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# A 158 fs 5.3 nJ fiber-laser system at 1 $\mu$m using photonic bandgap fibers for dispersion control and pulse compression

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**Abstract:** We demonstrate a 158 fs 5.3 nJ mode-locked laser system based on a fiber oscillator, fiber amplifier and fiber compressor. Dispersion compensation in the fiber oscillator was obtained with a solid-core photonic bandgap (SC-PBG) fiber spliced to standard fibers, and external compression is obtained with a hollow-core photonic bandgap (HC-PBG) fiber.



**OCIS codes:** (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers.

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## References and links

1. F. O. Ilday, H. Lim, J. R. Buckley, and F. W. Wise, "Practical all-fiber source of high-power, 120-fs pulses at 1 mu m," Opt. Lett. **28**, 1362-1364 (2003).
2. T. Schreiber, C. K. Nielsen, B. Orta, J. Limpert, and A. Tünnermann, "$\mu$J-Level all-polarization-maintaining femtosecond fiber source," Opt. Lett. **31**, 574-576 (2006).
3. C. K. Nielsen, B. Ortaç, T. Schreiber, J. Limpert, R. Hohmuth, W. Richter, and A. Tünnermann, "Self-starting self-similar all-polarization maintaining Yb-doped fiber laser," Opt. Express **13**, 9346-9351 (2005).
4. M. Hofer, M. H. Ober, R. Hofer, M. E. Fermann, G. Sucha, D. Harter, K. Sugden, I. Bennion, C. A. C. Mendonca, and T. H. Chiu, "High-power neodymium soliton fiber laser that uses a chirped fiber grating", Opt. Lett. **20**, 1701-1703 (1995).
5. I. Hartl, G. Imeshev, L. Dong, G. C. Cho and M. E. Fermann, "Ultra-compact dispersion compensated femtosecond fiber oscillators and amplifiers," CLEO, Baltimore, paper CThG1, May 2005.
6. J. C. Knight, J. Broeng, T. A. Birks, and P. St. J. Russell, "Photonic Band Gap Guidance in Optical Fibers," Science **282**, 1476-1478 (1998).
7. A. Argyros, T. A. Birks, S. G. Leon-Saval, C. M. B. Cordeiro, F. Luan, P. St. J. Russel, "Photonic bandgap with an index step of one percent," Opt. Express **13**, 309-313 (2005).
8. G. Bouwmans, L. Bigot, Y. Quiquempois, F. Lopez, L. Provino, and M. Douay, "Fabrication and characterization of an all-solid 2D photonic bandgap fiber with a low-loss region (¡ 20 dB/km) around 1550 nm)," Opt. Express **13**, 8452-8459 (2005).
9. H. Lim, F. O. Ilday, and F. W. Wise, "Femtosecond ytterbium fiber laser with photonic crystal fiber for dispersion control," Opt. Express **10**, 1497-1502 (2002).
10. H. Lim and F. W. Wise, "Control of dispersion in a femtosecond ytterbium laser by use of hollow-core photonic bandgap fiber," Opt. Express **12**, 2231-2235 (2004).
11. J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, and A. Tünnermann, "All fiber chirped-pulse amplification system based on compression in air-guiding photonic bandgap fiber," Opt. Express **11**, 3332-3337 (2003).
12. C. J. S. de Matos, J. R. Taylor, T. P. Hansen, K. P. Hanser, and J. Broeng, "All-fiber chirped pulse amplification using highly-dispersive air-core photonic bandgap fiber," Opt. Express **11**, 2832-2837 (2003).
13. A. Isomäki and O. G. Okhotnikov, "All-fiber ytterbium soliton mode-locked laser with dispersion control by solid-core photonic bandgap fiber," Opt. Express **14**, 4368-4373 (2006).

