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Fabrication and characterization of a three-core chalcogenide–tellurite hybrid optical fiber

Tonglei Cheng [a,*], Xiaojie Xue [a], Dinghuan Deng [a], Morio Matsumoto [b], Hiroshige Tezuka [b], Takenobu Suzuki [a], Yasutake Ohishi [a]

[a] Research Center for Advanced Photon Technology, Toyota Technological Institute, 2-12-1 Hisakata, Tempaku, Nagoya 468-8511, Japan

[b] Furukawa Denshi Co., Ltd., 2-3-2, Marunouchi, Chiyoda-Ku, Tokyo 100-8370, Japan

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ABSTRACT

A multicore chalcogenide–tellurite hybrid optical fiber is designed and fabricated with three cores arranged in a trigonal array. Cores with high refractive index are made of chalcogenide glass ($Ge_{15}Ga_3Sb_{13}S_{69}$), and the background with low refractive index is made of $76.5TeO_2$–$6Bi_2O_3$–$11.5Li_2O$–$6ZnO$ (mol%, TZLB). The diameters of three cores are ~3.12, 3.07 and 2.96 μm, and the calculated zero-dispersion wavelengths (ZDWs) are ~2.361, 2.298 and 2.193 μm, respectively. Supercontinuum (SC) generation in each core is investigated by pumping it with the wavelengths of ~2200 and 2400 nm from an optical parametric oscillator.

1. Introduction

Multicore fibers (MCFs) have been intensively studied because of their extraordinary advantages [1,2]. For example, they can overcome the limit of transmission capacity and offer solutions for high-power transmission [3,4]. As a result, MCFs have already been widely applied to microwave photonics (MWP), passive optical network (PON), the high-power fiber lasers and amplifiers and the space-division multiplexing (SDM) transmission systems, etc. [5–11]. However, presently most of the MCFs are made based on the silica glass and not fit to the mid-infrared (mid-IR) wavelength region.

Soft glasses, especially for tellurite and chalcogenide glasses, have raised attention due to their wide transparency in the infrared region and nonlinear refraction index close to 2 or 3 orders of magnitude larger than that of silica [12–19]. If these glasses are used for MCFs, it could lead to applications of great interest, such as the stress and temperature sensing, the high power laser or amplifier and high capacity signal transmission in the mid-IR region. Recently, a seven-core tellurite fiber has already been fabricated in our laboratory [20].

In the paper, we designed and fabricated a three-core chalcogenide–tellurite (CT) hybrid optical fiber with three cores arranged in a trigonal array. The three cores with high refractive index are made of $Ge_{15}Ga_3Sb_{13}S_{69}$ (GGSS) chalcogenide glass, while the background with low refractive index is made of $76.5TeO_2$–$6Bi_2O_3$–$11.5Li_2O$–$6ZnO$ (mol%, TZLB) glass. When the light beam was coupled in only one of the three cores, the fiber can be considered as a single core fiber and supercontinuum (SC) generation in each core was investigated under the pump of a ~2200 and 2400 nm femtosecond laser. The three-core CT fiber can be applied in sensing and switching dynamics in laser, etc. [7,21].

2. Three-core CT hybrid optical fiber fabrication

During the fabrication of the three-core CT hybrid optical fiber, GGSS and TZLB glasses were chosen because they have well-matched thermal and mechanical properties which can avoid cracking at the core-cladding interface [22]. The absorbance and transmission spectra of GGSS and TZLB glasses were measured and reported in Refs. [20,22], and the transmission ranges of GGSS and TZLB glasses were from ~0.54 to 12 μm and 0.36 to 6.1 μm. The linear material refractive indices of the two glasses were measured at different wavelengths from 500 nm to 3000 nm using prisms, as shown in Fig. 1. The measured values were fitted to the Sellmeier formula to get Sellmeier coefficients shown in Table 1, which was to obtain the material refractive indices of GGSS and TZLB glasses at random wavelength. The thermal expansion coefficients of GGSS and TZLB glasses have been measured by the thermal expansion analyzer (TMA8310) [22].

