High-Stability 1.5 μm External-Cavity Semiconductor Lasers for Phase-Lock Applications

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Abstract—**Applications using phase-locked semiconductor lasers, such as homodyne detection, require lasers with narrow linewidth and high-frequency stability. We describe the design and operating characteristics of two 1.5 μm external-cavity semiconductor lasers built for such applications. The measured beat linewidth is 4 kHz, and the spectral density of relative frequency noise deviates significantly from the intrinsic white spectrum only at frequencies below 4 kHz. We estimate that this frequency jitter will induce approximately 1.1° rms phase error in a second-order homodyne optical phase-lock loop that is optimized for the present beat linewidth.**

INTRODUCTION

AMONG schemes for coherent detection of optical signals, PSK homodyne offers the potential advantages of high sensitivity, close channel packing, minimum required receiver bandwidth, and reduced receiver thermal noise [1]. Narrow-line lasers are advantageous in homodyne systems based on pilot-carrier or Costas optical phase-lock loops (OPLL's) because they allow a narrow OPLL bandwidth, permitting small carrier-recovery penalties and long loop propagation delay. In the wavelength range of interest for high-speed fiber-optic communication systems, a narrow-line external-cavity semiconductor laser (ECL) [2] has been phase-locked [3], although no semiconductor-laser homodyne system has been reported. In this letter, we describe two 1.5 μm ECL's that have been phase-locked [4] and that have allowed homodyne detection of 1 Gbit/s pilot-carrier PSK signals [5] with an error rate below 10^{-9}.

LASER DESIGN

We employ a design (Fig. 1) similar to one used by Harrison and Mooradian [6] at 833 nm. The cavity, formed by the high-reflectivity (HR) coated facet of the laser chip and an output coupler, defines a comb of resonant frequencies (735 MHz free spectral range, FSR). A narrow-gap, angle-tuned intracavity etalon, combined with frequency-dependent rolloff of the semiconductor gain, provides loss discrimination to select one lasing frequency. The etalon-based design offers frequency stability because: 1) the entire cavity is made of a low-expansion Invar alloy ($\alpha < 3.4 \times 10^{-7}$/°C), 2) translation of the etalon does not change the cavity length, and 3) angular displacement of the near-normal-incidence etalon affects cavity length only to second order in the angle.

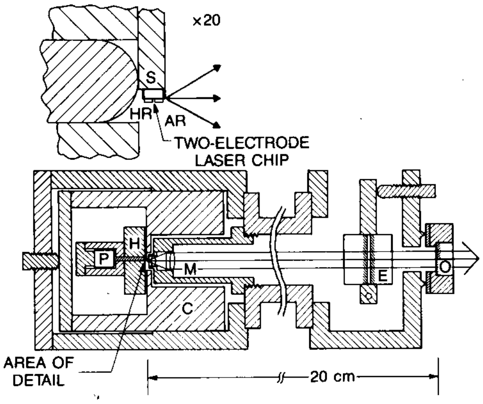

Fig. 1. Design of the external-cavity laser, S = stud, P = PZT element, H = heat sink, C = carriage, M = microscope objective, E = etalon, O = output coupler.

The 400 μm long, channeled-substrate buried heterostructure InGaAsP chips were etched to provide two electrodes of equal length (100 Ω isolation resistance), and had resulting room-temperature thresholds of about 40 mA (with the two electrodes in parallel). Chips were mounted on hard copper studs and coated with six-layer Si/SiO_2 HR ($R > 95$ percent) and nonstoichiometric SiO_x AR ($R < 0.5$ percent) coatings. The stud is held against a thermoelectrically cooled heat sink, fitted (in one ECL) with a pushrod and PZT element to allow continuous frequency tuning over one FSR of the cavity. The heat sink is provided with locking transverse positioners in a carriage which slides for beam focusing. Chip output is collimated by a 50X, 0.85 NA microscope objective, and the beam passes through a 100 μm air gap etalon coated for R = 90 percent at 1.3 and 1.55 μm. The output coupler of one ECL has its inner face coated for R = 50 percent at 1.3 and 1.55 μm; that in the second ECL is coated for R = 38 percent.

OPERATING CHARACTERISTICS

Both ECL's were operated with a total injection current of about 100 mA. In one ECL, this current was equally divided between the two electrodes. To allow frequency modulation [7], the second ECL was operated with only 30 mA in the rear section (HR-coated) to which the modulation signal was applied, and with 70 mA in the front section. Both ECL's exhibited CW output powers of approximately 3.5 mW and emitted at $\lambda = 1.508$ μm. Scanning Fabry–Perot beat spectra and RF spectra between the two lasers showed that spurious

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modes of the external cavity were suppressed by >40 dB, even when the PZT was used to tune one ECL over a full cavity FSR. An RF beat spectrum recorded with 300 kHz resolution bandwidth shows a full width of 2.8 MHz at −40 dB from the peak, allowing us to deconvolve [8] a beat linewidth of 4.0 kHz. This measurement technique assumes a Lorentzian lineshape and is insensitive to acoustic frequency jitter. No linewidth variation was observed as the PZT was used to tune one ECL over the full cavity FSR.

