PROGRESS REPORT ON DEVELOPMENT OF A 5-MICRON DRIVE LASER FOR DIELECTRIC LASER ACCELERATION*

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Abstract

A simple and robust ultrafast, high-peak-power 5-µm laser source for pumping a dielectric photonic structure for high-gradient electron acceleration has been designed and is being constructed. The 5-µm laser source consists of two components: (1) a type-II-BBO-based 2.05-µm optical parametric amplifier (OPA) as a pump source, and (2) a type-I-ZGP-based 5-µm OPA to produce mJ-class, <100 fs pulses. Our supercontinuum-seeded two-stage 2.05-µm OPA is pumped by a Ti:sapphire amplifier and produces pulse energy of ~2.2 mJ with a pulse duration of 87 fs. Carrier-envelope phase (CEP) stabilization is passively established for 2.05 µm pulses in our OPA design. A modified design of seed pulse generation for the 5-µm OPA based on several cascaded parametric processes can also result in CEP-stable operation for 5-µm amplified pulses.

INTRODUCTION

Ultrashort mid-IR pulses are attractive for high-order harmonic generation for isolated attosecond pulses since coherent x-ray photon energy cutoff can be siginifcatly extended by using a long-wavelength driver [1]. Recent progress in theoretical and experimental high field physics and the advancement of microfabrication techniques also motivate the quest for production of high-peak-power mid-IR laser pulses and their use for laser-driven particle acceleration in photonic structures [2]. The use of long wavelength drive lasers can mitigate the problem of dielectric structure breakdown caused by multiphoton ionization. In addition, structure fabrication requirements are relaxed and greater energy can be stored in the structure. Direct production of ultrashort mid-IR laser pulses is technically challenging due to the lack of broadband laser media and the general lack of technological maturity in this wavelength range. A more flexible approach to access the mid-IR spectral region is the use of optical parametric amplification. Broad gain bandwidth and favorable phase matching in certain nonlinear materials have been used to realize few-cycle mid-IR laser pulses [3,4]. While many of the proposed and demonstrated schemes to date are scalable to higher energies, they frequently rely on complex and unique pump laser designs. Here we report the production of 2.2-mJ, 87-fs pulses at a central wavelength of 2.05 µm using a compact two-stage OPA pumped by a robust, mature Ti:sapphire chirped-pulse amplification system, as well as a modified design capableof CEP-stable operation for 5-µm amplified pulses based on several cascaded parametric processes.

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SYSTEM REQUIREMENTS

Our proposed dielectric-based laser accelerator requires a mid-IR pulsed laser source which operates at 5 µm wavelength with 500 µJ of pulse energy and <1 ps pulse duration. An OPA system based on established and widely available high-energy short-pulse lasers, such as the Ti:sapphire laser, is a convenient approach to realize the 5-µm source for this application.

A schematic overview of our OPA system is presented in Fig. 1. The 5-µm mid-IR laser source will be realized by using an independent optical parametric generation (OPG)/OPA. Among a few candidates for nonlinear crystals which could be utilized in mid-IR wavelength region, $ZnGeP_2$ (ZGP) crystal is chosen for our 5-µm source since it has excellent transparency in the mid-IR wavelength region, it is phase matchable, and exhibits very high optical nonlinearity. With anti-reflection (AR) coating for both pump and output mid-IR wavelengths, the quantum conversion efficiency for ultrashort pump pulses could be expected to be >40% due to the extremely high damage threshold of the crystal and the relatively favorable group velocity matching.

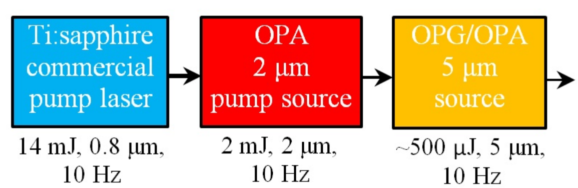

Figure 1: An overview of the technical approach for production of 5 µm pulses.

