Optical frequency self stabilization in a coupled optoelectronic oscillator

F. Quinlan, S. Gee, S. Ozharar, P. J. Delfyett
CREOL, The College of Optics and Photonics
University of Central Florida
Orlando FL, USA
fquinlan@creol.ucf.edu, delfyett@creol.ucf.edu

***Abstract*— The technique of incorporating a high finesse Fabry-Perot etalon (FPE) for optical frequency stabilization and supermode suppression of an actively, harmonically mode-locked laser has been combined with the basic coupled optoelectronic oscillator (COEO) design to produce a completely self contained optical frequency stabilized COEO. In this way the nominal COEO frequency, the stability of the optical frequencies, and the long term stability of the COEO signal are all referenced to a single intracavity high finesse FPE.**

I. Introduction

Low noise, high repetition rate mode-locked lasers have a number of potential applications in signal processing and coherent communications [1]. For applications such as the generation of arbitrary RF waveforms and photonic sampling, pulse-to-pulse timing and amplitude jitter are more important than optical frequency stability, and laser cavities can be designed that sacrifice optical stability in favor of increased timing stability [2]. However, a number of applications such as optical code division multiple access (OCDMA) and optical arbitrary waveform synthesis require a set of phase locked frequencies with multigigahertz spacing and high stability. A successful method to simultaneously achieve low timing and amplitude jitter as well as optical frequency stability is using an intracavity etalon in a harmonically mode-locked laser [3]. Harmonic mode-locking can be described in the frequency domain as a collection of interleaved optical supermodes. Each optical supermode consists of phase locked modes separated by the pulse repetition rate whereas different supermodes are separated by the inverse of the cavity round trip time [4]. Placing a high finesse etalon into the laser cavity with a free spectral range equal to the pulse repetition rate selects a single optical supermode that can then be used for frequency domain applications. Moreover, the optical frequencies can be stabilized via the Pound-Drever-Hall laser frequency stabilization method using the same intracavity etalon [3, 5]. By selecting a single optical supermode, the intracavity etalon also suppresses the supermode noise spurs that contribute to the pulse-to-pulse timing and amplitude noise. Also, by using a long laser cavity and harmonic mode-locking, the linewidth of the individual optical modes can be reduced while a high pulse repetition rate is maintained. The narrow optical linewidths produced are advantageous for high spectral efficiency coherent communication modulation formats [6], and the reduction of the spontaneous emission contribution to the timing jitter [4].

In addition to spontaneous emission, a major source of timing jitter in an actively mode-locked laser is the phase noise of the RF source used for mode-locking. A way to remove this source of timing jitter is to exploit the high Q of a mode-locked laser and convert it into a coupled optoelectronic oscillator (COEO) [7]. However, in the conventional COEO, no effort is made to generate a stabilized optical frequency comb. By combining the technique of incorporating a high finesse etalon in a harmonically mode-locked laser with the conventional COEO, a completely self contained optical frequency stabilized oscillator was built and characterized. With the incorporation of an etalon, a COEO can be utilized for a host of new applications relying on a stabilized optical frequency comb.

In the following section, the mode-locked laser used as the basis of the COEO is described in the actively mode-locked state. In Section III, the COEO with optical frequency self stabilization is presented. The results are summarized in Section IV.

II. Harmonic Mode-Locking with an Intracvity Etalon

The harmonically mode-locked, semiconductor gain-based laser with an intracavity etalon is shown in Fig. 1. The cavity fundamental frequency is 34 MHz corresponding to a cavity length of 5.9 m. A dispersion compensating fiber section of 43 cm is included to reduce the cavity dispersion. Mode-locking is achieved via loss modulation using a Mach-Zehnder style modulator at 10.24 GHz. This frequency corresponds to the ~300th harmonic of the cavity fundamental frequency. A high finesse (~100) air gap Fabry-Perot etalon (FPE) with

