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(Received 2 June 2016; accepted 26 August 2016; published online 7 September 2016)

Tunable mid-infrared dispersive waves are generated in a birefringent fluorotellurite microstructured fiber (FTMF) pumped by a 1560 nm femtosecond fiber laser. The FTMF have two zero-dispersion wavelengths (ZDWs) for each polarization axis. The second ZDWs for the fast and slow axes of the FTMF are 2224 and 2042 nm, respectively. As the pump laser is polarized along the fast (or slow) axis of the FTMF, tunable mid-infrared dispersive waves from 2680 to 2725 nm (or from 2260 to 2400 nm) are generated in the FTMF when the Raman soliton meets the second zero-dispersion wavelength of the fast (or slow) axis with increasing the pump power. Our results show that the designed FTMFs are promising nonlinear media for generating tunable mid-infrared light sources. Published by AIP Publishing. [http://dx.doi.org/10.1063/1.4962391]

Mid-infrared light sources have attracted much attention due to their potential applications in various fields, such as spectroscopy, biomedicine, bio-photonics, defense, and security.1–6 Raman soliton or dispersive wave generation in optical fibers, as one of the promising ways for obtaining fiber-based mid-infrared light sources, has been widely investigated.7–11 In 1980, Mollenauer et al. reported the generation of temporal solitons in silica fibers.12 Soon after that, Mitschke et al. and Dianov et al. found that the optical solitons can exhibit a strong self-frequency red-shift in silica fibers.13 It is because that the blue spectral part of a soliton pumps the red part, causing a continuous red shift in the soliton spectrum. In 2003, Skryabin et al. demonstrated that the soliton self-frequency-shift could be cancelled in a silica microstructured fiber with a negative dispersion slope and tunable red-shifted dispersive waves were generated in the silica microstructured fiber.14 In 2008, Chan et al. reported a tunable Raman soliton source from 1.2 to 2.2 μm in silica fibers pumped by a Cr: Forsterite laser.15 However, silica fibers are not suitable for generating mid-infrared light sources (>2.5 μm) because of very high material loss in the mid-infrared spectral region.16

To generate mid-infrared Raman soliton or dispersive waves, several types of specialty optical fibers including tellurite, fluoride, and chalcogenide microstructured fibers with low transmission loss in mid-infrared region have been developed. Koptev et al. reported tunable high-quality Raman solitons up to 2.25 and 2.65 μm with the pump at 1.6 and 2 μm, respectively.17 Liu et al. demonstrated a widely tunable Raman soliton source (1.93–3.95 μm) in a fluoride microstructured fiber pumped by a 1.93 μm fiber laser with a pulse width of 200 fs through numerical simulations.18 Cheng et al. reported tunable Raman solitons from 2.986 to 3.419 μm in a chalcogenide microstructure fiber pumped by an optical parametric oscillator operating at ~2.8 μm.19 Very recently, Novoa et al. demonstrated photoionization-induced emission of tunable few-cycle mid-infrared dispersive waves (4.2–4.6 μm) in gas-filled hollow-core photonic crystal fibers through numerical simulations.20 Despite recent progress in this field, tunable mid-infrared dispersive waves (>2.5 μm) have not yet been demonstrated experimentally in optical fibers and it is still necessary to explore microstructured fibers for constructing fiber-based mid-infrared light sources.

Very recently, fluorotellurite microstructured fibers (FTMFs) with low loss in the spectral region of 0.4–6 μm, good chemical and physical properties compared to fluoride fibers have been developed by us for constructing high power mid-infrared fiber lasers.21 Our previous results showed that FTMFs might be a promising nonlinear medium for generating mid-infrared dispersive waves.22 The wavelength of dispersive wave can be calculated from a phase matching condition between the soliton and the dispersive wave, which can be expressed as below:23

\[ \sum_{n \geq 2} \frac{(\omega_{CR} - \omega_s)^n}{n!} \beta_n(\omega_s) = \frac{1}{2} \gamma P, \]

