Optical Generation of a mHz-Linewidth Microwave Signal Using Semiconductor Lasers and a Discriminator-Aided Phase-Locked Loop

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***Abstract*— A discriminator-aided optical phase-locked loop (OPLL) with significantly enhanced frequency acquisition capability is presented. Its pull-in range is measured to be 300 MHz and can be easily extended further. Two grating-tuned external-cavity semiconductor lasers (ECSL's) were realized with more than 30-dB side-mode suppression ratio. These two lasers were allowed to beat on a fast detector and were offset phase locked. The generated microwave signal was found to be a replica of the reference RF signal close to the carrier. The noise level was measured to be −70 dBc/Hz close to the carrier and less than −100 dBc/Hz at 4 MHz away and beyond from the carrier. The total phase variance is 0.11 rad^2 over a 500-MHz bandwidth. The linewidth full width at half maximum (FWHM) of the locked signal was directly measured to be of order 1 mHz.**

***Index Terms*—Microwave/millimeter wave, microwave generation, phase-locked loops, semiconductor lasers.**

I. Introduction

OPTICAL FIBER is a medium of inherently low transmission losses, large bandwidth, good immunity to interference, and at the same time, of small size and light weight. These advantages make optical beamforming and steering of phased array antenna at either microwave or millimeter-wave frequencies an interesting alternative to more conventional approaches. One challenge facing this optical approach is to optically generate a microwave (or millimeter-wave) carrier with a well-controlled frequency and phase [1]–[3]. Optical injection locking and offset optical phase locking of two lasers are two effective techniques to achieve this goal [4]–[10]. The optical phase-locking method, which utilizes an optical phase-locked loop (OPLL) to force the heterodyne signal to track the phase of the reference signal, has important advantages over the optical injection method since it requires less stringent optical coupling and offers frequency-tuning capability.

OPLL's were originally suggested for coherent optical communication [11], and recently they were used to generate microwave and millimeter-wave carriers. Microwave signals of megahertz linewidth, SNR 70 dBc/Hz and frequency up to 34 GHz have been demonstrated using diode-pumped Nd:YAG lasers, which inherently have narrow linewidths and good frequency stability [6]. Semiconductor lasers are of special interest because of their compactness, their potential for integration, and their ability for high-speed modulation. They can also operate at different wavelengths—in particular, they can operate at 1.55 μm, the wavelength at which the optical fibers have the lowest loss coefficient. Although dispersion effect may introduce carrier-to-noise power penalty and phase-noise increase, this is known not to be significant for radar applications which require only short transmission distances [12], [13]. Conventional semiconductor lasers have linewidths of many megahertz or more. On the other hand, loop time delay will introduce an extra phase delay in the feedback signal of an OPLL, but the loop stability requirements require that the frequency of the unity open-loop gain not exceed the frequency of the $-180°$ phase crossover point of the open-loop transfer function. Thus, this will limit the maximum achievable gain, and in turn, limit the maximum closed-loop bandwidth, or equivalently, the maximum error function 3-dB bandwidth. Theoretical studies have shown that the maximum laser linewidth for realizable phase locking is 7–8 MHz [14] for a modified first-order loop and 4–10 MHz for a broad-band second-order loop [15]. Wide-band heterodyne OPLL's have been reported. One used multiquantum well lasers having a combined linewidth of 5 MHz to achieve a total phase variance of 1.02 rad^2 [8]. The other one used a high FM response current controlled oscillator laser as the slave laser, and a combined linewidth of 8 MHz to demonstrate a total phase variance of 0.04 rad^2 [9]. Another broad-band OPLL based on a homodyne technique exhibited a total phase variance of 0.15 rad^2 [16]. However, it is well known that semiconductor lasers exhibit a nonlinear frequency modulation response under current injection at different frequencies—thermal effects dominate at low frequencies and carrier effects dominate at frequencies around 10 MHz or higher. This effect, together with the circuit component response, phase-detector limitation, and loop delay time severely complicate the design of large bandwidth OPLL's. Another approach is to use narrow linewidth semiconductor lasers and utilize a narrow-band OPLL. Recent developments of tunable single-mode lasers with an intrinsic linewidth of less than 1 MHz, such as for bulk external-cavity semiconductor lasers (ECSL's), ECSL's with fiber gratings, semiconductor lasers with negative electrical feedback, can relax the requirements on the OPLL bandwidth and make the design of the PLL easier [7], [10], [17], [18].

