Ultrabroadband, coherent light source based on self-channeling of few-cycle pulses in helium

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Self-channeling of few-cycle laser pulses in helium at high pressure generates coherent light supercontinua spanning the range of 270–1000 nm, with the highest efficiency demonstrated to date. Our results open the door to the synthesis of powerful light waveforms shaped within the carrier field oscillation cycle and hold promise for the generation of pulses at the single-cycle limit. © 2008 Optical Society of America

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Shaping of the temporal profile of laser pulses on a femtosecond time scale has provided powerful means of steering the motion of atoms in microscopic systems with unprecedented resolution [1,2]. Extension of this control to electrons, giving rise to lightwave electronics [3], calls for intense light fields manipulated on an attosecond time scale and thus within a fraction of the optical cycle of visible light. Such light fields can be synthesized from coherent sources that span spectrally more than an optical octave.

Key steps toward this ultimate control of the electron motion include the generation of few-cycle laser pulses via nonlinear broadening of intense pulses in gaseous media [4] and compression with advanced multilayer optics [5]. Such pulses, recently endowed with carrier-envelope phase control [6], have enabled the generation of isolated attosecond soft-x-ray pulses [7,8] as well as the direct control of electron dynamics in atoms [9] and molecules [10].

Multiple-octave-spanning supercontinuum generation based on the nonlinear interaction of lasers with gaseous media has been demonstrated in a number of experiments in recent years [11,12]. However, high and near-uniform efficiency over several octaves, a prerequisite for the synthesis of light fields on a subcycle scale, has hitherto remained unattainable. Here we demonstrate that self-channeling of few-cycle laser pulses in helium enables the generation of such a supercontinuum, with an unprecedented efficiency and near-uniform spectral intensity over two octaves, covering the range of 270–1050 nm.

In our experiments, few-cycle laser pulses (~5 fs) carried at a central wavelength of ~750 nm are focused (f=60 cm) into a gas cell filled with helium gas with an energy of ~300 μJ. The 30-cm-long cell has been designed to sustain high gas pressure, adjustable in the range of 0 to 80 bar enclosed between two 0.5 mm thin, UV-grade fused-silica windows with a clear aperture of 0.5 cm. Higher pulse energies would come along with substantially lower critical gas pressure P_{cr} for the formation of a channeling and therefore allow for thinner input and exit windows. Self-channeling sets in at a pressure of ~25 bar, resulting in the formation of a ~5 cm-long channel and a substantial reduction of the beam divergence in the far field.

Following preliminary self-channeling tests in other noble gases, we opted for helium, because it appears to be the most resistive to multiple filamentation. Indeed, ~50% (~150 μJ/pulse) of the transmitted energy through the cell was delivered in a single beam. The rest of the energy is diffracted and manifests itself as a halo surrounding the output beam. We monitored the spectrum of the emerging supercontinuum using an intensity-calibrated fiber spectrometer (Ocean Optics, HR4000 200–1100 nm). An Ulbricht Sphere attached at the entrance of our spectrometer permits a beam-integrated spectral measurement of the light that reaches the spectrometer after attenuation by a pair of Fresnel reflections on fused-silica wedges. The generated spectrum is shown in Fig. 1; it spans two octaves, with almost-uniform intensity between 270 and 1000 nm that enables us to plot it on a linear scale. A spike centered at 750 nm (5% of the overall energy) is cut at about 60% to ensure appropriate visualization of the data. Further increase of the He pressure in the cell (tested up to ~40 bars) did not result in any significant effect on the observed spectra.

Access to the spectral phase or potential spatiotemporal distortions of such a broadband source is challenging even for the most advanced measuring techniques [13]. To gain insight into the physical process of self-channeling of few-cycle pulses in helium, which is responsible for the result summarized in Fig. 1, we have conducted numerical simulations modeling the underlying physical effects. These simulations allowed us to assess the extent to which

