Synchronously pumped optical parametric oscillator driven by a femtosecond mode-locked fiber laser

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A femtosecond all-fiber laser source incorporating a cw mode-locked Yb-doped silica fiber oscillator and amplifier has been used to synchronously pump an optical parametric oscillator based on periodically poled lithium niobate. The signal output, consisting of 330-fs pulses at a 54-MHz repetition rate and average powers up to 90 mW, was tuned from 1.55 to 1.95 μm, with a corresponding idler range of 2.30−3.31 μm. © 2002 Optical Society of America

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The synchronously pumped optical parametric oscillator (SPOPO) has undergone progressive developments since its proposal in 1969 and its experimental demonstration in 1970 (see Ref. 1 for a number of early references). The major innovations in SPOPOs have been achieved by way of improved pump sources and through the use of quasi-phase-matched (QPM) nonlinear materials, such as periodically poled lithium niobate (PPLN). These developments have led to threshold powers as low as a few milliwatts of average pump power,[2] thus enabling, for example, direct diode-laser pumping[3] and pumping with a fiber laser.[4] In the latter study, a quasi-cw mode-locked fiber laser was used with pump pulses of 20-ps duration at a repetition rate of 85 MHz. Here we report a SPOPO driven by a diode-pumped, all-fiber laser system that operates with much shorter pump pulses (270 fs) in a truly cw mode-locked mode at a repetition rate of 54 MHz. This has reduced the average power required for threshold compared with that reported in Ref. 4 by approximately an order of magnitude, to 21 mW. Average signal output powers of 90 mW have been obtained with pulses of 330-fs duration and >5-kW peak power. A signal tuning range from 1.55 to 1.95 μm has been covered with corresponding idler tuning from 2.30 to 3.31 μm.

This combination of diode-pumped, fiber laser technology with QPM nonlinear materials permits demonstration of compact, versatile, and inexpensive femtosecond sources with wide tunability in the infrared. Furthermore, large-mode-area fiber technology[5] and parabolic pulse amplification techniques[6] should allow power scaling of compact, fiber-laser-pumped SPOPOs to the multiwatt average power regime.

The femtosecond pump source is an Yb-doped fiber master oscillator power amplifier (MOPA) system, as shown in Fig. 1, which consists of a mode-locked Yb-doped fiber oscillator, an Yb-doped fiber amplifier chain, and a diffraction grating pulse compressor. Details of the master oscillator are given in Ref. 7. Briefly, mode-locked operation is achieved by use of the intensity dependent, nonlinear polarization rotation in the Yb-doped fiber as a fast saturable absorber, with a semiconductor saturable absorber mirror also incorporated into the cavity to facilitate reliable self-start mode locking. The pulse energy is increased to ~8 nJ by fiber amplifiers by use of the recently discovered parabolic pulse solution to the nonlinear Schrödinger equation.[6] In this situation, ultrashort pulses amplified in a fiber amplifier evolve asymptotically toward a configuration with a parabolic temporal and spectral profile. These parabolic pulses are of immediate practical application because

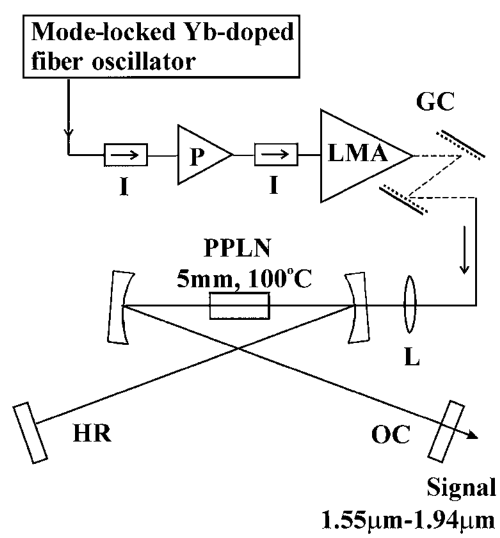

Fig. 1. Schematic of the Yb-doped fiber oscillator, Yb-doped fiber amplifier chain, and optical parametric oscillator (OPO) setup: P, diode-pumped fiber preamplifier; I's, optical isolators; LMA, diode-pumped, large-mode-area fiber amplifier; GC, grating compressor; L, focusing lens; HR, high reflector; OC, output coupler.