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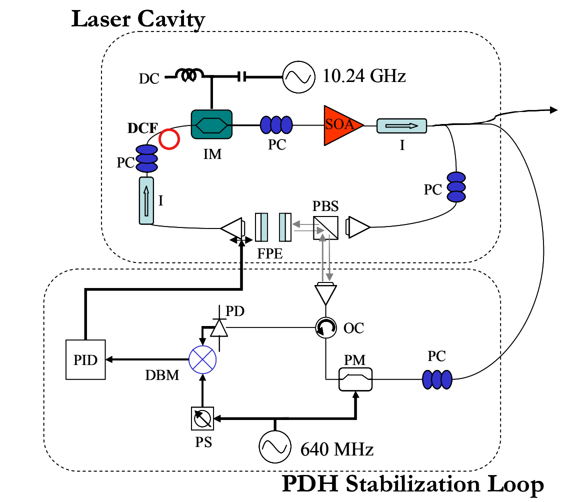

Figure 1. Actively mode-locked laser with laser frequency stabilization through Pound-Drever-Hall. SOA, semiconductor optical amplifier; DCF, dispersion compensating fiber; I, isolator; IM, intensity modulator; FPE, Fabry-Perot etalon; PC, polarization controller; PM, phase modulator; OC, optical circulator; DBM, double balanced mixer; PS, phase shifter; PD photodetector; PID, PID controller. Grey arrows indicate feedback loop beam path in free space.

three low thermal expansion coefficient spacers is also included in the cavity. The etalon's free spectral range (FSR) was set equal to the desired pulse repetition rate by making a high precision measurement of the free spectral range [8], and the length of the etalon spacers were adjusted accordingly. The final FSR of the etalon of 10.2401±0.0002 GHz matched well with the target FSR of 10.240 GHz.

The purpose of the etalon is twofold. First, the inclusion of the etalon allows only a single phase locked mode group, or supermode, to lase. Without the inclusion of the etalon, ~300 interleaved supermodes will compete, and the resulting random fluctuations in amplitude and phase will disturb the output pulse train. This noise manifests itself in the timing and amplitude noise spectra as a series of noise spurs, called supermode noise, at multiples of the cavity fundamental frequency (34 MHz in this case). Also, the simultaneous lasing of different optical supermodes precludes the use of a single phase locked frequency comb with multigigahertz spacing. In the frequency domain, the FPE may be considered as a periodic bandpass filter that selects a single optical supermode. Without stabilization of the laser cavity, however, environmental influences will cause the optical frequencies to drift relative to the transmission peaks of the FPE. These frequency fluctuations will destabilize the mode-locking. The modes of the laser cavity are therefore stabilized to the FPE with the Pound-Drever-Hall (PDH) laser frequency stabilization method [5]. The PDH stabilization loop uses the FPE to detect small changes to the optical frequencies of the laser to create an error signal that, after conditioning by a proportional gain-integration-differentiation (PID) controller, is fed back into a piezoelectric actuator to compensate for the frequency change. (Note that a second RF signal at a frequency much lower than the mode-locking rate is needed to create the PDH error signal.) Thus supermode suppression and optical frequency stabilization are achieved simultaneously with a single intracavity FPE.

The optical spectrum when the laser is actively mode-locked at 10.24 GHz is shown in Fig. 2. The spectrum spans 16 nm in a -10 dB bandwidth, corresponding to about 2 THz. The visibility of the 10.24 GHz spaced comb lines is resolution limited and indicates the suppression of all but one optical supermode. The dominance of a single optical supermode is confirmed with a high resolution spectrum of one of the comb lines, shown in Fig. 2(b). Other optical modes, spaced by the cavity fundamental frequency of 34 MHz, are suppressed below the measurement noise floor.

