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Idris Tiliouine, Geoffroy Granger, Cristian Esteban Jimenez-Durango, Yann Leventoux, Benjamin Wetzel, Vincent Couderc, S. Février

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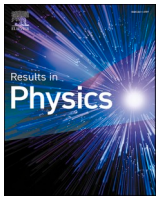

Microarticle

Two-octave spanning supercontinuum from a 4.53 μm fiber-based laser

I. Tiliouine, G. Granger, C.E. Jimenez-Durango, Y. Leventoux, B. Wetzel, V. Couderc, S. Février *

Université de Limoges, XLIM, UMR CNRS 7252, 123 Av. A. Thomas, 87060 Limoges, France

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ABSTRACT

We report on the generation of two-octave mid-infrared supercontinuum in stock, unprocessed, large core chalcogenide fiber pumped by a fiber-based laser delivering 35 kW, 180 fs pulses at 4.53 μm.

A compact and robust supercontinuum (SC) source in the mid-infrared (mid-IR) opens up new possibilities for applications such as molecular spectroscopy [1,2] and high resolution imaging [3,4]. Chalcogenide fibers, which emit light up to ~18 μm when pumped in the mid-IR [5], appear to be the most mature platform to achieve the full potential of fiber-based SC sources in spectroscopic applications. The broadest mid-IR SC are obtained when the wavelength of the laser source is matched with the anomalous dispersion regime of the fiber. To address this, dispersion-engineered chalcogenide fibers are pumped by optical parametric systems tuned to the mid-IR [5,6]. An alternative approach consists in exploiting the low phonon energy of fluoride glasses to increase the emission wavelength of rare-earth-doped fiber lasers [7] with the overall goal to build a compact and robust all-fiber mid-IR SC. Along this line, SC generation was obtained in dispersion-engineered small mode area chalcogenide microwire pumped in the weak normal dispersion regime by sub-nanojoule femtosecond Ho^{3+}-doped fiber laser at 2.8 μm [8]. Despite recent success in mode-locked operation of Er^{3+}-doped fluoride fiber at 3.5 μm [9], the wavelength range above 4 μm is not covered by ultrafast fiber lasers.

Using the soliton self-frequency shift (SSFS) effect originating from the intrapulse stimulated Raman scattering [10,11], we reported recently on the formation of mid-IR (~2900 – 3000 nm) pulses from various fiber-based laser systems emitting in the near-IR [12,13]. Along the same line, Robichaud *et al.* recently showed the generation of a supercontinuum up to 5 μm with a high peak power femtosecond source at 2.8 μm shifted to 3.6 μm by the SSFS effect [14]. In this communication, we extend the same approach to the design of a fiber-based source of highly energetic femtosecond pulses (8.3 nJ, 179 fs) at 4.53 μm and produce two-octave spanning SC by pumping a pristine, 11.4 μm core diameter, chalcogenide fiber with this fiber laser.

The experimental setup is schematically depicted in Fig. 1a, while the spectra measured at various points within the fiber cascade are displayed in Fig. 1b. The input sub-picosecond pulse is converted into an ultrashort pulse centered at 2940 nm by nonlinear interactions in the two first fibers (see blue spectrum in Fig. 1b). From frequency-resolved optical gating (FROG) measurement, we deduced a pulse full width at half maximum (FWHM) duration of 86 fs, corresponding to nine optical cycles [13]. In order to extend the wavelength further into the mid-IR, we spliced the 26 μm ZBLAN fiber to another ZBLAN fiber with a core diameter of 14 μm and numerical aperture (NA) of 0.12 by means of a CO_2 fusion-splicing machine. An average power of 230 mW was measured at the output of a 1.5 m long piece of 14 μm core ZBLAN fiber, corresponding to an insertion loss of 2 dB. The mode mismatch (mode field diameters of 32 μm and 19 μm at 3 μm, respectively) is expected to account for approx. 1.2 dB) while the effect of structural deformation is expected to account for 0.8 dB.

