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Widely tunable femtosecond solitonic radiation in photonic crystal fiber cladding

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We report on a means to generate tunable ultrashort optical pulses. We demonstrate that dispersive waves generated by solitons within the small-core features of a photonic crystal fiber cladding can be used to obtain femtosecond pulses tunable over an octave-wide spectral range. The generation process is highly efficient and occurs at the relatively low laser powers available from a simple Ti:sapphire laser oscillator. The described phenomenon is general and will play an important role in other systems where solitons are known to exist.

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Ultrashort pulsed lasers have now become an essential tool in fundamental and applied science. The most common technique for generating ultrashort optical pulses relies on laser mode-locking [1]. The spectral location of these pulses is typically restricted to the near IR because of the available gain media. Widely tunable ultrashort optical pulses may be obtained with optical parametric amplifiers, but those systems are bulky and the total efficiency is low [2]. Additional degrees of flexibility are offered by solitons in fibers. Indeed, propagation dynamics of higher order solitons in optical fibers provides an efficient means for compression and red-shifting of ultrashort pulses [3]. With the advent of photonic crystal fibers (PCFs), there has been a revived interest in solitonic dynamics because of its relevance in supercontinuum generation [4]. Here, we report on a PCF-based technique that exploits efficient generation of resonant dispersive waves (RDWs) emitted from a soliton formed in a Kagome-PCF cladding [5]. It allows us to generate femtosecond pulses at wavelength ranges not covered by the conventional mode-locked lasers and with almost an octave-wide tuning bandwidth spanning from ~380 to ~700 nm. Furthermore, provided a judiciously engineered dispersion is used, this mechanism of RDW-based ultrashort pulse generation can be generalized to other media such as mode-locked fiber lasers or ultra-fast optical switchers, to mention just a few. This technique can also be used to transfer the temporal and spectral structure of a soliton to another spectral region.

Solitons have been the subject of intense theoretical and experimental studies in many different fields, including hydrodynamics, nonlinear optics, plasma physics, and biology [6]. Temporal optical solitons [7,8] are widely applied in optical communications and ultrashort laser systems. When there is a perturbation acting on a soliton (e.g., by a localized loss in the fiber or modified parameters in the laser cavity), a soliton will reshape and shed excess energy into RDWs [9]. So far, the interaction between a soliton and a dispersive wave has been considered to be a parasitic effect and the prior work on RDW *per se* was kept marginal relative to the soliton dynamics. Indeed, in all the soliton-related applications, the RDW generation is a source of dissipation of the soliton energy, which affects the performance of soliton-based telecommunication systems [10] and limits the pulse duration in soliton lasers [11].

It is well known that nanojoule femtosecond light pulses can generate supercontinua in PCFs [12]. However, in many cases instead of a supercontinuum, narrower band femtosecond pulses tunable over an extremely large spectral range are needed [13]. One of the many applications which would benefit from widely tunable femtosecond optical pulses is Raman microspectroscopy, where low-energy ultrashort pulses are preferred [14].

One of the advantages of PCF is the capability of engineering and control the fiber's group velocity dispersion (GVD) [15]. As described in the following, it is this dispersion control that enables our RDW technique. As in convention fibers, optical solitons can be formed inside our PCF with negative GVD and Kerr nonlinearity at play [10]. The ultrashort soliton evolution inside the fiber can be described by the standard scalar generalized nonlinear Schrödinger equation (GNLSE) [10]

$$i\partial_z A(z,t) + \hat{D}(i\partial_t)A(z,t) + \gamma A(z,t) \times \int_{-\infty}^{t} R(t-t')|A(z,t')|^2 dt' = 0, \quad (1)$$

where $A(z,t)$ is the complex envelope of the electric field, $\gamma = n_2\omega_0/cA_{\mathrm{eff}}$ is the nonlinear coefficient, A_{eff} is the effective mode area, n_2 is the Kerr coefficient, ω_0 is the pump frequency, $\hat{D}(i\partial_t) = \sum_{m\geqslant 2}\frac{i^m}{m!}\beta_m\partial_t^m$ is the dispersion operator which takes into account the full complexity of the fiber GVD, and β_m is the mth order dispersion coefficient. $R(t)$ is a function describing the Kerr and the Raman contributions to the nonlinearity, and its explicit expression can be found in many textbooks [10]. The self-steepening term has been neglected as the linear fiber group velocity always dominates over the nonlinear one by several orders of magnitude [10]. As is well known, new frequencies will be generated by the soliton due to the perturbation resulting from higher order dispersion [9]. In the common case of a third-order dispersion perturbation, there is only one phase-matched frequency (i.e., only one RDW), but in the case of fourth-order dispersion (4OD), there are two symmetric frequency-detuned RDWs: one on each side of the soliton [9]. Recently, femtosecond 4OD RDW generation was observed in a Ti:sapphire laser, and tunability was achieved

