Broadband tunable optical parametric amplification from a single 50 MHz ultrafast fiber laser

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Abstract: We have demonstrated a 0.7 μm – 1.9 μm wavelength-tunable light source based on a single-pass optical parametric amplification (OPA) in a multiperiod magnesium oxide-doped periodically poled lithium niobate crystal. The OPA pump was a frequency-doubled ultrafast ytterbium-doped fiber oscillator, and the residual 1040 nm laser power after frequency doubling was recycled to generate a supercontinuum seeding source. Compared with conventional OPAs, this system is free from timing jitter between the pump laser and the seeding source. Over 50% conversion efficiency was obtained with 10 nJ pump energy. Combined with a 50 MHz repetition rate, this versatile source is ideal for biomedical and spectroscopic applications.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (160.3730) Lithium niobate; (060.5295) Photonic crystal fibers; (320.6629) Supercontinuum generation

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1. Introduction

Tunable ultrafast light sources are important for various spectroscopic and microscopic applications, such as pump-probe spectroscopy [1, 2], fluorescence lifetime imaging microscopy (FLIM) [3], and multiphoton microscopy/spectroscopy [4, 5]. Many previous applications were based on a Kerr-lens mode-locked Ti:sapphire laser, which has become one of the most promising solid-state ultrafast sources with two decades of development after its invention. Nowadays, most Ti:sapphire systems are turnkey operations, and are capable of delivering 100 fs or shorter pulses typically at a 80 MHz repetition rate. However, the tuning range of a Ti:sapphire laser is limited to around 700 nm – 1000 nm because of the laser gain bandwidth of the Ti:sapphire crystal. To extend the wavelength range of an ultrafast laser, supercontinuum generation (SCG) or optical parametric amplification (OPA) has been adopted. Based on the strong nonlinear response of some materials to ultrashort optical pulses, SCG is capable of extending input laser wavelengths into both shorter and longer wavelength directions. The invention of photonic crystal fibers greatly enhances SCG efficiency [6, 7], and bandwidth over two octaves has been demonstrated even with the pump pulse energy being only of the order of ten nanojoules [8]. However, inasmuch as SCG redistributes the pump power into a wide wavelength range, the power density of SCG is typically less than 1 mW/nm. In addition, the strong chromatic dispersion in the fibers significantly lengthens the pulses, and subsequently degrades the applicability of the SCG because of the reduced peak power and poor temporal characteristics.

On the other hand, OPA has been widely adopted, either with or without an oscillator geometry, to extend the Ti:sapphire laser or other ultrafast sources into longer wavelengths with better concentrated spectral power and ultrashort pulsewidth [9-11]. OPA is a $\chi^{(2)}$ process,

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and is related to the mixing of three waves, namely, the pump, the signal, and the idler. Both energy and momentum conservation have to be fulfilled when a shorter-wavelength pump wave is down-converted into a signal and an idler wave simultaneously. As a result of energy conservation, the photon energy of the pump is equivalent to the sum of the photon energy of the signal and the idler. Therefore, in an OPA process, equal numbers of signal and idler photons are generated simultaneously, while the same number of pump photons is annihilated. On the other hand, the momentum conservation, also known as phase-matching condition, determines the interacting wavelengths and thus the wavelength tunable range of the OPA. Typically, wavelength tuning in an OPA can be achieved by adjusting the crystal angle or temperature to fine-tune the phase-matching condition.

Although ultrafast tunable sources now routinely consist of an OPA pumped by a Ti:sapphire laser, this implementation requires either a high-energy, low-repetition rate pump source [12-14], or an oscillator cavity to improve the conversion efficiency [15, 16]. For biomedical imaging applications, excitation sources with higher repetition rates are preferred owing not only to the reduced nonlinear damage from lower pulse energy, but also to the enhanced signal intensity from higher average power [17]. Moreover, for sufficient image frame rate, the repetition rate should be no less than 10 MHz to ensure proper registering of each pixel. Therefore, the kHz repetition rate and 10 μJ pulse energy in common single-pass OPA demonstrations may not be suitable for imaging purposes.