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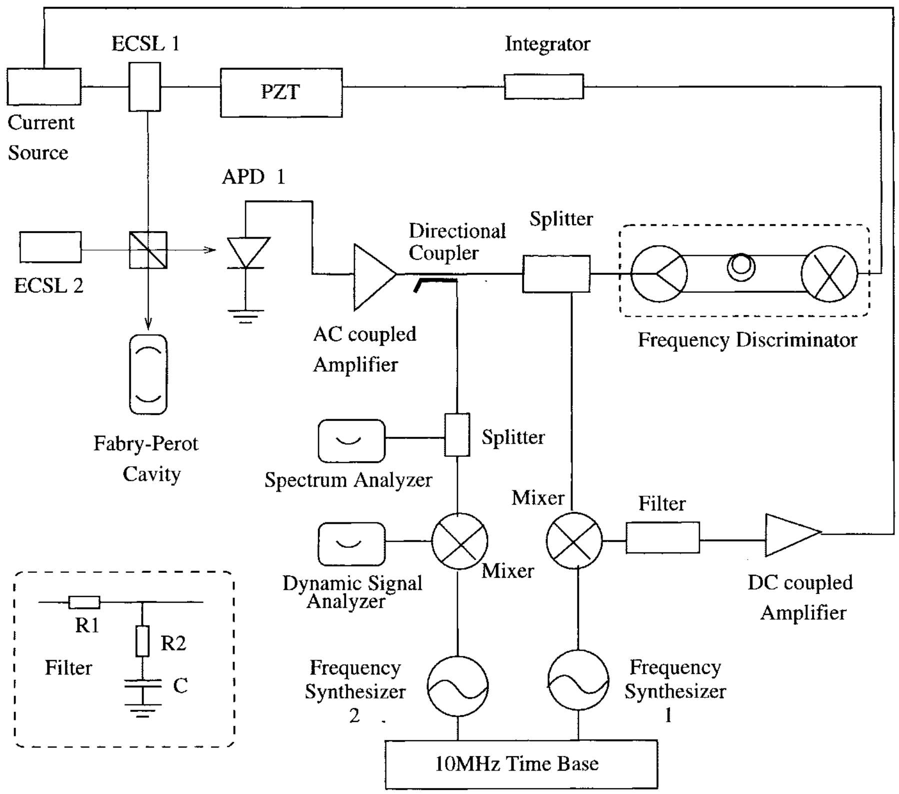

Fig. 1. Schematic of the experimental setup. A PZT is used in the frequency tracking loop and current injection is used in the second PLL.

However, these kinds of lasers have large frequency jitters due to mechanical vibration and acoustical noise, especially for applications such as on-satellite optical generation of microwave signals and airborne radar applications. Although the laser linewidths can be small, the initial heterodyne signal frequency might be far away from the reference RF signal. Therefore, OPLL's with large frequency acquisition capability are required. We note that OPLL's with very large bandwidths have also been demonstrated for large frequency acquisition [9]. However, this latter approach will put a stringent requirement on the loop circuit design as discussed earlier and not take advantage of the narrow linewidth offered by these lasers. Instead, if a simplified circuit can be built for tracking the center frequency and obtaining the initial pull-in, a simpler PLL of moderate bandwidth can then be used to further achieve phase-noise reduction, just as in the case of the aided-acquisition design RF PLL [19]. In such a case, no special care needs to be taken in order to achieve extremely short propagation time or to match the FM response at different frequency ranges. In this paper, we present a discriminator-aided OPLL, which utilizes a delay-line microwave discriminator as the frequency acquisition loop and a second PLL with a small bandwidth to achieve phase-noise reduction. This method was previously used to test the pump-diode modulation of microchip Nd:YAG lasers [20]. Here it is used in a much more demanding application. It is used for improving the frequency-acquisition capability and phase locking of two grating-tuned ECSL's which have a much larger frequency jitter. In our experiment, stable optical phase locking is achieved, phase-noise reduction is demonstrated, and a millihertz-level microwave-signal linewidth is obtained for the heterodyne signal generated by two semiconductor lasers.

