PROGRESS REPORT ON DEVELOPMENT OF NOVEL ULTRAFAST MID-IR LASER SYSTEM*

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Abstract

Of particular interest to X-ray FEL light source facilities is Enhanced Self-Amplified Spontaneous Emission (ESASE) technique. Such a technique requires an ultrafast (20-50 fs) high peak power, high repetition rate reliable laser systems working in the mid-IR range of spectrum (2μm or more). The approach of this proposed work is to design a novel Ultrafast Mid-IR Laser System based on optical parametric chirped-pulse amplification (OPCPA). OPCPA is a technique ideally suited for production of ultrashort laser pulses at the center wavelength of 2 μm. Some of the key features of OPCPA are the wavelength agility, broad spectral bandwidth and negligible thermal load. This paper reports on the progress of the development of the Ultrafast Mid-IR Laser System.

INTRODUCTION

For the past decade, FEL-based light sources have become an increasingly indispensible tool in innovative ultrafast x-ray research that has proven to be beneficial in areas ranging from atomic and molecular sciences to chemical, materials, and biological studies. Such light sources are employed or being built in a number of laboratories worldwide: SLAC Linac Coherent Light Source (LCLS) [1], PSI SwissFEL, DESY FLASH, European XFEL, SPARC, and SPring-8 to name a few [2]. The Enhanced Self-Amplified Spontaneous Emission (ESASE) technique has a great potential to benefit the FEL-based light sources. ESASE has the following principle of operation: an optical laser interacts with the electron beam in an upstream wiggler and induces energy modulation, which is converted to a large density modulation prior to entering the SASE undulator. [3]. Such modulated electron beam has a significantly shorter SASE gain length, allowing for saturation with sub-femtosecond slippage and hence the generation of ESASE attosecond x-ray spikes. The use of the optical laser also provides natural synchronization for pump-probe experiments. The ESASE offers potentially more precise synchronization capability and shorter pulses, which is instrumental in probing transient processes in condensed matter on an atomic scale [4]. The number of attosecond x-ray spikes depends on the length of the optical pulse and can in principle be reduced to a single spike with an ultra-fast laser system such as that proposed herein.

EXPERIMENTAL METHODOLOGY

While ultra-fast lasers are ubiquitous at 800 nm, one technical difficulty that needs to be resolved for the ESASE scheme to be applied directly at a facility such as LCLS is the unconventional spectral requirements for the optical laser. In order for the ESASE scheme to work efficiently, the duration of ESASE beamlets has to be longer than the amount of SASE slippage through saturation. A typical number of electrons per optical wavelength at 3400 A current is ~ $1\text{x}10^8$; it would take just over 8 FEL field gain lengths to reach saturation. Using the minimum cooperation length for ESASE estimated in [3] at ~ 5 μm yields a slippage value at saturation in the range of 80-100 nm. At the same time, the beamlet compression efficiency of the optimized wiggler-chicane system is only limited by uncorrelated energy spread (in the single digit keV range for LCLS) and for a reasonably large linear energy modulation in the wiggler, the compression ratio in the chicane can be as large as a factor of 20. Hence, in order to achieve the optimized efficiency of the ESASE process, the laser wavelength should comfortably exceed the product of the maximum slippage length and the compression ratio. More specifically to LCLS, a SASE slippage of 100 nm x 20 yields optical laser wavelength to be no less than 2 μm; which presents an engineering challenge.

Optical Parametric Chirped-Pulse Amplification (OPCPA) is a technique ideally suited for production of ultrashort laser pulses at the center wavelength of 2 μm. In OPCPA, an efficient energy transfer between the short-wavelength pump pulse and the long-wavelength signal is realized through a three-wave mixing process in a nonlinear crystal. Some of the key features of OPCPA are the wavelength agility, broad spectral bandwidth and negligible thermal load. The main challenge associated with the use of OPCPA has always been the availability of suitable pump lasers and the pump-signal synchronization. Since OPCPA is an instantaneous process with no energy storage, the pump pulse duration needs to be comparable to the pulse duration of the signal pulses; synchronization must be realized to within a small fraction of the signal pulse. This is very challenging for shorter pump pulses, especially if the seed and pump pulses originate from different lasers.

