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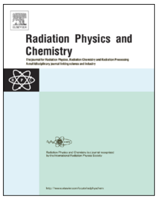

Reaching white-light radiation source of ultrafast laser pulses with tunable peak power using nonlinear self-phase modulation in neon gas

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HIGHLIGHTS

- A source of ultrafast white-light radiation has been developed.
- Observation of transform-limited pulses of 5.77 fs by compressing 32 fs pulses.
- Attainment of tunable peak power values varied from 57 GW up to 104 GW.

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ABSTRACT

A source of white-light radiation that generates few-cycle pulses with controlled peak power values has been developed. These ultrafast pulses have been observed by spectral broadening of 32 fs pulses through nonlinear self-phase modulation in a neon-filled hollow-fiber then compressed with a pair of chirped mirrors for dispersion compensation. The observed pulses reached transform-limited duration of 5.77 fs and their peak power values varied from 57 GW up to 104 GW at repetition rate of 1 kHz. Moreover, the applied method is used for a direct tuning of the peak power of the output pulses through varying the chirping of the input pulses at different neon pressures. The observed results may give an opportunity to control the ultrafast interaction dynamics on the femtosecond time scale and facilitate the regeneration of attosecond pulses.

1. Introduction

Generation of an artificial white-light radiation source of ultrashort laser pulses is essential for applications such as: x-ray free electron laser X-FEL era (Adams et al., 2015), and applications of pulsed radiation implied by femtosecond-laser-induced high harmonic generation (HHG) (Feng et al., 2012; Cairns et al., 2009; Rocca et al., 1994; Hentschel et al., 2001). For ultrafast white light pulses, the electronic dynamics induced in molecules during the interaction with the pulse can be controlled by tuning the phase between the envelope and the field, which cannot be achieved by using conventional light sources (Mignolet et al., 2015).

Since the invention of the laser, it has been a dream for many scientists to generate bright source of white-light source with spectrum spans from the deep-ultraviolet to near-infrared, to employ it for state-selective chemistry (Judson et al., 1992). The phenomenon of white light continuum or supercontinuum (SC) generation that occurs during the propagation of a short intense laser pulse in a nonlinear optical medium has been known for more than three decades (Chin et al., 1999). SC generation is a process where laser light is converted to light with a very broad spectral bandwidth, whereas the spatial coherence usually remains high and the temporal duration ranges from femtosecond to nanosecond, depends on the seeding laser source (Alfano and Shapiro, 1970; Ranka et al., 2000). In 2000, Ranka et al. developed the first SC laser that could reveal anomalous dispersion at visible wavelengths from 500 to 1600 nm (Ranka et al., 2000). They injected 100-fs-duration pulses with only 8 kW of peak power at ~800 nm to induce nonlinear interaction in a 75-cm length of air–silica microstructure optical fiber. Even though, the observed results have represented a great success in comparison with previous work that has employed pulses with megawatt peak powers for generation of similar spectra (Pshenichnikov et al., 1994), the limitation of the observed peak power to 1.6 kW has represented a disadvantage.

Classically, high power broadband-radiation laser systems rely on complicated Ti:Sapphire amplifier to reach terawatt-frontiers

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(Pittman et al., 2002; Ito et al., 2003; Barty et al., 1996; Ishii et al., 2005). However, these systems have several problems such as pulse deformation which is caused by thermal load and thermal lensing inside the laser gain media (Shank et al., 1982). Consequently, it is very challenging to reach ultrashort laser pulses using such complicated systems for energies above one joule levels (Martinez et al., 1984).

In general, relatively long pulses can be compressed to very short ones in by two methods: linear-pulse compression and nonlinear-pulse compression (Fork et al., 1984). In the first technique, as soon as laser pulses are chirped, their periods can be shortened by reducing this chirp, i.e. by spectral-phase broadening. Thus, in linear pulse compression, a chromatic dispersion takes place if the laser pulses go through a dispersive optical element such as chirped mirrors, an optical fiber, a diffraction grating pair and a pair of prisms (Tomlinson et al., 1984; Alfano et al., 1986; Takeshi Kamiya and Masahiro Tsuchiya, 2006). The shortest possible pulse duration is governed by the dispersive compression limits and the optical bandwidth of the pulses. However, for the case of nonlinear pulse compression process, the optical bandwidth can be enhanced by supercontinuum, which can be generated by self-phase modulation (SPM) in nonlinear medium (Eggleton et al., 2000). Furthermore, after SPM, linear compression is employed to further compact the resulted chirped pulses (Agrawal et al., 2001).

The Kerr-nonlinearity-prompted intensity-dependent modification of the refractive index is a key physical parameter associated with supercontinuum generation. Therefore, most of the nonlinear effects of optical martials, such as optical fibers, originate from nonlinear refraction, the intensity dependence of the refractive index resulting from a significant contribution of optical susceptibility χ. Hence, the refractive index of a medium with a Kerr nonlinearity is given by Boyd (2008):

$$n = n_0 + n_2 I(t) \tag{1}$$

where $I(t)$ is the laser light intensity, n_0 is the field-free unperturbed refractive-index of the optical medium, $n_2=(2\pi/n_0)^2 \chi^{(3)}(\omega;\omega,\omega,-\omega)$ is the nonlinear refractive index at the optical frequency ω, $\chi^{(3)}(\omega;\omega,\omega,-\omega)$ is the third-order nonlinear-optical susceptibility (Shen et al., 1984).

