پالسهای کوتاهتر از ۸ فمتو ثانیه: حاصل فشرده سازی نور سفید تولید شده توسط تار نوری توخالی

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چکیده – برای تولید نور سفید پیوسته با شدت طیفی بالا از تار نوری توخالی شیشه ای با قطر داخلی ۲۵۰ میکرومتر استفاده شد. این تار روی یک پایه V شکل درون یک محفظه لوله ای پر شده با گاز آرگون نصب شده است. پرتو یک لیزر تیتانیوم-سفایر با پالسهای ۳۰ فمتوثانیه توسط یک عدسی تخت-کوژ در ورودی تار نوری توخالی کانونی می شود. شدت بالای پرتو لیزر درون این تار توخالی باعث بروز پدیده تغییر فاز خود به خودی شده که نتیجه آن پهن شدگی طیف پرتو لیزر می شود. میزان پهن شدگی به پارامترهای مختلفی از جمله انرژی پالسهای ورودی، طول پالسها، طول تار نوری، فشار گاز درون تار و نسبت قطر پرتو ورودی در محل کانون به قطر داخلی تار بستگی دارد. در شرایط بهینه طول تار ۱۷۵ سانتی متر، انرژی پالس ۵۰۰ میکرو ژول، فاصله کانونی عدسی ۱۵۰ سانتی متر و فشار گاز آرگون ۰٫۶ بار طیف پیوسته نور سفید دارای گستره ۶۰۰ نانومتر تا ۹۵۰ نانومتر است که پس از عبور از درون یک فشرده ساز دارای ۸ آینه چیرپ منجر به تولید پالسهایی با طول پالس کمتر از ۸ فمتو ثانیه شد.

کلید واژه- اپتیک غیر خطی، پالسهای فمتو ثانیه، تار نوری توخالی، تغییر فاز خود به خودی، پیوستار نور سفید

Sub-8 fs Pulses: a Consequence of Compressing White Light Continuum Generated by Hollow Core Fiber

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Abstract - In order to generate high-spectral-irradiance white light continuum (WLC) a hollow fiber with 250 µm inner diameter was used. The hollow fiber was mounted on a V-groove holder inside a chamber filled with Argon gas. The output beam of a Ti:sapphire laser producing 30 fs pulses was focused at the entrance of the hollow fiber using a plano-convex lens. The high intensity of the incident laser beam inside the hollow fiber causes self-phase modulation leading to broadening the spectral of the input light. The broadening strength depends on many parameters such as the energy of the incident pulses, duration of incident pulses, length of hollow fiber, gas pressure inside the hollow fiber and the ratio of the beam waist diameter to inner diameter of the hollow fiber. At optimal conditions of 175 cm length hollow fiber, 500 µJ pulse energy, 150 cm focal length lens and 0,6 bar gas pressure the white light exiting the fiber possesses a spectrum ranging from 600 nm- 950 nm which results in generation of sub-8 fs pulses via compressing by a compressor consisting of 8 chirp mirrors.

Keywords: femtosecond pulses, hollow fiber, nonlinear optics, self–phase modulation, white light continuum

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1 Introduction

White light continuum (WLC) generation is a nonlinear optical process in which the spectral bandwidth of input pulses are broadened in the range from the UV to the IR as ultrashort laser pulses propagate through a transparent medium [1]. Alfano and Shapiro were the first to report WLC generation by focusing powerful picosecond pulses in glass samples in 1970 [2, 3]. WLC can also be generated by focusing high energetic ultrashort laser pulses into other transparent mediums such as deionized water [4], optical fiber [5], photonic crystals [6], dielectric and semiconductors [7], crystals such as YAG and Sapphire [8] and inert gases such as Krypton, Argon and Neon [9, 10]. Using a noble gas confined by a hollow fiber instead of a bulk medium for WLC generation provide several advantages. Propagation of light along hollow fibers occurs through grazing incidence reflections at the inner surface thus, the same spot size is maintained along the entire fiber length leading to enhancement of nonlinear effects. In a bulk material, a tight focusing necessary to obtain high irradiance would limit the interaction length. A hollow fiber filled with inert gas can handle higher energy pulses than a bulk material. In a bulk material, when the irradiance is too high, avalanche ionization occurs which leads to damage and destroys the transmission and spatial beam quality. We produced sub-8 fs pulses by compressing WLC generated by slightly focusing femtosecond pulses into a hollow fiber filled with Argon gas. This work was done in Applied Physics Institute at Vienna University of Technology in Austria.

