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

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Abstract

Finding alternate acceleration mechanisms that can provide very high gradients is of particular interest to the accelerator community. Those mechanisms are often based on either dielectric laser acceleration or laser wakefield acceleration techniques, which would greatly benefit from mid-IR ultrafast high peak power laser systems. The focus of this proposed work is the design of 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 – 5 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 design.

INTRODUCTION

Mid-IR ultrafast high peak-power laser systems are needed for a number of accelerator applications, ranging from dielectric laser acceleration and laser wakefield acceleration to FEL seeding and ESASE X-ray FEL [1, 2, 3]. Despite the prevalent need in accelerator applications, such laser systems are not commercially available. Ultrafast, high peak power laser systems that are available operate in the near-IR/visible range, while existing mid-IR lasers do not produce nearly as short pulses as required. A good example of laser parameters needed in the accelerator community are those required for the Dielectric Laser Acceleration effort at the SLAC E163 facility: a wavelength range of 1 µm – 4 µm, energy of 1 µJ to 1 mJ, pulse length of 1 ps or less, and repetition rate of 10 Hz – 1 kHz [4].

To accommodate the ever-increasing laser needs of the accelerator community, we are proposing a novel 2 µm – 5 µm Mid-IR Laser System (MIRLS) based on optical parametric chirped-pulse amplification (OPCPA) as described herein.

EXPERIMENTAL METHODOLOGY

Optical Parametric Chirped-Pulse Amplification (OPCPA) is a technique ideally suited for production of ultrashort laser pulses at the center wavelength of 2 µm – 5 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 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 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.

To produce light beyond 2 µm, a more general approach has to be taken and a number of different pumping schemes have to be considered, including Ti:sapphire–based laser systems (800 nm), Yb-based system (1 µm) and Tm/Cr/Ho-based systems (~2 µm) as well as their combinations. The latter type of laser system has the greatest potential. Tm/Cr/Ho-based laser technology is rapidly developing and has generated a lot of interest for use in military, medicine, and meteorology. For example, a thulium-doped YAG (Tm:YAG) laser naturally operates between 1930 and 2040 nm, hence making it very simple and inexpensive. Tm/Cr/Ho technology is not mature yet, but it is rapidly developing and it is expected that state-of-the-art commercial systems will be available within 2-5 years. Tm:glass fiber oscillators have been demonstrated with a few hundreds of fs pulse durations and nJ pulse energies [5], thus reaching levels that are competitive with other technologies.

One of the unique features of the proposed system is the wide acceptance of different pump sources with only limited modifications to the system design. The design is based on a Ti:sapphire-pumped two-stage OPCPA system, since such a pump is readily available and technologically mature. In this baseline design, a surrogate 2 µm source is pumped by a Ti:sapphire laser [6]. Once the Tm/Cr/Ho technology matures, the proposed system can be easily modified to accept a new pump at 2 µm, simplifying the OPCPA system by pumping it directly. The final optimized conceptual design is depicted in Figure 1. Here, a pulse generated by a Ti:sapphire laser system is split into two pulses of unequal energies. The low-energy pulse is injected into an optical parametric generator (OPG) or self-phase modulation medium such as photonic crystal fiber (PCF), and then passed through a spectral filter, resulting in 1.33 µm or 2 µm wavelength seed pulses for a two-stage OPA realized in a BBO crystal. This first OPA system produces a high-energy 2-µm pump pulse (by taking either the signal or the idler when the OPA is seeded with a 2 µm or a 1.33 µm pulse, respectively). This first portion of the system will be replaced by Tm/Cr/Ho-based laser pump source, once the technology sufficiently matures.

