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Enhanced supercontinuum generation in tapered tellurite suspended core fiber

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ABSTRACT

We demonstrate 400-THz (0.6–3.3 μm) bandwidth infrared supercontinuum generation in a 10 cm-long tapered tellurite suspended core fiber pumped by nJ-level 200-fs pulses from an optical parametric oscillator. The increased nonlinearity and dispersion engineering extended by the moderate reduction of the fiber core size are exploited for supercontinuum optimization on both frequency edges (i.e., 155-THz overall gain), while keeping efficient power coupling into the untapered fiber input. The remaining limitation of supercontinuum bandwidth is related to the presence of the high absorption beyond 3 μm whereas spectral broadening is expected to fully cover the glass transmission window (0.5–4.5 μm).

1. Introduction

Development of fiber-based supercontinuum (SC) light sources spanning the mid-infrared molecular fingerprint region is currently undergoing a dramatic increase, particularly stimulated by high-demanding applications such as biomolecular and environmental sensing. This can be largely attributed to the development of novel and high-quality mid-infrared (mid-IR) materials devoted to fiber optics. In the last several years mid-IR SC sources were implemented on alternative non-silica glass fibers and waveguides, such as fluoride, tellurite or chalcogenide glasses, since they represent an attractive solution thanks to their wide transparency and high nonlinearity [1]. For fluoride and tellurite fibers, the wavelength coverage in the mid-IR can reach 4.5 μm [2, 3], whereas for chalcogenide fibers and waveguides it can be extended until 8 μm [4, 5]. Recently, larger SC spectra up to 13 μm were also reported in multimode fibers [6], however such observations are restricted to the use of ultrashort amplifier laser chains and remain close to experimental configurations of SC generation in bulk media [7–11]. From a general point of view, it still remains very challenging to confirm such dramatic spectral broadenings that almost cover the entire glass transmission window, in particular when considering quasi-single-mode fibers and pump lasers at moderate energy levels for compact SC sources. Several detrimental effects related to the wavelength dependence of the fiber attenuation usually arise such as extra water (OH) pollution or other absorption mechanisms [12–17].

To improve the spectral range of SC light and dispose of possible limitations of both fiber and pump laser, various methods were already demonstrated for engineered SC generation in silica fibers based on the fine control of nonlinear propagation dynamics. Enhanced blue- and red-expansion of the SC bandwidth can be achieved through extra dispersion engineering of photonic crystal fibers (PCFs) along the fiber axis, i.e. tapered PCFs, the fabrication of microwires, and the cascaded fiber approach [18–21]. As a result, SC generation in silica fibers is now well-established and it usually covers the full transmission window of the material. The underlying mechanisms of spectral broadening in those methods are related to the tailoring of soliton dynamics (in anomalous dispersion) and associated dispersive waves (in normal dispersion) but also their mutual interactions. In most cases the SC bandwidth is fully driven by interactions such as the soliton trapping of dispersive waves, which modifies the short-wavelength edge (i.e., dispersive waves) as a function of the long-wavelength edge (i.e., solitons) in a way that satisfies group-velocity matching. In some sense, such techniques were recently applied to SC generation in soft-glass fibers but this remains restricted to chalcogenides microwires or waveguides, and near-IR studies of tapered tellurite PCFs [22–26]. More recently, tailoring SC generation was also investigated through accurate control of a novel fiber core design with high birefringence (i.e., an elongated core on a thin filament of glass) [27]. In this paper, we exploit both increased nonlinearity and dispersion engineering extended by the

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extra reduction of an initial suspended core microstructured tellurite fiber for SC optimization on both frequency edges, i.e. visible and mid-IR. We demonstrate a 155-THz increase of the full SC bandwidth by using a moderate tapering ratio over a short fiber segment by means of a commercial glass processing platform.

