Recent Progress in Tellurite Fibers

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Abstract: We shows new potential of tellurite fibers with high nonlinearity as optical signal processing and coherent light generation media by demonstrating applications of stimulated Raman and Brillouin scattering and supercontinuum generation.

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1. Introduction

Many efforts have been devoted to materials development and design for optical fibers, waveguide devices, fiber lasers and amplifiers to meet the demands of present and future telecommunication systems and other data transmitting services. There is still a strong need and interest to explore fiber materials in order to develop various fiber devices including fiber lasers, amplifiers, optical signal processing devices, etc. Silica fibers are currently used as major waveguide materials in telecom technology. However, they have limited performance if they are applied to active fiber devices. This leads to research focused on new fiber devices using non-silica glasses. Among non-silica glasses, such as heavy metal oxide and non-oxide glasses, tellurite glasses are promising materials for photonics applications, as they combine (i) a wide transmission window, (ii) good glass stability and durability, (iii) high refractive index, (iv) increased nonlinear optical properties, and (v) relatively low phonon energies[1].

We have focused on research of tellurite fibers, covering research of new fiber material, dispersion controlled new waveguide structures and applications, as optical signal processing fiber devices and coherent light sources. In this review, we present our recent progress on lightwave generation and processing using tellurite fibers.

2. Raman amplification

The Raman gain coefficient of TBSNW (TeO_2-BaO-SrO-Nb_2O_5-WO_3) was ~42 times higher that in the silica glass. The total gain bandwidth and Raman shifts achievable in fiber Raman amplifiers are also considerably greater in the present glasses than those in silica glass. The Raman gain bandwidth of TBSNWP (TeO_2-BaO-SrO-Nb_2O_5-WO_3-P_2O_5) was more than twice that of the conventional TeO_2-Bi_2O_3-ZnO-Na_2O glass and 70% larger than that of silica glass[2].

The net-gain-flattened profile of S+C+L bands TBSNWP FRA pumped at 8 wavelengths has been simulated. The effective gain bandwidth of the TBSNWP FRA is expanded to 208 nm with 8 wavelength pumping. It is easily understood that for a multi-wavelength pumped FRA, supposing the longest pump wavelength is 1460 nm, the effective bandwidth of such a FRA is nearly equal to the usable Raman shift pumped at 1460 nm. It means that for multi-wavelength pumped gain-flattened FRA, the fiber Raman gain medium with broader usable Raman shift and bandwidth gives larger effective gain bandwidth. As above mentioned, TBSNWP fibers showed the broadest usable Raman shift and bandwidth so far achieved in tellurite fibers, so we believed that multi-wavelength pumped gain-flattened TBSNWP FRA could give quite large effective gain bandwidth[3]. These results indicate that the TBSNWP fibers are promising candidates for ultra-broadband band fiber Raman amplifiers in photonic systems.

3. Laser source and slow light generation by stimulated Brillouin scattering

Stimulated Brillouin scattering (SBS) can amplify the light propagating in a direction opposite to the pump light. It has many applications such as optical amplification, lasing, optical fiber sensor, optical phase conjugation, slow light generation and stored light.

Figure 1(a) shows the Brillouin gain coefficients of tellurite fiber we measured. A peak value of Brillouin gain coefficient of 1.70×10^{-10} m/W was obtained for this tellurite fiber, which is about 3.4 times larger than that (5×10^{-11} m/W) of silica fiber. A Brillouin shift of 7.97 GHz and a 3 dB Brillouin gain linewidth is 20.98 MHz. Figure 1(b) shows the schematic of a Brillouin tellurite fiber laser[4]. A CW tunable single frequency laser beam (the linewidth ~ 100 KHz) was amplified with an EDFA for use as the pump source. The pump light was launched into the ring cavity by the terminal 1 of an optical circulator. An all-fiber Brillouin ring cavity laser was constructed by connecting terminals 2 and 3 of the circulator in the setup through a 200m tellurite fiber, a 10 dB WDM coupler and a polarization controller. To produce an Brillouin comb tellurite fiber laser, an EDFA was inserted into the ring cavity after the tellurite fiber. With increasing the Brillouin pump laser to 153 mW, we obtained 54.6 mW unsaturated Brillouin laser, which gives a slope efficiency of 38.2%. With the addition of an EDFA into the ring cavity in Fig. 1 (b) by connecting terminals 2 and 3 of the circulator in the setup through a 10% output coupler and a polarization controller, we obtained a tunable Brillouin comb tellurite fiber laser by tuning the wavelength of the pump laser. Figure 1 (c) shows the emission spectra of the tunable (~15 nm) Brillouin comb tellurite fiber laser. The fluctuation of the relative intensity of each lines of the comb laser was less than 5 % during the entire running period of 2 hours. Figure 1 (d) presents the emission spectrum of the Brillouin comb laser pumped at 1570 nm with 26 wavelengths spaced by 7.97 GHz, which is the Brillouin shift of tellurite fiber. It has many potential applications, such as precise spectroscopy, optical sensing and characterization of photonic components.