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14. J. Jasapara, Tsing Hua Her, R. Bise, R. Windeler, and D. J. DiGiovanni, "Group-velocity dispersion measurements in a photonic bandgap fiber," J. Opt. Soc. Am. B **20**, 1611-1614 (2003).
15. http://www.koheras.com/Menu/Products/Ultra+Wide+Band.
16. M. Guina, N. Xiang, A. Vainionpää, O. G. Okhotnikov, T. Sajavaara, and J. Keinonen, "Self-starting stretched-pulse fiber laser mode locked and stabilized with slow and fast semiconductor saturable absorbers," Opt. Lett. **26**, 1809-1811 (2001).
17. R. Herda and O. G. Okhotnikov, "Dispersion compensation-free fiber laser mode-locked and stabilized by high-contrast saturable absorber mirror," IEEE J. Q. Electr. **40**, 893-899 (2004).

## 1. Introduction

In many areas of research mode-locked lasers are an invaluable tool, and also in the industry mode-locked lasers are widespread researched (for e.g. micro-machining and marking). Traditionally solid-state mode-locked lasers have dominated the market, but the potential of making compact, rugged laser systems with low power consumption of relative low price makes amplified fiber lasers a very promising alternative.

The key properties that make rare-earth doped fibers attractive as laser gain media are the high single pass gain combined with broad gain band widths and excellent beam quality. The main reason for choosing ytterbium as the gain medium is the high quantum efficiency ($\sim 80$ %) and high doping concentrations, enabling very high single pass gains. This simplifies realizations of high efficiency fiber amplifiers. [1, 2] Therefore it is not difficult to obtain pulse energies similar to bulk mode-locked oscillators. Environmentally stable mode-locked fiber lasers based on polarization maintaining (PM) fibers has also been demonstrated recently, [3] but typically these implementations also make use of bulk components such as e.g. bulk grating compressors and hence a main advantage of fiber lasers is lost. To achieve the full potential of fiber lasers all-fiber implementations with no sections of free space has to be realized.

Standard fibers have a large normal dispersion at the lasing wavelength of ytterbium, and one of the main problems using ytterbium as gain fiber is the lack of fiber components with anomalous dispersion at this wavelength. Because of the high dispersion of standard fibers, dispersion compensating elements are necessary in fiber lasers to obtain broad spectra, which can result in short femtosecond pulses. Otherwise the spectrum narrows, and only longer pulses are possible. Dispersion compensation in fiber lasers based on chirped fiber Bragg grating has been researched since the mid-nineties, [4] and very compact all-fiber 100 fs, 4 nJ systems have been demonstrated. [5] An alternative solution is the use of photonic bandgap fibers (PBGs). As opposed to normal fibers where light is bound due to a higher refractive index of the core compared to the surrounding cladding, bound modes in PBGs are found due to a photonic bandgap in a micro structured cladding with a higher average index than the core. A guidance band is created in the core where light of certain wavelengths is not allowed to penetrate into the cladding. [6] This spectral guidance band of PBGs is usually quite narrow, and the dispersion of PBGs is strongly affected by the high loss at the edges of the guidance band. The dispersion changes from highly normal close to the short wavelength edge and to highly anomalous near the long wavelength edge, with a zero dispersion wavelength in between. Changing the dimensions of the fiber may move the position of the spectral transmission band in PBGs, and anomalous dispersion at any wavelength is in principle obtainable. Hollow-core photonic bandgap (HC-PBG) fibers have existed for some years now, [6] and quite recently solid-core photonic bandgap (SC-PBG) fibers have also been demonstrated. [7, 8] Using PBG fibers for dispersion compensation has the advantage that the anomalous dispersion of the cavity can be changed simply by changing the length of the PBG fiber. Further, PBG fibers can be manufactured in lengths, sufficient for many mode-locked lasers, and hence the use of PBG fiber potentially simplifies mass-production.

