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Wavelength conversion performance in a tellurite step-index optical fiber

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ABSTRACT

We demonstrated in this work the wavelength conversion performance based on the four-wave mixing process in a new tellurite step-index fiber as short as 1 m. The fiber was pumped by a femtosecond pulsed laser near the zero dispersion wavelength of the fundamental mode which was close to that of the material dispersion in the near-infrared region. When the pump and signal wavelengths were at 1795 and 1434 nm, respectively, the generated idler was obtained at 2400 nm and the conversion wavelength spacing could be as broad as 966 nm. In addition, a 17.5-dB signal gain at 1550 nm and 1.1-dB idler at 1757 nm were obtained when the pump was tuned to 1647 nm.

1. Introduction

Four-wave mixing (FWM) in optical fibers is a process which can amplify a weak signal and generate a new light wave known as the idler, simultaneously. It has attracted considerable attentions due to its high gain, low noise figure and broad bandwidth [1]. In recent decades, FWM has become very useful for many applications such as fiber-based optical parametric amplification [2], wavelength conversion [3], phase-sensitive amplifier [4], signal regeneration and all-optical sampling [5]. For instance, the parametric amplification based on FWM can provide a wideband and flat gain profile contrary to the conventional amplifiers such as the Raman and Erbium-doped fiber amplifiers [2]. In addition, FWM is a promising technique for wavelength conversion in optical networks due to its ultrafast response and high transparency to bit rate and modulation format [6]. FWM-based wavelength conversion has been reported by using high-nonlinearity DSF [7] and photonic crystal fiber (PCF) with complex structures [6,8] to shorten the fiber length from kilometers to tens of meters. To further improve the performance of FWM-based wavelength conversion such as its bandwidth and conversion efficiency, the nonlinearity of silica should be improved by using several soft glasses such as lead-silicate [9], bismuth-oxide [10], tellurite [11–13] and chalcogenide glasses [14,15]. In our previous reports, the performances of FWM and wavelength conversion in tellurite fibers have been studied by using continuous wave [11], nanosecond [12] and picosecond pulse laser [13]. In this paper, a tellurite step-index fiber with large core is fabricated to keep the zero-dispersion wavelength (ZDW) of the fundamental mode close to that of the material dispersion which is located in the near-infrared region. By using a femtosecond pulsed laser pumped in the vicinity of the ZDW, it is expected to broaden and extend the bandwidth of the FWM-based wavelength conversion towards the near-infrared window for potential applications.

2. Fiber fabrication

In this work, the fiber core and cladding materials were made of TeO_2-ZnO-Na_2O-Bi_2O_3 (TZNB) glasses. Their compositions are listed in Table 1. The analytic grade oxide powders of ZnO, Na_2CO_3 and Bi_2O_3 with high purity 99.99% and the TeO_2 powder with very high purity 99.999% were used as raw materials to reduce the loss of the fiber. The glass powder preparation, melting and casting processes were carried out in a glove box to minimize the water absorption. Each of the core and cladding mixtures was placed in a gold crucible and was melted in an electric furnace. The furnace was purged with dry Ar and O_2 atmosphere to prevent hydroxyl impurity contamination. Subsequently, the melts were cast into different preheated molds to make glass samples with specific shapes. Then, they were annealed around the glass-transition temperature for 3 hours to release residual stress.

A UV/VIS/NIR Spectrometer (Perkin Elmer, Lambda 900) and an FT-IR spectrometer (Perkin Elmer, Spectrum 100) were used to measure transmission spectrum of the core glass as shown in Fig. 1a. The thickness of the glass samples was 1 mm. The surfaces

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Table 1
The glass compositions of core and cladding materials.

Material	TeO_2 (mol %)	ZnO (mol %)	Na_2O (mol %)	Bi_2O_3 (mol %)
Core	75.25	14.50	5.6	4.65
Cladding	73.23	18.65	5.6	2.52

of the samples were polished carefully to satisfy the requirements of the transmission measurements. The transmittance of the core is over 70% in a broad wavelength range from 1.0 to 6.0 μm which is suitable for many nonlinear applications in the infrared window. A thermal mechanical analysis system (Rigaku, Thermo Plus TMA 8310) was employed to measure the glass thermal expansion and softening temperatures (T_s) of the core and cladding glasses. As shown in Fig. 1b, the difference of T_s between the core and cladding glasses is as small as 3 °C and the thermal expansion behavior of the core and cladding glasses are very similar when the temperature is raised from 50 to 330 °C. These compatible thermal properties of the core and cladding glasses are very advantageous to the stability of the following fiber fabrication process.

