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# Mid-infrared supercontinuum generation using dispersion-engineered $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ chalcogenide channel waveguide

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**Abstract:** We numerically investigate mid-infrared supercontinuum (SC) generation in dispersion-engineered, air-clad,  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  chalcogenide-glass channel waveguides employing two different materials,  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  or  $\text{MgF}_2$  glass for their lower cladding. We study the effect of waveguide parameters on the bandwidth of the SC at the output of 1-cm-long waveguide. Our results show that output can vary over a wide range depending on its design and the pump wavelength employed. At the pump wavelength of  $2\ \mu\text{m}$  the SC never extended beyond  $4.5\ \mu\text{m}$  for any of our designs. However, supercontinuum could be extended to beyond  $5\ \mu\text{m}$  for a pump wavelength of  $3.1\ \mu\text{m}$ . A broadband SC spanning from  $2\ \mu\text{m}$  to  $6\ \mu\text{m}$  and extending over 1.5 octave could be generated with a moderate peak power of 500 W at a pump wavelength of  $3.1\ \mu\text{m}$  using an air-clad, all-chalcogenide, channel waveguide. We show that SC can be extended even further when  $\text{MgF}_2$  glass is used for the lower cladding of chalcogenide waveguide. Our numerical simulations produced SC spectra covering the wavelength range  $1.8\text{--}7.7\ \mu\text{m}$  ( $>$  two octaves) by using this geometry. Both ranges exceed the broadest SC bandwidths reported so far. Moreover, we realize it using  $3.1\ \mu\text{m}$  pump source and relatively low peak power pulses. By employing the same pump source, we show that SC spectra can cover a wavelength range of  $1.8\text{--}11\ \mu\text{m}$  ( $>$  2.5 octaves) in a channel waveguide employing  $\text{MgF}_2$  glass for its lower cladding with a moderate peak power of 3000 W.

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## 1. Introduction

Recently chalcogenide glasses (ChGs) have emerged as promising nonlinear materials having a number of unique properties that makes them attractive for fabricating planar optical waveguides and using them for application such as mid-infrared (MIR) supercontinuum (SC) generation and optical sensing [1]. SC generation in MIR has increasingly become a focus for research because bright MIR light sources can be used for molecular fingerprint spectroscopy, frequency metrology, optical coherent tomography and microscopy [2,3]. Chalcogenide glasses can provide MIR transparency with sulphides transmitting to beyond 8.5  $\mu\text{m}$ , selenides to 14  $\mu\text{m}$  and tellurites to around 20  $\mu\text{m}$  [4]. A major advantage of chalcogenide glasses is their large ultra-fast nonlinearity amongst all glasses, making them good materials for planar waveguides to generate SC in the MIR [5–9]. A few of these ChG materials such as  $\text{As}_2\text{S}_3$ ,  $\text{As}_2\text{Se}_3$ ,  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  and  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glasses are highly suitable for making active and passive devices in the MIR region. Amongst them  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass has excellent film-forming

properties with high thermal and optical stability under intense illumination [10]. Recently interest has grown in designing and optimizing planar waveguides made from  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  chalcogenide glass for broadband MIR SC generation with suitably tailored group-velocity dispersion (GVD), including a zero-dispersion wavelength (ZDW) close to the central wavelength of the pump [11, 12].

In recent years, several experimental and theoretical investigations on mid-infrared SC generation were reported in ChG planar waveguides [13–15], ChG fibers [16–28], single crystal sapphire fibers [29], silicon-on-insulator (SOI) wire waveguides [30], ZBLAN fiber [31], fluoride glass [32] and germano-silicate fibers [33]. Gai *et al.* [13] reported SC generation from 2.9  $\mu\text{m}$  to 4.2  $\mu\text{m}$  in dispersion-engineered  $\text{As}_2\text{S}_3$  glass rib waveguide (6.6 cm long) pumped with 7.5 ps duration pulses at a wavelength of 3.26  $\mu\text{m}$  with a pulse peak power of around 2 kW. Yu *et al.* [14] reported SC generation up to 4.7  $\mu\text{m}$  using a 4.7-cm-long  $\text{As}_2\text{S}_3$  glass rib waveguide employing  $\text{MgF}_2$  glass as a substrate and pumped with 7.5 ps duration with a peak power of 1 kW pulses at a wavelength of 3.26  $\mu\text{m}$ . They observed a flat SC extending from 2.5  $\mu\text{m}$  to 7.5  $\mu\text{m}$  in 5-mm-thick bulk sample of  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass pumped with 150 fs duration pulses with up to 20 MW peak power at a wavelength of 5.3  $\mu\text{m}$ . They also reported theoretically that SC could be generated beyond 10  $\mu\text{m}$  in a dispersion-engineered all-chalcogenide  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass rib waveguide pumped with 250 fs duration pulses at a wavelength of 4  $\mu\text{m}$  or longer. Yu *et al.* [15] recently reported the generation of broadband SC spanning from 1.8  $\mu\text{m}$  to 7.5  $\mu\text{m}$  in dispersion-engineered  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass 1-cm-long rib waveguide pumped at 4  $\mu\text{m}$  using 320 fs pulses from a periodically-poled lithium niobate optical parametric amplifier pumped with commercially available mode-locked Yb laser with a peak power of 3260 W. For step-index fiber based on  $\text{As}_2\text{S}_3$ , Hudson *et al.* [25] reported 1.9-octave SC extending from 1.6  $\mu\text{m}$  to 5.9  $\mu\text{m}$  pumped at a wavelength of 3.1  $\mu\text{m}$  with a peak power of 520 kW. Al-Kadry *et al.* [26] reported MIR SC generation from 1.1  $\mu\text{m}$  to 4.4  $\mu\text{m}$  in 10-cm-long  $\text{As}_2\text{Se}_3$  microwires pumped with 800 fs duration pulses at a wavelength of 1.94  $\mu\text{m}$  with energy of 500 pJ. Petersen *et al.* [27] used 100 fs pulses at 6.3  $\mu\text{m}$  to generate SC covering the range 1.4–13.3  $\mu\text{m}$  in 85 mm long  $\text{As}_2\text{S}_3$  step-index fiber with a 16  $\mu\text{m}$  core. Møller *et al.* [28] used a 18 cm long, low-loss, suspended core  $\text{As}_{38}\text{S}_{62}$  fiber and generated a SC spanning from 1.7 to 7.5  $\mu\text{m}$  by pumping this fiber with 320 fs pulses with a peak power of 5.2 kW at a wavelength of 4.4  $\mu\text{m}$ . The SC generation in  $\text{As}_2\text{S}_3$  fibers and waveguides has been limited to 5  $\mu\text{m}$  due to their increased losses in the long wavelength region [13, 17, 18]. Although  $\text{As}_2\text{Se}_3$  chalcogenide glass has its loss edge in the long wavelength region around 16–17  $\mu\text{m}$ , the use of such materials for SC generation has so far been limited owing to high peak power pump sources required in the MIR region [4, 26, 27].

