Ultrabroadband, highly flexible amplifier for ultrashort midinfrared laser pulses based on aperiodically poled $Mg:LiNbO_3$

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We present an amplification medium for optical parametric chirped-pulse amplification that allows for ultrabroadband gain in a collinear configuration. Our approach is based on aperiodic quasi-phase-matching (QPM). For the first demonstration of this method in a mid-IR optical parametric chirped-pulse amplifier, we chose a QPM grating design with a linear chirp of its associated spatial frequencies. The resulting 7.4-mm-long, aperiodically poled $Mg:LiNbO_3$ amplification crystal has a chirp rate of $\kappa' = -250\ \mathrm{cm}^{-2}$ and provides gain over the 800 nm bandwidth centered at 3.4 μm. We were able to generate pulses as short as 75 fs and the pulse energy at the output of the optical parametric amplifier before compression was 1.5 μJ. Low thermal load on the amplification medium allows for operation at a high repetition rate, 100 kHz in our case, and high average power limited only by the available pump power.

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The generation of few-cycle pulses in the mid-IR region is a challenging task, because known laser crystals do not supply optical transitions with sufficient amplification bandwidth. Nonlinear optical frequency mixing is a common approach for generating short pulses at wavelengths where suitable laser crystals are not available [1]. In the mid-IR, this approach relies—with a few exceptions—heavily on Ti:sapphire technology with its associated cost, average power limitation, and limited wall-plug efficiency.

It has been demonstrated before that optical parametric chirped-pulse amplification (OPCPA) directly pumped by diode-pumped solid-state lasers operating at around the 1 μm wavelength is a powerful method for amplifying sub 100 fs pulses in the mid-IR at high repetition rates [2,3]. These previous results were based on conventional periodically poled lithium niobate (PPLN), and it was shown by numerical simulations that the achievable bandwidth while maintaining efficient amplification is limited with this gain medium [4]. For the specific pump and seed wavelengths and parameters of our system, this limitation was found to be of the order of 300 nm at a 3.6 μm center wavelength. To overcome this constraint while keeping the benefit of the high nonlinearity of PPLN, we use chirped quasi-phase-matching (QPM) for femtosecond optical parametric amplification. The concept of chirped or aperiodic QPM for increased acceptance bandwidth, and even pulse shaping, has previously been successfully applied to other nonlinear optical interactions.

While the first proposal of chirped QPM was limited to the idea of extending the acceptance bandwidth for cw second-harmonic generation (SHG) [5], it was soon realized that chirped QPM also has interesting properties for the broadband conversion of ultrashort optical pulses [6]. The first application was to exploit the localized conversion of different frequency components in aperiodically quasi-phase-matched SHG for phase shaping and compression of the output pulses [6] and was soon extended to more general pulse shaping [7]. The phase shaping and very large bandwidth of these devices was exploited for the production of sub 6 fs pulses by SHG from Ti:sapphire few-cycle pulses [8,9]. The idea of aperiodic QPM was also transferred to other applications of second-order nonlinearities, such as optical parametric amplifiers (OPAs) [10] and optical parametric oscillators [11]. However, to our knowledge, there exists no prior experimental demonstration of femtosecond OPA or OPCPA using aperiodic QPM. It turns out that the extension of the approach to this particular application is nontrivial. Several critical aspects of aperiodic QPM OPAs have been addressed in [12–14].

In this new amplification medium, near-arbitrary bandwidths are possible because the grating provides the range of k vectors to phase match all frequencies of interest. The spectral gain of such a device is inversely proportional to its chirp rate (k vector change per unit length) [12]. For a given chirp rate and gain, the available bandwidth is proportional to the length of the device and, thus, only extrinsically limited by the transparency range of the material, and by practically available crystal sizes. The grating can be engineered to overcome spectral gain narrowing, tailor the group delay spectra, and improve efficiency by reducing backconversion [12]. These capabilities enable pulse durations beyond what was possible by conventional means with the given input parameters.

For our first demonstration, the local QPM period is varied smoothly across the range of phase-matching k vectors for the signal bandwidth. The grating k vector is varied linearly (Fig. 1), which, in the near-field limit and small bandwidth, leads to a flat amplification spectrum with low-order polynomial phase suitable for subsequent compression. Amplification occurs for each spectral component around its phase-matched point until the local phase mismatch becomes too large or until the pump is significantly depleted. In contrast to periodically poled gratings, where pump depletion is followed by complete backconversion in a sufficiently long grating, in aperiodically poled lithium niobate (APPLN), pump depletion increases monotonically with pump and seed intensity, except for

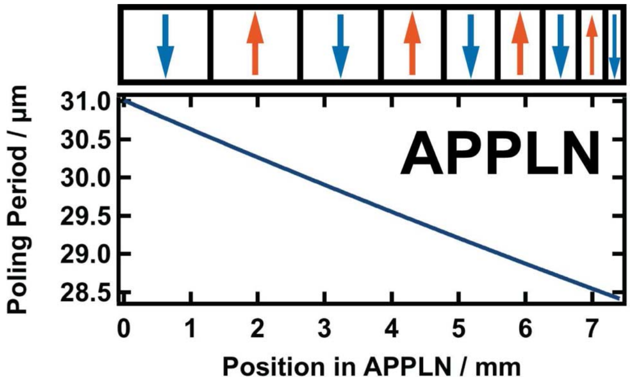

Fig. 1. (Color online) The grating used has a length of 7.4 mm and a negative chirp rate of $\kappa' = -250$ cm. It has perfect phase-matching points for wavelengths ranging between 3 and 4 μm.