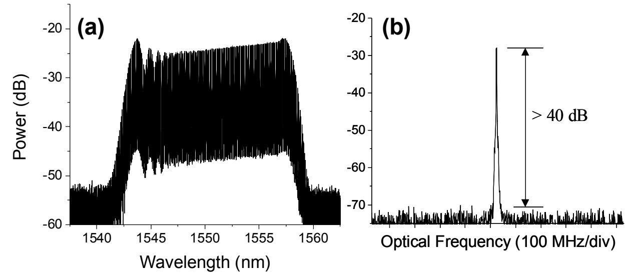

Figure 2. Actively mode-locked laser optical spectrum. (a) Full spectrum with a 16 nm -10 dB width, (b) high resolution optical spectrum of a single mode demonstrating >40 dB sidemode suppression

A measurement of the optical frequency stability of the mode-locked laser was performed by measuring the stability of a photodetected beat tone between a mode of the mode-locked laser and a stable, narrow linewidth CW laser. The narrow linewidth of the CW laser (<1 kHz) also allows an estimation of the linewidth of the optical frequencies of the mode-locked laser. These results are shown in Fig. 3. In Fig. 3(a), the width of the beat tone is limited by the resolution of the measurement of 10 kHz. As shown in Fig. 3(b), a maximum hold on the rf spectrum analyzer shows a maximum deviation in 30 seconds to be only 780 kHz.

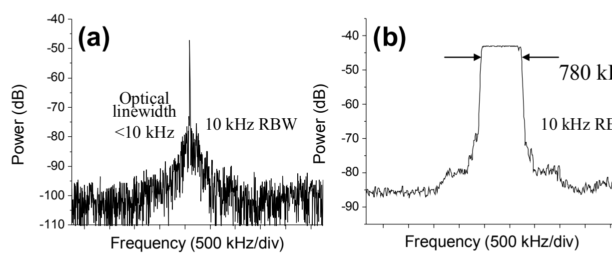

Figure 3. Actively mode-locked laser (a) linewidth and (b) frequency stability measurements in the RF domain

Also of note are the time domain characteristics of the mode-locked laser. Fig. 4 shows the pulse-to-pulse timing jitter, pulse-to-pulse amplitude noise, sampling scope trace and pulse autocorrelation. The timing jitter and amplitude noise are 11.4 fs and 0.04%, respectively, over the measurement band of 1 Hz to 100 MHz. Note the high suppression of the supermode noise spurs in the phase noise power spectrum, the first to a level of -143 dBc/Hz, and the second below -150 dBc/Hz. The supermode noise spurs are similarly suppressed in the amplitude noise. By extrapolating to the Nyquist frequency, the total rms jitter from 1 Hz -5.12 GHz is estimated to be 31 fs. The pulse autocorrelation is shown in Fig. 4(c). The pulses generated by the mode-locked laser have a large linear chirp. The output pulses were externally compressed with a dual grating pulse compressor with an autocorrelation FWHM of 880 fs. A sampling scope trace of the pulse train is shown in Fig. 4(d).

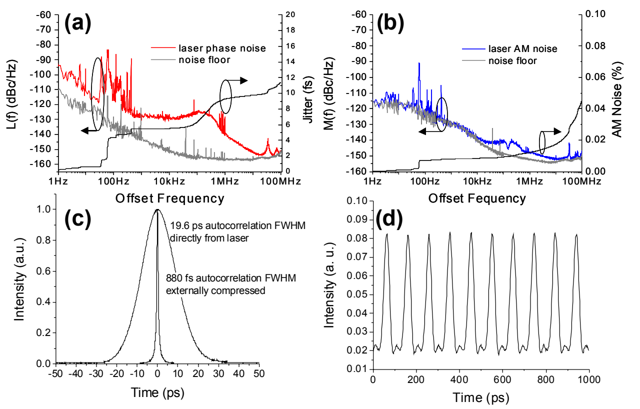

Figure 4. Actively mode-locked laser time domain characteristics . (a) phase noise and timing jitter; (b) AM noise and percent pulse-to-pulse energy fluctuation; (c) autocorrelation trace; (d) sampling scope trace

III. OPTICAL FREQUENCY STABILIZED COEO

Using the harmonically mode-locked laser described above as the basis, a COEO was constructed. The schematic is shown in Fig. 5. To convert the laser to a COEO, part of the laser output was photodetected, amplified, and used to drive the Mach-Zehnder modulator to form the electrical feedback loop. The inclusion of the FPE in the laser cavity makes this COEO significantly different from a conventional COEO. First, a 10.24 GHz spaced optical comb with a high optical signal to noise ratio (OSNR) is produced just as in the actively mode-locked laser. These optical frequencies are still stabilized via the PDH method, however a separate RF source is not used. Instead, the 10.24 GHz COEO signal is frequency divided down to 640 MHz and then used to drive the PDH feedback loop. Using the frequency divided COEO signal allows the oscillator to produce a frequency stabilized 10.24 GHz spaced comb while remaining completely self-contained.

