Environmentally Stable Mode-Locked Fiber Laser With Dispersion Compensation by Index-Guided Photonic Crystal Fiber

Robert Herda, Samuli Kivistö, Oleg G. Okhotnikov, Aleksey F. Kosolapov, Andrei E. Levchenko, Sergei L. Semjonov, and Evgueni M. Dianov

***Abstract*—We exploit the anomalous dispersion generated by an index-guided photonic crystal fiber (PCF) for dispersion compensation in an ytterbium fiber laser passively mode-locked with a semiconductor saturable absorber. A PCF, reasonably compatible with standard fiber, and a Faraday rotator in the cavity allow for robust all-fiber subpicosecond operation at 1 μm, insensitive to environmental disturbance.**

***Index Terms*—Dispersion compensation, Faraday rotator, fiber lasers, mode-locked lasers, photonic crystal fibers.**

I. Introduction

PRACTICAL femtosecond fiber lasers require all-fiber low-loss means for group-velocity dispersion compensation. Among the different types of photonic crystal fibers (PCFs), photonic bandgap (PBG) fibers, both hollow-core and solid-core, can generate a large amount of anomalous dispersion and may have large mode size [1], [2]. Hollow-core PBG fibers with air holes in a glass cladding allow propagation with much smaller nonlinearity and larger damage threshold compared with normal fibers. An all-silica solid-core PBG fiber is typically made of a silica core and an array of higher index Ge-doped strands in the cladding. It has the advantage of good mode matching with standard fibers and is attractive as a low-loss intracavity dispersion compensator for femtosecond fiber lasers [2], [3]. In addition, the solid-core structure exhibits no surface modes, allowing for high anomalous dispersion with low nonlinearity compared with index-guiding PCFs, and can have a core doped with rare-earth ions. Studies have shown, however, that PBG fibers exhibit a large amount of high-order dispersion that has a notable effect on the pulse formation [4]. Another constraint expected with PBG fibers is that the presence of a bandgap structure would eventually limit the shortest pulsewidths achievable with such fibers. With these arguments in mind, an index-guided PCF may provide a competitive alternative to PBG fiber because of the absence of bandgap restrictions and because of low higher order dispersion which is as low as in ordinary fibers.

In this letter, an index-guided PCF to be used for dispersion compensation in a mode-locked fiber laser was developed that generates a sufficient amount of anomalous dispersion around 1 μm with mode-size and nonlinearity close to that of ordinary fiber. An environmentally stable femtosecond fiber laser is demonstrated using a Faraday rotator mirror for compensation of the high birefringence typical for PCF [5], [6]. In contrast to [5], double pulsing is avoided due to the compensation of the birefringence; however, the birefringence of the PCF in combination with the Faraday rotator controls the polarization. The laser incorporates a semiconductor saturable absorber mirror (SESAM), exhibits robust self-starting single-pulse operation, and could be of interest as a practical oscillator with moderate output powers. This approach should allow for a commercially packaged femtosecond laser system without the need for polarization control.

II. Photonic Crystal Fiber

The preform from which the PCF was drawn was fabricated by mechanical drilling. An F-300 glass rod (Heraus) with a diameter of 22 mm and a height of 100 mm was mechanically drilled with a tube instrument with a diamond crown. Note that the fabrication of microstructured preforms by mechanical drilling offers a number of advantages compared to the "stack and draw technique" and extrusion method. In particular, almost all kinds of glasses, except strongly strained, can be drilled. A complicated hole geometry can be produced simply by using mechanical drilling, and in addition this method also substantially reduces the number of technological operations. The drilled preform was etched, resized, and jacked. Thermal processing was performed in the flame of an oxygen–hydrogen burner. This results in the polishing of the internal surface of the holes. During drawing and jacketing, a noble gas at excess pressure was introduced into the internal holes to compensate for surface tension forces tending to collapse the holes.

The cross section and the measured group-velocity dispersion of the PCF are shown in Fig. 1. As can be seen, the air filling factors are different in the first and second ring of holes. The air filling factor for the first ring of holes is $k_1 = d/\Delta = 0.75$, and for the second ring of holes $k_2 = 0.79$. The core diameter of the fiber is 2.9 μm and the measured zero dispersion wavelength is

Manuscript received June 3, 2007; revised September 24, 2007. This work was supported by the EU-FP6 URANUS Project, by the Graduate School of Tampere University of Technology, by the Finnish Foundation for Economic and Technology Sciences, by the Jenny and Antti Wihuri Foundation, and by the Nokia Foundation.

R. Herda, S. Kivistö, and O. G. Okhotnikov are with the Optoelectronics Research Centre, Tampere University of Technology, FIN-333101 Tampere, Finland (e-mail: robert.herda@tut.fi).

A. F. Kosolapov, A. E. Levchenko, S. L. Semjonov, and E. M. Dianov are with the Fiber Optics Research Center, Moscow 119333, Russia.

