Chirped-pulse-amplification circuits for fiber amplifiers, based on chirped-period quasi-phase-matching gratings

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A new type of compact chirped-pulse-amplification circuit for high-power amplification of femtosecond pulses in an optical fiber is demonstrated. This circuit is based on a novel pulse compressor, chirped-period quasi-phase-matching gratings in electric-field-poled lithium niobate. The main advantages of this circuit are simplicity, the small number of components, compactness, and wavelength conversion of Er-doped fiber output to the technologically important 780-nm wavelength region. © 1998 Optical Society of America

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The most significant trend in the current development of ultrafast technology is the increasing use of ultrafast techniques in diverse practical applications. Therefore, there is a growing need for highly reliable and compact sources of ultrashort optical pulses. Fiber-based systems are of particular interest in this respect.

Recent developments in fiber-based ultrashort-pulse sources have led to the demonstration of watt-level average-power compact systems.[1] Such powers were previously obtainable only with large-scale solid-state femtosecond lasers. The key technological development that enabled researchers to overcome the peak-power limitations in ultrashort-pulse fiber amplifiers was chirped-pulse amplification (CPA) implemented by use of chirped fiber-grating dispersive delay lines.[2] Fiber gratings allow one to design compact CPA systems, which, essentially, are fiber-optic circuits.[3]

Here we demonstrate a new type of CPA circuit for high-power amplification in an optical fiber; this circuit is based on a novel pulse compressor, a chirped-period quasi-phase-matching (QPM) grating.[4] Such a QPM grating is unique in that it allows simultaneous second-harmonic generation and frequency-chirp compensation in one crystal. The use of a chirped-QPM compressor extends the functionality of a CPA system in a few important aspects. First, a QPM compressor works in transmission, unlike a fiber-grating compressor, which works in reflection. Consequently, chirped-QPM compressor-based CPA circuits have a significantly reduced component count, which is an important technological advantage over fiber Bragg-grating-based CPA circuits. Second, such a compressor directly provides second-harmonic output, which is particularly useful in conjunction with Er-doped fiber systems for producing femtosecond pulses in the technologically important 780-nm wavelength region. The overall system efficiency can be substantially increased compared with that of the conventional combination of a fiber-grating compressor and a separate second-

harmonic generator (SHG) crystal. Third, unlike in waveguide devices (such as fiber gratings), in bulk QPM gratings one can choose the size of a propagating beam to allow for the generation of high-energy pulses.

Implementation of a chirped-QPM grating in an electric-field-poled LiNbO$_3$ crystal [chirped periodically poled lithium niobate (CPPLN)] and experimental demonstration of its properties were reported recently.[5] A chirped QPM grating does not provide any real group-velocity dispersion. It is through the second-harmonic generation process that the effect of group-velocity dispersion appears in the phase of the generated second-harmonic pulse with respect to the phase of the fundamental-wavelength pulse. Second-harmonic pulses generated with such a device experience an effective dispersion $\beta_{2\text{eff}} = (\nu_{\text{GVM}}^2 2D_{\text{QPM}})^{-1}$ that is determined by the spatial chirp rate of the QPM grating period $D_{\text{QPM}} = \mathrm{d}[\pi/\Lambda_{\text{QPM}}(z)]/\mathrm{d}z$ and by the group-velocity mismatch $\nu_{\text{GVM}}^{-1} = \nu_{2\omega}^{-1} - \nu_{\omega}^{-1}$ in the material with the QPM grating. Here $\Lambda_{\text{QPM}}(z)$ is the QPM grating period varying along the beam-propagation direction z and $\nu_{2\omega}$ and ν_{ω} are group velocities at the second-harmonic and the fundamental wavelengths, respectively.

Other properties that are relevant for using chirped-QPM gratings in CPA circuits are the spectral bandwidth and the maximum recompressible stretched-pulse duration. The bandwidth $\Delta\lambda$ of a linearly chirped QPM grating is determined by the grating-period span $\Delta\Lambda$ and, therefore, is a fully engineerable parameter. The maximum recompressible stretched-pulse duration T_{max} is determined by the grating length L and the group-velocity mismatch $T_{\text{max}} = L\nu_{\text{GVM}}^{-1}$ and, consequently, is a material parameter. Note that in a Bragg grating $T_{\text{max}} = L\nu_g^{-1}$ is determined by the group velocity ν_g rather than ν_{GVM}. Typically $\nu_{\text{GVM}}^{-1} \approx 0.01\nu_g^{-1}$ and the maximum duration allowed by a QPM grating is considerably smaller than that of a similar-length fiber grating. Nevertheless, QPM gratings allow one to achieve significant

compression factors, as was demonstrated in Ref. 5 by compression of 15-ps stretched fundamental pulses at 1580 nm to 100-fs bandwidth-limited second-harmonic pulses in a 5-cm-long CPPLN crystal.

