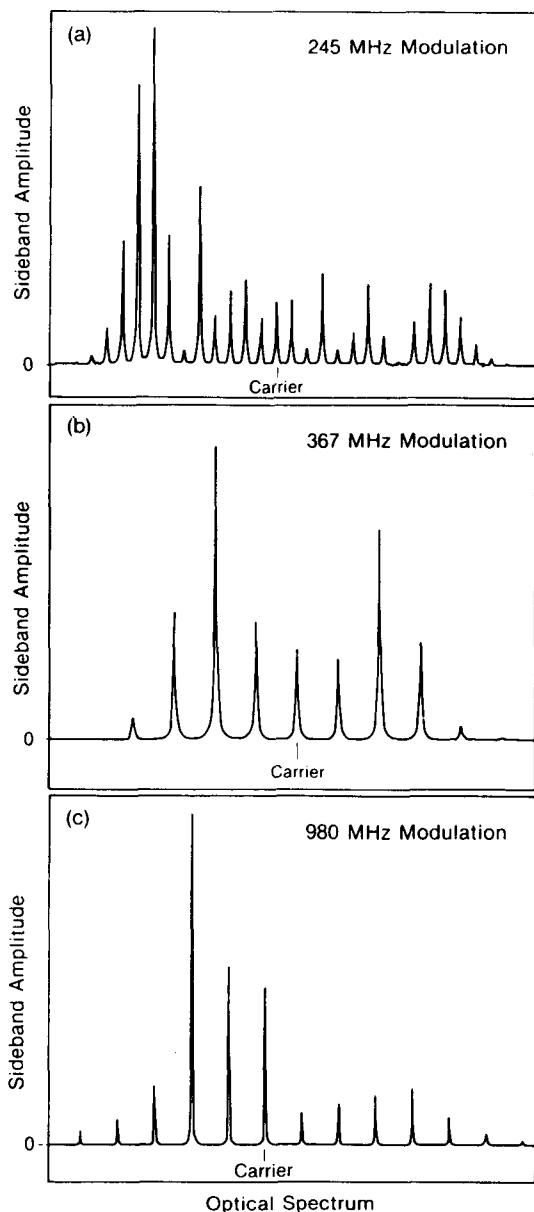


FIG. 3. Sideband structure of a modulated, optically locked, semiconductor laser taken with an optical spectrum analyzer (FSR = 7.5 GHz, finesse = 150) for three of the resonant modulation frequencies. In all of these cases a high-modulation index  $\beta$  is obtained while maintaining the narrow laser linewidth and center frequency stabilization. In (a) the modulation frequency is equal to the locking cavity FSR of 245 MHz. Here a modulation current of  $\sim 7$  mA is added to the dc bias of 97 mA. We see that more than 20 narrow-linewidth, frequency stable, sidebands are produced. In (b) the 4 mA of modulation current is at a frequency of 367 MHz which is  $3/2$  the cavity FSR. In (c) the laser is modulated with  $\sim 10$  mA at 980 MHz (four times the FSR), and the laser generates more than ten useful sidebands covering a total frequency range of more than 10 GHz (in this case the overlapping sidebands from the adjacent 7.5 GHz FSR have been removed for clarity).

that the linewidth is unchanged when the laser is modulated at frequencies that correspond to the locking resonances that are shown in Fig. 2. This is to be compared with linewidths that are measured to be 20 MHz when the laser is not locked or is strongly modulated at a frequency that is not an optical locking resonance frequency. When modulated at such non-locking frequencies the OSSL's linewidth degrades progres-

sively from 10 kHz to 20 MHz as the modulation index is increased.

A good optical lock occurs when the laser is modulated at a resonance frequency consistent with Eq. (2). However, these resonances are fairly narrow in modulation frequency and depend directly on the  $Q$  of the cavity, the modulation index, and the optical feedback level. For example, with a locking cavity  $Q \sim 10^7$  (corresponding to a cavity finesse of 10 and a FSR of 245 MHz) and an optical feedback power ratio of about  $10^{-4}$ , the modulation frequency range for good optical locking is approximately 6 MHz wide (centered at the modulation resonance frequency at 245 MHz; see Fig. 2). This range is for a modulation index  $\beta \approx 8$  and increases, as we might expect with smaller modulation index. This resonant character of the laser's FM modulation response limits the modulation formats that can be employed with the OSSL.

Using the technique of optical feedback locking, we find that it is possible to simultaneously have a narrow-linewidth semiconductor laser with a high-sensitivity frequency modulation capability. Frequency modulation induced via the injection current is compatible with the optical stabilization (and narrow linewidth) when the ratio of the modulation frequency to cavity FSR is a rational number. One of the promising applications is to use the modulated OSSL to provide an array of frequency-stabilized local oscillators for frequency-division-multiplexed coherent communication systems. There is also the potential for measuring optical absorption and dispersion with high sensitivity using the techniques of optical heterodyne spectroscopy<sup>10</sup> as well as applications in precision laser measurements and frequency control.<sup>11,12</sup>

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