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STABILIZATION OF THE ABSOLUTE FREQUENCY AND PHASE OF A COMPACT, LOW JITTER MODELOCKED SEMICONDUCTOR DIODE LASER

University of Central Florida

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13. ABSTRACT *(Maximum 200 Words)*
This research project was aimed at the stabilization of the frequency and phase of a set of optical combs from a semiconductor laser operating in an active mode-locked regime. To achieve this, an intracavity Pound-Drever-Hall technique was used on a 10 GHz harmonically mode-locked semiconductor ring laser and obtained a simultaneous optical frequency comb stabilization within ±3 MHz range and supermode phase noise suppression. Together with an additional phase-lock-loop, the timing jitter integrated from 10 Hz to 10 MHz (5 GHz) was 63.5 fs (161 fs). Approximately 25 fsec of the integrated noise is attributed to line noise, resulting in a net jitter of 38 fsec. This work represents, to our knowledge, the first stabilized modelocked diode laser using PDH that achieves both supermode elimination and optical frequency comb stabilization. The resulting optical comb source may be useful for advanced RF imaging radar for optical sampling in ADC or in novel waveform generation (DAC's).

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Introduction

Executive Summary

The overall goal of this program was to stabilize the frequency and phase of a set of optical frequency combs generated from a mode-locked semiconductor laser diode system.

Key achievements

- Completed stabilization and locking of the generated optical frequency combs to an intracavity etalon. Stable optical frequency comb locking was achieved for periods of hours.

- Noise reduction using a second phase locked loop that is designed to better track the low frequency phase fluctuations with respect to the primary RF synthesizer (mode-locked driving signal).

Technical Discussion

Low noise mode-locked lasers have drawn considerable attention for potential applications, such as optical clock distribution [1], and photonic analog to digital converters [2]. Recent development of few cycle optical pulse generation and optical frequency metrology have enabled the precise control of optical frequency combs for applications of frequency references for telecommunications, coherent optical waveform synthesis [3] and coherent optical communications [4]. Low noise mode-locked semiconductor lasers are very attractive optical comb sources in the 1.5 μm wavelength range owing to their compact, efficient, and high repetition rate nature. Our previous work showed that mode-locked lasers with long cavities are beneficial for low noise operation owing to their high quality factor [5]. One drawback of large cavity lengths is the inevitable necessity for harmonic mode-locking to obtain high repetition rates, as is often required in many applications. This mode of harmonic mode-locked operation leads to super mode noise. One of the most effective methods to suppress the supermode noise is to use an intracavity Fabry-Perot (FP) etalon [6]. There have been many attempts to stabilize the optical frequency of mode-locked lasers. One approach is a self referencing technique that takes advantage of an octave spanning optical bandwidth [7]. Other approaches use very stable, ultra narrow atomic lines as a reference [8]. In comparison to these techniques, the Pound-Drever-Hall technique (PDH) is particularly interesting because it utilizes a FP etalon as a reference [9]. In this final report, the combination of two techniques utilizing etalons, namely, super mode suppression and optical frequency stabilization, is demonstrated using a single intracavity FP etalon.

Figure 1 shows the schematic of the laser. The thick solid line represents the ring cavity of the entire laser system. The cavity length is about 6.5 m corresponding to the fundamental mode-locking frequency of 31 MHz. The gain medium is a semiconductor optical amplifier and mode-locking was achieved by an electro-optic amplitude modulator at 10 GHz. A high finesse (~150) FP air gap etalon with a free spectral range

