

1-1-2008

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Recommended Citation

Lee, Shinwook; Mandridis, Dimitrios; and Delfyett, Peter J. Jr., "eXtreme chirped pulse oscillator operating in the nanosecond stretched pulse regime" (2008). *Faculty Bibliography 2000s*. 593.
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eXtreme Chirped Pulse Oscillator Operating in the Nanosecond Stretched Pulse Regime

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Abstract : An eXtreme Chirped Pulse Oscillator (XCPO) implemented with a Theta cavity and based on a semiconductor optical amplifier (SOA) is presented for generating 10ns frequency-swept pulses and 3.6ps compressed pulses directly from the oscillator. In this experiment, we show the two distinct characteristics of the XCPO which are the scalability of the output energy and the mode-locked spectrum. By using these characteristics, we obtain a pulse energy of 58.4pJ from the stretched pulse and a mode-locked optical bandwidth of 14.6nm (10dB) directly from the oscillator. The laser cavity design allows for low repetition rate operation <100MHz, as well. The cavity, significantly, reduces nonlinear carrier dynamics, integrated self phase modulation (SPM), and fast gain recovery in an SOA. Due to the laser's ability to generate directly frequency-swept pulses from the oscillator, this oscillator can be used for high speed frequency-swept optical coherence tomography (OCT) and time-stretched photonic analog to digital converters (P-ADC).

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OCIS codes: (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers; (320.7160) Ultrafast technology

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1. Introduction

High power mode-locked semiconductor lasers are extremely attractive to commercial and defense use for a variety of applications, including signal processing, material processing, free space communication, range finding and medical tools. However, the gain saturation and the damage threshold from the facets of semiconductor optical amplifiers (SOAs) are the limiting factors for realizing high power mode-locked semiconductor lasers. In order to increase the output power from semiconductor mode-locked lasers, several approaches have been proposed and demonstrated, such as, surface emitting area structures including grating-coupled surface-emitting lasers (GCSELs) [1] and vertical-external-cavity surface-emitting lasers (VECSELs) [2], a master oscillator and power amplifier (MOPA) system with tapered amplifiers [3] or inverse bow-tie amplifiers [4]. However, in these approaches high power operation approach is achieved by taking advantage of an increase in the active area. As a generic high power laser system, the MOPA approach is very attractive due to the compactness and simple electrical pumping. In the case of short pulse amplification, however, the nonlinear carrier dynamics is strongly involved.

When a short pulse from a master oscillator is passing through a semiconductor optical amplifier, the gain is depleted, and which leads to a change in the refractive index. The change of refractive index is inversely proportional to the gain. Consequently, this refractive index change over the pulse duration results in an instantaneous frequency due to self phase modulation (SPM). This strong carrier dynamics in the SOA lead to pulse broadening in the temporal domain and spectral broadening in the spectral domain [5, 6], especially for short pulses, on the order of 1ps. In cases when the input pulse is $< 1ps$, the carrier heating and cooling effects can be observed.

The basic amplification dynamics of an SOA as it relates to the input pulse width is summarized in Fig. 1. Fig. 1 shows gain depletion, refractive index change and instantaneous frequency generation in an SOA with respect to the input pulse widths. When the pulse width is longer than the carrier cooling time or carrier-phonon scattering time, the gain is slowly depleted and the refractive index is slowly changed, which leads to lower instantaneous frequency generation (Fig. 1(a)). However, if the input pulse width is shorter than the carrier cooling time, carrier heating effects are induced. The gain partially recovers as the carrier temperature relaxes to equilibrium. The carrier heating and cooling generates both lower frequencies and higher frequencies. The deviation of the instantaneous frequency of shorter pulses ($< 1ps$) is larger than that of longer pulses ($> 2ps$) due to fast gain depletion and recovery (Fig. 1(b)).