II. Experimental Setup

Fig. 1 shows the schematic diagram of the experimental setup using the discriminator-aided OPLL. Two ECSL's built using commercial 830-nm GaAs double heterostructure laser diodes (Sharp/LT015MF0, with front- and back-facet reflectivities $R \sim 5\%$ and $R \sim 95\%$, respectively) are used as the master and slave lasers. Each laser has a holographic grating (1800/mm) set at an angle between the Littrow and Littman configuration [21], with an extra mirror to retroreflect the light twice on the grating for improving the grating dispersion. The grating is oriented such that its groove direction is parallel to the active layer of the laser diode. A half-wave plate is inserted between the lens and the grating. In this design, the laser active region acts as a narrow spectrometer slit with high wavelength selectivity. The elliptically shaped laser beam covers a large portion of the grating, and the dominant TE emission from the laser diode is rotated by the half-wave plate so that it is perpendicular to the grating grooves. In this way, maximum reflectivity from the grating is achieved [22]. Both lasers are operated at around 10% above the threshold. Each laser has a power output about 3 mW and both the lasers lase in a single longitudinal mode with a side-mode suppression ratio better than 30 dB. Coarse tuning of the laser wavelength was achieved by changing the diode temperature and the grating angle so that both lasers can lase at almost the same wavelength to generate the beat signal. Fig. 2 shows the

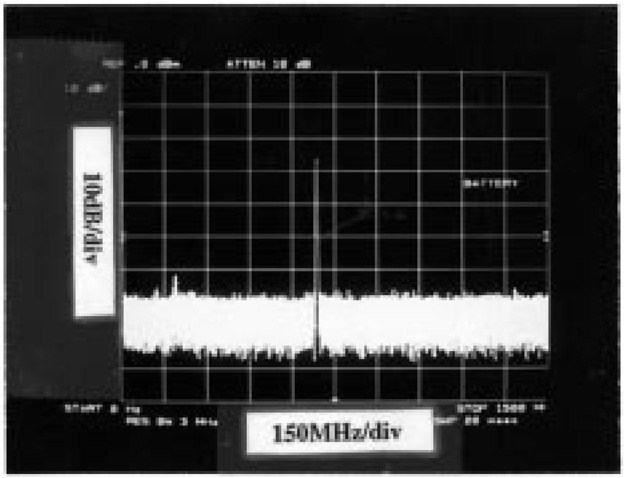

Fig. 2. Beat-signal power spectrum of the free-running lasers showing more than 30-dB side-mode suppression ratio.

beat signal spectrum of two free-running ECSL's. A PZT was attached to the slave laser mirror for adjusting the cavity length and fine tuning the laser frequency. The PZT and the injection-current frequency-tuning coefficients were 50 MHz/V and 15 MHz/mA, respectively. The laser diode temperatures are controlled by TE coolers to better than 0.1 °C. The whole setup was built on a super-invar plate to reduce the temperature drift and was enclosed in a Plexiglas box to reduce the air flow. No temperature-controlled housing was used to achieve further reduction of the mechanical instability. The linewidth of the free-running heterodyne signal between the two lasers was measured to be about 50 kHz for a sweep time of 30 ms and the short-term jitter was measured to be about 2 MHz for 1-s sweep time by an RF spectrum analyzer. The heterodyne-frequency long-term drift was 10 MHz/min. These short- and long-term jitters were due to mechanical and thermal instabilities. This was confirmed by measurement of the jitter-noise frequency spectrum, which showed that most of the jitter-noise energy had frequencies less than 2 kHz and was concentrated mainly around several hundred hertz. The continuous tuning range of the ECSL's without mode hopping was measured to be 150 MHz and more than 1 GHz for current injection and PZT tuning, respectively. The external-cavity longitudinal-mode spacing in the lasers is about 800 MHz, but the residual reflectivity on the diode facet creates an internal cavity which broadens the PZT tuning range.

The two laser beams are attenuated and combined on an avalanche photodetector (APD). The output of the APD is amplified by ac-coupled amplifiers and then split into two parts and sent to two different control loops. The laser output power is sufficient to permit the use of a p-i-n detector in place of the APD, if desired.

A delay-line microwave discriminator has an output characteristic as $\sin(2\pi\delta f\frac{\Delta l}{c/n}) \sim \delta f\frac{\Delta l}{c/n}$, where n is the diffraction index, c is the speed of light, δf is the difference between the input frequency and the quadrature point f_q, and Δl is the length difference between the two arms of the discriminator. The discriminator has a free spectral-range $\frac{c}{n\Delta l}$, which is 600 MHz for the one used in our experiment. Once the signal falls within the half of the free spectral range which includes a quadrature point, the output of the discriminator can be fedback negatively to the slave laser and be used to drive the heterodyne signal to the quadrature point. Since a second-order loop is used for the PLL, a first-order loop is appropriate for this first loop [18]. A simple integrator without any lead zero is used as the loop filter after the discriminator. The output after the integrator is sent to the PZT to control the heterodyne-frequency slow drift by adjusting the slave laser-cavity length. The laser FM response is positive with an increase of the PZT voltage. Thus, when a positive slope for the discriminator is selected, the slave laser is negatively detuned with respect to the master laser so that an overall negative feedback is achieved and vice versa.

