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Dimitrios Mandridis
University of Central Florida

Charles Williams
University of Central Florida

Ibrahim Ozdur
University of Central Florida

Peter J. Delfyett
University of Central Florida

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Low noise chirped pulse mode-locked laser using an intra-cavity Fabry-Pérot etalon

Dimitrios Mandridis,[1,2] Charles Williams,[1] Ibrahim Ozdur,[1] and Peter J. Delfyett[1,*]

[1]*CREOL, The College of Optics and Photonics, University of Central Florida, 4000 Central Florida Boulevard, Orlando, Florida 32816, USA*

[2]*dimitrismandridis@gmail.com*

**delfyett@creol.ucf.edu*

Abstract: This work presents an extensive investigation of the performance characteristics of a semiconductor-based Theta cavity design laser with an intra-cavity Fabry-Pérot etalon operating at 100 MHz repetition rate. The Theta laser being an external cavity harmonically mode-locked semiconductor laser exhibits supermode noise that impairs its performance. A fiberized Fabry-Pérot periodic filter inserted within the Theta laser cavity mitigates the contribution of the supermode noise to the pulse-to-pulse energy variance by 20 times. The laser has both a compressed output with picosecond pulse duration and a uniform intensity quasi-CW linearly chirped pulse output with 10 nm bandwidth. Long-term stability is attained by referencing the cavity length to the etalon using an intra-cavity Hänsch-Couillaud locking scheme.

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OCIS codes: (050.2230) Fabry-Pérot; (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers; (140.7090) Ultrafast lasers.

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1. Introduction

Pulsed laser sources with repetition rates on the order of 100 MHz are very common, since they are easily attained by meter-long laser resonators. On the other hand, semiconductor-based lasers tend to operate in the multi-GHz repetition rates, corresponding to millimeter-long resonators. Short cavities and fast repetition rates from semiconductor gain laser is a consequence of the electron-hole pair recombination lifetimes, which are in the nanosecond range [1]. While using solid state and fiber gain media to address the 100 MHz regime of laser repetition rates is advantageous, semiconductor media can be preferred for some applications due to their properties. Semiconductor based lasers have a small footprint, are rugged, temperature stable, power efficient, and inexpensive, when massively produced. However, conventional linear or ring cavity designs cannot be used in conjunction with semiconductor gain media in the 100 MHz repetition rate regime. This work focuses on an unconventional laser cavity design, the Theta laser [2], which enables long cavities and low repetition rates for semiconductor gain. The Theta laser operation is discussed in section 2.

In addition to the low repetition rate addressed by the Theta laser design, there are a variety of applications that call for laser sources with uniform intensity and extremely chirped pulses. Specifically, photonic time-stretched (TS) analog-to-digital conversion (ADC) requires a low noise uniform linearly chirped pulse train that fills the time slot between the pulses for continuous operation [3]. In photonic TS ADC, electrical signals are imposed on the chirped optical pulses using an intensity modulator; subsequently the pulses are stretched and wavelength demultiplexed using passive components. The stretched and demultiplexed signals have only a fraction of the bandwidth of the initial signal, thus the technical limitations of available converters can be overcome and the effective converted bandwidth is increased [4]. Linearly chirped pulses that have uniform time intensity profile covering the time slot between them are essential for photonic TS ADC.

Furthermore, some implementations of optical coherence tomography can also make use of uniform intensity and linearly chirped laser sources. Typical laser sources that have been demonstrated for this use include a swept optical filter within the laser resonators [5]. The swept bandwidths demonstrated are in the 100 nm range. However, the response of the piezo-electric transducers of the swept filter limits the system frame rate to a few tens of kHz. Moreover, the instantaneous bandwidth is increased by the poor effective quality of the laser cavities that support only few photon round-trips.

The motivation of this work is to improve the noise performance of the Theta laser design via the use of the intra-cavity Fabry-Pérot etalon and extend the intra-cavity etalon's use to a different cavity design having a dual purpose; to demonstrate a short pulse low noise semiconductor-based laser at repetition a rate of 100 MHz and to provide a low noise uniform intensity quasi-CW chirped pulse output for use the aforementioned applications. This manuscript presents an extensive investigation of the performance of a Theta laser with an intra-cavity periodic filter in the form of a Fabry-Pérot etalon. Relatively to previous work, this manuscript presents an improvement by of a factor of two of the swept bandwidth, a deployment of the Hänsch-Couillaud locking scheme and the characterization of the pulse-to-pulse amplitude modulation noise, which are essential for the purpose of this work [6,7].