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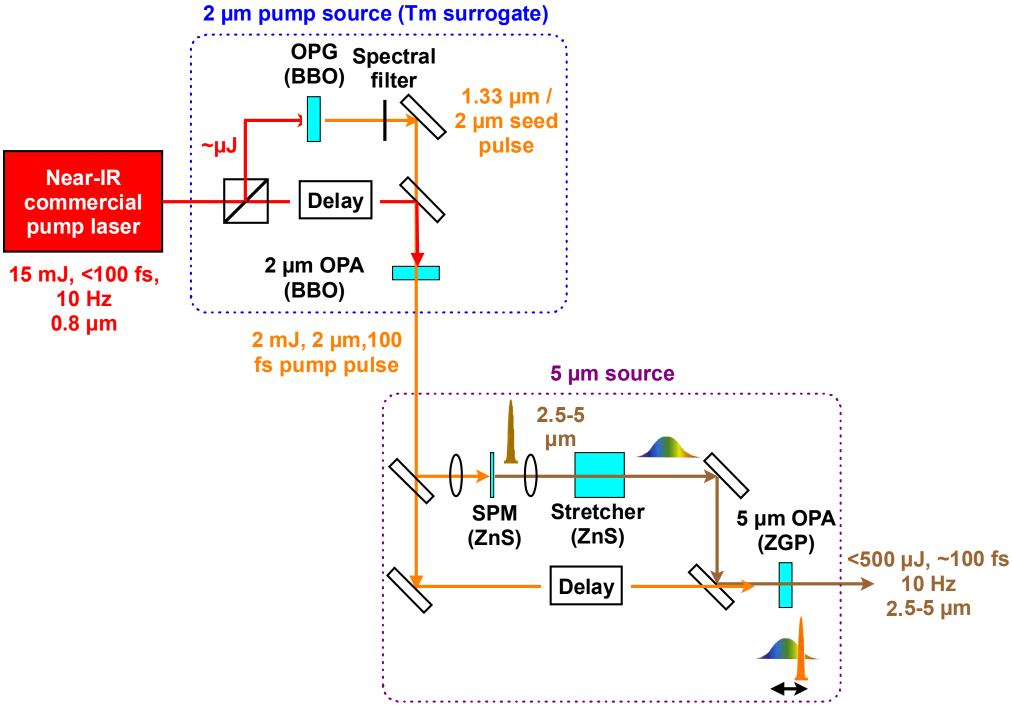

Figure 1: Non-degenerate 2 µm - 5 µm OPCPA system pumped by a standard Ti:sapphire ultrafast laser system.

NONLINEAR CRYSTAL SELECTION

A number of promising crystal candidates were investigated and a crystal of zinc-germanium diphosphide (ZGP) was selected. It showed a great promise given the combination of relatively short interaction length needed to produce the required pulse energies and the relatively low group velocity mismatch and broad calculated bandwidth. For such short interaction lengths, the transparency of ZGP crystal in the range of interest (2 µm – 5 µm) is expected to be adequate.

High-gain OPCPA is known to produce a significant parametric fluorescence background. In the case of our design, this fluorescence background will have the pulse duration nearly identical to that of the amplified signal, but can reduce the available pump energy available for signal amplification. This fluorescence will be suppressed by separating the amplification process into several amplification stages, with careful spatial filtering between stages, or the use of simple propagation (parametric fluorescence has a greater angular spread than the amplified signal).

Modeling of the broad-bandwidth difference-frequency process used to produce up to 5 µm pulses is of paramount importance for the implementation of the proposed laser system. We modeled a collinear OPCPA process using a ZGP crystal pumped by 2 µm pulses, using a simplified numerical model. The results indicate that the bandwidth of the process is sufficiently high to support production of ultrashort laser pulses at >2 µm. A code was specifically adapted for this task from prior work [7]. The code is based on the numerical solution of coupled wave equations for difference-frequency mixing, with dispersion effects in birefringent or quasi-phase-matched nonlinear crystals taken into account.

OPA PERFORMANCE SIMULATION

Complete analysis of the system requires dispersion modeling and design of appropriate dispersion compensation. In our system the effect of dispersion on the final mid-IR pulse will be primarily determined by the stretch of the continuum performed in ZnS and the duration of the 2 µm pump pulse which performs the spectral selection prior to mid-IR amplification in ZGP. The SPM stage can produce the adequate spectral bandwidth, and the required dispersion compensation is expected to be small in magnitude; it will be accomplished at the output of the entire system, if needed. This dispersion compensation at the system output can be particularly elegant and lossless if the idler rather than signal is used following amplification in ZGP. In this case, the idler will exhibit a small negative chirp (opposite of the injected signal). If needed, this chirp can be readily compensated by normal material dispersion. In practice, the way this would be accomplished is by inserting another block of ZnS, which would function as a nearly lossless pulse compressor. The ZGP OPCPA system stages exhibit short gain lengths and thus will not significantly contribute to pulse broadening.