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by adjusting cavity dispersion [16,17]. This is not, however, practical for a fiber system. Special dispersion characteristics of PCF glass features have allowed efficient RDW generation over a broad wavelength range [5]. Hitherto, however, little work has been reported on the temporal dynamics of the generation process and on temporal characteristics of the output light. Furthermore, RDWs generated in fibers have never been suggested as a possible source of ultrashort pulses, because of the suspected strong role of dispersion.

The pump laser source is a mode-locked Ti:sapphire oscillator (KMLabs, TS laser kit) with tunable bandwidth and center wavelength (with a repetition rate of 85 MHz). A pair of fused silica prisms is used to compensate for the dispersion of optics outside the cavity, including a 20× microscope objective lens used to couple the laser pulses into the PCFs. The pump laser pulse duration is 30 fs (at the fiber input), and the average power is 150 mW (measured before the objective lens). The efficiency of coupling into a single PCF cladding knot is 10%–15%; the loss mostly comes from the mismatch of the 5-μm focal spot and the 1-μm knot size. This mismatched configuration allows convenient alignment and provides an additional confirmation of how little energy is needed for such a strong nonlinear effect. The output spectra are recorded by a fiber-coupled spectrometer (Ocean Optics, HR4000CG-UV-NIR) for the visible and an FT-IR Spectrometer (Nexus 870) for the infrared spectral range.

We couple the compressed femtosecond laser pulses into the cladding of a 3.2-cm-long Kagome hollow-core PCF (the size of each knot being about 1 μm as shown in the inset of Fig. 1), and record output spectra are shown in Fig. 2. Because of the limitations imposed by phase matching, the soliton transfers energy only to a certain range of wavelengths, and only for the optimal polarization (axis 1 marked in Fig. 1.). We observe generation of two RDWs placed on the blue and red sides of the soliton central wavelength (around 450 and 1800 nm, respectively). We choose this relatively short fiber length so that the infrared RDW does not experience too much material absorption, while keeping the level of RDW generation sufficiently high. Finally, we keep our pulse energy to a certain range so that the nonlinear processes are dominated

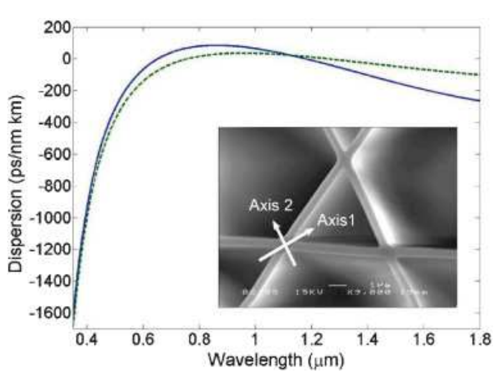

FIG. 1. (Color online) GVD as a function of wavelength for two orthogonal polarizations in a sample knot. The dispersion for polarization along the long axis (axis 1) is shown by the blue solid line, and that for the orthogonal one (axis 2) is shown by the green dashed line. The inset presents a scanning electron microscope image of the cladding.

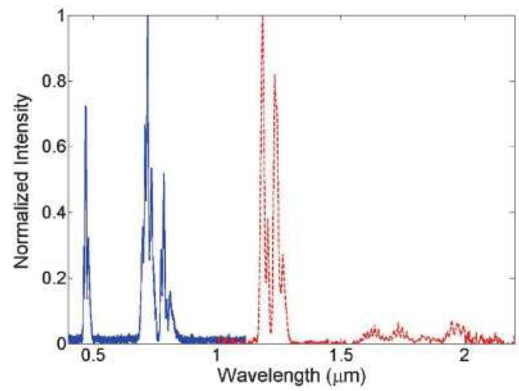

FIG. 2. (Color online) Output spectra obtained by coupling the laser pulses (with center wavelength of 745 nm) into the cladding of a 3.2-cm-long PCF for the optimum polarization (along axis 1 in Fig. 1). The blue solid line and red dashed line are the spectra recorded by two different spectrometers for visible and infrared regions, respectively.

by the formation of the fundamental soliton and its RDW emission [18]. This is made possible by the dispersion of the chosen guiding feature. The measured power of blue RDW shown in Fig. 2 is larger than 10% of the total output power.