The maximum possible SPM that can induce spectral-broadening of the laser pulse after passing through a distance L in a nonlinear material can then be estimated as (Hasegawa et al., 1973):

$$\Delta\omega(t) = \frac{\omega}{c} n_2 L \frac{I_0}{\tau} \tag{2}$$

where τ is the laser pulse width, c is the speed of light in vacuum and I_0 is the peak intensity of the pulse. Actually, SPM is accountable for spectral broadening of ultrashort pulses and the presence of optical-solitons in the anomalous-dispersion regime of the optical fibers. The third-order of susceptibility controls the nonlinear effects, which appear to be elastic, assuming that no energy is exchanged between the dielectric medium and the electromagnetic field. Another part of nonlinear effects results from stimulated-inelastic-scattering because the optical field transfers contribution of its energy to the nonlinear medium. In case of focusing of the laser beam into a hollow-fiber fused silica capillary filled with a noble gas, the observed optical spectrum will be broadened to both longer and shorter wavelengths due to nonlinear SPM in the gas. In fact, the hollow-fiber allows observing a large-mode-area, which is suitable for higher pulse energy. Moreover, the use of noble gases permits many advantages for SPM. For instance, in case of moderate pressures, these gases have purely third-order nonlinearity, and one can control the nonlinearity impact by varying the gas type and its pressure. Usually, the multi-photon ionization (MPI) is avoided by keeping lower laser intensity than the threshold of MPI, which is principally appropriate for femtosecond pulses. Consequently, the propagation of light wave along hollow-fiber can be determined as grazing incidence reflections at the dielectric inner surface. Taking into consideration the multiple internal reflections, only the fundamental mode can propagate in a suitably long hollow-fiber, whereas the higher order modes cannot propagate because of higher losses in this case. If a hollow-fiber with a capillary radius (a) is much larger than the beam wavelength and the lowest loss mode is EH_{11} hybrid mode, its beam intensity profile as a function of the radial coordinate r given by Marcatili and Schmeltzer (1964):

$$I_0(r) = I_0 J_0^2(2.405r/a) \tag{3}$$

where Jo is the zero-order Bessel function and I_0 is the peak intensity. It is worth noting that, even though higher-order modes maybe excited, mode refinement would take place anyway, according to the higher loss rate of EH_{1m} with respect to fundamental mode. Mode selection in the capillary-fiber allows one to perform a spatial filtering of the input pulses.

In case of Gaussian pulse profile, if both of dispersion and self-focusing are ignored, the maximum output broadening spectrum that can occur after propagating a length of l inside a capillary-fiber can be written as;

$$\delta\omega_{max} = 0.86\gamma P_0 Z_{eff}/T_0 \tag{4}$$

where P_0 is the peak power; T_0 is the half-width (at the 1/e intensity point) of the pulse; $Z_{eff}=[1-\exp\alpha l]/l$, α is the imaginary part of the propagation constant; γ is the nonlinear coefficient and is given by $\gamma = n_2 p(z)\omega_0/cA_{eff}$ [n_2 is given by Eq. (1)], where n_2 is the nonlinear index coefficient, ω_0 is the laser central frequency; A_{eff} is the effective mode area; c is the light speed in vacuum.

A single-cycle optical pulse, the shortest possible waveform at a given wavelength takes place when the electric field within the envelope of an ultrafast optical pulse completes just one period before the pulse ends. In the near infrared region at around 0.8 µm, the duration of one optical cycle is approximately 2.7 fs. In this paper, a new method to control the pulse peak power of few-optical-cycle light pulses is described. In the proposed setup, the pulse compression is achieved by the nonlinear SPM in neon gas filled hollow-fiber and the output peak power value is found to be regulated by both the applied pulse duration and the neon gas pressure.

2. Experimental method

The ultrafast white-light radiation system is composed of a femtosecond oscillator, a regenerative amplifier and a final pulse compressor using neon gas as shown in Fig. 1. The oscillator laser is a mode-locked TEM_{00} 800 nm Ti:sapphire with of 425 mW for pulses of 18 fs and repetition rate of 80 MHz. The basic oscillator setup consists of pump beam mirrors, a pump beam focusing lens, folded cavity mirrors, a couple of concave spherical mirrors lined up with the Ti:Sapphire laser rod, metal coated mirrors, an output coupler, a slit as a spectral tuning element compensation and a set of prisms to compensate the dispersion. The seed beam can be tuned from 780 nm to 820 nm range by moving the tuning-slit up and down. A 4 W CW solid-state diode-pumped DPSS laser Opus (Laser Quantum Ltd.) at wavelength 532 nm, was used to pump the oscillator. Additionally, the observed seed beam was stretched in temporal domain by using a stretcher. The stretcher is composed of a standard two-pass scheme with a single diffraction