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Highly Coherent RF Signal Generation by Heterodyne Optical Phase Locking of External Cavity Semiconductor Lasers

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***Abstract*— Two narrow-linewidth (<50 kHz) external cavity semiconductor lasers are successfully offset phase-locked to a reference radio-frequency (RF) signal by using a discriminator-aided optical phase-locked loop. By incorporating a phase advance circuit to increase the loop bandwidth, a highly coherent optically heterodyned RF signal with a total phase variance of 1.19×10^{-4} rad^2 is demonstrated. The measured noise level is -116 dBc/Hz close to the carrier (200-kHz offset), increases to -110 dBc/Hz at an offset of 5.5 MHz, and then decreases to less than -120 dBc/Hz at offset frequencies larger than 10 MHz.**

***Index Terms*—Fiber optics, microwave generation, microwave/millimeter wave, phase-locked loop, RF, semiconductor lasers.**

f 711 MHz

I. INTRODUCTION

OPTICAL fiber is a promising medium for analog signal transmission since it has inherently low transmission loss, large bandwidth, immunity to interference, and is of small size and lightweight. One challenge facing this approach is to optically generate a radio-frequency (RF), microwave, or millimeter-wave carrier with a well-controlled frequency and phase. Heterodyne optical phase locking of two lasers has been used to achieve this goal [1]–[8]. However, many radar and communication systems require a narrow carrier linewidth with a very low noise level over a large bandwidth [9], [10]. Grating tuned external cavity semiconductor lasers (ECSL's) are promising sources for optical heterodyne generation of a high-quality carrier signal. Unlike diode pumped Nd:YAG lasers, ECSL's have very large tuning capabilities and are available at fiber compatible wavelengths, such as 830 nm, 1.3 μm, and 1.55 μm. Compared to conventional Fabry–Perot semiconductor lasers, ECSL's have intrinsically narrower linewidths, therefore, lower phase noise levels. This not only relaxes the stringent requirements on the phase-locked loop design, but also provides the potential of generating heterodyned signals with very low phase noise. Despite the center frequency jitter induced by mechanical and thermal instabilities, two ECSL's have recently been reliably offset phase locked by a discriminator-aided optical phase-locked loop (OPLL) with an improved frequency acquisition capability [8]. Here, we report on an enhanced OPLL, that generates a highly coherent RF signal with a phase variance of only 1.19×10^{-4} rad^2, an improvement of more than an order of magnitude over previous results [4]–[8].

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PZT = Piezoelectric Transducer

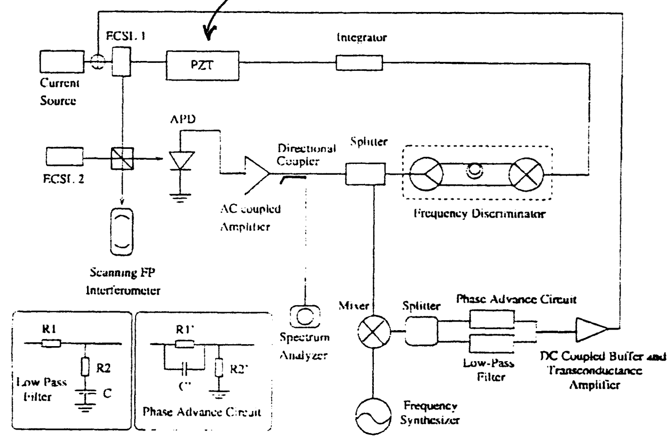

Fig. 1. Schematic of the OPLL experimental setup.

II. EXPERIMENTAL SETUP

Fig. 1 shows the schematic diagram of the experimental setup using the discriminator-aided OPLL. Two grating coupled ECSL's built using 830-nm GaAs laser diodes (Sharp/LT015MF0, with front and back facet reflectivities $R \sim 5\%$ and $R \sim 95\%$, respectively) are used as the master and the slave lasers. Each ECSL has a holographic grating (1800/mm), with an extra mirror for double pass reflection to improve the grating dispersion. Both ECSL's operate in a single longitudinal mode with a sidemode suppression ratio greater than 38 dB.

The optical output beams from both ECSL's are combined on an avalanche photodetector (APD). The resultant heterodyned RF signal from the APD is amplified by ac-coupled amplifiers. A small portion of the heterodyned signal is sampled for monitoring on an RF spectrum analyzer. The remainder of the signal is used to drive the OPLL.