Previously mode-locked fiber lasers have been demonstrated with the use of standard photonic crystal fibers (PCFs), [9] and HC-PBG fibers. [10] HC-PBG fibers have also previously been used to realize all-fiber chirped-pulse amplifications systems. [11, 12] PCFs and HC-PBG fibers have some disadvantages when used for intra cavity dispersion compensation. The main problem with PCFs is the small core size which is necessary to achieve anomalous dispersion. As a result these fibers have a high nonlinear coefficient, which is less attractive as it limits the obtainable pulse energy. HC-PBG fibers have a very low nonlinear coefficient, and can be spliced to standard fibers with low loss, but the splice introduces a Fresnel-reflection at the interface due to the different refractive indexes of the cores. Single-pulse mode-locking cannot be obtained if the cavity contains such Fresnel-reflections, and these fibers are therefore not attractive for realizations of lasers with no sections of free space optics. In this paper we demonstrate a mode-locked laser using a solid-core photonic bandgap (SC-PBG) fiber for dispersion compensation. After the submission of this paper, result on a similar oscillator using SC-PBG fiber for dispersion compensation were published. [13] A minimum pulse duration of 460 fs was obtained, by operating the oscillator in the net anomalous (soliton) dispersion regime. In this paper we demonstrate 158 fs pulse duration from a fiber oscillator, amplifier and compressor system. The oscillator was operated in the net normal dispersion regime to explore the limits in spectral width and pulse duration set by the high total third order intra cavity dispersion. Transform limited pulses were obtained through nonlinear pulse propagation in the amplifier.

## 2. Fiber characterization

The SC-PBG and HC-PBG fibers used to realized the femtosecond laser system were manufactured at Crystal Fibre A/S. The HC-PBG fiber was manufactured from pure silica, creating a cladding with air-holes surrounding the hollow core. The SC-PBG fiber was composed of an array of Ge-doped rodes embedded in a silica matrix surrounding a silica core (see inserts in Fig. 1 (right)). The dispersion of the PBGs was measured using the low coherence interference method, [14] and a super continuum white light source. [15] The dispersion was calculated by analyzing the wavelength dependent phase difference of the two arms of the interferometer. In Fig. 1 (left) the measured dispersion can be seen. The dispersion of the SC-PBG fiber was measured to: $\beta_2 = -0.085$ ps$^2$/m, $\beta_3 = 1.7 \cdot 10^{-3}$ ps$^3$/m at 1030 nm. The dispersion of the HC-PBG fiber was measured to: $\beta_2 = -0.049$ ps$^2$/m, $\beta_3 = 3.1 \cdot 10^{-4}$ ps$^3$/m at 1030 nm, and the dispersion of the standard fiber was measured to $\beta_2 = 0.023$ ps$^2$/m, $\beta_3 = 3.9 \cdot 10^{-5}$ ps$^3$/m at 1030 nm. The third order dispersion (TOD) of the SC-PBG fiber is almost an order of magnitude larger than the TOD of the HC-PBG, and almost two orders of magnitude larger than

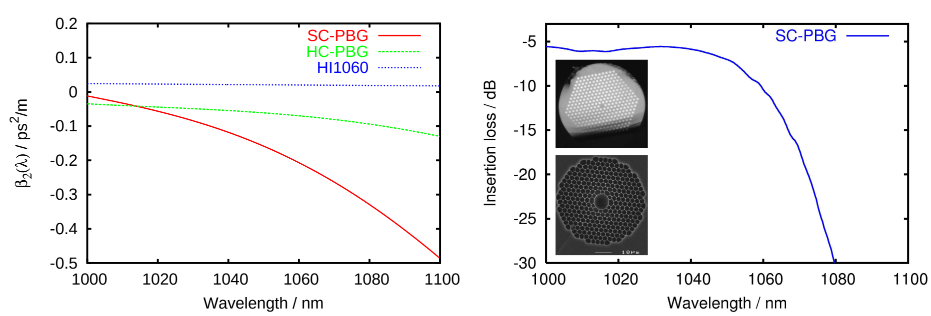


Fig. 1. Left: Dispersion of the SC-PBG, HC-PBG and standard fiber. Right: The insertion loss of the 0.36 m long SC-PBG fiber. The insertion loss is relative high compared to other components, but can be compensated by the high single pass gain of ytterbium. Insert: image of the SC-PBG fiber (top) and HC-PBG fiber (bottom).