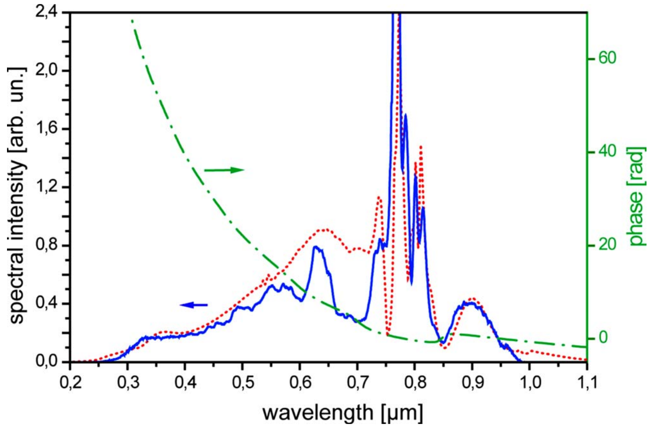

Fig. 1. (Color online) Supercontinuum generated by self-channeling of ~5 fs laser pulses carried at ~750 nm into a cell filled with helium at a pressure of 25 bars (solid curve). Dotted curve, spectra resulting from the numerical simulations; dashed-dotted curve, calculated spectral phase over the emitted bandwidth.

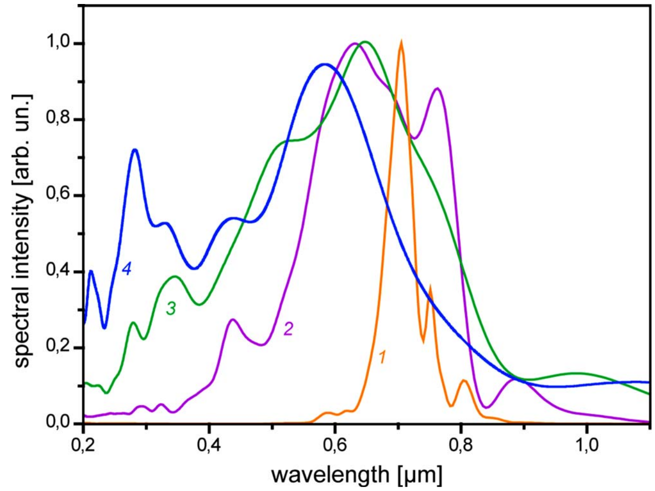

Fig. 2. (Color online) Calculated spectral broadening of ultrashort light pulses with different initial pulse widths of a Gaussian envelope in a gas chamber filled with 25 atm of He. The input pulse width is (1) 50, (2) 10, (3) 5, and (4) 3 fs. The input peak power is 44 GW.

spatiotemporal distortions may deteriorate compressibility of the spectrally broadened output pulses, and their results suggest the feasibility of compressing the pulses near to their Fourier limit (<2 fs).

Simulations were performed by numerically solving pulse-evolution equations in the framework of the slowly evolving wave approximation (SEWA) [14,15] adapted to include ionization phenomena and high-order dispersion effects (see the recent insightful review [16] for the discussion of the formalism and the computational aspects involved). Ionization effects were included in the simulations through the use of the Keldysh model [17] of ionization and the relevant kinetic equation for the electron density. Our simulations reveal the significance of both multiphoton and tunneling ionization for the considered experimental conditions, justifying the use of the full Keldysh model for the ionization rate.

The propriety of the above approach is further substantiated by the excellent qualitative and quantitative agreement between the measured and simulated spectra depicted in Fig. 1 for comparison. Few-cycle laser pulses used in these experiments play a particular role in reaching the observed efficiency. As the pulse envelope becomes shorter, the shockwave term, whose significance for spectral broadening is controlled by the ratio of the field cycle period T_0 to the pulse width τ_p, and the ionization-induced blueshift tend to play a progressively more important role in spectral broadening, leading to a dramatic enhancement of the high-frequency wing of the spectrum. Simulations are shown in Fig. 2. With the pulse width τ_p approaching the field cycle period T_0, high-frequency spectral components in the output spectrum are enhanced to such an extent that a plateau develops within the wavelength range from roughly 270 to 600 nm in place of an exponentially decaying short-wavelength tail of the spectrum, which is observed for longer pulses (cf. curves 1–4 in Fig. 2). This plateau is readily seen in the spectrum of the output field presented on a linear, rather than logarithmic scale, which would be necessary to visualize an exponentially decaying blue wing in the spectra emanating from longer light pulses. As illustrated by curve 4 in Fig. 2, with an input pulse width below 5 fs, spectral broadening can be further enhanced, allowing the generation of high-power supercontinua within an even-broader spectral range.