In this paper, we demonstrate numerically that a 1-cm-long dispersion-engineered  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass rectangular channel waveguide can generate broadband SC in the MIR regime. In our previous work [8], a dispersion-engineered  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  nanowire was designed, with polymer as top and silica as bottom claddings, for low-power wideband SC generation. To extend the SC to the MIR region and to ensure that the claddings as well as the core materials are transparent at such long wavelengths, rectangular channel waveguides were designed with air on top and either  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  or  $\text{MgF}_2$  glass as the lower cladding material. To tailor the dispersion to obtain the ZDW close to the pump wavelength, two separate geometries were employed, one with a lower cladding of  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass having lower index contrast and another with a lower cladding of  $\text{MgF}_2$  glass having larger index contrast. Both were designed and optimized by adjusting the waveguides dimensions. In earlier experiments it was found that the extension of SC depends on the pump wavelength, among many other factors. To achieve sufficiently long wavelength extension in MIR region, the pump wavelength will need to be used around 4–5  $\mu\text{m}$  or longer. The nonlinear parameter,  $\gamma = 2\pi n_2 / \lambda A_{\text{eff}}$ , where

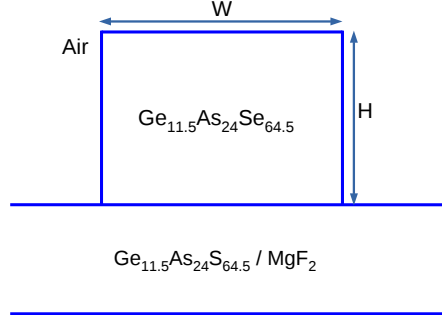


Fig. 1. Waveguide geometry.

$n_2$  is the nonlinear refractive index and  $A_{\text{eff}}$  is the effective area of the mode, of the ChG waveguide decreases with the increasing pump wavelength,  $\lambda$ . As  $A_{\text{eff}}$  also increases, high pump powers would be required to generate SC in the long-wavelength region, which can cause damage to the ChG waveguides if relatively wider pump pulses are employed [14]. For this reason we choose, for our numerical simulation, sub-picosecond pulses of 85 fs (FWHM) duration at a pump wavelength of  $3.1 \mu\text{m}$  with a repetition rate of 160 kHz [45] and with low to moderate peak powers. The propagation loss ( $\alpha$ ) and nonlinear refractive index ( $n_2$ ) were taken to be 0.5 dB/cm and  $4.3 \times 10^{-18} \text{ m}^2/\text{W}$ , respectively [10, 15]. Since the actual  $n_2$  of ChG glasses has not been measured in the MIR region, its measured value at  $1.55 \mu\text{m}$  [12] was reduced by a factor of two at the pump wavelength of  $3.1 \mu\text{m}$  [15].

