A Low Phase Noise Dual Loop Optoelectronic Oscillator as a Voltage Controlled Oscillator with Phase Locked Loop

Daryl T. Spencer*, Sudharsanan Srinivasan, Aaron Bluestone, Danielle Guerra, Luke Theogarajan, and John E. Bowers
Department of Electrical and Computer Engineering
University of California Santa Barbara, Santa Barbara, CA 93106 USA
* darylt@ece.ucsb.edu

Abstract: We demonstrate phase noise improvement in a high frequency 20 GHz optoelectronic oscillator through dual delay lines and phase locking to a low frequency oven controlled crystal oscillator.

Introduction

Modern wireless communication systems, such as analog to digital converters and radar systems, require low phase noise local oscillators at frequencies greater than 10 GHz. At such high frequencies, electrical oscillators suffer from parasitic losses that decrease the quality factor and increase close to carrier phase noise which degrades the signal-to-noise ratio at the receiver. Direct up-conversion of stable oscillators at low frequencies suffer from a $20\times\log_{10}(N)$ increase in phase noise for a multiplication factor of N. Optoelectronic oscillators (OEO) utilize the low loss of optical fiber to achieve very high microwave quality factors at high frequencies that are much higher than those achievable in the electrical domain [1]. However, further research into proper operation, tunability, and stabilization for long time scales is required. We present a dual loop OEO operating at 20 GHz that has been stabilized with multiple techniques in the optical domain as well as electronically stabilized as a voltage controlled oscillator (VCO) with a phase lock loop (PLL) to a low frequency reference for long term stability, a region in which OEOs usually suffer due to fiber drift.

OEO System Design

The OEO generates spectrally pure microwave tones through the use of an analog optical link with electronic feedback. The output of a high power fiber laser passes through an intensity modulator, fiber delay, and is detected on a high speed photodetector (PD). The frequency of oscillation is selected with a microwave filter, and any required amplifiers and phase shifter are added before closing the microwave loop to the intensity modulator. The main advantages of the OEO architecture are the tunability of microwave frequency with a microwave phase shift, and the long delay times that can be achieved because of very low optical losses of 0.2 dB/km. The longest delay of 10 km used in this study can produce effective microwave quality factors of 10 billion, though this is degraded by any component's flicker noise. With such long lengths, the free spectral range (FSR) of the loop becomes very narrow (20 kHz) and requires additional filtering for mode selection and spurious tone suppression. Since 20 GHz microwave filters are not commercially available with sub-MHz linewidths, we implement a dual loop OEO that utilizes the Vernier effect of a second 100 m loop to select a single oscillating mode, as shown in the left side of Fig. 1. Two microwave amplifiers are placed directly after the photodetectors to keep the open loop noise figure low.

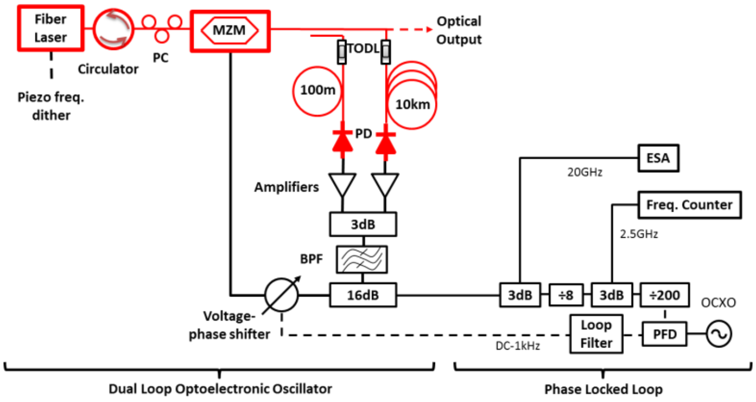


Fig. 1. Schematic of the dual loop OEO (left) utilized as a VCO for PLL feedback (right). The fiber laser output is controlled with a polarization controller (PC) before being sent to a Mach-Zender Modulator (MZM). Tunable optical delay lines (TODL) control the Vernier effect, and the photodetectors (PD) generate the microwave signal sent through the band pass filter (BPF). After frequency division, the phase frequency detector (PFD) compares the dual loop OEO noise to an oven controlled crystal oscillator (OCXO), and sends the feedback signal to the OEO. Measurements are performed on an electrical spectrum analyzer (ESA), frequency counter, and optical frequency discriminator.