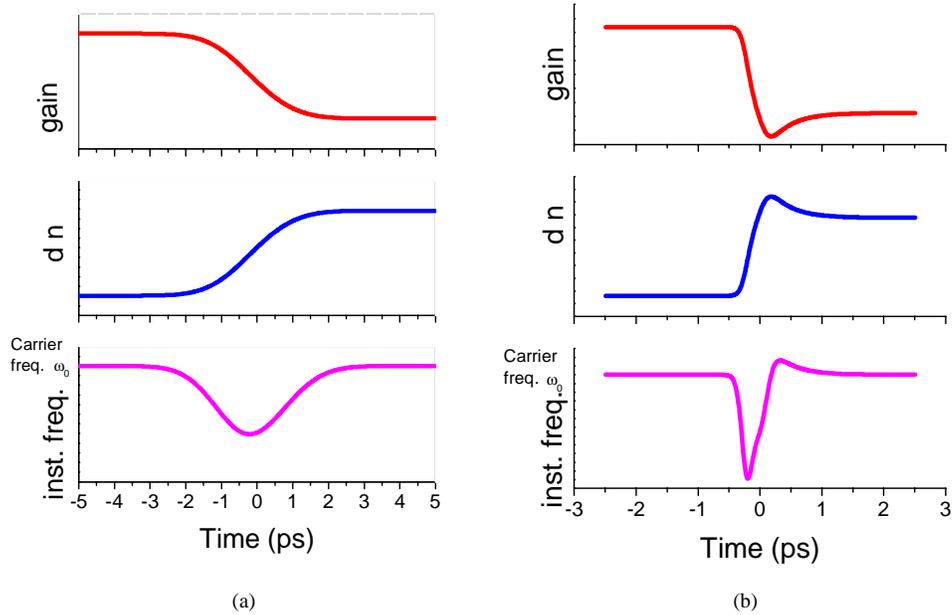


Fig. 1. Short pulse amplifications of (a) long pulse regime (>2ps) and (b) short pulse regime (<0.5ps). Top: Gain change, Middle: Refractive index change, Bottom: Instantaneous Frequency generation.

In order to reduce SPM, nonlinear gain dynamics, or to increase the power, a dispersion managed or breathing mode approach [7] can be used for an oscillator. To date, the breathing mode cavity has produced the shortest pulses from SOAs. In this case, however, the stretched pulse width is limited by the maximum dispersion from the grating geometry [8].

Recently, we proposed and demonstrated eXtreme Chirped Pulse Amplification (XCPA) [9] and an eXtreme Chirped Pulse Oscillator (XCPO) [10] to reduce detrimental nonlinearities caused by SPM, carrier cooling and heating, and to increase the output power from semiconductor mode-locked lasers. These approaches are different from the high power pulse generation approaches mentioned above. The XCPA and the XCPO are temporal power scaling approaches unlike the spatial scaling approaches. In our previous results, we obtained record peak powers from the XCPA and 520ps CW-like linearly frequency-swept output pulses from the mode-locked XCPO.

In this paper, we demonstrate 10ns frequency-swept pulses which are substantially longer than the upper state carrier life time of the SOA (~1ns), and a 100MHz repetition rate which is the lowest repetition rate semiconductor mode-locked laser with loss modulation while maintaining the beneficial characteristics of the XCPO. This direct stretched pulse generation from the oscillator can be used in applications, such as, swept-source optical coherence tomography (OCT) [11], and time stretched photonic analog to digital converters (P-ADC) [12].

2. eXtreme Chirped Pulse Oscillator (XCPO or Theta cavity) and experimental setup

The saturation power the limits maximum output power of mode-locked semiconductor MOPA systems. The saturation power may be expressed as [3],

$$P_s = \frac{h\nu A}{\Gamma \alpha \tau} \quad (1)$$

where, P_s is the saturation power, $h\nu$ is the photon energy, A is the active region area, Γ is the optical confinement factor, α is the differential gain and τ is the gain recovery time. In order to increase the saturation power, one can increase the area of the active region or use quantum dot gain media whose gain recovery time is shorter than quantum well gain media.

Unlike other approaches which take advantage of the active area, our approach uses a swept frequency or a stretched pulse to extract more pulse energy. If the stretched pulse duration is longer than the upper state carrier life time, one can extract more energy from the SOA and obtain a scalable energy extraction factor based on the power saturation with respect to stretched pulse duration as shown in following equation,

$$E \propto \frac{t_p}{\tau}, \quad (2)$$

where, E is the energy extraction, t_p is the stretched pulse duration in the SOA and τ is the gain recovery time of the SOA. We refer to this as the XCPA gain effect.

This approach is successful in terms of mitigating nonlinearities of the SOA, as well. In this regime, the mode-locked pulses are temporally stretched to a temporal duration that equals the pulse repetition period, converting the pulse train into a CW signal by using a long-length chirped fiber bragg grating (CFBG). By amplifying this CW signal in the SOA, the detrimental effects of transient gain saturation, such as carrier heating and cooling, and integrating self phase modulation are eliminated. Since the gain dynamics of the semiconductor optical amplifier operate in the CW injection regime, the limitation to the extracted pulse energy under transient optical amplification can be circumvented [5].

