Broadly tunable femtosecond parametric oscillator using a photonic crystal fiber

Yujun Deng, Qiang Lin, Fei Lu, Govind P. Agrawal, and Wayne H. Knox

The Institute of Optics, University of Rochester, Rochester, New York 14627-0186

Received December 3, 2004

Pulses as short as 460 fs and a tuning range as wide as 200 nm around 1 μm have been achieved from a photonic-crystal-fiber-based parametric oscillator. The ring cavity with only 65 cm of photonic crystal fiber is synchronously pumped with a tunable passively mode-locked Yb-doped fiber laser. Widely extended tunability is achieved by using the modulation instability gain in normal dispersion as the result of high-order dispersion in the photonic crystal fiber. © 2005 Optical Society of America

OCIS codes: 060.2320, 320.7090.

Short-pulse optical parametric oscillators may find applications in many fields, from physics and chemistry to biology.[1] Conventionally, the $\chi^{(2)}$ nonlinearity inside a crystal is used for parametric oscillation; however, this approach requires a complicated cavity alignment for regenerative oscillation and phase matching. Recently, fiber-optic parametric oscillators (FOPOs) based on four-wave mixing (FWM) occurring inside optical fibers have attracted considerable attention.[2–4] The first synchronized pulse-pumped FOPO was reported in 1989 by Suzuki *et al.*[5]; however, significant pulse pedestals were observed.

Because of the phase matching required for efficient FWM, operating wavelengths of FOPOs are confined to the vicinity of the zero-dispersion wavelength (ZDWL) of conventional fibers[2,5] ($\geqslant$1.3 μm). Newly developed photonic crystal fibers (PCFs) exhibit flexibility in engineering fiber dispersion[6] and enhanced nonlinearity, leading to significantly higher FWM efficiencies.[7] A FOPO operated around 800 nm was recently shown.[3]

Previous FOPOs are all based on conventional modulation instability (MI) occurring in the anomalous-dispersion regime of a fiber. Although a tuning range of tens of nanometers can be obtained,[2,3] it is well known that this kind of MI is generally confined to a narrow spectral region, resulting in a limited tunable bandwidth.[8] Recently, it has been shown that widely separated MI gain can be obtained by use of higher-order dispersion in PCFs for pumping around the normal-dispersion regime.[6,9,10] A balance among the different orders of fiber dispersion helps to create a MI gain spectrum that is far from the ZDWL. As a result MI can be dramatically extended to the visible and far-infrared regime, and it can be used to provide parametric generation in spectral regions that cannot be reached by other techniques. Conversions between largely separated wavelengths have been demonstrated in PCFs[9,10]; however, ultrashort-pulse parametric generation under these conditions has not yet been attempted.

In this Letter we show that, with this new kind of MI, clean subpicosecond pulses can be obtained over a 200-nm-wide spectral region around 1 μm from a FOPO made of a PCF with proper dispersion and an optimal cavity design. To the best of our knowledge, this is the first clear demonstration of such a broadly tunable short-pulse FOPO in this wavelength regime.

The experimental setup is shown in Fig. 1. The ring oscillator cavity consists of 65 cm of PCF (SC-5.0-1040, Blaze Photonics, Inc.). The FOPO is pumped through a long-pass dichroic filter that has a cutoff wavelength at 1040 nm. The pump light is launched in *s* polarization (vertical). The first achromatic half-wave plate P1 is adjusted so that the pump polarization overlaps the principal axis of the PCF. An extinction ratio greater than 1:1000 is maintained between orthogonal linear polarizations for the pump light after it passes the PCF, indicating that the fiber is linearly birefringent. The polarizing beam splitter cube combined with a diffraction grating (300 lines/mm) in the Littrow configuration is used as a tunable bandpass filter with an ~2-nm bandwidth.[3] It also ensures that the signal wave polarized in *s* (vertical) polarization overlaps the pump wave for maximum parametric gain. The output coupler is a broadband-coated window (BK7) with ~15% reflectivity. All the mirrors in the cavity are ER.2-protected silver-coated mirrors (Newport, Inc.). A newly developed passively mode-locked Yb-doped fiber laser[11] with two stages of Yb:fiber amplifiers is used as a pumping source. It is operated in the soliton mode-locked region, producing subpicosecond pulses at 36.6 MHz with a 5-nm bandwidth (FWHM). The center wavelength of pulses can be tuned from 1020 to 1038 nm. The bandwidth of pump pulses is filtered down to ~1.5 nm (FWHM) with a tunable fil-

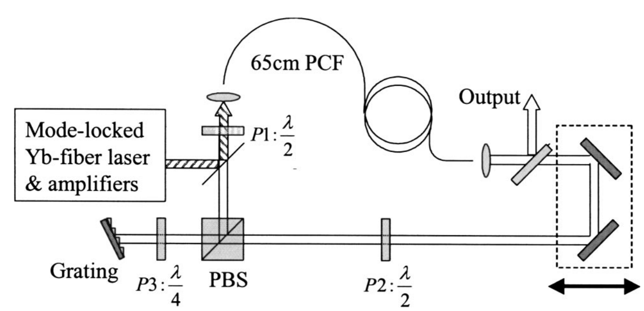

Fig. 1. Experimental configuration: PBS, polarizing beam splitter; P1, P2, P3, achromatic wave plates.