Nevertheless, to extend the wavelength range of a high-repetition-rate laser such as an 80 MHz Ti:Sapphire laser, an optical parametric oscillator (OPO) is usually incorporated to reduce the threshold of the parametric process. However, the synchronously pumped cavity in an OPO results in both increased complexity and cost of the system. To reduce the complexity/cost of the system and to maintain a high enough repetition rate for bio-imaging purposes, we demonstrate in this study a single-pass 50 MHz OPA system based on a single mode-locked ytterbium-doped fiber (Yb:fiber) source. In this paper, the reduced peak power and poor temporal characteristics of the SCG are improved in the 50 MHz OPA system.

The advantages of an Yb:fiber laser over a Ti:sapphire laser lies in power scalability, efficiency, and reliability. Owing to the thermal effect in the Ti:sapphire crystal, the average output power of a Ti:sapphire laser is limited to around one watt. In contrast, fiber lasers are capable of providing much higher average power and pulse energies owing to their exceptional heat dissipation capability [18-20]. The electrical-to-optical conversion efficiency of a Yb:fiber laser is also much higher than that of an Ti:sapphire laser, not only because of the excellent mode confinement in fibers, but also because of the single-stage conversion in Yb:fiber lasers. Moreover, 980 nm laser diodes, which are the single-stage pump of Yb:fiber lasers, are typically more durable than the 808 nm laser diodes for building Ti:sapphire lasers. Therefore, Yb:fiber lasers are more suitable as pump sources for high-repetition rate OPA.

Because there is no synchronously pumped cavity in our OPA system, two strategies are adopted to enhance the efficiency of the parametric conversion process. The first is to employ a doubly seeding scheme in seeding the OPA by SCG, that is, seeding at both signal and idler wavelengths. The second is to utilize a highly efficient nonlinear crystal, that is, magnesium oxide-doped periodically poled lithium niobate (MgO:PPLN) crystal to enhance the parametric gain. In the past few years, there have been several demonstrations on supercontinuum-based OPA (SCOPA) [21-23]; however, because of the high pulse energy required for efficient OPA, the repetition rates reported (10 Hz – 1MHz) are not suitable for biomedical imaging applications. To our knowledge, this system is the first single-pass OPA with > 50% conversion efficiency at 50 MHz.

2. Experimental setup

The broadband tunable femtosecond source is based on a single-pass OPA, which is pumped by a frequency-doubled Yb:fiber laser and is seeded by SCG excited from the recycled residual infrared laser after frequency doubling. The setup scheme is shown in Fig. 1. The heart of the system is a mode-locked Yb:fiber laser (Uranus 005, PolarOnyx, CA) with ~ 1 ps pulse width, 1040 nm central wavelength, 5 W average power, and a 50 MHz repetition rate.

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After frequency doubling in a 1 cm long LBO crystal under type I noncritical phase-matching, the 520 nm second harmonic generation (SHG) wave was sent to pump the single-pass OPA in a 1 cm long multichannel MgO:PPLN crystal (HC Photonics, Taiwan). The residual 1040 nm fundamental waves were coupled into a 1 m long photonic crystal fiber (PCF) for SCG, which was subsequently delivered into the MgO:PPLN crystal to be the seed of the single-pass OPA. Both the SHG pump and SCG seed were focused onto the center of the MgO:PPLN crystal by a lens with a 10 cm focal length. The MgO:PPLN channel periods were 6.25 μm to 7.45 μm with a 0.2 μm step increment, and the crystal temperature was adjustable from 30 ^{o}C to 200 ^{o}C in a copper oven to manipulate the OPA quasi-phase-matching condition from 700 nm to 2000 nm.

The conversion efficiency of SCG in the PCF was about 65% (1.8 W output). The specifications of the nontapered PCF have been described earlier . The spectral range of SCG extended from 550 nm to 1900 nm, which overlapped well with the OPA spectral range for both the signal and idler. The extraordinarily high OPA conversion efficiency of this scheme is due not only to the large nonlinear coefficient in the MgO:PPLN crystals, but also to the doubly seeding scheme in the SCG seed. The temporal and spatial overlap between the SHG pump and SCG seed in the MgO:PPLN crystal was achieved through a translational stage in the pump arm and a cold mirror before the MgO:PPLN crystal, respectively. The pulse width was characterized by a home-built real-time autocorrelator. The spectra were acquired with a HR4000 from Ocean Optics (200 nm – 1100 nm) and a Wavescan-IR from APE (1000 nm – 2600 nm), respectively.