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the TOD of the standard fiber. The large TOD of the SC-PBG is a consequence of the solid core, contributing with normal GVD. To obtain anomalous GVD at a certain wavelength, the long wavelength edge of the transmission band has to be moved closer, as the waveguide contributes with a larger anomalous GVD here. The TOD, however, is also larger here, and as a consequence the resulting TOD will be higher. The mode field diameter (MFD) of the SC-PBG fiber was 8 $\mu$m, and hence the fiber has a lower nonlinear coefficient compared to the standard fiber (MFD = 6 $\mu$m). The HC-PBG fiber was observed to be birefringent, and the group birefringence of the fiber was measured to be $\Delta n_g = 3.1 \cdot 10^{-5}$. The dispersion of both polarization axes was indistinguishable. The SC-PBG fiber was not observed to be birefringent.

## 3. Laser design

Figure 2 shows a diagram of the laser system. The cavity of the oscillator consists of a WDM, 8.5 cm of highly doped ytterbium fiber (1200 dB/m absorption  976 nm), a PM 20:80 coupler with PM fiber pigtails (output coupling: 20 %), and 0.36 m of SC-PBG fiber. The coupler also works as a polarizer, transmitting only the light in the slow axis (extinction ration: 24 dB), and thereby ensures that the output from the cavity is linear polarized. The total length of fibers in the cavity were 1.79 m. The non-PM fibers of the cavity were all kept straight in order to avoid polarization rotation. It is, however, unavoidable that a small amount of light is coupled into the fast axis of the fiber pigtails of the coupler, but this is not a problem as light coupled to the fast axis is terminated at the coupler.

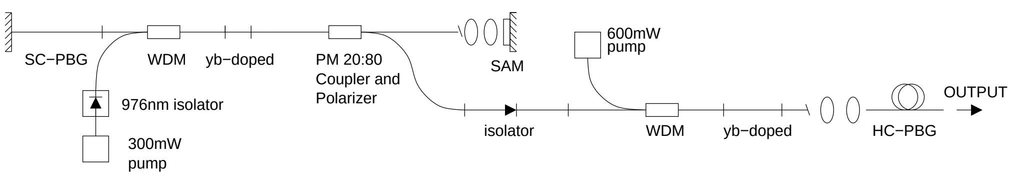


Fig. 2. Diagram of the laser system.

One end of the SC-PBG fiber was spliced to a standard fiber using a standard Ericsson Fusion splicer. The other end of the fiber was butt-coupled to a high reflecting dielectric mirror. In Fig. 1 (right) the insertion loss of the SC-PBG fiber can be seen. The long wavelength edge of the transmission band is clearly visible $> 1060$ nm. The insertion loss includes the double pass through the fiber, and the double loss at the interface between the standard fiber and the SC-PBG fiber. The high loss was found mainly to be a result of a high coupling loss when coupling light from the SC-PBG fiber into the standard fiber. In spite of the high intra cavity losses, lasing is possible due to the high single passe gain of ytterbium. A saturable absorber mirror (SESAM) with a modulation depth of 24 %, a recovery time of $< 10$ ps, a saturation fluence of $\sim 70$ $\mu$J/cm$^2$, and non-saturable losses of 16 % was used to mode-lock the laser. Two aspheric lenses was used to focus onto the SESAM, and the fiber end was cleaved at an angle of 8° in order to avoid back reflections. A 300 mW fiber pigtailed 976 nm laser diode was used to pump the oscillator. A fiber pigtailed 976 nm isolator was used to protect the pump diode.

