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Generation of Sub-2 Cycle Optical Pulses with a Differentially Pumped Hollow Fiber *

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We report the generation of optical pulses with an energy of 0.55 mJ and duration of 1.6-cycle (4.4 fs) at repetition rate of 1 kHz using a differentially pumped hollow fiber and chirped mirrors. Compared to the statically gas-filled scheme, the differentially pumping hollow fiber is demonstrated to support more energy output with higher transmission efficiency, and to increase the spectral broadening due to a reduction of ionization defocusing in plasma at the fiber entrance. The differentially pumping technique is proved to be an effective way to obtain optical pulses with mono-cycle and higher energy.

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The generation of sub-10 fs optical pulses has opened a door for scientists with an essential tool in many fields, such as femto-chemistry,[1] high field physics,[2] time resolved laser spectroscopy[3] and high harmonic generation (HHG).[4,5] In 2006, a single isolated 130 attosecond pulse based on HHG is obtained by using driving pulses as short as 5 fs with energy of hundreds of microjoules.[6] Employing a hollow fiber filled with noble gas in combination with a chirped mirror compressor is an effective way for generation of few-cycle laser pulses.[7,8] Zhu *et al.* have achieved pulses with duration of 5.1 fs and energy of 0.4 mJ using a statically gas-filled hollow fiber in 2008.[9] The hollow fiber technique permits significantly longer interaction distance between high energy laser pulses and noble gas,[10] which results in a very broad spectral bandwidth. However, in a statically gas-filled hollow fiber, owing to ionization defocusing, damage and self-focusing at the entrance,[11,12] transmission efficiency is greatly limited and also the spot spatial shape is complicated.[13] To solve these problems, the differentially pumped hollow fiber was proposed, for its improvements of transmission efficiency and enhancement of spectral broadening.[10,13] The differentially pumped hollow fiber is defined such that the fiber entrance is pumped to vacuum and the gas is filled from the other side, so the gas pressure in the fiber is gradually increased when the laser pulses propagate from the entrance to the exit side.[14] Recent studies show that similar effect can be achieved by heating the entrance of the fiber and cooling the other side.[15]

Spectral broadening from a laser pulse propagating inside a gas-filled hollow fiber is mainly induced by self-phase modulation (SPM), as well as cross phase modulation (XPM), four-wave mixing (FWM) and stimulated Raman scattering (SRS) processes will occur simultaneously,[16] which result from the interaction between intense optical pulse and nonlinear medium. Intensity of input pulse, gas pressure and also optical coupling will strongly affect the spectral broadening. The two most widely filled noble gases in hollow fibers are argon and neon, especially neon, for its higher critical power for self-focusing. In this Letter, we report a careful study on comparison of spectral broadening in statically neon-filled and differentially pumped hollow fibers. The results show that a differentially pumped hollow fiber has significant enhancement of energy throughput and spectral broadening. At an optimum pressure in the differentially pumped case, we obtain an ultra-broad spectrum covering the range from 420 nm to 960 nm, which can support 3.3 fs transform-limited pulses. After fine compensation of dispersion induced by air, gas and optical components, we obtain pulses with duration of 1.6 cycle, which is close to mono-cycle, and with energy of 0.55 mJ, corresponding to a transmission efficiency as high as 68.8% for the seed pulses of 0.8 mJ in energy and 25 fs in duration. To the best of our knowledge, this is the highest transmission efficiency for neon gas filled hollow fibers so far.

Figure 1 shows the experimental setup. A typical chirped-pulse amplifier (CPA) based on Ti:sapphire laser delivers pulses with energy of 0.8 mJ and dura-

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tion of 25 fs at repetition rate of 1 kHz. The beam from this amplifier was focused into a fused silica hollow fiber with a length of 1 m and inner diameter of 250 μm by a lens with 1.5 m focal length. The fiber was kept on a V-groove and then placed inside a tube chamber made of stainless steel with Brewster-cut input and output windows (0.5-mm-thick fused silica). The vacuum chamber was filled with neon at the exit end and connected to vacuum pump at the entrance, so the pressure would gradually change along the fiber when the pump was running and was constant when it is turned off. Furthermore, the beam from the hollow fiber was collimated using a silver concave mirror with curvature radius of 4 m. The dispersion induced by gas in the hollow fiber, air and optical components such as lens, two windows, was compensated for by a set of broadband chirped mirrors and a pair of fused silica wedges.