A comprehensive OPCPA code that was specifically adapted for this task from prior work has been extensively tested in experiments [8]. This code allows for the accurate prediction of the pulse front tilt effects and angular dispersion, as well as detailed calculation of

OPCPA energetics with temporally and spatially non-uniform pump and signal beams that are used in real experiments. While this code also takes into account diffraction, this effect is not expected to be pronounced due to the short interaction length in nonlinear crystals.

To illustrate the predicted performance of MIRLS we study the following mixing process in a two stage OPCPA system:

5 μm (e) + 3.47 μm (e) → 2.05 μm (o)

For this process in ZGP in collinear geometry, phase matching will occur at the crystal cut angle of 56.1° with respect to the crystal principal plane. The effective nonlinearity at this angle is relatively high at 75.9 pm/V. The crystal is also calculated to exhibit broad angular and temperature acceptance (5.7 mrad-cm and 20 K-cm, respectively). The first ZGP OPA can be considered as a high-gain preamplifier with spectral selection, in which the conversion efficiency is not paramount for efficient operation of the entire system.

To obtain the first estimate of the effect of beam profile, dispersion, and group velocity dispersion on the spatial and temporal beam profile of the amplified signal and to estimate the conversion efficiency, we have utilized the nonlinear code SNLO [9]. For the following calculations we focus on the second ZGP optical parametric amplifier (power amplifier), in which we require a gain on the order of 10^3 to amplify the ~1 μJ signal obtained from the first ZGP optical parametric amplifier. It is assumed that the pump pulse has a center wavelength of 2 μm, pulse duration of 100 fs, and a pulse energy of 2 mJ. All beam profiles are assumed to be Gaussian, and all injected beam diameters are set at 7 mm, yielding conservative pump and seed intensities of 34 GW/cm^2 and 17 MW/cm^2, respectively.

The injected signal is delayed with respect to the pump by 0-50 fs to partially compensate for the differences of group velocity dispersion among the signal, idler, and pump pulses. The maximum theoretical conversion efficiency that can be realized in this difference-frequency mixing process is 40% to 5 μm pulse, or 60% to 3.33 μm pulse. A more conservative estimate for conversion efficiency expected from this process involves the imperfect spatial and temporal overlap of pulses, group velocity dispersion, and non-uniform beam profiles, and yields a considerable reduction in maximum efficiency without spatio-temporal beam shaping. We still calculate good conversion efficiencies on the order of 12% to 5 μm or 19% to 3.47 μm. Thus, we can expect that with 2 mJ pump pulses we can produce ~250 μJ pulses at 5 μm or ~370 μJ pulses at 3.47 μm. The predicted optimal crystal length for the second ZGP optical parametric amplifier for these conditions is 450 μm.

A refined temporal model obtained by including the effects of group velocity dispersion results in a better estimate of the resulting pulse shape and duration following the second ZGP optical parametric amplifier. With an assumption of a 100 fs Gaussian input signal pulse from the first optical parametric amplifier, a modest pulse shortening and distortion is expected, as shown in Figure 2. The pump depletion is also evident in the pump temporal profile.

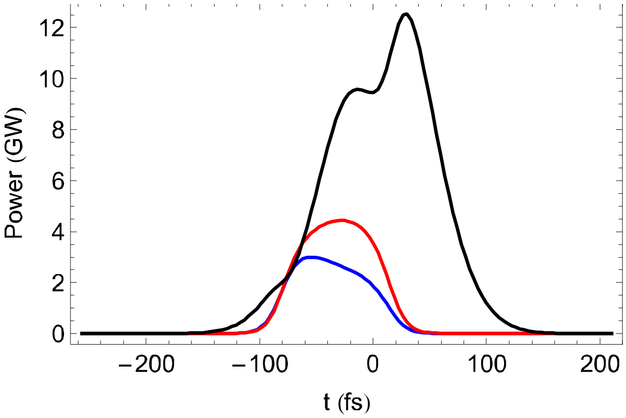

Figure 2: Temporal profiles of 2-μm pump pulse (black), 5-μm pulse (blue), and 3.33-μm pulse (red) following amplification in the second ZGP OPA with optimized crystal length of 450 μm.

SUMMARY

We described a preliminary design of a novel ultra-fast OPCPA-based laser system operating at 2 μm – 5 μm range, which has a great potential to be beneficial to future DLA efforts at facilities such as SLAC.

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