The OPLL contains two control loops: a slow discriminator-aided frequency acquisition loop and a fast phase-locked loop. The first control loop consists of a delay line discriminator with a free-spectral range of 600 MHz, an integrator and a piezoelectric transducer (PZT) controller. A PZT is attached to the mirror of the slave ECSL for adjusting the cavity length and fine tuning the optical frequency with a tuning coefficient of 50 MHz/V. The polarity of the integrated feedback signal is carefully controlled so that an overall negative feedback is achieved. Once the heterodyned signal frequency falls within half the free-spectral range of a discriminator quadrature point, the integrated output of the discriminator drives the PZT to lock the heterodyned signal to the quadrature point. This discriminator-aided control loop provides initial frequency acquisition and also compensates for the slow frequency drift of the heterodyned signal [8].

The second control loop compares the heterodyned signal to a reference RF signal tuned to the quadrature point of the discriminator. The error signal is split with half the signal passing through a passive low-pass filter and the other half passing through a phase advance circuit (PAC), as shown in Fig. 1. The first-order low-pass filter has a transfer function $F(s) = (s\tau_2 + 1)/(s(\tau_1 + \tau_2) + 1)$, where $\tau_1 = R_1C$, $\tau_2 = R_2C$, and $s = i2\pi f$ is the Laplace variable. This filter was chosen to efficiently suppress the low frequency (~kHz) phase noise of the ECSL's. It provides a standard second-order closed-loop response [11]. The purpose of the PAC is to increase the loop bandwidth and its design will be discussed in the next section. The control voltage from the output of this complex filter is fedback using a high-speed buffer amplifier followed by a wide bandwidth transconductance amplifier. The transconductance amplifier has a transconductance of 60 mA/V with a bandwidth of approximately 200 MHz. The current output is then combined with the slave laser dc-bias current, and it corrects the phase error after the first loop achieves initial frequency acquisition. The injection current frequency tuning coefficient of the slave laser is 15 MHz/mA.

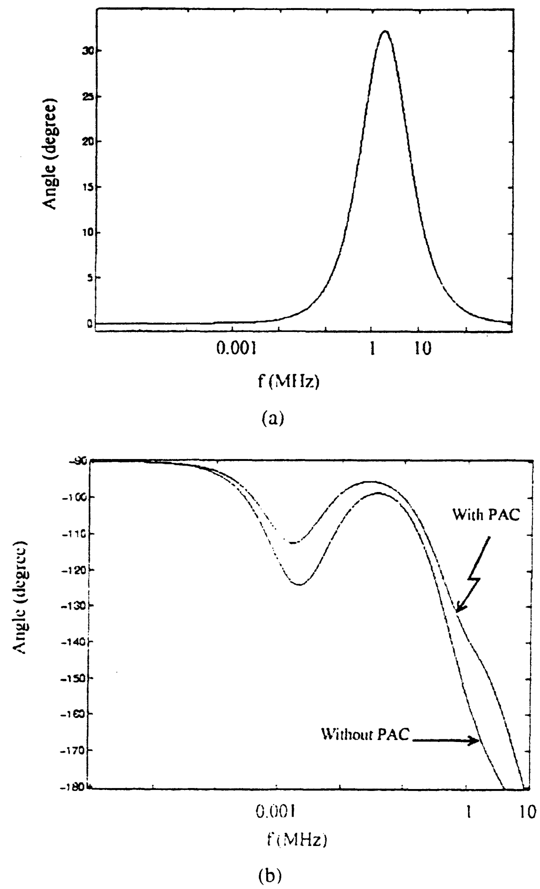

Fig. 2. (a) Phase response of the PAC. (b) Phase response of the open-loop transfer function. The following parameters are used in the simulation: $R_1 = 5$ kΩ, $R_2 = 2$ kΩ, $C = 20$ nf, $R_1' = 8$ kΩ, $R_2' = 3.5$ kΩ, $C' = 20$ pf, $\alpha = 500$ kHz, $\tau_d = 5$ ns.