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they have a strictly linear chirp, which permits the use of a diffraction grating compressor to produce high-quality <300-fs pulses. In contrast, chirped pulse amplification techniques, although they are still required for femtosecond fiber amplifier systems that produce higher pulse energies,[8] require the additional complication of a pulse stretcher. This all-fiber laser system generates 270-fs (FWHM) pulses at a repetition rate of 54 MHz and delivers a maximum average power of 410 mW to the nonlinear medium of the SPOPO. An operating pump wavelength of 1.056 μm was used for these experiments. The time–bandwidth product of the pump source was measured to be 0.65 (FWHM bandwidth, $\Delta\lambda = 9.0$ nm, and with the assumption of a Gaussian pulse shape).

The SPOPO investigated in this study is configured as a singly resonant, standing-wave resonator (see Fig. 1), with high reflectivity at signal wavelengths for three of the mirrors and signal output taken from a plane output coupler. A 5-mm-long, antireflection-coated PPLN crystal with grating periods ranging from 30.0 to 30.8 μm was used for these experiments. Different wavelength regions were obtained by lateral translation of the crystal to insert different grating periods into the cavity. The crystal was held in an oven at a fixed temperature of 100 °C to minimize photorefractive effects. The pump beam was focused to a waist spot size, w_0, of 21 μm at the center of the PPLN crystal, giving essentially confocal focusing (pump-focusing parameter ξ_p, the ratio of crystal length to confocal parameter, is 0.9). The curved cavity mirrors (100-mm radius of curvature) define a spot size for the resonated signal of 22 μm; hence the corresponding signal-focusing parameter, ξ_s, is 1.3.

An oscillation threshold of 21-mW average pump power was achieved for a signal wavelength of 1.7 μm for a cavity with a high reflector in place of an output coupler. The losses for the signal beam were determined by a technique similar to that used by Findlay and Clay[9] for a four-level laser, with which they observed the threshold dependence on reflectivity R of the output coupler. To ensure the validity of this technique within the context of an OPO (see Ref. 10 for a discussion), we used output mirror reflectivities greater than 90%, thus imposing low-gain conditions and hence linearity of the parametric gain dependence on pump power. Then, from a plot of $-\ln(R)$ versus threshold power, the round-trip losses for the resonant signal beam were found to be ~11%. Using an output coupling reflectivity of 63% and an average pump power of 410 mW incident on the PPLN crystal, we measured a maximum signal output of 90 mW at 1.7 μm, which corresponds to a signal conversion efficiency of 23% (see Fig. 2). The slope efficiency for the signal beam with respect to pump power was 28%. Without any deliberate attempt at active stabilization, e.g., of the SPOPO cavity length, the variation in average output power over several hours was measured to be <4%.

Temperature tuning of the PPLN crystal (from ~80 to 160 °C) for each grating period provided broadly tunable signal output over the 1.55–1.94-μm wavelength range. The tuning behavior was in agreement with predictions of the temperature-dependent Sellmeier equation.[11] The corresponding idler tuning range was 2.32–3.31 μm, although direct measurements of the idler wavelength and power were not made. From the observation of pump depletion (approximately 60%) and the Manley–Rowe relation, one can deduce that several tens of milliwatts of idler power are generated in the crystal. This tuning range was limited only by the PPLN grating periods available on the crystal used for this study, and significant further extension is possible, particularly to much longer idler wavelengths.[12,13]