2 WLC Generation

Figure 1 schematically shows the setup used for WLC and sub-8 fs pulse generation in this work. The laser source used as a pump for WLC generation is a compact pro Ti:sapphire laser system producing 500 µJ, 30 fs, 800 nm pulses at 1 kHz repetition rate. The 10 mm laser beam is slightly focused using a plano-convex lens at the entrance of the 175 cm long hollow fiber. The inner diameter of the hollow fiber is 250 µm. we examined different lenses with focal length ranging from 100 cm to 175 cm to make the best matching between the laser beam waist diameter and the hollow fiber diameter. Using 150 cm focal length lens resulted in a 190 µm beam waist leading to best matching required for sustaining the single mode propagation through the entire length of the 175 cm long fiber. The hollow fiber is mounted on a V-groove holder inside a chamber filled with Argon gas. The chamber itself is mounted on a pair of xz translation stage allowing the adjustment of the fiber axis so that the pump beam travel through the hollow fiber without striking the fiber wall. Since the beam spot stability is very crucial, the pump beam path from the amplifier output to the chamber entrance is covered to prevent even the air flow. The laser spot at the focus should possess a high circularity to achieve the maximum efficiency of the WLC generation and also to attain a perfect beam profile demonstrating a spatially Gaussian distribution. To this end the focusing lens is mounted on a 2D rotation stage to adjust the incident angle on the focusing lens and consequently control the circularity and astigmatism. The guided light to the exit of the hollow fiber is spectrally broadened as a consequence of self-phase modulation and very high-order nonlinear processes [9]. The efficiency of WLC generation in this setup is higher than 40% leading to output pulse energies of greater than 200 µJ. The WLC beam emerged from the chamber is then travel through an ultra-broadband dispersive mirror compressor consisting of 8 chirped mirrors to remove the chirp and produce Fourier transformed pulses possessing the shortest possible duration. The first mirror in the compressor is a concave mirror to re-collimate

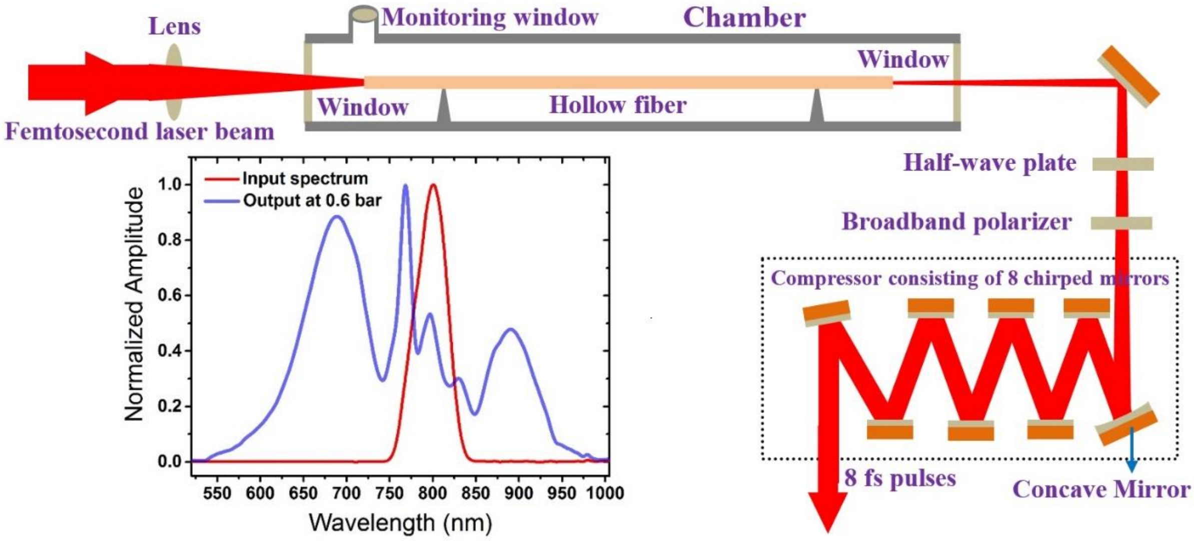

Figure 1. Schematic setup used for WLC generation in order to produce sub-8 fs pulses

the divergent beam exiting the hollow fiber. A set of half-wave plate and a polarizer can be mounted before the compressor to control the pulse energy required for different purposes.

2.1 Gas Pressure Dependence of the WLC Spectral Bandwidth

Argon gas was used to fill the chamber at different pressure to investigate the effect of gas pressure on the generated bandwidth. The spectral bandwidth of the WLC produced by Argon gas-filled hollow fiber showed strong dependency on the pressure of the Argon gas inside the chamber. Figure 2 shows how the WLC bandwidth broadens as the gas pressure inside the chamber is increased. When the chamber is evacuated (i.e. zero pressure) the spectrum of light exiting the hollow fiber is identical to the input pump (i.e. amplifier beam) with a peak at 800 nm and a bandwidth of 40 nm corresponding to a pulse duration of 30 fs. When the chamber is filled with Argon gas at pressure of 0.4 bar two blue-shifted and red-shifted peaks appear at 745 nm and 860 nm respectively. As the pressure of Argon gas is increased to 0.6 bar the peaks shift to 690 nm and 890 nm. At pressure of 1 bar the peak positions are 677 nm and 945 nm. When the pressure increased to 1.4 bar the peaks relocated to 585 nm and 980 nm so that the spectrum covers a large range of wavelengths from 500 nm to 1050 nm.