RDW tuning can be achieved by adjusting the generating system's dispersions [17]. Since in a premanufactured fiber dispersion for a given mode is fixed, a change of the RDW wavelengths can be achieved by exciting different knots of the PCF cladding [shown in Fig. 3(a)], or different modes in the same knot [19]. The generation efficiency for the longer wavelengths RDWs (blue-detuned) is larger than that in the previous case. Furthermore, we are able to fine-tune the wavelengths of RDWs straightforwardly by tuning the soliton center wavelength. As shown in Fig. 3(b), when the pump light wavelength is tuned from 750 to 850 nm, the RDW wavelength changes over a range of up to 70 nm. Figure 3(b) shows that when the soliton wavelength is increased, the wavelength of the RDWs (blue side) decreases, which is somewhat counterintuitive. This is because the phase-matching condition is determined by the waveguide dispersion (which also results in the output frequency being stable against any variation of environment). By changing the coupling conditions (either by coupling into a different knot or into a different PCF modes), in conjunction with tuning the soliton wavelength, we can achieve an RDW tuning range covering the entire visible spectrum. To our knowledge, this is the largest reported tuning range for efficient nonlinear optical frequency conversion obtained with a simple unamplified femtosecond laser.

For potential applications, it is important to confirm the femtosecond duration of the frequency-tunable RDW pulses, as well as to check their temporal delay with respect to the pump pulses. Femtosecond pulses are expected to stretch considerably while propagating through dispersive media. If the generation is sufficiently efficient to occur over a short (few-centimeter) length of (low-dispersion) fiber, the dispersion can be minimized and one could reasonably hope that the output pulse duration remains short. We performed a cross-correlation measurement for the RDW and pump pulses with an autocorrelator (APE, Pulse Check). This measurement gives information on both the pulse duration of each pulse

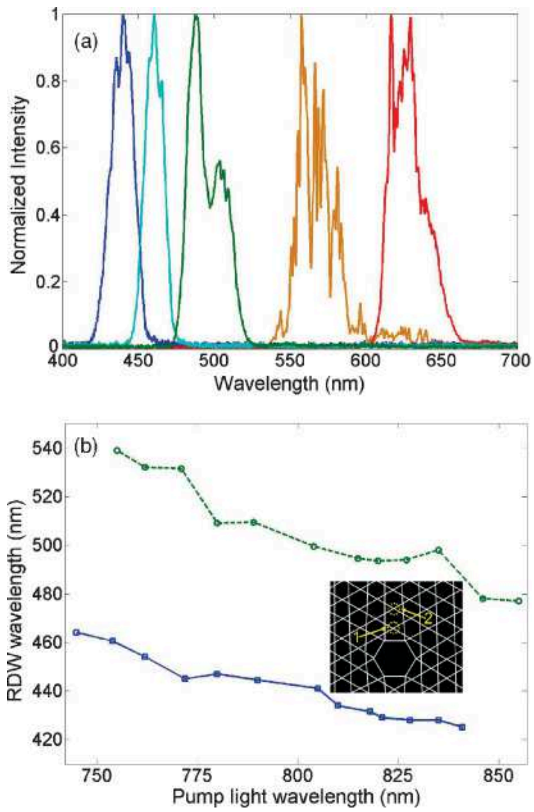

FIG. 3. (Color online) (a) PCF output spectrum varied by coupling the same input femtosecond pulse (with center wavelength of 800 nm) into different knots of the PCF cladding. (b) RDW tuning by varying the pump wavelength (while keeping the same pump power); blue squares correspond to blue RDWs generated in a cladding knot next to the hollow core (marked as 1 in the inset), and green circles represent those generated in an adjacent knot (marked as 2 in the inset).