We carry out simulations for two different structures of ChG channel waveguides assuming that the input pulse excites the fundamental quasi-TE mode. The peak power varies in the range of 25-500 W and 100-3000 W for two pump sources at wavelength of  $2 \mu\text{m}$  and  $3.1 \mu\text{m}$ , respectively. Using the pump source at  $2 \mu\text{m}$  with a peak power of 500 W, the SC bandwidth extended in the range  $1.3\text{-}3.3 \mu\text{m}$  and  $1.3\text{-}3.5 \mu\text{m}$  for the waveguides designed and optimized with  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass or  $\text{MgF}_2$  glass acting as lower cladding, respectively. A broadband MIR SC extending over 1.5 octave from  $2 \mu\text{m}$  to  $6 \mu\text{m}$  could be generated with a lower cladding of  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass. The SC extended over more than 2 octave ( $1.8 \mu\text{m}$  to  $7.7 \mu\text{m}$ ) when a lower cladding of  $\text{MgF}_2$  glass was employed. We calculate the SC bandwidth at the -30 dB level from the peak. Our calculated bandwidths are the largest reported so far for SC generated using chalcogenide glass waveguides pumped at a wavelength of  $3.1 \mu\text{m}$  with a moderate peak power of 500 W.

## 2. Theory

The schematic diagram of the  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  chalcogenide glass channel waveguide used in our simulations is shown in Fig. 1. The wavelength-dependent linear refractive index of  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$ ,  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  and  $\text{MgF}_2$  glasses over the entire wavelength range used in the simulation was obtained using the Sellmeier equation,

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

Here  $\lambda$  is the wavelength in micrometers. We use the Sellmeier coefficients calculated by fitting smooth curves to the measured refractive index data for the ChGs [10] and the  $\text{MgF}_2$  [34] glasses. The values of the integer  $m$  and the fitting coefficients are given in Table 1.

Table 1. Sellmeier fitting coefficients

Material	Ge <sub>11.5</sub> As <sub>24</sub> Se <sub>64.5</sub> [10]		Ge <sub>11.5</sub> As <sub>24</sub> S <sub>64.5</sub> [10]		MgF <sub>2</sub> [34]	
$m$	2		2		3	
	$A_j$	$\lambda_j$	$A_j$	$\lambda_j$	$A_j$	$\lambda_j$
$j = 1$	5.78525	0.28795	4.18011	0.31679	0.48755708	0.0433840
$j = 2$	0.39705	30.39338	0.35895	22.77018	0.39875031	0.09461442
$j = 3$					2.3120353	23.793604

Dispersion of the waveguide plays an important role in determining the SC spectrum. Ideally the dispersion near the pump wavelength should be anomalous with a small value that does not change much [35–40]. Small flattened anomalous dispersion with high nonlinearity is required for large frequency shifts of the Raman soliton. ChG glasses generally have smaller material dispersion than silicon and to obtain the ZDW close to the pump wavelength, relatively larger waveguide dispersion is required to offset the material dispersion [12, 41]. We use a finite element (FE) based mode-solver [42] to obtain the propagation constant  $\beta(\omega)$  of the fundamental mode over a range of frequencies and calculate the effective index,  $n_{\text{eff}} = \lambda\beta(\omega)/2\pi$  from this  $\beta(\omega)$ , which is subsequently used for numerically calculating the GVD parameter,  $D(\lambda) = -\frac{\lambda}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2}$  (ps/nm/km) as well as all other higher-order dispersion parameters. Spectral broadening of a SC mainly depends on these dispersion parameters and the nonlinear coefficient,  $\gamma$  which in turn depends on the nonlinear refractive index of the material,  $n_2$  and effective mode area of the waveguide. Pump wavelength is also an important factor for the extension of SC spectrum in the long wavelength region. Optimized mode area,  $A_{\text{eff}}$  can be obtained with our FE mode-solver and  $\gamma$  of the waveguide can be calculated using  $A_{\text{eff}}$ .

The FE approach used here is based on the vector- $\mathbf{H}$ -field formulation, since it is one of the most accurate and numerically efficient approaches to obtain the modal field profiles and mode propagation constants  $\beta(\omega)$  of various quasi-TE and quasi-TM modes. The full-vectorial formulation is based on the minimization of the full  $\mathbf{H}$ -field energy functional [42],

$$\omega^2 = \frac{\iint \left[ (\nabla \times \mathbf{H})^* \cdot \hat{\epsilon}^{-1} (\nabla \times \mathbf{H}) + p (\nabla \cdot \mathbf{H})^* (\nabla \cdot \mathbf{H}) \right] dx dy}{\iint \mathbf{H}^* \cdot \hat{\mu} \mathbf{H} dx dy}, \quad (2)$$

where  $\mathbf{H}$  is the full-vectorial magnetic field,  $*$  denotes a complex conjugate and transpose,  $\omega^2$  is the eigenvalue ( $\omega$  being the angular frequency),  $p$  is a weighting factor for the penalty term to eliminate spurious modes and  $\hat{\epsilon}$  and  $\hat{\mu}$  are the permittivity and permeability tensors, respectively. The two-dimensional cross-section of the waveguide is discretized by using a large number of triangular elements. All three components of the magnetic fields can be represented as piece-wise polynomials within the elements. With a proper choice of waveguide discretization we can accurately calculate the energy functional by integrating it over each element.

