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1.4kW high peak power generation from an all semiconductor mode-locked master oscillator power amplifier system based on eXtreme Chirped Pulse Amplification (X-CPA)

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Abstract: The concept of eXtreme Chirped Pulse Amplification (X-CPA) is introduced as a novel method to overcome the energy storage limit of semiconductor optical amplifiers in ultrashort pulse amplification. A colliding pulse mode-locked semiconductor laser is developed as a master oscillator and generates 600fs pulses with 6nm bandwidth at 975nm. Using a highly dispersive chirped fiber Bragg grating (1600ps/nm) as an extreme pulse stretcher and compressor, we demonstrate ~16,000 times extreme chirped pulse amplification and recompression generating optical pulses of 590fs with 1.4kW of peak power. These pulses represent, to our knowledge, the highest peak power generated from an all semiconductor ultrafast laser system.

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1. Introduction

Compact ultrashort pulse, high energy laser sources are desirable for various applications such as free space optical communications, material processing, biomedical imaging etc. Due to their compactness, high wall-plug efficiency, broadband wavelength emission (UV to far IR) and cost-effectiveness, a mode-locked semiconductor laser and amplifier system [1-3] can be considered as a prime candidate. However, it is well-known that the energy storage time of semiconductor gain media is short, typically <1ns. Therefore this characteristic makes the semiconductor gain medium an inappropriate material for amplifying ultrashort optical pulses to high pulse energies. As a result, the amplification of ps or sub-ps pulses, whose temporal durations are much shorter than energy storage lifetime is limited by the small stored energy inside the gain media [2,4,5].

In this paper, we propose a novel method to overcome the energy storage limit of semiconductor gain media which will be referred as “eXtreme Chirped Pulse Amplification (X-CPA)” [6]. In addition, we develop a novel colliding pulse mode-locked semiconductor laser as a master oscillator. Incorporating this oscillator with a large dispersive chirped fiber Bragg grating (CFBG, ~1600 ps/nm with 6nm bandwidth at 974nm center wavelength) as an extreme pulse stretcher and recompressor, in conjunction with cascaded InGaAs semiconductor optical amplifiers in X-CPA system, we were able to generate diffraction limited ultrashort pulses with 1.4kW peak power, which, to our knowledge, is the highest peak power generated from an all-semiconductor MOPA system.

2. Concept of X-CPA

Assuming that the input energy injected into an SOA is close to its saturation energy, the output energy after the SOA is more or less independent of input energy i.e. a small additional increase in the input energy does not produce a significant increase in the output optical power from the SOA. Generally, this is considered as a fundamental limitation of the stored energy of SOAs. However, in an all semiconductor CPA system as shown in Figure 1, if a temporally stretched pulse has a much longer temporal duration than the energy storage time of the gain media, the amplification through the semiconductor gain media will not be limited by the stored energy inside the SOA. The energy extraction from the SOA will be approximately given by the continuous wave output power from the SOA multiplied by the stretched pulse temporal duration injected into the SOA. In other words, even if energy gain...
saturation induced by the leading part of optical pulse, the trailing part of optical pulse will experience optical gain from the SOA because there is sufficient time to re-pump the SOA. This process is called “X-CPA” owing to the extreme stretched temporal durations that are required. Recently, the development of chirped fiber Bragg gratings that possess large dispersion (>1600 ps/nm with 6 nm at 974 nm center wavelength) [7] allow the concept of X-CPA to be realized.

Fig. 2. colliding pulse, hybrid mode-locked semiconductor laser, (a) cavity setup (HR : high reflector, MQW SA : multiple quantum well saturable absorber, IBTSOA : inverse bowtie semiconductor optical amplifier, OC : output coupler, slit : adjustable slit, L : cavity length), (b) autocorrelation trace of optical pulse from CPMLL after an external bulk grating pulse compressor) and (c) optical spectrum of GFMLL and transmitted optical spectrum of MQW SA