To obtain broadest possible spectra a net GVD close to zero is needed. However, a relative large net GVD, $\sum_k 2\beta_2^k L_k \sim 0.004$ ps$^2$, was chosen in order to reduce the significance of the large total TOD, $\sum_k 2\beta_3^k L_k \sim 0.0013$ ps$^3$ on the pulse shaping. As a result of the large net GVD, the output pulses from the oscillator were prestretched with a positive chirp. Cavities with a smaller net GVD were also investigated, but did not result in broader spectra. The obtainable spectral width is limited by the high intra cavity total TOD.

The amplifier consisted of an isolator, a WDM, 22.5 cm highly doped ytterbium fiber

(1200 dB/m absorption  976 nm), and a FC-APC fiber connector. A 600 mW single mode fiber pigtailed 974 nm diode laser was used to pump the amplifier. The amplifier was spliced directly onto the oscillator, and again all non-PM sections were kept straight in order to avoid polarization evolution. The total fiber length after the coupler was 2.5 m and the length of standard fiber after the ytterbium fiber in the amplifier was 14.5 cm. The compressor consisted of 2.63 m HC-PBG fiber. The transmission was measured to be 82.2%, and was obtained with two aspheric lenses.

## 4. Experimental results

The repetition rate of the oscillator was 55.3 MHz, and stable CW mode-locking was obtained at a pump power of 145 mW. The pulse stability was measured with an RF-spectrum analyzer, and the fundamental peak was 72 dB above the background. This corresponds to a relative amplitude fluctuation of less than $10^{-3}$. [16] The general stability of the laser compares to that of other non-PM fiber lasers - that is the laser was not environmentally stable, and the output could be affected by moving the fibers. However, stable operation was obtained if the fibers were left untouched.

Figure 3 (left) shows the output spectrum of the oscillator. The spectrum resembles that of a stretched pulse mode-locked laser in the positive net GVD regime, and the spectral modulations is often observed in lasers comprising a nonlinear element with finite recovery time. [17, 16] The central wavelength of the laser was 1030 nm, and the spectral 10 dB width was 17.1 nm. The output pulse energy from the oscillator was 40 pJ, and the pulses were compressible to 182 fs with a bulk grating compressor. This is 15 % above the transform limit. The residual uncompressible chirp we ascribe to be a result of the high TOD of the SC-PBG fiber. This was also the conclusion in [10] where 160 fs pulses (40 % above the transform limit) were obtained, with the use of HC-PBG fiber for intra cavity dispersion compensation.

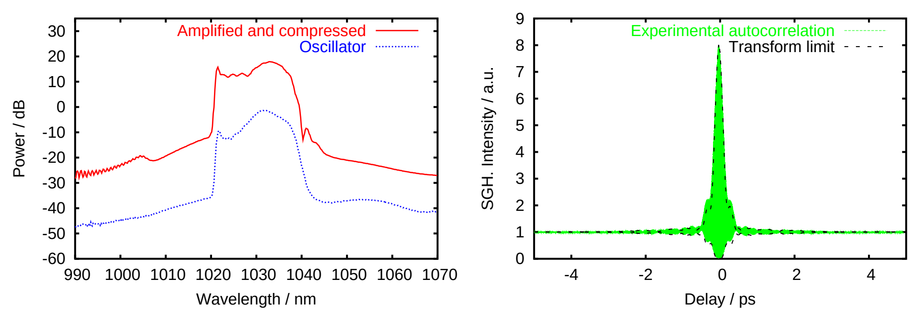


Fig. 3. Left: Output spectrum from the oscillator and output spectrum after the amplifier and compressor at maximum amplification. Right: Experimental autocorrelation trace at maximum amplification. The autocorrelation trace is compared to the autocorrelation trace of the transform limited pulse, and the deconvoluted pulse duration is 158 fs (FWHM).

