Role of apodization in optical parametric amplifiers based on aperiodic quasi-phasematching gratings

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Abstract: We experimentally demonstrate and analyze two different techniques for apodizing the nonlinear coupling in aperiodically poled MgO:LiNbO$_3$ (APPLN) used in an ultrabroadband optical parametric chirped pulse amplifier (OPCPA). With an adiabatic increase of the nonlinear coupling, a smooth gain spectrum and spectral phase is preserved during amplification in such media. The two approaches we explore are poling period apodization (PPA) and duty cycle apodization (DCA). For the first implementation of the apodized APPLN amplifier we use a constant chirp-rate in the grating k-vector. The nonlinear coupling is apodized over 10% of the total length at each side of the APPLN chip. This allows us to achieve high-intensity output pulses with clean temporal structure.

OCIS codes: (140.7090) Ultrafast lasers; (190.4970) Parametric oscillators and amplifiers; (140.3580) Lasers, solid-state.

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1. Introduction

There is a growing interest in high-intensity ultrashort laser pulses at wavelengths which cannot directly be accessed with laser oscillators. Long wavelengths in the mid-infrared are of special interest for the investigation of the wavelength scaling of non-perturbative laser-matter interactions [1]. A common technique to reach these spectral regions is to convert available laser radiation to the desired spectral region by nonlinear frequency mixing [2]. A very popular class of such sources exploits the second-order nonlinear susceptibility, χ_2, for implementing parametric amplification schemes. Parametric processes are particularly interesting for high-power applications, because in principle no energy needs to be deposited in the amplification medium and thus thermal load is kept at a minimum.

One promising χ_2 medium is aperiodically poled lithium niobate (APPLN) to custom design the quasi-phase matching (QPM) for broadband operation [3]. For parametric amplification with such non-uniform QPM structures we can engineer the gain spectrum and spectral phase over an almost arbitrary bandwidth [4], and we can effectively suppress back-conversion upon saturation of the pump [5]. With a linearly chirped grating we have achieved more than 800-nm amplification bandwidth at µJ-level output pulse energy [6]. However, such a simple linearly chirped QPM design cannot maintain a smooth spectral phase of the amplified pulse, because of the abrupt onset of the nonlinear coupling at the edges of the grating [3].

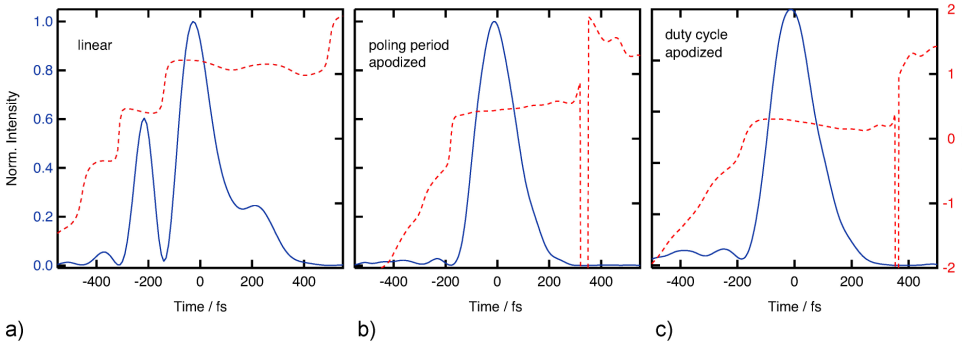

Fig. 1. Measured temporal pulse intensities (solid blue line) and phase (dashed red line) after amplification in an unapodized linear (a), a poling period apodized (b), and a duty cycle apodized (c) APPLN amplifier using a SHG-FROG [7].

2. Apodization of nonlinear interaction

In this paper we experimentally demonstrate two methods to improve a linearly chirped QPM grating to obtain a smooth spectrum and spectral phase after amplification. These methods thus yield pulses with clean temporal profiles holding almost all the energy in the main pulse (see Fig. 1). Both methods are based on the idea to gradually turning on and off the nonlinear coupling between the pump, signal and idler fields at the edges of the grating. This adiabatic approach is also referred to as apodization [3]. One method smoothly detunes the poling period away from the phase-matching condition (poling period apodization, PPA). Another method varies the duty cycle away from the 50% condition necessary for first order QPM (duty cycle apodization, DCA) [8, 9]. To our knowledge, this is the first practical

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implementation of an optical parametric amplifier (OPA) that uses apodization techniques to preserve a smooth spectral phase as required for few-cycle pulse generation [10, 11].