To study SC generation in the MIR region, simulations were performed using a generalized nonlinear Schrödinger equation (GNLSE) for the slowly varying envelope of the pulse [8, 12]:

$$\begin{aligned} \frac{\partial}{\partial z} A(z, T) = & -\frac{\alpha}{2} A + \sum_{k \geq 2} \frac{i^{k+1}}{k!} \beta_k \frac{\partial^k A}{\partial T^k} + i \left( \gamma + i \frac{\alpha_2}{2A_{\text{eff}}} \right) \left( 1 + \frac{i}{\omega_0} \frac{\partial}{\partial T} \right) \\ & \times \left( A(z, T) \int_{-\infty}^{\infty} R(T) |A(z, T - T')|^2 dT' \right), \end{aligned} \quad (3)$$

where  $A$  is the electrical field amplitude,  $\alpha$  is the linear propagation loss of the waveguide,

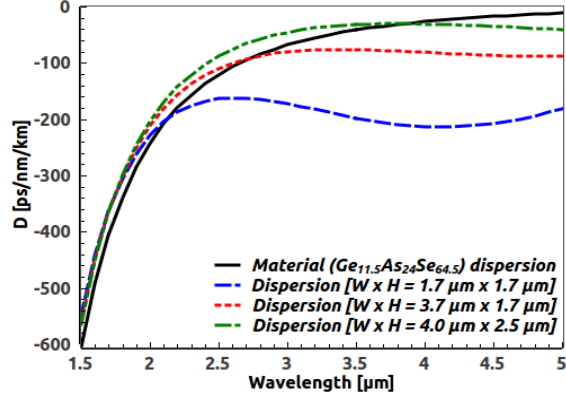


Fig. 2. GVD curves for the fundamental quasi-TE mode calculated from  $n_{\text{eff}}$  for three waveguides geometries employing  $\text{As}_{36}\text{S}_{64}$  glass for both the upper and lower claddings. The black solid line curve shows the material dispersion curve for comparison.

$\beta_k(\omega) = \left. \frac{d^k \beta}{d\omega^k} \right|_{\omega=\omega_0}$  ( $k \geq 2$ ) is the  $k^{\text{th}}$  order dispersion parameter, and  $T = t - \frac{z}{v_g}$  is the retarded time frame moving with the group velocity  $v_g = \frac{1}{\beta_1(\omega_0)}$  at the pump frequency  $\omega_0$ . The nonlinear coefficient is  $\gamma = \frac{n_2 \omega_0}{c A_{\text{eff}}(\omega_0)}$ , where  $n_2$  is the nonlinear refractive index and  $c$  is the speed of light in vacuum,  $A_{\text{eff}}(\omega_0)$  is the effective area of the mode at the pump frequency  $\omega_0$ , and  $\alpha_2 = 9.3 \times 10^{-14}$  m/W is the two-photon absorption coefficient [12]. Finally the material response function includes both the instantaneous electronic response (Kerr type) and the delayed Raman response and has the form

$$R(t) = (1 - f_R) \delta(t) + f_R h_R(t), \quad (4)$$

$$h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2} \exp\left(-\frac{t}{\tau_2}\right) \sin\left(\frac{t}{\tau_1}\right). \quad (5)$$

The  $f_R$  represents the fractional contribution of the delayed Raman response. The other parameters used for the simulation are listed in Table 2.

Table 2. Parameters used for simulation of the SC generation

Parameters	Waveguide length	Linear loss ( $\alpha$ ) [10, 15]	$f_R$ [43]	$\tau_1$ [43]	$\tau_2$ [43]
Unit	cm	dB/cm	Null	fs	fs
Value	1	0.5	0.031	15.5	230.5

### 3. Numerical results

As the MIR SC generation requires the cladding as well as core materials of a waveguide to be transparent at long wavelengths, we first choose a channel waveguide fabricated using only chalcogenide materials with a rectangular core made of  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass and using  $\text{As}_{36}\text{S}_{64}$  glass for both the upper and lower claddings, whose refractive index of 2.37 at 1.55  $\mu\text{m}$  provides an index contrast of 0.3. By varying waveguide dimensions for realizing ZDW in the range of 2-4  $\mu\text{m}$  or longer, we numerically calculated GVD for three different structures as a function of wavelength for the fundamental quasi-TE mode and plot them with material dispersion in Fig. 2. It can be observed from this figure that the material dispersion, shown by a



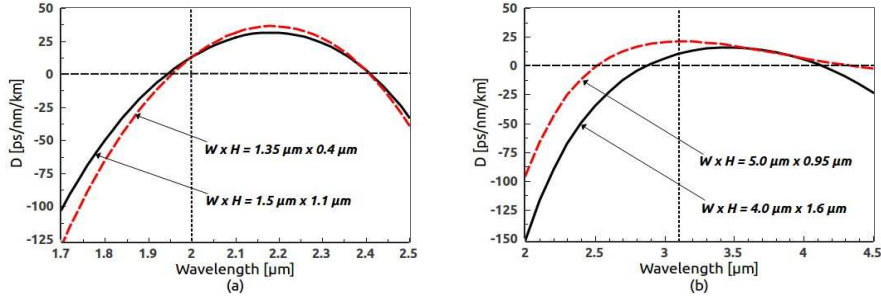


Fig. 3. GVD curves for the waveguide geometries employing two different lower claddings (solid black curve for  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  and red dashed curve for  $\text{MgF}_2$ ) for the fundamental quasi-TE mode (a) at a pump wavelength of  $2 \mu\text{m}$  and (b) at a pump wavelength of  $3.1 \mu\text{m}$ . Vertical dotted line indicates the position of pump wavelength.