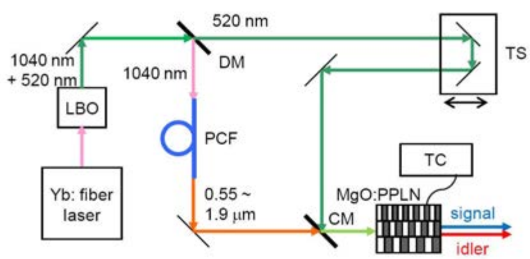

Fig. 1. SCOPA setup. DM: dichroic mirror; PCF: photonic crystal fiber; CM: cold mirror; TS: translational stage; MgO:PPLN: MgO-doped periodically poled lithium niobate; TC: temperature control.

3. Results and discussion

Figure 2(a) shows the SCG spectrum after a 1 m long PCF. By using a 1 ps excitation at 1040 nm, the SCG extends from 550 nm to 1900 nm [24]. The output power of SCG is 1.8 W, corresponding to 65% efficiency, and the residual excitation power around 1040 nm is less than 0.3 W.

Figure 2(b) provides several typical spectra of signal tuning in the range of 700 nm – 1000 nm. Please note that there is a SCG lying below each OPA spectrum, but because the OPA signal is larger than two orders of magnitude, the SCG is hardly visualized. The spectra are normalized to eliminate the spectrometer sensitivity variance at different wavelengths. The average power of OPA exceeds 200 mW (signal + idler) with signal wavelength at 850 nm, corresponding to 40% external conversion efficiency. By taking into account the reflection at the input and output surfaces of the MgO:PPLN crystal, the internal conversion efficiency of this single-pass OPA is higher than 50%. The reason for such high conversion efficiency can be attributed to both the novel doubly seeding scheme from the SCG seed and the quasi-phase matching in the MgO:PPLN crystal. If the SCG seed is removed, optical parametric generation (OPG) is still observed under the same phase-matching condition; however, the remaining output power degrades to only a few microwatts. Since OPG arises from quantum noise, the microwatt OPG output is already adequate to verify the MgO:PPLN crystal as an efficient parametric wavelength converter.

#108826 - $15.00 USD Received 16 Mar 2009; revised 10 Apr 2009; accepted 11 Apr 2009; published 22 Apr 2009

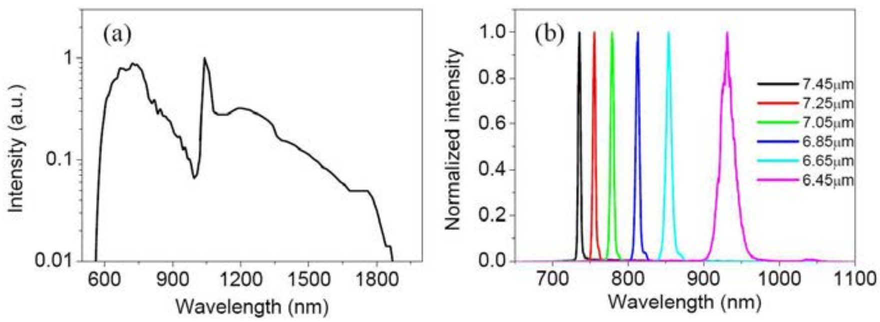

Fig. 2. (a). A typical SCG spectrum after the PCF and (b) Broadband tunable spectra of SCOPA.

The OPA pulse width is measured to be ~1 ps, which is slightly longer than the 520 nm pump, but much shorter than the SCG seed. Since the parametric gain is provided by the pump, it is reasonable to find the OPA pulse width similar to the pump width. The slight stretching may be due to the dispersion and group velocity mismatch between pump and seeds in the MgO:PPLN crystal.

The complete tuning range from 700 nm to 1900 nm of our SCOPA is given in Fig. 3. The upper branch of hollow symbols denotes the 1040 nm – 1900 nm idler waves, while the lower branch of solid symbols shows the 700 nm – 1040 nm signal waves. The coarse wavelength tuning is achieved by channel selection of different grating periods, while the fine tuning is achieved by temperature adjustment. Continuous tuning from 700 nm to 2000 nm is accomplished with seven grating periods and 30 ^{o}C to 200 ^{o}C temperature range. Based on the Sellmeier equation of MgO:PPLN crystals in a recent study [25], the theoretical curves are calculated and fitted to our measured results. The overall fitting is good, although there are some minor deviations. One possible reason for the deviation is that the Sellmeier equation of [25] was deduced from near-infrared measurement around 1500 nm. Fabrication errors from the lithograph mask and environment variation may also contribute to the source of errors.