The three-core CT hybrid optical fiber was fabricated by rod-in-tube drawing technique which can also be used for other MCFs,

* Corresponding author. Fax: +81 52 809 1869.
E-mail address: chengtonglei@gmail.com (T. Cheng).

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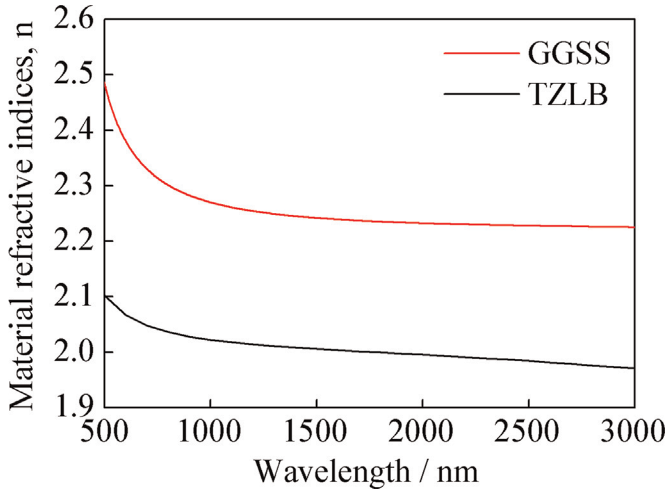

Fig. 1. Linear material refractive indices of GGSS and TZLB glasses.

Table 1
Sellmeier coefficients of GGSS glass.

$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - L_i^2}$

	TZLB		GGSS	
	A_i	$L_i^{\ 2}$/ μm^2	A_i	$L_i^{\ 2}$/ μm^2
1	1.67189	0.0004665	2.51696	0.0218087
2	1.34862	0.0574608	1.41612	0.1034606
3	0.6218	46.725427	0.0601	153.82497

such as four-, five- or seven-core fibers. The process was shown in Fig. 2. A GGSS glass rod (the diameter of ~12 mm) was prepared by a direct synthesis from the elements in an evacuated silica ampoule. The obtained rod was annealed near the glass transition temperature for 2 h to stabilize the structure and to relieve internal stresses [20]. First, the GGSS glass rod was elongated to prepare the capillaries with the diameter of ~3 mm, as shown in Fig. 2(a). Second, a capillary was inserted into a circular TZLB glass tube (the center core diameter of ~3 mm), and elongated together to obtain a preform with the diameter of ~1.3 mm, as shown in Fig. 2(b). Third, three preforms were inserted into another TZLB tube, and elongated to obtain the cane with the diameter of ~3 mm. Finally, the cane was inserted into another jacket TZLB glass tube (g) and drawn into fiber at a temperature ~307 °C which was the same with T_s. The jacket tube (g) was utilized to decrease the diameter of GGSS cores. During the fiber-drawing process, a negative pressure which was ~3–5 kPa lower than the standard atmospheric pressure filled the fiber to avoid the interstitial hole formation, and no crystallization and chemical reaction were found. Fig. 3 shows the photos of the GGSS rod and TZLB tube.