solid black line, remains normal for the wavelength range  $1.5 \mu\text{m}$  to  $5 \mu\text{m}$ , considered here. The total dispersion curve for a waveguide with,  $W = 4 \mu\text{m}$  and  $H = 2.5 \mu\text{m}$  is shown by the green dot-dashed line, and it follows the material dispersion curve quite closely. As the waveguide dimension is reduced, waveguide dispersion becomes larger. However, total dispersion curves shown by red dotted and blue dashed lines for structures with,  $W = 3.7 \mu\text{m}$ ,  $H = 1.7 \mu\text{m}$  and  $W = 1.7 \mu\text{m}$ ,  $H = 1.7 \mu\text{m}$ , respectively. After increasing the width and thickness of a structure to  $W = 4.0 \mu\text{m}$  and  $H = 2.5 \mu\text{m}$ , total dispersion of the waveguide still remains normal ( $-40 \text{ ps}/\text{nm}/\text{km}$ ) at  $3.1 \mu\text{m}$  and continues to remain normal over a wide range of wavelengths exceeding  $5 \mu\text{m}$ . It appears unlikely that a waveguide can be designed to have anomalous dispersion in this wavelength range by employing such a lower index contrast cladding material such as  $\text{As}_{36}\text{S}_{64}$  glass.

For realizing anomalous dispersion around the pump wavelength, cladding materials with larger index contrast than the  $\text{As}_{36}\text{S}_{64}$  glass are required. To realize the ZDW between  $2 \mu\text{m}$  and  $4 \mu\text{m}$ , we have chosen two different channel waveguides by replacing upper cladding with air and lower cladding with either  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass or  $\text{MgF}_2$  glass, respectively. With  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass as the lower clad, index contrast increases to  $\sim 0.4$  but with  $\text{MgF}_2$  glass this value increases significantly to 1.3. To obtain the ZDWs of both designs close to the pump wavelength of  $2 \mu\text{m}$  and to make GVDs slightly anomalous at these wavelengths, we optimized the dimensions of the waveguides. Similarly, another set waveguides were optimized for the longer pump wavelength of  $3.1 \mu\text{m}$ . Figures 3(a) and 3(b) show the GVD curves obtained for two different waveguide geometries optimized to work at the pump wavelengths of  $2 \mu\text{m}$  and  $3.1 \mu\text{m}$ , respectively.

To study SC generation, we solve the generalized nonlinear Schrödinger equation (GNLSE) given in Eq. (3). We used the same computational method that was used in Karim *et al.* [8]. That study has indicated that there is a possibility to obtain spurious results if the adequate number of dispersion terms is not included during SC simulations. We solved Eq. (3) with the split-step Fourier method (SSFM) including up to  $10^{\text{th}}$  order dispersion. We tested accuracy of the finite-element modal solution for a channel waveguide by a powerful extrapolation technique called Aitken's extrapolation [44]. We observed the convergence between the raw FEM results and extrapolated values as the number of FE elements increases along the transverse dimensions of the waveguide. We also tested the accuracy of numerically calculated GVD parameters for different number of elements used along the transverse dimensions of a channel waveguide. We fitted the dispersion data with a Taylor series expansion including up to  $10^{\text{th}}$  order dispersion and found that this method accurately reproduced the GVD curves obtained by FE mode-solver

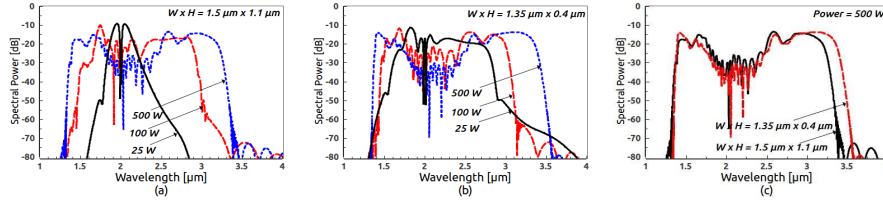


Fig. 4. Simulated SC spectra at a pump wavelength of  $2 \mu\text{m}$  for (a) air-clad all-chalcogenide waveguide at peak power from 25, 100, and 500 W; (b) air-clad chalcogenide core employing  $\text{MgF}_2$  for its lower cladding at the same power levels; (c) waveguides with two different lower claddings at a peak power of 500 W only.

over the whole wavelength range of calculations. A sufficiently small time step was chosen to accommodate the spectral expansion of the generated SC during numerical simulations.

