Photonic band gap fibre compressed chirped-pulse oscillator

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Abstract. One of the most successful techniques for generating high-energy femtosecond laser pulses directly out of an oscillator without external amplification is based on intracavity pulse broadening due to a net positive round-trip group-delay dispersion. The main disadvantage of this concept, however, is the need to have an external compressor, often a pair of prisms separated by an optical path length of several metres. In this paper, we demonstrate for the first time an all-fibre compressor based on a photonic band gap fibre. Compared to a standard prism pair the total length of the set-up can be reduced by up to two orders of magnitude while its throughput is increased at the same time.

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1. Introduction

Standard femtosecond laser oscillators deliver pulse energies in the range of only a few nanojoules [1]. This is generally insufficient for microfabrication tasks ranging from surface ablation [2] and the generation of microvoids in glass [3] to waveguide writing [4]–[7]. Thus, master-oscillator power-amplifier systems have to be employed [8]. These typically suffer from relatively high pulse-to-pulse energy fluctuations with a correspondingly reduced overall process quality and a very low throughput in consequence of their low repetition rate in the kilohertz range.

In order to generate high-energy pulses with megahertz repetition rates directly out of an oscillator, two approaches have been demonstrated in the past: cavity dumping [9] and the insertion of a multipass cell into the resonator in order to substantially increase the resonator length [10]. What both techniques have in common is the need to find a way of avoiding excessive nonlinear effects in the laser medium which eventually lead to pulse breakup [11]. While a high net-negative intracavity dispersion can mitigate these effects to some extent [12], the introduction of a small amount of net-positive intracavity dispersion has been shown to be the most promising approach to generate microjoule level pulses from a femtosecond oscillator [13]. In this case, the laser delivers heavily chirped pulses with a correspondingly reduced peak intensity [14]. Consequently, these systems have been referred to as chirped-pulse oscillators (CPOs) [15]. In order to re-compress the pulses, however, an extracavity compressor, typically a pair of prisms, has to be used. As the actual amount of chirp on the output pulses can be as high as 20 000 fs², either highly dispersive prism materials have to be used or one has to accept prism separations of up to 10 m or more. While the former concept inevitably leads to the introduction of a large amount of higher-order dispersion, which can impair the quality of the compressed pulses, the latter one has a negative impact on the beam pointing stability of the laser source, which is unacceptable for high precision microfabrication tasks. An alternative approach would be the use of a femtosecond pulse shaper in a grating-based zero-dispersion stretcher set-up. While acousto-optic modulators [16] are not suitable for lasers with high repetition rates [17], spatial light modulators based on liquid crystals (LC) offer the advantage that the Fourier limit can be reached exactly and that even specifically shaped pulses can potentially be generated [18]. However, such systems are complex, have a maximum throughput of only about 70% and the used LC-arrays are pixellated with dead spaces.

In this paper, we show for the first time that it is possible to use an air-guiding photonic band gap fibre [19], which possesses anomalous dispersion around 800 nm, for this purpose. While similar fibres have been successfully implemented in all-fibre based amplifier systems in the past [20], their use in Ti:Sapphire based systems has not been reported so far. Using this approach we use a short 15 cm long piece of fibre to compress the 150 nJ, 1.3 ps pulses generated by our CPO down to 88 fs. Due to the relatively large air-core of the fibre and the absence of Fresnel-losses on the end-facets, the total transmission through the fibre is even higher than the typical prism compressor throughput of around 90%.

2. Experimental set-up

The fibre used in these experiments was an air-guiding photonic band gap fibre—AIR-6-800 from Crystal Fibre, Denmark. This fibre has a transmission window starting from about 745 nm and
ranging to about 800 nm (losses <2dB m$^{-1}$) or 860 nm (losses <7dB m$^{-1}$), respectively. As the radiation is confined to the hollow core, the nonlinear coefficient of the fibre is basically equal to that of air and the risk of damage is greatly reduced. As a consequence of the Kramers–Kronig relation, the dispersion characteristic of the fibre is resonant with anomalous values for wavelengths above about 755 nm.