In the case of slow light generation via SBS, tunable all optical delay lines via SBS using an optical fiber have been demonstrated [5], which shows that SBS delay line is a promising candidate for all-optical buffers in optical communication system.

We have applied tellurite fiber to slow light generation via SBS. A time delay of 74 ns and its corresponding broadening factor of ~1.785 were achieved for an input pulse of 40 ns width and a Brillouin gain of 41.4 dB, corresponding to a pump power of 19.7 mW, in a 200 m long fiber. It gave the highest value (~3.76 ns/mW) of the time delay per unit power ever reported, to our best knowledge[6].

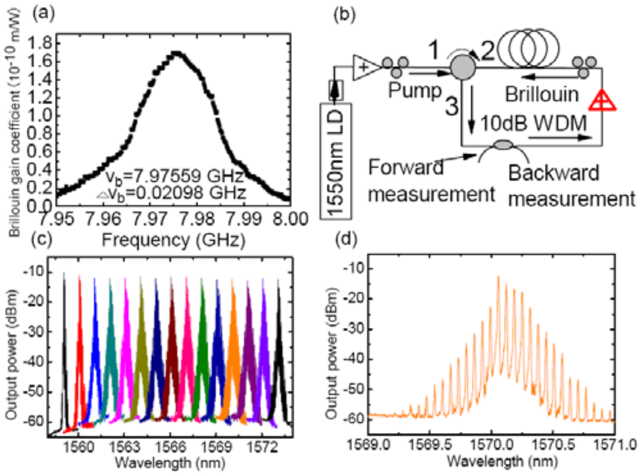


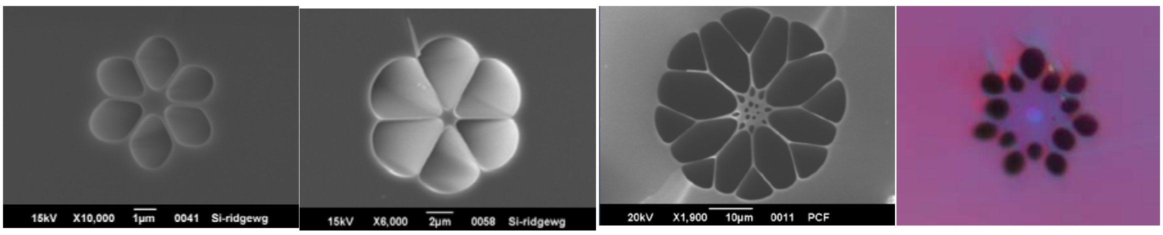
Fig. 1 (a) Brillouin gain coefficients of tellurite fiber, (b) the schematic of a Brillouin tellurite fiber laser, (c) Emission spectrum of the tunable (~ 15 nm) Brillouin comb tellurite fiber laser, (d) Emission spectrum of the Brillouin comb laser pumped at 1570 nm with 26 wavelengths spaced by 7.97 GHz.

4. Supercontinuum generation by tellurite MOFs

Supercontinuum generation (SC) by photonic crystal fiber has had revolutionary impact on the development of nonlinear optics. Highly nonlinear fiber is the prerequisite of a SC source composed of low-cost and compact devices. Nonsilica glasses are transparent in the mid-infrared range, and have a non-linear refractive index much higher than silica glass. Investigations on SC from these nonsilica glass microstructure fibers have already been reported in some papers lately [7-8]. However, the reported tellurite highly nonlinear fibers do not always show SC spectra with desirable peformance.

The tellurite microstructure optical fibers (MOFs) we fabricated for this SC generation experiment have a microstructure of "wagon wheel" design and consist of a tellurite core with the diameters of 1.1. 2.7 and 4.2 μm surrounded by six large air holes. They were fabricated by rod-in-tube method. The background loss of the fiber was measured to be ~ 5 dB/m at 1550 nm. The corresponding zero dispersion wavelengths for the above fibers were 977, 1337, and 1547 nm, respectively. The calculated nonlinear coefficients at 1.55 μm for the above fibers were 2843, 939, and 342 $km^{-1}W^{-1}$, respectively, by using a nonlinear refractive index of 5.9×10^{-19} m^2W^{-1} for tellurite glass. We have successfully fabricated tellurite MOFs and composite MOFs shown in Fig. 2 by this technique.