We consider a waveguide containing a core of dimensions  $W = 1.5 \mu\text{m}$  and  $H = 1.1 \mu\text{m}$  with air and  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass as upper and lower claddings, respectively. Another geometry has a core with  $W = 1.35 \mu\text{m}$  and  $H = 0.4 \mu\text{m}$  but  $\text{MgF}_2$  glass as the lower cladding. Using FE mode-solver, we obtain  $A_{\text{eff}} = 1.09 \mu\text{m}^2$  which yields  $\gamma = 24.79 \text{ /W/m}$  for the structure with  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  lower cladding and  $A_{\text{eff}} = 0.51 \mu\text{m}^2$  which yields  $\gamma = 53.39 \text{ /W/m}$  for the structure with  $\text{MgF}_2$  lower cladding at a pump wavelength of  $2 \mu\text{m}$ . The GVD parameter calculated at the pump wavelength for both waveguides has a value of  $13 \text{ ps/nm/km}$ . These waveguides supported propagation of the fundamental TE mode up to the cut-off wavelength near  $3.1 \mu\text{m}$  for the air-clad all-ChG structure and around  $4 \mu\text{m}$  for the structure employing  $\text{MgF}_2$  glass as lower cladding. A sech pulse of 150 fs duration (FWHM) was launched with peak power between 25 W and 500 W for numerical simulations. We included a wavelength-independent propagation loss of  $2.5 \text{ dB/cm}$  [10] for our 1-cm-long rectangular channel waveguides. Figure 4 shows the predicted SC spectra for the two waveguides at three different power levels at a pump wavelength of  $2 \mu\text{m}$ . In the case of 100 W input power the SC spectrum extends from  $1.5 \mu\text{m}$  to around  $3 \mu\text{m}$ , producing a -30 dB bandwidth of 1500 nm for the waveguide using  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass for its lower cladding. At the same power level the SC spectrum extends from  $1.4 \mu\text{m}$  to around  $3.1 \mu\text{m}$  producing a -30 dB bandwidth of 1700 nm for the waveguide with  $\text{MgF}_2$  glass for its lower cladding. After increasing input peak power level at 500 W, the SC spectra broadened from  $1.3 \mu\text{m}$  to  $3.3 \mu\text{m}$  (output bandwidth of 2000 nm) and from  $1.3 \mu\text{m}$  to  $3.5 \mu\text{m}$  (output bandwidth of 2200 nm) for these two waveguides, respectively. The spectral evolution plots corresponding to Fig. 4(c) are shown in Fig. 5. It is apparent that a

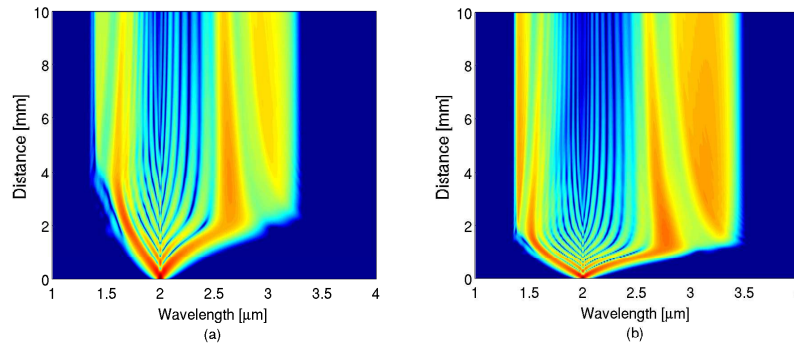


Fig. 5. Spectral evolution along the waveguide length corresponding to Fig. 4(c).

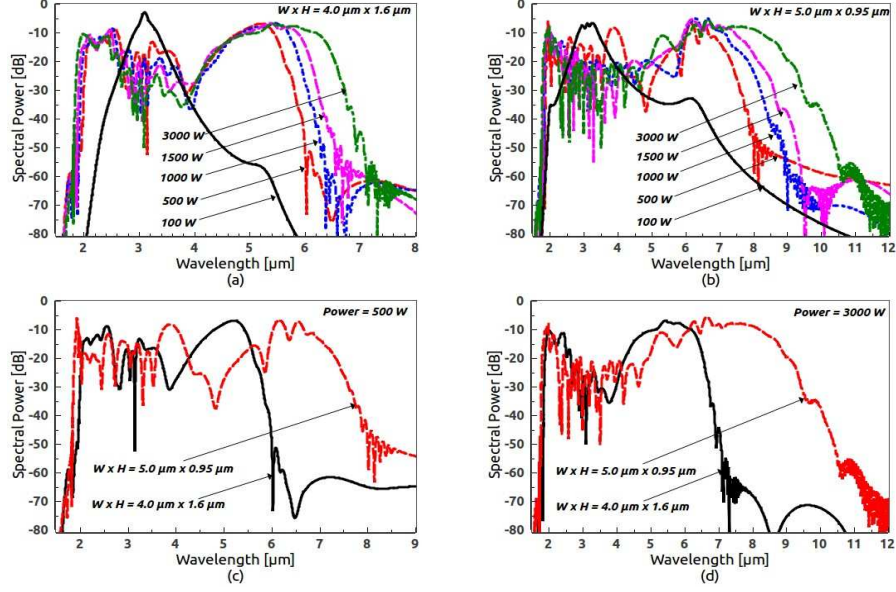


Fig. 6. Simulated SC spectra at a pump wavelength of  $3.1 \mu\text{m}$  for (a) air-clad all-chalcogenide waveguide at peak power between 100 W and 3000 W; (b) air-clad chalcogenide core employing  $\text{MgF}_2$  for its lower cladding for the same power levels; (c) waveguides employing with two different lower claddings at a peak power of 500 W only; (d) waveguides with two different lower claddings at peak power of 3000 W only.

larger output bandwidth can be realized by using a waveguide employing  $\text{MgF}_2$  glass for its lower cladding. The reason behind this bandwidth enhancement solely related to the higher index contrast between the core and cladding materials when  $\text{MgF}_2$  glass is used for the lower cladding. However, it was not possible to extend the SC spectrum to beyond  $3.5 \mu\text{m}$  by using a pump wavelength of  $2 \mu\text{m}$ .