The actual laser source which was utilized in these experiments was based on a commercially available Ti:Sapphire CPO-system from Femtolasers GmbH, Austria (Femtosource scientific XL). This system was pumped with up to 10W from a frequency-doubled solid state laser (Coherent Verdi V10). The layout of the CPO is very similar to the one described in [15] and the oscillator normally emits pulses with a repetition rate of 11 MHz and a spectral width of about 40 nm, centred at 800 nm. In order to match the spectral characteristics of the high-energy oscillator to the fibre properties and to keep the compressor throughput high, the centre wavelength had to be shifted. By using a different combination of chirped dielectric mirrors we modified the intracavity dispersion distribution of the oscillator with a resulting shift of the centre wavelength down to 780 nm at a reduced bandwidth of 20 nm. Although Ti:Sapphire exhibits its peak gain at 800 nm, its extremely broad emission spectrum ensured that the maximum pulse energy generated by the laser remained unchanged and was 150 nJ at the full available pump power.

3. Results and discussion

As a first step, we have measured the optical pulses directly emitted by the CPO using a second-harmonic frequency-resolved optical gating (SH-FROG) apparatus [21]. Figure 1 shows the measured and the retrieved FROG-trace, respectively. As can be seen in figure 2(a), the retrieved spectral intensity has a full-width at half-maximum (FWHM) bandwidth of 21 nm and is almost identical to the separately measured fundamental spectrum, showing the high accuracy of our measurement set-up. In the time domain, the pulses are strongly chirped (figure 2(b)) and the FWHM pulse duration is 1329 fs. By fitting a higher-order polynomial to the spectral phase

Figure 1. Measured (left) and retrieved (right) FROG-Trace of the uncompressed laser pulses directly emitted by the oscillator.
we could estimate the total amount of negative group-delay dispersion (GDD) necessary to recompress the pulses which turned out to be $-25700 \text{ fs}^2$. By comparison, a standard fused-silica prism compressor introduces an amount of $-933 \text{ fs}^2$ per metre prism separation which would bring the total compressor length to more than 27 m.

In a second set of experiments the pulses were launched into a $<20 \text{ cm}$ long piece of the band gap fibre mentioned above, using an objective lens with a numerical aperture (NA) of 0.6 and a magnification of 32× (Leitz). As the diameter of the output beam of the laser was much smaller than the input aperture of the lens, the effective NA was much smaller than 0.6 and closely matched to the fibre’s NA of 0.2. Therefore, and also due to the fact that the hollow core means that there are no Fresnel-losses on the fibre end facets, we have measured a total fibre throughput of $>95\%$ regardless of the fibre length. In accordance with the manufacturers specifications (attenuation $<0.4 \text{ dB m}^{-1}$) we can conclude that this represents coupling losses of 5% and negligible transmission losses. As our objective lens was not anti-reflexion coated at 800 nm we lost about 12% of the laser light in this component. However, this issue can easily be addressed by utilizing appropriate lenses and is not a fundamental problem of the fibre compression scheme. Furthermore, the full available laser power (corresponding to a pulse energy of 150 nJ) could be coupled into the fibre without any signs of degradation or damage.

Starting from a 200 mm long piece we recorded the FROG-trace of the compressed pulses for different lengths of band gap fibre. As a consequence of the limitations of our cleaver, the step-size for these cut-back measurements was 15 mm, which, as will be explained later, corresponds to a GDD step-size of about $2000 \text{ fs}^2$.

