Temporal pulse compression in a xenon-filled Kagome-type hollow-core photonic crystal fiber at high average power

O. H. Heckl,[1,*] C. J. Saraceno,[1] C. R. E. Baer,[1] T. Südmeyer,[1] Y. Y. Wang,[2] Y. Cheng,[2] F. Benabid,[2] and U. Keller[1]

[1] *Department of Physics, Institute of Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland*
[2] *Gas-phase Photonic Material Group, Centre for Photonics and Photonic Materials, Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK*
**heckl@phys.ethz.ch*

Abstract: In this study we demonstrate the suitability of Hollow-Core Photonic Crystal Fibers (HC-PCF) for multiwatt average power pulse compression. We spectrally broadened picosecond pulses from a SESAM mode-locked thin disk laser in a xenon gas filled Kagome-type HC-PCF and compressed these pulses to below 250 fs with a hypocycloid-core fiber and 470 fs with a single cell core defect fiber. The compressed average output power of 7.2 W and 10.2 W at a pulse repetition rate of approximately 10 MHz corresponds to pulse energies of 0.7 µJ and 1 µJ and to peak powers of 1.6 MW and 1.7 MW, respectively. Further optimization of the fiber parameters should enable pulse compression to below 50 fs duration at substantially higher pulse energies.

OCIS codes: (320.0320) Ultrafast optics; (320.5520) Pulse compression.

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1. Introduction

The highest average output power and pulse energy from mode-locked laser oscillators are currently achieved using thin disk lasers [1] in combination with semiconductor saturable absorber mirrors (SESAM) [2] for passive mode locking. Average powers of up to 108 W [3] and pulse energies of more than 30 μJ [3] were achieved with the well-established gain material Yb:YAG at pulse durations of approximately 1 ps. The highest average output power of 141 W directly out of a mode-locked oscillator was achieved with a thin disk laser using the Ytterbium doped sesquioxide Lu_2O_3 as an active medium with a pulse duration of 738 fs [4]. While various materials are being investigated for short pulse generation in thin disk lasers [5–8] it has not yet been possible to generate sub-100-fs pulses directly out of an oscillator. So far, the shortest pulses of a mode-locked thin disk laser have been 195 fs with 9.5 W average power using the gain material $Yb:LuScO_3$ [9].

Efficient compression of the pulse duration resulting in increased peak power levels is important for various applications in fundamental science and technology. Temporal compression via SPM-induced spectral broadening in fibers [10,11] is particularly attractive due to the large achievable compression factors and high efficiencies. Previously, 760-fs pulses from a thin disk oscillator were compressed to 24 fs at 32 W average power and 50% overall efficiency using a large-mode area (LMA) silica microstructured fiber [12].

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An alternative approach is compression and amplification in a fiber amplifier and grating compressor stage directly after the thin disk laser. This is an attractive but more complicated approach to increase the peak power delivered by a SESAM mode-locked thin disk laser with moderate power levels. With this approach pulses as short as 65 fs with pulse energies exceeding 3 μJ were demonstrated [13].

These two compression schemes are very promising for compression of μJ-class laser pulses. However, pulses with peak power levels above 4 MW cannot be directly compressed in standard fused-silica solid core fibers because self-focusing would occur [14]. Therefore other methods are needed for temporal compression of a state-of-the-art thin disk laser delivering 30-μJ pulses with 25 MW peak power [3].

Substantially higher pulse energies in the 100-μJ to mJ regime can be efficiently compressed by using filaments [15] or gas filled capillaries [16], which are standard schemes for compression in Ti:Sapphire amplifier systems [17]. The employed capillaries, which are filled with noble gases, are not a proper waveguide and, thus, need to be kept straight. Furthermore, it requires a stringent alignment for optimum laser coupling with grazing incidence. Recently 35-fs pulses with a compressed pulse energy of 380 μJ were demonstrated driven by a fiber amplifier scheme [18]. However due to the strong power leakage of the guided modes in the capillary, this technique seems not to be feasible for the use of very small mode field diameters since the grazing incidence condition cannot be fulfilled. Hence this scheme seems only suitable for pulse energies in the range of several hundred μJ and above, a regime that is not yet reached directly from femtosecond oscillators.