Digital Object Identifier 10.1109/LPT.2007.913236

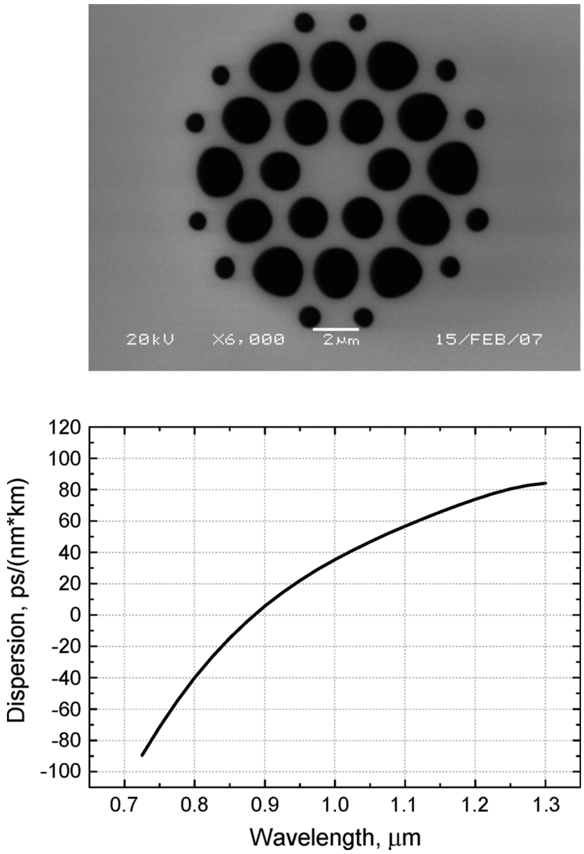

Fig. 1. Actual fiber cross section and measured group-velocity dispersion.

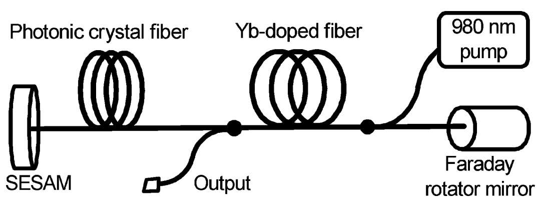

Fig. 2. Schematic of the mode-locked laser cavity.

874 nm. The loss at 1060 nm is 7 dB/km. The calculated effective mode area A_{eff} is 4.86 μm^2, and the calculated nonlinear coefficient γ is 26 $\text{W}^{-1} \cdot \text{km}^{-1}$.

III. Mode-Locking Experiments

The fiber laser used in this experiment is shown in Fig. 2. The active material is an 80-cm-long ytterbium-doped fiber pumped by a 300-mW diode laser. The light is coupled out via a 25% tap coupler. The length of passive HI-1060 fiber in the cavity is 120 cm.

The birefringence of the cavity is compensated for by a Faraday rotator mirror acting as a cavity end reflector. Another cavity mirror, the high modulation depth SESAM, is capable of starting passive mode-locking both with and without the dispersion compensation by the PCF [7], [8]. The resonant absorber mirror used in this study is similar to the absorber described in [8]. The In–GaAs–GaAs quantum-well absorber has a modulation depth of 10% and a saturation fluence of 7 $\mu\text{J/cm}^2$.

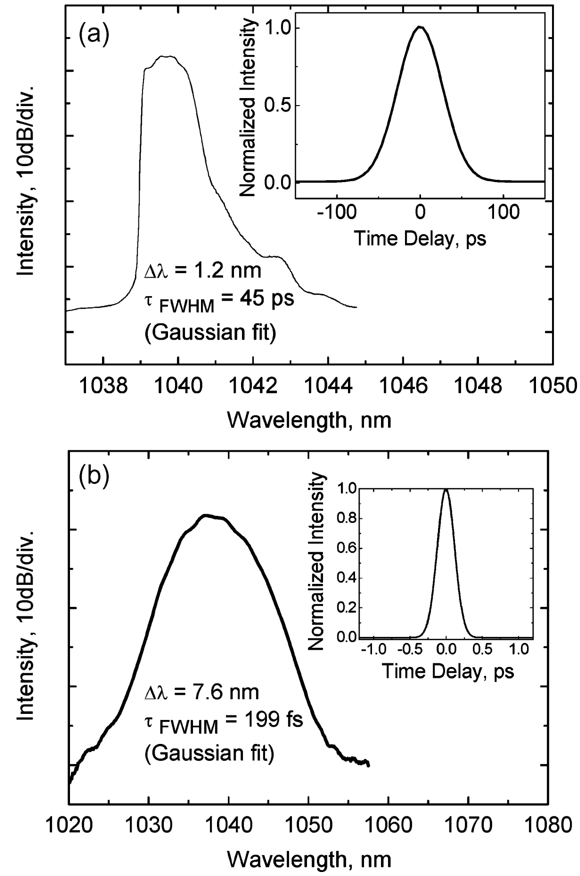

Fig. 3. Optical spectrum and intensity autocorrelation (inset) of the mode-locked pulse (a) without PCF and (b) with PCF.

