High-energy femtosecond pulse amlification in a quasi-phase-matched parametric amplifier

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A new type of solid-state femtosecond amplifier is demonstrated that is based on quasi-phase-matched parametric amplification. Such gain media are different from conventional solid-state amplifiers in that their amplification bandwidths and pump and signal wavelengths can be engineered. Furthermore, high gain is characteristic of parametric amplification, permitting extraction of high energies without the need to resort to multiple-pass configurations. We report a parametric chirped pulse amplification system in which femtosecond pulses from a mode-locked Er-doped fiber laser system are amplified to 1-mJ energies in a single pass by use of a 5-mm-long periodically poled $LiNbO_3$ (PPLN) crystal. This amplifier is pumped by 5-mJ and 0.5-ns pulses at 786 nm, demonstrating that limitations associated with a low optical-damage threshold for long pump pulses can be overcome because of the high nonlinearity of PPLN and that relatively simple Q-switched lasers can be used with such parametric amplifiers.

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Diverse applications including surgery, material processing, precision ranging, environment monitoring, x-ray lithography, and ultrafast chemistry and biology require subpicosecond duration pulses with energies in the microjoule to millijoule range and higher. Currently, such femtosecond-pulse energies are obtained with solid-state amplifiers by the use of multiple-pass or regenerative architectures,[1,2] the complexity and size of which pose a significant technological limitation on their widespread use. The necessity for use of such multiple-pass architectures stems from the low gain of a population-inversion-based solid-state gain medium; for bulk crystals it is typically less than 10 dB per pass.

A parametric gain medium can serve as a high-gain solid-state alternative to a population-inversion-based medium for pulse-energy amplification.[3] Traditionally, however, traveling-wave optical parametric amplifiers have been used only with short-pulse, femtosecond or picosecond pump sources and exclusively for wavelength conversion rather than for pulse-energy amplification.[4] For achieving significant gain, conventional birefringently phase-matched optical parametric amplifiers require unacceptably high pumping intensities, which cause optical damage for long pulses and therefore have not been considered to be practical solid-state amplifiers.

In this Letter we demonstrate the use of a quasi-phase-matched (QPM) parametric gain medium pumped by nanosecond pulses as a practical femtosecond-pulse amplifier. Using a periodically poled lithium niobate (PPLN) crystal, we obtained 40-dB single-pass gain and millijoule amplified energies. Such an amplifier avoids the technological limitations of multiple-pass schemes. It also offers other advantages compared with conventional solid-state gain media. Quasi-phase matching permits the design of optical properties of an amplifier, including the gain spectrum or the signal and pump wavelengths. A parametric amplifier typically has negligible absorption at pump and signal wavelengths, promising lower susceptibility to thermal effects at high power levels.

For a practical parametric amplifier it is essential that simple and inexpensive nanosecond lasers rather that picosecond lasers be used as pump sources. This requirement leads to the necessity to solve two main problems. First, significant optical gain has to be achieved at pump intensities safely below the damage threshold for the long pump pulses. Second, parametric amplification is an instantaneous process, and energy extraction efficiency for direct amplification of ultrashort pulses is unacceptably small because of the large pulse-duration mismatch between the nanosecond pump and the femtosecond signal.

The solution of the first problem relies on the engineerability of the optical properties of QPM materials. As follows from the phase-matching conditions $k_p - k_s - k_i - 2\pi/\Lambda = 0$, where k_p, k_s, and k_i are the pump, the signal, and the idler wave vectors, respectively, and Λ is the QPM grating period,[5] Λ provides an adjustable parameter that is independent of the intrinsic material properties. The QPM structure can be fabricated with a photolithographic mask,[5] permitting control of Λ and, consequently, control of the optical parameters related to the phase-matching conditions.

This engineerability of a QPM material allows one to achieve substantially improved parametric gain properties compared with those of birefringence phase-matched materials. First, quasi-phase matching permits the use of the highest optical nonlinearity available in the material. In QPM $LiNbO_3$ the highest available effective nonlinearity, $d_{\text{eff}} = 17$ pm/V,[5]

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constitutes more than an order-of-magnitude improvement compared with birefringence-phase-matched $LiNbO_3$ and other conventional nonlinear materials (e.g., β-barium borate[6]). Second, it permits noncritical phase matching, eliminating the limitation on the interaction length associated with spatial walk-off.

