Ultra-Broadband Mid-IR OPCPA Schemes Enabled By Quasi-Phase-Matching

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Abstract: We present mid-IR OPCPA system configurations producing sub-four-cycle pulses, based on PPMgO:$LiNbO_3$. We demonstrate an all-collinear system via APPLN, and a hybrid system with a noncollinear PPLN power amplifier. Combining these techniques could offer octave-spanning-OPCPA.
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1. Introduction

Optical parametric chirped pulse amplification (OPCPA) is of great interest for applications such as strong-field physics and attosecond science where there is a need to generate few-cycle pulses with high energies and at high average power levels. The need for broadband OPCPA is especially pressing in wavelength regions such as the IR and mid-IR which are not accessible to conventional Ti:sapphire laser technology. In this paper, we present system architectures based on quasi-phase-matching (QPM) to enable few-cycle 1-µm-pumped mid-IR OPCPA.

Our systems are depicted in Fig. 1(a). The first system layout is based on three collinear OPA stages, each based on aperiodic (i.e. chirped) periodically poled lithium niobate (APPLN) [1]. The unique benefit of this approach is the design freedom in the APPLN devices, in particular that there is essentially no limit on the phase-matching bandwidth. Nonetheless, there are several design challenges that must first be overcome to develop a practical OPCPA system. Based on a comprehensive design study [2], we re-designed our system to achieve our latest experimental result. The system produced 12-µJ pulses of duration 41.6 fs at a center wavelength of 3.4 µm, using a pump power at the final OPA stage of 15.2 W. Efficient operation of this power amplifier relies on so-called adiabatic frequency conversion (AFC) [3,4], operated in the OPA regime [4]. The operating constraints of this new regime of frequency conversion are only now being explored [2]. Motivated by these constraints, and by our OPCPA design study, we have implemented a complementary power amplification scheme based on noncollinear OPA in PPLN, which enables group-velocity (GV-)matching of the signal and idler. A related noncollinear PPLN OPA scheme was proposed in [5], but has not been demonstrated until now. With this noncollinear configuration, our system produces 17.2-µJ pulses of duration 43.1 fs at a center wavelength of 3.4 µm, using a pump power at the final OPA stage of 17.8 W. Combining both techniques we demonstrate here, via a noncollinear APPLN power amplifier, represents a potential route to OPCPA bandwidths approaching and even exceeding an octave.

2. Experimental system and results

Figure 1(a) shows our two OPCPA systems, with the two different power amplifier (OPA3) configurations (collinear APPLN, and noncollinear PPLN). Dispersion management is mainly performed on the 1.5-µm seed pulses; both OPA3 schemes use the same layout for OPA1, OPA2, and the bulk sapphire compressor. Fig. 1(b) shows the phase mismatch versus idler wavelength for the two schemes. For the θ=0 curve, the Δk-bandwidth originates mainly from the QPM chirp profile. In the noncollinear θ=6.5° curve, OPA between 3- and 4-µm can be supported at the signal-idler coupling rate obtained at pump intensities of around 10 GW/cm^2.

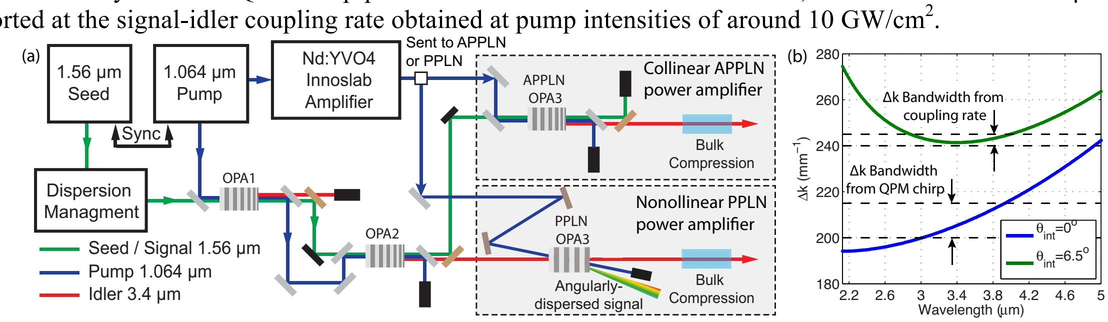

Fig. 1: (a) Schematic of our experimental system. The 1.56-µm seed is generated from a fiber laser system that we spectrally broaden in a dispersion-shifted fiber. Dispersion management is based on a Si prism pair and a 4-f pulse shaper on the stretcher side, in principle enabling compensation of 2nd, 3rd, and 4th -order dispersion on the amplified 3.4-µm idler pulses. Pre-amplification occurs in two APPLN OPA stages (OPA1 and OPA2). For the collinear APPLN layout (upper box), OPA3 is seeded by the 1.5-µm signal from OPA2. For the noncollinear PPLN layout (lower box), OPA3 is seeded by the 3.4-µm idler from OPA2. (b) Phase-mismatch for the two OPA3 configurations.