From the perspective of portability and robustness of the OPA system, as well as the compactness of the design and its final integration with the dielectric particle accelerator, the optimal solution for the pump source for the 5 µm OPA system is a Tm/Ho/Cr-doped high-energy solid-state laser which operates around 2 µm. Because of the limited performance and maturity of Tm/Ho/Cr-laser technologies, however, alternative approach to realize high-energy 2-µm pump source has to be taken into consideration. In our design, a surrogate OPA source pumped by mature Ti:sapphire technology is employed. This approach is mid-IR-pump-compatible and can be directly replaced by a Tm/Ho/Cr-based high-energy short-pulse laser in the future when such systems become available in the required energy range and with sufficient

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robustness. The detailed technical approach of our laser system is discussed in the following sections.

IMPLEMENTATION OF 2 MICRON OPA

A surrogate high-energy 2 µm pump source has been designed and is constructed by using a two-stage OPA. The experimental setup is depicted in Fig. 2. The OPA is pumped by a commercial amplified Ti:sapphire laser system, producing 40-fs, 14-mJ, 10 Hz pulses centered at 0.8 µm. Two BBO crystals with dimensions of 5×5×2.5 mm^3 and 15×15×2.0 mm^3 have been used in first and second OPA stage, respectively. The crystals were cut at an angle θ = 25.9º for type II ($e_p \rightarrow o_s + e_i$) phase matching. Both OPA crystals were coated for all three wavelengths occurring in OPA. The relatively small group velocity mismatch among the three wavelengths in BBO allows the use of relatively thick crystals, even for 40-fs pump pulses, thus reducing the required pump intensity to realize high gain in each OPA stage. Full-fledged crystal growth techniques available for BBO crystals offer large aperture and high optical quality, resulting in high-peak-power scalability. In addition, BBO exhibits a much lower absorption (only ~0.04 cm^{-1}) near 2 µm wavelength when compared to BiBO (~1.05 cm^{-1}), which is often used in ultrashort pulse OPA.

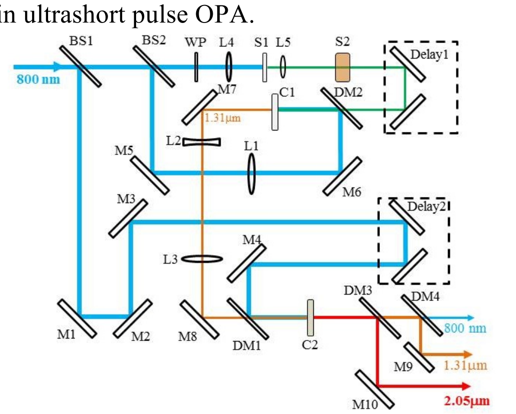

Figure 2: Layout of high-energy 2.05-µm OPA.

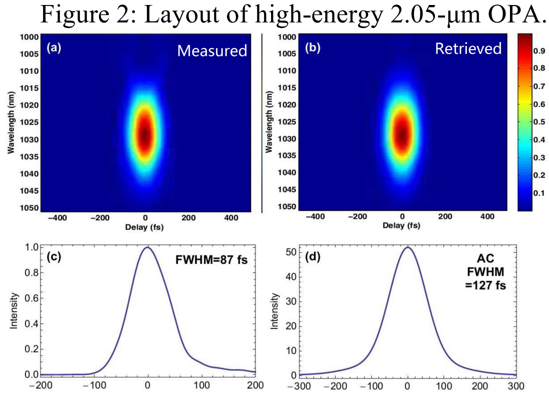

Figure 3: SHG-FROG results of 2.05 µm pulses.

In our experimental setup, the pump pulse energy is split by two beamsplitters (BS1 and BS2). The pulse transmitted by BS2 is used to produce a white-light continuum (WLC). After passing through a neutral density filter and an iris, the pulse with <1 µJ energy is focused onto a 3-mm-thick sapphire plate to generate a stable single-filament continuum. The WLC is collimated by a lens and directed to the first OPA crystal via a delay line, with the residual pump beam removed by a dichroic mirror DM2. The ~0.8-mJ pulse reflected by BS2 is focused onto the first BBO crystal by a 500-mm focal length lens. A ~2º angle between the seed WLC and the pump beam is employed to separate the signal and idler beams from the first OPA. The signal beam at 1.31 µm is subsequently used to seed the second OPA. Most of the pump laser pulse energy (~12.4 mJ) is reflected by BS1 and is directed to the second OPA crystal via another delay line, without using any focusing lenses to minimize self-focusing and self-phase-modulation effect on the pump beam in this part of the system. Finally, the amplified signal pulse at 1.31 µm, the idler pulse at 2.05 µm, and the residual pump pulse at 800 nm are separated using two dichroic mirrors.

