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# Mid-infrared supercontinuum generation using $As_2Se_3$ photonic crystal fiber and the impact of higher-order dispersion parameters on its supercontinuum bandwidth

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ABSTRACT

A dispersion engineered $As_2Se_3$ chalcogenide hexagonal photonic crystal fiber which can produce a mid-infrared supercontinuum (SC) spectral evolution spanning from 2 µm to beyond 15 µm with a low peak power of 3 kW is numerically designed and demonstrated. Numerical analysis is carried out to investigate the impact of higher-order dispersion (HOD) parameters on the output SC bandwidth and shows that the SC spectral broadening at the output of the proposed design depends on the convergence of the Taylor approximation with increasing fitting parameters, which implies a sufficient number of HOD parameters must be included during numerical simulations. Four designs with different structural parameters are optimized for pumping, each operating at a different pump wavelength to test the convergence of output SC by the successive addition of HOD parameters. To realize spurious free SC spectral evolution by the proposed designs, HOD terms up to the sixteenth-order are included during all SC simulations. The proposed design can be used in molecular finger print spectroscopy, biomedical imaging as well as various mid-infrared region applications.

## 1. Introduction

Mid-infrared (MIR) spectral region (2–20 µm) supercontinuum (SC) generation has recently become the focus of considerable interest owing to its diverse applications in optical coherence tomography, biomedical imaging, high precision frequency metrology and molecular finger print spectroscopy [1,2]. Almost all molecules in this region undergo strong vibrational absorption, providing significant pathways for MIR spectroscopy to trace and quantify the molecular species in a certain atmospheric condition [3]. Two vital spectral windows, at 3–5 µm and 8–13 µm are located in this region in which the atmosphere is relatively transparent and can thus be used to detect the scent of exotic/toxic gases that are detrimental for a multitude of industrial and atmospheric applications [4].

In order to produce ultrabroadband SC sources with high brightness that can cover a spectral evolution up to the molecular fingerprint region, researchers have proposed the use of optical waveguides made with different host materials such as fluoride, tellurite and chalcogenide glasses [5–13]. The MIR transparencies of fluoride and tellurite glasses are not more than 5 µm [14] and to date the highest SC extension in the long wavelength edge by these two materials are 6.28 µm [15] and 4.87 µm [16] respectively. At the same time, chalcogenide (ChG) glasses have shown wider MIR transparency exceeding 20 µm, depending on the compositions of glass components. These glasses possess high third-order Kerr nonlinearity which is hundreds of times larger than that of fluoride and tellurite glass, making more suitable as host materials for waveguide fabrication than most other materials with significant promise for MIR region applications [17–30].

A number of numerical and experimental ultrabroadband SC spectra in the MIR region using ChG waveguides and fibers have been demonstrated recently [4,10–14,31–33]. Yu et al. [12] demonstrated an SC spectrum covering a wavelength range from 1.8 to 10 µm with a pulse duration of 330-fs pumped at 4 µm in a 11-cm long ChG step-index fiber using $Ge_{12}As_{24}Se_{64}$ as a core and $Ge_{12}As_{24}S_{64}$ for its outer cladding with an input peak power of 3 kW. The same research group also experimentally demonstrated in the following year an SC generation covering a spectral range of 2–10 µm by an all-ChG rib waveguide made using GeAsSe glass as the core and GeAsS glass as both the upper and lower claddings with 330-fs pulses pumped at 4.184 µm with an input peak power of 4.5 kW [10]. Petersen et al. [11] reported a MIR SC

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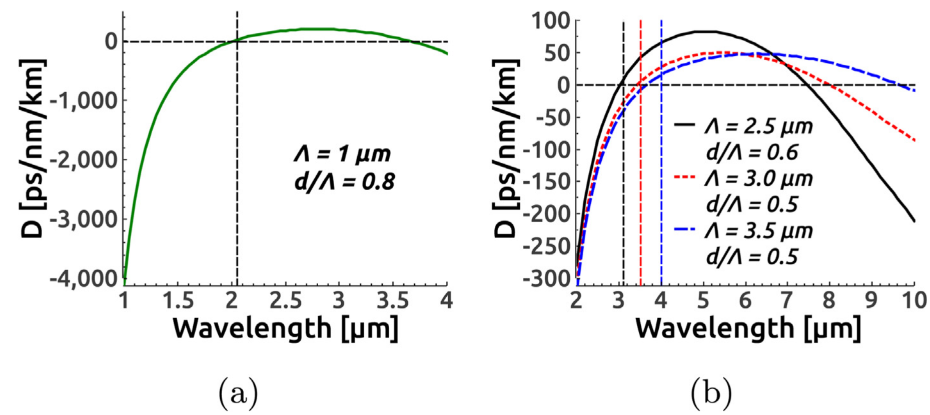


**Fig. 1.** GVD curves of four $As_2Se_3$ PCF designs tailored for fundamental mode ($H_x^{11}$) by varying Λ and $d/\Lambda$ for pumping at four different locations such as (a) 2.05 µm; (b) 3.1 µm, 3.5 µm and 4 µm, respectively. Vertical dashed lines indicate pump wavelengths.