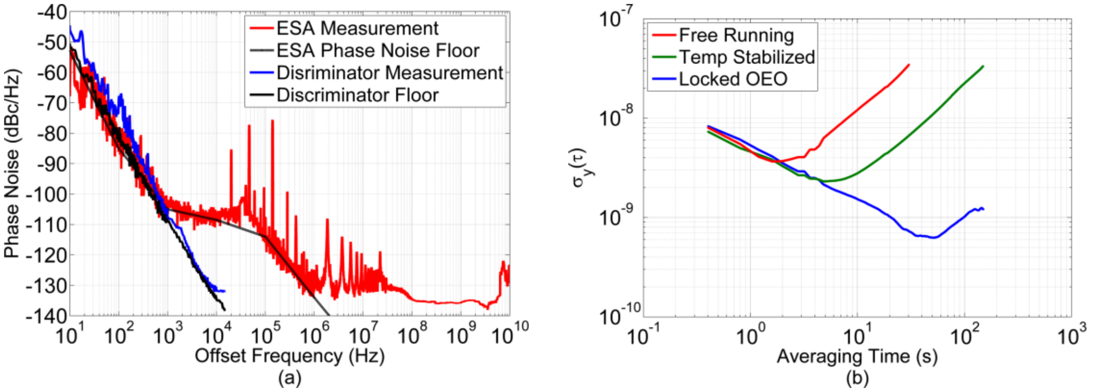
The OEO is also known to be highly sensitive to reflections reaching the laser, and the intracavity optical power can become limited by fiber scattering [2]. To circumvent these problems, we added a fiber circulator after the high power fiber laser and broaden the fiber linewidth by dithering the built in piezo frequency tuner, respectively. The resulting short term linewidth of the microwave signal is sub-Hz level, but a major issue with fiber delays is the $dn/dT \sim 1.2\times10^{-5}/°\text{C}$ associated

978-1-4577-1504-4/14/$26.00 ©2014 IEEE

with thermal fluctuations [3]. A change in the optical path length from temperature drift will cause the 20.05 GHz oscillating frequency to shift, which we observed to be ~1 kHz/min. We reduced this to ~200 Hz/min by placing the system in a sealed anechoic enclosure with a stabilization time of 5 hours. To further reduce the long term linewidth (or close in phase noise), we have used a PLL circuit board which utilizes the dual loop OEO as a VCO. As shown in the right side of Fig. 1, the PLL circuit requires the 20.05 GHz signal to be frequency divided to a digital 12.5 MHz signal. The on board mixer then compares the OEO noise to a 100 MHz OXCO, and sends the correction signal to the voltage controlled microwave phase shifter with a bandwidth of 1 kHz. Tunable optical delay lines were placed in each arm to precisely tune the oscillating frequency to a multiple of the reference frequency at the PFD.

Results

Three measurement methods were employed to characterize the performance of the OEO. The ESA (Rhode & Schwarz FSU50) provides the most straightforward method of measuring phase noise, as it has an internal synthesizer, reference oscillator, and tunable filters for a large measurement of offset frequencies from 1 Hz to the Nyquist rate. The second method used an optical delay line based frequency discriminator and an Agilent E5505 phase noise test set, to provide a lower phase noise floor versus the ESA for certain frequency offsets. Both results are shown in Fig. 2a. Using the ESA, the white phase noise floor is -138 dBc/Hz, limited by the thermal noise of our microwave amplifiers. The rise in phase noise at 1 MHz in is due to the ESA's internal noise floor. Using the frequency discriminator, we show a phase noise of -134 dBc/Hz at 10 kHz with a $1/f^3$ slope, limited by the residual noise of our discriminator.



(a) (b)

Fig. 2. (a) Phase noise spectrum of the dual loop OEO as measured by the ESA and 4.2 km optical frequency discriminator. (b) Overlapping Allan deviation of the dual loop OEO, measured at 2.5 GHz.

We also used a frequency counter with an OCXO reference to characterize the difference between the locked and unlocked OEO. Fig. 2b plots the frequency deviation, $\Delta f / f$, for different averaging times to obtain the Allan deviation. Both the locked and unlocked oscillators show white frequency noise ($\tau^{-1/2}$), but the locked oscillator converges to a stability of less than 1 ppb at 50 seconds averaging time before reaching frequency drift (τ^2). We believe the current results to be limited by the quantization error of our frequency counter.

Conclusion

We have demonstrated a low phase noise dual loop OEO operating in the K band. To achieve low noise and stable performance, multiple tactics have been applied to the basic OEO architecture. Fiber scattering, spurious tones, and mode hopping effects have been decreased through linewidth broadening and adding a second fiber loop. To increase the long term stability, we have implemented a PLL to transfer the ppb stability of a low frequency OCXO to the high frequency dual loop OEO. The challenges in operating the dual loop OEO as a VCO were overcome with optical path tuning control and temperature stabilization. This structure can be integrated onto the hybrid silicon platform [4] using ultralow loss waveguides to replace the fiber loops and that should greatly increase the stability and sensitivity to environmental fluctuations. This research was supported by DARPA MTO under the EPHI contract and NSF Fellowship for DS (Grant No. DGE-1144085). The authors thank Josh Conway, Martijn Heck, Greg Book, Erik Norberg, and Leif Johansson for helpful discussions.

References

1. X. S. Yao, L. Maleki, and D. Eliyahu, in *2004 IEEE MTT-S International Microwave Symposium Digest* (IEEE, 2004), Vol. 1, pp. 287–290.
2. D. Eliyahu, D. Seidel, and L. Maleki, IEEE Trans. Microw. Theory Tech. **56**, 449 (2008).
3. D. Eliyahu, K. Sariri, A. Kamran, and M. Tokhmakhian, in *Proceedings of the 2002 IEEE International Frequency Control Symposium and PDA Exhibition* (IEEE, 2002), pp. 580–583.
4. M. J. R. Heck, J. F. Bauters, M. L. Davenport, D. T. Spencer, and J. E. Bowers, Laser Photon. Rev. (2014).