Fiber-laser-based femtosecond parametric generator in bulk periodically poled $LiNbO_3$

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A diode-pumped system for optical parametric generation of wavelength-tunable femtosecond pulses is demonstrated. It comprises an Er-doped fiber mode-locked laser, a fiber chirped-pulse amplifier, and a bulk periodically poled $LiNbO_3$ (PPLN) optical parametric generator. The parametric generator is pumped at 777 nm with frequency-doubled microjoule pulses from the fiber amplifier and produces 300-fs pulses tunable from 1 to 3 μm with output energies up to ~200 nJ. Use of a PPLN nonlinear crystal substantially reduces the pump energies required for efficient parametric generation. Saturated single-pass parametric energy conversion of 38% (internal) has been achieved with only 220 nJ of pump inside the crystal. A parametric generation threshold of 54 nJ is observed, and efficient parametric conversion is obtained with repetition rates up to 200 kHz. © 1997 Optical Society of America

Laser systems based on rare-earth-doped fibers are the emerging technology for compact, robust, and reliable ultrashort pulse sources. The capability of tuning the operating wavelength of a laser in a wide range from the visible to the mid-infrared is essential for many applications. However, until now fiber sources had no such capability owing to the low output powers and energies directly from a fiber oscillator, which are insufficient for parametric frequency conversion.

Two recent developments have changed the situation. First, high average output powers and relatively high, microjoule pulse energies have been achieved with various amplified fiber systems[1,2] by the chirped-pulse amplification method.[3] Second, quasi phase matching (QPM) in ferroelectric bulk materials has been implemented through periodic electric field poling,[4,5] permitting efficient frequency conversion with substantially lower pumping energies compared with those in conventional birefringent phase matching.[6–8]

QPM uses periodic modulation of the nonlinear (or linear) properties of a crystal to compensate for the mismatch between the wave vectors of the interacting light beams,[9] enabling one to engineer nonlinear properties of the crystal by defining this periodic structure with conventional photolithographic techniques. This permits the utilization of any component of the nonlinear susceptibility tensor and the implementation of noncritical phase matching at any wavelength within a crystal's transparency range. Specifically, periodically poled lithium niobate (PPLN) has the large nonlinear coefficient d_{33} accessible only through QPM ($d_{\text{eff}} = 2d_{33}/\pi \approx 17$ pm/V).

An advantage of an optical parametric generator[10] (OPG) over other ultrafast parametric conversion systems, such as a synchronously pumped optical parametric oscillator[11] and a continuum-seeded optical parametric amplifier,[12] is its inherent simplicity and robustness; it requires no external resonators, cavity length stabilization, or seed signals. However, the majority of existing OPG systems require large pump energies, tens to hundreds of microjoules, and consequently are based on large and complex pumping systems, outweighing in many cases the advantage of the simplicity of OPG. Efficient nonlinear materials such as PPLN allow one to take full advantage of the simplicity of a single-pass OPG because of the accessibility of the required pump energies with compact fiber-based amplified sources.

In the Letter we report an Er-doped-fiber-based diode-pumped system for efficient parametric frequency conversion in bulk PPLN. Frequency-doubled microjoule ultrashort optical pulses from the fiber laser-amplifier system were used to pump a single-pass OPG to yield pulses tunable from 1 to 3 μm with durations of ~300 fs and energy up to 200 nJ. This implementation of a quasi-phase-matched OPG in a periodically poled material demonstrates up to 38% energy conversion (internal) with 100–200 nJ of pump.

All PPLN crystals used in this experiment were not antireflection coated, and therefore at each of the surfaces an optical beam encountered ~14% reflection. Both second-harmonic and parametric frequency conversion were achieved through noncritical phase matching, preventing spatial beam walk-off. All interacting waves were of extraordinary polarization.

The experimental setup is shown in Fig. 1. The OPG was pumped at 777 nm. The pump source was a frequency-doubled Er-doped-fiber chirped-pulse amplification system.[1] Pulses of 200-fs duration from a mode-locked fiber oscillator were stretched in a diffraction-grating stretcher, amplified in a two-state

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fiber amplifier (EDFA I, EDFA II), recompressed in a diffraction grating compressor, and then frequency doubled. Both the oscillator and the amplifier were diode pumped. The oscillator was cladding pumped with a 1-W 100-μm-stripe diode laser.[13] The amplifier was pumped with two single-transverse-mode 0.75-W master-oscillator power-amplifier diodes with 200 and 450 mW of power launched into the first and second stages, respectively. An acousto-optic modulator (AOM) between the two amplifications stages prevented spontaneous-emission cross coupling and permitted lowering of the repetition rate of the amplified pulses for increased energy extraction. Repetition rates of the amplified pulses were selectable at different subharmonic frequencies of the mode-locked-oscillator fundamental repetition rate of 20 MHz.