(FSR) of 10 GHz was used to suppress the super mode noise by selecting a single set of longitudinal cavity modes separated by 10 GHz. Ten percent of the output was amplified by an Erbium Doped Fiber Amplifier (EDFA), phase modulated at 500 MHz and then injected back into the cavity via a polarizing beam splitter (PBS) for the Pound-Drever-Hall optical frequency stabilization technique. Part of injected pulses are reflected by the etalon, polarization rotated by a pair of Faraday rotator and half-wave plate, reflected by another PBS and detected by a photo detector. The details of the Pound-Drever-Hall technique can be found in the ref. [9]. The remaining injected pulses were transmitted through the etalon and dumped from the cavity by an optical circulator, which was also used to monitor the power level of the injected pulses. Since the injected pulses have a polarization orthogonal to the intracavity pulses, cross talk between them were suppressed to -60 dB and -41 dB for counter-propagating and co-propagating pulses respectively. In addition, the timing of the injected pulses was adjusted to be positioned midway between the two intracavity pulses so that the injected pulses will pass the amplitude modulator and the Semiconductor Optical Amplifier (SOA) at their lower transmittance and lower gain, respectively. Considerable care was employed to match the RF modulation frequency of the amplitude modulator, the FSR of the etalon and the optical cavity length. Since the etalon was regarded as the primary frequency reference, the other two parameters were adjusted to match it. First, the FSR of the etalon was measured to 1 MHz precision using another mode-locked laser by tuning the repetition rate of the laser and monitoring the spectrum of etalon transmitted light. Then the RF modulation frequency was set at the etalon FSR and optical cavity length was adjusted for the minimum output noise.