The shortest pulse duration was obtained with a fibre length of 155 mm. Figure 3 shows the measured (left) and retrieved (right) FROG-traces of these pulses. The corresponding spectral and temporal pulse shape can be seen in figure 4. Once again there is a close match between the retrieved spectral intensity and the directly measured one but the spectral phase is now fairly flat across the major part of the optical spectrum. In the time domain, the pulses are as short as 88 fs with a flat phase across the central peak. Due to remaining uncompressed higher-order phase terms, the phase rolls off at the edges of the pulse. The pulse shape, however, shows only a very small pedestal and almost non-existing pre- or post-pulses. For comparative purposes, the Fourier-limited pulse shape with a duration of about 75 fs is also shown in figure 4.

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Figure 3. Measured (left) and retrieved (right) FROG-trace of the compressed laser pulses after the band gap fibre.

Figure 4. (a) Directly measured (red) and with FROG retrieved (blue) spectrum of the compressed laser pulses. Dashed line: spectral phase. (b) Temporal intensity (red) and phase (blue, dashed) of the compressed laser pulses measured with FROG. For comparison, the Fourier-limited pulse is also shown (black, dashed).

From the difference in spectral phase $\varphi(\omega)$ between the compressed and the uncompressed laser pulses, the dispersion characteristic of the band gap fibre can quantitatively be obtained. Using

$$\varphi_{\text{compressed}}(\omega) = \varphi_{\text{uncompressed}}(\omega) + k(\omega) \cdot z$$

and a Taylor expansion for the propagation constant $k(\omega)$

$$k(\omega) = k(\omega_0) + \frac{\omega - \omega_0}{v_g} + \frac{\text{GDD}}{2} (\omega - \omega_0)^2 + \frac{\text{TOD}}{6} (\omega - \omega_0)^3 + \frac{\text{FOD}}{24} (\omega - \omega_0)^4 + \cdots,$$

where TOD is the third-order dispersion coefficient and FOD is the fourth-order dispersion coefficient, we have fitted a high-order polynomial to the phase difference and obtained

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the dispersion values. We estimate values of GDD = $-142 \text{fs}^2 \text{mm}^{-1}$, TOD = $1090 \text{fs}^3 \text{mm}^{-1}$ and FOD = $-3580 \text{fs}^4 \text{mm}^{-1}$ with $\omega_0 = 2416 \text{fs}^{-1}$ corresponding to a centre wavelength of $\lambda_0 = 780 \text{nm}$. Figure 5 shows a plot of the dispersion parameter $D = \frac{2\pi c \cdot \text{GDD} \lambda^2}{\lambda^2}$ of the fibre which compares well with the data points provided by the manufacturer [22].

Based on these results it should be feasible to generate even shorter laser pulses by applying this technique to oscillators with an even broader output spectrum. The crucial part, however, is to design the intracavity dispersion such that the laser operates in the full window where the fibre has a high transmission and anomalous dispersion, i.e. from 755 to 800 nm. In this spectral range Ti:Sapphire offers almost constant gain, thus additional losses are not expected. If one can accept a lower compressor throughput the long wavelength side of the pulse spectrum can be extended up to 860 nm, a wavelength which is still guided by the fibre at anomalous dispersion. Moreover, in an air-guiding photonic band gap fibre the position and the width of the transmission bands are controlled by the geometry of the photonic crystal structure which constitutes the cladding and by the diameter of the central air core. Therefore custom-designed fibres for the specific task of CPO compression could further enhance the capabilities of the proposed scheme. In any case, more sophisticated cleaving methods must be used as the high dispersion of the fibre means that small changes in length can result in large changes in the compressed pulse duration.

4. Conclusions

We have shown that an air-guiding photonic band gap fibre exhibiting anomalous dispersion around 800 nm can efficiently be used to compress the heavily chirped pulses generated by a high-energy femtosecond oscillator operating at net-positive intracavity dispersion. In contrast to a prism compressor, which has to be up to 30 m in length, a short 15 cm long piece of fibre was sufficient to recompress the pulses close to their Fourier-limit. This greatly enhances the beam-pointing stability of the complete laser system, a crucial parameter for high-precision micromachining applications. At the same time, the total compressor throughput can be as high as 95% which is superior to other compression methods.

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