To extend the SC in the MIR regime, we need to shift the pump wavelength toward longer wavelengths [14]. We employ a pump wavelength of  $3.1 \mu\text{m}$  since such a pump source has been realized at a repetition rate of 160 kHz [45]. Using 85 fs duration pulses at a wavelength of  $3.1 \mu\text{m}$ , we focus on a waveguide with  $W = 4 \mu\text{m}$  and  $H = 1.6 \mu\text{m}$  with  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass for its lower lower cladding. The second waveguide structure had  $W = 5 \mu\text{m}$  and  $H = 0.95 \mu\text{m}$  but employed  $\text{MgF}_2$  glass for its lower cladding. Using the FE mode-solver, we obtain  $A_{\text{eff}} = 4.25 \mu\text{m}^2$  and  $\gamma = 2.05 \text{ /W/m}$  for the first structure and  $A_{\text{eff}} = 3.32 \mu\text{m}^2$  and  $\gamma = 2.63 \text{ /W/m}$  for the second structure. The GVD parameter calculated at the pump wavelength for these waveguides has values of 10.22 ps/nm/km and 21 ps/nm/km, respectively. These waveguides supported propagation of the fundamental TE mode up to the cut-off wavelength around  $6.5 \mu\text{m}$  for the air-clad all-ChG structure and beyond  $12 \mu\text{m}$  for the structure employing  $\text{MgF}_2$  as lower cladding.

After evaluating higher-order dispersion terms up to tenth-order from GVD curves shown in Fig. 3(b), we performed numerical simulations for SC generation in both the waveguide geometries at a power level between 100 W and 3000 W. The dispersion length,  $L_D = T_p^2 / |\beta_2|$  for the 85 fs pump pulse for these two structures is 45 mm and 28 mm and the nonlinear length,  $L_{\text{NL}} = 1/\gamma P$  at a peak power of 500 W is 0.98 mm and 0.76 mm, respectively. The soliton order,  $N = \sqrt{L_D/L_{\text{NL}}}$  was 7 and 6 for the two waveguides, respectively, and the soliton fission length,  $L_{\text{fiss}} \approx L_D/N$  was found to be 6.6 mm and 4.1 mm, respectively. Figure 6 shows the predicted

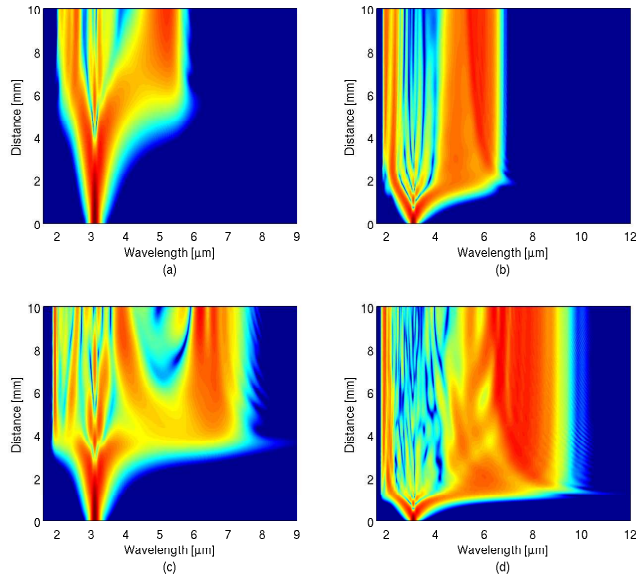


Fig. 7. Spectral evolution along the waveguide length corresponding to Fig. 6(c) (left column) and 6(d) (right column), respectively.

spectra at various power level up to 3000 W for the two waveguide geometries at a pump wavelength of  $3.1 \mu\text{m}$ . The spectral evolution plots corresponding to Fig. 6(c) and 6(d) are shown in Fig. 7. It is observed from Fig. 7 that the SC generation is dominated by soliton fission, which results in many short pulses generated through the soliton fission process whose spectra shifted towards the long wavelength side of the input spectrum. Raman-induced frequency shift (RIFS) is reducing gradually as solitons moved towards the second ZDWs located near  $4.15 \mu\text{m}$  and  $4.4 \mu\text{m}$  for the two waveguide geometries, respectively. Due to the spectral recoil effect [46, 47], RIFS were completely suppressed near the second ZDWs. At the same time, nonsolitonic radiation in the form of dispersive wave is produced at a wavelength that lies beyond the second ZDW. For the waveguide geometry employing  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass as a lower cladding, it can be observed from Fig. 6 that the SC extends over  $4 \mu\text{m}$  covering a wavelength range from  $2 \mu\text{m}$  to  $6 \mu\text{m}$  and for the structure employing  $\text{MgF}_2$  as a bottom cladding, the SC extends over  $6 \mu\text{m}$  covering a wavelength range from  $1.8 \mu\text{m}$  to around  $7.7 \mu\text{m}$  both at a peak power of 500 W. By increasing power level up to 3000 W, one can generate a SC spectrum that extends from  $2 \mu\text{m}$  to  $10 \mu\text{m}$  producing a bandwidth of  $8 \mu\text{m}$  ( $> 2$  octave) for the first waveguide and bandwidth of  $9.2 \mu\text{m}$  ( $> 2.5$  octave) for the second waveguide employing  $\text{MgF}_2$  glass for its lower cladding.

