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Tailoring chromatic dispersion in chalcogenide–tellurite microstructured optical fiber

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ABSTRACT

We report fabrication of a highly nonlinear hybrid microstructured optical fiber composed of chalcogenide glass core and tellurite glass cladding. The flattened chromatic dispersion can be achieved in such an optical fiber with near zero dispersion wavelength at telecommunication wavelengths $\lambda = 1.35–1.7$ μm, which cannot be achieved in chalcogenide glass optical fibers due to their high refractive index, i.e. $n > 2.1$. We demonstrate a hybrid 4-air hole chalcogenide–tellurite optical fiber ($\Delta n = 0.25$) with flattened chromatic dispersion around $\lambda = 1.55$ μm. In optimized 12-air hole optical fiber composed of the same glasses, the chromatic dispersion values were achieved between −20 and 32 ps/nm/km in a broad wavelength range of 1.5–3.8 μm providing the fiber with extremely high nonlinear coefficient 86,000 $km^{-1}W^{-1}$. Hybrid chalcogenide/tellurite fibers pumped with the near infrared lasers give good promise for broadband optical amplification, wavelength conversion, and supercontinuum generation in the near- to mid-infrared region.

1. Introduction

Since the first demonstration of microstructured optical fiber (MOF) by Russell et al. [1], MOFs have attracted much attention due to their high nonlinearity, low loss and strong light confinement, and tunable chromatic dispersion (group velocity). These parameters are necessary for efficient nonlinear optical processes such as self-phase modulation, cross-phase modulation, four wave mixing, soliton self-frequency shift or super-continuum generation (SC). Except for high nonlinearity, MOFs brought enhanced options for tuning of the chromatic dispersions of optical fibers, whose zero or near zero values [2,3] are required for effective generation of nonlinear processes. Chromatic dispersion tuning was first developed on silica glass fibers [4,5]. However, silica glass fibers have provided low nonlinear coefficients, i.e. less than 70 $km^{-1}W^{-1}$ [6], so far.

Therefore, recent efforts have been also devoted to the study of promising nonlinear non-silica glasses such as heavy oxide doped silica glasses [7], tellurite [8,9] or fluoride [10] glasses with transparency window extended up to 6 or 8 μm, and their microstructured fibers, respectively. Furthermore, chalcogenide glasses (ChG) have broadened infrared transparency up to ~12, ~18, and ~23 μm for sulfides, selenides, and tellurides, respectively. Also the third order nonlinearity coefficients (χ^3) of ChG are approximately 100–300 times larger than that of silica glass [11], which together with high refractive index ($n > 2.1$) elevates nonlinearity of chalcogenide MOFs to highest reported values. ChG optical fiber fabrication brings some difficulties such as costly purification, drawing under inert atmosphere, lower mechanical and thermal stability of the fibers, higher sensitivity to humidity and certain health issues. Despite these difficulties, ChG are worth to study since they make possible the extension of the application wavelengths of the optical fibers to the middle infrared region, where they can be used for environmental sensing, medical diagnosis, and cure applications [11–14].

In fabrication of chalcogenide MOFs, two main techniques have been used successfully. The capillary-stacking "stack and draw" technique is commonly used for fabrication of silica MOFs. We have used this method for fabrication of our hybrid MOF. The main advantage of the technique is its ability to fabricate structured preform with a complex geometry. On the other hands complex geometries require multiple preparation steps, whose increase exposure of the glass to the atmosphere, and also require very precise pressure control during the processing in order to preserve the structure of the preform for the microstructure of the optical

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fiber. The second commonly used technique is the extrusion technique, which has simpler processing with the advantage of reduced number of fabrication steps. However, the extrusion technique is still quite challenging for fabrication of optical fibers with complex microstructures.

In this paper, we demonstrate the ability of a hybrid chalcogenide/tellurite MOF to achieve flattened and near zero chromatic dispersion (important for broad SC generation) at the wavelengths of currently available pico- and femto-second pulse lasers operating at telecommunication wavelengths, typically at $\lambda = 1.55$ μm. We show the influence of various cladding materials on the chromatic dispersion of a hybrid chalcogenide/tellurite MOF with 4-air hole structure. We also demonstrate flattened chromatic dispersions in a complex chalcogenide/tellurite MOF with near zero chromatic dispersion values, i.e. from −20 to 32 ps/nm/km, over a wide range of infrared wavelengths $\lambda = 1.5$–3.8 μm. Such a MOF has extremely high nonlinear coefficient $\gamma \approx 86{,}000\ \mathrm{km^{-1}W^{-1}}$.

2. Calculations

2.1. Chromatic dispersion calculations

Chromatic dispersion of hybrid chalcogenide–tellurite MOF was calculated based on its geometrical microstructure taking into account the refractive index dispersion of both glasses given by the Sellmeier Eq. (1):

$$n^2 = 1 + \sum_{i=1}^{i=3}\left[A_i\lambda^2/(\lambda^2 - L_i^2)\right] \quad (1)$$

where the fitting coefficients, A_i and L_i^2, for GGSS and TZLB glasses are summarized in Table 1 and λ is the wavelength of the light. By using a Finite Element Method (FEM), we calculated chromatic dispersion of the fiber (D) as (2):

$$D = -\frac{1}{2\pi c}\frac{d}{d\lambda}\left(\lambda^2\frac{d\beta}{d\lambda}\right) \quad (2)$$

where c is the speed of the light in vacuum and β is the propagation constant of the fiber.The nonlinear coefficient was then calculated according to Eq. (3) [2],

$$\gamma = \frac{2\pi}{\lambda}\frac{\int\int_{-\infty}^{\infty} n_2(x,y)|F(x,y)|^4 dxdy}{\left(\int\int_{-\infty}^{\infty}|F(x,y)|^2 dxdy\right)^2} \quad (3)$$

where $F(x,y)$ is the profile of the electric field, and $n_2(x,y)$ is the nonlinear refractive index, which we took from Refs. [15,16], i.e. $n_2 = 1.8\times10^{-17}$, 5.9×10^{-19}, and $2.3\times10^{-23}\ \mathrm{m^2/W}$ for GGSS glass, TZLB glass, and air hole, respectively.