To realize the most efficient amplification in this two-stage OPA design employing BBO crystals, both type I and type II phase matching in BBO have been investigated. We also experimentally implemented a type I OPA design, with both BBO crystals having same dimensions as in the type II design, but cut at θ = 19.9º. The motivation for using type I phase matching is its ~25% higher effective nonlinearity, ~3.5x broader PM bandwidth, and ~3x lower group velocity mismatch. However, the parasitic second-harmonic generation (SHG) at phase matching angles neighboring that for type I OPA (θ = 21.3º for SHG of 2.05 µm) significantly reduces the output pulse energy and beam quality. After replacing the type I crystals with type II crystals, parasitic SHG of both signal and idler were efficiently suppressed. In the type II phase matching configuration we produced mid-IR laser pulses at 2.05 µm with average pulse energy of 2.2 mJ, excellent beam quality, and energy stability of 1.46% rms over 30 minutes.

By using a home-made autocorrelator, an autocorrelation width of 126 fs for 2.05-µm pulse has been measured. The spectrum of 2.05 µm pulses has been measured by a scanning-grating-spectrometer with an InSb photodiode and shows a central wavelength at 2.05 µm with a FWHM of 142 nm. A more complete temporal characterization of output 2.05 µm pulses has been performed using SHG frequency resolved optical gating (SHG-FROG), and the result is shown in Fig. 3. FROG measurement results are in excellent agreement with the simple autocorrelation measurement, and reveal a pulse duration of 87 fs for 2.05 µm pulse. It is worth nothing that in the present two-stage OPA, carrier-envelope-phase (CEP) stabilization is passively achieved for the produced 2.05 µm pulses. Unlike in the OPA design seeded by OPG, in which the seed pulse for parametric amplification is initiated by quantum noise with random phase, a constant phase relationship is present between the WLC and the pump pulse. This phase relationship is preserved when the signal pulse is amplified in the OPA. Thereafter, the amplified signal pulse and the pump pulse produce and idler pulse at 2.05 µm with fixed CEP, regardless of the CEP of the pump pulse, as experimentally verified in prior work, for example in [5].

DEVELOPMENT OF 5 MICRON OPA

The preliminary design of 5 μm source is based on an OPG seeded OPA. The experimental setup is being constructed and the optical layout is presented in Fig. 4. Two ZGP crystals with identical dimension of 10×10×1.0 mm^3 have been used in the OPG and the OPA stage, respectively. The crystals were cut at an angle θ = 56.1° for type I ($o_p \rightarrow e_s + e_i$) phase matching. The ZGP crystals had broadband antireflection coatings for 2 μm and 3-5 μm. Although the group velocity mismatch among three interaction wavelengths in ZGP is of moderate magnitude (~170 fs/mm between the 5-μm pulse and the 2.05-μm pump pulse), the high nonlinearity of ZGP crystal (d_{eff}>70 pm/V) over 3-8 μm wavelength range still enables high gain in OPA stage in thin crystals.

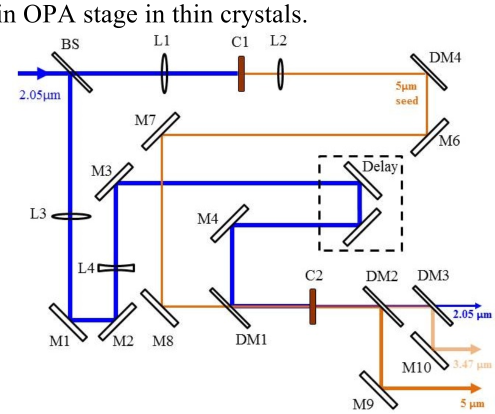

Figure 4: Layout of 5-μm OPA source.