Unlike the schemes used to date [5], we will not construct a new pump laser but rather use the same 800-nm Ti:sapphire laser to produce pump pulses and pump a non-degenerate OPCPA operated with relatively small chirp, within approximately 100x of the transform limited pulse duration.

A pulse generated by a Ti:Sapphire laser system is split into two pulses of unequal energies. The high-energy pulse is used to pump the OPCPA and the low-energy pulse is injected into a photonic crystal fiber (PCF), where

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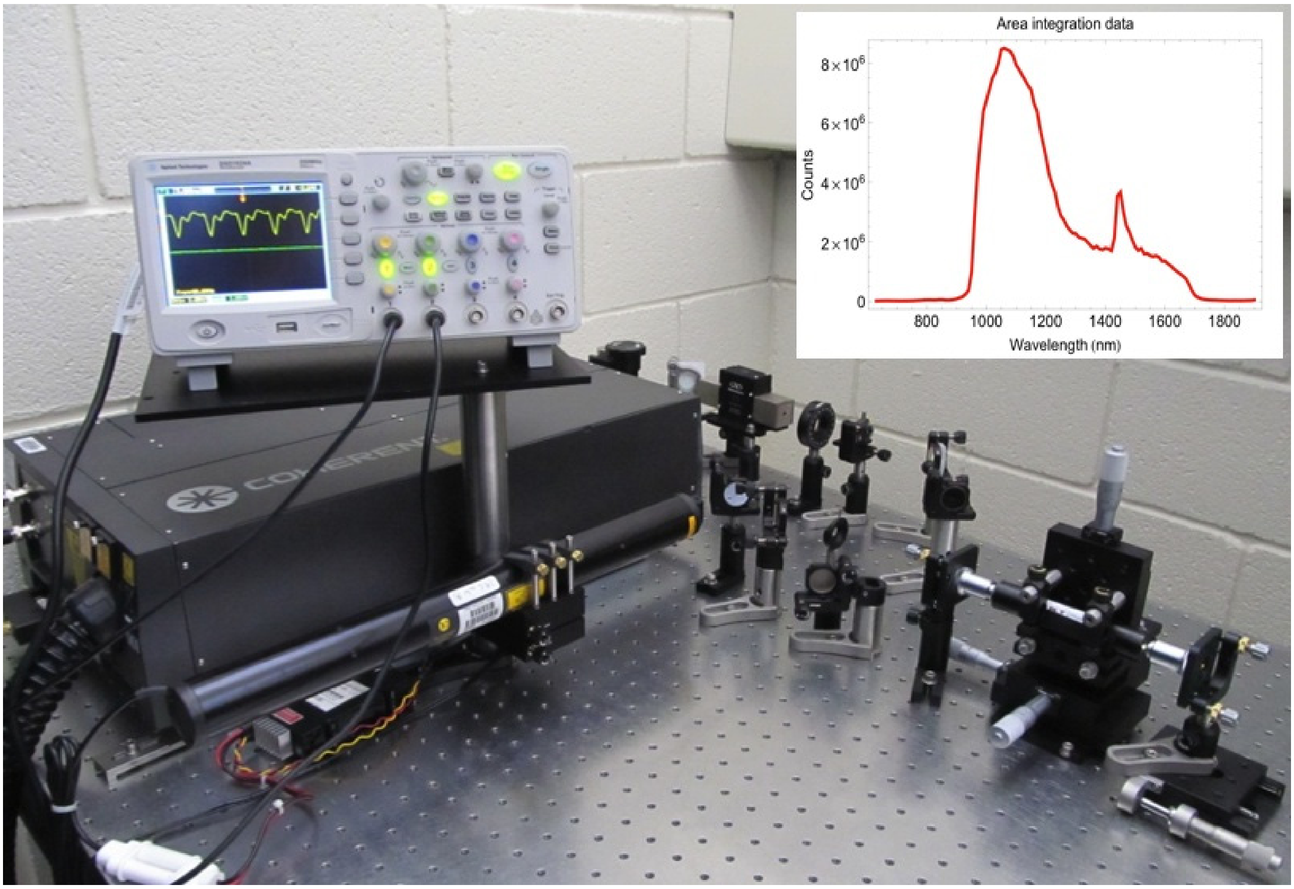