The output from the oscillator was now amplified and compressed in the external amplifier and HC-PBG fiber compressor. Figure 3 (left) shows the output spectrum after the amplifier and compressor. The 10 dB width increased to 17.4 nm at maximum amplification. Figure 4 (left) shows the output power after the compressor vs. pump power of the amplifier. At the highest pump power the output pulse energy was 5.3 nJ. Before launching the amplified pulses into the HC-PBG fiber, an external grating compressor was initially used to compress the pulses. When increasing the amplifier pump power, a dependence was observed on the compressed pulse duration. At higher pump powers shorter pulses could be obtained, and slightly less dispersion

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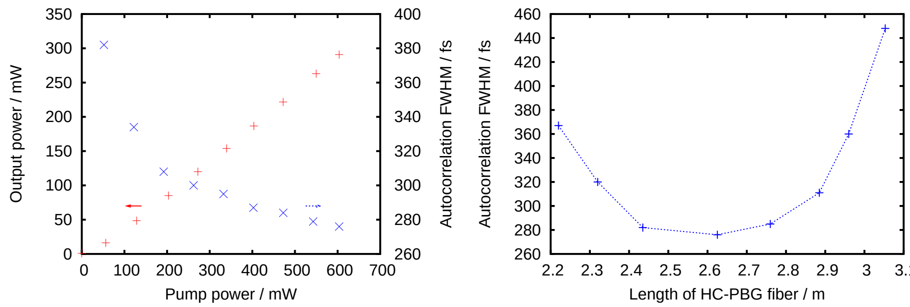


Fig. 4. Left: Output power and output autocorrelation FWHM (of the top envelope) after the HC-PBG fiber. Right: Cut-back of HC-PBG fiber at the highest pump power.

was needed in the grating compressor to find the minimum pulse duration. Due to this pump power dependence, the length of the HC-PBG fiber was optimized to give shortest possible pulses at maximum amplification. The optimal length was found with a cut-back experiment (see Fig. 4 (right)), and the shortest possible pulses were obtained with 2.63 m of HC-PBG fiber.

In Fig. 3 (right) The autocorrelation trace at maximum amplification can be seen. The autocorrelation trace is almost identical to the autocorrelation trace calculated from the transform limited pulse, which was obtained by numerically Fourier transforming the measured spectrum with zero phase. To deconvolute the experimental autocorrelation trace, the trace is compared to the calculated autocorrelation trace. The calculated transform limited pulse has a pulse duration of 158 fs, and hence the experimental autocorrelation trace is deconvoluted to this pulse duration. To illustrate the pump power dependence of the compressed pulse duration, the autocorrelation FWHM (of the top envelope) vs. pump power after the HC-PBG fiber can be seen in Fig. 4 (left). This decrease in pulse duration with increasing pump power is a consequence of nonlinear pulse propagation in the amplifier. In the laser system, transform limited pulse durations were only obtained at the highest pump power in the amplifier. As there is a power dependence on the pulse duration, it must be a result of nonlinear pulse propagation in the amplifier. We suggests that the decreasing pulse duration is due to the combined effect of self-phase modulation and the third order chirp of the pulse as it enters the amplifier. The chirped pulse duration (before the HC-PBG fiber) was calculated to 1.6 ps (FWHM) by numerically adding the dispersion of the HC-PBG fiber to the transform limited pulse. From this value the total nonlinear phase shift in the amplifier can be estimated to $\sim \pi$.

## 5. Summary

In summary a compact laser system delivering 5.3 nJ 158 fs pulse has been realized with the use of a solid-core photonic bandgap (SC-PBG) fiber for intra cavity dispersion compensation and a hollow-core photonic bandgap fiber for external pulse compression. The obtainable spectral width was found to be limited by the large third order dispersion of the SC-PBG fiber inside the cavity. Transform limited pulses were obtained through nonlinear pulse propagation in the amplifier.

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