Consequently, high parametric gain can be obtained in PPLN pumped with nanosecond pulses without causing optical damage. Calculations of the parametric gain in PPLN for near-field focusing and collinear (noncritical) phase-matching conditions[7] show that as much as 90 dB of single-pass gain is expected with pump intensities in the range from tens to hundreds megawatts per square centimeter. The reported studies of the optical-damage threshold in $LiNbO_3$ (Refs. 8–11) indicate that these intensity values are below the damage threshold of pulses shorter than 10 ns, the duration range easily accessible with Q-switched lasers.

The solution of the second problem is to amplify stretched rather than unstretched femtosecond pulses, as was first suggested in Ref. 3. Stretching increases the amount of extractable pump energy in proportion to the ratio between the stretched pulse and the pump pulse durations, until those durations are matched. Because this technique uses pulse stretching primarily for increasing the energy efficiency of a parametric amplifier, it can be called parametric chirped pulse amplification.[3] This name distinguishes it from conventional chirped pulse amplification,[12] in which pulse stretching is required solely for eliminating pulse distortions and optical damage at high peak intensities.

The experimental arrangement for demonstrating high-gain single-pass amplification in a PPLN crystal is shown in Fig. 1. Its principal parts comprise an Er-doped fiber laser system that produces femtosecond seed pulses at 1550 nm, diffraction-grating arrangements for signal-pulse stretching and compression, a PPLN crystal for parametric amplification, and an alexandrite-based laser system for pumping the parametric amplifier. Femtosecond pulses from a mode-locked fiber oscillator are stretched to 350 ps and then amplified in an Er-doped fiber preamplifier, providing signal seed energies of as much as 100 nJ. Because of gain narrowing in the fiber amplifier the spectral width of the preamplified pulses is 7 nm, corresponding to ~700-fs bandwidth-limited pulse durations.

An acousto-optic modulator (AOM) is used as an optical gate for reducing the pulse repetition rate from 20 MHz to 10 Hz, synchronized to the pump pulses. Accurate timing between the signal and the pump pulses is achieved by use of a pulsed laser diode to seed the lamp-pumped alexandrite amplifier.[13] The seed diode is driven with an electric nanosecond-pulse generator, which is triggered by pulses from the mode-locked fiber oscillator. The estimated ~50-ps timing jitter between pump and signal pulses is significantly smaller than the duration of these pulses. This pump source provides 786-nm and 0.5-ns pump pulses with as much as 5 mJ of energy at the PPLN crystal.

The pump and the signal pulses are combined with a dichroic beam splitter and launched collinearly into a parametric amplifier crystal. Both the pump and the signal beams are close to diffraction limited, with measured M^2 values of 1–1.2. Spot sizes and divergences of both beams are appropriately matched by telescoping of the pump beam (not shown in the figure). The beams are focused loosely into a 5-mm-long and 500-μm-thick crystal of PPLN by separate 50-cm focal-length lenses. The QPM grating period of the sample is 19.5 μm. Photorefractive damage is eliminated by heating of the PPLN crystal to 100 °C. Energy conversion efficiency from pump to signal is critically dependent on the spatial and temporal overlap and the collinearity of the pump and signal pulses in the crystal.

The maximum amplified signal energy of 1 mJ was obtained with 5-mJ pump pulses for 100-nJ signal seed pulses and with the pump beam focused to a 450-μm-diameter spot. This result constitutes a 40-dB gain and a 20% pump-to-signal energy conversion efficiency. Similar gain and conversion efficiency values were obtained for lower pump energies by the use of smaller focused spots. Equivalently, higher amplified signal energies are possible with even higher pump energies and proportionally larger focused spot sizes.