The damage limitations of solid core fibers can be overcome by spectral broadening inside a gas-filled Hollow-Core Photonic Crystal Fiber (HC-PCF) [19]. This combines the advantage of guiding the light in a fiber with the possibility to use gases as nonlinear medium. HC-PCFs offer a combination of long effective interaction length and small mode areas, which has resulted in several major breakthroughs in low-power nonlinear optics [20–22]. Compression of 120-fs pulses to 50 fs at mW average power levels has been demonstrated in a xenon-filled standard photonic band-gap fiber [23]. Here we used a Kagome-type HC-PCF [24] for which the field overlap with the surrounding silica structure is more than ten times lower [22]. In contrast to the photonic bandgap-type fibers, the guiding mechanism is based on the inhibited coupling between the core and cladding modes [22] and not the bandgap-effect.

The fiber is immune to core-mode and surface-mode coupling [25], which represents one of the major sources of optical overlap with the silica surrounding the fiber core. Furthermore, typical core sizes of Kagome-type HC-PCF are larger than 30 μm. Since the damage threshold scales with the inverse of the optical overlap on one hand and with the modal effective area on the other, guidance of very high pulse energies and peak power levels becomes feasible. Furthermore, Kagome-type HC-PCFs have advantages in terms of showing very low dispersion and an ultrabroad guiding bandwidth, which are particularly important for applications with ultrashort laser pulses [22]. These advantages were confirmed by the recent demonstration of high harmonic generation inside a Kagome-PCF at peak intensities above 10^{14} W/cm^2 and peak powers around 300 MW [26].

In this work we show the suitability of Kagome-type HC-PCF to compress pulses in the multi-Watt average power regime. We demonstrate efficient compression of μJ-class pulse energies using xenon as the nonlinear medium. The subsequent compression is done with a single-pass grating compressor. We achieved a maximum compression factor of 4.3 and an efficiency of above 70%. The output beam was linearly polarized and we observed only a negligible amount of depolarization.

2. Choice of HC-PCF

We have evaluated two Kagome-type fibers: The first is a recently developed 7-cell 3-ring hypocycloid-core Kagome-cladding HC-PCF. This design offers extremely low loss, broad bandwidth [27], lower coupling between core and cladding modes and larger mode diameters compared to previous Kagome HC-PCF designs. Figure 1(a) shows the scanning electron microscope (SEM) image of this fiber. It has a core diameter of 36 μm, a pitch of 16 μm and an outer diameter of 200 µm. The fiber has a perfect 6-folded symmetry without any distortion in the core structure; this helps to avoid nonlinear polarization breakup. Indeed, the HC-PCF typically exhibits a residual birefringence in its HE_{11} mode, which is enhanced by either polarization sensitive coupling between the core modes and those of the cladding, or by core form-distortion from a perfect 6-fold symmetry shape. A distorted fiber core exacerbates both mechanisms. Figure 1(c) shows the transmission and attenuation spectrum of this fiber. Using a cutback measurement from 21 m to 5 m with a supercontinuum source, the loss is estimated to be below 200 dB/km in the spectral range of interest: from 1050 nm to 1350 nm.