Figure 1: The set-up of 80-MHz Ti:sapphire oscillator and a PCF-800 commercial photonic crystal fiber device was used to generate the supercontinuum. The spectrum (insert) was measured using a Jobin-Yvon MicroHR spectrometer and a Xenics XS-1670 InGaAs camera.

it is spectrally shifted and broadened and then passed through a spectral filter, resulting in 1.33 µm wavelength seed pulses for OPCPA. This seeding method is the first important innovation in our proposed laser system: instead of using the PCF to spectrally shift and broaden the 800-nm pulse to 2 µm, the PCF is used to produce a spectral shift to 1.33 µm. This more modest spectral shift significantly relaxes the requirements on the pulse energy in the PCF and the complexity of subsequent dispersion compensation. The 1.33 µm pulse is used in the first stage of OPCPA to produce the required 2 µm pulse *concurrently with amplification.* The difference-frequency process used is 800 nm → 1333 nm + 2000 nm, and the 2000 nm pulse is generated as the idler beam in the first stage of OPCPA. This idler beam will have angular dispersion, which will be compensated before injection into the next OPCPA stage by use of a prism or grating. In the subsequent OPCPA stage(s), the 2 µm pulse will be used in a standard configuration, as a signal beam. The scheme of idler-seeding has been previously successfully demonstrated in an OPCPA system [6] and is thus expected to be applicable to this system.

The proposed three-wave mixing process is highly non-degenerate, which results in narrow gain bandwidths in conventional collinear beam configurations.

PRELIMINARY TEST RESULTS

As discussed above, a small portion of the Ti:Sapphire laser pulse (<1 µJ) will be split from the main pulse and injected into a PCF. The pulses emerging from the photonic crystal fiber are spectrally broadened, resulting in 1.33 µm wavelength seed pulses for seeding the first stage of OPCPA. The proper spectral region is selected at the output of PCF using a filter. This approach has been tested experimentally by our Penn State PI, as described in the following.

We have used a 80-MHz Ti:sapphire oscillator (Coherent Micra-5) and a PCF-800 commercial photonic crystal fiber device (Newport SCG-800) to generate the supercontinuum. The laser is isolated from the photonic crystal fiber using a Faraday isolator due to the considerable feedback from the coupling microscope objective coupler, which affects the laser mode-locked operation. The experimental setup is shown in Figure 1.

Since PCF-800 has extremely small core size (1.8 µm), a good coupling scheme with high-precision multi-axis alignment capabilities has to be used. A 20x input coupling objective and a 40x output collimation objective were employed. We first measure the coupling efficiency and transmission of the power by the use of a power meter at the fiber output. The color of the output beam changes noticeably as the power is increased, indicating effective spectral shift and broadening, The coupling efficiency measured is ~38-44%, which meets the fiber specifications.

The spectrum was measured using a Jobin-Yvon MicroHR spectrometer and a Xenics XS-1670 InGaAs camera. The spectrum collected is shown in the insert of the Figure 1, and indicates a considerable amount of light near the 1.33 μm wavelength.

Overall, the results clearly indicate success in producing the required light at 1.33 μm wavelength with broad bandwidth; that can be used as a seed for the first stage of OPA.

SUMMARY

A novel ultra-fast OPCPA-based laser system operating at 2 μm has a great potential to be beneficial to future ESASE efforts at facilities such as SLAC LCLS.

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