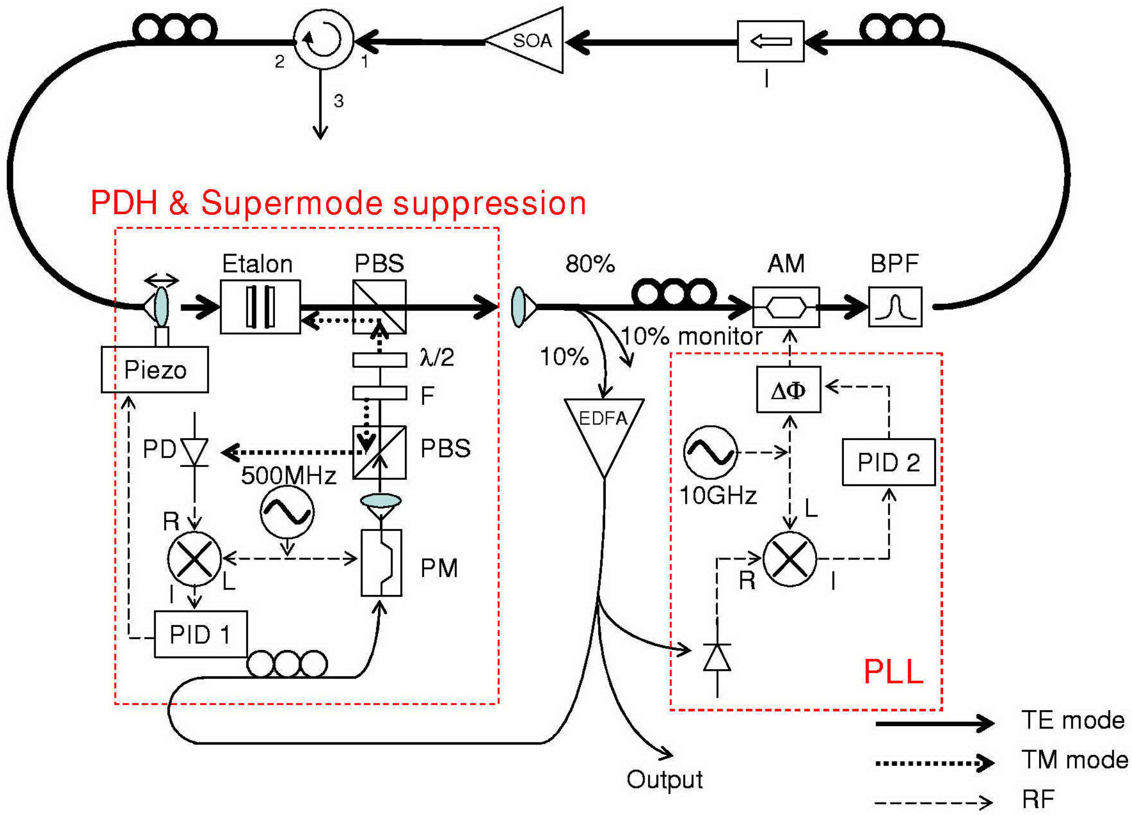

Figure 1: Schematic diagram of the setup

Without proper active control of the cavity length, optical cavity length changes owing to environmental influences, such as temperature and mechanical vibrations, will result in a change of the optical frequency. For example, our measurement shows the overall cavity length change ratio caused by temperature is 14 ppm/°C, indicating a 2.8 GHz optical frequency shift for 1° C temperature change. Considering the cavity mode separation is only 31 MHz, 0.01° C of temperature change can cause the hopping from one set of longitudinal modes with spacing of 10 GHz (super modes) to another longitudinal mode group. Since the spectral window provided by the etalon is about 67 MHz, two sets of super modes can coexist, resulting in an intermittent halt of super-mode suppression scheme using the etalon. This is when the intracavity PDH scheme comes into play. When there is an optical frequency shift, the PDH setup detects the amount of shift with a precision on the order of kHz, sends the error signal to an analog proportional-integral-differential (PID) feedback control circuit, then adjusts the cavity length using a piezoelectric actuator, accordingly, to compensate for any optical frequency change.

Fig. 2 is a maximum-hold RF power spectra of the photo detector output when a Continuous Wave (CW) laser light is combined with the mode-locked laser output. The narrow peak at the center corresponds to the10 GHz beat signal among mode-locked optical combs while the two side bands are two beat signals between the CW laser and two different longitudinal modes of mode-locked output combs. When the PDH feedback was off, the beat signals between the CW and mode-locked output drift more than 20 MHz indicating that the optical combs are almost freely moving. On the other hand, when the PDH feedback was on, the comb frequency fluctuates only ±3 MHz. Subsequent single sideband residual phase noise measurement using a phase detector also supports this explanation. When the PDH feedback was off, as the optical comb freely drifts, strong supermode noise peaks at 31 MHz (and harmonics thereof) were observed, while several hours of continuous suppression of supermode spurs were maintained with the PDH feedback on.

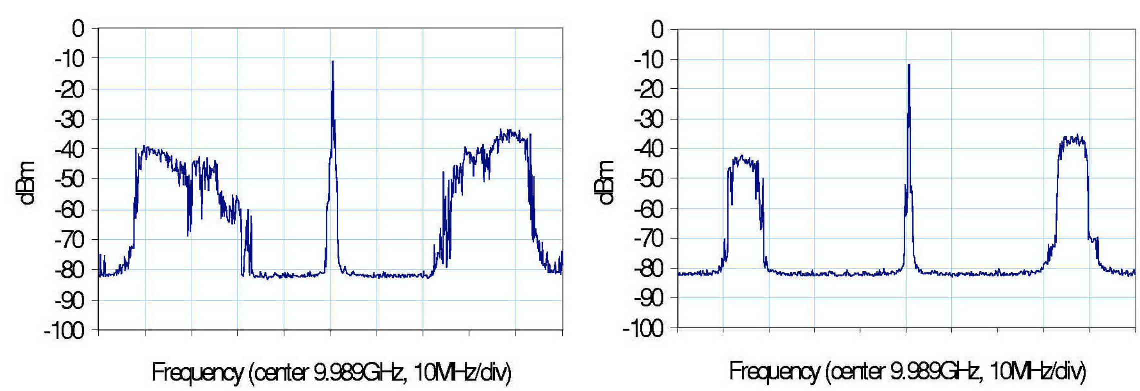

Figure 2: Time integrated RF heterodyne beat signals
(shown as the offset signals from the 9.989 GHz tone), which shows the reduction in optical frequency comb drift to below +/- 3 MHz.

