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Spectral broadening of femtosecond laser pulse through ionizing-gas-filled capillary

Xiaowei Song, Jingquan Lin*

Department of Physics, Changchun University of Science and Technology, Weixing Road 7089, Changchun 130022, China

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ABSTRACT

This paper presents experimental results of spectral broadening of femtosecond laser pulses induced by self phase modulation from plasma nonlinearity while propagating through ionizing-gas-filled capillary. Spectral broadening of the output laser pulses from capillary is in excess of 50 nm under experimental conditions of 10 mm long capillary and with a back pressure of 50 Torr nitrogen. The input and output laser pulse energy is 27 and 5.4 mJ, respectively. Both the maximal input and output energy of laser pulses under this scheme are much higher than those employing Kerr-effect exclusively with laser intensity lower than multi-photon or self-focusing threshold of the gas. Phase of the spectrally broadened laser pulses is measured to be quadratic at exit of the capillary. This novel plasma nonlinear source has the potential application in the direct generation of few-optical-cycle pulses with energies of at least several mJ.

1. Introduction

The spectral broadening of optical pulses employing Kerr-effect in gas-filled capillary and their subsequently compression in a dispersion delay line has been reported in several papers [1–3], and this technique has the ability to generate 5 fs pulses with moderate level pulses energy. The maximum of input energy for ultrashort pulses compression in gas-filled hollow capillary is limited by the multiphoton ionization or self-focusing threshold, this gives the usable pulses energies in sub-mJ level according to recent experiment [3]. As a solution, a novel nonlinear source used for pulses compression, which shows that pulses energy constraint can be relaxed by use of plasma nonlinearity of an ionizing gas in a hollow capillary, has been proposed [4].

A capillary tube with dielectric walls is a leaky guide. Besides the losses that are due to coupling laser pulses at the entrance of the capillary tube, losses associated with refraction of the beam at the wall occur during propagation. Wave propagation along the hollow capillary can be thought as occurring through grazing incidence reflections at the dielectric surface. Since the losses caused by these multiple reflections greatly discriminate against higher order modes, only the fundamental mode can propagate in a sufficiently long capillary. Therefore, it is important to select a suitable capillary to minimize the energy loss caused by propagation. The modes of hollow capillary with diameters much larger than laser wavelength were considered by Marcatili and Schmeltzer [5]. For the fused silica hollow capillary the lowest loss mode is the EH_{11} mode. The intensity profile as a function of the radial coordinate r is given by $I(r) = I_0 J_0^2(2.405r/a)$, where I_0 is the peak intensity, J_0^2 is the zero-order Bessel function, and a is the bore radius. For this mode, the damping length is given by

$$L_{\mathrm{d}}^{-1} = Im\left[\frac{2.405^2}{2a^3}\left(\frac{\lambda}{2\pi}\right)^2 \frac{1+\varepsilon^2}{\sqrt{1-\varepsilon^2}}\right] \quad (1)$$

where λ is the laser wavelength in free space, and ε the index of refraction of dielectric capillary tube. Theoretically, it is most favorable for EH_{11} mode excitation when $\omega_0/a = 0.645$, where ω_0 is the focal spot radius at $1/e^2$ intensity.

Laser pulses with high intensity will experience spectral broadening due to the arising nonlinearity effect when propagating through the gas-filled hollow capillary. If laser intensity is lower than multiphoton or self-focusing threshold of a gas, the broadened spectrum exhibits a feature of shifting towards both red and blue sides. However, spectral broadening with intensity higher than multiphoton or self-focusing threshold shows a different picture. As an intensive femtosecond laser pulse propagates through a gas-filled capillary, around pulse peak ionization can cause a rapid increase in the electron density. The plasma refractive index can be written as $n = (1 - N_e/N_{cr})^{1/2}$, where N_e is free electron density, and N_{cr} is critical electron density of plasma. Hence a decrease in the refractive index will be resulted from increase of the electron density. This self-phase-modulation leads to the complementary effects of spatial defocusing and spectral broadening. The effects

* Corresponding author. Tel.: +86 431 85582496.
E-mail address: linjingquan@cust.edu.cn (J. Lin).

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are remarkably different to those which result from self-phase-modulation at lower intensity [6], because the polarizibility is relatively large and the rate of ionization is a highly nonlinear function of the intensity. In addition, the ionization process is essentially irreversible in a femtosecond time scale, and as a result the spectral broadening is mainly towards one side, containing predominantly blue-shift component. More importantly, around pulse peak the refractive-index change due to the free electron is far larger than that due to Kerr nonlinearity of neutral gas, and so it is with the extent of spectral broadening. This kind of plasma-induced spectral broadening has been analyzed in the reference [7]. The spectral broadening can be expressed as

$$\Delta\lambda = -\frac{e^2 N_i \lambda_0^3 L}{8\pi\varepsilon_0 m_e c^3}\frac{dZ}{dt} \tag{2}$$

where N_i is the ion density, Z is the degree of ionization, λ is the incident wavelength, L is the effective plasma length. Therefore, it is possible to efficiently broaden the spectrum of high energy pulses by optimizing experimental parameters such as gas pressure, laser intensity, and capillary length according to above equation. Naturally, the usable input laser energies employing plasma nonlinearity in spectral broadening is higher than that based on neutral electronic nonlinearity.