In this work, we generate a 10ns stretched pulse directly from the oscillator, noting that this temporal duration is substantially longer than the carrier life time and represents a 19 fold improvement compared to our previous work [10]. In this operating regime, the stretched pulse duration enables one to observe the XCPA gain in the oscillator. The use of a Theta cavity design operating in the XCPA regime in semiconductor gain media opens the possibility that with increased temporal stretching, where the pulse duration is longer than the carrier life time, one can extract more pulse energy in which the pulse energy is linearly proportional to the ratio of the stretched pulse duration to the carrier life time. In addition, one can obtain a scalable mode-locked spectral width with respect to pulse repetition rate. The tendency that the temporal duration of the stretched pulse equals the pulse repetition period forces the spectral width to scale in terms of the repetition period due to the large group delay of the CFBG. This characteristic is understood as a spectral filtering of frequency-swept pulse train to avoid overlapping of the stretched pulses.

The XCPO implemented with a Theta cavity schematic is depicted in Fig. 2. An SOA is inserted in an external cavity incorporating a CFBG, having a group delay of 2000 ps/nm, and a 10GHz modulator. The single CFBG is used as both the stretcher and the compressor in order to minimize the total group delay ripple. Because the difference between the transmittance and the reflection of the CFBG is only 8dB, a polarizer with a polarization controller is inserted to block any residual transmitted light. An optical band pass filter with a 10nm bandwidth is used to remove the transmitted light outside of the bandwidth of CFBG.

Active mode-locked operation via loss modulation is performed as follows: an intensity modulator incorporating an electric comb generator produces a short optical pulse, and then it is stretched in the CFBG. The SOA amplifies the CW-like mode-locked pulse using a DC-bias. The chirped and amplified light is compressed by the same CFBG, and reinserted into the intensity modulator. A single CFBG is used for reducing the group delay ripple (GDR) that would be caused from the mismatch of group delays if two independent CFBGs are used. Two output couplers with a 10% output coupling ratio are inserted into the cavity to monitor the performance of the stretched and compressed pulses.

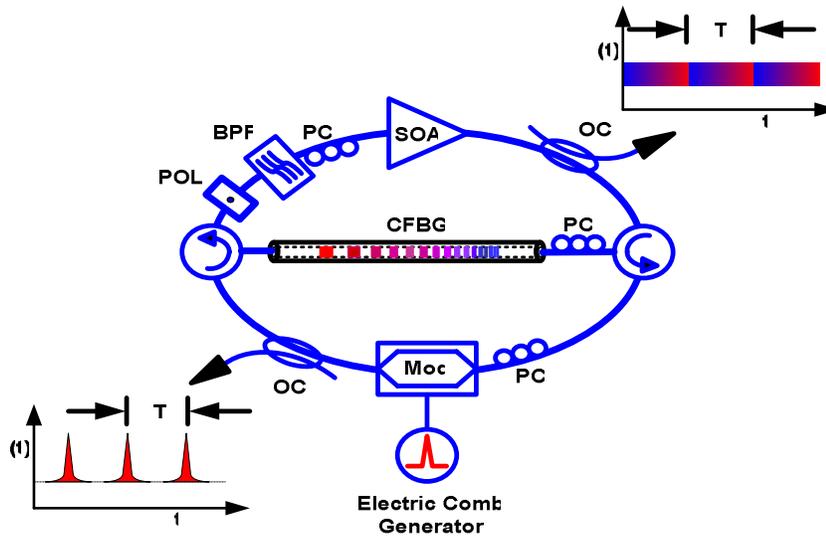


Fig. 2. Diagram Theta cavity for Extreme Chirped Pulse Oscillator (XCPO) made with an SOA. CFBG: Chirped Fiber Bragg Grating, SOA: Semiconductor Optical Amplifier, Mod: Intensity Modulator, OC: Output Coupler, PC: Polarization Controller, POL: Polarizer, BPF: Optical Band Pass Filter, T: Repetition Rate.