The optical spectrum of the COEO is shown in Fig. 6. The full spectrum with a -10 dB width of 13 nm is shown in Fig. 6(a) while the high OSNR is of a single mode is shown in Fig. 6(b). When comparing Fig. 6 to Fig. 2, it can be seen that the quality of the optical spectrum has been maintained when the actively mode-locked laser was converted to a COEO. Furthermore, optical frequency stability was measured using the same technique as described above for the actively mode-locked laser. The result is shown in Fig. 7. The linewidth and optical frequency stability are also maintained, demonstrating the ability of the COEO to self-stabilize the 10.24 GHz-spaced optical frequency comb.

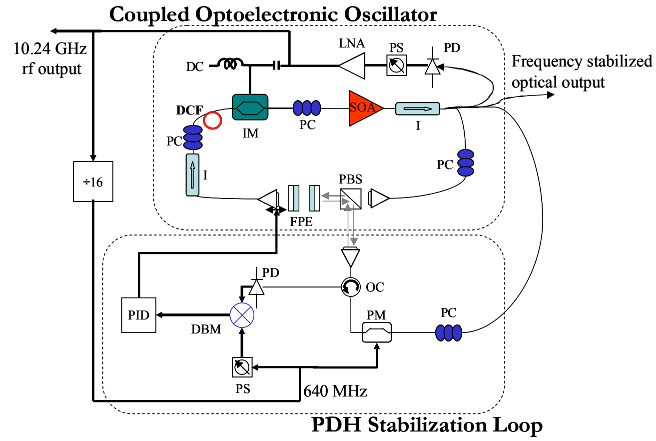

Figure 5. Optical frequency stabilized coupled optoelectronic oscillator schematic. The PDH loop is driven by the frequency divided COEO signal. LNA, low noise amplifier

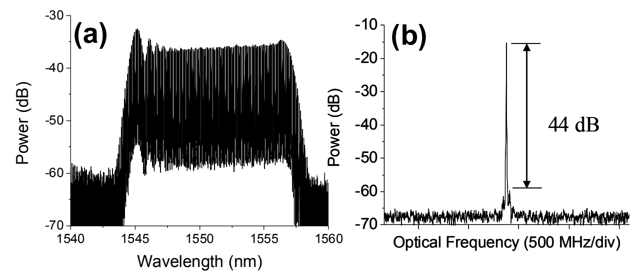

Figure 6. Optical frequency stabilized COEO optical spectrum (a) Full spectrum with a 13 nm -10 dB width, (b) high resolution optical spectrum of a single mode demonstrating 44 dB sidemode suppression

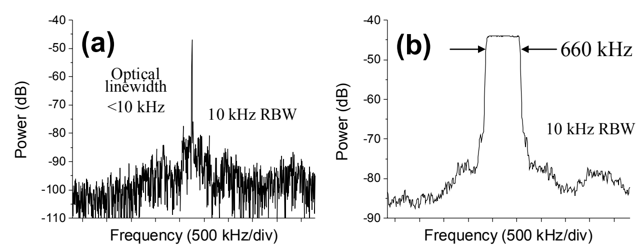

Figure 7. Optical frequency stabilized COEO (a) linewidth and (b) frequency stability measurements in the RF domain