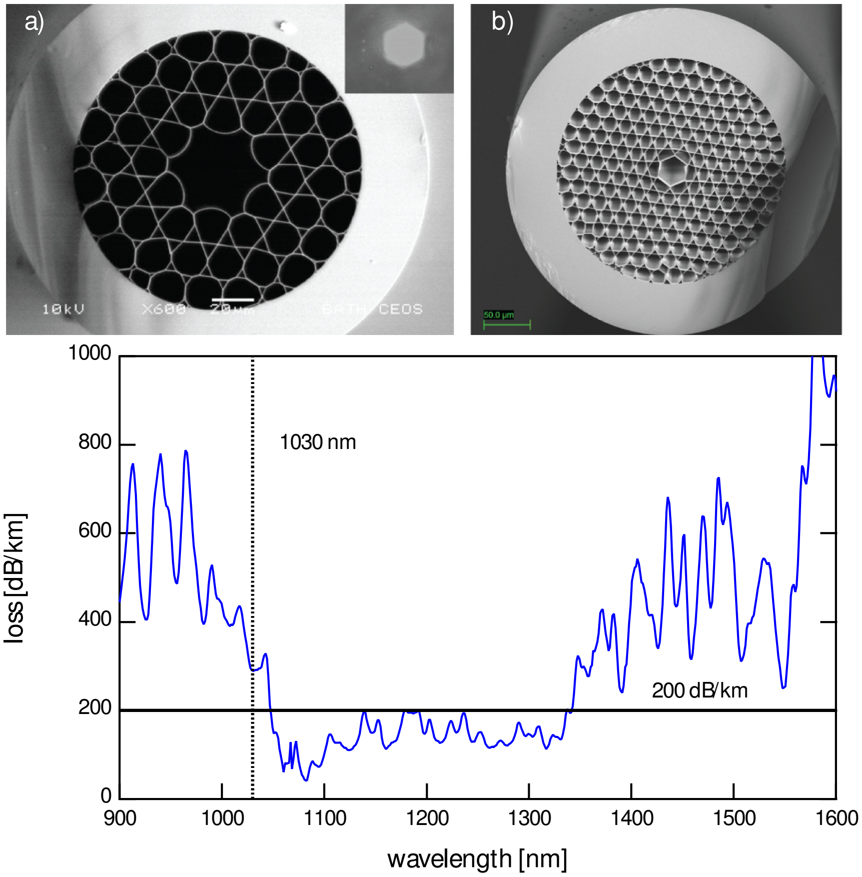

Fig. 1. Kagome-type HC-PCFs: (a) HC-PCF Nr. 1: SEM image of the hypocycloid core Kagome HC-PCF exhibiting a core of 36 µm and a pitch of 16 µm. The inset on the upper right shows the near field image of the transmitted mode looking at the exit face of the fiber. It can be seen that the fiber guides mainly in fundamental core mode with almost no spatial overlap with the silica surface. (b) HC-PCF Nr. 2: SEM image of the single cell core defect Kagome HC-PCF with a mode field diameter of 25 µm. (c) Loss spectrum of the hypocycloid core Kagome HC-PCF (Nr. 1). The loss spectrum was measured with the cutback method and shows the broad guiding bandwidth ranging from 1050 nm up to 1330 nm with losses below 200 dB/km. The point of operation of our system is indicated with the dashed line at 1030 nm, where the losses are around 300 dB/km.

Furthermore, the near field image (Fig. 1(a), upper right) shows that the fiber guides mainly in fundamental core mode with almost no spatial overlap with the silica surface, making it an ideal host for high power delivery. Unfortunately this fiber was not intended for use at 1030 nm, which leads to extra losses and dispersion.

The second fiber was a single cell core defect Kagome-type HC-PCF especially designed for operation at 1030 nm. Since the fiber was designed for operation at our laser wavelength, the laser pulses experiences negligible Group Delay Dispersion (GDD) and loss figures in the range of 1-0.5 dB/m [22]. With this fiber we could achieve more than 80% transmission through a 30.5 cm piece of fiber, including the coupling losses. The mode field diameter of this fiber is 25 µm and the fiber cladding has larger ring number compared to the first fiber. Unfortunately our supply of this fiber was limited to 30.5 cm and we could not measure a loss spectrum with the cutback method. The structure of the fiber is displayed in Fig. 1(b).

3. Experimental setup and results

The experiments were driven by a standard mode-locked Yb:YAG thin disk laser, similar to the laser driving the experiments in [13]. It operates at a repetition rate of 10.6 MHz and delivers a maximum average output power of 14.3 W, resulting in pulse energies of 1.35 µJ, pulse durations of 1 ps and a peak power of 1.1 MW. Modelocking is achieved by a dielectrically top coated SESAM with a saturation fluence $F_{sat} = 46\ \mu J/cm^2$, a modulation depth of $\Delta R = 0.58\%$ and non-saturable losses of $\Delta R_{ns} < 0.1\%$. The details of the measurement of these parameters are presented in [28].

The entry and exit facets of the fibers are then mounted into gas cells by fixing them into a rubber cylinder with a hole in the middle. The rubber is compressed from both ends to seal the gas cell. In this way the fiber can be loaded with gas, which then diffuses through the hollow core. Whenever the fibers were loaded with gas we did allow the gas distribution to settle into equilibrium to avoid any pressure gradient in the fiber (Fig. 2).