3. Experimental results

The performance of the stretched or frequency-swept pulse is summarized in Fig. 3. The spectrally resolved streak camera traces depicted in Fig. 3(a) for 3 repetition rates of the XCPO show the CW-like output which fills the repetition interval by broadening the mode-locked spectrum. The grating used in the spectrally resolved streak camera measurement is 500g/mm. It should be noted that the bright spots in lower wavelength at 102MHz are artifacts from damage of our streak camera. In this data, the down chirped pulse completely spans the pulse period, which means that as the repetition rate is reduced, the mode-locked optical bandwidth becomes linearly proportional to the repetition interval for a given group delay of the CFBG, as shown in Fig. 3(b). As mentioned earlier, ultrafast carrier dynamics and the integrated SPM effect in the SOA are completely eliminated due to CW injection into the SOA. The stable 102MHz stretched pulse result shows that the theta cavity design overcomes the fast gain dynamics in the SOA. The slope of Fig. 3(b) matches the group delay of the CFBG in this experiment, which is 2000ps/nm, e.g., note the same slope of the stretched pulse in the spectrally resolved streak camera trace. The output pulse energy is summarized in Fig. 3(c). At 102MHz repetition rate, a 33pJ energy is obtained directly from the oscillator with a 10% output coupler. The linear slope of Fig. 3(b) implies that the average power of the oscillator is maintained, owing to the CW injection into the SOA. As mentioned earlier, one obtains a scalable energy extraction with respect to the stretched pulse width. In addition to the scalable energy extraction from the oscillator, the scalable mode-locked bandwidth due to the large group delay of the CFBG and repetition rate of the Theta cavity is a distinct characteristic of the Theta cavity.

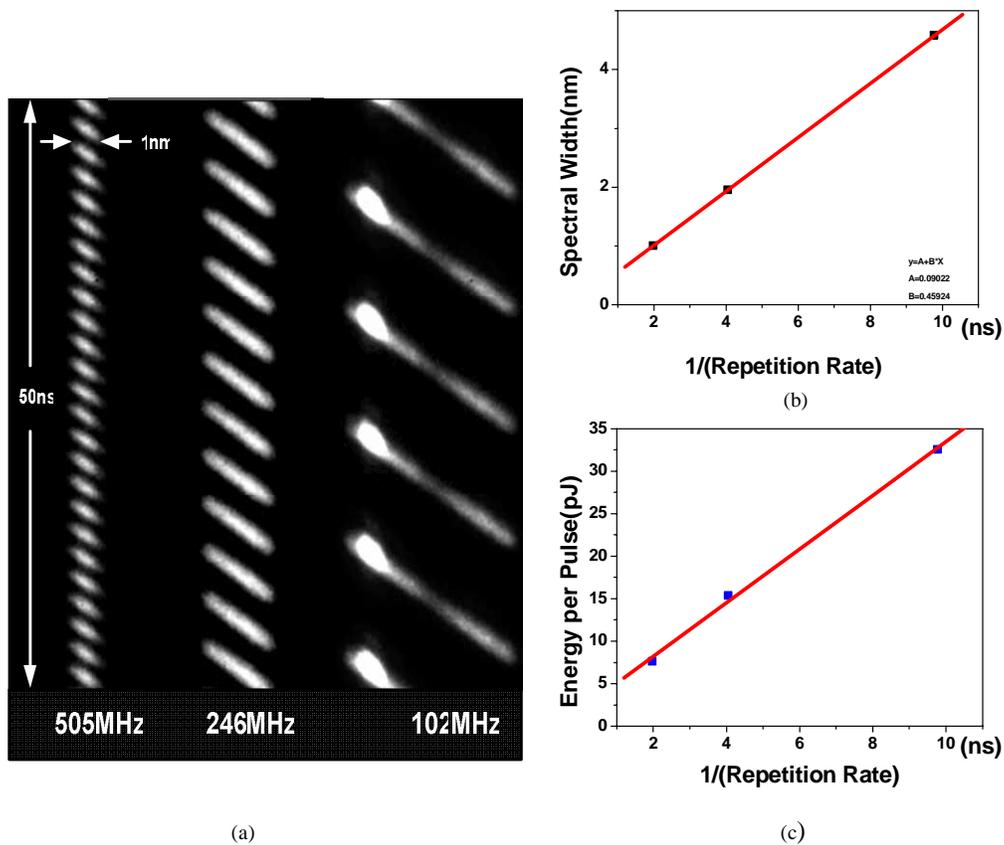


Fig. 3. Stretched pulse performance. (a) Spectrally resolved streak camera traces, (b) Mode-locked spectral bandwidth vs. repetition period, and (c) Energy per pulse for 505MHz, 246MHz, and 102MHz repetition rate. All data are taken at 600 mA DC-biased SOA.

