Influence of initial frequency chirp on the supercontinuum generation in As2S3 chalcogenide fiber

Yan Li and Pinghua Tang

Hunan Key Laboratory for Micro-Nano Energy Materials and Devices, School of Physics and Optoelectronics, Xiangtan University, Xiangtan 411105, China

E-mail: pinghuatang@xtu.edu.cn

Abstract. Initial frequency chirp has significant influence on spectral evolution when the pulse propagates along the fiber. We report on the numerical results of supercontinuum (SC) generation in As2S3 chalcogenide fiber that positive initial chirp is beneficial for spectral broadening, while the negative chirp does the opposite. Besides, when the initial frequency chirp is lower than 30, the SC bandwidth increases with initial frequency chirp. The maximum SC bandwidth is ~2800 nm, which spans from near infrared (IR) to mid-IR region.

1. Introduction

When ultra-short pulse propagates in highly nonlinear optical fibers, their temporal as well as spectral evolution is affected by various nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM), stimulated Raman scattering (SRS), and four-wave mixing (FWM). For sufficiently intense pulse, this spectral evolution may lead to the generation of supercontinuum. Up to now, much attention has been paid to SC generation in optical fiber. Compared with other ultra-short pulse light sources, the supercontinuum light source has the characteristics of high brightness, wide spectrum, and stable reliability. Therefore, supercontinuum has significantly potential applications in many fields such as spectral analysis [1], high precision optical frequency measurement [2] and optical fiber communication [3]. At present, supercontinuum is mainly produced from silica fiber. However, silica fiber has some limitations for SC generation such as low nonlinearity and narrow IR transmission edge. In order to address these limitations, some non-silica glass fibers including tellurite fiber [4, 5], fluoride fiber [6, 7], and chalcogenide fiber [8, 9] have been put forward to obtain SC.

Chalcogenide glass has very high nonlinearity (two or three orders of magnitude higher than silica) and extremely high IR radiation transmission. Although chalcogenide fiber is usually less tough than tellurite fiber [4, 5] and fluoride fiber [6, 7], it possesses much broader transmission window than the other two. Hence, the chalcogenide fiber is considered as one of the most promising nonlinear medium for SC generation in mid-infrared region. The SC generation in chalcogenide fiber has been widely investigated both numerically and experimentally [10–19]. However, all the theoretical studies only concern the pulse without initial chirp; experimental studies also lack systematic investigations on the effect of initial chirp due to the difficulties in chirp manipulation.

In this paper, to better understand the impact of initial frequency chirp on SC generation in As2S3 chalcogenide fiber, the input pulse with different initial frequency chirps is considered in our investigation. The simulation results indicate that positive initial chirp is beneficial for spectral broadening, while the negative chirp does the opposite. Besides, when the initial frequency chirp is lower than 30, the SC bandwidth increases with initial frequency chirp.
2. Theoretical Model

We can get the generalized nonlinear schrödinger equation (GNLSE) according to the fact that the propagation of optical fields in fibers is governed by Maxwell’s equations [20], we convert this equation to the time domain and write it in the form:

\[
\frac{\partial A}{\partial Z} + \frac{\alpha}{2} A - \sum_{k=2}^{4} \frac{i^{k+1}}{k!} \beta_k \frac{\partial^k A}{\partial T^k} = i \gamma (1 + i \tau \delta \frac{\partial}{\partial T}) \times (A(Z,T) \int_{T}^{\infty} R(T') [A(Z,T - T')]^2 dT')
\]

(1)

where \( A = A(Z, T) \) is the complex electric field envelope, with \( \alpha \) is the total fiber loss, \( \beta_k \) is \( k \)-th order dispersion coefficients with the central frequency \( \omega_0 \), \( \gamma \) is the nonlinear coefficient, the time scale is usually defined as \( \tau_{\text{layer}} = \tau_0 = 1/\omega_0 \) [21], \( R(t) \) is the nonlinear response function including the instantaneous electronic and the vibrational (Raman) contributions [22] usually modeled as:

\[
R(t) = (1 - f_R) \delta(t) + f_R h_R(t)
\]

(2)

where \( f_R \) represents the fractional contribution of the delayed Raman response and \( \delta(t) \) is the Dirac delta function, and \( h_R(t) \) is the Raman response function which is given by:

\[
h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2} \exp(-t/\tau_2) \sin(t/\tau_1)
\]

(3)

where \( \tau_1 \) and \( \tau_2 \) are two adjustable parameters for As_{2}S_{3} chalcogenide glass, \( n_2(\omega_0) \) is the nonlinear refractive index, \( A_{\text{eff}}(\omega_0) \) is the effective mode area and it can be given by [23]:

\[
A_{\text{eff}}(\omega) = \frac{\left( \int_{-\infty}^{\infty} |F(x, y, \omega)|^2 dxdy \right)^2}{\int_{-\infty}^{\infty} |F(x, y, \omega)|^4 dxdy}
\]

(4)

The pulse propagation along the chalcogenide fiber can be obtained by solving Equation (1) using the symmetrized split-step Fourier method [24]. Such propagation is dependent on the interaction between the dispersive and nonlinear effects. The input pulses are assumed to be of the form:

\[
A(0, T) = \sqrt{P_0} \text{sech}(\frac{T}{T_0}) \exp(-iCT^2/2T_0^2)
\]

(5)

where \( P_0 \) is the peak power, \( T_0 \) is the half width (at 1/e of the peak intensity) which relates to the (full width at half maximum) FWHM by \( T_{\text{FWHM}} \approx 1.763 \ T_0 \), and \( C \) is the initial frequency chirp.

