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DEVELOPMENT OF A HIGH-PEAK-POWER 5-μm PARAMETRIC SOURCE FOR DIELECTRIC LASER ACCELERATION *

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Abstract

We present a design and preliminary performance of a compact, high-peak-power 5-μm pulsed laser source for pumping a dielectric photonic structure to produce an acceleration gradient of order GV/m in dielectric laser acceleration. The 5-μm laser source is based on two cascaded optical parametric amplifiers (OPA): a 2-μm BBO OPA with a mixed phase matching scheme is used as a pump source, and a type-I phase-matched ZGP OPA is designed to produce sub-mJ 5-μm laser pulses. Preliminary result of ~53 μJ pulse energy at 5 μm is demonstrated using a two-stage optical parametric generator (OPG)/OPA scheme, and an improved OPA scheme with dispersion management for production of higher pulse energy at 5 μm is under development.

INTRODUCTION

Ultrashort high-energy mid-infrared laser pulses are attractive for driving dielectric photonic structures in high-gradient electron acceleration to generate a compact and robust source of tunable monochromatic X-rays. By using pulses that extend into the mid-infrared region, the problem of laser-induced breakdown in dielectric structures at high optical intensities can be mitigated, thereby relaxing structure fabrication requirements and allowing greater pulse energies to be injected into the structure. Despite the benefits of such advanced X-ray sources in medical imaging, security, and scientific applications, the production of ultrashort high-energy mid-IR laser pulses is technically challenging because of several limitations. These constraints include the lack of suitable pump lasers, dispersion considerations, limited range of available optical materials, and lack of mature ultrafast diagnostics at these wavelengths. It is still desirable to use long-wavelength drive lasers to take advantage of the available nonlinear materials (for example, $ZnGeP_2$(ZGP) or $AgGaS_2$(AGS)), which exhibit ultra-high nonlinearity for production of mid-IR pulses, but are transparent and/or can be phase matched only for wavelengths ≥2 μm. Furthermore, the use of a long-wavelength pump laser greatly increases the theoretically achievable conversion efficiency in a parametric down-conversion system. Production of 5-μm pulses in a 2-μm-pumped optical parametric amplifier (OPA) results in a maximum conversion efficiency of 40%.

We present an approach for production of high-energy ultrashort mid-IR laser pulses to demonstrate 5-μm mid-IR pulses compatible with one of the recently proposed acceleration approaches [1]. We also describe the progress on the design, construction, and operation of a 5-μm parametric source based on ZGP, capable of generating pulses in the range of a few hundred μJ for direct laser acceleration.

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SYSTEM DESIGN

The high-energy 5-μm ultrafast source is realized using a two-stage optical parametric generation (OPG)/OPA system. Due to its excellent transparency in the mid-IR region and very high effective nonlinearity (77.3 pm/V in our phase matching conditions), ZGP was chosen as a nonlinear medium to generate 5-μm pulses. The ZGP crystal is coated with broadband anti-reflective coating (2–5 μm) on both surfaces and cut at $\theta = 56.1°$ for type I phase match-

