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Discussion

Numerical simulation on the coherent time-critical 2–5 μm supercontinuum generation in an As_2S_3 microstructured optical fiber with all-normal flat-top dispersion profile

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ABSTRACT

A detailed design of As_2S_3 microstructured optical fiber (MOF) with all-normal flat-top (ANFT) dispersion profile is presented by adjusting the air hole filling ratio of inner layers. The simulated supercontinuum (SC) generation in such fiber has flat and smooth profile, covers the wavelength range from 2 μm to 5 μm, and demonstrates perfect coherent properties while limiting all spectral components into ± 1 ps range in temporal domain.

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1. Introduction

Mid-infrared microstructured optical fiber (MOF), firstly reported in 2000 [1], has become one of the hottest topics [2] to study in optical and photonic science due to the remarkable merits of mid-infrared glass in combination with MOF technique. Usually, mid-infrared glasses have broader transmission window and higher nonlinear refractive index than that of silica. Meanwhile, the MOF technology allows high freedom of controlling the fiber parameters by changing the configuration of air holes in the cross section, permitting fiber designs with high nonlinearity and dispersion-engineered properties. Several cm of such fibers or waveguides can demonstrate very strong nonlinear effect even at quite low pump level. Consequently, the characteristic design and manufacture [3,4] of mid-infrared MOF and its supercontinuum generation (SCG) are boosting [3–11] in the recent few years. Casting method [8] was utilized for producing chalcogenide MOFs with a quite low-loss level near the material losses. A fiber-based mid-infrared SC source with over 4000 nm bandwidth was firstly demonstrated from an 8 mm length of highly nonlinear tellurite MOF [9]. Hu [10] theoretically described the procedure for maximizing the bandwidth of SCG in As_2Se_3 chalcogenide fibers by utilizing four-wave mixing and Raman-induced soliton self-frequency shift, while R. Cherif theoretically obtained more than two octaves SCG when pumped at the anomalous dispersion region [11]. However, SCG in MOF pumped at anomalous dispersion relies exquisitely on soliton dynamics [12,13] which largely degrade the coherence of continuum.

Recently, SCG in all-normal dispersion MOF has become an attractive hot topic due to the intrinsic coherent properties [13–17], which is of particular importance for time critical applications like optical coherence tomography, pump-probe spectroscopy, metrology or non-linear microscopy. The previous works have demonstrated visible and infrared coherent continuum in silica-based all-normal dispersion MOF [16], and achieved sub-two cycle pulses compression [17] thanks to the superior quality of continuum in the temporal domain. However no previous work discussed mid-infrared SCG in all-normal-dispersion designed chalcogenide fiber. Especially, the mid-infrared SC in wavelength range of 2–5 μm, endowed with the strongest rovibrational transitions and covering the 3 μm window for molecular spectroscopy, is the most favorable window for high-sensitivity and high-resolution spectroscopic investigations, such as atmospheric physics, environmental monitoring and cosmological studies [18]. In this paper, we design the all-normal flat-top (ANFT) As_2S_3 MOF with high nonlinearity coefficient, and achieve the 2–5 μm SCG within only 2 cm propagation length. The generated SC shows superior coherence properties in

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our fiber design. Meanwhile, all the pulse components are limited into ± 1 ps so as to meet the time critical applications.

This paper is organized as follows. In Section 2, we briefly describe the simulation method and parameters setting involved. In Section 3, the strategy of flat-top design is covered in detail. In Section 4, the SCG behaviors are discussed, the influence related to the pulse parameters as well as peak power, pulse duration, and the fiber dispersion design are analyzed in detail. At last, the coherent aspect of the SCG in our As_2S_3 ANFT MOF is presented.

2. Methods for numerical simulation

Refractive index dispersion for As_2S_3 is given by the Sellmeier dispersion equation, and the fitting coefficients A_i and L_i^2 for As_2S_3 glass are taken from [19]:

$$n^2 = 1 + \sum_{i=1}^{l} \frac{A_i \lambda^2}{\lambda^2 - L_i^2} \tag{1}$$

The chromatic dispersion D is defined [20] as:

$$D = -\frac{\lambda}{c} \frac{d^2 n_{eff}}{d\lambda^2} \tag{2}$$

where, c is the light velocity in vacuum and λ is the operating wavelength; n_{eff} is the effective index that is obtained by calculating the fundamental mode with full-vector finite element method. Numerical simulations are performed by solving the generalized nonlinear Schrödinger Equation with the split-step Fourier method and the 4th-order Runge–Kutta algorithm [21].