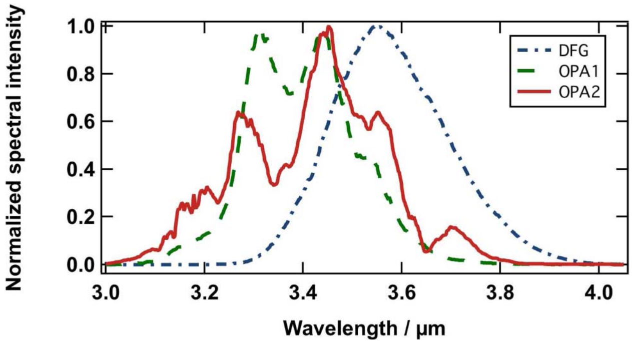

Fig. 3. (Color online) The power spectrum of the seed (blue dashed–dotted curve) supports 71 fs transform-limited pulses. After the first amplifier (green dashed curve), the spectrum is broadened, supporting 65 fs pulses, and further broadened after the second amplifier (red solid curve), yielding spectral bandwidth for 54 fs pulses.

ripples associated with abrupt onset and offset of phase matching at the edges of the grating. These ripples can be suppressed by apodization techniques, which reduce the local coupling strength by adiabatically increasing the phase mismatch (increasing or decreasing the QPM period) or by reducing the effective coupling coefficient by, for example, reducing the QPM duty cycle [12]. Misalignment of pump and seed can occur when optimizing the amplifier gain, leading to a self-apodization effect where the beam interaction is gradually turned on as the beams walk across each other through the crystal.

We use two OPA stages designed to operate in the mid-IR around 3–4 μm wavelength. The system is seeded by an intrinsically carrier-envelope offset phase (CEP)-stable difference frequency generation setup, delivering pulses from 50–100 fs in the spectral region from 3.2 to 4.8 μm [15]. This seed source is expected to enable CEP-stable output pulses from our amplifier. Both OPA stages are pumped at a wavelength of 1.064 μm with a commercial solid-state laser delivering 11 ps pulses at energies of up to 120 μJ and a repetition rate of 100 kHz (Time-Bandwidth Products AG, Duetto). By using a 1 μm pump laser technology, power scaling should be easy to achieve. The pulse train of this laser is stabilized to the pulse train of the seed laser with a phase-locked loop yielding a timing jitter of less than 150 fs rms [16].

The pulses of our mid-IR seed source are stretched to approximately 2.5 ps by propagation through 50 mm bulk Al_2O_3. The two OPA crystals are 7.4 mm long uncoated MgO:APPLN with a poling structure illustrated in Fig. 1. With a chirp rate of $\kappa' = -250$ cm^{-2} (defined as the slope of the spatial frequencies of the grating) we could achieve an amplification bandwidth of more than 800 nm (Fig. 2). In the first stage, the obtained gain is 40 dB and the second stage adds another 14 dB, resulting in pulse energies of up to 1.5 μJ at a repetition rate of 100 kHz, which corresponds to 150 mW of uncompressed average output power. Because of pump depletion, the spectrum is broadened after the second stage, supporting 54 fs transform-limited pulses. This occurs because the central spectral components are saturated before the wings. Ripples on the spectra (Fig. 3) and the corresponding prepulses on the compressed pulse originate primarily from the abrupt onset of nonlinear coupling at the ends of the grating, and can be suppressed by apodization of the QPM grating, as discussed above [12].

After compensation of second- and third-order dispersion with a four-prism silicon compressor, we reached a nearly transform-limited pulse of 75 fs (Fig. 4). The transmission of the compressor [17] amounted to only 30% due to an increased sensitivity to surface roughness at near-grazing-incidence on the silicon Brewster prisms at our operation center wavelength of 3.4 μm.

APPLN OPAs are sensitive to optical parametric generation (OPG) because quantum noise can be amplified throughout the whole grating [14]. In contrast, the seeded collinear amplification process occurs only over a relatively small region for each spectral component. This results in an unwanted OPG background, which can be suppressed by using two short amplification crystals, pushing the required gain below the OPG threshold.

