1.2- to 2.2-μm Tunable Raman Soliton Source Based on a Cr : Forsterite Laser and a Photonic-Crystal Fiber

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***Abstract*—A 1.2- to 2.2-μm tunable femtosecond light source based on the soliton-self-frequency-shift effect of high-power Cr : forsterite laser pulses propagating inside a highly nonlinear photonic crystal fiber is reported. The demonstrated soliton self-frequency shift is higher than 42% of the pump laser frequency, corresponding to a record 910-nm wavelength tuning range. Due to the advantages of simplicity, easy tunability, high-temperature stablility, and low cost of this new femtosecond light source, it accordingly, could be widely applicable for many applications.**

***Index Terms*—Nonlinear optics, ultrafast optics, lasers tuning, optical solitons.**

WIDELY wavelength-tunable femtosecond sources with ~nJ pulse energy are desirable in many applications such as optical communications, coherent anti-Stokes Raman (CARS) microscopy [1], carrier heating research in quantum wells [2], multiphoton multiharmonic laser-scanning microscopy [3], and the study of time-resolved ultrafast molecular dynamics [4], etc. Conventional frequency-tunable sources utilize the optical parametric generation (OPG) effect inside nonlinear crystals to convert a high-energy photon into two or more low-energy photons. By changing the phase-matching condition inside the nonlinear crystal, the wavelength of the converted low-energy photons can be tuned. However, the threshold pumping power is on the order of watts so that an external amplifier is usually needed. Moreover, the phase-matching condition is so critical that the entire system is very sensitive to temperature and is hard to tune effectively. In addition, the cost of an OPG system is high. Therefore, a simple, easily tunable, temperature stable and less expensive frequency-tunable source is highly desired for many different applications.

In 1986, Mitschke and Mollenauer reported the first Raman-induced soliton-self-frequency-shift (SSFS)-based tunable source by seeding 1.5-μm-wavelength pulses into a 0.4-km-long conventional fiber [5]. The pulses experienced anomalous dispersion so that the blue components of the pulse propagated faster than the red components. Moreover, for subpicosecond pulses, the pulse spectral width was broad enough so that the Raman gain spectrum pumped by the blue components could cover the followed red components. Thus, through the anomalous fiber dispersion and the Raman gain, the energy of the blue components was continuously converted to that of the red components. In Mitschke and Mollenauer's work, by simply changing the coupling power into the fiber, the wavelength shift range was higher than 100 nm. However, this tunable source did not attract much attention due to the limited tunable range arising from the dispersion property of a conventional fiber.

Since the invention of photonic crystal fibers and higher order mode fibers, the SSFS range can be extended to below 1.3 μm due to the artificial dispersion characteristics achieved by engineering the fiber structure. Recently, several groups have demonstrated SSFS-based frequency-tunable sources with different excitation sources, such as Ti : sapphire lasers [6], [7], Yb-doped fiber lasers [8]–[10], optical parametric oscillators [11], Er-doped [12] and Tm-doped fiber lasers [13]. These widely tunable sources may individually be utilized for different applications, such as light detection and ranging beyond the 2-μm eye-safe regime [14], single source covering the whole optical communication band from 1.3 to 1.7 μm [15], and the excitation sources for CARS microscopy [1].

In this letter, a novel 1.2- to 2.2-μm-tunable femtosecond light source based on the soliton-self-frequency-shift effect of high-power Cr : forsterite laser pulses propagating inside a highly nonlinear photonic crystal fiber is reported. The demonstrated soliton self-frequency shift is higher than 42% of the pump laser frequency, corresponding to a record 910-nm wavelength tuning range. Due to the advantages of its simplicity, easy tunability, high-temperature stability, and low cost, this new femtosecond source should be widely applicable for many different applications.

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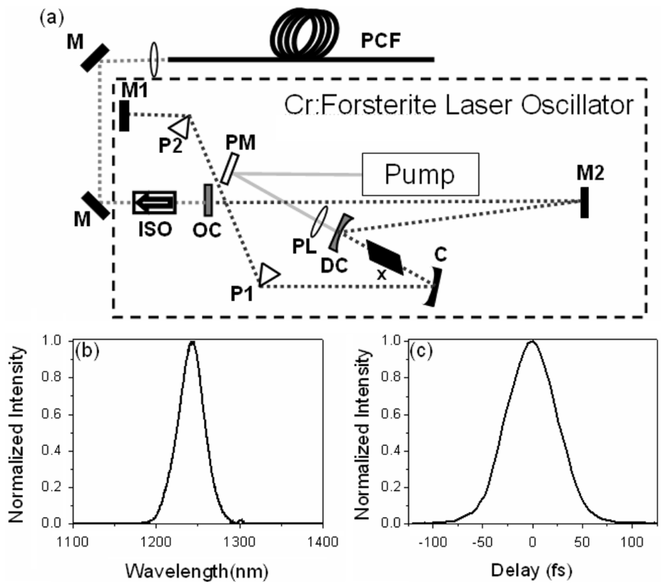

