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Mirror dispersion control of a hollow fiber supercontinuum

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ABSTRACT Ultrabroadband chirped mirrors with a bandwidth of 270 THz have been manufactured using the BASIC design approach. These mirrors were used to compress the supercontinuum of cascaded hollow fibers down to 4.6 fs. The pulse duration was measured with spectral phase interferometry for direct electric-field reconstruction (SPIDER).

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1 Introduction

Pulse compression in gas-filled hollow fibers has allowed for the generation of some of the shortest light pulses ever reported. Compared to bulk materials or conventional fibers, the hollow fiber geometry can host significantly higher pulse energies in the millijoule range. The first demonstration of hollow-fiber compression employed a simple silica prism sequence for dispersion compensation and resulted in a 14-fold compression of 140-fs pulses [1]. The use of chirped mirrors, providing a large high reflection bandwidth and negative dispersion compensation [2, 3], allowed for an important improvement in the pulse durations obtained by compression of hollow fiber continuum and represented a breakthrough in ultrafast optics [4]. In fact, using an advanced dispersion compensation scheme composed of a thin prism sequence and chirped mirrors, a pulse duration of 4.5 fs was reached [5]. Pulse durations of 5 fs have been demonstrated employing a single hollow fiber and a dispersion line based only on chirped mirrors with an energy of 0.55 mJ [6]. Using two cascaded hollow fibers, a 510-THz spanning continuum has been generated [7]. Provided proper dispersion compensation, this vast bandwidth theoretically holds the potential for a $\simeq 2$ fs pulse duration. Initially, only relatively small spectral slices of this supercontinuum could be compressed. Using different types of chirped mirrors, a pulse duration of about 6 fs was reached, realizing a tunable source of ultrashort pulses over the visible and near infrared region.

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Recently, several attempts to adaptively compress octave-spanning hollow fiber continua were reported [8, 9]. Placing a liquid crystal array inside a zero-dispersion grating sequence allows for a much finer compensation of residual dispersion. Consequently, this approach allowed for a progression of pulse duration well into the sub-4-fs range [8]. However, compared to chirped mirrors or prism compressors, the grating-based shaper exhibits greater losses and, therefore, only allows for relatively small pulse energies.

It is desirable to find static dispersion compensating elements, which support close to an optical octave bandwidth and do not exhibit prohibitive losses. Similar efforts to design chirped mirrors for the compression of pulses from a noncollinear optical parametric amplifier (NOPA) allowed for spectral phase control over a bandwidth of 170 THz in the visible range, yielding a pulse duration of 5.7 fs at an energy of 2 μJ [10]. Again, even shorter pulses (4 fs) have been achieved using a NOPA but at the expense of a more complex dispersive line composed of chirped mirrors, gratings and a deformable mirror, thus, reducing the energy content of the pulses to much less than 1 μJ [11]. Finally, pulse durations as low as 3.8 fs have been obtained by ultrafast molecular phase modulation in a hollow waveguide and using chirped mirrors for dispersion compensation with an energy of 1.5 μJ [12].