Despite the power loss, the soliton was shifted to 3.43 μm as shown in Fig. 1b, green curve. The spectrum of the soliton was isolated by means of a 500 nm bandpass filter centered at 3.5 μm. We measured a soliton energy of 30 nJ. The characteristics of the soliton are well suited to further wavelength-shift in fibers with anomalous dispersion, higher nonlinear coefficient (smaller mode area) and broader transparency window such as fluoro-indate (InF_3) glass singlemode fibers [15]. Then, the output of the 14 μm ZBLAN fiber was coupled by proximity to 7 m of InF_3 fiber with a core diameter of 9.5 μm and NA of 0.3. The soliton was then further shifted to 4.53 μm (orange curve in Fig. 1b). The energy measured within the bandwidth of a 500 nm bandpass filter centered at 4.5 μm was 8.3 nJ. We also measured the temporal profile of the laser

* Corresponding author.
E-mail address: sebastien.fevrier@unilim.fr (S. Février).

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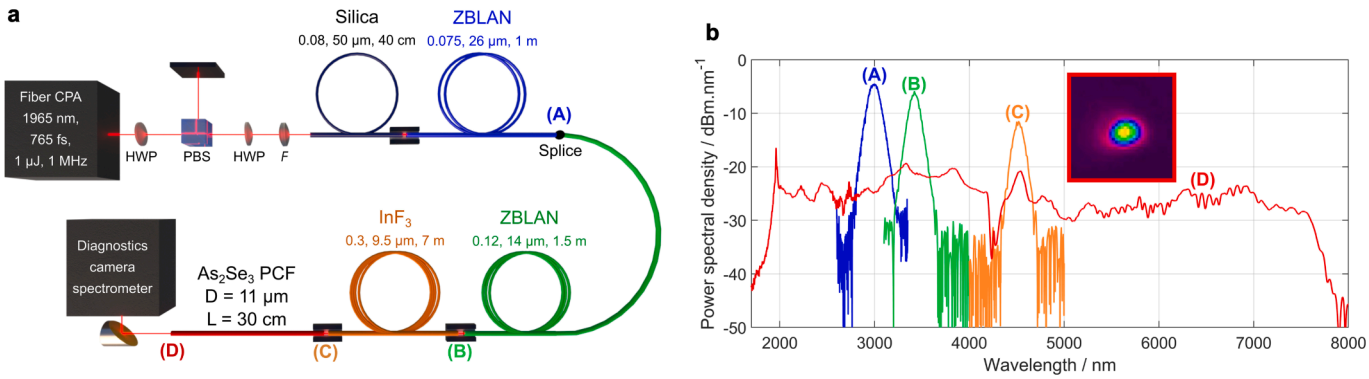

Fig. 1. (a) Schematic of the setup used for the generation of fiber-based two-octave spanning mid-IR SC. HWP: half-wave plate, PBS: polarization beam splitter, F: focusing lens. The fibers are characterized by their NA, core diameter and length. (b) Spectra measured at four positions in the cascaded fiber system. The inset shows the near-field intensity distribution measured at the output of the chalcogenide fiber.