2. The Theta laser with an intra-cavity etalon and long-term stabilization

The development of semiconductor-based lasers with MHz repetition rates depends on overcoming the medium's short carrier lifetime [1]. The impediment of the short carrier lifetime of semiconductor gain media in the extraction of increased energy per pulse during the amplification of short pulses is overcome by using extreme chirped pulse amplification

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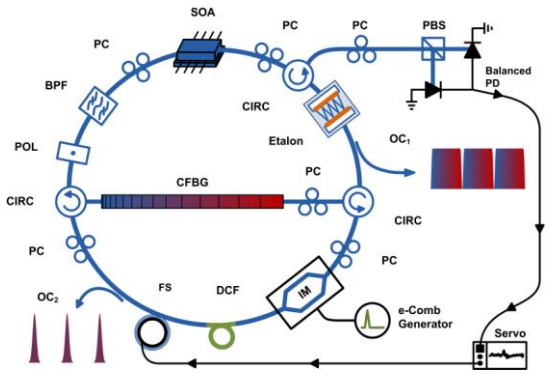

Fig. 1. Scematic of the the Theta laser with an intra-cavity etalon and long-term referencing. BPF, optical band-pass filter; CFBG, chirped fiber Bragg grating; CIRC, optical circulator; DCF, dispersion compensating fiber; FS, fiber stretcher; IM, electro-optic intensity modulator; OC, output coupler; PBS, polarization beam splitter; PC, polarization controller; PD, photodetector; POL, polarizer; SOA, semiconductor optical amplifier.

(X-CPA) [8]. In X-CPA the pulses are stretched to durations much longer that the carrier lifetime, amplified and subsequently recompressed to their initial duration.

The Theta (Θ) laser cavity design employs X-CPA within the laser cavity [2]. The optical pulses stretch and recompress on every round trip inside the laser, using the opposite ports of a single chirped fiber Bragg grating (CFBG), as seen in Fig. 1. In the laser's steady state, the pulses pass through the gain medium fully stretched, filling the period of the laser as a uniform intensity quasi-CW frequency chirped pulse train. The Theta laser provides access to two different polarized outputs, with uniform polarization across the optical spectra; a primary port with quasi-CW stretched pulses and a second port with compressed pulses. It should be noted that the compressed pulses from the laser have increased energy per pulse compared to conventional laser cavity designs due to the X-CPA effect and they can be used for experiments that require high energies per pulse.

The Theta laser is an external cavity actively and harmonically mode-locked laser. Mode-locking is attained via loss modulation using an intensity modulator driven by an electrical pulse generator ($\Delta\tau \approx 100$ ps). The total length of the fiberized cavity is nominally on the order of 100 m and ~50 pulses circulate in the laser simultaneously. It is well known that harmonic operation of mode-locked lasers gives rise to noisy laser performance due to the limited correlation between the intra-cavity pulses, which is demonstrated as supermode noise spurs (SNS) in the RF spectra of the photodetected pulse train [9].

The effect of the SNS in a harmonically MLL can be mitigated by increasing the homogeneity of the laser pulses [10]. A Fabry-Pérot etalon with a free spectral range (FSR) equal to the laser repetition rate, a harmonic of its cavity's fundamental frequency, can act as a mechanism that stores and inter-mixes the pulses. This is equivalent to filtering the unwanted interleaved optical mode groups attributed to the harmonic nature of the laser. The etalon's storage time must be sufficiently large, such as all the pulses are allowed to intermix, or equivalently the finesse of the etalon has to be large enough for the undesired optical modes to be filtered by the etalon. Suppression of the SNS has been demonstrated for conventional ring laser resonators operating at 10 GHz [10]. In a recent extension of this line of work, a 10 GHz spaced optical frequency comb was generated with excellent short and long term characteristics [11].