2 Design of BASIC mirrors for pulse compression

For the application of chirped mirrors, the case of an octave-spanning hollow-fiber continuum is particularly challenging in terms of bandwidth. Spurious Gires–Tournois interferometer (GTI) effects tend to corrupt the spectral phase of broadband chirped mirrors. The original chirped mirror design was refined by the double chirped mirror (DCM) concept, which takes into account the impedance matching problem which occurs at the air mirror interface and the grating structure in the mirror [13, 14]. The impedance matching concept allowed for a much better insight to the design limitations and allowed for the first time for an analytical design with custom-tailored dispersion characteristics which required only minor numerical optimization [15]. These double chirped mirrors resulted in new world-record pulse durations in the two-opticalcycle regime from KLM Ti:sapphire lasers [16, 17]. However, the impedance matching to the air sets a limit. This impedance matching is based on a broadband AR-coating that interferes with the rest of the multilayer mirror design and, therefore, has to be of very high quality with a very low residual power reflectivity of less than 10^{-4} [18]. However, this can only be achieved over a limited bandwidth and impossible for more than 0.7 optical octaves in the near-infrared and visible spectrum [19]. The invention of the back-side coated (BASIC) mirrors [18] or later the tilted front-side mirrors [20] resolved this issue. In the back-side coated mirror, the ideal DCM structure is matched to low index material of the mirror which ideally matches the mirror substrate material. This DCM structure is deposited on the back of the substrate and the AR-coating is deposited on the front of the slightly wedged or curved substrate, so that the residual reflection is directed out of the beam and does not deteriorate the dispersion properties of the DCM structure on the other side of the substrate. Thus, the purpose of the AR-coating is only to reduce the insertion losses of the mirror at the air-substrate interface. For most applications, it is sufficient to get this losses as low as 0.5%. Therefore, the bandwidth of such an AR-coating can be much broader. The trade-off is that the substrate has to be as thin as possible to minimize the overall material dispersion. In addition, the wedged mirror leads to an undesired angular dispersion of the beam. Another possibility to overcome the AR-coating problem is given with the idea to use an ideal DCM at the Brewster-angle incidence [21]. In this case, the low index layer is matched to air. Other methods to overcome the AR-coating problem are based on using different chirped mirrors with slightly shifted GTI oscillations that partially cancel each other. Normally, these chirped mirrors are very difficult to fabricate [18]. Many different growth runs normally result is strong shifts of those GTI oscillations so that a special selection of mirrors makes it ultimately possible to obtain the right dispersion compensation. Some tuning of the oscillation peaks can be obtained by the angle of incidence [22]. A specially designed pair of DCMs has been used to cancel the spurious GTI oscillation [23] where an additional quarter wave layer between the AR-coating and the DCM structure was added in one of the DCMs. Also this design has its drawbacks and limitations because it requires an extremely high precision in fabrication and restricts the range of angles of incidence.

In this paper, we use the BASIC DCM concept for ultrabroadband dispersion compensation of a hollow fiber supercontinuum. A schematic view of the construction of the BASIC mirror is shown in Fig. 1. First, the coating was deposited on the thick carrier substrate. After the coating deposition, the BK7 cover slide was cemented on top of the coating and then polished down to a 2 degree wedge angle. BK7 was chosen, as it delivers the best index matching to both the optical cement used and the sputtered SiO_2 in the mirror stack. For the maximum amount of dispersion compensation, it is necessary to produce the thinnest possible cover slide. This means to polish down to the carrier substrate and create a wedge with effectively zero thickness on one side. Despite some irregularities at the knife edge side of the wedge, these irregularities do not extend further than 2 mm from the edge, allowing for an effective cover slide thickness of 50–100 μm in the experiments. To reduce the losses of the mirrors, the top surface was finally coated with an ultrabroadband antireflection coating with a single pass loss of 0.3% (500–900 nm). This loss can be easily tolerated in the BASIC design approach, even if it would be prohibitively large for regular chirped mirrors.

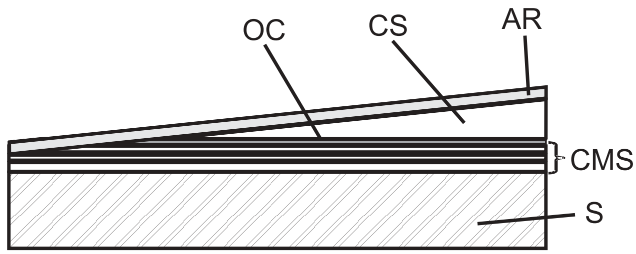

FIGURE 1 Back-side coated (BASIC) chirped mirror. S: substrate, CMS: chirped mirror stack consisting of 69 alternating SiO_2/TiO_2 layers. OC: optical cement. CS: wedged cover slide (BK7 glass, wedge angle 2°, thickness ranging from 200 μm to approximately zero). AR: antireflection coating. The index of refraction of the cover slide and the optical cement are matched to the sputtered SiO_2 in CMS