The inset of Fig. 3(a) shows the cross section image (taken by an optical microscope) of the tellurite microstructure fiber with the core diameter of 4.2 μm (Fiber 1). Figure 3(a) shows the dependence of the SC spectra from a 30 cm long Fiber 1 on the pump power of the femtosecond fiber laser (the maximum launched peak power of pump laser is 9.4 kW). Note that, the sharp peaks between 1 and 1.4 μm come from the 1480 nm high power Raman fiber laser as the pump source of the 1557 nm femtosecond fiber laser and amplifier. It is seen that, with slightly increasing the pump power, the spectrum around the pumping wavelength ~1557 nm is broadened, and an emission (E1) peaked at 800 nm appears, which corresponds to the frequency doubling of the lowest order Raman-shifted soliton peaked at 1600 nm. With further increasing the pump power, an emission (E2) peaked at 560 nm appears, which corresponds to the frequency tripling of the Raman-shifted soliton peaked at 1680 nm. It is suggested from Fig. 3(d) that E1 and E2 are caused by the second or third harmonic generation induced by multimode phase matching[9].



(a) (b) (c) (d)

Fig. 2 Tellurite MOFs ((a)～(c)) and chalcogenide core/tellurite cladding MOF(d) [10]

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In addition, SC light expanding from 474 nm to 2400 nm could be achieved from 25 cm Fiber 2. The profiles of SC spectra for Fiber 1, 2 and 3 are different due to the change of chromatic dispersion of the fibers. The mechanisms of SC generation pumped by femtosecond laser have been widely investigated[11]. The fission of higher-order solitons into red-shifted fundamental solitons and blue-shifted nonsolitonic radiation are the main mechanism for spectral broadening when the pumping wavelength is located at the anomalous dispersion region, which is our case. The main difference between the Raman-shifted solitons and the blue-shifted non-solitonic radiation is that the latter may occur when the critical phase-matching condition is satisfied. The changes of profiles of SC spectra for Fiber 1, 2 and 3 are mainly due to the changes of such critical phase-matching conditions related to the chromatic dispersion of the fibers. Our experimental results have shown that the chromatic dispersion controlled tellurite microstructure fiber could generate flattened SC spectra expanding from visible to mid-infrared.

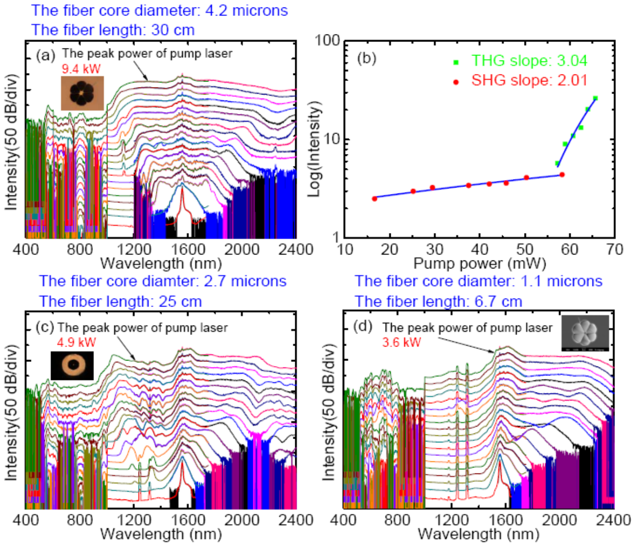

Fig. 3 (a) The dependence of second, third harmonics and SC spectra from a 30 cm long Fiber 1 on the pump power of the femtosecond fiber laser. Inset: The cross section image (taken by an optical microscope) of Fiber 1. (b) The intensity dependence of second or third harmonic on the pump power. (c) and (d) The dependence of the emission spectra of tellurite microstructure optical fibers with the core diameter of 2.7 (Fiber 2) or 1.1 μm (Fiber 3) on the pump power of 1557 nm femtosecond fiber laser. Inset: The cross section image of Fiber 2 or Fiber 3.

5. Conclusions

The effects of Raman spectrum on the relative gain flatness and the effective bandwidth were investigated using the TBSNWP glass with one broad main Raman shift peak. Our results have shown that the TBSNWP tellurite fibers can realize a broad band Raman gain spectra covering the S+C+L band. Highly efficient Brillouin slow light generation was demonstrated in a tellurite fiber. Tellurite fiber gave the highest value (~3.76 ns/mW) of the time delay per unit power ever reported, to our best knowledge.

We have successfully fabricated dispersion controlled tellurite microstructure fibers with high nonlinearity. We have obtained broadband SC spectra expanding from 474 to 2400 nm in a tellurite MOF. We have shown that the chromatic dispersion controlled tellurite microstructure fiber can generate flattened SC spectra expanding from visible to mid-infrared.

We have shown that tellurite fibers have high potential as optical signal processing and coherent light source media. We can expect tellurite fiber devices will open a new prospect for optical signal processing and coherent light generation.

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