Another important difference between the COEO presented and the conventional COEO is the inclusion of the etalon obviates the need for an RF bandpass filter in the electrical feedback loop. In a conventional COEO, a multiplicity of frequencies are available as possible oscillation frequencies of the COEO. These frequencies correspond to multiples of the laser cavity fundamental frequency, and one of these modes is selected for oscillation by including a high quality factor RF bandpass filter in the electrical feedback loop. By placing a FPE inside the laser cavity, the undesired modes are suppressed in the optical domain making the RF bandpass filter unnecessary. The removal of the RF filter can be advantageous, for the RF filter can be very susceptible to environmental fluctuations. The change in the delay due to environmental changes for a 10.24 GHz signal through a bandpass filter was measured using the setup shown in Fig. 8(a). The tested filter had a -10 dB bandwidth of 27 MHz centered at 10.24 GHz. A low noise 10.24 GHz signal was split with half the power going through the filter to the RF port of a double balance mixer and half the power going through a phase shifter to the LO port of the mixer. The two signals on the mixer were set to phase quadrature by the phase shifter to create a phase to voltage converter. By monitoring the DC voltage level after the mixer, the relative phase shift between the two inputs to the mixer was measured. The results are shown in Fig. 8(b). Also shown is the result of the same measurement when the filter is replaced by a short length of cable. When the RF filter is placed in the electrical feedback loop of a COEO, these changes in the accumulated phase translate into frequency fluctuations of the COEO signal. The direct effect of the RF bandpass filter stability on the COEO frequency stability is shown in Fig. 9. When the bandpass filter is placed in the electrical feedback loop (directly after the low noise amplifier), the maximum frequency deviation of the COEO signal is more than an order of magnitude greater than when there is no filter in the feedback loop. The maximum frequency deviation of the COEO signal when the RF filter is removed corresponds to 0.06 ppm.

Additional RF spectra were measured to determine the purity of the COEO signal and the suppression of the supermode noise spurs. The level of suppression of the supermode noise spurs of the RF output of the COEO is shown in Fig. 10(a). The spurs are barely visible above the noise floor, corresponding to noise level better than -130 dBc/Hz. This level of supermode suppression is the same as the directly measured photodetected spectrum of the actively mode-locked laser (not shown). A 5 kHz span measurement of this signal, shown in Fig. 10(b), shows the well defined COEO frequency for this oscillator.

Finally, the pulse autocorrelation was measured for the COEO. Again, the output pulse has a large linear chirp and can be compressed to under 1 ps as shown in Fig. 11.

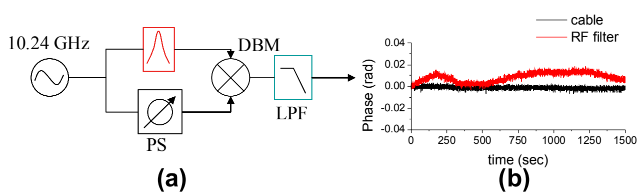

Figure 8. Phase to voltage converter (a) setup and (b) result showing the suseptibility of the RF filter to environmental influences

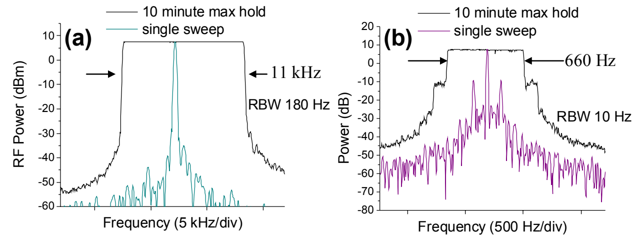

Figure 9. Stability of the 10.24 GHz output of the COEO (a) when an RF filter for mode selction is included in the electrical feedback loop and (b) when the RF filter is removed. Note the different scales on the horizontal axes.

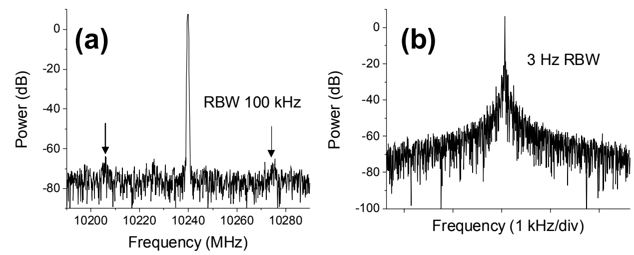

Figure 10. RF spectra of the COEO output. (a) 100 MHz span measurement; the arrows indicate the location of the supermode noise spurs. (b) 5 kHz span measurement showing a well defined COEO frequency.