The short pulse performance of the Theta cavity operating at 102MHz is summarized in Fig. 4(a, b). The bandwidth of the detection system for short pulse measurement is 18GHz. The sampling scope trace shows a clean pulse train and the intensity autocorrelation shows a 3.6ps pulse width, estimated by the 2.0 deconvolution factor which is calculated from the mode-locked spectrum. The autocorrelation width is measured to be 1.8 times larger than the transform-limited pulse, considering the calculated autocorrelation. It should be noted that low repetition rate operation, such as 100MHz, is generally very difficult to be realized, in semiconductor mode-locked lasers owing to the fast gain recovery of the semiconductor gain medium, especially for loss modulation, however, the XCPO approach provides a solution for low repetition rate semiconductor mode-locked lasers and high power operation while maintaining other key advantages of semiconductor gain media. Moreover, it should be noted that a further reduction in repetition rate can be achieved by increasing the group delay of a long CFBG.

In order to generate the shortest pulse at 102MHz, the bias current of SOA is reduced to 250mA. This reduces the mode-locked bandwidth to ~1nm with a strongly asymmetrical shape. This is a primarily due to the CFBG which limits the performance of the theta cavity. Even though a single CFBG is used to reduce the GDR of the CFBG, the fabrication process of the CFBG, such as single-side inscription, produces birefringence effects in the CFBG [13] which leave a residual GDR in the Theta cavity. An addition effect that limits the bandwidth of the mode-locked spectrum is the “stitching” error introduced into the grating during fabrication. Typically, long length CFBGs are written in sections, using multiple masks. This

leads to discontinuities in the Bragg condition at stitching location and increases loss at corresponding wavelengths. We believe that these limit the temporal duration of pulses generated from the Theta cavity.

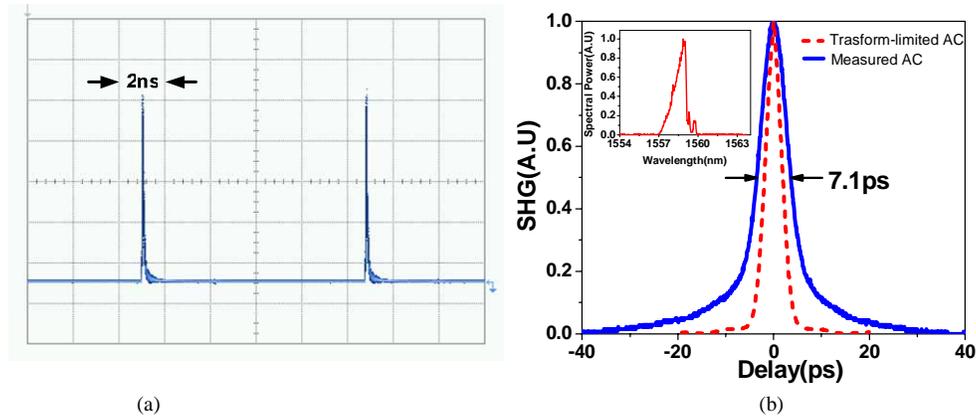


Fig. 4. Compressed pulse performance. (a) Sampling scope trace at 102MHz, and (b) second harmonic autocorrelation. Inset is the mode-locked spectrum for generating short pulses.

In order to increase the mode-locked bandwidth and increase the output power from the stretched port, we use a 660ps/nm group delay CFBG, a 20nm optical band pass, a 20% output coupler after the SOA, and a 10% output coupler after the modulator.

The CFBG has less than 3dB insertion loss over C-band and the group delay of the CFBG has opposite slopes depending on the input port from the CFBG as shown in Fig. 5(a). It is common that the reflection from the blue port shows a higher reflection than that from the red port in the shorter wavelength due to the cladding modes in long length CFBG. The stretched pulse in the spectrally resolved streak camera data shows that the spectrum fills the repetition interval in Fig. 5(b). The grating used in spectrally resolved streak camera trace is 50g/mm. In this case, the mode-locked bandwidth is 14.6nm (10dB) as shown in Fig. 5(c). The stretched pulse duration is estimated to be ~9.6ns (10dB) due to the wavelength and time mapping of the stretched pulses. The pulse energy from the stretched pulse is 58.4pJ directly from the oscillator. The sampling scope trace of the compressed port is shown in Fig. 5(d) which depicts a clean pulse train at 99MHz.