The main problem that one encounters when considering the use of a QPM grating in a fiber CPA system is due to the following trade-off: In an amplifier fiber the maximum peak power of stretched pulses is limited by the onset of phase distortions. Conversely, efficient second-harmonic generation in a QPM compressor requires sufficiently high peak powers of stretched pulses.

Phase distortions in a fiber amplifier arise from an intensity-dependent phase shift that is caused by self-phase modulation. In general the self-phase modulation effect can be neglected if the maximum phase shift is smaller than $\sim\pi$.[6] This maximum phase shift $\Delta\phi_{max}$, which occurs at the peak of the stretched pulse, is given by $\Delta\phi_{max} = \gamma P_{peak} z_{eff}$,[7] where P_{peak} is the pulse peak power, $\gamma = 2\pi n_2/(\lambda A_{eff})$ is a fiber nonlinearity coefficient, A_{eff} is the effective core area, n_2 is the fiber-glass nonlinear-index coefficient, and z_{eff} is the effective propagation distance in the amplifier.

For unchirped periodically poled lithium niobate the ultrashort-pulse SHG efficiency can be expressed as $\eta = \xi E_{pump}$, assuming optimum length of the crystal (temporal walk-off between the pump and the second-harmonic equal to the pump-pulse duration), confocal focusing, and no pump depletion.[8] The value of ξ is determined by the material properties of lithium niobate and the particular pulse shape. For a Gaussian pulse $\xi \approx 100\%/nJ$.[8] It is straightforward to generalize the above expression for the case of CPPLN and stretched pump pulses: $\eta = \xi E_{pump}/(\tau/\tau_0)$. Here τ_0 is the bandwidth-limited duration and τ is the stretched-pulse duration. In terms of the peak power, $\eta = \xi P_{peak} \tau_0$, where $P_{peak} = E_{pump}/\tau$.

Consequently, the above trade-off puts the following requirements on the peak power of stretched and amplified pulses: $\eta/(\tau_0\xi) < P_{peak} < \pi/(\gamma z_{eff})$. Assuming that $\eta = 30\%$, $\tau_0 = 300$ fs (typical pulse duration supported by Er-amplifier bandwidth), $z_{eff} = 1$ m, $A_{eff} = 200\ \mu m^2$ (maximum mode size for a single-mode fiber[9]), and the pulse shape is Gaussian one can calculate that these requirements can be fulfilled simultaneously: $1\ kW|_{CPPLN} < P_{peak} < 5\ kW|_{fiber}$. This indicates that because of the high nonlinearity of periodically poled lithium niobate the above-noted trade-off can be overcome and efficient SHG output can be achieved without phase distortions in an amplifier fiber.

Experimental confirmation of the above was obtained with a fiber CPA system and is shown in Fig. 1. This setup demonstrates the simplicity that one can achieve in a CPA circuit design by employing a chirped-QPM-grating compressor. The system consists of a femtosecond fiber oscillator, a short length of fiber serving as a stretcher, a large-core Er-doped fiber amplifier, and a CPPLN crystal for SHG pulse compression. To extract higher peak powers we used a large-core single-mode fiber for the amplification

stage. The Er-doped fiber design is based on a small refractive-index difference between the core and the cladding.[9] The resulting low numerical aperture of the fiber allows for an increase of the fiber core diameter while maintaining the single-mode characteristics of the propagating signal. In this particular fiber a numerical aperture of 0.06 made possible a core diameter of 15 μm. Furthermore, the fiber is highly doped to 2000 parts in 10^6 so that efficient amplification with short amplifier lengths is achieved. These measures significantly reduce detrimental self-phase modulation effects, allowing an increase in extractable pulse energies.

The seed pulses are generated with a passively mode-locked fiber oscillator[10] operating at 1560 nm and providing 20-MHz repetition-rate pulses with 200-fs duration and 250 pJ of energy. After stretching, these pulses are amplified in a 1.2-m-long large-core Er fiber. The amplifier is in-core pumped at 980 nm by a 750-mW single-mode beam from a master-oscillator power-amplifier diode laser. The amplified spectrum is 10 nm wide, which corresponds to an $\sim$300-fs bandwidth-limited pulse duration. Some spectral narrowing and reshaping occurred in the amplifier owing to a mismatch between the seed pulse and the amplifier gain spectra.