There may be a disadvantage for ChG waveguides fabricated using  $\text{MgF}_2$  glass for the lower cladding owing to its fragility. This problem becomes severe for long waveguides but is manageable for short waveguides around 1-cm-long [14]. Ma *et al.* [10] have shown experimentally that, if the top surface of the waveguides made from chalcogenide materials is left uncoated, the bare waveguide surface becomes rapidly contaminated by absorbing water and hydrocarbons from surrounding environment, resulting in increased losses. To prevent the surface contamination, a thin 10-nm protective coating layer of fluoro-polymer may be placed on top of the waveguide geometries proposed in this paper. We have tested numerically placing of such a thin

layer and found that the dispersions at a pump wavelength of  $3.1 \mu\text{m}$  for the two waveguides used in our work was  $9.85 \text{ ps/nm/km}$  ( $10.23 \text{ ps/nm/km}$  without coating) and  $21.68 \text{ ps/nm/km}$  ( $21 \text{ ps/nm/km}$  without coating). Such relatively small changes in the  $\beta_2$  value do not produce noticeable changes on the SC generated at the waveguide output.

Recently Yu *et al.* [15] proposed an air-clad rib waveguide whose core was made with  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass and whose lower cladding was made with  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  glass. They were able to generate SC covering the wavelength range  $1.8\text{-}7.5 \mu\text{m}$  when pumped with an optical parametric amplifier at  $4 \mu\text{m}$  with a peak power of  $3260 \text{ W}$ . By rigorous numerical simulations, it is shown here that MIR SC can be generated with dispersion-engineered air-clad rectangular channel waveguide employing the same materials and covering the wavelength range of  $1.9\text{-}7 \mu\text{m}$  by employing a pump source at a wavelength of  $3.1 \mu\text{m}$  with a peak power of  $3000 \text{ W}$ . It is observed from Fig. 6 that MIR SC can be extended in the long wavelength regime up to  $11 \mu\text{m}$  for a waveguide employing  $\text{MgF}_2$  glass for its lower cladding when pumped with the same power and pump source although  $\text{MgF}_2$  glass would be expected to absorb beyond  $9 \mu\text{m}$  [10].

#### 4. Conclusions

We have numerically demonstrated MIR SC generation by using dispersion-engineered, air-clad, channel waveguides designed and optimized such that they use either  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  ChG glass or  $\text{MgF}_2$  glass for its lower cladding material. The SC is generated with the waveguides proposed here by using pump pulses with low to moderate peak power at wavelength near  $2 \mu\text{m}$  or  $3.1 \mu\text{m}$ . Although the nonlinear parameter has larger values at a pump wavelength of  $2 \mu\text{m}$ , the SC spectra were extended only over  $1.3\text{-}3.3 \mu\text{m}$  and  $1.3\text{-}3.5 \mu\text{m}$ , respectively even at the highest but moderate peak power of  $500 \text{ W}$  for the two proposed structures. To extend SC to beyond the  $5 \mu\text{m}$ , it is necessary to choose a longer pump wavelength around  $4\text{-}5 \mu\text{m}$ . To realize the ZDW of the waveguide around this wavelength the core size of the waveguide must be increased which increases the effective mode area and hence reduces the nonlinear parameter. The only solution is to increase the peak power of the input pulse toward MW levels which can damage the input facet of the waveguide. Considering these factors, we designed and optimized air-clad two rectangular channel waveguides by employing two different lower cladding materials and choose  $3.1 \mu\text{m}$  for the pump wavelength such that broadband SC could be generated at moderate peak power levels.

Using pump source at a wavelength of  $3.1 \mu\text{m}$  with a relatively low peak power of  $500 \text{ W}$  we obtained a SC spectrum extended over 1.5 octave and covering the wavelength range from  $2\text{-}6 \mu\text{m}$  with an air-clad all-ChG structure. However, when we used an optimized waveguide using  $\text{MgF}_2$  glass for its lower cladding, the SC spectrum extended over more than two-octaves covered a wavelength range of  $1.8\text{-}7.7 \mu\text{m}$ . This, to the best of our knowledge, is the broadest MID SC at such a low peak power and at a lower pump wavelength of  $3.1 \mu\text{m}$  using a chalcogenide waveguide. We have also found that, MIR SC can be extended over in the wavelength range  $1.9\text{-}7 \mu\text{m}$  and  $1.8\text{-}11 \mu\text{m}$  with a moderate peak power of  $3000 \text{ W}$  when the air-clad channel waveguide is designed with a  $\text{Ge}_{11.5}\text{As}_{24}\text{Se}_{64.5}$  glass core and employs  $\text{Ge}_{11.5}\text{As}_{24}\text{S}_{64.5}$  or  $\text{MgF}_2$  glass for its lower cladding, respectively.