The tellurite step-index optical fiber was successfully fabricated by using the suction casting [16] and rod in tube methods [17]. As the first step, the cladding glass melt was poured into a cylindrical mold whose hole diameter was 5 mm. Then, the core glass melt was promptly cast onto the cladding glass melt to form the second layer. During their solidification, significant volume contraction of the cladding glass occurred. It resulted in a suction of the core glass into the depressed center of the cladding glass and formed the initial fiber preform. This technique is known as suction casting process [16]. The first fiber preform was inserted into a cylindrical cladding tube with an inside diameter of ~5 mm prepared by the rotational casting method. They were elongated at around 340 °C to obtain the second preform with an outside diameter of ~5 mm. The second preform was inserted into another cladding tube and was drawn into fiber. The cross-sectional image of the fabricated tellurite fiber is shown in Fig. 2a. The fiber diameter is ~128 μm. The core diameter is ~6.3 μm. At 1800 nm, the refractive indices of the core and cladding glasses were ~1.9997 and ~1.9596, respectively. The chromatic dispersion of the fundamental mode was calculated by a commercial software (Lumerical-Mode Solution) with the full-vectorial finite-difference method (FV-FDM). The ZDW of the fiber fundamental mode is at 1829 nm. As shown in Fig. 2b, it is very close to that of the material dispersion at 1855 nm. The nonlinear coefficient of the fabricated fiber is calculated by using the nonlinear refractive index of the TZNB glass (5.9×10^{-19} $m^2 W^{-1}$). At 1800 nm, it is about 93 $W^{-1} km^{-1}$. The effective mode area is 21.6 μm^2. The fiber loss is about 3 dB/m measured by the cut-back method.

3. The performance of wavelength conversion

The idler beam of an optical parametric oscillator (OPO, Chameleon Coherent Inc.) was used as the pump source. The pulse duration was ~200 fs and the repetition rate was 80 MHz. Due to the experimental setup, the idler beam included the OPO idler and the residual of the OPO signal. The intensity of the residual signal was about 40-dB lower than that of the idler. The idler beam of the OPO was coupled into the fabricated tellurite fiber by a focus lens whose numerical aperture was ~0.47. The idler component acted as the pump and the residual signal component played the role of the signal for the FWM process. Because the signal and idler wavelengths of the Chameleon OPO are tunable, the wavelengths of the pump and the signal which propagated in the tellurite fiber can be tuned. But, the average power of the pump and the signal was fixed at 30 mW and 3 μW, respectively. The tellurite fiber was as long as 1 m. The spectrum at the output of the fiber was recorded by an optical spectrum analyzer (OSA: Yokogawa AQ6375). The whole experimental setup is illustrated in Fig. 3.

The FWM-based wavelength conversion spectra obtained by pumping at different wavelengths are shown in Fig. 4(a–l). As can be seen, a new idler wave was generated by the FWM process and located at the longer wavelength side of the pump. The weak input signal was noticed to be amplified. When the pump wavelength was tuned from 1647 to 1795 nm, the input signal was blue-shifted from 1550 to 1434 nm, and the idler was red-shifted from 1757 to 2400 nm, correspondingly. The conversion wavelength spacing became broader but the signal gain and the idler conversion efficiency gradually decreased. The extracted signal/idler evolution versus the pump wavelength λ_p is shown in Fig. 4(m) and the idler conversion efficiency versus the idler wavelength is shown in Fig. 4(n). When λ_p was 1647 nm, the intensity of the signal at 1550 nm was amplified from 3 μW to ~170 μW and the intensity of the generated idler at 1757 nm was ~3.9 μW. It means that a 17.5-dB signal gain (output signal power/input signal power) and an 1.1-dB idler conversion efficiency (output idler power/input signal power) were obtained. When λ_p was 1795 nm, the signal gain at 1434 nm was 0.5 dB and the idler conversion efficiency at 2400 nm was −18.3 dB. This decrease in the signal gain and the idler conversion efficiency were attributed to the increased walk-off effect.

4. Conclusions

In summary, the FWM-based wavelength conversion performance in a tellurite step-index optical fiber pumped by a femtosecond laser was studied. In order to achieve a low-loss tellurite

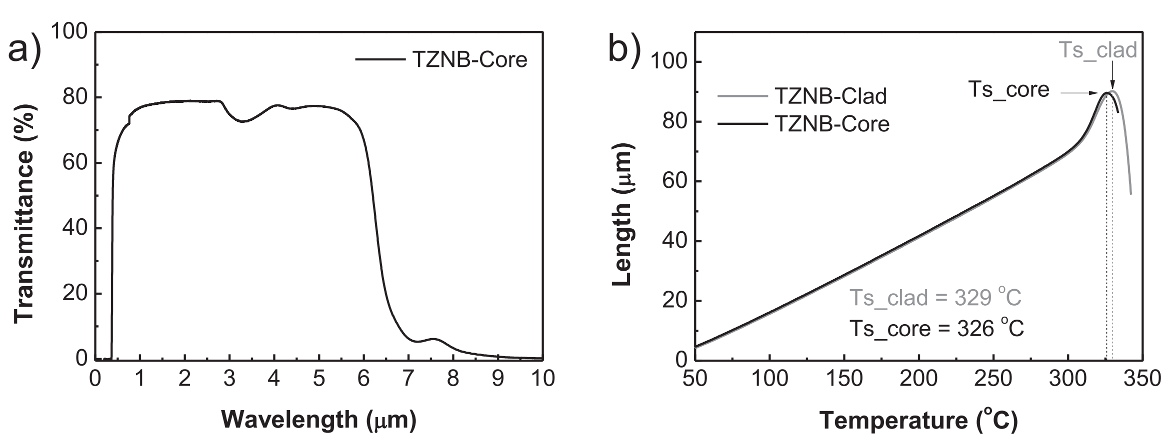

Fig. 1. (a) Transmission spectrum of the TZNB core material and (b) TMA curves of the TZNB core and cladding glasses.