where \( \omega_{CR} \) and \( \omega_s \) are the dispersive wave and soliton frequency, respectively, the \( \beta_n(\omega_s) \) is the n-th order derivative of the propagation parameter \( \beta \) of the soliton wavelength, the \( P \) is the peak power of the soliton, and the \( \gamma \) is the nonlinear coefficient. So we can obtain the mid-infrared dispersive waves from the designed microstructured fibers with appropriate dispersion profiles.
Furthermore, we consider that by introducing the birefringence into FTMFs, two polarization axes including slow and fast axes exist in birefringent FTMFs. Since each polarization axis has its own dispersion profile, two sets of tunable mid-infrared dispersive waves can be generated in birefringent FTMFs. As a result, the tuning range of mid-infrared dispersive waves in birefringent FTMFs is larger than that in non-birefringent FTMFs. Tunable mid-infrared Raman solitons or dispersive waves have not yet been reported in birefringent FTMFs owing to the difficulty of fabrication of such fibers.

In this paper, we reported tunable mid-infrared dispersive waves generation in a birefringent FTMF pumped by a 1560 nm femtosecond fiber laser. The FTMFs based on TeO$_2$-BaF$_2$-Y$_2$O$_3$ glasses were fabricated by using a rod-in-tube method. The FTMF had a birefringence of 3.5 $\times$ 10$^{-2}$ and two zero-dispersion wavelengths (ZDWs) for each polarization axis. As the pump laser was polarized along the fast (or slow) axis of the FTMF, tunable mid-infrared dispersive waves from 2680 to 2725 nm (or from 2260 to 2400 nm) were generated in the FTMF.

In our experiments, we fabricated birefringent FTMFs by using the rod-in-tube method. The glass compositions of the core and cladding of the FTMFs were 70TeO$_2$-20BaF$_2$-10Y$_2$O$_3$ and 65TeO$_2$-25BaF$_2$-10Y$_2$O$_3$, respectively. For the above glass system, the addition of Y$_2$O$_3$ was not only to avoid the occurrence of crystallization during fiber drawing but also to obtain glasses with high transition temperatures ($\sim$424 $^\circ$C). Such a value was much higher than that of previously reported tellurite or fluorotellurite glasses, which would be preferable for obtaining high power fiber-based light sources.$^{24}$ The absorption coefficient at $\sim$3.1 $\mu$m caused by the residual hydroxyl groups in the glass was $\sim$0.08 cm$^{-1}$, which indicated that the loss in the mid-infrared range was relatively low for generating mid-infrared light sources. The inset of Fig. 1(a) shows the scanning electron microscope image of the fabricated birefringent FTMF. The fiber had a "wagon wheel" structure, consisting of an unsymmetrical solid core with a size of 1.08 $\times$ 10$^{-2}$ by using the formula $B_m = |n_x - n_y|$, where $n_x$, $n_y$ are the effective indexes of polarization modes for the fast and slow axes, respectively, which was large enough for observing the birefringence effect in the above fiber. Figure 1(a) shows the calculated group velocity dispersion (GVD) profiles of the fundamental propagation mode in the FTMF by using the full vectorial finite difference method. The fiber had two zero-dispersion wavelengths (ZDWs) for each polarization axis, which was required for generating tunable red-shifted dispersive waves. The ZDWs for the fast axis were 1000 and 2224 nm, respectively. Similarly, the ZDWs for the slow axis were 897 and 2042 nm, respectively. The calculated nonlinear coefficients (\(\gamma\)) at 1560 nm of the fundamental propagation modes were 4451 and 5322 km$^{-1}$ W$^{-1}$ for the fast and slow axes, respectively, by using a nonlinear refractive index of 1.4 $\times$ 10$^{-18}$ m$^2$ W$^{-1}$ for fluorotellurite glasses.$^{22}$ Figure 1(b) shows the calculated confinement losses of the fundamental propagation mode for the fast and slow axes by using the full vectorial finite difference method. The confinement losses for both cases increased very much when the operating wavelength was longer than 2.8 $\mu$m. The background loss at 1560 nm of the FTMF was measured to be 0.14 dB/cm by using a cutback method.