In this paper, we report the experimental results of efficient spectral broadening by self phase modulation from plasma nonlinearity in gas-filled hollow capillary. The aim of this work is to study the nonlinear source which is potential for the direct generation of ultrashort and high energies pulses. The experimental results show that we have succeeded in obtaining spectral-broadened pulse with energy of 5.4 mJ while the input pulse energy is 27 mJ. These values are higher by an order of magnitude than the pulses energies that have been realized to date in hollow-capillary pulse-compression systems that used Kerr nonlinearity exclusively [3]. The measured phase over the temporal FWHM is quadratic and can be potentially compensated by a chirped mirror.

2. Experiment

The laser system we used is a commercially available (Coherent), 10 Hz Ti:sapphire chirped pulse amplification system with a pulse duration of 100 fs and a maximum energy output of 30 mJ. Fig. 1 shows the target configuration for the gas-filled capillary experiment. The linearly polarized laser pulse passed though a 5 mm MgF_2 window into an evacuated chamber, and was focused by an f = 400 mm MgF_2 lens onto a capillary target. The Rayleigh range of the focusing optics was Z_R = 0.8 mm. The capillary was put in small chamber as shown in Fig. 1. In order to couple the high intensity laser pulse into the capillary, we fixed the capillary holder on a 5-dimensional translation stage. For each experiment, we first pump down the chamber to 10^{-3} Torr, and then filled the chamber with nitrogen gas. We measured the input and output laser energies with a calorimeter (FieldMaxII-Top, Coherent, USA), and the output broadening spectra is measured by fiber spectrometer with an operating spectral range between 300 and 1700 nm

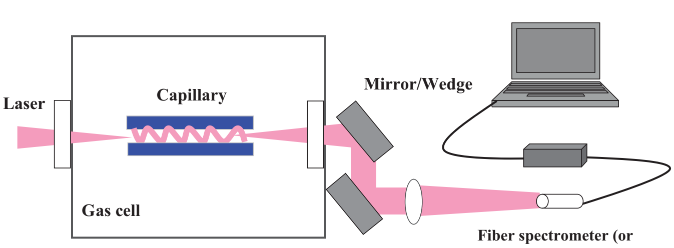

Fig. 1. Experimental setup for the nonlinear plasma source and its characterization.

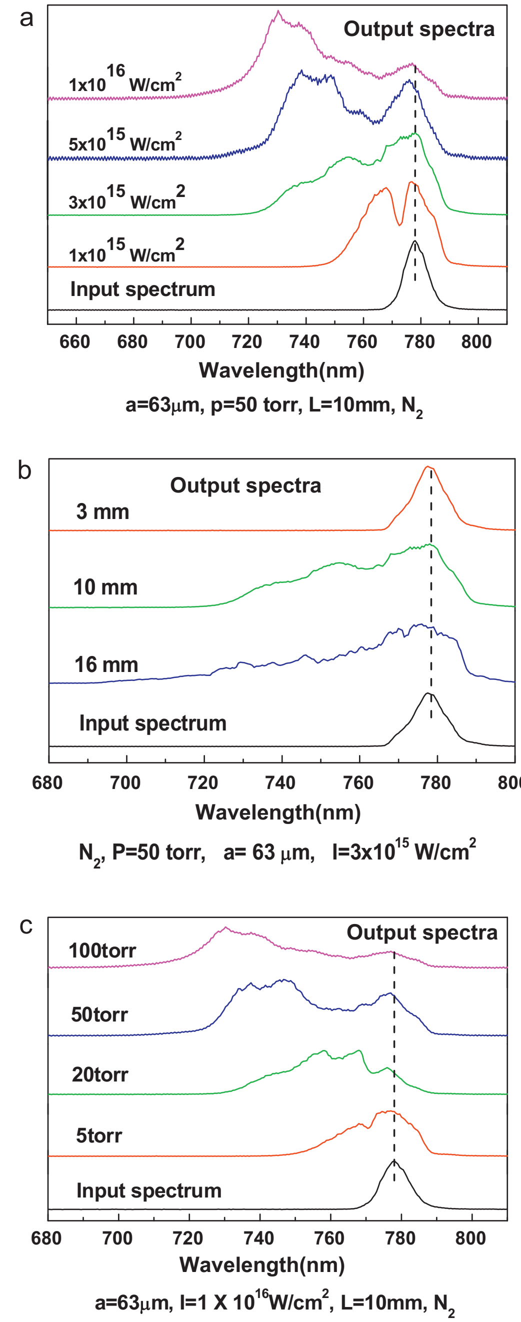

Fig. 2. Spectral broadening of the output pulses from plasma-filled capillar, where (a) shows the spectral broadening vs laser intensity, (b) vs capillary length, and (c) vs nitrogen pressure.

(AvaSpec-2048-NIR256-USB2). Phase of the output pulse is measured by frequency resolved optical grating (FROG) technology [8]. Different bore radius fused silica was tested, and the highest laser energy transmission for our case of ω_0 = 30 μm was obtained by use of the capillary with bore radius of 63 μm.

3. Results and discussion

Fig. 2 shows results of spectral broadening measured at the exit of the gas-filled capillary versus gas pressure, laser intensity and capillary length. As shown in the figure, spectral broadening generally increases with the increasing of those parameters. The spectral broadening (FWHM) is about 50 nm after a capillary with length of only 10 mm at input laser intensity of 1×10^{16} W/cm^2 as shown