III. PAC Design

In order to understand the effect of the PAC, we need to consider the open-loop response of the complete OPLL. The slave laser has approximately a single-pole FM modulation response $D(f) \sim \alpha/(if + \alpha)$. The physical mechanism for FM modulation is the variation of the laser diode refractive index due to heating induced by the injection current. The time constant for this thermal effect is a few microseconds, hence, α is at the order of several hundred kilohertz to 1 MHz. The loop component response and the physical size of the system introduce a loop time delay τ_d. Including all these effects, the total open-loop transfer function can be expressed as [11]

$$G(f) = G_0F(f)\frac{1}{i2\pi f}D(f)\exp(-i2\pi f\tau_d) \qquad (1)$$

where G_0 accounts for the overall gain from all the loop components. We can see that both the slave laser FM modulation response and the loop time delay induce a phase delay in the feedback signal. Loop stability requires that the amplitude of this open loop transfer function should be less than unity at the $-180°$ phase cross-over frequency ($f_{-\pi}$) of $G(f)$ [11]. This limits the maximum achievable gain, and thus the maximum loop bandwidth. Beyond this point, the loop starts to oscillate. The PAC, in parallel with the low-pass filter, has a characteristic high-pass response $F'(s) = (sC'R_1' + 1)/(sC'R_1' + R_1'/R_2' + 1)$. Fig. 2(a) indicates that the PAC has a nonnegative phase at all frequencies and significantly advances the phase over a large frequency band. By proper design, the overall open-loop transfer function will be dominated by the low pass filter in the low-frequency regime, while the PAC introduces a phase increase of the open-loop transfer function in the high-frequency regime as compared to the case without the PAC. This strategy can introduce an extra phase margin and increase the $f_{-\pi}$. Therefore, it can increase the maximum achievable gain and produce a larger loop bandwidth.

Numerical simulations were carried out to verify this behavior. These simulations used $\alpha = 500$ kHz and an estimated loop time delay $\tau_d = 5$ ns. Fig. 2(b) shows the phase response of the open-loop transfer function for both the case without and with the PAC. If the PAC is not used, $f_{-\pi}$ is 3.9 MHz; if the PAC is used, $f_{-\pi}$ is increased to 8.3 MHz. The maximum achievable gain (with 0 phase margin) was calculated to be 0.62 GHz for the case without the PAC and 1.2 GHz for the case with the PAC. For the case with the PAC and G_o set to 0.62 GHz, the unity gain frequency is 5.2 MHz and the corresponding phase is $-168°$. These simulation results demonstrate that the PAC introduces an additional 12° phase margin enabling 5.3-dB higher open-loop gain compared to the

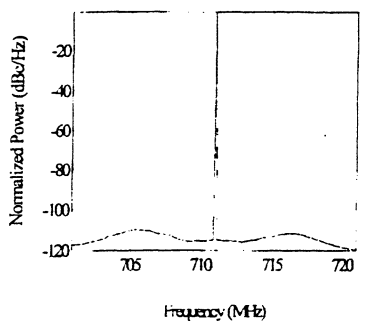

Fig. 3. Power spectrum of the phase-locked heterodyned RF signal.

identical circuit without the PAC. Hence, the PAC can increase the loop bandwidth of the OPLL.

IV. Results and Discussion

The free running heterodyned RF signal was observed on a spectrum analyzer prior to engaging the OPLL. Its linewidth was measured to be about 50 kHz for a sweep time of 30 ms. In the locking experiment, the RF reference signal power level was carefully adjusted so that the overall gain was varied until the best locked signal was achieved.

Approximately a 5.5-MHz loop bandwidth was achieved after the PAC was built, compared to a 2.5-MHz loop bandwidth in the case without the PAC. The RF power spectrum of the phase-locked heterodyned signal is shown in Fig. 3. This figure shows that the noise is effectively suppressed within the OPLL loop bandwidth corresponding to approximately ± 5.5 MHz around the the 711-MHz center frequency of the heterodyned signal. This compares favorably with the 2.5-MHz loop bandwidth obtained without the PAC. The noise level is measured to be -116 dBc/Hz at 200 kHz away from the carrier. The noise peaks at -110 dBc/Hz at 5.5-MHz carrier offset, then decreases at larger frequencies. It is less than -120 dBc/Hz for carrier offsets larger than 10 MHz. The total phase variance is estimated as in [8] by numerically integrating the noise power inside the 20-MHz spectral range and approximated using a Lorentzian tail up to ± 250 MHz. A total phase variance of 1.19×10^{-4} rad^2 over a 250-MHz bandwidth is determined. This is the lowest phase variance result yet reported [4]–[8]. By mixing the heterodyned signal down to 50 kHz using a second signal generator and displaying it on a high resolution HP3562A dynamic signal analyzer, the full-width at half-maximum (FWHM) linewidth of the generated signal is confirmed to be not more than 1 mHz. Hence, within the resolution bandwidth of our instrument, this measurement verifies that close to the carrier, the offset phase-locked signal replicates the reference RF signal.

