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Optical solitons and supercontinuum generation in a tellurite microstructured optical fiber

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ABSTRACT

We demonstrate soliton self-frequency shift (SSFS), multiple optical solitons and supercontinuum (SC) generation in a tellurite microstructured optical fiber (TMOF). By using an optical parametric oscillator (OPO) with the pulse of ~80 MHz and ~200 fs as the pump source, the evolution of SSFS is investigated at the pump wavelengths of ~1730, 1750, 1810 and 1900 nm with the fiber length of ~20 cm. At the pump wavelength of ~1730 nm, SSFS with the soliton center wavelength from ~1850 to 1995 nm is observed. Increasing the pump wavelength to ~1920 nm and the fiber length to ~100 cm, stable multiple optical solitons and dispersive waves (DWs) are obtained. Changing the pump source to a SC source which is generated in a single mode fiber (SMF) pumped by a nanosecond laser with the wavelength of ~1550 nm, a broadband SC spectrum from ~580 to 2796 nm is obtained at the pump power of ~202 mW. To the best of our knowledge, this is the first demonstration of SC generation in the TMOF by using SC light generated by a nanosecond laser.

1. Introduction

Microstructured optical fibers (MOFs) are optical fibers with air-holes in the cladding and extending along the axial direction [1–5]. Compared with conventional fibers, their large index contrast and the two dimensional nature of the microstructure greatly widen the range of waveguide parameters attainable [6–9]. The recent research on MOFs was focused on the non-silica materials, such as soft glasses like fluoride, tellurite and chalcogenide [10–14]. The soft glass MOFs have higher nonlinearities and wider transmission ranges, which are greatly advantageous for soliton self-frequency shift (SSFS) and supercontinuum (SC) generation in the mid-infrared (MIR) region [15–21]. SSFS experiences a continuous redshift because of intrapulse stimulated Raman scattering (SRS) from optical phonons [22,23]. A lot of studies on SSFS have been conducted involving various optical fibers [24,25]. Judge et al. reported optimization of SSFS in a tapered photonic crystal fiber (PCF) [26]. Yan et al. demonstrated the transient Raman response effects on SSFS in a tellurite MOF (TMOF) [27]. For SC generation, Qin et al. reported an ultrabroadband SC generation from 0.35 to 6.28 μm in a step-index fluoride fiber [28] and Théberge et al. obtained a SC spectrum from 2.7 to 4.5 μm with 20 dB spectral flatness in a fluoroindate fiber [29]. Domachuk et al. demonstrated a SC generation with the bandwidth over 4000 nm in a TMOF [18]. Petersen et al. presented a SC spectrum spanning 1.4 μm to 13.3 μm in an ultra-high NA chalcogenide step-index fiber [30]. Yuan numerically simulated a MIR SC generation from 2 to 10 μm in an As_2Se_3 photonic crystal fiber [31]. And Kubat et al. theoretically demonstrated a MIR SC generation from 0.9 to 9 μm in fluoride and chalcogenide glass MOFs [32].

In this paper, we demonstrate SSFS, multiple optical solitons and SC generation in a TMOF. First, the pulse of ~80 MHz and ~200 fs emitted from an optical parametric oscillator (OPO) was used as the pump source. The evolution of SSFS was investigated at different pump wavelengths with the fiber length of ~20 cm. When the pump wavelength shifted to the deep anomalous chromatic dispersion range, stable multiple optical solitons and dispersive waves (DWs) were obtained with the fiber length of ~100 cm. Second, by changing the pump source to a SC source which was generated in a single mode fiber (SMF) pumped by a nanosecond laser with the center wavelength of ~1550 nm, a broadband SC spectrum from ~580 to 2796 nm was obtained at the pump power of ~202 mW.

2. Characterization of the TMOF

The TMOF with four air holes was fabricated by the rod-in-tube drawing technique [33,34]. The tellurite tube and rod were prepared by the rotational casting method and the casting method in

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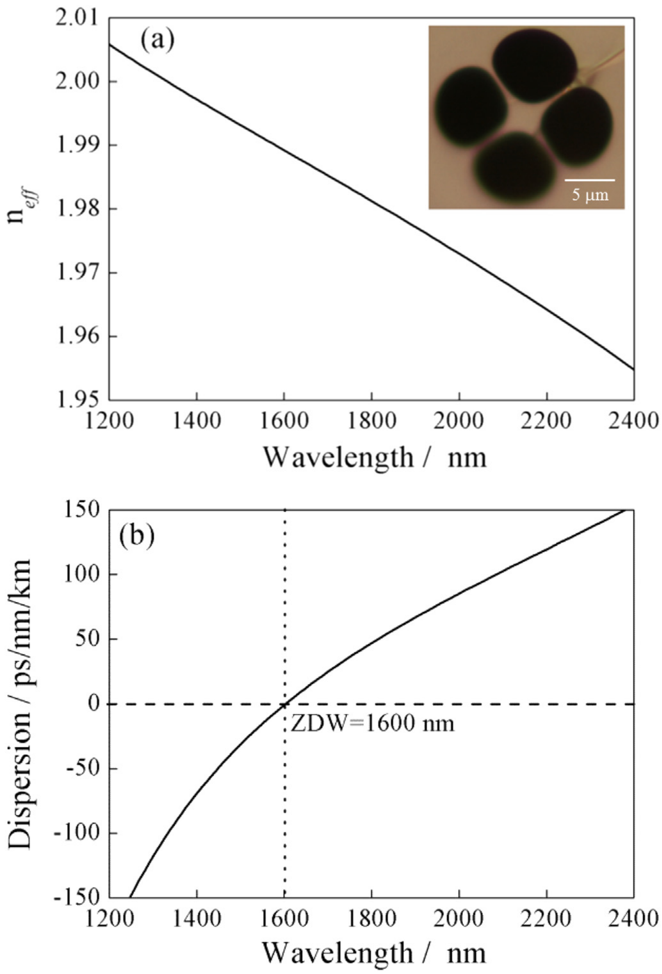

Fig. 1. (a) Fundamental mode refractive index of the TMOF. Inset is the cross section of the TMOF. (b) Calculated chromatic dispersion curve of the TMOF.