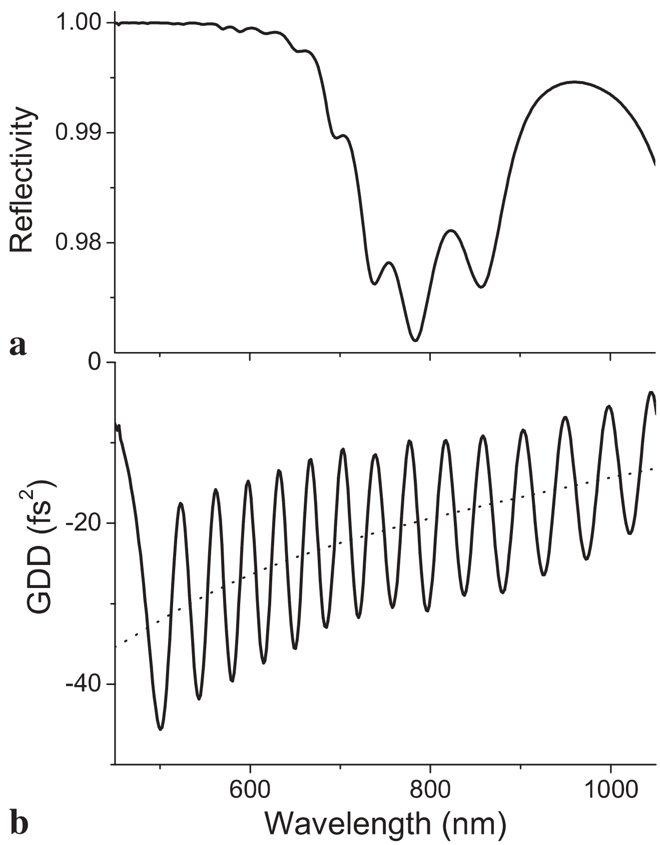

FIGURE 2 Designed reflectivity **a** and group delay dispersion **b** of the BASIC chirped mirror coatings. The target dispersion is shown in **b** as a dotted line. Note that the variable dispersion of the cover slide is not included in this calculation

The design of the chirped mirrors was based on a measurement of the group delay, which was determined from a spectrally resolved cross-correlation between the supercontinuum and the 25-fs laser pulses directly from the amplifier [7]. The measured group delay dispersion of the supercontinuum of 73 fs^2 roughly resembles that of 2 mm of fused silica. The measured third-order dispersion of 40 fs^3 also only slightly deviates from 2 mm of fused silica. The major part of the

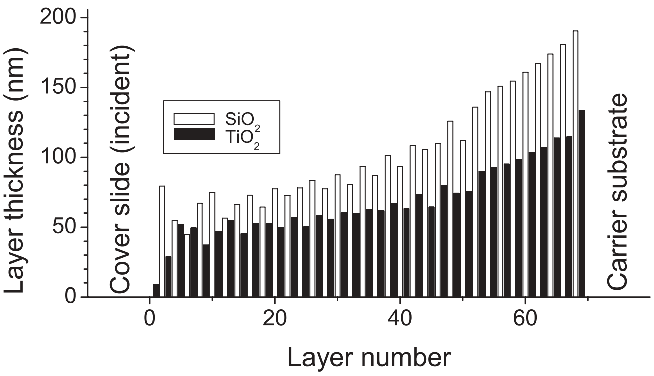

FIGURE 3 BASIC mirror design. Layer thickness vs. layer number. Numbering starts at the interface between cover slide and layer stack. The total physical thickness of the mirror stack amounts to 5.9 μm

pulse's group delay dispersion, therefore, appears to be due the combined material dispersion of the two 0.5 mm silica windows, the dispersion of the noble gas fill of the hollow fiber, and external air paths. For design of the mirror, this measured dispersion was augmented by the dispersion of 2.4 mm of BK7 glass to account for the cover glass in the BASIC design approach. The total net dispersion was divided into 12 bounces (see solid line in Fig. 2b). For nominal operation, the compressor mirrors need to be operated at a cover slide thickness of 100 microns.

Figure 2 shows the design of the chirped mirror coating. The coating consists of 69 layers with a total physical thickness of 5.9 μm. Optimizing the coating design, a strong emphasis was put on the best possible dispersion properties. This results in a low-ripple design with an rms dispersion ripple of 12 fs^2, ranging from 480 nm to more than 1050 nm. Some compromises had to be made concerning the reflectivity of the coating. The reflectivity exhibits a dip in the 800 nm region of the coating. For an external compression application, this reduced reflectivity is tolerable in the pump region. Together with losses from the antireflection coating of the top surface of the cover slide, all losses add up to about 30%–40% at 800 nm. Outside the pump region, however, they are considerably lower.

Both coatings, the AR coating and the chirped mirror section, were deposited by ion beam sputtering. This technique is often favored when high performance coatings with particularly stable spectral characteristics and minimum optical losses are required. The thickness tolerances of the coating lie in the region of from 0.2 to 1 nm, with the most sensitive layers close to the interface between layer stack and cover slide. In order to fulfill these stringent tolerances for each dielectric layer in the stack, a broadband optical monitoring system was utilized [25, 26]. This thickness monitor renders an in-growth measurement of the transmittance of the layer system possible and allows controlling the coating plant automatically according to the desired design.