Figure 2(a)-(c) show our experimental results from our pre-amplification scheme (including OPA1 and OPA2), together with the final idler output generated from the APPLN OPA3 configuration. The seed is described in Fig. 1(a); the energy reaching OPA1 is 92.5 pJ. The pump source is an industrial laser operating at 1.064 µm and delivering 12-ps pulses at 50 kHz and average output power up to 10 W. Some of this power is split off and directed to a Nd:YVO_4 Innoslab amplifier, the output of which is used to pump OPA3. The remaining power is used to pump OPA1 and OPA2. The mid-IR idler output around $\lambda = 3.4$ µm is extracted after the third amplification stage (OPA3). The resulting idler spectrum is shown Fig. 2(b). In all stages we use uncoated MgO:$LiNbO_3$ crystals, each having an 11-mm-long, 1-mm by 3-mm-wide APPLN design. For compression, the generated idler pulses from OPA3 are sent through a 50-mm bulk sapphire rod. We compressed the 3.4-µm-pulses to 41.6 fs (sub-4-cycles), with 12 µJ pulse energy. The compressed pulses were characterized with SHG-FROG, shown in Fig. 2(c).

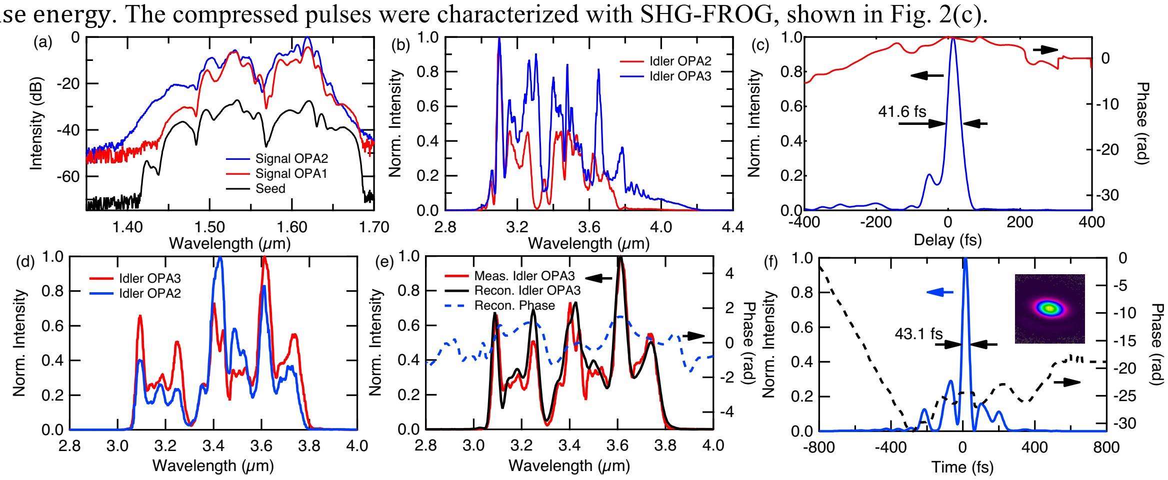

Fig. 2: (a)-(c): Characterization of the OPCPA system using the collinear APPLN power amplifier [upper dashed box in Fig. 1(a)]. (a) 1.56-µm signal seed spectrum, and the amplified signal spectrum from OPA1 and OPA2. (b) Idler spectra from OPA2 and OPA3. The spectral ripples, visible in (a) on a log scale and (b) on a linear scale, originate from nonlinear spectral broadening of the seed pulses, rather than from the OPCPA stages (as also predicted quantitatively by numerical modeling). (c) Compressed idler pulse, characterized via SHG FROG. (d)-(f): Characterization of the OPCPA system using the noncollinear PPLN amplifier [lower dashed box in Fig. 1(a)].

We next consider the noncollinear OPA3 configuration implemented with an uncoated PPLN crystal. The results are shown in Figs. 2(d)-(f). In this case, the collinear idler output of OPA2 is directed to OPA3 [lower dashed box in Fig. 1(a)]. The pump angle inside the crystal (~6.25^{o}) is selected to obtain GV-matching around our center idler wavelength; the required QPM period is then ~26 µm [Fig. 1(b)]. The average powers for the idler seed and pump are 31 mW and 17.8 W, respectively. The pump is focused to an intensity of ~13 GW/cm^2. In Fig. 2(d), we show the measured idler spectra before and after the power amplifier. The amplified idler pulses were again compressed by propagation in bulk sapphire, yielding an output energy of 17 µJ. Fig. 2(e) shows the measured and retrieved spectra and spectral phase from an SHG-FROG characterization. The temporal intensity profile is shown in Fig. 2(f): the pulse duration is 43.1 fs, again corresponding to less than four optical cycles. For both OPCPA configurations we confirmed that the parametric fluorescence background was negligible.

3. Conclusions

In conclusion, we have experimentally demonstrated two mid-IR OPCPA schemes based on QPM technology, generating sub-four cycles at a center wavelength of 3.4 µm. The all-collinear configuration utilizes chirped-QPM and AFC for efficient conversion, which is a new physical regime for OPCPA with the potential for both high efficiencies and broad bandwidths, once several design constraints are addressed. The noncollinear configuration combines the advantages of noncollinear phase-matching with QPM, enabling wavelength-flexible GV-matched OPA. At the meeting, we will detail the two system configurations, give an overview of our comprehensive study of APPLN OPCPA, and show that by combining the two techniques (noncollinear APPLN OPCPA), the limitations of both techniques can be overcome, enabling the possibility of OPCPA bandwidths exceeding an octave.

4. References

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