Fig. 3 (a) shows a plot of the typical residual phase noise spectral density with PDH feedback. This noise spectral density shows typical characteristics of mode-locked semiconductor lasers [5], i.e., a white noise plateau at a low offset frequency, a noise knee at around 200 KHz, and a -20 dB/decade roll-off afterward. It should be noted that the relatively long cavity length has pushed the knee position toward a lower frequency in comparison to a shorter length cavity, for example, a noise knee at 55 MHz for a 15 mm cavity length [5]. Close observation of the phase noise spectrum shows a small remnant of a super mode noise spur at 31 MHz, but its contribution to the overall jitter is negligible. Clearly, the higher order super mode noise peaks have been completely suppressed below the noise floor of the measurement. In order to reduce the residual phase noise further, a second phase-lock loop (PLL) was added. Using the phase detector output as an error signal, another PID control circuit controls a microwave phase shifter located between the RF synthesizer and the electro-optic amplitude modulator [10].

Fig. 3 (b) shows that a near uniform 10 dB reduction of noise up to 50 KHz is obtained, with a small increase in noise around 200 KHz. This type of noise reduction at low offset frequencies and over shooting at high offset frequencies has been observed by many other researchers [10, 11]. Our simple modeling suggests that this phenomenon occurs at a frequency near the band edge of the electronics used in the PLL, when the bandwidth of the electronics is wider than the bandwidth of the PLL, which is limited by the latency of a control signal from an impulse of noise. The timing jitter integrated from 10 Hz to Nyquist's limit of 5 GHz is 161 fs. Even though the roll-off of the noise stops at around 10 MHz, we believe the roll-off will continue all the way to the thermal noise floor. Our separate experiments suggest that the white noise like behavior beyond 10 MHz is caused by signal-spontaneous emission beat noise of the EDFA, rather than the laser output itself. If that is the case, then noise contribution to timing jitter beyond 10 MHz is negligible and the total integrated timing jitter is calculated to be ~ 63 fs. We believe that an improved optical amplification scheme with reduced spontaneous emission will determine the validity of the statement above. It should also be noted that the 60 Hz line noise and its harmonics are contributing about 25 fs of timing jitter.

Isolation of the laser from these deterministic spurs will allow the laser to operate with a timing jitter of ~ 38 fs.

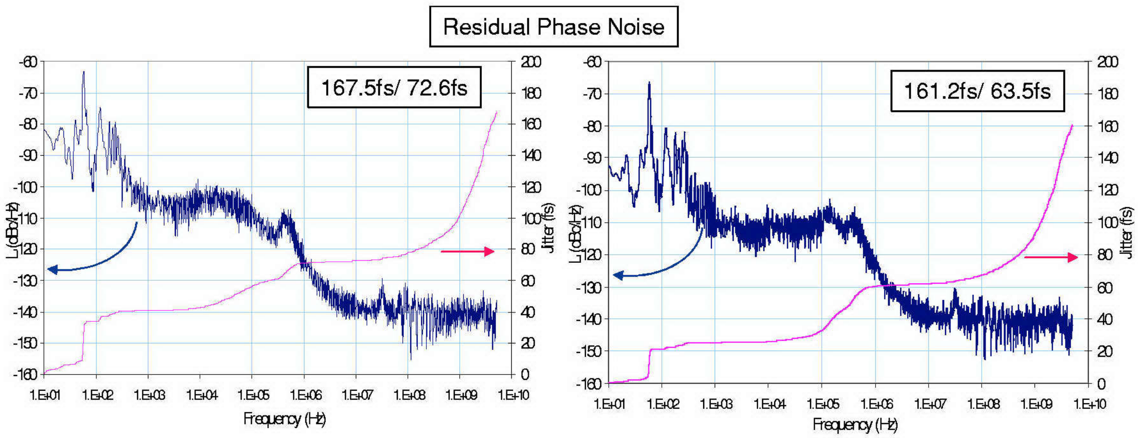

Figure 3: Residual phase noise.
(a)Left (Supermode suppression only). (b) Right: Supermode suppression with additional phase noise reduction. Jitter integration bands are to 5 GHz/ 10 MHz.

Fig. 4 (a) shows the optical intensity spectrum with Full Width, Half Maximum (FWHM) of 0.75 nm clearly showing stable optical combs. The autocorrelation measurement shows 16.9 ps FWHM suggesting the pulse width of 11 ps using a conversion factor 1.5.