To assess the limits of compressibility of the light emerging by the transformation of our few-cycle pulse in a filament, we need to study its complete spatiotemporal profile. The spectral phase corresponding to light emerging at the center of the channel $\phi(\omega,0)$ is shown in Fig. 1 along with the corresponding measured and simulated spectrum. Figure 3(b) shows the field intensity $I(t,r)$ of the emerging light at the end of the He cell as a function of time t and the radial coordinate $r$after compensating for all orders of temporal dispersion. The latter can be considered feasible in the near future, as developments in advanced dielectric multilayer optics, dealing with both complex phase curves as well as a multioctave-broad spectral bandwidth, have resulted in impressive progress [18]. Figure 3(b) shows the calculated

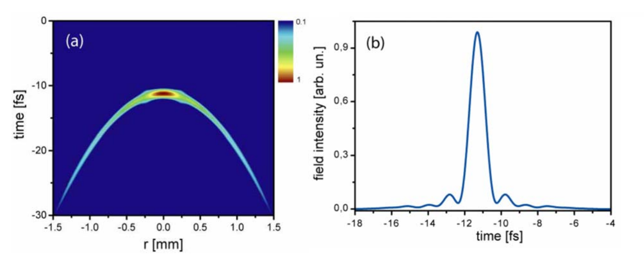

Fig. 3. (Color online) (a) Field intensity I calculated as a function of time τ and the radial coordinate r and after full compensation of the temporal phase; (b) a one-dimensional cut of the $I(t,r)$ map at $r=0$ for a few-cycle pulse transmitted through a gas chamber filled with 25 atm of He and a compressor compensating for the spectral phase of the output field. Parameters of the input laser pulse and focusing geometry were chosen to model the experimental conditions specified in the text.

intensity profile of a fully compressed pulse taken $I(t,0)$ right at the center of the channel. The pulse intensity profile in that case has a FHWM around $\sim$1 fs.

Although SEWA results cannot be absolutely accurate for a field with a spectral content supporting a 1 fs pulse width, an earlier numerical analysis of coupled Maxwell equations for subcycle-pulse evolution [19,20] suggests that dramatic deviations from SEWA predictions should not be expected either, unless the dispersion profile exhibits some special, resonance-type behavior, uncharacteristic of the pulse-propagation regime considered in this paper.

Despite the ultrashort duration indicated by our calculations, the spatiotemporal effects illustrated in Fig. 3(a), manifested as a gradual variation of the group delay and intensity drop as a function of the radial coordinate r, can result in a deterioration of the overall pulse contrast [21], in the absence of elaborate spatial filtering. Nevertheless, by spatially selecting some 15% of the energy carried within an area $\sim$1 mm, a high pulse contrast can be achieved, yielding an averaged duration of $\sim$2.5 fs. Furthermore, a pulse as short as $\sim$1 fs could be filtered with a smaller aperture transmitting almost 10% of the generated light. Higher efficiency should be possible by means of adaptive optics.

In conclusion we have been able, for the first time to our knowledge, to efficiently generate a powerful two-octave-spanning supercontinuum of coherent UV/VIS/NIR light with near-uniform intensity utilizing the self-channeling of few-cycle laser pulses in helium at high pressure. We have modeled the interaction and have been able to reach excellent agreement with the experimental results. This has enabled us to draw first conclusions on the spatiotemporal structure of the emerging ultrabroadband pulses and potential compressibility. By extending our simulation to even shorter pulses [22], we have been able to predict a great potential for extending highly efficient broadband sources, even to the VIS–UV part of the electromagnetic spectrum. The latter will benefit advanced-light waveform synthesis over several octaves of light. Decomposition of such a broadband light source into individual bands [3] and subsequent compression utilizing advanced multilayer optics [23] will open the door to the synthesis of powerful subcycle-shaped electric fields. Complete access into the temporal evolution of such fields might become possible with attosecond light sampling [24]. Furthermore, our broadband pulses could serve as a tunable source for molecular excitation and spectroscopy.

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