Generation of intense 100 fs solitons tunable from 2 to 4.3 μm in fluoride fiber: supplementary material

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1. FLUORIDE FIBERS

The zirconium fluoride (ZrF_4) fiber has a core diameter of 9 μm and NA of 0.19. The single-mode cutoff wavelength is 2.3 μm , and the propagation loss is specified as lower than 0.2 dB/m over 2.0–3.7 μm . The zero-dispersion wavelength for the ZrF_4 fiber is $\sim 1.62 \mu\text{m}$. The parameters of the fluoride fibers used in the experiments are plotted in Fig. S1.

Numerical simulations of soliton self-frequency shift (SSFS) in a 1-m long ZrF_4 fiber with the same input pulse parameters in the paper exhibit similar results, with the soliton shifting out to 3.4 μm . Experimentally, output solitons up to 3.4 μm are obtained with estimated pulse duration of 70 fs, as predicted by the simulation.

Fig. S1. The parameters of the fluoride fibers used in the experiments. The group velocity dispersion (GVD) of the fundamental mode and the propagation loss for the (a) InF_3 fiber; (b) ZrF_4 fiber. The horizontal blue dashed line indicates the position of the zero GVD value. The vertical blue dashed line indicates the single mode cutoff wavelength.

2. INPUT PULSES AT 1900 NM

The spectrum and autocorrelation of the input pulses at 1.9 μm are shown in Fig. S2. The fringes on the spectrum are due to interference with residual light left from a second soliton centered at 1.7 μm . The pulse duration is measured using an interferometric autocorrelator based on two-photon absorption in a silicon photodetector. A deconvolution factor of 1.54 is assumed.

Fig. S2. (a) The spectra and (b) the interferometric autocorrelation of the input light source at 1.9 μm .

3. NUMERICAL SIMULATIONS

Numerical simulations were performed assuming only fundamental-mode propagation using the generalized nonlinear Schrödinger equation to model the electric field envelope $A(z, T)$ [1].

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - \sum_{n \geq 2} \frac{i^{n+1}}{n!} \beta_n \frac{\partial^n A}{\partial T^n} = i\gamma \left(1 + i\tau_{\text{shock}} \frac{\partial}{\partial T} \right) \left(A(z, T) \int_{-\infty}^{\infty} R(T') \times |A(z, T - T')|^2 dT' + i\Gamma_R(z, T) \right) \quad (\text{S1})$$

The equation is solved with the standard split-step technique, with a 4th order Runge-Kutta integration for the nonlinear step. A temporal resolution of 0.44 fs and spectral resolution of 8.6 GHz are used. The frequency range extends over 1200 THz. A time window of 120 ps and step size of 1 μm in

propagation are employed. The convergence of the simulation results is confirmed by comparing with those obtained using higher resolution.

The β_n terms up to the 8th order are the dispersion values for the fundamental mode in the fluoride fibers, calculated based on the Sellmeier equations with their refractive indices and numerical aperture, measured by the manufacturer. The linear propagation loss α is set to be 0.2 dB/m for the wavelengths shorter than the pump wavelength and increases exponentially into the deep MIR region. The frequency dependence of the loss is modeled as:

$$\alpha(f) = a \times e^{-\frac{f-f_0}{b}} + c \quad (\text{S2})$$

where f is the frequency in the unit of PHz and f_0 is the frequency at pump wavelength. The coefficients for the InF_3 fiber at pump wavelength of $1.9 \mu\text{m}$ are $a = 1.13 \times 10^{-10}$ dB/m, $b=0.00434$ PHz, $c=0.0997$ dB/m. The coefficients for the ZrF_4 fiber at pump wavelength of $1.9 \mu\text{m}$ are $a = 1.12 \times 10^{-11}$ dB/m, $b=0.00328$ PHz, $c=0.0423$ dB/m.