3. Colliding Pulsed, Hybrid Mode-locked Semiconductor Laser : development of master oscillator

As a master oscillator in the X-CPA system, we developed a novel colliding-pulse, hybrid mode-locked semiconductor laser (CPMLL). The schematic diagram of the CPMLL is displayed in Fig. 2(a). A transmission-type multiple quantum well saturable absorber (MQW SA), used as a passive mode-locker, is placed at the half cavity position and an inverse bowtie semiconductor optical amplifier (IBTSOA) [2], as a gain medium, is placed at the 1/3 cavity position. IBTSOA is driven by an amplified 285MHz RF sinusoidal wave, which is the second harmonic pulse repetition frequency of the external cavity, as well as a 215mA DC current. There is an adjustable slit inside the cavity to control the spatial mode profile into the MQW SA and IBTSOA. The MQW SA consists of 75 repetitive layers of 8.5 nm In0.18Ga0.82As quantum well and 10 nm Al0.33Ga0.67As barrier on a GaAs substrate and both surfaces are anti-reflection coated with silicon nitride [8]. The excitonic absorption peak at room temperature is located at 970nm (Fig. 2(c)). The IBTSOA used as gain medium inside
the CPMLL cavity has the design of a 1mm-long InGaAs inverse bowtie shaped stripe at an angle of 6 degrees with respect to the facets, linearly tapered from a 10um width at the facet to about 20um with at the center. The 10um aperture on both facets makes output beam closer to diffraction limited and a wide tapered center region is incorporated for generating high power [2]. By optimizing the cavity length and the output coupler, we are able to generate >20pJ output pulse energy directly from the oscillator. The salient feature of the CPMLL is that 40–50ps compressible up-chirped pulses are generated directly from the oscillator. This feature of generating a pre-chirped pulse is useful for minimizing nonlinearities inside the CFBG used as a compression stage. In Figure 2(b), the output optical spectrum from the CPMLL has a typical spectral shape from passively mode-locked semiconductor lasers using MQWSAs [1] and its bandwidth is from 971nm to 977nm. Compensating the impressed chirp by an external dual bulk grating compressor [9], we are able to compress the 45ps pulse from the oscillator down to 0.92ps (FWHM at autocorrelation trace). With the assumption of a hyperbolic secant pulse, a deconvolved pulse width becomes 0.60ps, which is ~3.5 times the transform-limited pulse duration.

Fig. 3. (a) chirped fiber Bragg grating as an extreme pulse stretcher and compressor, group delay and reflectance band from (b) red port and (c) blue port of CFBG

4. Chirped Fiber Bragg Grating: extreme pulse stretcher and compressor

A highly dispersive chirped fiber Bragg grating (Figure 3, 3M) used as an extreme pulse stretcher and compressor [7] plays an important role in realizing the X-CPA concept. As shown in Fig. 3(a) and (b), the group delay of the CFBG is linear and is ~ 1600 ps/nm with 6nm bandwidth at 974nm center wavelength and the physical length of the CFBG (t_{stretch} = c/2nL) is about 0.96m considering the refractive index of the fiber core. The grating is written in photosensitive PS1060 fiber that supports a single spatial mode (MFD~5.9um²) within the reflectance wavelength band. Due to cladding modes of the CFBG, the reflected blue shifted wavelengths from the red port of the CFBG experiences more loss than the red shifted wavelengths. This is clearly seen from the reflectance spectrum measured from the red port (Fig. 3(b)). However, the reflectance band of blue port is flat (Fig. 3(c)). The maximum
stretched pulse will be \( \sim 9.6\text{ns} \) which realizes at least a ten times larger energy extraction from the semiconductor optical amplifier considering \(<1\text{ns} \) energy storage lifetime of SOA.

5. eXtreme Chirped Pulse Amplification (X-CPA) system

Figure 4(a) illustrates the X-CPA system combining 1) the CPMLL as the master oscillator (Fig. 2(a)), 2) a pulse picker, 3) one CFBG as an extreme pulse stretcher and compressor (Fig. 3(a)), 4) cascaded amplifiers and 5) a dual bulk grating compressor as a final compressor. In this case, the CPMLL generates 39pJ per pulse with compressible up-chirped \( \sim 38\text{ps} \) pulses (Fig. 6(a)) at \( \sim 285\text{MHz} \) and \( \sim 6.5\text{nm} \) bandwidth at a center wavelength 974nm (Fig. 6(b)) that well-matches the center wavelength of the CFBG (Fig. 3(b) and (c)). As we mentioned previously, \( \sim 38\text{ps} \) pre-chirped pulses supports reducing the peak power at the end of the CFBG pulse compression stage, reducing possible nonlinearities such as self phase modulation and Raman scattering, which cause a pulse distortion at high peak power. If a 285MHz pulse train from the CPMLL (Fig. 5(a)) is stretched directly using a CFBG, then three pulses will temporally overlap, leading to gain competition and a reduction of the efficiency of energy extraction from the cascaded semiconductor optical amplifier chain (Fig. 5(c)). In order to prevent the temporal pulse overlapping, a pulse picker is inserted between the CPMLL and an extreme pulse stretcher. A 1mm long IBTSOA, identical to the SOA inside the oscillator, is used as the pulse picker and is pulse biased to reduce the repetition rate from 285MHz down to 95MHz (Fig. 5(b)). The pulse picker is driven by a \( \sim 3\text{ns} \) electrical pulse at 95MHz amplified through a high power RF amplifier. The salient feature of the SOA pulse picker is that we are able to amplify the optical pulse to compensate loss arising from single mode fiber coupling and an insertion loss inside the CFBG as an extreme pulse stretcher, as well as reduce the pulse repetition rate. Also, by putting a reverse bias between forward biased 95MHz electrical pulses, the transmitted pulses under an unbiased condition can be suppressed by absorption and it improves the signal to noise ratio of the 95MHz pulse train. A 95MHz pulse train after the pulse picker is extremely stretched to \( \sim 9.6\text{ns} \) after reflecting from the red port of the CFBG (Fig. 3(a)). The average power of the stretched pulses at 95MHz is \( \sim 1.3\text{mW} \) which is sufficient to saturate a 1mm long preamplifier biased at.