Fig. 1. (a) Schematic diagram of the tunable Raman soliton source. The Cr : forsterite laser cavity was enclosed in the dashed box. PM: pump mirror; PL: pump lens; DC: dichroic mirror; X: crystal; C: curve mirror; P1, P2: prism pair; OC: output coupler; ISO: optical isolator; M1, M2: high reflection cavity mirror; M: high reflection mirror; PCF: photonic crystal fiber. (b) Laser output spectrum and (c) the measured laser intensity autocorrelation.

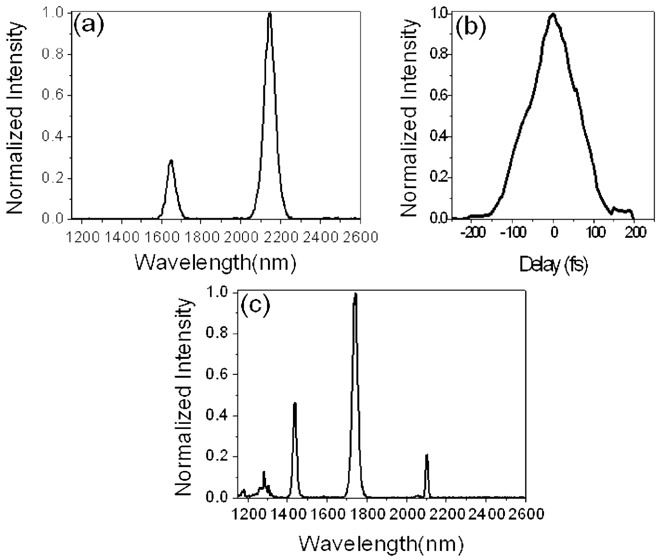

Fig. 2. (a) Fiber output spectrum and (b) corresponding autocorrelation measurement of the self-frequency-shifted solitons at 2.16 μm. The fiber length was 70 cm. (c) Another fiber output spectrum with a 3.6 m fiber length.

As shown in Fig. 1(a), this tunable source is composed with a nonlinear photonic crystal fiber and a home-made femtosecond Kerr-lens Cr : forsterite laser pumped by a Yb-doped fiber laser. Typically, with a 10-W pump power, as shown in Fig. 1(b) and (c), the Cr : forsterite laser oscillator can emit 65-fs pulses (under Gaussian-shaped waveform assumption) with a 700-mW average output power and a 35-nm full-width at half-maximum (FWHM) bandwidth with a ∼1245-nm center wavelength. The time-bandwidth product of the laser output pulse was 0.449. The laser repetition rate was 100 MHz. At laser output, an optical isolator (1230-IO-5, OFR) was inserted to suppress the back-reflection. The stability of the laser output power was typically within 5% in 1 h. The output laser pulses were delivered into a 70-cm-long nonlinear photonic crystal fiber (NL-3.5-975, Crystal-Fiber A/S) with a typically 60% coupling efficiency. The wavelength of zero group-velocity dispersion (GVD) of the fiber is 975 nm and the dispersion value at 1245 nm is around 40 ps/nm/km. With a measured mode-field diameter at 1250-nm wavelength to be ∼3.0 μm, the calculated nonlinear coefficient at 1250 nm was 18.4 $(\mathrm{W}\cdot\mathrm{km})^{-1}$ and the corresponding soliton-order was 7.

As shown in Fig. 2(a), when the average power at fiber output was up to 300 mW (including 30-mW anti-Stokes visible light and 270-mW infrared (IR) light), a clear frequency-shifted soliton with a 70-nm FWHM and a maximum carrier wavelength shift of 910 nm (or ∼102 THz in frequency) was observed. The autocorrelation-measured pulsewidth of the 2160-nm soliton was 137 fs (under hyperbolic-secant-square-shaped waveform assumption) as shown in Fig. 2(b), with a corresponding time-bandwidth product of 0.57. The relatively asymmetric shape of the autocorrelation trace is due to the low signal-to-noise ratio of the measurement system in this long wavelength regime primarily attributed to the improper second-harmonic-generation crystal coating. When the characteristics of coupled femtosecond pulses and the length of the adopted fiber were changed, the generated soliton spectrum also varied, as predicted by Gordon [16]. Fig. 2(c) shows an example output spectrum by injecting 180-fs 1245-nm pulses with a 45-nm bandwidth into a 3.6-m-long NL-3.5-975 fiber. Fig. 2(a) and (c) both reveal a wavelength upper-limit of soliton self-frequency shift around 2.1–2.2 μm, which can be attributed to the abruptly increased absorption of silica fibers [13], [17].