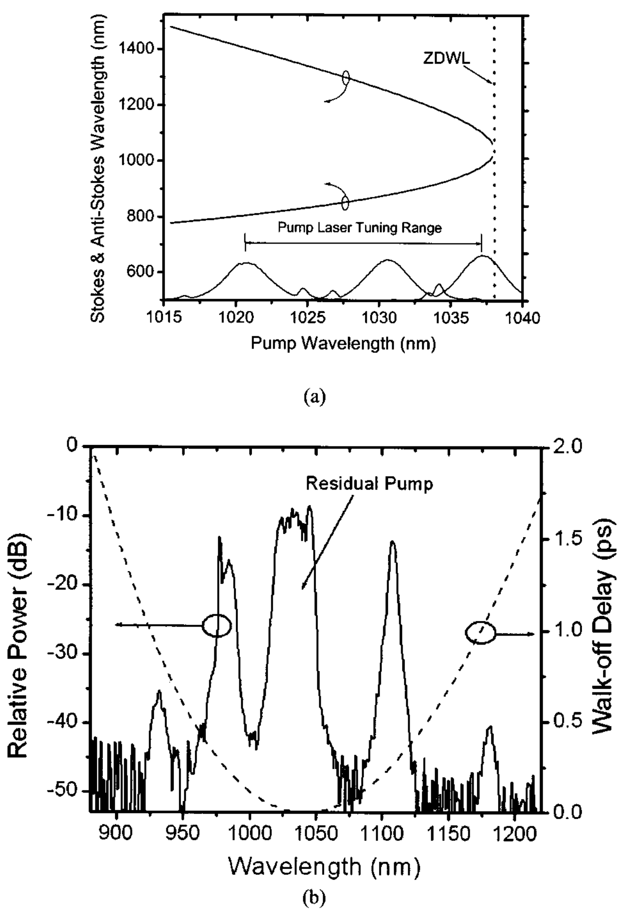

Fig. 2. (a) Phase-matching curve and pump laser tuning range. Dotted line, ZDWL of the PCF. (b) Walk-off delay for the PCF, when the wavelength is detuned from the ZDWL ($\lambda_0 \approx 1038$ nm), and a typical output spectrum from the FOPO. (The spike at 977 nm is the residual diode pump light of the Yb-fiber amplifier.)

ter before being sent to two fiber amplifiers. After the amplifiers, the pulse width is 1.3 ps with up to 260 mW of average power. The total cavity length of the FOPO is precisely adjusted to match the length of the pumping laser cavity for synchronous pumping.

The PCF has a mode field diameter of 3.2 μm, corresponding to a nonlinear coefficient γ of $\sim 22.7\ \mathrm{W}^{-1}/\mathrm{km}$. The detailed loss and dispersion properties of this fiber are shown in Ref. 12. The loss of 65-cm fiber in the wavelength range of 970–1230 nm is estimated to be less than 0.0016 dB, which is negligible compared with an ~2-dB coupling loss at the entrance of the fiber. The dispersion coefficients at the ZDWL (1038 nm) are estimated to be $\beta_3 = 0.06541\ \mathrm{ps}^3/\mathrm{km}$, $\beta_4 = -1.0382 \times 10^{-4}\ \mathrm{ps}^4/\mathrm{km}$, $\beta_5 = 3.3756 \times 10^{-7}\ \mathrm{ps}^5/\mathrm{km}$, and $\beta_6 = -1.1407 \times 10^{-10}\ \mathrm{ps}^6/\mathrm{km}$.

Taking into account higher-order dispersion, the phase-matching condition between the Stokes or anti-Stokes wave and the pump wave is given by

$$\Delta k = \beta_2 \Omega^2 + \beta_4 \Omega^4/12 + \beta_6 \Omega^6/360 + 2\gamma P_p = 0, \quad (1)$$

where P_p is the pump power and $\Omega = \omega_a - \omega_p = \omega_p - \omega_s$ is the frequency difference between the anti-Stokes and the pump wave or between the pump and the Stokes wave.