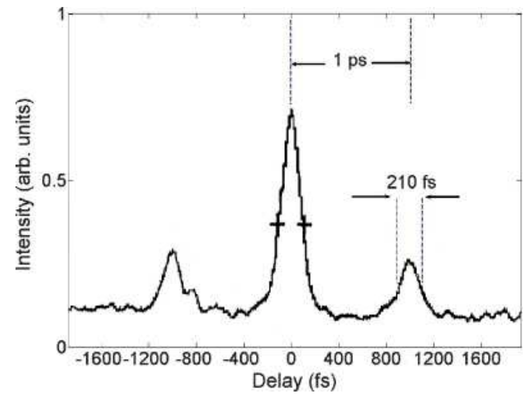

FIG. 4. (Color online) Auto- and cross-correlation traces of the pump pulse and the 470-nm RDW. The 1-ps separation between the peaks corresponds to the delay between the two pulses. The two side peaks correspond to cross-correlation traces between the RDW pulse and the pump pulse, and it shows that the pulse duration of the 470-nm RDW is less than 160 fs (with a Gaussian pulse assumed) after PCF and other optics (with no dispersion compensation being used).

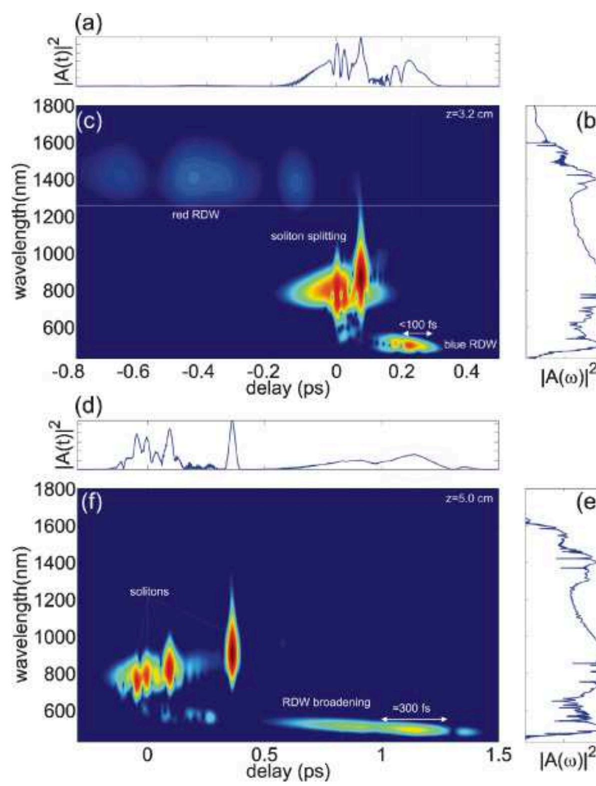

FIG. 5. (Color online) Results of a numerical simulation where the GNLSE [Eq. (1)] (including high-order dispersion terms and the Raman effect) is solved numerically. Parts (a) and (b) give, respectively, the temporal and the spectral domain pictures of the output field, both in logarithmic scale, for a propagation length of 3.2 cm. Part (c) shows the XFROG spectrogram of the field, showing the soliton splitting phenomenon and the emission of short RDWs in the infrared and blue regions of the spectrum. Parts (d), (e), and (f) are the same as in (a), (b), and (c), but for a slightly longer propagation distance of 5 cm. It can be seen that RDWs have rapidly increased their temporal duration. The input pump power (150 mW before coupling; coupling efficiency 15%) and input pulse duration (30 fs before the PCF) match the conditions of our experiments. The repetition rate is 85 MHz.

and the relative delay between each pulse. The measured RDW wavelength is then restricted to being longer than that of the second harmonic of the pump pulse, since otherwise the autocorrelator cannot discriminate the signal. At the same time, we want to set the wavelength difference between the RDW and the pump pulse as large as possible so that we may measure the most stretched pulse for the RDW and the largest delay between pump and RDWs (see the GVD in Fig. 1). Figure 4 shows the auto- and cross-correlation trace for the RDW (470 nm) and the pump pulse. The trace has a standard double-pulse auto- and cross-correlation appearance, where the central peak corresponds to an autocorrelation trace of the pump pulse. (Our device cannot measure direct autocorrelation of the RDW because its second harmonic is out of the working range.) The side-peak separation corresponds to the delay between the two pulses, and two side peaks represent the cross-correlation between the RDW and the pump pulse. Since the frequency difference between the soliton and RDW is so large, the dispersion of the optics after the fiber contributes to the measured 1-ps delay between the two pulses (e.g., 1-cm-thick fused silica will cause a relative delay of about 0.4 ps between these two wavelengths). The cross-correlation measurement confirms that after the 3.2-cm-long PCF, a 40× objective lens, and neutral density filters, the pulse duration