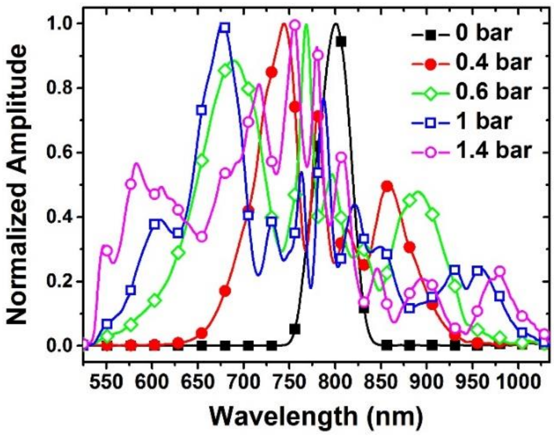

Figure 2. WLC spectrum at different gas pressure

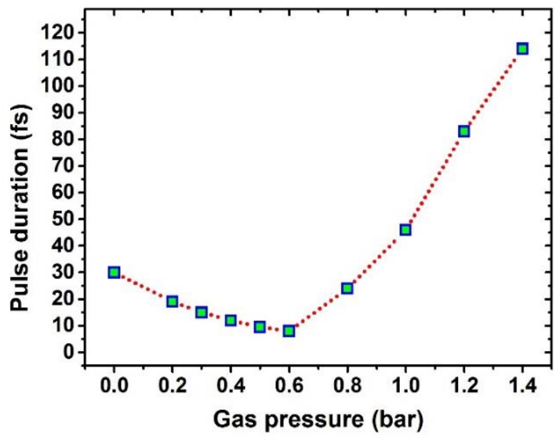

Figure 3. Pulse duration of compressed pulses at different gas pressures

3 Pulse Width Measurements for Compressed WLC Pulses

The pulse duration of the compressed pulses was measured using an autocorrelater after the compressor (see figure 4).

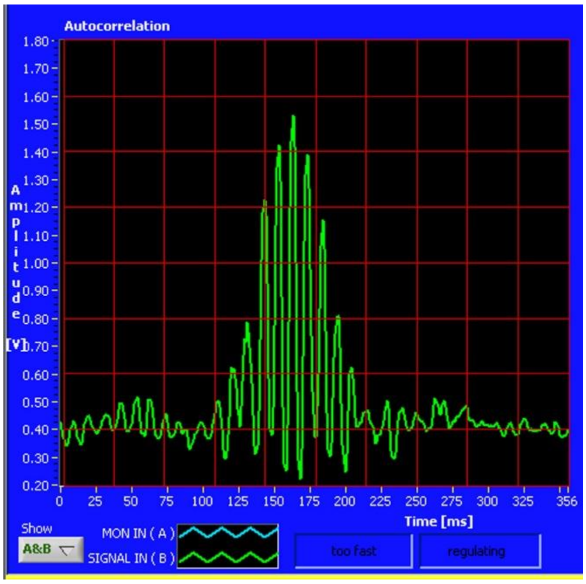

Figure 4. Interferometry Autocorrelation measurement showing 8 fs pulses.

Although the spectrum of the WLC broadens with increasing the Argon gas pressure inside the hollow fiber the pulse width of the pulses exiting the compressor does not accordingly decreases. As shown in Figure 3 the pulse duration decreased from 30 fs (for pump pulses) to below 8 fs as the pressure inside the hollow fiber is increased up to 0.6 bar. It is an expected trend since for Fourier-bandwidth-limited pulses the pulse duration is proportional with the reciprocal of the spectral bandwidth. Thus, the pulse duration has to decrease as the WLC bandwidth becomes wider as a consequence of pressure increase.

By further increasing of the gas pressure inside the chamber the observed results do not follow the same trend. The WLC spectral bandwidth although broadens the pulse duration no longer decreases but increases. This behavior happens because a complete compensation of the chirp carried by the spectrally broadened pulses cannot be achieved by the compressor when the spectral bandwidth grows beyond the range of 600-950 nm. In fact, at 0.6 bar gas pressure the setup outcome is nearly Fourier-bandwidth-limited pulses whereas this does not happen at higher gas pressures. As far as the generation of shorter pulses is concerned, the gas pressure of 0.6 bar is optimal value.

4 Conclusion

We generated sub-8 fs pulses by compressing the WLC generated by Argon filled hollow core fiber. The 10 mm diameter Ti-Sapphire laser was focused into 190 µm waist diameter inside a 250 µm inner diameter 175 cm long hollow fiber using a 150 cm focal length lens. The WLC spectral bandwidth increased by increasing the gas pressure inside the hollow fiber. The WLC then traveled through a compressor consisting of 8 chirped mirrors to eliminate the chirp carried by pulses exiting the fiber. The shortest pulses were obtained at gas pressure of 0.6 bar when the WLC spectrum covered the range of 600-950 nm.

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