For further increase of the frequency tuning range beyond 2.2 μm, fluoride glass fibers or telluride glass fibers with a low mid-IR absorption loss [17] may be combined with this silica photonic crystal fiber, where the silica photonic crystal fiber will be in charge of the SSFS in the 1.5- to 1.8-μm regime and the fluoride glass fiber or the telluride glass fiber or fluoride glass fibers could take charges of the rest SSFS beyond 1.8 μm to avoid the mid-IR absorption of Silica fibers. In this work, we also quantitatively studied the behaviors of the SSFS in the 1.5- to 1.8-μm wavelength regime with a 70-cm-long NL-3.5-975 fiber for possible further SSFS applications beyond 2.2-μm.

Fig. 3(a) shows the typical power-dependent spectra of the Raman-shifted solitons at fiber exit. As the output power from the fiber was below 17 mW, a single soliton was formed. As the power increased, a single soliton pulse was observed against a background of nonsolitonic radiation. Finally, for the output power exceeding 100 mW, the excitation pulse energy was sufficient to produce two solitons. The wavelength shift was increased monotonously with the increase of the input power. The average power of the soliton could be estimated from the measured spectrum and the total output power, and can be rechecked by directly measuring the soliton power after different long-pass filters. The average measured power for the 1800-nm soliton was about 114 mW.

Typical pulsewidths for the 1520- and 1800-nm solitons [Fig. 3(b) and (c)] were measured as 70 and 110 fs, with

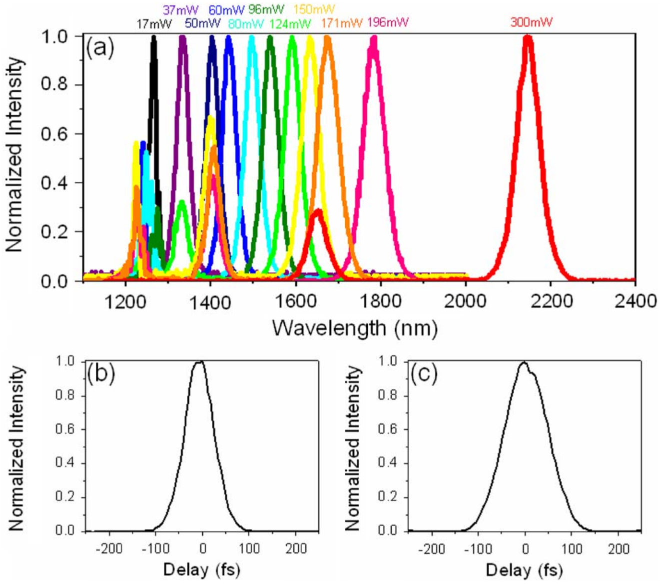

Fig. 3. (a) Various fiber output spectra. The values inserted in the figure represent the total average output power after the photonic crystal fiber. (b) Autocorrelation measurement of the self-frequency-shifted soliton at 1.52 μm. (c) Autocorrelation measurement of the self-frequency-shifted soliton at 1.80 μm.

a corresponding time-bandwidth product of 0.38 and 0.61, respectively. The fact that the solitons become progressively longer in the time domain with increased red shift could correlate with the dispersion profile of the PCF. Indeed, light pulses sense a higher local GVD as they are shifted toward longer wavelength, which dictates a longer local soliton pulsewidth [18], [19]. For wavelengths exceeding 2 μm, on the other hand, the increased fiber loss may also be partially responsible [19], [20] for the lengthening of red-shifted solitons. It is worth mentioning that in this work, the wavelength was tuned by adjusting the coupling power inside fibers. Adjusting the pulsewidth of incident light and the length of fiber are alternative ways.

In conclusion, based on a Cr : forsterite laser and a photonic crystal fiber, we have demonstrated a widely tunable Raman soliton source and in general 65- to 137-fs output pulsewidth. The wavelength tuning range was from 1245 to 2160 nm, which reached the long-wavelength-tuning-limit arising from the sharp increase of material absorption in silica fiber over 2.15 μm [13], [15]. To our best knowledge, the 910-nm wavelength-tuning range is higher than those of previous reports. The output spectrum of this widely tunable source covers not only the eye-safe regime beyond 2 μm, but also the whole optical communication band from 1.3 to 1.7 μm. This low-cost, easily tunable, temperature stable wavelength-tunable source without any external amplifier should have a great potential for many applications.

REFERENCES

[1] A. Zumbusch, G. R. Holtom, and X. S. Xie, “Three-Dimensional vibrational imaging by coherent anti-stokes raman scattering,” *Phys. Rev. Lett.*, vol. 82, no. 20, pp. 4142–4145, May 17, 1999.