Fig. 3(a) shows the spectrum and the autocorrelation of the mode-locked laser without dispersion compensation at a pulse energy of 500 pJ. A pulse duration of 45 ps was derived from measurements assuming Gaussian pulse shape corresponding to a time bandwidth product of 16.

The PCF was spliced to single-mode fiber using a standard fusion splicer. Reflections from the PCF to silica fiber interface and losses due to the mode field mismatch were minimized using repeated arc discharges. This allows for smooth collapse of the air holes and causes an adiabatic mode field transformation in the PCF which results in optimized mode matching [9]. Ripples in the spectrum, caused likely by reflections, are smaller than 0.2 dB. The splice loss was measured to be 1.5 dB.

Splicing the PCF of 3.5-m length with a total dispersion of 0.09 ps^2 resulted in a net cavity dispersion of -0.04 ps^2 assuming a dispersion of 25 ps^2/km for the ytterbium and the HI 1060 fiber. Fig. 3(b) shows the optical spectrum and autocorrelation of the mode-locked laser.

The PCF dispersion compensation results in soliton operation with transform-limited pulses. The pulse duration of 199 fs was derived using a Gaussian fit resulting in a time-bandwidth product of 0.42. The pulse energy was 460 pJ at a fundamental repetition rate of 18 MHz. It is important to note from Fig. 3 that the optimized compensator using PCF with reduced nonlinearity does not display noticeable Raman scattering. Another remarkable feature of the laser performance is the obvious tendency to operation with a single pulse in the cavity. There was no evidence of multiple pulse mode-locking at the available pumping power.

Without the use of the Faraday rotator, the pulse operation start-up and mode-locking performance were very sensitive to changes in the polarization state. A polarization controller was then essentially needed to optimize the pulse duration and quality. Due to environmental changes, the polarization controller has to be frequently realigned to maintain operation state.

In contrast, with the Faraday rotator, self-starting and steady-state operation was independent of the fiber bending up to a few centimeters bending radius. Stable mode-locking was observed for several hours without the need for any readjustment and there was no need for readjustment when restarting the laser after a few days.

IV. Conclusion

We have demonstrated an environmentally stable femtosecond ytterbium laser using index-guided PCF for dispersion compensation at 1 μm. The self-starting mode-locked operation of the subpicosecond soliton laser is achieved by the use of a semiconductor saturable absorber. This approach may constitute an important step towards highly practical ultrafast fiber oscillators. Further experiments to increase the pulse energy are in progress.

References

[1] H. Lim, A. Chong, and F. W. Wise, "Environmentally-stable femtosecond ytterbium fiber laser with birefringent photonic bandgap fiber," *Opt. Express*, vol. 13, no. 9, pp. 3460–3464, May 2005 [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?URI=oe-13-9-3460

[2] A. Isomäki and O. G. Okhotnikov, "All-fiber ytterbium soliton mode-locked laser with dispersion control by solid-core photonic bandgap fiber," *Opt. Express*, vol. 14, no. 10, pp. 4368–4373, 2006.

[3] A. Isomäki and O. G. Okhotnikov, "Femtosecond soliton mode-locked laser based on ytterbium-doped photonic bandgap fiber," *Opt. Express*, vol. 14, pp. 9238–9243, 2006.

[4] R. Herda, A. Isomäki, and O. G. Okhotnikov, "Soliton sidebands in photonic bandgap fibre lasers," *Electron. Lett.*, vol. 42, no. 18, pp. 19–20, 2006.

[5] H. Lim, F. Ilday, and F. Wise, "Femtosecond ytterbium fiber laser with photonic crystal fiber for dispersion control," *Opt. Express*, vol. 10, pp. 1497–1502, 2002 [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?URI=oe-10-25-1497

[6] A. Peyrilloux, T. Chartier, A. Hideur, L. Berthelot, G. Mélin, S. Lempereur, D. Pagnoux, and P. Roy, "Theoretical and experimental study of the birefringence of a photonic crystal fiber," *J. Lightw. Technol.*, vol. 21, no. 2, pp. 536–539, Feb. 2003.

[7] R. Herda and O. G. Okhotnikov, "Effect of amplified spontaneous emission and absorber mirror recovery time on the dynamics of mode-locked fiber lasers," *Appl. Phys. Lett.*, vol. 86, no. 1, p. 011113, 2005.

[8] R. Herda and O. G. Okhotnikov, "Dispersion compensation-free fiber laser mode-locked and stabilized by high-contrast saturable absorber mirror," *IEEE J. Quantum Electron.*, vol. 40, no. 7, pp. 893–899, Jul. 2004.

[9] L. Xiao, W. Jin, and M. S. Demokan, "Fusion splicing small-core photonic crystal fibers and single-mode fibers by repeated arc discharges," *Opt. Lett.*, vol. 32, pp. 115–117, 2007.