3 Experimental set-up

In the experimental set-up shown in Fig. 4, the output of a 1-kHz Ti-Sapphire laser amplifier with 25 fs pulse duration and 0.5 mJ energy is launched into a first 60 cm long tapered hollow fiber with an inner input radius of 250 μm and an inner output radius of 150 μm, filled with argon at a pressure of 0.2 bar. The gas pressure was adjusted in order to obtain pulse duration of 10 fs after compression using 5 bounces off standard chirped mirrors, which introduce a total negative dispersion of $-180\,fs^2$. These pulses are then focused into a second cylindrical hollow fiber with an inner radius of 150 μm, filled with argon at a pressure $p = 0.1$ bar. The generated coherent supercontinuum from the second stage covers the whole visible and near infrared spectral region from 400 to 1000 nm with an energy of $\simeq 100$ μJ in a nearly diffraction limited beam.

The ultrabroadband chirped mirrors described in the previous section were used to correct the spectral phase dispersion of the output of the second fiber. For an optimal recompression, 20 bounces off the chirped mirrors were used. The mirrors were aligned in a symmetric configuration

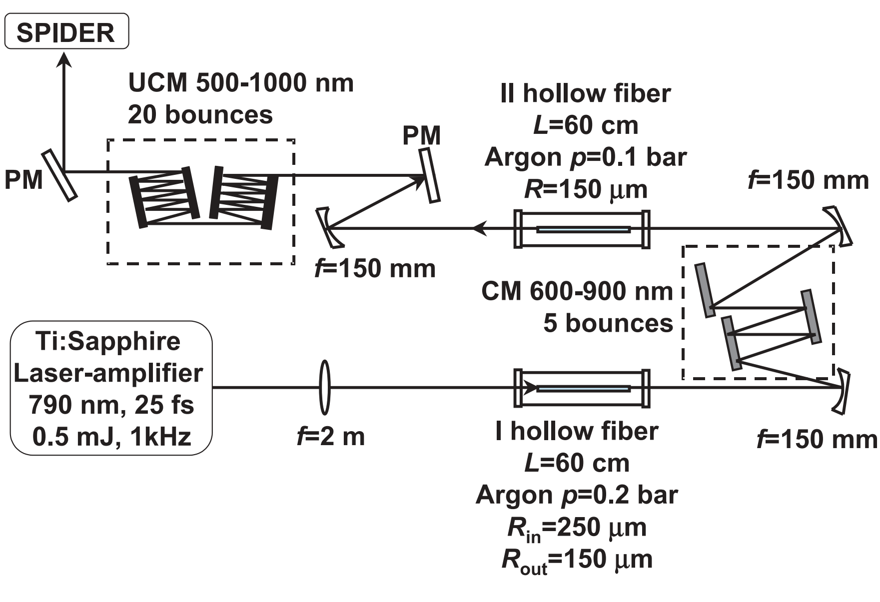

FIGURE 4 Experimental setup. PM plane mirrors; CM conventional chirped mirrors for dispersion compensation after the first fiber; UCM ultrabroadband chirped mirrors for dispersion compensation after the second fiber

(see Fig. 4) in order to cancel the angular dispersion introduced by the wedge plate of a single ultrabroadband chirped mirror.

4 Compression results

For a complete temporal characterization of the pulse, we used spectral phase interferometry for direct electric-field reconstruction (SPIDER) [28]. The SPIDER apparatus was optimized for sub-10 fs pulses [29]. In order to prevent temporal broadening of the pulses, we used two 400 μm thick ultrabroadband dielectric beam splitters optimized for ultralow dispersion over the 450–1000 nm spectral range in a symmetric configuration and a 30 μm thick type-II BBO crystal for broad bandwidth. The measured SPIDER trace is shown in Fig. 5a.