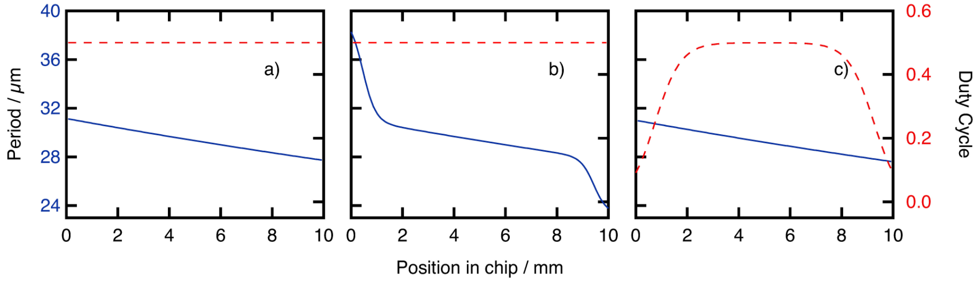

Fig. 2. QPM structures used in the amplifier: (a) linear grating (no apodization), (b) apodization by poling-period change (PPA) and (c) duty cycle apodization (DCA). The blue solid line represents the poling period whereas the duty cycle is plotted as a red dashed line.

With QPM the wave-vector mismatch Δk can be minimized for efficient energy transfer between the interacting waves. This is achieved by an additional k-vector K_g provided by the quasi-phasematching grating: $\Delta k = k_p - k_s - k_i - K_g$. In uniform QPM gratings with a fixed poling period $\Lambda_g = 2\pi/K_g$, $\Delta k = 0$ is achieved for only a single frequency. In APPLN $K_g(z)$ is varied along the grating to produce perfect phase-matching points (PPMP) for many frequencies at differing spatial positions [3]. In our case the linear chirp has the form $K_{g0}(z) = K_{gc} - \kappa' (z - L/2)$, with K_{gc} phase-matching the center frequency. In a QPM grating of finite length and with just a linear chirp profile, there is an abrupt turn-on of the nonlinear coupling between the interacting waves at the edges of the crystal. This abrupt change results in oscillatory structures in the spatial frequency spectrum of the grating. As discussed in Ref [3], such modulations lead to a ripple in the optical frequency spectrum of the output signal and idler waves in a high-gain OPA device. This is the direct origin of the ripples in the gain spectrum and the oscillatory spectral phase contributions.

To avoid such distortions of the amplified pulses, the nonlinear coupling is turned on and off adiabatically at the start and end of the QPM grating. We have chosen smooth tanh-shaped apodization profiles. A possible implementation of the nonlinear coupling apodization is to rapidly detune the poling period from the phase-matched conditions otherwise found toward the ends of the grating. This method is referred to as poling-period apodization (PPA). A possible PPA implementation uses a grating vector of the form:

$$K_g(z) = \left\{1 - K_{apod}(z)\right\} K_{g0}(z) + \\ K_{apod} \left\{K_{gc} - a(z) K_a\right\}$$

$$K_{apod}(z) = \frac{1 - \tanh\left(\frac{z - l_r}{w_r}\right) \tanh\left(\frac{L - z - l_r}{w_r}\right)}{1 - \tanh\left(-\frac{l_r}{w_r}\right)}$$

$$a(z) = \begin{cases} 1 & \text{for } z < L/2 \\ -1 & \text{for } z \geq L/2 \end{cases}$$

Apodization begins at a distance of $l_r = 1$ mm from the edges of the grating with a width of $w_r = 0.5$ mm and extends all the way to the edges on either side of the grating as shown in Fig. 2(b). The total length of the grating is $L = 10$mm and $K_a = 5$ cm^{-1} determines the degree of phase-mismatch at the edges of the grating. $K_{apod}(z)$ increases monotonically towards

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$K_{\mathrm{apod}}(0) = 1$ and $K_{\mathrm{apod}}(L) = 1$ at the edges and is zero in the middle, leaving the linearly chirped center unmodified.