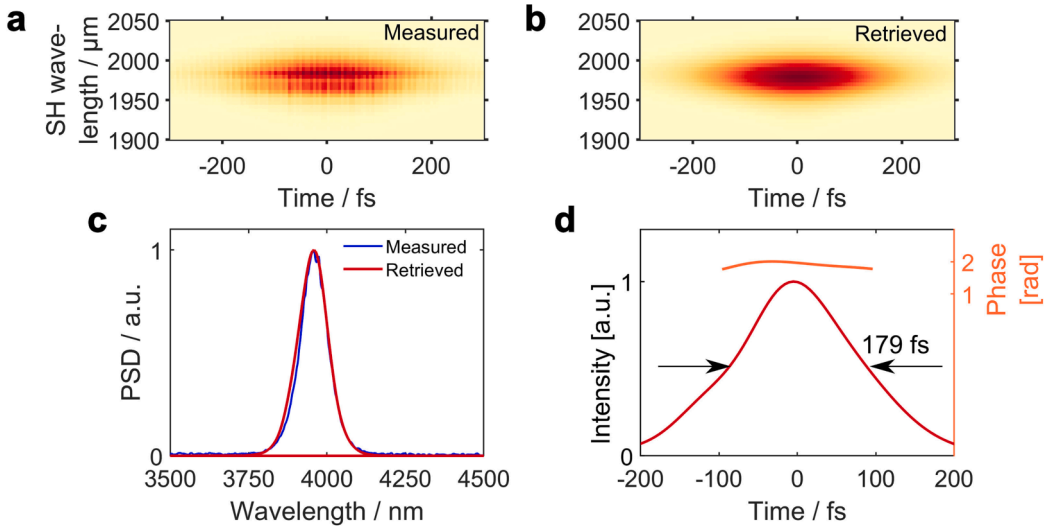

Fig. 2. Results of FROG characterization of the solitonic pulse at the output of the InF_3 fiber. (a) Measured and (b) retrieved FROG traces. (c) Spectral profiles retrieved from the FROG trace and measured with the FTIR spectrometer. (d) Retrieved temporal intensity (purple) and phase (orange) profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pulse at 3.95 µm by FROG. We slightly decreased the wavelength of the pulse to ensure proper SH detection by means of the spectrometer with a spanning range 900–2100 nm. Fig. 2a-b show the measured and retrieved FROG traces, respectively. The two traces are in good agreement, which is confirmed by the low rms error of the reconstruction of 0.4% and the good agreement between the measured and reconstructed spectra overlaid in Fig. 2c. From the retrieved temporal intensity profile shown in Fig. 2d, we deduced a pulse FWHM duration of 179 fs (12 optical cycles), which corresponds to a pulse peak power of 35 kW. The FWHM bandwidth of the pulse of 98 nm leads to a time-bandwidth product of 0.33, indicating that the $sech^2$-shaped soliton is close to transform-limited.

The possibility to generate mid-IR SC from such fiber-based source was explored using stock arsenic selenide photonic crystal fiber (SeleNOptics). The fiber has a hole-to-hole spacing of 9 µm and a ratio of air hole diameter to hole-to-hole spacing of 0.4 making it singlemode at the wavelength of 4.53 µm. The core diameter is equal to 11.4 µm. The zero dispersion wavelength of the fiber is located at 4.8 µm. The chromatic dispersion at the wavelength of 4.53 µm is weakly normal (–8.8 $ps.nm^{-1}.km^{-1}$). The fiber sample is 30 cm in length. The fluoride fiber and the chalcogenide fiber were coupled to each other by proximity. Results are plotted in Fig. 1b, red curve. The SC spans two octaves from 1.7 µm to 7.8 µm measured at −20 dB of the PSD of the residual pump at 4.53 µm. From the PSD measured by the FTIR spectrometer and the independently determined total power of 20 mW over the whole SC, we deduce a PSD of –23.5 $dBm.nm^{-1}$ at $\lambda = 6.9$ µm, corresponding to a power of 69 µW in 0.1% of the FWHM band around the wavelength of 7 µm and a photon flux of 2.47×10^{15} $ph.s^{-1}$ 0.1 $\%BW^{-1}$. Owing to the singlemode characteristic of the PCF at 7 µm we assume that the mid-IR beam emerges from the fiber with a radius of $w = 4.7$ µm, corresponding to an effective area of 70 μm^2, a divergence angle of $\lambda/(\pi w) = 0.47$ rad, and a solid angle of 0.69 sr. The resulting brightness calculated at 6.9 µm is then $2.2\ 10^{19}$ $ph\ s^{-1}\ mm^{-2}\ sr^{-1}$ 0.1 $\%BW^{-1}$, that is three orders of magnitude higher than that of third generation synchrotron source [16].

We have demonstrated the generation of two-octave spanning mid-infrared supercontinuum from a femtosecond fiber-based laser source at 4.53 µm. The performances of the source in terms of spectral coverage, brightness and temporal coherence facilitate the development of spectroscopic applications, which are currently confined to large synchrotron facilities.

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CRediT authorship contribution statement

I. Tiliouine: Investigation, Software, Visualization. **G. Granger:** Investigation. **C.E. Jimenez-Durango:** Software, Validation. **Y. Leventoux:** Investigation, Resources, Data curation. **B. Wetzel:** Investigation. **V. Couderc:** Supervision. **S. Février:** Funding acquisition, Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Disclosures

The authors declare no conflicts of interest.

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