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Fig. 4. experimental setup of X-CPA system (CPMLL : colliding pulse hybrid mode-locked semiconductor laser, OI : optical isolator, PBS : Polarizing Beam Splitter, HWP : half wave plate, FR : faraday rotator, lens: coupling/collimating lens, RWGSOA : ridge waveguide single mode semiconductor optical amplifier, TA : tapered amplifier, BPF : band pass filter, PC : polarization controller, CFBG : chirped fiber Bragg grating)
150mA. The preamplifier is a 5-degree angle tilted ridge waveguide InGaAs/AlGaAs semiconductor optical amplifier. After boosting the optical power after the pulse stretcher, the optical power after the preamplifier is maximized through a tapered amplifier used as a power amplifier. The tapered amplifier is 3mm long with a 3um input aperture and a 200um output aperture and is biased at 2.5A DC. After the tapered amplifier, the maximum average optical power of 1W is obtained with 16mW input power from the preamplifier. The salient feature of the amplifier chain is that the 9.6ns extremely stretched pulses at 95MHz nearly fill the time window between pulses and thus simulates cw optical injection into the cascaded amplifiers. This allows us to have an extremely good signal to noise ratio and results in most of the 1W output power from the tapered amplifier being contained to the amplified signal (Fig. 5(d)). It should be noticed that this corresponds to 10.5nJ per 9.6ns stretched pulse and clearly demonstrates the advantage of energy extraction of the X-CPA concept.

![Image](image-url)

Fig. 5. spectrally resolved streak camera images of (a) optical pulse from CPMLL combined with a DC biased pulse picker, (b) stretched pulses from extreme pulse stretcher without a pulse picking and (c) stretched pulses from extreme pulse stretcher with a pulse picking (horizontal axis : wavelength with 22nm full window, vertical axis : time with 50ns full window), (d) optical spectrum from tapered amplifier output with and without injection (dark line : with injection, light line : without injection, dotted line : reflectance band edges of CFBG).

Incorporating beam shaping optics which consists of an aspheric lens (f=2.84mm, 0.67NA) as a collimator, a cylindrical lens (f=4mm) as an astigmatism compensator and a microscope objective lens (40X) as a single mode fiber coupler, we are able to couple an average power of 560mW into a single mode fiber, which represents 56% coupling efficiency, and given the insertion loss of the CFBG as an extreme pulse compressor and the external dual grating compressor as a final pulse compressor, an average output power of 194mW is measured after compressing the optical pulse. The optical spectrum of recompressed pulse is measured to possess 6nm bandwidth which is well matched with the bandwidth of the CFBG. The energy per pulse is 2.0nJ and the autocorrelation trace of the recompressed pulse is 0.91ps at FWHM (Fig. 6(c)). With assumption of a hyperbolic secant pulse shape, the pulse width of the recompressed pulse is 0.59ps. Even though a 39ps pre-stretched pulse from the CPMLL is injected into the X-CPA system to reduce the nonlinearity, we are able to observe the nonlinearity due to high peak power from the optical spectrum and autocorrelation. In Fig. 6(d), the generation of sidebands in the optical spectrum is observed corresponding to
temporal wings in the autocorrelation trace (Fig. 6(c)). Considering the energy in the center lobe of the autocorrelation trace, we are able to generate a peak power of 1.4kW. This peak power, to our knowledge, is the highest peak power and first >kW demonstration generated from an all-semiconductor mode-locked laser system. It should be noted that through the extreme pulse compressor, we demonstrate that 9.6ns extremely stretched pulses are recompressed down to 0.59ps (Fig. 5(b)→Fig. 6(c)), which represents near 16,000 times extreme pulse recompression. Since the output beam is obtained directly from a single mode fiber, the spatial beam quality from the X-CPA system is purely diffraction limited. We believe that by replacing the PS1060 CFBG with a large mode area CFBG or/and by inserting a pre-stretcher before the extreme pulse stretcher, nonlinearity will be reduced improving the X-CPA system output performance. In reference [10], we reported the generation of 238nJ per 16ns stretched pulse before pulse compression, with 13000-times optical gain. This shows the potential to obtain high pulse energy from a compact all-semiconductor mode-locked laser system using the X-CPA concept.

![Figure 6](image)

**Fig. 6.** (a) autocorrelation trace [12.5ps/div] and (b) optical spectrum of compressible up-chirped optical pulse from CPMLL, (c) autocorrelation trace [5ps/div, 2ps/div] and (d) optical spectrum of recompressed pulse from X-CPA system, dotted lines in Fig. (b) and (d): reflectance band edges of CFBG

### 6. Conclusion

In conclusion, we demonstrate the generation of diffraction limited ultrafast optical pulses with 1.4kW record peak power from an all semiconductor mode-locked laser system using the X-CPA concept. This result represents to our knowledge first kW demonstration from an all semiconductor laser system. In addition, we develop a sub-ps colliding pulse, hybrid mode-locked semiconductor laser as a master oscillator and demonstrate ~16,000 times extreme pulse recompression using a CFBG. We believe that these results represent a significant step toward a compact, high energy all semiconductor ultrafast laser system.

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