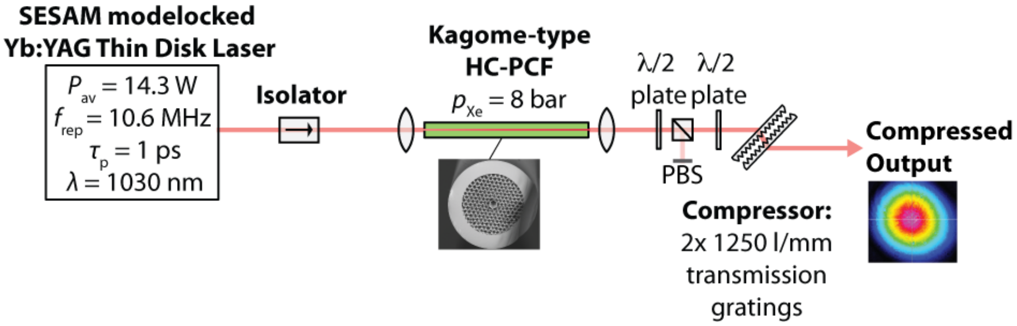

Fig. 2. Experimental setup driven by a SESAM mode-locked thin disk laser delivering 14.3 W of average power with a repetition rate of 10.6 MHz. The 1-ps laser pulses are launched directly into the xenon gas-filled HC-PCF. The spectrally broadened pulses after the fiber are then temporally compressed with a single-pass grating compressor.

In a first set of experiments we worked with the recently developed 7-cell 3-ring hypocycloid-core Kagome-cladding HC-PCF, which is described in the first section of this work, see Fig. 1(a). This fiber is very promising for compression experiments due to its wide transmission bandwidth and low transmission losses of about 200 dB/km ranging from 1050 nm up to 1330 nm (see Fig. 1(c)). However, this fiber was designed for operation with laser pulses centered in the range between 1050 nm and 1330 nm. Our laser wavelength is on the lower wavelength side of the transmission band centered on a little side plateau; see dashed line in Fig. 1(c). This leads to higher transmission losses in the order of 300 dB/km. Furthermore, we expect a relatively higher dispersion near our operating wavelength because of the resonant coupling between the core modes and the cladding modes as is indicated by the attenuation peaks in the loss spectrum. Nevertheless, this fiber could be operated with launched average powers of up to 12.8 W without damage which corresponds to pulse energies of 1.2 µJ. Higher power levels lead to damage in the fiber. When increasing the input power, damage occurred at the point where the fiber was mounted into the rubber cylinder, about 1 cm after the entry facet of the fiber. Observation of the damaged fiber under an optical microscope indicates that the structure of the fiber at the entry facet stayed intact. We therefore conclude that the damage occurs due to stress on the structure, which was induced by our method of mounting. The stronger mechanical stress at the mounting point induces power coupling of the guided mode and the jacket. In a previous experiment we were able to transmit 10.5-μJ pulses with 40-fs pulse duration through a similar fiber [26], which was glued stress-free into a capillary. This corresponds to more than 300 MW of peak power and is clearly above the self-focusing limit for solid core large mode area fibers, which is reported to be around 4 MW [14].

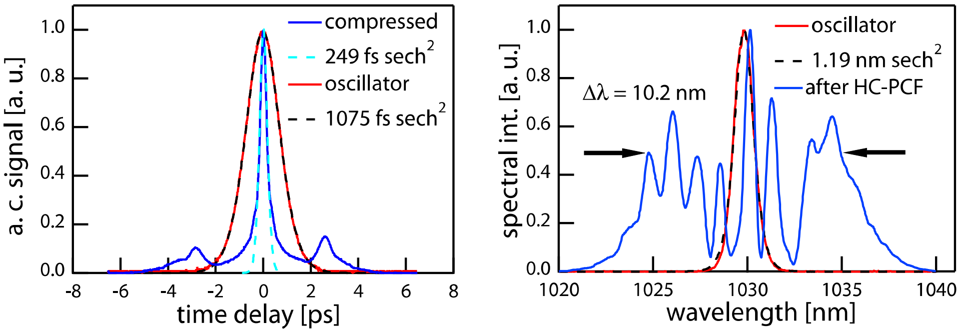

Fig. 3. Pulse compression using HC-PCF Nr. 1: Left: Autocorrelation trace of the input pulses (red line) and the compressed pulses (blue line). The compressed output power exceeds 7.2 W and a sech^2 fit into the main peak (turquoise) reveals pulse durations of below than 250 fs FWHM. Right: Optical spectrum of the input pulses (red line) and the compressed pulses.