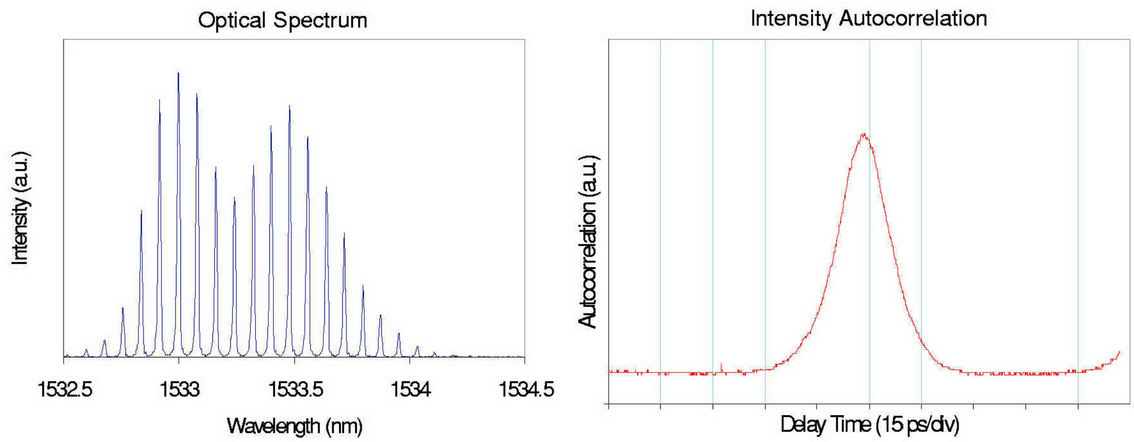

Figure 4: Output (a) spectral and (b) temporal characteristics of the stabilized modelocked optical comb source.

Conclusion

In this work, we have demonstrated simultaneous supermode suppression and optical frequency stabilization using a single intracavity FP etalon for a 10 GHz harmonically mode-locked semiconductor ring laser, which proves that a long laser cavity for realizing a high quality factor, along with supermode suppression, is a promising concept for low noise mode-locked lasers. The timing jitter integrated over the entire Nyquist's frequency range was measured to be ~ 63 fs excluding the signal-spontaneous beat noise. Optical frequency fluctuations were maintained to be less than ±3 MHz. The overall laser system feedback control systems were stable enough to operate for many hours without any readjustment. Owing to its well defined stable optical frequency comb and low phase noise, this laser has applications in areas such as optical coherent communications, arbitrary optical waveform synthesis, optical clock distribution and photonic analog to digital converters.

Recommendations

The work described in this report shows that stable optical frequency combs can be robustly achieved by using extended cavity mode-locked lasers operating in a harmonically mode-locked regime by using an intracavity etalon to select a single longitudinal mode group. To maintain the mode selection, the Pound-Drever-Hall method was used to maintain the stable operation of a single longitudinal mode set. In addition, a second phase lock loop was incorporated to reduce the laser noise so that the laser better tracks the RF oscillator used to provide the mode-locking signal.

1. The PDH technique is robust and works well. However, if another frequency locking technique is available that is passive, i.e., does not require a modulating signal to generate an error signal, the same frequency comb set might be able to be achieved using less optics and electronics, making the overall laser system, smaller, lighter, and more efficient.

2. The use of the extended cavity is useful for pushing the 'phase noise knee' closer to the carrier, and thus reducing the noise. Further improvements may be achieved by increasing the cavity length, with the caveat that the proper intracavity etalon may be more difficult to realize.

3. Line noise proves to be critical in determining the overall jitter performance. Methods to isolate the 60 Hz line noise and it associated harmonics will be useful for additional jitter/noise reduction.

4. Environmental stabilization proves to be a critical and an important aspect for robust stabilization. Active components that minimize the generation of heat and vibration/acoustic noise are critical for the overall performance of low noise combs.

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