2.2. Chromatic dispersion in one air hole ring chalcogenide–tellurite MOF – compositional aspects

We calculated the chromatic dispersion of our hybrid chalcogenide–tellurite MOF, where the refractive index contrast between the core and the cladding glass was $\Delta n = 0.25$ at 1.55 μm. The refractive index dispersions and fiber structures resulted in fiber chromatic dispersion values depicted in Fig. 1. Dispersion curves shown in Fig. 1 were calculated from the microstructure of the fabricated fiber shown in Fig. 2 but the diameter of chalcogenide glass core varies from 0.8 to 1.3 μm. The chromatic dispersion of our prepared fiber corresponds to the curve with $d = 0.9$ μm. The chromatic dispersion values at 1.55 μm increased from −360 to −190 ps/nm/km with increasing core diameter. The values are still far from near zero dispersion values suitable for generating efficient nonlinear effects. On the other hand, the chromatic dispersion of the hybrid fiber was much more flattened than that achievable by any chalcogenide MOF at telecommunication wavelengths [17]. This is given by the fact that the effective refractive index of the hybrid MOF is reduced due to low refractive index tellurite glass cladding.

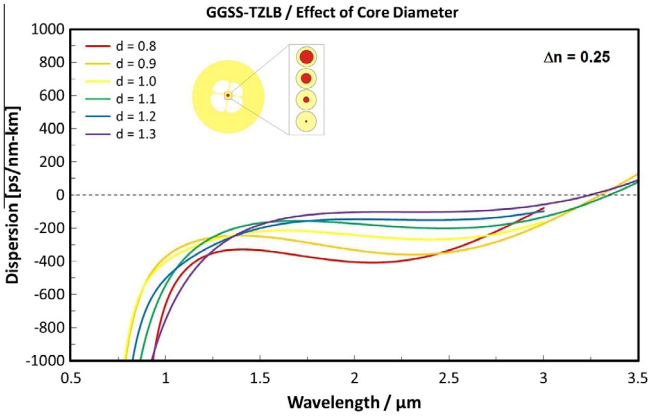

Fig. 1. Chromatic dispersion calculated for a hybrid 4-air holes GGSS–TZLB MOF. The comparison shows the dispersion curves calculated for changing core diameter $d = 0.8$–1.3 μm.

Indeed, there is a way how to achieve flattened and near zero chromatic dispersion values at wavelengths around $\lambda = 1.55$ μm even for structured fibers with chalcogenide glass cores. The key issue is the tuning of the refractive index contrast between chalcogenide glass core and tellurite glass cladding. Fig. 3 shows the chromatic dispersion curves calculated for MOFs with the similar microstructure such as that shown in Fig. 2, but with changing the cladding glass and thus changing the refractive index contrast between the core and the cladding materials.

Fig. 3a shows chromatic dispersion curve for a hybrid chalcogenide–tellurite MOF with the index contrast $\Delta n = 0.45$. The core remained the same chalcogenide GGSS glass but the cladding glass whose material dispersion we considered was TeO_2-ZnO-Li_2O-Na_2O-P_2O_5 (TZLNP). For this material choice, we should note that it is only a theoretical material choice, and the chromatic dispersion values of $D = -20$ to +20 ps/nm/km were obtained for a MOF with the core diameter of $d = 1$ μm in the wavelength range of $\lambda = 1.1$–1.6 μm. Similar chromatic dispersion values were obtained for a MOF with the core diameter of $d = 1.3$ μm in the wavelength range of $\lambda = 1.6$–2.5 μm, which gives promise for the efficient pumping of the fiber at $\lambda > 2$ μm, i.e. suitable for mid-IR SC generation in chalcogenide core MOFs [18,19].

Similarly, by replacing tellurite TZLNP glass for lower refractive index phosphate P_2O_5-ZnO-Na_2O-K_2O (PZNK) glass cladding, again this is a theoretical material choice, we obtained chromatic dispersion curves shifted to normal dispersion values (see Fig. 3b) caused by high refractive index contrast between the core and the cladding glass corresponding to $\Delta n = 0.7$. Combination of high refractive index GGSS core and low refractive index phosphate glass cladding did not provide flattened dispersion curves. Certain advantage can be seen in the fact that normal dispersion values were achieved in relatively broad interval of wavelengths, i.e.

Table 1
Sellmeier coefficients determined for GGSS and TZLB glasses based on the refractive index measurements by using a prism coupler method.

Materials	GGSS		TZLB	
	A_i	L_i^2	A_i	L_i^2
$i = 1$	2.51696	0.0218087	1.67189	0.0004665
$i = 2$	1.41612	0.1034606	1.34862	0.0574608
$i = 3$	0.0601	153.82497	0.6218	46.725427