To clarify the potential of the birefringent FTMF for the generation of mid-infrared dispersive waves, we performed the following experiments and the experimental setup was shown in Fig. 2. A 1560 nm femtosecond fiber laser with a pulse width of $\sim$150 fs, a repetition rate of $\sim$50 MHz, and a maximum output power of 500 mW (the corresponding pulse energy: $\sim$10 nJ) was used as the pump source. The pump laser was launched into the birefringent FTMF through a couple of aspheric lens and the measured coupling efficiency, defined as the launched power divided by the power incident on the lens, was about 25%. The polarization state of the pump laser was controlled by a polarization controller. The output signals were monitored by using an optical spectrum analyzer (OSA Yokogawa 6375A, the spectral range: 1200 nm–2400 nm) and a grating spectrometer with an InSb detector through a large mode field area ZBLAN fiber cable mechanically spliced the output end of the birefringent FTMF.

Figure 3(a) shows the dependence of the measured output spectra from a 5 cm long birefringent FTMF on the launched average power of the 1560 nm femtosecond laser when the pump laser was polarized along the fast axis of the fiber. Since the dispersion for the fast axis was anomalous in the wavelength range of 1000–2224 nm, the pumping wavelength was located at the anomalous dispersion region of the birefringent FTMF. The group velocity dispersion value ($\beta_2$) at 1560 nm for the FTMF was about $-218$ ps$^2$/km and the
calculated dispersion length was \(\sim 10\) cm. For the 5 cm long birefringent FTMF, the first soliton was generated by the soliton fission as the average pump power reached \(\sim 25\) mW. With further increasing the average pump power, the soliton self-frequency shift (SSFS) was clearly observed due to the Raman effect, where the blue spectral part of the soliton pumped the red part, causing a continuous red shift in the soliton spectrum. Interestingly, as the average pump power was increased to 39.9 mW, the first Raman soliton met the second ZDW point with a negative dispersion slope \(\beta_3 < 0\) for the fast axis, and the SSFS cancellation occurred.

Meanwhile, the red-shifted dispersive wave with the wavelength at 2725 nm was observed. With further increasing the pump power, the red-shifted dispersive wave shifted from 2725 to 2680 nm. Besides, we also found that the second Raman soliton appeared as soon as the average 1560 nm femtosecond pulse power reached 39.7 mW. The above phenomena could be explained as follows. As the Raman soliton shifted into the spectral region in which the dispersion slope of the fiber was negative \(\beta_3 < 0\), the soliton would emit a radiation band with a wavelength of longer than the second ZDW through the Cherenkov mechanism.\(^{25}\) Because of the momentum conservation, as the dispersive wave was emitted in the normal GVD regime, the soliton should recoil further into the anomalous GVD regime, the spectral recoil mechanism was responsible for the suppression of SSFS.\(^{26}\) As far as the spectral recoil was large enough, the SSFS cancellation occurred and the dispersive wave was amplified with an increase of the pump power. The above experimental results showed that tunable red-shifted dispersive waves from 2680 to 2725 nm could be obtained in the birefringent FTMF when 1560 nm femtosecond laser was polarized along the fast axis of the fiber.

Figure 3(b) shows the dependence of the output spectra from a 5 cm long birefringent FTMF on the average pump power of the 1560 nm femtosecond laser when the pump laser was polarized along the slow axis of the fiber. Since the dispersion for the fast axis was anomalous in the wavelength range of 897–2042 nm, the pumping wavelength was also located at the anomalous dispersion region. The \(\beta_2\) at 1560 nm for the slow axis of FTMF was about \(-388\) ps\(^2\)/km and the calculated dispersion length was \(\sim 5.6\) cm. As the pump power reached 31 mW, the first Raman soliton was observed, and the red-shift dispersive wave at 2400 nm was observed when the pump power reached 34 mW. With further increasing the pump power to 35.3 mW, the red-shift dispersive wave can be tuned from 2400 to 2260 nm.