Single-shot second-harmonic autocorrelation traces of the 680-fs recompressed pulses are shown in Fig. 2. The energy transmission through the compressor

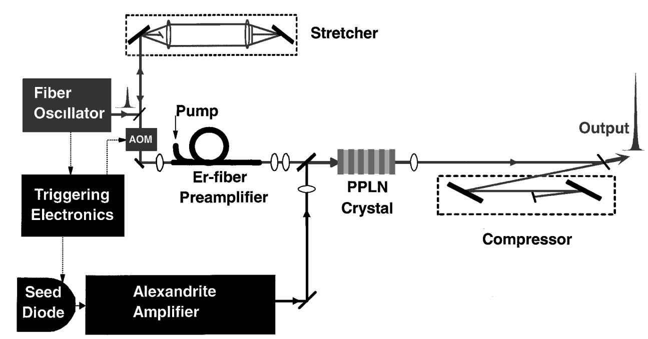

Fig. 1. Experimental setup for demonstrating millijoule single-pass amplification in a PPLN crystal.

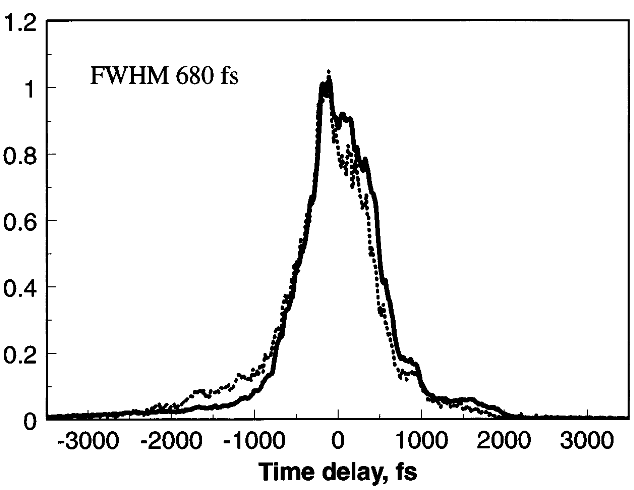

Fig. 2. Single-shot second-harmonic autocorrelation traces of recompressed optical pulses. Solid curve, the parametrically amplified millijoule pulse; dotted curve, the unamplified seed pulse.

is 60%. Comparison of the amplified and the unamplified pulse traces indicates the absence of any significant phase or spectral distortions in the parametric amplifier. Spectrally and temporally resolved streak-camera images of pump, signal, and idler pulses also indicated that the pump-pulse phase irregularities, caused by the multiple longitudinal mode emission from the seed diode, are affecting the phase of the idler pulses only. The absence of any observable spectral narrowing in the parametric amplifier is consistent with the ~150-nm signal gain bandwidth expected for a 5-mm-long PPLN nondegenerate parametric amplifier at 1560 nm pumped at 786 nm. In this experiment the recompressed duration of amplified pulses was limited only by the bandwidth of the fiber preamplifier.

No crystal damage was observed during several hours of operation with 5-mJ pulses focused to a 450-μm spot, although the corresponding fluence was close to the anticipated surface damage threshold [~3 J/cm^2 (Refs. 8–11)]. Indeed, with tighter focusing (~50% smaller spot area), damage at the front surface did occur. Inspection of the damaged samples, however, did not reveal any trace of bulk damage. With longer PPLN crystals, higher gain per unit intensity can be achieved and the reliability margin can be greatly increased by use of pump fluences several times below the damage threshold.

In conclusion, we have demonstrated a practical parametric gain medium for high-energy ultrashort-pulse amplification. The essential advantage is that high single-pass gain is achievable with relatively low pump energies in the microjoule or millijoule range, eliminating the need for regenerative or multiple-pass amplification. Such an amplifier can be pumped with a variety of standard Q-switched lasers. One can scale output energies from millijoules to joules by increasing the spot size of overlapping pump and signal beams to avoid optical damage. Despite the technological limitations on the domain thickness in PPLN this scaling is attainable by use of cylindrical focusing optics, diffusion-bonded PPLN stacks,[14] or both. Furthermore, the engineerable optical properties of a QPM parametric amplifier permit the choice of pump and signal wavelengths and, through the use of QPM-period chirping, potentially can provide extremely broad gain bandwidths suitable for amplification of few-femtosecond pulses.

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