As a first step we launched the laser beam into the air filled fiber. We observed the onset of spectral broadening for transmitted power above 6.5 W, however only marginally changing the FWHM of the spectrum. The coupling efficiency into the fiber was estimated to be ≈80%, by comparing the transmission through a short and a long piece of fiber. The transmission loss of the fiber is measured to be 300 dB/km, (see Fig. 1(c)).

In a next step we filled the fiber with 8 bar of xenon and launched up to 12.8 W average power directly into the fiber. The spectral width of the 1.2-μJ pulses broadened from 1.2 nm to a FWHM of 10.2 nm, see Fig. 3 right side.

With the 2nd order dispersion compensation of our single-pass grating compressor [29], we were able to compress these spectrally broadened pulses starting from 1 ps down to sub-250 fs. Each grating had a first order transmission efficiency of 95%, resulting in a total efficiency of over 90% for the grating compressor. The line density of the transmission gratings was 1250 l/mm and the distance between the gratings was 6 mm, which results in a GDD of –0.076 ps^2. The spatial chirp, which is acquired with this configuration, can be neglected. Assuming a completely flat phase the theoretical pulse duration limit is at 200 fs for the measured spectrum. As can be seen in the autocorrelation trace, there were clearly visible side peaks due to higher order dispersion, which could not be compensated for with our grating compressor. Fitting a pulse to the measured spectrum and autocorrelation trace reveals that we have about 60% of the energy in the main peak and obtain a peak power level of 1.6 MW.

In a second set of experiments we worked with a single cell core defect Kagome-type HC-PCF (Nr. 2), which was especially designed for operation at 1030 nm. This fiber, which can be seen in Fig. 1(b) showed a higher damage threshold - despite exhibiting a smaller core diameter, and we could operate the system at our full laser power of 14.3 W. We believe this was only due to the much thicker cladding, which reduced the induced stress on the fiber structure at the mounting point. Unfortunately we only had 30.5 cm of this fiber available, so we could not measure the loss spectrum of the fiber. Filling the fiber with 8 bar of Xenon and launching the 1.35 μJ pulses into the fiber resulted into a spectral broadening of 4.2 nm. These spectrally broadened pulses were then compressed down to pulse durations of below 470 fs at pulse energies of 1 μJ, corresponding to an average output power of 10.2 W. Even though the fiber was rather short we could increase the peak power to above 1.7 MW with close to 90% of the pulse energy in the main peak. The efficiency of this system was 71%, while the coupling and transmission efficiency was 80% through a 30.5-cm long piece of fiber. The depolarization losses were negligible.

We used a split-step Fourier-transform algorithm to numerically reproduce our measurement, which can be seen in the spectrum in Fig. 4, right side. The measured mode area of the fiber is 490 μm^2 and its length 30.5 cm. Near the high-frequency edge of a transmission window of a Kagome HC-PCF, the GDD is negative and close to zero dispersion (see the online supplement of reference [22]). We did not have a precise dispersion measurement of the fiber, but the influence of the expected dispersion in the regime of 0 ps^2/km to -0.10 ps^2/km on the simulated peak power is negligible. The nonlinearity of xenon was measured to be $(8.1+/-0.8)\cdot 10^{-23}$ W/m^2 at 800 nm and a pressure of 1 bar [30]. We could reproduce our measurement data best by assuming a nonlinear coefficient of $7.4\cdot 10^{-22}$ W/m^2 at the 1030-nm center wavelength and 8 bar. Assuming linear scaling of the nonlinearity with pressure, this corresponds to a deviation of 12.5% to the literature value for 800 nm. We did not include any Raman effects since single atom gases such as Xe do not show a Raman response [30]. Furthermore we did include losses of 500 dB/km for this fiber.