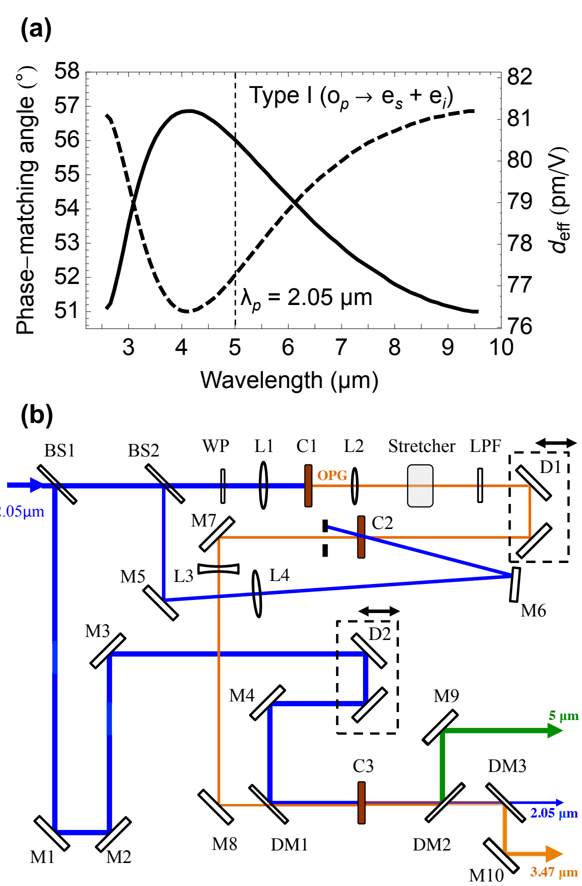

Figure 1: (a) Calculated phase-matching angle (solid) and effective nonlinearity (dashed) for type-I phase-matching in a ZGP crystal, producing 5-μm pulses pumped with 2.05-μm pulses. (b) System architecture of two-stage OPG/OPA. BS–beamsplitter; WP–$\lambda/2$ waveplate; DM–dichroic mirror; LPF–long-pass filter; C–type-I ZGP crystal.

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ing at 5 µm with a 2.05-µm pump wavelength, as shown in Fig. 1(a). A 2.05-µm ultrashort pump source to serve as a surrogate for a future 2.5-µm Cr:ZnSe pump laser has been developed using the widely available and relatively inexpensive β-BaB_2O_4(BBO) crystals. The wavelength of the surrogate source is chosen to be within the transparency and phase matching range of both the chosen 5-µm OPA crystals and the BBO. While the surrogate pump source operates at a somewhat shorter wavelength than a Cr:ZnSe laser, it nevertheless allows experimental validation of the performance characteristics of the 5-µm source architecture, and minimal changes to the setup will be required when replacing the surrogate source with a Cr:ZnSe laser in the future. The 2.05-µm pump pulses are produced by a compact ultrafast parametric amplifier pumped by a commercial Ti:sapphire laser [2]. This surrogate source for a mid-IR pump laser generates up to 2.2 mJ, 42 fs pulses with excellent beam quality and rms energy stability <1% measured over 3 minutes.

The overall 5-µm source design is shown in Fig. 1(b). The favorable group velocity mismatch among the three wavelengths in ZGP increases the effective interaction length, allowing the use of relatively thick crystals and reducing the required pump intensity to achieve high gain in each OPA stage. The pump pulse energy is split by two beamsplitters (BS1 and BS2). The pulse energy transmitted by BS2 is focused onto a 1-mm-thick ZGP crystal to produce OPG. The 5-µm seed pulse is then stretched with a 5-mm-thick germanium plate and the residual pump energy is removed with a long-wave-pass filter. The residual near-infrared absorption of the ZGP crystal is low (~0.04 cm^{-1}) at 2.05 µm [3]. Accordingly, in the single-pass OPG configuration, linear absorption losses for a pump wavelength of 2.05 µm never exceed 1%. The OPG is directed to the first OPA crystal via a delay line. The pump pulse reflected by BS2 is focused onto the first OPA crystal with a 500-mm focal length lens. A small noncollinear angle is employed to separate the signal and idler pulses at the first OPA stage. The signal beam at 3.47 µm is subsequently used to seed the second OPA stage. The energy reflected by BS1 is directed to the second OPA stage via a delay line. At the output, the amplified idler pulses at 5 µm, the signal pulse at 3.47 µm, and the residual pump pulse at 2.05 µm are separated using dichroic mirrors.