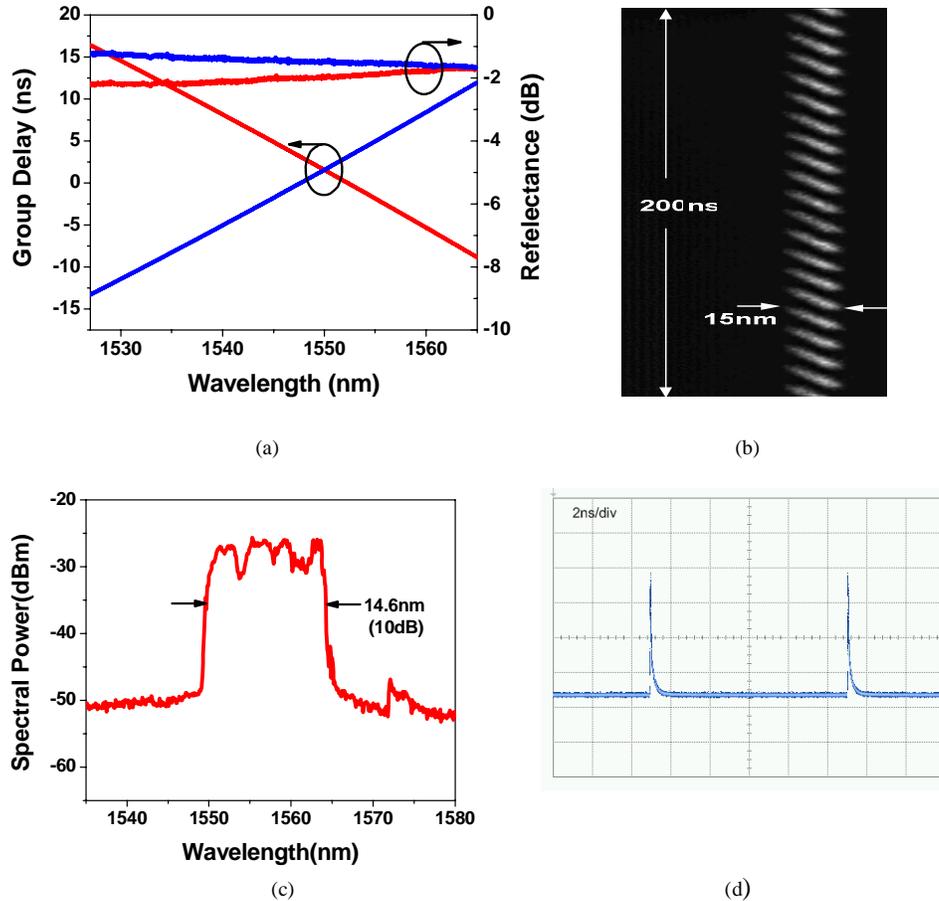


Fig. 5. Mode-locking with 660ps/nm group delay of CFBG. (a) Group delay of CFBG, (b) spectrally resolved streak camera of the stretched pulse, (c) mode-locked spectrum, and (d) sampling scope trace of 99MHz.

4. Conclusion

In conclusion, we have demonstrated a mode-locked eXtreme Chirped Pulse Oscillator (XCPO) implemented with a Theta cavity design that generates 10ns linearly chirped pulses and compressed pulses of 3.6ps in duration while maintaining various key advantages.

In this experiment, the two distinct advantages of the Theta cavity that are the scalability of pulse energy and the mode-locked spectrum of semiconductor gain medium have been demonstrated. These characteristics have been shown in the nanosecond stretched pulse regime which is longer than carrier life time (~ 1 ns) of a quantum well based semiconductor gain medium. By using these characteristics, we obtained a pulse energy of 58.4pJ from the stretched pulse and a mode-locked optical bandwidth of 14.6nm (10dB) directly from the oscillator at a repetition rate of 99MHz. The oscillator can be used for high speed frequency-swept optical coherence tomography (OCT) and time-stretched photonic analog digital converters (P-ADC). As a new regime in semiconductor mode-locking, future directions will focus on expanding the mode-locked bandwidth and to use high power semiconductor amplifiers in the gain medium.

Acknowledgments

This work was supported by DARPA/MTO PHOBIAC Program.