The above results showed that two sets of tunable mid-infrared dispersive waves could be generated in birefringent FTMFs by varying the polarization state of the pump laser and the tuning range of mid-infrared dispersive waves in birefringent FTMFs could be larger than that in non-birefringent FTMFs.

In addition, we performed numerical simulations by solving the generalized nonlinear Schrödinger equations.\(^{27}\) In the simulations, we took the calculated chromatic dispersion data shown in the inset of Fig. 1(a); the aforementioned nonlinear coefficients; the pumping laser with an operating wavelength of \(\sim 1560\) nm, a pulse width of \(\sim 150\) fs, a repetition rate of \(\sim 50\) MHz, and a maximum average pump power of \(\sim 40.8\) mW (the corresponding pulse energy: \(\sim 810\) pJ);
and the Raman response function derived from the Raman gain spectrum of tellurite glass.28 Figs. 4(a) and 4(b) showed the dependence of the simulated supercontinuum spectra on the average pump power of the pump laser for the fast and slow axes of the fiber, respectively. The dashed curves of Figs. 4(c) and 4(d) show the simulated supercontinuum spectra as the average pump power was 40.8 and 35.3 mW for the fast and slow axes of the fiber, respectively. The solid curves of Figs. 4(c) and 4(d) show the corresponding measured output spectra as the average pump power was 40.8 and 35.3 mW for the fast and slow axes of the fiber, respectively. The simulated results agreed with the corresponding measured ones for both the fast and slow axes of the fiber. The discrepancy between the simulated and experimental results might be caused by large loss at long wavelengths (including the confinement loss of the fiber and the material loss caused by the absorption of residual OH- in the fiber material) of the fiber we used. Figs. 4(e) and 4(f) showed the simulated spectrograms of output pulse corresponding to the simulation results of Figs. 4(c) and 4(d). The spectrograms display the temporal and spectral characteristics of the soliton and dispersive wave. From the spectrograms, the pulse width of the dispersive waves at 2725 and 2260 nm were estimated to be 1.2 and 1.05 ps, respectively.

In addition, the achieved maximum output powers of the dispersive waves at 2725 and 2260 nm were measured to be 0.035 and 0.19 mW, and the corresponding conversion efficiencies were 0.9% and 2.97%, respectively. Generally, the conversion efficiencies of DWs were related to the pulse energy, pulse width of the pump laser, the mode-field diameter, the transmission loss at long wavelengths, and the dispersion characteristics of the fiber.29,30 In the future, we will try to improve the conversion efficiency by increasing the pulse energy of the pump laser or optimizing the dispersion characteristics of the fiber.

Note that, by using the designed birefringent FTMFs with varied ZDWs as the nonlinear media and a 2 μm femtosecond laser as the pump source, the operating wavelength of mid-infrared dispersive waves can be extended to longer wavelength (>3 μm) (see Fig. S1 of supplementary material). In the future, we will try to obtain mid-infrared tunable dispersive waves (>3 μm) from the designed birefringent FTMFs.

In summary, we demonstrated tunable mid-infrared dispersive waves from 2680 to 2725 nm (or from 2260 to 2400 nm) in the birefringent FTMFs by varying the polarization state of the 1560 nm femtosecond fiber laser. Our results showed that the designed birefringent FTMFs were promising nonlinear media for generating tunable mid-infrared light sources.

See supplementary material for details for extending the dispersive wave wavelength to beyond 3 μm.

This work was supported by NSFC (Grants 61378004, 61527823, 61535009, 60908001, 61077033, 60908031, 11274139, and 11474132), the Opened Fund of the SKLIO, and TNList Cross-discipline Foundation. One of the authors (Y. Ohishi) was supported by MEXT, the Support Program for Forming Strategic Research Infrastructure (2011–2015).