With a modulation signal applied to the low-biased rear electrode, RF beat spectra were used to measure the FM properties of one ECL. Measured FM deviation was a constant 7 MHz/mA at modulation frequencies from 10 kHz to 10 MHz, the highest measured. The FM was in phase with the small residual intensity modulation; as expected, the observed FM was dominated by carrier-density modulation, not thermal modulation.

We used the beat signal between the two ECL's at an IF of 30 MHz, processed by a frequency discriminator, to measure the free-running relative frequency noise and drift. The ECL's were housed in Plexiglas boxes in a ±0.5°C temperature-controlled environment. Ideally, one expects the relative frequency noise spectrum to be white, with a single-sided density $(\Delta\upsilon_{\text{beat}}/\pi)^{1/2} = 35.7\ \text{Hz}/\sqrt{\text{Hz}}$, and we measured a value of 35 $\text{Hz}/\sqrt{\text{Hz}}$ from 1 MHz (the highest frequency measured), down to 40 kHz. Below 40 kHz, the frequency noise density rises due to acoustic and electronic noise. Fig. 2 shows the measured spectral density of frequency noise over the range 600 Hz–20 kHz. The peak at 10 kHz is from intentional FM of one ECL, which was used for calibration of the measurement. An acoustic resonance is seen near 15 kHz, and the noise begins to rise substantially below 4 kHz.

The time dependence of free-running relative frequency is illustrated in Fig. 3. The 3 kHz measurement bandwidth is sufficient, in view of Fig. 2, to show almost the entire relative frequency excursion. The frequency jitter is 1 s [Fig. 3(a)] is 400 kHz pp, dominated by the 60 Hz line noise of a PZT power supply. The frequency drift in 5 min [Fig. 3(b)] shows a total excursion of 600 kHz.

DISCUSSION

For homodyne detection, the effect of the white component of frequency noise (or equivalently, Lorentzian phase noise density) is well understood [9]. Clearly, the present 4 kHz beat linewidth is adequately small for homodyne systems at any bit rate above ~100 Mbits/s, up to the limit imposed by electronics. Also, the relative frequency drift is sufficiently small that in OPLL's with easily realized dc gains, it will induce acceptable phase errors. For example, the second-order OPLL of [4] has a dc loop gain [10] $K_v = 1.3 \times 10^9\ \text{s}^{-1}$, so that the 600 kHz frequency drift of Fig. 3(b) will result in a phase error of 0.17°.

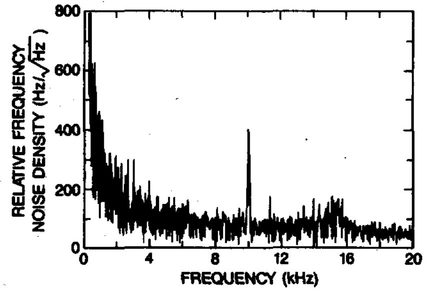

Fig. 2. Density of the relative frequency noise between two lasers. Peak at 10 kHz is from intentional FM used for measurement calibration.

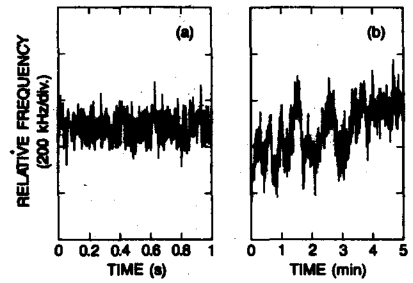

Fig. 3. Time dependence of relative frequency between two lasers. Measurement bandwidth is 3 kHz. Recordings are sampled with Nyquist frequencies: (a) 100 Hz, (b) 1.67 Hz.

To understand the effect on an OPLL of the nonwhite excess frequency noise, consider a sinusoidal noise component of angular frequency ω_m, having peak angular frequency deviation $\Delta\omega$. For a high-gain, second-order OPLL of natural frequency ω_n and damping factor ζ, and for $\omega_m \lesssim \omega_n/4\zeta$, the result [10] is a sinusoidal phase error of peak value:

$$\theta_e\ (\text{rad}) = \frac{\omega_m \Delta\omega}{2\zeta^2\omega_n^2}. \tag{1}$$

This expression can be used to convert the excess frequency noise density (that above the intrinsic white noise) in Fig. 2 to an excess phase error density. We use the parameters ω_n = 590 krad/s and ζ = 0.72 of an OPLL optimized for the present 4 kHz beat linewidth [4]. Integrating this excess phase error density from 600 Hz up to 40 kHz (where the excess frequency noise becomes negligible) yields a total excess phase error of 1.1° rms. This is expected to have negligible incremental impact on an optimized OPLL with 10° rms phase error since these independent errors add in quadrature. The frequency noise density below 600 Hz, which cannot be extracted from Fig. 2, clearly accounts for the majority of the relative frequency excursion [Fig. 3(a)]. However, it is easily shown using (1) that this low-frequency jitter gives negligible contribution to the excess phase error in an OPLL because of the low frequencies involved.

In conclusion, we have built two 1.5 μm ECL's with 4 kHz beat linewidth. Making use of the measured density of relative frequency noise, it has been shown that the frequency jitter should have only a small impact on the phase error in an OPLL optimized for the present beat linewidth.

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