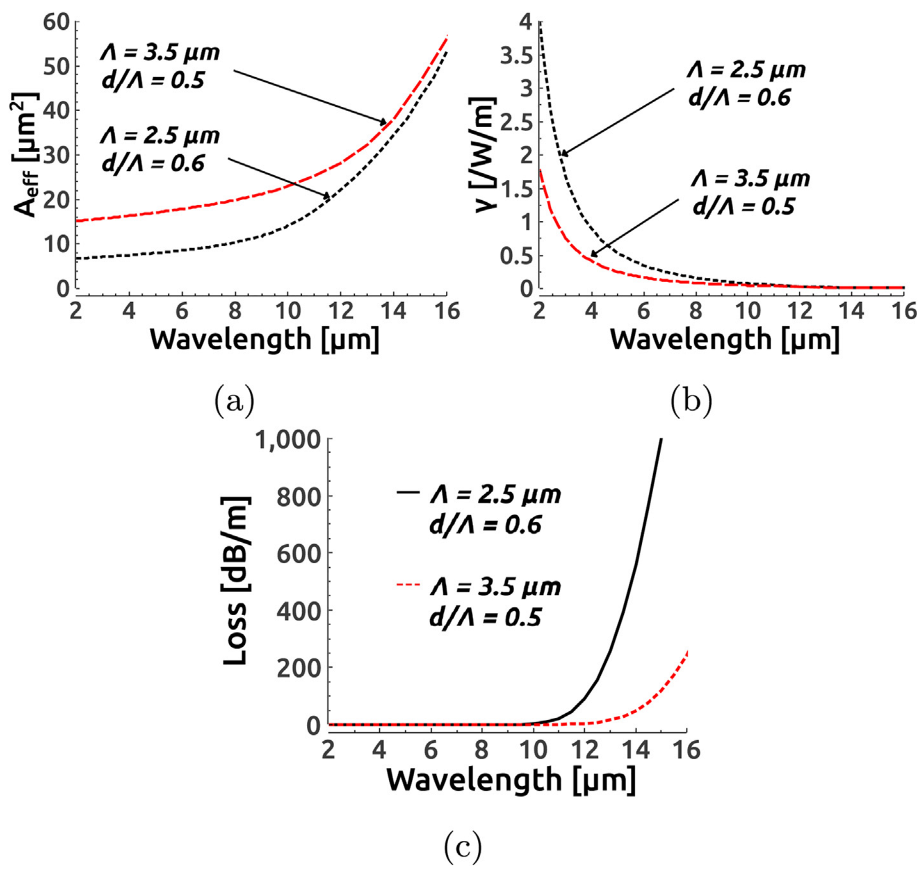


**Fig. 2.** (a) Mode effective areas; (b) Nonlinear coefficients and (c) Confinement losses of fundamental mode are evaluated over a wide wavelength range for the PCF structures of Λ = 2.5 µm, $d/\Lambda$ = 0.6 and Λ = 3.5 µm, $d/\Lambda$ = 0.5, respectively.

spectra spanning from 1.4 µm to 13.3 µm with a 85-mm-long ChG step-index fiber made using $As_{40}Se_{60}$ as the core and $Ge_{10}As_{23.5}Se_{66.6}$ glass for its outer cladding, pumped at 6.3 µm with pulses of 100-fs duration and an input peak power of 2.29 MW. Ou et al. [14] reported a MIR SC spectral evolution up to 14 µm with a 20-cm-long ChG step-index fiber made using $Ge_{15}Sb_{25}Se_{60}$ glass as the core and $Ge_{12}Sb_{20}Se_{65}$ glass for its cladding, pumped with a 150-fs pulse duration at 6 µm and a peak power of 750 kW. Similarly, Cheng et al. [13] reported a MIR SC spectrum spanning the wavelength range 2–15.1 µm in a 3-cm-long ChG step-index fiber using $As_2Se_3$ as the core and $AsSe_2$ as outer cladding when pumped with a 170-fs pulses in 9.8 µm with a peak power of 2.89 MW, while Zhao et al. [4] demonstrated a MIR SC spectra extending up to 16 µm using a 14-cm-long step-index fiber made from Ge-Te-AgI glass when pumped at 7 µm with 150-fs duration pulses and a pulse repetition rate of 1 kHz with a peak power of 77 MW. Petersen et al. [31] experimentally demonstrated a broadband MIR SC generation spectra covering the wavelength from 1 to 11.5 µm with a high average output power above 4.5 µm in tapered large-mode-area ChG $Ge_{11}As_{22}Se_{68}$ photonic crystal fiber (PCF). Hudson et al. [32] reported a broadband MIR SC spectrum spanning from 1.8 to 9.5 µm using a $As_2Se_3/As_2S_3$ tapered fiber by launching 230-fs pulses with a pulse peak power of 4.2 kW, and Saini et al. [33] numerically demonstrated MIR SC generation covering a wavelength range 2–15 µm in a 5-mm long triangular core graded index $As_2Se_3$ PCF when pumped at 4.1 µm with a largest peak power of 3.5 kW. Wang et al. [34] recently reported MIR region SC generation covering a wavelength from 2 to 12.7 µm using a