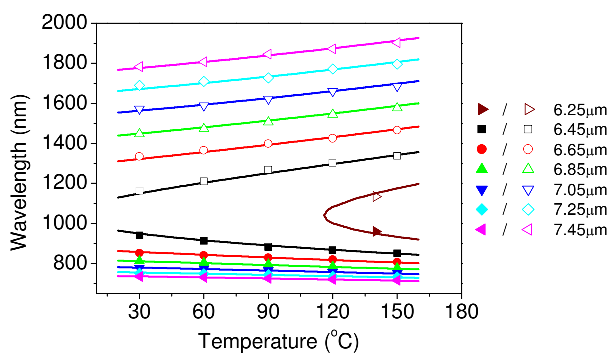

Fig. 3. The complete OPA signal and idler spectra of wavelength versus temperature with different MgO:PPLN grating periods at temperatures from 30 °C to 150 °C. The solid symbols are signals, while the hollow ones are idlers. The fitting curves were calculated from ref [25].

From the coupled wave equations of the three-wave mixing process, doubly seeded OPA has higher conversion efficiency than a singly seeding case. This phenomenon is similar to the case of doubly resonant OPO, which has a lower threshold than singly resonant OPO. However, wavelength tuning mechanisms in a doubly resonant OPO are complicated because the converted wavelengths are determined by both resonance conditions and phase-matching conditions. Moreover, mode-hopping effects decrease output power stability [26]. Without a resonant cavity, the operation wavelengths in our system are solely determined by phase-matching conditions, avoiding the complicated mode-hopping effect in a doubly resonant

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OPO. Furthermore, the whole optical parametric bandwidth can be accessed in the OPA scheme.

To evaluate the performance of the OPA system, the conversion efficiency is determined by comparing the output power versus the input green SHG pump power. The green SHG power is removed after the MgO:PPLN crystal with the aid of a color filter; however, part of the SCG seed still passes through to the detector. Therefore, the OPA power has to be evaluated by comparing the power difference with the green pump turning on and off. Currently, over 200 mW output power is achieved, corresponding to internal conversion efficiency larger than 50%. Figure 4 shows the dependency of OPA power at 850 nm and the input green SHG pump power. A clear saturation in conversion efficiency is observed when pump power exceeds 350 mW. The saturation phenomenon may originate from the limited parametric gain bandwidth of MgO:PPLN crystals and pump depletion effects. Similar saturation phenomena have been observed in optical parametric conversions recently [27, 28]. Because optical parametric processes are considered three-wave frequency mixing processes and not stimulated emission processes, please note that no saturation is observed in terms of OPA power, indicating the possibility of output power scaling.

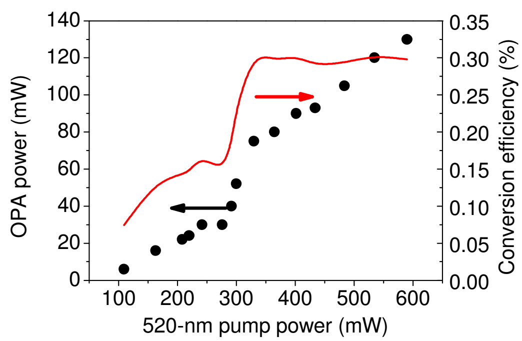

Fig. 4. The dependency of OPA output power (black dots) and conversion efficiency (red line) on the green SHG pump power. Although saturation of the OPA conversion efficiency occurs when pump exceeds 350 mW as a result of pump depletion, the overall OPA power still increases with pump power, providing the power scaling potential.

4. Conclusion

In summary, we have demonstrated an efficient single-pass SCOPA based on a single mode-locked Yb:fiber laser. The OPA pump is provided by the SHG of the Yb:fiber laser at 520 nm, while the OPA seed is provided by the SCG excited with the residual 1040 nm Yb:fiber laser after SHG. The OPA gain bandwidth nicely overlaps with the SCG spectrum, providing a continuous wavelength tunable range throughout the near-infrared regime of 700 nm – 1900 nm. Over 50% internal conversion efficiency is achieved at 50 MHz repetition rate and 10 nJ pump energy which, to our knowledge, is the highest single-pass OPA efficiency at such high repetition rate. The low pulse energy and high repetition rate characteristics of this broadband tunable source are beneficial for biomedical imaging and spectroscopic applications.

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