We achieved more agile wavelength tuning by changing the cavity length of the OPO. The explanation of this effect is based on the presence of group-velocity dispersion in the resonator, arising predominantly from the PPLN crystal.[10,14] In the absence of any element to select the signal wavelength deliberately, oscillation occurs at the wavelength that maximizes the net gain, this being determined by a compromise between the temporal constraint imposed by synchronism and the frequency constraint imposed by the parametric gain line. An increase in cavity length requires, for synchronism, a higher signal group velocity. In PPLN the group-velocity maximum occurs at 1.93 μm, and, for signal wavelengths shorter than this, an increase in cavity length leads to an increase in signal wavelength. We found that, at a signal wavelength of 1.7 μm, some 35 nm of continuous tuning of the signal was achieved for a cavity length change of 300 μm.

We measured the signal pulse duration using a two-photon intensity autocorrelation method and found it to be 330 fs (FWHM for an assumed Gaussian pulse shape) at a signal wavelength of 1.7 μm. A typical intensity autocorrelation and corresponding spectrum are shown in Fig. 3, with an associated time–bandwidth product ($\Delta\nu\Delta\tau_p$) of 0.76. There are several possible contributions that could be responsible for this time–bandwidth product's being greater than the transform-limited value (0.44). The mismatch between group velocities for the pump and signal (at 1.7 μm) is ~110 fs/mm and hence, with a 5-mm-long crystal, is capable of adding significantly to the signal pulse duration. Estimates of the contributions to

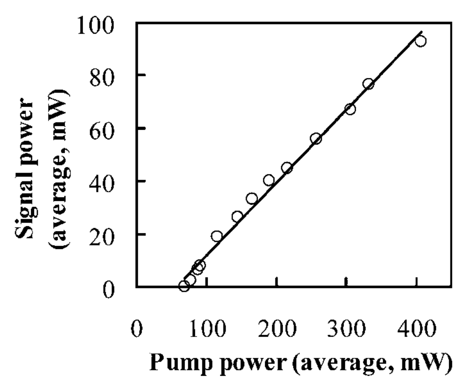

Fig. 2. Signal output power as a function of pump power. The output coupling reflectivity is 63%, the signal optical conversion efficiency is 23%, and the signal slope efficiency is 28%.

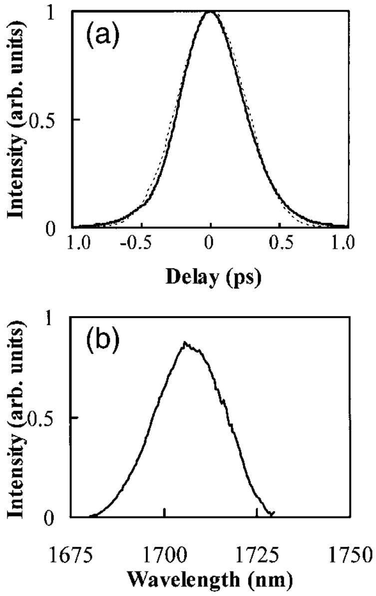

Fig. 3. (a) Two-photon intensity autocorrelation of signal output (solid curve) and Gaussian curve fit for $\Delta\tau_p = 330$ fs (FWHM) (dotted curve). (b) Associated spectrum $\lambda = 1706$ nm and $\Delta\lambda = 22$ nm (FWHM).

spectral broadening from self-phase-modulation and to temporal broadening from group-velocity dispersion suggest that these effects are small (e.g., for a 1.7-μm signal pulse of 330 fs, the dispersion length for lithium niobate is approximately 0.6 m). These effects can accumulate significantly by virtue of many round trips,[15] but in our case the large output coupling (~37%) reduces this. A further contribution to the time–bandwidth product comes from the non-transform-limited pump pulses used in our experiments. A careful examination of factors that determine the signal time–bandwidth product, to include the use of intracavity dispersion compensating prisms, will be made using transform-limited pump pulses from an optimized fiber laser source.