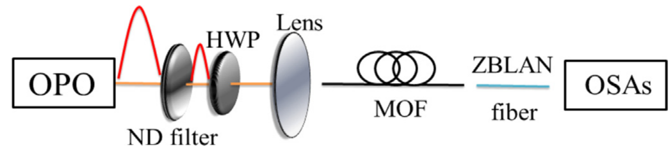

Fig. 2. Experimental setup for measuring the TMOF.

the atmosphere, respectively. Frist, the rod was elongated to match the center hole of the tube. Second, the elongated rod was inserted into the tube and elongated together to obtain a preform. Third, the preform was inserted into another tube and drawn into a fiber at the temperature of ~307 °C. During the fiber-drawing process, a positive pressure of nitrogen gas was filled into the four holes to avoid their collapse.

The cross section of the TMOF was shown in the inset of Fig. 1(a), which was observed by an optical microscope. The fundamental mode refractive index was calculated from 1200 to 2400 nm by the commercial software (Lumerical MODE Solution) using the full-vectorial mode solver technology. The core and cladding diameters were ~4.15 and 135 μm, respectively. At the wavelength of 1550 nm, the loss measured by the cutback technique was ~1.3 dB/m, and the calculated nonlinear coefficient was ~249 W^{-1} km^{-1} based on the nonlinear refractive index of ~5.9×10^{-19} m^2 W^{-1} for tellurite glass. Fig. 1(b) shows the chromatic dispersion curve of the TMOF, and the zero-dispersive wave (ZDW) was ~1600 nm.

3. Experimental results and discussion

3.1. SSFS generation in the TMOF pumped by a femtosecond laser

A laser pulse with the pulse duration of ~200 fs and the repetition rate of ~80 MHz generated from an optical parametric oscillator (OPO, Coherent Inc.) was used as the pump source, and the experimental setup was shown in Fig. 2. The idler wavelength of the OPO could be tuned from ~1800 to 3200 μm and the signal wavelength could be tuned from ~1060 to 1440 nm. The output beam was linearly polarized. After a neutral density (ND) filter, a half-wave plate (HWP) was inserted to adjust the polarization state of input laser beam to the axis of the tellurite MOF. The pulse was coupled into the core of the tellurite MOF by a lens with the focus length of ~5.95 mm and the numerical aperture (NA) of ~0.56 (THORLABS, C028TME-D, 1.8–3 μm). The output signal was then butt-coupled into a 0.3 m long large-mode-area (LMA) fluoride (ZBLAN) fiber with the core diameter of ~105 μm and the transmission window from 0.4 to 5 μm. Finally, the LMA ZBLAN fiber was connected to optical spectrum analyzers (OSAs; Yokogawa AQ6373, 350–1200 nm and Yokogawa AQ6375, 1200–2400 nm) to record the spectra.

First, the evolution of SSFS was investigated at different pump wavelengths with different pump powers in a TMOF of given fiber length (~20 cm). Fig. 3 shows the measured SSFS at the pump wavelength of ~1730 nm which was close to the ZDW in the anomalous chromatic dispersion range. The coupling efficiency was ~8%, which was defined as the ratio between the power transmitting in the core and the power before the lens. The average powers measured before the lens were ~160, 230, 350 and 500 mW. Considering the coupling efficiency, the peak powers launched into the fiber were calculated to be ~800, 1150, 1750 and 2500 W. If the pump power exceeds the Raman threshold, the central frequency of the fundamental soliton will experience a continuous redshift because of intrapulse SRS. Therefore, when the average pump power increased from ~160 to 350 mW, an obvious SSFS with the soliton center wavelength from ~1850 to 1995 nm was observed. Meanwhile, the center wavelength of dispersive wave (DW) shifted from ~1535 to 1396 nm, which was emitted by the soliton under the phase-matching (PM) condition. At the average pump power of ~500 mW, SC generation with the

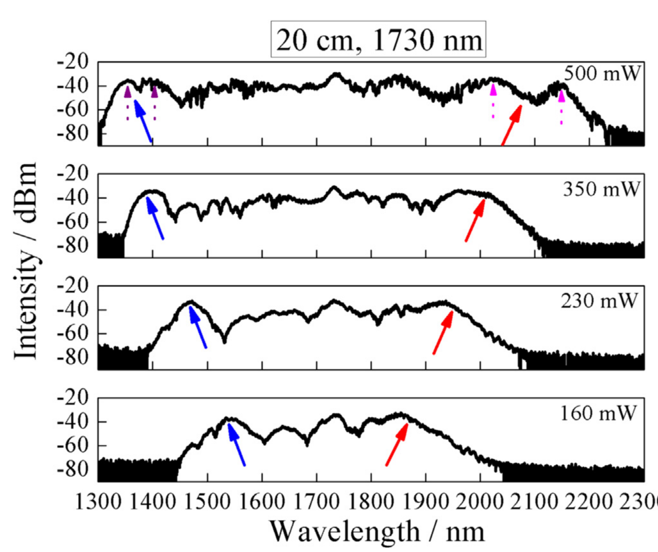

Fig. 3. Measured SSFS in the 20 cm-long TMOF at the pump wavelength of ~1730 nm with the average pump power of ~160, 230, 350 and 500 mW.