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Design and optimization of As_2S_5 chalcogenide channel waveguide for coherent mid-infrared supercontinuum generation

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We numerically demonstrate mid-infrared supercontinuum generation in dispersion-engineered chalcogenide glass channel waveguide. The proposed ridge waveguide consists of arsenic pentasulfide (As_2S_5) strip deposited on magnesium fluoride (MgF_2) substrate and air acting as an upper cladding. The structure parameters are calculated and optimized by using the fully vectorial finite-difference in the frequency-domain (FDFD) method Results indicates that the proposed waveguide exhibits an all normal dispersion (ANDi) profile over a wide spectral range with a zero dispersion wavelength (ZDW) around 2 μm. By solving the generalized nonlinear Schrödinger equation, we demonstrate supercontinuum generation extending from the near infrared to the mid infrared region. Indeed, a broad and perfectly coherent ultra-flat supercontinuum spectrum spanning the region from 700 to 5200 nm is successfully generated by using a 25 kW peak power 100 fs input pulse pumped at 2.5 μm, in a waveguide of 5 mm length.

1. Introduction

Supercontinuum (SC) generation refers to the considerable spectral broadening through the interaction of intense and short optical pulses with nonlinear materials such as solids, liquids and gases [1]. Since its discovery for the first time in the beginning of the 1970s [2], SC has attracted tremendous attentions due to its wide applications to metrology, pulse compression, optical communications, coherence tomography, spectroscopy and tunable multi-wavelength laser sources [3]. SC arises from a series of nonlinear processes depending on the waveguide chromatic dispersion regime where the femtoseconde pulses are injected. In the anomalous regime, SC generation is dominated by soliton-related propagation dynamics [4]. The generated spectra are broad, mainly due to the creation of new pulses resulting from the fundamental Soliton Fission (SF) process. However, these spectra are partially coherent due to their sensitivity to the noise-related pump

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pulse intensity fluctuations [5]. In the normal regime, Self Phase Modulation (SPM) and Wave Breaking (WB) are responsible for the spectral broadening. The generated spectra are relatively narrower than in the anomalous dispersion regime, but highly coherent and smooth [6].

The nonlinear dynamics of spectral broadening results from the interplay between chromatic dispersion and nonlinearity [4]. These properties can be easily tailored in guiding medium rather than bulk. Thus, optical fiber based SC generation sources has been the target of many researchers, in particular due to the invention of photonic crystal fibers (PCF) [7]. Owing to their design flexibility, PCFs transverse structures can be optimized to tailor the chromatic dispersion and achieve high nonlinearity [8]. Recently, planar waveguides have gained much attention for on-chip SC sources due to their low cost, reduced size and high nonlinear parameter [9]. These waveguide based SC sources are of growing importance for photonic integrated circuits [10].

Chalcogenide (ChG) glasses are based on the chalcogen elements S, Se, and Te covalently bounded with glass forming materials such as As, Ge and Ga [11,12]. Thanks to their suitable optical properties, they have been widely used to design waveguide based mid-infrared SC sources [11]. Compared to silica, ChG exhibits higher optical Kerr nonlinearities, high refractive indices and wide transparency window covering near-infrared and mid-infrared [13]. Many ChG based waveguide structures have been reported aiming the generation of broad mid-infrared Zhang et al. reported mid-infrared SC generation from 1 μm to 7 μm in tapered As_2S_3 on MgF_2 rib waveguide pumped with 50 fs duration pulses at 1.55 μm with a pulse peak power of around 2 kW [14]. By using the same ChG glass, Lamont et al. reported SC spectrum spanning 750 nm in dispersion-engineered highly nonlinear chalcogenide planar waveguide by using 610 fs pulses with peak power of 68 W [15]. As_2Se_3 ChG glass based waveguide has been, also, considered. Saini et al. reported SC generation form 2 μm to 15 μm through a dispersion-engineered As_2Se_3 chalcogenide glass rib waveguide pumped with 50 fs pulses at a wavelength of 2.5 μm with a pulse peak power of around 1.1 kW [16]. Moreover, Alizadeh et al. reported SC spectrum extending from 1.5 μm to 12 μm over highly nonlinear rib waveguide employing a 100 W peak power 85 fs pulses pumped at 2.4 μm [17]. Furthermore, Karim et al. reported ultra-flat SC generation in 1 cm long all normal dispersion (ANDi) channel waveguide made using $Ge_{11.5}As_{24}Se_{64.5}$ ChG glass with various materials in the lower cladding [18]. In particular, when MgF_2 glass is used as a lower cladding, the authors have found that SC spectrum spanning from 1.6 μm to 6 μm can be produced by employing 3 kW peak power 85 fs width pulses pumped at 3.1 μm. Recently, SC generation in A_s2S_5 ChG glass PCF has been demonstrated numerically and experimentally. Compared to As_2S_3, the As_2S_5 glass exhibits higher transmission in the wavelength range extending from 0.5 μm to 9 μm combined with a shorter cut-off wavelength in the visible domain [19]. Gao et al. reported mid-infrared SC generation in a four-hole As_2S_5 ChG microstructured optical fiber [20]. A wide spectrum spanning from 1.37 μm to 5.65 μm has been achieved in a 4.8-cm-long fiber pumped at 2300 nm. In order to generate ultra-flat and coherent SC, Salem et al. studied a kind of hybrid As_2S_5-borosilicate PCF with ANDi regime [21]. A broadband and flat SC spectrum extending from 1 μm to 5 μm has been realized by pumping 28.16 kw peak power 50 fs pulses at 2.5 μm in only 4 mm fiber length. Nevertheless, and to the best of our knowledge, analyzing mid-infrared SC in As_2S_5 based planar geometries has been not achieved.

In this paper, we numerically investigate mid-infrared SC generation in a ridge waveguide consisting of As_2S_5 ChG glass strip deposited on MgF_2 substrate and air acting as an upper cladding. The propagation characteristics of the fundamental guided mode such as chromatic dispersion, effective mode area and nonlinearity are calculated by using a finite-difference in the frequency-domain (FDFD) method. The waveguide structure is optimized to exhibit an ANDi profile over the entire computational domain by properly adjusting its high and width. Furthermore, we demonstrate spectral broadening of an intense femtoseconde pulse pumped at 2.5 μm, by solving the Generalized Nonlinear Schrödinger Equation (GNLSE). The impact of pulse peak power on the generated spectra bandwidth is then examined. Additionally, we analyze the statistical properties of the SC source by calculating its first order spectral coherence in the aim to investigate its sensitivity to input pump noise.

2. Theoretical background

2.1. Structure of the proposed As_2S_5 ridge waveguide

The cross sectional view of the proposed ridge waveguide is given by Fig. 1. As mentioned in the previous section, the proposed ridge waveguide consists of As_2S_5 strip deposited on MgF_2 substrate, and air acting as an upper cladding. The parameters W and H are the core width and high, respectively. The wavelength dependent refractive index of the core and the cladding are given via the Sellmeier equation:

$$n(\lambda) = \sqrt{1 + \sum_{j=1}^{m} \frac{A_j \lambda^2}{\lambda^2 - \lambda_j^2}} \tag{1}$$

Were the coefficients are given in Table 1 [19,22].

The variation of the refractive index with wavelength for both As_2S_5 and MgF_2 is depicted in Fig. 2. The large index contrast between the core and the cladding permits a strong light confinement inside the core whatever its wavelength. The inset Fig. 2 shows the optical field distribution at the excitation wavelength 1 μm and 4 μm respectively.