In conclusion, we have demonstrated a SPOPO based on PPLN, driven by a diode-pumped, all-fiber femtosecond laser source. The performance characteristics presented here confirm the practicality of using a compact and robust fiber laser system to synchronously pump a PPLN OPO. Further optimization will be investigated, including the use of an intracavity diffraction grating to provide agile wavelength tuning. This technique, recently demonstrated in a picosecond SPOPO,[10] should be compatible with this femtosecond system because of the low threshold and associated high gain obtained. Likewise, there is scope for tuning the OPO by tuning the Yb-doped fiber MOPA within its broad gain bandwidth. Further improvement of the parabolic pulse amplification scheme could include scaling to much higher average powers (into the multiwatt region) and the generation of shorter pulses. Another potential development to exploit the combination of fiber lasers and QPM materials is the use of a mode-locked thulium-doped fiber oscillator[16] and amplifier, operating at ~1.9 μm, for synchronous pumping of a QPM gallium arsenide OPO, with prospects for tuning from 2 μm to beyond 12 μm.

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References

1. B. Bareika, G. Dikchyus, A. Piskarskas, and V. Sirutkaitis, Sov. J. Quantum Electron. **10,** 1277 (1980).
2. L. Lefort, K. Puech, S. D. Butterworth, G. W. Ross, P. G. R. Smith, D. C. Hanna, and D. H. Jundt, Opt. Commun. **152,** 55 (1998).
3. A. Robertson, M. E. Klein, M. A. Tremont, K.-J. Boller, and R. Wallenstein, Opt. Lett. **25,** 657 (2000).
4. N. J. Traynor, L. Lefort, A. B. Grudinin, J. D. Minelly, J. E. Caplen, and D. C. Hanna, in *Conference on Lasers and Electro-Optics*, Vol. 6 of OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998), paper CTuK6.
5. N. G. R. Broderick, H. L. Offerhaus, D. J. Richardson, R. A. Sammut, J. Caplen, and L. Dong, Opt. Fiber Technol. **5,** 185 (1999).
6. M. E. Fermann, V. I. Kruglov, B. C. Thomsen, J. M. Dudley, and J. D. Harvey, Phys. Rev. Lett. **84,** 6010 (2000).
7. J. H. V. Price, L. Lefort, D. J. Richardson, G. J. Spuhler, R. Paschotta, U. Keller, C. Barty, A. Fry, and J. Weston, in *Conference on Lasers and Electro-Optics*, Vol. 56 of OSA Trends in Optics and Photonics (Optical Society of America, Washington, D.C., 2001), paper CTuQ6.
8. A. Galvanauskas, Z. Sartania, and M. Bischoff, in *Advanced Solid State Lasers*, Vol. 50 of OSA Trends in Optics and Photonics (Optical Society of America, Washington, D.C., 2001), postdeadline paper PD3.
9. D. Findlay and R. A. Clay, Phys. Lett. **20,** 277 (1966).
10. D. C. Hanna, M. V. O'Connor, M. A. Watson, and D. P. Shepherd, J. Phys. D **34,** 2440 (2001).
11. D. H. Jundt, Opt. Lett. **22,** 1553 (1997).
12. L. Lefort, K. Puech, G. W. Ross, Y. P. Svirko, and D. C. Hanna, Appl. Phys. Lett. **73,** 1610 (1998).
13. P. Loza-Alvarez, C. T. A. Brown, D. T. Reid, and W. Sibbett, Opt. Lett. **24,** 1523 (1999).
14. M. E. Klein, A. Robertson, M. A. Tremont, R. Wallenstein, and K.-J. Boller, Appl. Phys. B **73,** 1 (2001).
15. J. M. Dudley, D. T. Reid, M. Ebrahimzadeh, and W. Sibbett, Opt. Commun. **104,** 419 (1994).
16. R. C. Sharp, D. E. Spock, N. Pan, and J. Elliot, Opt. Lett. **21,** 881 (1996).