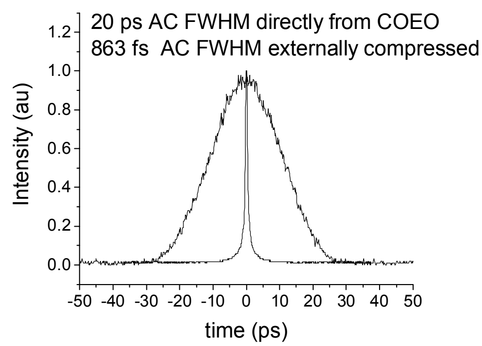

Figure 11. Pulse autocorrelaion for the optical frequency stabilized COEO

IV. CONCLUSION

In summary, a COEO containing a high finesse Fabry-Perot etalon in the laser cavity has been characterized. The inclusion of the etalon makes the COEO quite distinct from the conventional COEO. First, the optical filtering of the etalon suppresses all but a single optical supermode making this oscillator available for applications relying on a multigigahertz spaced optical frequency comb. Second, the etalon is utilized for optical frequency stabilization with the Pound-Drever-Hall method. The signal used to generate the error PDH error signal is derived from the COEO signal by frequency dividing to an appropriate frequency, 640 MHz in this case. Using the frequency divided COEO signal allows for the oscillator to be optical frequency stabilized while remaining completely self contained. Also, the inclusion of the etalon makes RF bandpass filter in a conventional COEO unnecessary. It was found that the removal of the RF bandpass filter increased the stability of the COEO signal by more than an order of magnitude.

The performance of the optical frequency self stabilized COEO depends heavily on the performance of the FPE. Increasing the finesse of the etalon would not only improve the stability of the optical modes (by increasing the discriminant of the PDH error signal), but it would also allow for a longer optical cavity, thereby increasing the effective microwave quality factor of the mode-locked laser.

REFERENCES

[1] P. J. Delfyett, S. Gee, M. T. Choi, H. Izadpanah, W. Lee, S. Ozharar, F. Quinlan, T. Yimaz, "Optical frequency combs from semiconductor lasers and applications in ultrawideband signal processing and communications," J. Lightwave Technol., vol. 7, pp. 2701-2719, 2006

[2] S. Gee, S. Ozharar, F. Quinlan, J. J. Plant, P. W. Juodawlkis, P. J. Delfyett, "Self stabilization of an actively mode-locked semiconductor-based fiber-ring laser for ultralow jitter," Photon. Technol. Lett., vol. 19. pp. 498-500

[3] F. Quinlan, S. Gee, S. Ozharar, P. J. Delfyett, "Frequency stabilized low timing jitter mode-locked laser with an intracavity etalon," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies 2007 Technical Digest* (Optical Society of America, Washington, DC, 2007), CThHH6

[4] T. Yilmaz, C. M. Depriest, A. Braun, J. Abeles, P. J. Delfyett, "Noise in fundamental and harmonic modelocked semiconductor lasers: experiments and simulations," J. Quantum Electron., vol. 39, pp. 838-849, 2003

[5] R. W. Drever, P. J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, H. Ward, "Laser phase and frequency stabilization using an optical resonator," Appl. Phys. B. vol. 31, pp. 97-105, 1983

[6] J. M. Kahn, "Modulation and Detection Techniques for Optical Communication Systems," *in Optical Amplifiers and Their Applications and Coherent Optical Technologies and Applications on CD-ROM* (The Optical Society of America, Washington, DC, 2006), CThC1

[7] N. Yu, E. Salik, L. Maleki, "Ultralow-noise mode-locked laser with coupled optoelectronic oscillator configuration," Opt. Lett., vol. 30, pp. 1231-1233, 2005

[8] S. Gee, S. Ozharar, F. Quinlan, P. J. Delfyett, "High precision measurement of free spectral range of etalon," Electron. Lett., vol. 42, pp. 715-716, 2006