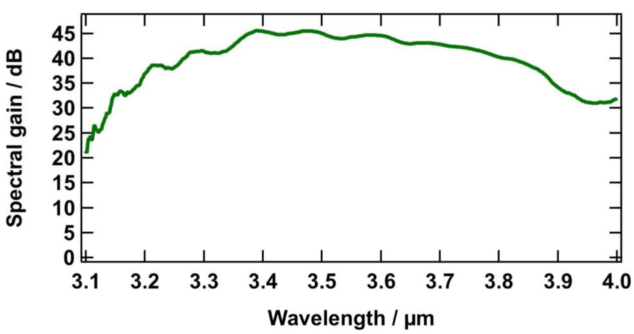

Fig. 2. (Color online) Gain spectrum of the first OPA stage, showing more than 800 nm amplification bandwidth when pumped at 1.9 GW/cm^2. The measurement is limited only by the available seed bandwidth, giving rise to noise in the spectral wings.

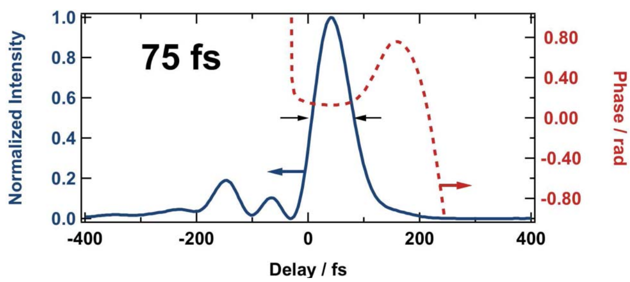

Fig. 4. (Color online) After compensation of group-delay dispersion and third-order dispersion, the pulses are compressed to 75 fs FWHM.

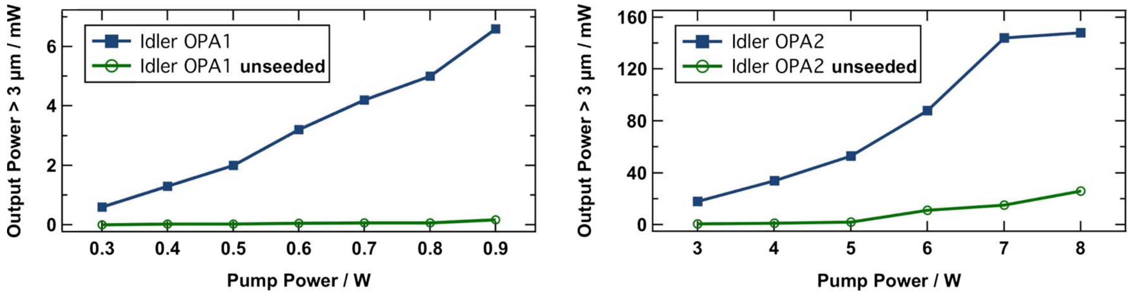

Fig. 5. (Color online) Left graph shows the power scaling of OPA1. There is only negligible OPG output. In the right graph. one can clearly see the amplification of the remaining OPG of OPA1. This can be suppressed by the use of a steeper long-pass filter between the two OPA stages. A completely unseeded OPA2 generates less than 2 mW OPG.

Nevertheless, some OPG remains. For our QPM grating design, this occurs primarily below 3 μm and can be spectrally filtered with a long-pass filter. To estimate an upper limit for the remaining OPG power, we did a conservative analysis by measuring the unseeded output power of both OPAs. After the first OPA stage, there is nearly no measurable radiation above 3 μm (Fig. 5). When the input to the second OPA is blocked, the OPG is below 2 mW of the amplified seed power, which confirms that the amount of spontaneous radiation after the second stage is still small. If one directs the small remaining OPG output (mostly leakage of our long-pass filter) of the first OPA into the second stage, the output power is 25 mW (Fig. 5). This means that an appropriate filter with higher suppression of the radiation below 3 μm from the first OPA could suppress the overall OPG contribution to less than 1.5%.

With APPLN, one can overcome the bandwidth limitations of conventional PPLN in a collinear OPCPA. We have demonstrated this new amplification concept with a femtosecond mid-IR OPCPA based on aperiodically poled Mg:$LiNbO_3$ crystals. In this first implementation, we used linearly chirped gratings and were able to achieve 75 fs output pulses characterized by SHG frequency-resolved optical gating [18], maintaining the 72 fs transform limit of the seed. The spectral ripples and temporal prepulses are understood and can be suppressed with apodization.

Other issues associated with conventional OPCPAs can be overcome with APPLN. QPM engineering can be used to achieve a flat gain profile, even with a non-flat-top temporal pump profile. With tandem amplifier designs [19], the group delay of the pulses can be engineered to achieve the transform limit of the gain spectrum. Furthermore, with APPLN, the intrinsic damage threshold of the material is no longer a limitation to the bandwidth. Finally, backconversion limiting efficiency and spectral broadening in conventional PPLN devices is significantly reduced in APPLN.

This first-generation APPLN design clearly shows the potential of the technique and holds promise for significant further improvements of pulse duration and system efficiency. With an upgraded seed source bandwidth and improved QPM designs, we expect to extend the output of our system into the few-cycle regime (one cycle at 3.4 μm is 11.3 fs).

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