In the experiment, the ECSL's were locked to quadrature point at 711 MHz. They were also locked at 1.31 GHz and similar results were obtained. Other higher frequency quadrature points can be used to lock the ECSL's depending primarily upon the availability of microwave/millimeter wave components. Also, the exact frequency locking point can be tuned by changing the frequency locking loop integrator offset voltage so that the center frequency of the frequency loop overlaps with the reference signal. In future work, the loop delay time of the second loop can be reduced by using miniature ECSL's with fiber grating or ECSL's with micro-machined optics. This will increase the loop bandwidth and improve the OPLL performance even further. A differential detector pair can also be used to eliminate the error induced by amplitude noise. This work is currently being extended to 1.3 and 1.55 μm.

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V. Conclusion

Two grating coupled, narrow-linewidth ECSL's were successfully offset phased locked by using a discriminator-aided optical phase-locked loop with a new phase advance circuit design. A highly coherent RF signal with a total phase variance of 1.19×10^{-4} rad^2 was obtained over a 250-MHz bandwidth. The noise level was less than -116 dBc/Hz close to the carrier, increases to -110 dBc/Hz at 5.5-MHz offset, and then decreases to less than -120 dBc/Hz at offset frequencies larger than 10 MHz. The phase-locked heterodyned RF signal was observed to replicate the reference signal close to the carrier within the limit of our instrumentation (1-mHz linewidth). These results show that with proper phase-locked loop design the phase variance of the optically generated signal can be significantly reduced which is crucial in many actual system applications.

References

[1] K. J. Williams, L. Goldberg, R. D. Esman, M. Dagenais, and J. F. Weller, "6–34 GHz offset phase-locking of Nd:YAG 1319 nm nonplanar ring lasers," *Electron. Lett.*, vol. 25, no. 18, pp. 1242–1243, 1989.

[2] R. C. Steele, "Optical phase-locked loop using semiconductor laser diodes," *Electron. Lett.*, vol. 19, no. 2, pp. 69–70, 1983.

[3] J. Harrison and A. Mooradian, "Linewidth and offset frequency locking of external cavity GaAlAs lasers," *IEEE J. Quantum Electron.*, vol. 25, no. 6, pp. 1152–1155, 1989.

[4] R. T. Ramos and A. J. Seeds, "Fast heterodyne optical phase-lock loop using double quantum well laser diodes," *Electron. Lett.*, vol. 28, no. 1, pp. 82–83, 1992.

[5] U. Gliese, T. N. Nielsen, M. Bruun, E. L. Christensen, K. E. Stubkjaer, S. Lindgren, and B. Broberg, "A wideband heterodyne optical phase-locked loop for generation of 3–18 GHz microwave carriers," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 936–938, Aug. 1992.

[6] C. Shin and M. Ohtsu, "Heterodyne optical phase-locked loop by confocal Fabry-Perot cavity coupled AlGaAs lasers," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 297–300, Apr. 1990.

[7] G. Santarelli, A. Clairon, S. N. Lea, and G. M. Tino, "Heterodyne optical phase-locking of extended-cavity semiconductor lasers at 9 GHz," *Opt. Commun.*, vol. 104, no. 4, pp. 339–344, 1994.

[8] Z. F. Fan and M. Dagenais, "Optical generation of a MHz linewidth microwave signal using semiconductor lasers and a discriminator-aided phase-locked loop," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pt. II, pp. 1296–1300, Aug. 1997.

[9] R. S. Raven, "Requirements for master oscillators for coherent radar," *Proc. IEEE*, vol. 54, pp. 237–243, Feb. 1966.

[10] D. B. Leeson and G. F. Johnson, "Short term stability for a Doppler Radar: Requirements, measurements and techniques," *Proc. IEEE*, vol. 54, pp. 244–248, Feb. 1966.