As is shown in Eq. (1), with balance between the even-order dispersion, phase matching can be realized far from the pump wavelength by pumping in the normal dispersion regime,[6,10] and, with such a steep phase-matching curve, a widely tuning parametric gain results from a small change in pump wavelength. As is shown in Fig. 2(a), for pumping in the normal dispersion regime, outputs between 800 and 1400 nm could be covered with only a 20-nm pump tuning. A short piece of PCF (65 cm) is used as the gain medium to minimize the walk-off delay between the pump and the signal pulses, thus permitting generation of short pulses. Figure 2(b) shows the walk-off delay for the 65-cm-long PCF as the wavelength is detuned from the ZDWL. Furthermore, a broader gain bandwidth in the parametric amplification can be achieved, as a shorter fiber length decreases the gain-narrowing effect.

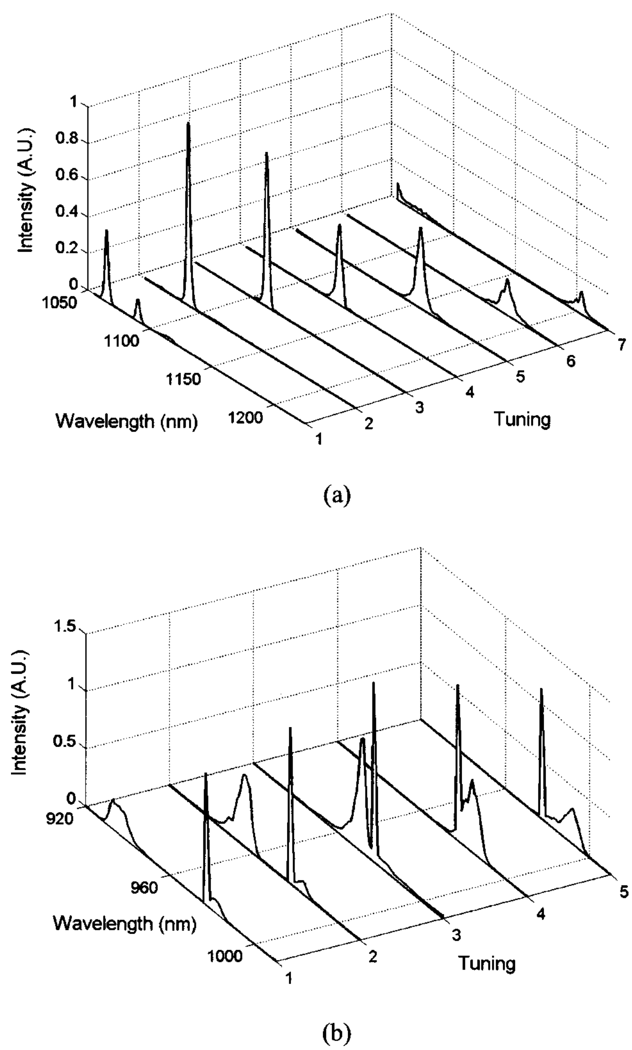

Fig. 3. (a) Signal wavelength tuning on the longer wavelength side of the pump. The smaller peak at ~1090 nm in the first trace is a cascaded FWM component. (b) Idler wavelength tuning on the shorter wavelength side of the pump. The component near 977 nm is the residual diode pump light leaking through the FOPO.

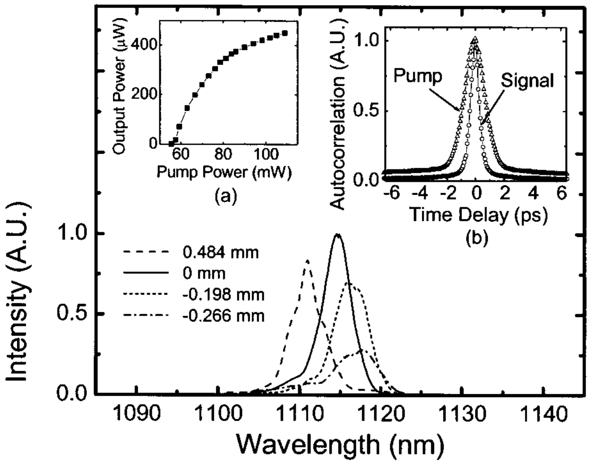

Fig. 4. Changes in the signal pulse spectrum as the FOPO cavity length is detuned. Insets: (a) output power of the Stokes component near 1110 nm from FOPO as the function of average pump power; (b) autocorrelation traces of the pump pulses (wider curve) and the output signal pulses from FOPO.