Another apodization method, which we refer to as duty-cycle apodization (DCA), is to adiabatically change the duty cycle away from the usual 50% used in first-order QPM [9, 12]. In this context, duty cycle refers to the ratio of the lengths of two neighboring ferro-electric domains with opposite poling. In conventional, periodically poled devices, a duty cycle of 50% (equal length of neighboring domains) is chosen since this maximizes the amplitude of the first Fourier order of the grating, and hence the conversion efficiency. The variation of the duty cycle $D(z)$ along the propagation direction takes the following form:

$$D(z) = 0.5\, D_{\mathrm{apod}}(z)$$

$$D_{\mathrm{apod}}(z) = \frac{1}{4}\left\{1 + \tanh\left(\frac{\mathrm{z} - \mathrm{l_d}}{\mathrm{w_d}}\right)\left[1 + \tanh\left(\frac{\mathrm{L} - \mathrm{z} - \mathrm{l_d}}{\mathrm{w_d}}\right)\right]\right\}$$

The distance to the end of the grating is indicated by $l_{\mathrm{d}} = 0.75$ mm and the width of the apodizing hyperbolic tangent function is $w_{\mathrm{d}} = 1$ mm (Fig. 2(c)). With DCA the nonlinear coupling of the interacting waves cannot be turned off completely. Even for very small duty cycles approaching zero, zero order QPM result in a finite coupling. We just reduce the duty cycle so far, that in numerical simulations a smooth spectral gain is achieved.

One difficulty of the DCA lies in the manufacturing of the very short ferroelectric domains ($\Lambda_{\mathrm{min}} = D(L)K_{\mathrm{g}}(L) = 2.6$ µm) that need to be realized toward the edges of the grating. In comparison, the smallest grating period that occurs with poling period apodization is $\Lambda_{\mathrm{min}} = 14.8$ µm, which is much easier to realize. However, the smallest periods occur at the edges of the grating structure, where apodization is only completing the switch-off of the coupling that started with longer periods towards the center of the grating. Manufacturing errors at these most extreme values do therefore not significantly affect the quality of the overall apodization effect.

3. Experimental demonstration

We investigated the influence of the amplification process in APPLN on the spectral phase in the context of a few-cycle mid-infrared (MIR) two-stage OPCPA [6, 13]. A mode-locked femtosecond 1.56-µm fiber laser seeds the first OPA with 160 pJ pulse energy. The pulses are temporally stretched with a sequence of a 2-prism and a grating stretcher to a duration of ~3 ps and overlapped with our 1-µm pump beam. The pump system consists of an industry-grade 12-ps passively mode-locked master-oscillator

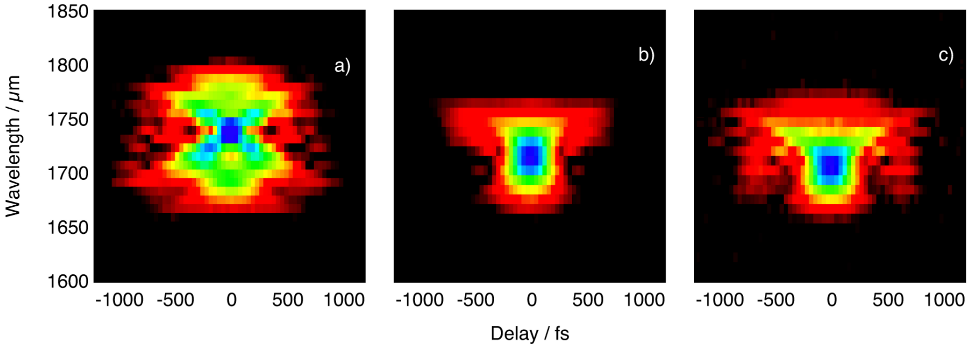

Fig. 3. SHG-FROG traces of pulses after amplification in linearly chirped APPLN. (a) without apodization (b) with rapid-poling-period-change apodization and (c) with duty-cycle apodization. Breakup into multiple sub-pulses occurs without proper apodization of the nonlinear coupling.