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A - \left(\sum_{k \geq 2} \beta_n \frac{i^{n-1}}{n!} \frac{\partial^n A}{\partial t^n} \right) + i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t} \right) \left[A(z,t) \int_{-\infty}^{\infty} R(t') \left| A(z,t-t') \right|^2 dt' \right] \tag{3}$$

where α is the transmission loss of the fiber. The term β_n is group velocity dispersion (GVD) and n is up to 10 in our simulation. The nonlinear coefficient $\gamma = 2\pi n_2 / \lambda A_{\text{eff}}$, here n_2 is the nonlinearity of the refractive index with a value of $\sim 2.92 \times 10^{-18}$ m^2/W [22,23], and A_{eff} is the effective area of fundamental mode. The response function $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$ includes both instantaneous electronic and delayed Raman contributions, with $f_R = 0.11$ [23] representing the Raman contribution. For Raman response function h_R, it is common to use an approximate analytic form.

$$h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp\left(-\frac{t}{\tau_2} \right) \sin\left(\frac{t}{\tau_1} \right) \tag{4}$$

For As_2S_3 waveguides, the Raman period $\tau_1 = 15.5$ fs and lifetime $\tau_2 = 230.5$ fs [24]. To check the spectral coherence of the generated continuum, we numerically calculate the complex degree of first-order coherence at each wavelength, which is defined as [12]:

$$\left| g_{12}^{(1)}(\lambda, t_1 - t_2) \right| = \left| \frac{\langle E_1^*(\lambda, t_1) E_2(\lambda, t_2) \rangle}{\sqrt{\langle \left| E_1(\lambda, t_1) \right|^2 \rangle \langle \left| E_2(\lambda, t_2) \right|^2 \rangle}} \right| \tag{5}$$

where $E_1(\lambda)$ and $E_2(\lambda)$ are continuum spectra generated by successive input pulses, or, as in our simulation, spectra generated independently from input pulses with random noise seeds (1% of the pulse intensity). The angular brackets denote an ensemble average over 200 pairs of such continuum spectra.

3. Design of As_2S_3 ANFT MOF

We propose a fiber structure with four layers of air holes, of which the inner first layer has a filling ratio of f_1 (defined as d_1/Λ), while the outer layers have a filling ratio of f_2 (defined as d_2/Λ), as shown in Fig. 1. It is a common dispersion flattened design as in silica MOF [25]. The air holes with nanostructure have been fabricated as in Ref. [26].

Fig. 2(a) shows the dispersion curves as $\Lambda = 1$ μm, $f_2 = 0.8$, but f_1 is reduced from 0.58 down to 0.32. Evidently the right edge rises up along with the decrease of f_1 while the left edge red-shrinks. In the case of $f_1 = 0.396$, the overall dispersion curve falls in all normal region and maintains a broad flat-top profile, which is expected to be beneficial for pulse-preserving SCG. Fig. 2(b) illustrates the dispersion curves with the increase of f_2 while keeping $\Lambda = 1$ μm and $f_1 = 0.396$. It is evident that the overall dispersion curves rise up when f_2 is increased; this trend is especially distinct at the long wavelength direction. Consequently, the flat top can be adjusted in all-normal, near zero and anomalous region by simply modifying the f_1 and f_2, the corresponding curves are shown in Fig. 2(c) for a fixed pitch of $\Lambda = 1$ μm.

When the pitch is reduced, the f_1 and f_2 should be increased to get the flat top as shown in Fig. 2(d). Due to the enhanced waveguide dispersion, the left edge of dispersion curve would move to shorter wavelength, meanwhile, its right edge shrinks to the short wavelength seriously, and the width of flat top is greatly narrowed, *e.g.* the case of $\Lambda = 0.6$, $f_1 = 0.53$, $f_2 = 0.96$. Although this design can be pumped by the ~ 2 μm Thulium-doped fiber laser, the narrow flat top is an adverse factor for generation of broader continuum. On the other hand, its small fiber core is a disadvantage for pump coupling and even the actual fabrication. For comparison, the case of $\Lambda = 1.4$, $f_1 = 0.3$, $f_2 = 0.6$ has a broad flat top favorable for the coherent SCG further into the long wavelength, but unsuitable for shorter wavelength pumping near the top center position.

Fig. 3 shows the calculated confinement loss of the fundamental mode LP_{01} and the second order mode LP_{11} for MOF with $\Lambda = 1$ μm and $f_2 = 0.82$. We notice that the confinement loss increases rapidly as the wavelength increases, because that more energy penetrates into clad at the longer wavelength. This can be confirmed by the calculated field mode at 3 μm and 5 μm as shown in the illustrations. So it is best to use a short length of fiber for SCG. In addition, our calculation shows that the LP_{11} mode has the confinement loss about two orders larger than that of LP_{01} mode, and cuts off beyond 3 μm. Consequently, the LP_{01} mode can be selectively pumped by adjusting the coupling condition. Fig. 4 shows the calculated nonlinear coefficient γ and effective mode area A_{eff} for the ANFT MOF with $\Lambda = 1.0$ μm and $f_2 = 0.82$. At $\lambda = 3$ μm, the γ is ~ 2600 W^{-1} km^{-1} and the A_{eff} is 2.3 μm^2.

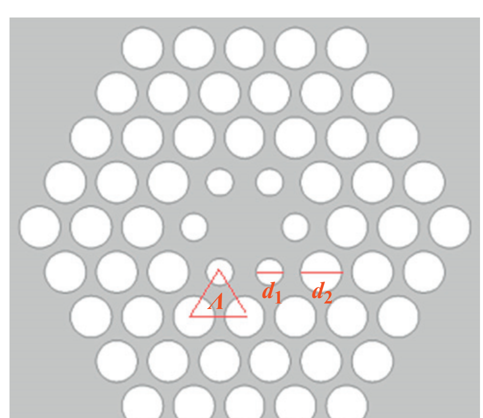

Fig. 1. The cross section of As_2S_3 ANFT MOF.

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