Figure 2(b) shows a typical spectrum from the output coupler of the FOPO. In this case the diffraction grating is tuned to reflect only the 1110-nm component back to the cavity for seeding the Stokes wave. The power of the anti-Stokes component at 985 nm generated with single-pass parametric gain is ~3 dB less than its Stokes counterpart. The center component (~1040 nm) is the residual pump, with dips in the middle of the spectrum as the result of stronger pump depletion. Two cascaded FWM components are also generated at 932 and 1180 nm.

By turning the intracavity grating and rematching the cavity length, as shown in Fig. 3, the signal wavelength can be tuned over 140 nm on the longer wavelength side (1060–1200 nm), while the idler covers ~60 nm on the shorter wavelength side (930–990 nm). The total tuning range is greater than 200 nm. Further tuning is limited by walk-off between the pump and the signal. When the signal wavelength passes 1200 nm, the walk-off delay becomes >1.4 ps [Fig. 2(b)], which is comparable with the pump pulse width. This decreases the interaction length between the pump and the signal and thus limits the gain beyond 1200 nm.

It is worth noting that, when operating close to ZDWL, the walk-off delay is largely contributed from β_3, the slope of the dispersion curve, while the phase-matching curve relies on the even-order dispersion. This may allow one to design a special PCF that offers ultrabroad tunability for short-pulse parametric amplification.

The typical characteristics of the Stokes component are shown in Fig. 4. The rolloff of the output power is likely caused by the spectral broadening of the pump as its power increases, since pump depletion is much stronger in part of its spectrum, as shown in Fig. 2(b). Autocorrelation measurement indicates that the pulse width is 460 fs, assuming a sech^2 pulse shape. The wider autocorrelation trace is from the pumping pulse with a 1.3-ps pulse width. The spectrum of the pulse has an ~4-nm FWHM bandwidth. The time–bandwidth product of the pulse is ~0.44. The chirp of the pulse is likely induced by the cross-phase modulation from the pump pulse. One indication is the asymmetry in the pulse spectrum. As the cavity length of the FOPO is detuned, the signal central wavelength can be tuned over a 7-nm range because of the time dispersion tuning.[13] As is shown in Fig. 4, typical cross-phase-modulation-induced spectra are observed.[13,14] The spectrum with positive detuning has a relatively symmetric structure, which indicates that the signal pulse walks across the central part of the pump pulse. The negative detuning leads to more asymmetric spectra, which are likely caused by the cross-phase modulation on the signal pulse from the leading edge of the faster-moving pump pulse.[8,14]

The authors gratefully acknowledge the support from the New York State Office of Science, Technology, and Academic Research.

References

1. M. H. Dunn and M. Ebrahimzadeh, Science **286**, 1513 (1999).
2. D. K. Serkland and P. Kumar, Opt. Lett. **24**, 92 (1999).
3. J. E. Sharping, M. Fiorentino, P. Kumar, and R. S. Windeler, Opt. Lett. **27**, 1675 (2002).
4. C. J. S. de Matos, J. R. Taylor, and K. P. Hansen, Opt. Lett. **29**, 983 (2004).
5. K. Suzuki, M. Nakazawa, and H. A. Haus, Opt. Lett. **14**, 320 (1989).
6. W. H. Reeves, D. V. Skryabin, F. Biancalana, J. C. Knight, P. St. J. Russell, F. Ominetto, A. Efimov, and A. J. Taylor, Nature **424**, 511 (2003).
7. J. E. Sharping, M. Fiorentino, A. Coker, P. Kumar, and R. S. Windeler, Opt. Lett. **26**, 1048 (2001).
8. G. P. Agrawal, *Nonlinear Fiber Optics*, Optics and Photonics Series (Academic, San Diego, Calif., 2001).
9. W. J. Wadsworth, N. Joly, J. C. Knight, T. A. Birks, F. Biancalana, and P. St. J. Russell, Opt. Express **12**, 299 (2004), http://www.opticsexpress.org.
10. J. D. Harvey, R. Leonhardt, S. Coen, G. K. L. Wong, J. C. Knight, W. J. Wadsworth, and P. St. J. Russell, Opt. Lett. **28**, 2225 (2003).
11. Y. Deng and W. H. Knox, Opt. Lett. **29**, 2121 (2004).
12. http://www.thorlabs.com/ProductDetail.cfm?DID =6&ObjectGroup_ID=1002&Product_ID=34974.
13. M. N. Islam, L. F. Mollenauer, R. H. Stolen, J. R. Simpson, and H. T. Shang, Opt. Lett. **12**, 625 (1987).
14. G. P. Agrawal, P. L. Baldeck, and R. R. Alfano, Phys. Rev. A **40**, 5063 (1989).