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power amplifier system operating at 100 kHz repetition rate with 120 µJ pulse energy (Time-Bandwidth Products Inc., Duetto). Part of the Duetto output is further amplified to 460 µJ by a Nd:YVO_4 slab amplifier [14, 15]. The pulse train of this laser is stabilized to the pulse train of the seed laser with a phase locked loop (PLL) yielding a timing jitter of less than 150 fs rms.

The 1.56 µm signal beam is amplified in two subsequent OPA stages. The 3.4 µm idler wave is kept only after the last stage. With the help of the prism and grating stretchers we are able to precisely pre-compensate the total dispersion mismatch between the stretcher section and the 150-mm-long Al_2O_3 bulk compressor. Pump and seed beams are overlapped in the first and second OPA stage at pump intensities of 3.2 GW/cm^2 $(r_{1/e^2} = 250\,\mu\text{m})$ and 4.7 GW/cm^2 $(r_{1/e^2} = 400\,\mu\text{m})$, respectively. In both stages we use a L = 10 mm long, 1-mm-thick APPLN chip made from MgO-doped lithium niobate (Crystal Technology, LLC). A chirp-rate of κ' = –250 cm^{-2} is used to achieve a broad phase-matching spectral window ranging from 2.71 to 4.24 µm.

We examined three different quasi-phase matching gratings implemented in APPLN with linear chirp and no apodization (a), rapid-poling-period-change apodization (b) and duty cycle apodization (c) (see Fig. 2). The poling quality in the OPA section of the QPM grating common to all three designs is excellent, which can be attributed to the moderate change in poling period in this region. The output pulse energy after the first OPA is 3.0 nJ, 2.5 nJ, and 1.8 nJ, respectively. The pulses are pre-amplified in OPA1 just enough to enable characterization by second harmonic generation frequency-resolved optical gating (SHG FROG) after amplification in OPA2 to ~1 µJ (gain < 30 dB). This operation point of OPA1 is well in the unsaturated pump regime. In our QPM grating designs, we used a moderate range of periods in order to facilitate more reliable fabrication, and the QPM duty cycle is limited by the poling process. The imperfections in nonlinear coupling apodization resulting from these factors become exaggerated by pump depletion effects. We therefore avoided excessive pump saturation in both amplifiers to minimize these distortions. This enables us to properly study the impact of our apodization schemes on pulse quality. For all measurements identical gratings are used in OPA1 and OPA2. The influence of the apodization can be directly seen in the FROG trace (see Fig. 3). In the case of no apodization, breakup into multiple sub-pulses in the time-frequency domain occurs. By the use of either type of apodization the pulse energy is contained in one contiguous area. In the case of duty-cycle apodization some remaining side-lobes are present. This can be attributed to the more difficult poling of the small ferroelectric domains in the apodization section at both ends of the grating and the resulting manufacturing errors.

After reconstruction of the temporal pulse profile, the difference becomes even more pronounced (see Fig. 1). Without apodization non-polynomial spectral phase contributions of the amplification process cause the energy to be spread over many overlapping sub-pulses.

5. Conclusion and outlook

We have experimentally demonstrated the importance of nonlinear coupling apodization in aperiodic QPM for OPA applications. An adiabatic turning-on and turning-off of the coupling can be achieved by either tapering off the duty cycle of the QPM periods on either side of the QPM structure or by dephasing the waves through a smooth variation of the QPM periods. Our data shows a significant improvement in pulse quality through both apodization techniques. Due to the easier manufacturing and thus better device quality, poling-period apodization is found to yield slightly better results.

With APPLN one can overcome the bandwidth limitations of conventional PPLN in a collinear OPCPA [16, 17] and the common energy-bandwidth trade-off for few-cycle pulse amplification [5]. Amplification in a linear chirped QPM grating can distort the pulse structure of few-cycle pulses. With a proper apodization non-polynomial spectral phase contributions can be easily avoided. The presented concept of apodized quasi-phasematched amplification is not limited to APPLN, but can be implemented in any QPM material. By choosing a proper range of grating k-vectors, pulses can be amplified within the whole transparency range of the selected crystal.

With apodized QPM in APPLN we expect to significantly raise the output energy and peak intensity of our high-power MIR OPCPA system while maintaining clean pulses. This will allow us to explore the non-perturbative regime of laser-matter interaction at long wavelength.

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