A second loop compares the heterodyne signal to a reference RF signal tuned to the quadrature point of the discriminator. The error signal is passed through a first-order passive filter, of which the transfer function is $F(s) = (s\tau_2+1)/(s(\tau_1+\tau_2)+1)$ with $\tau_1 = R_1C$ $\tau_2 = R_2C$, and s is the Laplace variable. The control signal from the output of this filter is fedback to the slave laser-current driver, which amplifies the feedback voltage and transforms it to an output current to modulate the injection current. The transconductance is 100 mA/V. This loop has a second-order closed-loop response and it corrects the phase error after the first loop achieves the initial frequency acquisition.

III. Results and Discussion

Once the heterodyne signal is tuned to the vicinity of the quadrature point, the locking happens. By using the first loop alone, the heterodyne signal is stably locked within a range of less than 2 MHz, which is adequate for the second loop to phase lock the two lasers. It was observed that the long-term drift was fully controlled and the short-term jitter was partially reduced.

Fig. 3 shows the spectral shape of the heterodyne signal when both loops are turned on. This figure shows that the phase noise within the 3-dB bandwidth of the error-function response is drastically controlled and is effectively suppressed up to a range of about 720 kHz around the center frequency of the beat signal. The noise power spectrum is an important measure of the quality of a microwave signal for applications in communication [10]–[12] or for radar systems [23], [24]. The noise is measured to be −70 dBc/Hz close to the carrier, less than −65 dBc/Hz at the side peaks, and less than −100 dBc/Hz when it is measured 4 MHz away and beyond from the carrier. The total phase variance is estimated by using $\exp(-\sigma^2) = P_0/\int P\,df$ [18]. The phase-noise power is integrated numerically inside the 2-MHz spectral range and estimated using a Lorentzian tail up to ±250 MHz. This gives a total phase noise of 0.11 rad^2 over a 500-MHz bandwidth. In our experiment, no special care is taken to increase the second loop bandwidth. A commercial laser-diode driver fabricated with low-speed operational amplifiers was used. The circuit had only a 1-MHz bandwidth and an associated large time delay, therefore limiting the second loop bandwidth. It is expected that the phase noise can be reduced further by using

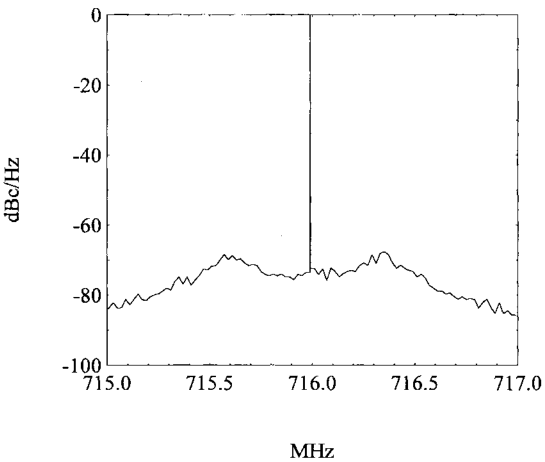

Fig. 3. Power spectrum of the heterodyne signal with both loops closed: vertical scale is 10 dB/div and horizontal scale is 200 kHz/div. Total sweep time is 5 s.

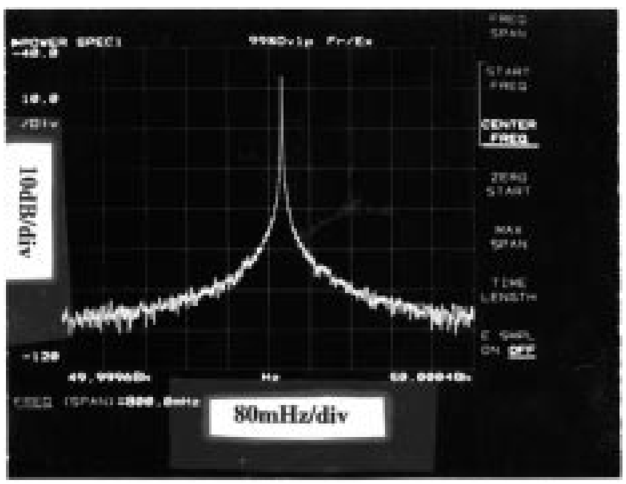

Fig. 4. Detailed spectral shape of the phase-locked heterodyne signal: vertical scale is 10 dB/div and horizontal scale is 80 mHz/div. Total sweep time is 16.7 min and resolution bandwidth is 1 mHz.