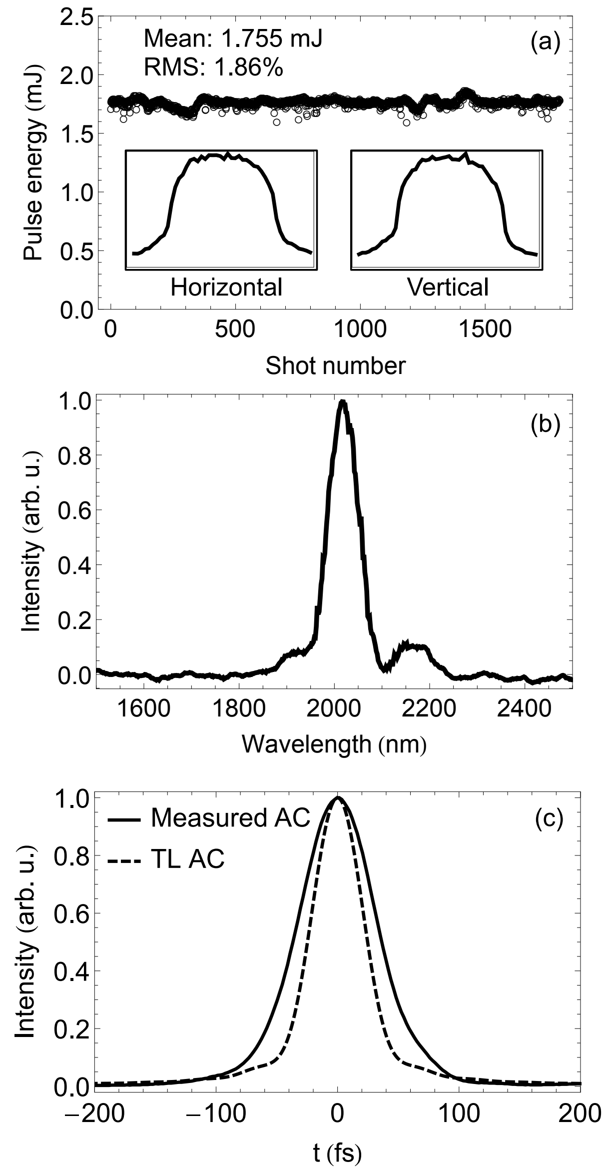

Figure 2: Energy stability of (a) 2.05-µm pump pulses; inset: horizontal and vertical beam profiles, (b) amplified pump pulse spectrum, and (c) autocorrelation of the amplified 2.05 µm pulses. Solid line, experimental measurement; dashed line, transform-limited autocorrelation calculated from the measured spectrum.

EXPERIMENTAL RESULTS

Energy measurement of both the 2.05-µm pump pulses and the 5-µm idler pulses have been conducted using a pyroelectric detector, providing a sensitivity of ~20 nJ. The 2.05-µm pulses used to pump the OPA system have a pulse energy of 1.8 mJ with an rms energy stability of 1.9% measured over 3 minutes (Fig. 2(a)) and a uniform beam profile (Fig. 2(a), inset). Laser pulses are spectrally analyzed using a 55-cm monochromator (300 mm^{-1} grating blazed at 4 µm) in combination with a thermoelectrically-cooled InSb photodetector. The pump pulse is centered at a wavelength near 2.05 µm with a spectral bandwidth of 130 nm, as shown in Fig. 2(b), potentially supporting a transform-limited autocorrelation full-width at half-maximum (FWHM) of 42 fs. The autocorrelation of pump pulses has been measured with a FWHM pulse duration of 63 fs, as shown in Fig. 2(c). An available AGS crystal with a thickness of 2 mm and a cut angle of $\theta = 50°$ has also been tested for seed pulse generation via OPG. The AGS crystal is coated with broadband anti-reflective coatings (1.1–2.6 µm and 2.6–11 µm) at the entrance and exit surfaces, respectively, and can also be used in a type-I phase matching configuration. The output energy of the 5-µm pulse produced by AGS OPG was below the noise level of the pyroelectric detector and could