Amplified pulses at 1.554 μm were recompressed to 600 fs and then frequency doubled in an 18.75-μm-period PPLN crystal. The duration of second-harmonics pulses was 500 fs FWHM. The second-harmonic crystal was 400 μm long (30-nm FWHM acceptance bandwidth), which we set to the correct phase-matching wavelength by heating the crystal to 100 °C. Maximum second-harmonic energy conversion efficiency at saturation was 47% (external). Both the fundamental beam at 1.55 μm after the compressor and the second-harmonic beam at 777 nm after the harmonic-generator were close to Gaussian in spatial profile, with $M^2 = 1.25 \pm 0.05$. Maximum pulse energies were obtained when the system was operated at 1–10-kHz repetition rates; after recompression, the maximum fundamental pulse energy at 1.554 μm was 4 μJ and the maximum second-harmonic energy at 777 nm was 1.9 μJ. However, pulse energies sufficiently high to pump the parametric generator were also obtained at higher repetition rates.

Second-harmonic pulses at 777 nm were used to pump the single-pass parametric generator shown in Fig. 1. Second-harmonic pulses were separated from the fundamental with a dichroic mirror and cascaded optical filters to prevent seeding of the parametric generator. Several different 0.5-mm-thick PPLN samples fabricated by electric-field poling[6] with quasi-phase-matched grating periods ranging from 19 to 20 μm and crystal lengths from 1 to 5 mm were used in this generator. Focusing optics for each of the crystal lengths was chosen to ensure confocal focusing conditions. 3-mm-long crystals were found to be optimum in terms of power conversion efficiency. This observation can be related to the magnitude of signal-to-pump temporal walk-off (300 fs/mm) in PPLN. For crystal lengths longer than the optimum length, walk-off between the pump and the signal pulses significantly exceeds the pump pulse duration. We accomplished tuning of the signal and the idler wavelengths by heating the OPG crystal. Calculated (solid curves) and measured tuning curves for a 19-μm-QPM-period sample are shown in Fig. 2. Changing the temperature from 60 to 375 °C tunes the signal wavelength from ~1.4 μm to ~1.05 μm and the idler wavelength from ~1.65 μm to ~2.9 μm. It is useful to note that one can achieve the same tuning characteristics at a fixed temperature by using a multigrating PPLN crystal, as was demonstrated recently in a nanosecond optical parametric oscillator configuration.[14] Although the fundamental was suppressed with optical filters by ~80 dB, close to the degeneracy point at ~1.55 μm the system operated as a parametric amplifier of the residual fundamental rather than as a parametric generator. This could partly account for the slight measured deviation from the calculated tuning characteristics near degeneracy. Additionally, an accurate match between experiment and calculations at degeneracy is difficult for type I phase-matched interactions because of the sensitivity of the tuning to small variations in refractive-index dispersion.

The dependence of the conversion efficiency on pump energy in a 3-mm-long sample, measured with a pyroelectric detector, is shown in Fig. 3. The signal wavelength for this measurement was 1.2 μm, and the pulse repetition rate was 71 kHz. The internal conversion efficiency (with energy losses at each of the uncoated facets of the PPLN crystal taken into account) is shown here. Losses at the crystal facets can be eliminated by antireflection coatings. We found that, depending on the focusing conditions, it was possible to reach either the lowest threshold (circles) or the highest conversion efficiency (diamonds). With

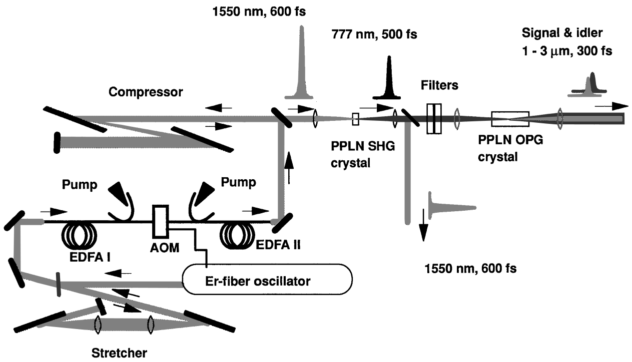

Fig. 1. Experimental setup. All pump sources are diode lasers.

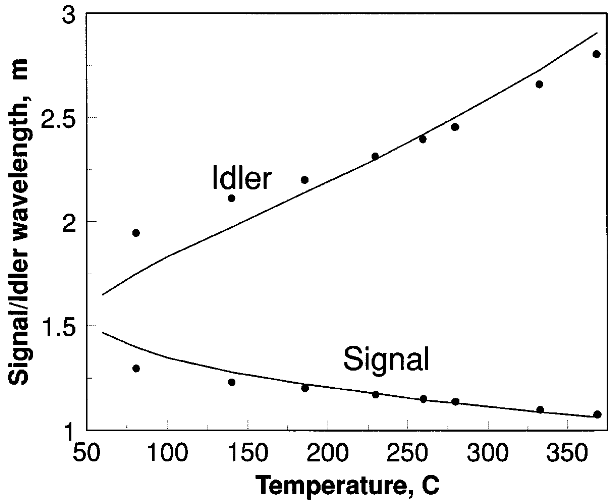

Fig. 2. Temperature tuning curves for a 19-μm QPM-period PPLN OPG pumped at 777 nm. Lines are calculated curves, and circles are experimentally measured values.