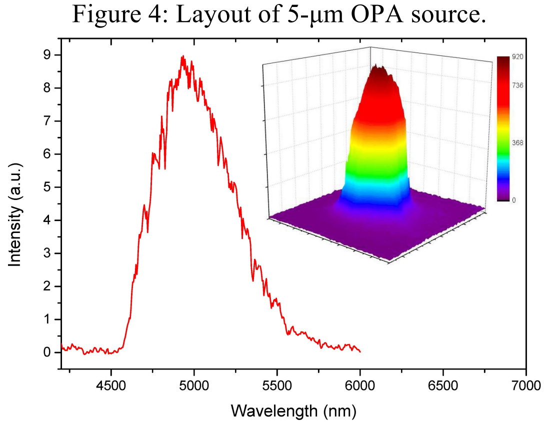

Figure 5: Spectrum and beam profile (inset) of amplified 5-μm pulses.

The 2.05-μm pump pulses produced by the high-energy OPA described in previous section are split to two arms. About 10% of incident pump pulse energy is transmitted by a beamsplitter (BS), and focused on the OPG crystal by a CaF_2 lens with f=150mm to generate seed pulses at 5 μm. The residual pump and corresponding parametrically produced pulse at 3.47-μm are removed by dichroic mirror DM4 and filter. The ZGP crystal is placed at upstream optimized position near focal point to avoid optical damage and assure sufficient pump intensity to generate OPG seed pulses. Then the seed pulses are collimated by another lens and directed to the OPA crystal via a beam combiner DM1. The majority of the incident pump energy reflected by BS is directed to the OPA crystal via a delay line. The beam resizing telescope reduces the beam size of pump pulses by a factor of 2.5 and provides a peak intensity of ~200 GW/cm^2 on OPA crystal. Finally, the amplified signal pulse at 5.0 μm, the idler pulse at 3.47 μm, and the residual pump pulse at 2.05 μm are separated by using two dichroic mirrors.

A preliminary experiment for 5-μm pulse production has been performed with a pump pulse energy of 1.6 mJ at 2.05 μm. Pulse energy of ~47 μJ at 5 μm has been obtained. The spectrum of amplified 5-μm pulses measured using a scanning-grating spectrometer, together with thermoelectrically cooled InSb photodetector, is presented in Fig. 5. A broad spectrum with FWHM of ~530 nm originates from seeding by OPG and from the broadband parametric gain of ZGP. The beam profile shown in the inset of Fig. 5 indicates that the amplified 5-μm pulses have relatively good beam quality. An increase of the pulse energy of amplified 5 μm pulses should result from optimization of beam alignment and collimation both for pump and seed pulses.

IMPROVED DESIGN OF 5 MICRON OPA

OPG-seeded OPA cannot achieve CEP stabilization due to the random phase of quantum noise from OPG. In order to produce CEP-stabilized 5-μm pulses with short pulse duration, we present a modified design of 5-μm OPA in Fig. 6. Assuming that the initial phase of the pump pulse at 2.05 μm is ψ, the second-harmonic pulse will have a phase of 2ψ + π/2 and the supercontinuum will have a phase of ψ + π/2. The phase of signal beam is preserved to ψ + π/2 via amplification in a lithium niobate OPA. Thereafter, the phase of 5-μm seed pulse from difference-frequency generation is 0, and it is subsequently preserved in the OPA process. Thus the CEP stabilization of 5-μm pulse is passively preserved and independent of the phase of pump pulses [6].

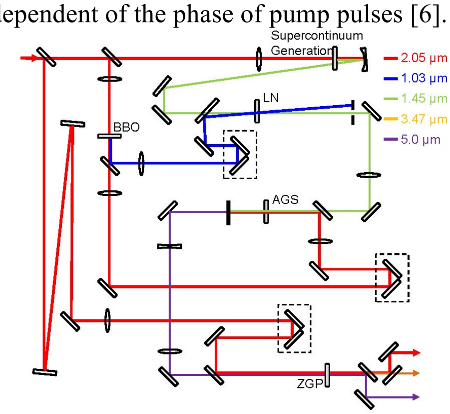

Figure 6: Layout of CEP-stabilized 5-μm OPA.

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