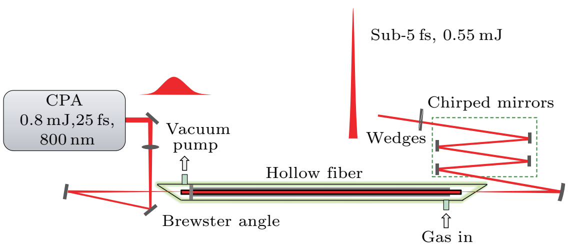

Fig. 1. Schematic of the experimental setup. The laser beam is focused into the differentially pumped hollow fiber by a lens with focal length of 1.5 m and then compensated for by chirped mirrors and a pair of thin wedges

With comparison of spectral broadening from statically filled and differentially pumped hollow fibers, the spectral broadening was obtained at different pressures, as shown by the spectra in Fig. 2. In the statically filled case, as the gas pressure increases, the spectrum broadens obviously, even at very low pressure. The broadest bandwidth covers the range from 460 nm to 930 nm (Fig. 2(c)) with transmission efficiency of 50% under the optimum pressure of 1.5 bar. When the pressure becomes higher, the broadening becomes unconspicuous and then the bandwidth starts to narrow with lower transmission and significant spot splitting, because of the energy loss due to ionization and defocusing at the fiber entrance. In the differentially pumped case, the bandwidth is almost unchanged at the pressure lower than 1 bar. With the increasing pressure, the spectrum continuously broadens with nearly constant transmission efficiency, which is only limited by the windows pressure capacity. The broadest spectrum obtained in this case is from 420 nm to 960 nm (Fig. 2(h)) with 0.55 mJ pulse energy, transmission efficiency of 68.8% at the pressure of 2.5 bar, which is more bandwidth broadening and more energy output compared with the statically filled case. These results show the obvious advantages of the differentially pumped hollow fiber, which supports 3.3 fs transform limited pulses with higher transmission efficiency. Based on a set of negative dispersion chirped mirrors and fine adjustment of the small angle wedges, laser pulses as short as 4.4 fs are obtained, as shown in Fig. 3. It corresponds to only 1.6 cycles at the central wavelength. The compressed pulse duration obtained is 1.3 times the Fourier transform limitation, the reason is that the higher order dispersions cannot be compensated perfectly.

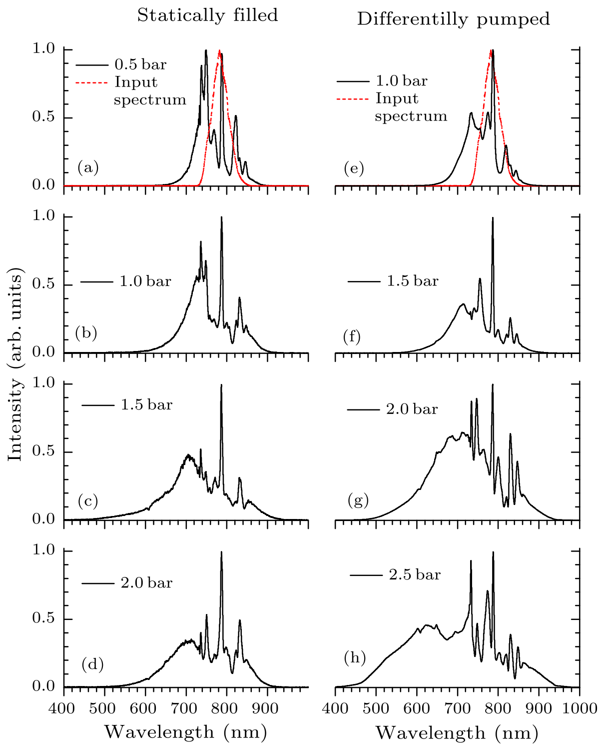

Fig. 2. Spectral broadening in the hollow fiber for the statically gas-filled (a)–(d) and differentially pumped (e)–(h) cases as a function of gas pressure. The dashed lines show the spectrum of the input pulse.

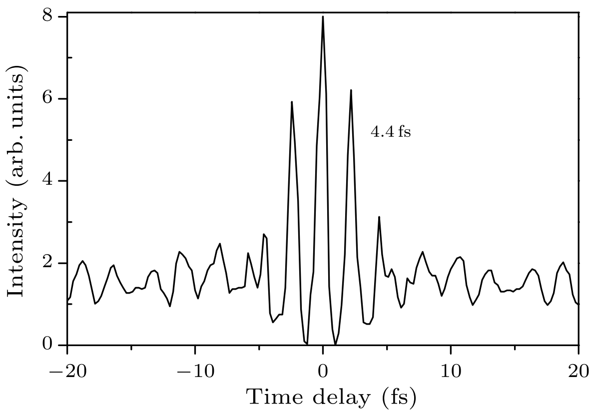

Fig. 3. Interference autocorrelation trace of the pulses after compression with chirped mirrors and wedges in the differentially pumped case.