The etalons used in the aforementioned work are air-spaced and are assembled using curved mirrors and low expansion quartz spacers, corresponding to a mirror separation of 1.5 cm. For the scope of the work presented in this manuscript, the FSR needed for the etalon is 100 MHz, which makes the required mirror separation 100 times larger, or 1.5 m. Instead, a commercially available fiberized Fabry-Pérot etalon is used, constructed by two thin films connected to a dispersion shifted fiber with zero dispersion wavelength in the vicinity of 1550

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nm. Using a fiberized version for the optical filter versus its free space alternative has the detriments of FSR drift and susceptibility to acoustic and mechanical vibrations, as will be discussed later in this work. The etalon finesse is 160 ± 5 [12].

Moreover, residual birefringence of the fiberized etalon demonstrated as a slight difference in the FSRs for the two polarization eigenstates, prohibits the use of the Pound-Drever-Hall (PDH [13]) technique for long-term stabilization [10,11]. Nonetheless, the birefringence of the etalon is exploited to enable the use of an intra-cavity Hänsch-Couillaud scheme that provides an error signal for referencing the MLL to the etalon [14]. This scheme is advantageous in that it consists of fewer and solely passive components compared to the PDH technique.

It should be noted that since the Theta laser is an actively MLL, the electrical pulse generator must be driven at the appropriate frequency, which for this work is the FSR of the etalon. Thus the frequency corresponding to the etalon FSR must be known with high accuracy. Reference [12] provides an ultra-high precision measurement (1 part in 10^9) of the etalon properties.

An important experimental design parameter for the Theta laser is the dispersion of the cavity. Since the fiberized etalon has reduced but measurable dispersion, (2 ps/nm/km), the modes of the etalon are not evenly spaced in frequency. However, the dispersion of the fiberized laser cavity must match the dispersion of the etalon, in order for the modes supported by the laser cavity to overlap with the etalon transmission windows. If the laser dispersion is not addressed the lasing bandwidth is reduced and the stretched port time intensity profile does not appear as quasi-CW. In the work presented here, 8 m of dispersion compensating fiber balances the laser cavity dispersion to that of the etalon.

3. Performance analysis

The developed Theta laser has a repetition rate equal to the FSR of the fiberized etalon, which is: $f_{rep} = FSR_e = 99.580$ MHz [12]. The dispersion of the commercially available CFBG used is 990 ps/nm. Assuming perfect linearly chirped pulses with uniform time intensity profiles that fill the period of the laser, the corresponding spectral bandwidth is 10 nm.

Figure 2 shows the characterization of the compressed port output of the Theta laser described above. The sampling scope trace of the laser is depicted in Fig. 2(a). Pulses of ~30 ps in duration are measured with a ~10 ns period, resulting in a duty cycle <0.3%. There are no satellite pulses and the extinction demonstrated is high. It should be noted that high quality MLL operation with duty cycles in this range cannot be attained using conventional cavity designs for semiconductor-based lasers at this repetition rate regime.

In Fig. 2(b) the black trace depicts the results for the Theta laser operating with all the components shown in Fig. 1 except for the fiberized etalon, while red depicts results for the

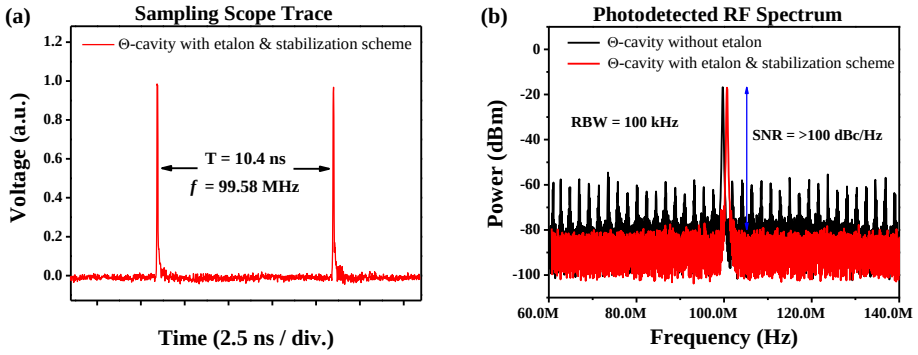

Fig. 2. Characterization of the compressed-port pulses. (a) Sampling scope trace acquired using a 15 GHz photodetector. (b) Photodetected RF spectrum. Note the absence of the supermode spurs on the red spectrum due to the filtering by the etalon. (The red spectrum has been shifted for viewing purposes).