2. Simulations

2.1. Group-velocity matching

First we performed numerical simulations of the nonlinear pulse propagation in tapered tellurite suspended core fibers to evaluate the impact of the tapering process on both soliton and group-velocity matching dynamics. Detailed studies were already reported to optimize taper profiles for enhanced soliton self-frequency shift and blue-shifted dispersive waves [28–33]. Here the goal is to take advantage of such existing tools without going into details of wave interactions. Our simulations used a well-known generalized nonlinear Schrödinger equation that has successfully described the SC generation process over a wide parameter range [34]. The longitudinal variation of the fiber core diameter as a function of propagation distance is accurately taken into account through its effect on the fiber dispersion and nonlinearity. The fiber dispersion requires particular care because the group velocity varies greatly over the supercontinuum bandwidth (as seen in Fig. 1), our accurate modeling includes the full dispersion profile. In particular, for the fundamental guided mode we calculated the wavelength dependence of both the mode effective refractive index and the effective mode area by means of a commercial software using a fully vectorial finite-element model. Such calculations were repeated for various core diameters (in the range 1–4 μm) of our suspended core fiber structure used in our experiments (see Fig. 4). The value of the fiber parameters were then modeled locally along the taper profile through a lookup table. Our model also takes into account the measured losses of a single-material fiber made from our low-OH tellurite TeO_2–ZnO–Na_2O (TZN) glass composition including some fluoride ions (i.e., with typical background losses of ~1 dB/m up to 3 μm, and below 10 dB/m in the range 3–4 μm, see Ref. [35] and Fig. 3(a)). It also includes Kerr effect (nonlinear Kerr coefficient is deduced from numerical calculation of effective area, and with nonlinear refractive index $n_2 = 3.8 \times 10^{-19}$ m^2/W [36]), self-steepening term with dispersion of the nonlinearity, and the Raman response function for our TZN glass adapted from Ref. [37]. Fig. 1 reports the beneficial impact of moderate tapering on SC generation in our typical tellurite suspended core fiber design used in Ref. [35] and shown in Section 3. We consider an initial 3.6-μm suspended-core fiber pumped by 200-fs pulses at 1730 nm with 12 kW peak power (i.e., similar parameters to Refs. [12,35] and used in the experiments that follow). The initial fiber exhibits a zero dispersion wavelength (ZDW) close to 1.6 μm; our pumping then occurs in the anomalous dispersion regime with input conditions corresponding to a high soliton order ($N > 20$) [34]. The resulting SC generation is found to be sensitive to input noise, which leads to significant shot-to-shot fluctuations in the SC bandwidth and a low average SC coherence as well. Detailed studies of the noise properties of supercontinuum spectra generated at different power levels in uniform and tapered photonic crystal fibers can be found in Ref. [38]. Here the input pulse shot noise was modeled by adding a noise seed of one photon per mode with random phase on each frequency discretization bin [34]. Consequently, we performed an averaging over 20 simulations with different input noise imposed on the initial 200-fs pulse, thus creating typically smooth SC spectra similar to average spectral measurements. A 10-cm long fiber segment was chosen due to experimental restrictions on both the overall tapered section ~7 cm (see Section 3) and the maximum pump power coupled into the uniform fiber (i.e. spectral broadening almost saturates for longer propagation). Our taper design to enhance SC generation through group-velocity matching is here based on a long down-tapering section (as proposed in Refs. [31,32]) and a moderate reduction of the fiber core size (i.e., reduction ratio of 1/3) to save the suspended core structure (see taper profile shown in Fig. 1(a)). Fig. 1(b,c) show the numerical results of simulated SC spectra at three main positions along the taper and the corresponding group-index curves for the fundamental guided mode in order to highlight the major stages of nonlinear dynamics.

The first stage (blue lines) corresponds to the input uniform fiber section wherein the SC spectrum extends in the infrared from 1 μm to 3 μm (for the –20 dB bandwidth) similarly to our previous studies [12,35]. The shortest wavelength generated (i.e., a DW) is determined by the maximum soliton shift towards the infrared. The group-index matching between both spectral components is confirmed when transferring the corresponding wavelengths on the group-index curve of the tested fiber section, we clearly join the point on either edge by a straight line. We checked that further uniform propagation does not significantly extend the spectral

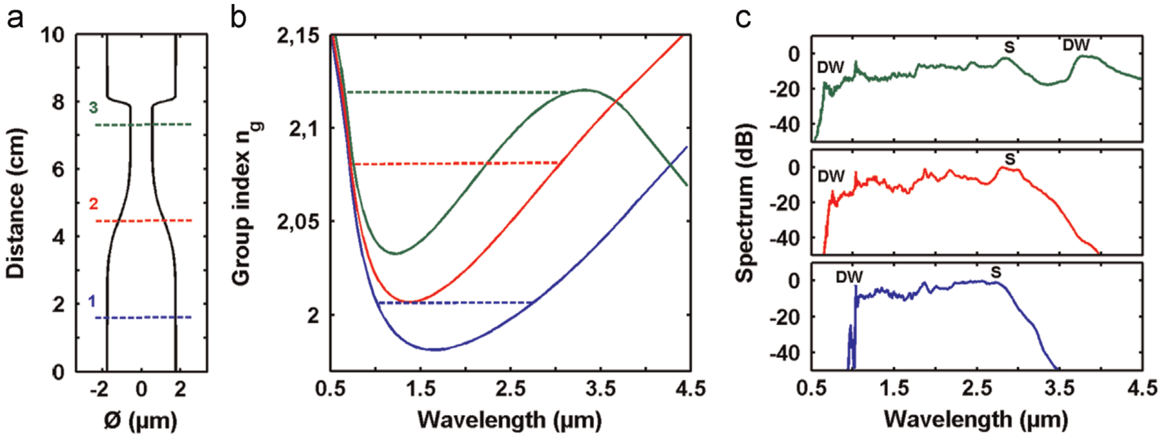

Fig. 1. (a) Taper suspended core profile: initial and final core diameters are 3.6 μm, and the core waist diameter is 1.3 μm. Dashed lines indicate three major stages of nonlinear dynamics studied in the following subfigures (i.e., (1) end of the uniform fiber input, (2) middle of the first transition region, and (3) taper waist). (b) Group-index curves of the fundamental guided mode at the corresponding positions along the taper. Dashed horizontal lines confirm the group-velocity matching between the most red-shifted soliton and related dispersive wave observed during spectral broadening along the taper profile as shown in subfigure (c). (c) Numerical results of SC generation recorded at the different positions denoted in (a) along the taper (S: most-red shifted soliton, DW: related dispersive wave).