Theoretically, the spectral broadening is primarily due to SPM when the laser pulses propagate inside the gas-filled hollow fiber. Assuming a Gaussian pulse, neglecting dispersions, the maximum bandwidth $\delta\omega_{\rm ab}$ obtained from the fiber can be approximated as[17]

$$\delta\omega_{\max} = 0.86\int_0^l \gamma(z)P_0\xi e^{-\alpha z}dz/T_0, \qquad (1)$$

where l is the length of the fiber, z is propagating distance, $\gamma(z) = n_2 p(z)\omega_0/cA_{\rm eff}$, n_2 is the nonlinear index coefficient ($7.4\times10^{-25}\,{\rm m^2/W}$ bar in neon), $p(z)$ is the gas pressure along the fiber, ω_0 is the central frequency, c is the light speed in vacuum, $A_{\rm eff}$ is the effective mode area, P_0 is the peak power, ξ is the coupling efficiency, α is the attenuation coefficient of the fiber, and T_0 is the temporal half-width at the $1/e$ intensity point of the input pulse. In the statically gas-filled case, the pressure is constant along the fiber. While in the differentially pumped case, the pressure is chosen to be a minimum (0 bar) at the entrance and gradually increases along the fiber. This leads to the pressure distribution

$$p(z) = \left[p_0^2 + \left(\frac{z}{L}\right)(p_L^2 - p_0^2)\right]^{1/2}, \qquad (2)$$

where p_0 and p_L are the pressure at the entrance and the exit, respectively.[18] Then the bandwidth broadened in both the cases can be expressed as

$$\Delta\omega_{\rm SF} = 0.86\omega_0 n_2 P_0\xi p_L(1-e^{-\alpha L})/\alpha c T_0 A_{\rm eff}, \qquad (3)$$

$$\Delta\omega_{\rm DP} = 0.86\omega_0 n_2 P_0\xi p_L\int_0^L \frac{\sqrt{z}e^{-\alpha z}}{\sqrt{L}\,cT_0A_{\rm eff}}dz. \qquad (4)$$

At the entrance of the fiber, the laser beam is focused to a spot in diameter of 130 µm with a peak power of 30 GW, resulting in a peak intensity of $2.34\times10^{14}\,{\rm W/cm^2}$. In the statically gas filled case, the neon gas pressure is constant along the fiber, so the intense laser can easily ionize the neon gas at the entrance. This leads to a considerable energy loss and strong beam defocusing, and then reduces coupling efficiency and SPM effect in the fiber. While in the differentially pumped case, the neon gas is pumped to vacuum at the entrance, preventing ionization, reducing energy loss due to defocusing at the entrance, and enhancing coupling efficiency. To compensate for the shortening of the virtual interaction length in the fiber, the gas pressure at the exit end must be increased, compared to that in the statically case. In this way, the spectrum can continue to broaden without large energy loss. According to our calculations and experiments, the calculated and measured bandwidths broadening at the full-width-half-maximum (FWHM) level for each case are shown in Fig. 4. When the pressure is around the optimum situations, the experimental results are broader than the calculations. It is due to the fact that SPM process is taken in account in our calculation, but actually SPM is the main but not the only process which broadens the spectra in the fiber, XPM, FWM, SRS processes also contribute to the spectral broadening when the laser intensity and the pressure are strong enough.

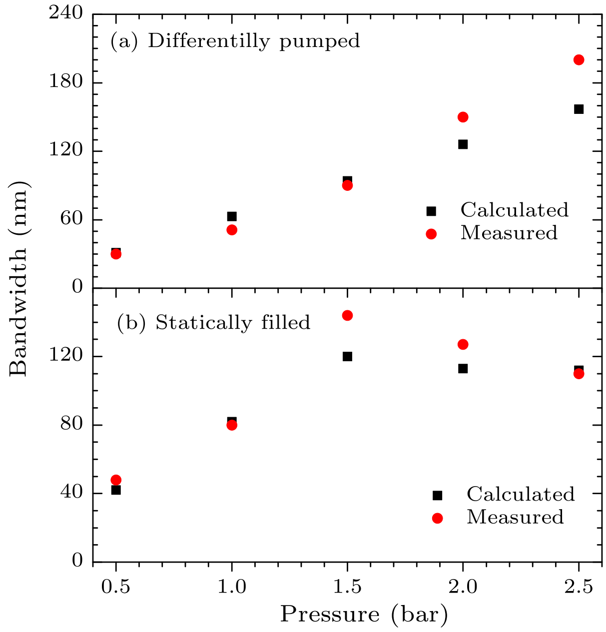

Fig. 4. Calculated and measured bandwidths broadening at the full-width-half-maximum (FWHM) for both the differentially pumped (a) and statically gas filled (b) cases.

In conclusion, we have carried out studies on spectral broadening based on the differentially pumped and statically gas filled hollow fibers. Through the 1-m-long differentially pumped hollow fiber, the broadened spectra cover from 420 nm to 960 nm with 68.8% transmission efficiency at 0.55 mJ level, and subsequently compressed pulses with duration of 4.4 fs have been achieved, the spectra cover from 460 nm to 930 nm with transmission efficiency of lower than 50% in the statically gas-filled case. The enhancement of transmission efficiency and broaden spectra is due to no ionization and no defocusing effect at the entrance in the differentially pumped hollow fiber. This scheme is very helpful for the generation of mono-cycle pulses with high energy, and a powerful driving laser for HHG and the generation of single attosecond pulses.

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