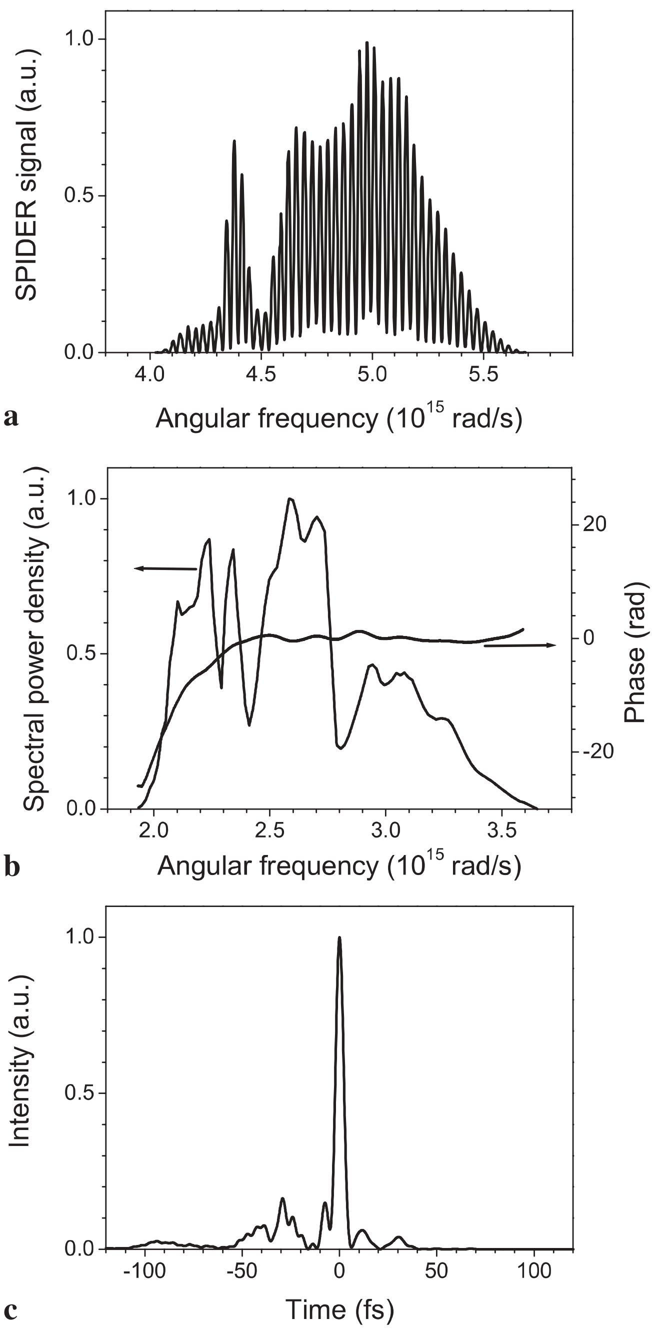

FIGURE 5 **a** Measured SPIDER trace. **b** Measured spectrum and reconstructed phase from the SPIDER measurement. **c** Temporal profile of the pulse after 20 bounces off the ultrabroadband chirped mirrors

The measured spectrum and the reconstructed phase after 20 bounces off the ultrabroadband chirped mirrors are shown in Fig. 5b. The spectrum extends over a bandwidth of 270 THz, corresponding to a transform-limited duration of 3.8 fs. The measured phase is quite flat from 3.6×10^{15} rad/s down to 2.4×10^{15} rad/s; in the infrared part of the spectrum, the rapid decrease of the residual phase is responsible for the temporal broadening of the pulse.

Figure 5c shows the reconstruction of the temporal profile of the pulse with a FWHM of 4.6 fs. Due to uncompensated dispersion in the infrared region, some satellite pulses with less than 20% of the intensity of the main pulse appear. In order to fully exploit the potential of the cascading scheme and obtain sub-4-fs pulses, the development of new ultrabroadband chirped mirrors with corrected phase in the infrared is required. One novel possibility for the design of such mirrors is the Brewster-angle method [21]. Nevertheless, the current results already confirm the possibility of generating sub-5 fs pulses using only chirped mirrors for dispersion control. This static approach ensures an excellent stability of the pulses in terms of pulse duration and spectral phase due to the absence of moving parts for the dispersion optimization control [27].

5 Conclusion

In conclusion, we have demonstrated the compression of a coherent supercontinuum generated by cascaded hollow fibers using exclusively chirped mirrors. Pulse widths down to 4.6 fs were reached with an energy of 20 μJ. The 270 THz bandwidth is the broadest bandwidth ever controlled by dispersive mirrors at this energy level. The short pulse duration and the high peak intensity make the combination of a cascaded hollow fiber and ultrabroadband chirped mirrors a very compact and reliable tool for extreme nonlinear optics experiments.

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