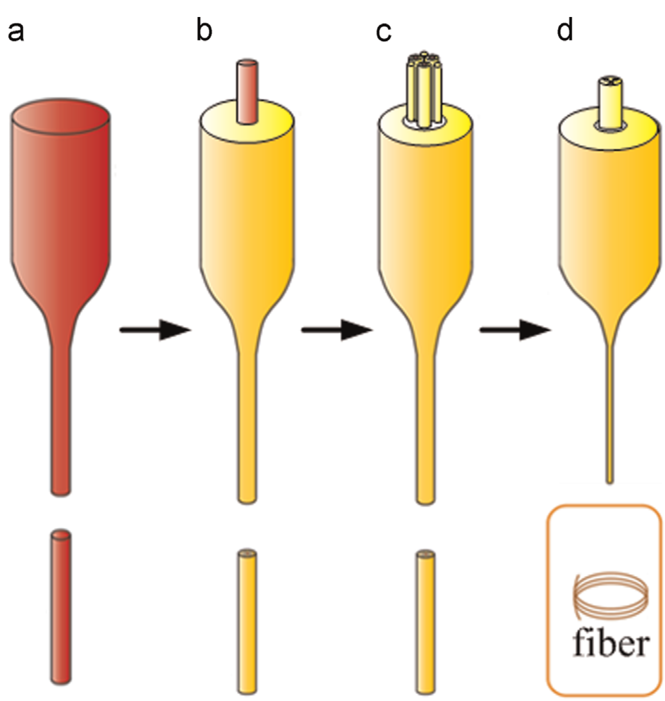

Fig. 2. Schematic diagram for the fabrication of the three-core CT hybrid optical fiber. (a) Elongated GGSS rod. (b) Preform. (c) Cane. (d) Three-core CT hybrid optical fiber.

Fig. 4(a) shows the cross-sectional structure of the three-core CT hybrid optical fiber. The diameters of three GGSS glass cores were ~3.12 (core(1)), 3.07 (core(2)) and 2.96 μm (core(3)), respectively. And the pitch (core–core) was 10.4 μm. The cores can be considered separately, and their optical properties are different due to diameter disparity. The loss of each core was almost same and ~2 dB/m at 2000 nm due to impurities of glasses, which was measured by the cut-back technique. The fundamental mode-field profiles of each core at ~2.2 μm was simulated by a commercial software (Lumerical MODE Solution) using the full-vectorial mode solver technology, as shown in the inset of Fig. 4(b). The nonlinear refractive index of GGSS glass was $n_2 = 1.8 \times 10^{-17}$ m^2/W [23], and the effective mode areas of the three cores were ~5.547, 5.409 and 5.120 μm^2 at ~2.2 μm respectively. The calculated chromatic dispersions were shown in Fig. 4(b), and the zero-dispersion wavelengths (ZDWs) were ~2361(core(1)), 2298 (core(2)) and 2193 nm (core(3)).

3. Experimental results and discussion

The experimental setup for SC generation in the three-core CT hybrid optical fiber was shown in Fig. 5. In our experiment, the laser pulse tuned from 1700 nm to 3000 nm with the pulse duration ~200 fs and the repetition rate of ~80 MHz generated from an optical parametric oscillator (OPO, Coherent Inc.) was used as the pump light. The pulse was coupled into the core of a 10 cm long three-core CT hybrid optical fiber by a lens with the focus length of ~4.0 mm and the numerical aperture (NA) of ~0.56 (THORLABS, CO36TME-D). The output signal was butt-coupled into a 0.3 m large-mode-area (LMA) fluoride fiber with the core diameter of ~105 μm and the transmission window from 0.4 to 5 μm. The LMA fluoride fiber was connected to an optical spectrum analyzer (OSA, 1200–2400 nm) and a Fourier-transform infrared (FT-IR) spectrometer to record the SC spectra.

When the light beam was coupled in each core of the three-core CT hybrid optical fiber, no coupling effect was found and the fiber can be considered as a single core fiber. SC generation in each core were measured at the pump wavelength of ~2200 nm with the average pump powers from ~200 to 240 mW, as shown in Fig. 6. The coupling efficiency in each core was similar (~10%), which was defined as the ratio between the power transmitting in the core and the power before the lens. Because only a little power leaked into the cladding, which can be neglected, the power transmitting in the core can be measured by OSA from the output end of the fiber. Considering the coupling efficiency, the launched peak powers were ~1.25 and 1.5 kW. First, the light beam was coupled in core(1) and core(2). The pump wavelength was in the normal dispersion region and SC spectra were shown in Fig. 6 (a) and (b). The mechanism of spectrum broadening was