[2] C. K. Sun, H. K. Choi, C. A. Wang, and J. G. Fujimoto, “Studies of carrier heating in InGaAs/AlGaAs strained-layer quantum-well diode-lasers using a multiple wavelength pump probe technique,” *Appl. Phys. Lett.*, vol. 62, pp. 747–749, Feb. 1993.

[3] G. McConnell and E. Riis, “Photonic crystal fibre enables short-wavelength two-photon laser scanning fluorescence microscopy with fura-2,” *Phys. Med. Biolog.*, vol. 49, pp. 4757–4763, Oct. 2004.

[4] A. A. Ivanov, M. V. Alfimov, and A. M. Zheltikov, “Wavelength-tunable ultrashort-pulse output of a photonic-crystal fiber designed to resolve ultrafast molecular dynamics,” *Opt. Lett.*, vol. 31, pp. 3330–3332, Nov. 2006.

[5] F. M. Mitschke and L. F. Mollenauer, Opt. Lett. “Discovery of the soliton self-frequency shift,” Oct. 1986, vol. 11, no. 10, pp. 659–661.

[6] I. G. Cormack, D. T. Reid, W. J. Wadsworth, J. C. Knight, and P. S. J. Russell, “Observation of soliton self-frequency shift in photonic crystal fibre,” *Electron. Lett.*, vol. 38, no. 4, pp. 167–169, Feb. 2002.

[7] E. E. Serebryannikov, A. M. Zheltikov, N. Ishii, C. Y. Teisset, S. Kohler, T. Fuji, T. Metzger, F. Krausz, and A. Baltuska, “Soliton self-frequency shift of 6-fs pulses in photonic-crystal fibers,” *Appl. Phys. B*, vol. 81, pp. 585–588, Sep. 2005.

[8] H. Lim, F. O. Ilday, J. Buckley, A. Chong, and F. W. Wise, “Fibre-based source of femtosecond pulses tunable from 1.0 to 1.3 microns,” *Electron. Lett.*, vol. 42, pp. 1523–1525, Aug. 2006.

[9] J. Takayanagi, T. Sugiura, M. Yoshida, and N. Nishizawa, “1.0–1.7-μ m wavelength-tunable ultrashort-pulse generation using femtosecond Yb-doped fiber laser and photonic crystal fiber,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 21, pp. 2284–2286, Nov. 1, 2006.

[10] J. van Howe, J. H. Lee, S. Zhou, F. Wise, C. Xu, S. Ramachandran, S. Ghalmi, and M. F. Yan, “Demonstration of soliton self-frequency shift below 1300 nm in higher-order mode, solid silica-based fiber,” *Opt. Lett.*, vol. 32, pp. 340–342, Feb. 2007.

[11] X. Liu, C. Xu, W. H. Knox, J. K. Chandalia, B. J. Eggleton, S. G. Kosinski, and R. S. Windeler, “Soliton self-frequency shift in a short tapered air-silica microstructure fiber,” *Opt. Lett.*, vol. 26, pp. 358–360, Mar. 2001.

[12] N. Nishizawa and T. Goto, “Widely wavelength-tunable ultrashort pulse generation using polarization maintaining optical fibers,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 4, pp. 518–524, Jul. 2001.

[13] S. Kivisto, T. Hakulinen, M. Guina, and O. G. Okhotnikov, “Tunable Raman soliton source using mode-locked Tm–Ho fiber laser,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 12, pp. 934–936, Jun. 15, 2007.

[14] S. W. Henderson, C. P. Hale, J. R. Magee, M. J. Kavaya, and A. V. Huffaker, “Eye-safe coherent laser-radar system at 2.1 μm using Tm,Ho-YAG lasers,” *Opt. Lett.*, vol. 16, pp. 773–775, May 1991.

[15] J. S. Harris, “Tunable long-wavelength vertical-cavity lasers: The engine of next generation optical networks?,” *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 1145–1160, Nov. 2000.

[16] J. P. Gordon, “Theory of the soliton self-frequency shift,” *Opt. Lett.*, vol. 11, no. 10, pp. 662–664, Oct. 1986.

[17] T. Miyashita and T. Manabe, “Infrared optical fibers,” *IEEE J. Quantum Electron.*, vol. QE-18, no. 10, pp. 1432–1450, Oct. 1982.

[18] G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd ed. San Diego, CA: Academic, 2001.

[19] A. M. Zheltikov, “Perturbative analytical treatment of adiabatically moderated soliton self-frequency shift,” *Phys. Rev. E*, vol. 75, no. 037603, Mar. 2007.

[20] J. K. Lucek and K. J. Blow, “Soliton self-frequency shift in telecommunications fiber,” *Phys. Rev. A*, vol. 45, no. 9, pp. 6666–6674, May. 1, 1992.