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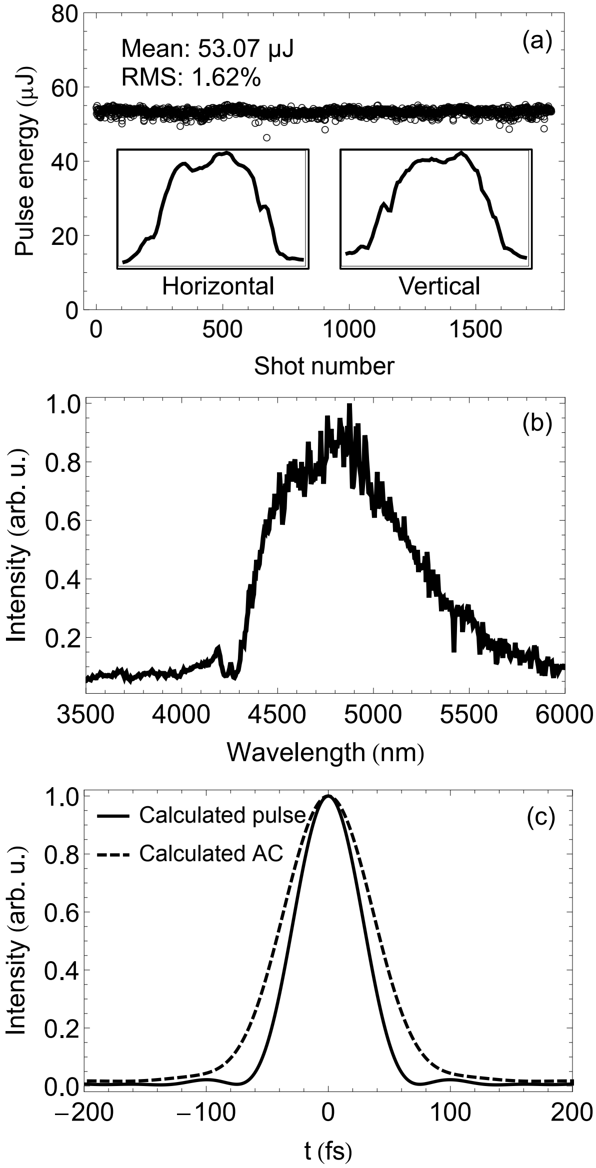

Figure 3: Energy stability of (a) 5-μm idler pulses; inset: horizontal and vertical beam profiles, (b) amplified idler pulse spectrum, and (c) solid line: calculated transform limited pulse shape; dashed line: calculated transform limited autocorrelation.

not be directly measured. However, by replacing the AGS with a ZGP crystal in the same setup, the OPG 5-μm pulse energy was well above the noise threshold of the detector. By pumping the OPG/OPA system with the pump pulses described, the idler pulses at 5-μm have been produced with a pulse energy of 53 μJ (or 58 μJ before the long-pass filter) and an rms energy stability of 1.6% measured over 3 minutes, as shown in Fig. 3(a). At the expense of higher energy output energy from the OPA, the noncollinear angle of the second OPA stage was adjusted to improve the beam quality of the idler pulses (Fig. 3(a), inset). As shown in Fig. 3(b), the spectrum is centered at a wavelength of ~5 μm with a spectral bandwidth of 750 nm, potentially supporting a transform-limited pulse duration of ~49 fs, as shown in Fig. 3(c), with the measured spectrum, assuming a Fourier time-bandwidth product of 0.44.

Due to strong atmospheric absorption near 2.5 μm, measuring the pulse duration in a technique that utilizes second harmonic generation (SHG), such as autocorrelation, is technically challenging. The absorption issue can be circumvented with little effect on system performance by shifting the output of the mid-IR system to a slightly shorter or longer wavelength. At the SHG of this wavelength, the atmospheric absorption is significantly reduced. The system design supports this small spectral shift by the change of pump-seed delay and small adjustment of the OPA crystal angle orientations. The limited conversion efficiency of the second 5-μm OPA stage is currently under investigation. A likely cause of the low conversion efficiency is the mismatch between the pump pulse duration (63 fs) and the preamplified signal pulse that experiences significant dispersion by propagating through a CaF_2 lens and dichroic beam-combiner prior to entering the second OPA crystal. Proper management of the seed pulse group delay dispersion is believed to result in higher conversion efficiency because of the longer chirped seed pulse compared to the pump pulse and subsequent increase in the pulse splitting length. The second possible cause for limited conversion efficiency is the nonlinear absorption of the pump in the ZGP crystal, reducing the effective pump intensity. A significant uncertainty of the nonlinear absorption coefficient has been reported in the past work, such that numerical estimates of this effect are unreliable without additional measurement.

CONCLUSION

A 5-μm parametric source has been designed for dielectric laser acceleration, even without the use of a complex source architecture, such as optical parametric chirped-pulse amplification (OPCPA). This work demonstrates the capability to produce ultrashort mid-IR pulses in ZGP with a simple design scheme in the energy range required for pumping dielectric laser accelerators. Production of higher-energy ultrashort mid-IR pulses for other applications still requires the use of a more energy-scalable technique (for example, OPCPA).

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