The fiber stretcher contains 3 m of positive-dispersion fiber with $\beta_2 = +0.108\ ps^2/m$. With some amount of additional pulse compression occurring in the negative-dispersion amplifier fiber the net dispersion experienced by the stretched and amplified pulses is $+0.3\ ps^2$. This arrangement yields 2.2-ps pulses at the amplifier output (Fig. 2). These pulses are subsequently compressed in a 2-cm-long CPPLN crystal with an effective dispersion of $-0.3\ ps^2$.

An autocorrelation trace of the compressed 320-fs second-harmonic pulses is shown in Fig. 2. The presence of a small amount of phase distortion is evident from the trace shape. This distortion is caused by nonlinear effects in the fiber amplifier and occurs at only the highest amplified pulse energies of $\sim$10 nJ.

The average power of the recompressed second-harmonic output as a function of the input fundamental power is plotted in Fig. 3. The maximum average second-harmonic power of 70 mW is achieved with 200 mW of fundamental input. The inset shows the same data plotted as SHG conversion efficiency versus the fundamental pulse energy. The maximum second-harmonic pulse energy of 3.5 nJ is reached for
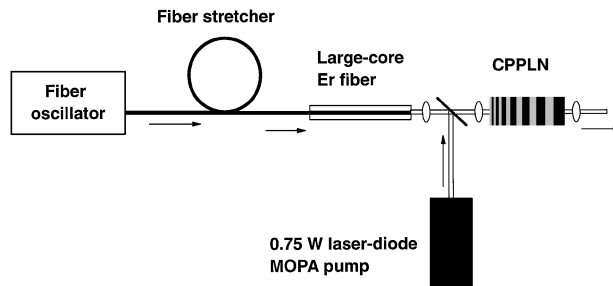

Fig. 1. Experimental setup. MOPA, master-oscillator power amplifier.
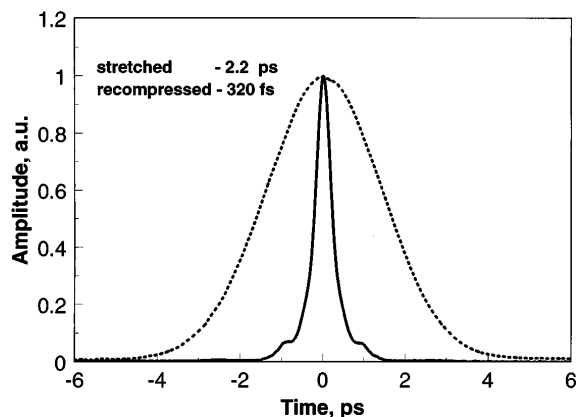
Fig. 2. Autocorrelation traces of stretched fundamental (doted curve) and compressed second-harmonic (solid curve) pulses.
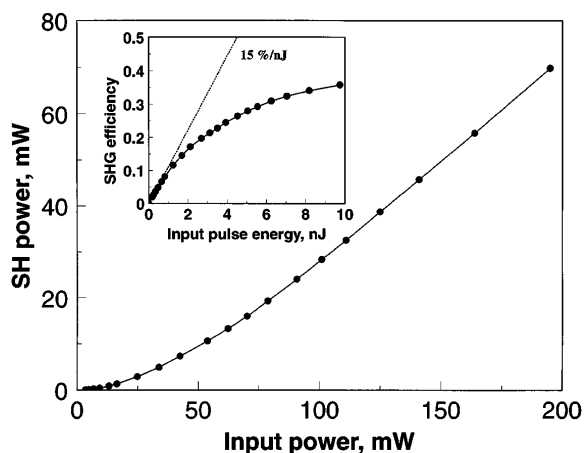

Fig. 3. Second-harmonic (SH) average power from a CPPLN compressor plotted against the incident fundamental average power. The inset shows the conversion efficiency plotted against the fundamental pulse energy.

10 nJ of fundamental pulse energy. The dotted line represents the expected 15%/nJ small-signal conversion efficiency for the stretching factor of ~7 that was used in this CPA system, indicating good agreement be-

tween measured and expected efficiencies at low input energies.

In conclusion, we have demonstrated a new integrated CPA system for high-power femtosecond pulse amplification in a fiber amplifier. This system, based on a chirped-QPM-grating pulse compressor, is significantly simpler to implement than a fiber-grating-based CPA circuit. We have demonstrated that a peak-power trade-off, which is inherent owing to the SHG conversion, can be overcome by use of QPM compressors in periodically poled lithium niobate. The use of longer QPM compressors and higher fiber pump powers will further increase obtainable average powers and pulse energies from such compact CPA systems.

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