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complete system with the long-term stabilization scheme employed. In the black trace, the SNS are observed, owing to the harmonic nature of the laser. When the etalon is inserted in the laser cavity and the long-term stabilization scheme is employed the etalon's inter-mixing function leads to the suppression of the SNS. The demonstrated suppression is in excess of 10 dB and the SNS are suppressed below the noise floor of the instrument. The RF tone at the laser's repetition rate has spur-free dynamic range in excess of 100 dBc/Hz.

Figure 3 shows the spectral characterization of the stretched port of the Theta laser. On the optical spectra of Fig. 3(a), acquired using a conventional optical spectrum analyzer, the spectral uniformity of the laser is 2 dB, while it reduces to 4 dB for the laser with the intra-cavity etalon. Suppression of the undesired spontaneous emission by the etalon is measured to ~10 dB. Careful dispersion compensation of the ~100 meter-long laser cavity enables lasing at the full supported bandwidth even with the use of the Fabry-Pérot etalon. The laser pulses are linearly chirped and the time intensity profile of the stretched port appears continuous.

The high resolution spectra presented in Fig. 3(b) demonstrate a critical effect of the insertion of the etalon in the Theta laser. Due to the filtering function of the etalon, the unwanted optical comblines owing to the harmonic nature of the laser are suppressed and a frequency comb with spacing equal to the active drive frequency and the FSR of the etalon is generated. Using the etalon, the power distributed every ~50 optical modes is concentrated in

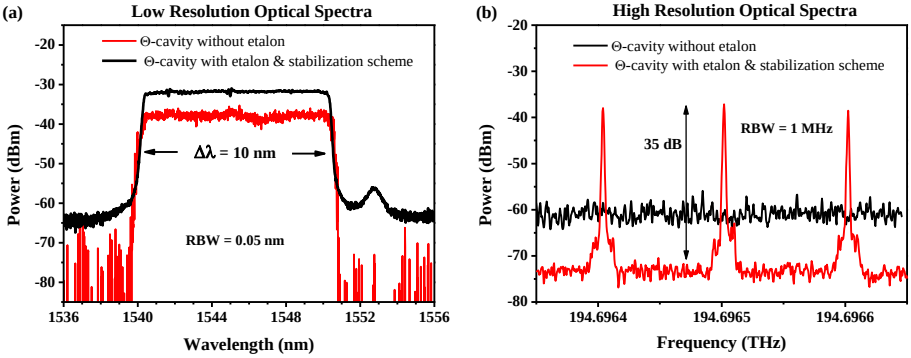

Fig. 3. Optical spectra of the Theta laser's stretched port. (a) Wide span optical spectra with and without the intra-cavity Fabry-Pérot Etalon. (b) High resolution optical spectra. The sidebands tones are artifacts of the measurement and the red line is vertically shifted (from –61dB) for viewing purposes.

a single combline. To the authors' knowledge this is the first demonstration of a stable optical frequency comb generated using a semiconductor based laser in the 100 MHz regime. The combline contrast measured is in excess of 25 dB, while the power output is 4.0 mW for the stretched port and 0.28 mW for the compressed port.

All potential applications for the Theta laser put stringent requirements for the pulse energy fluctuation of the pulses. The inhomogeneity of the pulses in the simple Theta cavity due to its harmonic nature and the excess noise of the electrical pulse generator drive, lead into excess noise for the laser pulses. This is shown in Fig. 4(a), where the laser noise is measured using an Agilent E5500 noise testset. The solid lines show the power spectral density (PSD) of the amplitude noise relative to the carrier for the laser with and without the etalon, while the lighter traces show the integration giving the pulse-to-pulse energy variance for two frequency offset regions; the full band [10 Hz, 20 MHz], and the region covering the SNS [1 MHz, 20 MHz]. The relative pulse energy variance ($\Delta E/E$) for the full band in both cases is ~1%.