We then used the model to predict the optimum fiber length for maximizing the compressed peak power. Here we simply iteratively increased the length of the fiber while maintaining all other parameters constant until no further increase in peak power was achieved. For compression we used second order dispersion compensation. For a fiber length of 6.3 m, we obtain a spectral broadening of 79 nm. Using only second order dispersion compensation of -4800 fs^2, we obtain a pulse duration of below 35 fs and a peak power of 10.6 MW.

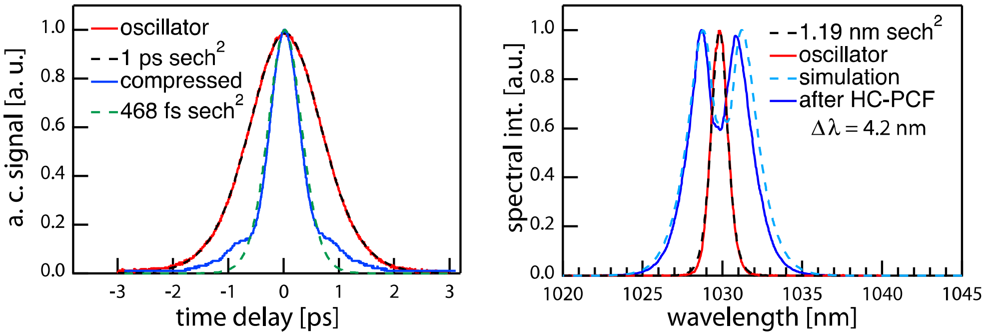

Fig. 4. Pulse compression using HC-PCF Nr. 2: Left: Autocorrelation trace of the input pulses (red line) and compressed pulses (blue line). The compressed output power exceeds 10 W and a sech^2 fit into the main peak (turquoise) reveals pulse durations of 470 fs FWHM. Right: Optical spectrum of the input pulses (red line), compressed pulses and a simulated fit. This simulation is then used to predict the shortest possible pulse duration of below 50 fs if the fiber is prolonged from 0.3 m to 4 m until the soliton pulse shape starts to deform.

4. Conclusion

Our results show, that Kagome-type HC-PCFs are well suited for nonlinear optics and beam delivery at megawatt peak powers and tens of watts of average power. The thin disk laser technology is energy-scalable, and energy levels of 30 μJ have already been achieved in 1–ps pulses [3]. These lasers operate in a regime, where pulse compression with solid-core fibers, bulk material or gas-filled capillaries is challenging. Gas-filled Kagome-type PCFs are a promising technology for efficient compression of these laser pulses into the sub-100-fs regime.

We used a SESAM mode-locked thin disk laser operating at 1030 nm, which delivers 14.3 W of average power at a repetition rate of 10.6 MHz. The pulses had pulse durations of 1 ps, pulse energies of 1.35 μJ and a peak power of 1.1 MW. These pulses were launched directly into Kagome-type HC-PCFs and spectrally broadened in xenon gas filled fibers. With a hypocycloid-core Kagome-type HC-PCF, we obtain sub-250 fs pulses at an average power of 7.2 W, corresponding to pulse energies of 0.7 µJ with a peak power of 1.6 MW. With a single cell core-defect fiber we were able to increase the compressed output power to 10.2 W of average power and achieved peak power levels of 1.7 MW.

While our experiments were limited by the available fiber length and the mounting technique in our pressure chambers, we believe that the transmitted peak powers can be improved significantly [26]. Our simulations show that compression in a longer single cell core defect type fiber of about 4 m would allow compression into the sub-50 fs regime. Furthermore, we expect that better mounting techniques should allow for operation with at least 10 µJ of pulse energy. Here we have demonstrated the feasibility of using HC-PCF for compression of laser pulses in the 1-µJ and 1 MW regime. The transmitted average power of 11.3 W (10.2 W compressed) is to our knowledge the highest average power transmitted through a HC-PCF. Based on these results we are confident that this approach will allow for temporal compression of pulses in the 10-µJ and 10-MW regime.

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