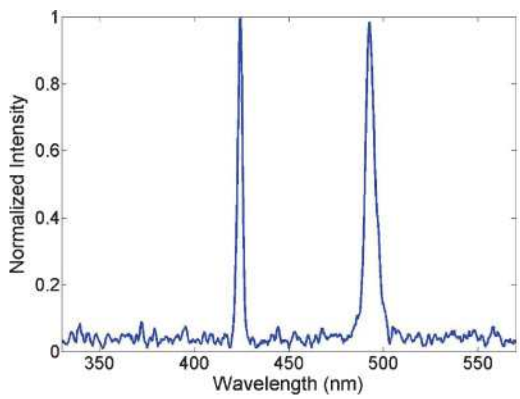

FIG. 6. (Color online) The output spectrum of a 10-cm-long PCF with pump laser wavelength at 1500 nm. The peak around 500 nm is the third harmonic of the pump laser, and the peak around 425 nm is the generated RDW (where here we use a 50-fs pulse obtained from an optical parametric amplifier).

of the 470-nm RDW is less than 160 fs (assuming a Gaussian pulse) without any dispersion compensation. Pulse stretching is also caused by dispersion in the aforementioned optics, and then shorter pulses can be obtained by adding extra dispersion compensation elements after the fiber output coupler.

As we have mentioned, when 4OD dominates, the other (conjugate) RDW is generated in the infrared region (as shown in Fig. 2), and it is expected to possess tuning and temporal features similar to the visible RDW [5]. Comparing our PCF dispersion in the infrared with that in the visible region (Fig. 1) we conclude that the output infrared pulse should be even shorter than the (measured, 160-fs) blue RDW pulse. Therefore, our method can possibly be used to produce tunable femtosecond pulses in the near- to mid-infrared spectral range. A numerical simulation described in the following confirms this prediction.

In our simulation the GNLSE (which includes all high-order dispersion terms) is solved numerically with a split-step Fourier scheme [10]. The enhanced nonlinear coefficient γ due to small core size is taken into account here phenomenologically [20]. Results are given in Fig. 5. Figures 5(a) and 5(b) show the fiber output in the temporal and spectral domain, respectively, after a propagation of 3.2 cm along the fiber; these are in good agreement with our measurements presented in Figs. 2 and 4, and they confirm the generation of an infrared femtosecond RDW pulse when the propagation is limited to short distances. Figure 5(c) displays the cross-correlation frequency-resolved optical gating (XFROG) spectrogram, which combines both temporal and spectral features of the resultant waveform. Note that short duration of the RDW pulse is a result of efficient (coherent) RDW emission at early stages of soliton formation and propagation. When the propagation progresses a bit further [see Figs. 5(d), 5(e), and 5(f)], the dispersion may stretch RDWs almost linearly with propagation distance. This demonstrates that, in order to achieve femtosecond RDWs with good efficiency, the fiber length needs to be optimized. It is noteworthy that the pulse stretching in the experiments is less severe than that in simulation.

Our work shows efficient and broadly tunable RDW generation in a PCF where 4OD dominates. However, the described mechanism is based on rather general aspects of solitonic behavior (as demonstrated in active and passive systems). Therefore, the tuning methods studied here should be applicable to, for example, other types of Cherenkov radiation [9], modulation instability [21], as well as to other systems where solitons exist. Moreover, the studied tuning mechanism holds promise for greatly extending the tunability range. As an example of an extremely large frequency shift that can be obtained in such a converter, we show generation of an RDW whose frequency exceeds that of a third-harmonic radiation for a fundamental wavelength at 1500 nm in Fig. 6; here we use a 10-cm-long PCF and 50-fs pulses obtained from an optical parametric amplifier.

In conclusion, in this Rapid Communication we demonstrate efficient RDW generation within the cladding of PCF pumped by a simple mode-locked Ti:sapphire oscillator. We have achieved an extremely broad tunability, by combining varied fiber coupling conditions with tuned pump wavelength. Furthermore, we have confirmed the femtosecond pulse duration of the generated RDWs. These results elucidate interesting physics occurring in the guiding feature within PCF and may aid applications that require frequency-tunable (visible and infrared) femtosecond pulses.

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