However, a significant difference is observed for the frequency offset range containing the SNS [1 MHz, 20 MHz], where an improvement of 20 times from ~1% to ~0.05% is calculated. Moreover, one can see an increase in the noise PSD at low offsets, which can be attributed to PM-AM noise conversion for frequencies within the servo mechanism's bandwidth, due to the mismatch of the etalon FSR with the fixed active drive frequency. Also,

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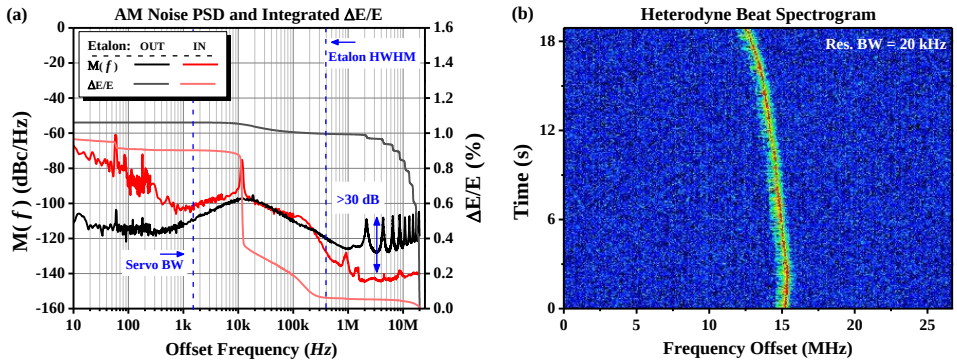

Fig. 4. (a) Theta laser power spectral density of the AM noise of the laser and integrated pulse-to-pulse energy fluctuation with and without the etalon. The supermode noise spurs are suppressed by >30 dB. The 10 kHz spike is technical noise and can be suppressed further. (b) Spectrogram of the heterodyne beat between a single combline of the Theta MLL and a narrow linewidth laser. Color code: rainbow [-91 dB,-61dB].

there is a spike in the PSD at 11.5 kHz due to the resonance of the piezo drum used for referencing the cavity length to the etalon. Since, the aforementioned applications use signals with durations shorter than 10 ms, the appropriate noise integration band starts from 100 kHz and ends at the Nyquist frequency of the pulses, (49.79 MHz). Thus, the use of the fiberized etalon offering significant suppression of the SNS, is advantageous for use with the Theta cavity, enabling its use in low noise applications.

A heterodyne beat of one of the laser comblines with a commercially available laser with linewidth 1 kHz is presented in Fig. 4(b). The beat tone drifts by 4 MHz monotonically during a measurement of 20 s, while the laser linewidth is <1 MHz measured in 1 s. This behavior is explained by taking into consideration the fact that the laser is referenced to a fiberized etalon. As, discussed in [12], the FSR of the etalon drifts in time and so will the optical frequency comb of the Theta laser. Moreover, the etalon's FSR is affected by acoustic and mechanical noise and special care was taken to isolate the laser components and especially the etalon from room noise. The laser components are in nested acrylic boxes with a foam insulation layer in between. As a result of the etalon drift and noise response, this specific Theta laser implementation cannot be characterized with the pure definition of a frequency comb source. Nonetheless, if a better reference were used, better long term stability would be attained, and a semiconductor-based 100 MHz optical frequency comb can be realized, if required.

5. Conclusion

This manuscript presents an extensive investigation of the performance of a 100 MHz Theta laser which includes an optical periodic filter in the form of a fiberized Fabry-Pérot etalon. The laser has dual outputs; a compressed port with ~30 ps duration pulses and a stretched port giving ~10 ns quasi-CW linearly chirped pulses with 10 nm of bandwidth. The intra-cavity optical filter results in suppression of the supermode noise spurs in excess of 30 dB, as observed by the AM noise spectra of the compressed port output. The contribution of the SNS to the pulse-to-pulse noise is reduced 20-fold, to 0.05%. This advanced laser source can be used in low repetition rate applications that can benefit from either the uniform chirped pulse output, or the use of semiconductor as the gain medium.

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