The nonlinear coefficient γ is evaluated at the pump frequency ω_0 and the generally accepted value of nonlinear refractive index is $n_2 = 2.1 \times 10^{-20} \text{ m}^2/\text{W}$ [2], which is used in the simulations. Due to the large variation of the effective area of the mode over this wide wavelength range, the frequency-dependence of the effective area is accounted for by introducing a first-order correction to the timescale τ_{shock} at the pump wavelength. The variation of the nonlinear refractive index is negligible.

$$\tau_{\text{shock}} = \frac{1}{\omega_0} - \left[\frac{1}{A_{\text{eff}}(\omega)} \frac{dA_{\text{eff}}(\omega)}{d\omega} \right]_{\omega_0} \quad (\text{S3})$$

The response function $R(t)$ includes both instantaneous electronic and delayed Raman contributions. The Raman response is modeled as a simple damped oscillation in the temporal domain with two time constants $\tau_1=16.67$ fs and $\tau_2=20.32$ fs [3]. The fraction of Raman contribution in the nonlinearity is taken to be $f_R=0.20$ [4]. The effects of spontaneous Raman noise are introduced through $\Gamma_R(z, T)$.

4. DATA PROCESSING FOR MEASUREMENTS OF SPECTRA

The spectrum of Fig. 3(a) was measured with an instrument that covers the range 1-5.6 μm . The spectra in Fig. 3(c,e) were measured with an instrument that covers the range 3.3-8.0 μm . We are not certain why the latter spectra are noisier than the former.

The filtered spectra data shown in Fig. 3 and Fig. 4 in the letter are obtained after background subtraction and noise removal by an FFT low pass filter. The background noise from the OSA is scaled to the same level with the soliton spectra at wavelengths where there's no signal. We measured the soliton spectra after passing the long pass filters (LPF). Wavelengths of 3.3 μm and 6.5 μm are selected to scale the background noise when a LPF which cuts on 3.75 μm was used. Wavelengths of 2 μm and 4.5 μm are selected to scale the background noise when a LPF which cuts on 2.85 μm was used.

5. SUPERCONTINUUM SPECTRA

The complete output spectra were recorded using three optical spectrum analyzers (ANDO AQ6315E: 0.35-1.7 μm , noise floor

of -70 dBm/nm; Thorlabs OSA203: 1.0-2.5 μm , noise floor of -70 dBm/nm; and Thorlabs OSA206: 3.3-8.0 μm , noise floor of -45 dBm/nm). The measured full spectra of the supercontinuum for a 2-m long InF_3 fiber with shifted solitons at 3.9 μm is shown in Fig. S3. The spectra data measured by AQ6315E and OSA203 are stitched together at 1.67 μm . The gap from 2.5 μm to 3.3 μm could not be covered by available spectrum analyzers, since the instrument that covers 1-5.6 μm was not available when we did the experiments in the 2.5-3.3 μm range.

Fig. S3. Measured full spectra in a 2-m long InF_3 fiber with shifted solitons at 3.9 μm . PSD: power spectral density.

6. STABILITY MEASUREMENT

We performed a long-term (taken to be one hour) stability measurement of the pump pulses, the seed pulses and the output soliton pulses in terms of the center wavelengths and pulse powers (Fig. S4).

Fig. S4. The stability measurement of the power and center wavelength variation of (a,b) the pump pulse; (c,d) the seed pulse; (e,f) the output soliton at 3.6 μm . SD: standard deviation.

For the pump pulses near 1550 nm, the coefficient of variation (standard deviation/mean) of the power is 1.8 %. The coefficient of variation of the pump wavelength is 0.002 %. Comparing the seed and output solitons, the coefficients of variation of the power are on the same levels (8 % vs. 9 %). The coefficients of variation of the wavelengths for the output soliton (1%) is 3 times larger than that of the seed pulses (0.31%), sharing the same order of magnitude.

We don't observe much amplification of the instability during the SSFS process in the fluoride fibers. We attribute this to the short pulse duration (70 fs) we used for pumping, since for short pulse excitation, the SSFS process is known to remain coherent even during the propagation in the anomalous dispersion regime [5]. Based on these measurements, this light source based on SSFS has the potential of being useful provided stable and short input pulses are available.

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