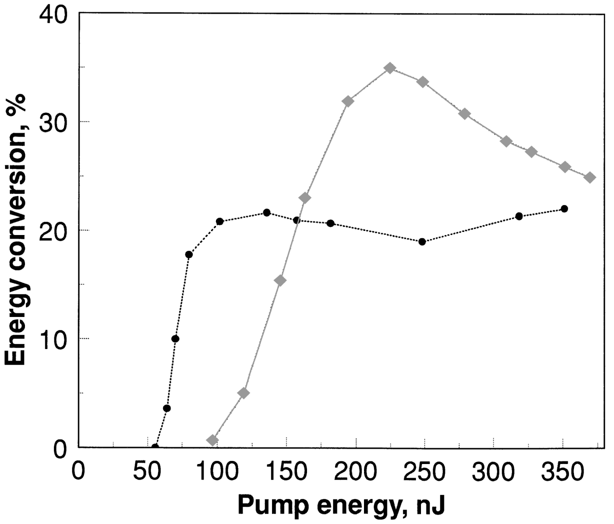

Fig. 3. Total energy conversion efficiency (internal) in a 3-mm-long single-pass OPG. The signal wavelength is 1.2 μm. Pump energy is given inside the crystal.

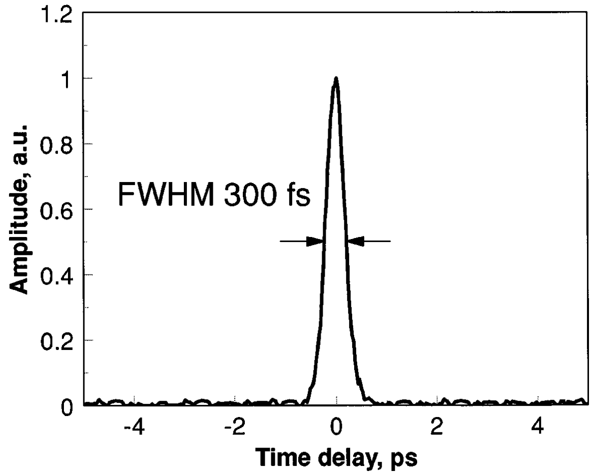

Fig. 4. Second-harmonic autocorrelation trace of a signal. Assuming a Gaussian pulse shape, the deconvolved pulse width is 300 fs.

symmetric focusing (minimum waist in the center of the crystal) the OPG threshold was 54 nJ and the conversion efficiency reached saturation at ~ 23% with 100 nJ of pump inside the crystal. With the minimum waist located at the back facet, the OPG threshold was 100 nJ and the maximum total conversion efficiency as ~38%, with 220 nJ of pump inside the crystal. These nanojoule pump energies constitute more than an order-of-magnitude improvement over the best previously reported OPG pumping results (~2 μJ in Ref. 15). The idler power was measured to be approximately one third of that of the signal at 1.2 μm, consistent with photon conservation. Maximum detected signal energies of 200 nJ were obtained with the maximum pump energy of 1.9 μJ at 1–10-kHz repetition rates. It is important to note that, even at the highest pump energies, no crystal damage occurred and that the low OPG threshold permitted operation of the parametric generator at high repetition rates of up to 200 kHz.

An autocorrelation trace of the signal pulse, shown in Fig. 4, reveals a profile corresponding to a 300-fs deconvolved pulse duration (assuming a Gaussian pulse shape). The duration of the idler pulses is expected to be similar to that of the signal because the temporal walk-off between the idler and the signal over the entire tuning range is <60 fs/mm, which for a 3-mm crystal is smaller than the pulse duration. The FWHM signal bandwidth was ~80 nm, which is 5–6 times broader than the transformed-limited bandwidth of ~ 300-fs pulses. Non-transform-limited pulses are typical for a simple single-pass OPG. One can eliminate this drawback by resorting to more-complex systems, such as a double-pass OPG with spectrum selection[15] or a continuum-seeded optical parametric amplifier.[12]

In conclusion, we have demonstrated what is to our knowledge the first diode-pumped femtosecond OPG system. The achieved OPG threshold energy is lower than that for continuum generation. Practical advantages come from the ruggedness of the fiber-based pump source and from the fact that a single-pass OPG system is substantially simpler than an optical parametric amplifier or a synchronously pumped optical parametric oscillator system. It is a promising alternative to tunable bulk solid-state-laser-based systems.

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