a larger bandwidth design. Another important aspect of a microwave signal used for a radar system, especially for a Doppler radar system, is the carrier linewidth, because this will determine the measurement resolution of such a system [23], [24]. It has previously been assumed that the linewidth of the locked carrier signal will be similar to that of the reference signal [8]–[10], but such a direct measurement has not yet been done on a PLL system using semiconductor lasers. In our experiment, since the RF power-spectrum analyzer has a minimum resolution bandwidth of 10 Hz, a second signal generator is used to mix the generated microwave signal down to 50 kHz and a high-resolution HP3562A dynamic-signal analyzer is used to measure the very narrow locked-signal linewidth. These two signal generators are phase locked to the same 10-MHz time base to get rid of their relative frequency drift. Fig. 4 shows that the full width at half maximum (FWHM) linewidth of the locked signal is not more than the resolution bandwidth of the measurement, which is 1 mHz. This verifies that the PLL can track the RF reference signal to better than 1 mHz when using semiconductor lasers.

The pull-in range in this experiment was equal to a half of the discriminator free spectral range, which was 300 MHz, limited by the chosen discriminator length difference Δl. If the length difference is made shorter, this range can be further increased up to the limit set by the PZT continuous tuning range, which is more than 1 GHz. This greatly relaxes the bandwidth requirement on the second PLL, and indeed, makes it possible for the second PLL with a bandwidth below 1 MHz to successfully phase lock the two ECSL's with large frequency jitter. Different quadrature points can be used to lock the lasers. In different experiments, the lasers were offset locked to two different quadrature points at frequencies of 716 MHz and 1.31 GHz. Other quadrature points can be used as well. The exact frequency locking point can be tuned by changing the frequency locking-loop offset voltage so that the center frequency of the frequency loop overlaps with the reference signal.

Directly related to the increase of the pull-in range is a reduction of the pull-in time. A second-order PLL with bandwidth $\omega_{\rm LB}$ has a pull-in time $t_p = 4.2(\delta f)^2/(\omega_{\rm LB})^3$, where δf is the initial frequency separation between the heterodyne signal and the reference signal [14]. For a narrow bandwidth PLL and when δf is large, it would take a significantly long time for the loop to achieve the initial pull-in. It is important to realize that a discriminator output is directly proportional to the initial frequency separation, in a similar way to an optical frequency detector used for automatic frequency control (AFC) in coherent optical detection [25]. The pull-in process is very fast and is limited only by the loop delay and the slave laser response, which was estimated to be of the order of milliseconds in our experiment, largely determined by the PZT response. This frequency loop, if combined with a fast-tuning DFB laser, could be used as a fast frequency-switching technique.

The laser diodes used in our experiments have front-facet reflectivity of 5%. If angled-facet laser diodes are used, an ultra-low reflectivity can be achieved and a 50-dB side-mode suppression ratio has recently been realized [26]. This will further help the phase-noise reduction. In our experiment, only a single detector was used. This implies that when the laser is modulated using current injection, the amplitude is slightly altered as well. This will induce an error in the feedback signal and thus limit the phase-noise reduction. If a differential detector pair is used, this kind of intensity-induced error can be eliminated.

The work presented here was done at 830 nm, but it can be easily extended to 1.3 or 1.55 μm. In future work, miniature ECSL's with fiber grating and ECSL's with micromachined mirrors can be used. If they are combined with the large frequency acquisition and the good phase-noise reduction capability of the discriminator-aided OPLL presented here, a simple, robust, and inexpensive optical microwave-signal generation system can be realized.

IV. Summary

A discriminator-aided OPLL was demonstrated using grating-tuned ECSL's. A pull-in range of 300 MHz was achieved and two grating-tuned ECSL's with large drift were successfully phase locked. A total phase variance of 0.11 rad^2 was obtained over a 500-MHz bandwidth. This experiment verifies that a discriminator-aided OPLL can significantly improve the frequency acquisition capability of a moderate bandwidth PLL. The results also show that microwave signals of millihertz-level linewidth with good phase-noise suppression can be achieved using offset phase locking of two semiconductor lasers. This is an important step toward the practical realization of optically generated microwave/millimeter-wave signals.

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