3. Results and discussion

In order to understand the effect of initial frequency chirp on the SC generation in the As_{2}S_{3} chalcogenide fiber, the dynamics of the spectral and temporal evolution along the As_{2}S_{3} fiber for the input pulse with different chirp parameters in anomalous dispersion region are investigated. In the investigation, we consider a highly nonlinear As_{2}S_{3} chalcogenide photonic crystal fiber with the pitch of the lattice \( A = 1.9 \ \mu m \), the diameter of each air hole \( d = 1.3 \ \mu m \), the effective mode area \( A_{\text{eff}} = 3.98 \ \mu m^2 \), and the nonlinear refractive index \( n_2 = 3.0 \times 10^{-18} \ m^2/W \) as the reference fiber [11]. The As_{2}S_{3} chalcogenide fiber with the zero dispersion wavelength (ZDW) of 1985 nm (the wavelength dependent dispersion curve can be found in ref. 11), so the dispersion is anomalous by taking \( \lambda = 2000 \ nm \) as the pumping wavelength of the input pulse. Here we would like to mention that all the fiber parameters including the dispersions coefficients, nonlinear coefficient, and Raman response in the simulation are cited from ref. 11; they are listed as follows: \( \beta_2 = -0.0107 \times 10^3 \ ps^2/km, \beta_3 = 1.45 \ ps^3/km, \beta_4 = -3.92 \times 10^3 \ ps^4/km, \beta_5 = 2.1 \times 10^4 \ ps^5/km, \beta_6 = -1.25 \times 10^7 \ ps^6/km, \beta_7 = 8.50 \times 10^{10} \ ps^7/km, \beta_8 = -5.68 \times 10^{12} \ ps^8/km, \beta_9 = 1.51 \times 10^{14} \ ps^9/km, \beta_{10} = 6.51 \times 10^{16} \ ps^{10}/km; \gamma = 2362 \ W^{-1}km^{-1}; f_R = 0.031, \tau_1 = 15.2 \ fs, \tau_2 = 230.5 \ fs \).

The input pulse with peak power \( P_0 = 1 \ kW \), and pulse duration \( T_{\text{FWHM}} = 500 \ fs \) is selected. The propagation loss is neglected due to the very short reference fiber length (0.04 m).

Figure 1(a)-(c) shows the simulation results of the spectral evolution along the As_{2}S_{3} fiber for the input pulse with initially negative chirp (\( C = -12 \)), zero chirp (\( C = 0 \)), and positive chirp (\( C = 20 \)),
respectively; the corresponding temporal evolution are shown in Figure 1(c)-(f). From Figure 1 we can see that there are several distinct features for the input pulse with different initial frequency chirp. First of all, positive initial chirp is beneficial for spectral broadening, while the negative chirp does the opposite. This can be explained as follows. As the pulse propagates along the fiber, a positive initial chirp will add to the SPM-induced chirp near the pulse center, which is beneficial for the initial pulse compression and getting higher peak power; as a result, it enhances the SC generation and creates a broader SC. Conversely, a negative initial chirp will hinder the spectral broadening from SPM by counteracting the SPM-induced chirp, and in turn, creating a narrower SC. Secondly, the distance for high-order soliton fission decreases with increasing initial frequency chirp; meanwhile the longer wavelength soliton walks off more quickly and separates faster for larger frequency chirp. In addition, the efficiency of dispersion wave generation increases with the initial frequency chirp.

Figure 2 shows the output spectra of the As$_2$S$_3$ fiber for the input pulse with six initial frequency chirps of $C = -12$, $-7$, $0$, $10$, $20$ and $30$, respectively. Obviously, the 20-dB spectral bandwidth of the SC increases with initial frequency chirp. Further increasing the initial frequency chirp beyond 30, the SC bandwidth will no longer increase any more. The maximum SC bandwidth is ~2800 nm, which spans from near-IR ($\sim$1200 nm) to mid-IR ($\sim$3500 nm). Here we would like to mention that the initially input pulse ($T_{\text{FWHM}} = 500$ fs) with chirp such as $C = 30$ or larger is possible in reality. For example, the chirped sech$^2$-shaped pulse ($T_{\text{FWHM}} = 500$ fs, $C = 30$) can be realized by injecting an unchirped sech$^2$-shaped pulse with $T_{\text{FWHM}} = \sim 12$ fs into a Gires-Tournois interferometer with $D_2 = 3000$ fs$^2$.

Figure 1. Results from numerical simulations showing (a)-(c) spectral and (d)-(f) temporal evolution along the fiber for the input pulse with initial chirp of $C = -12$, $C = 0$, and $C = 20$, respectively.
Figure 2. Output spectra of the As$_2$S$_3$ fiber for the input pulse with different initial frequency chirps of $C = -12, -7, 0, 10, 20$, and $30$, respectively.

4. Conclusions

In summary, we numerically investigate the influence of initial frequency chirp on SC generation in As$_2$S$_3$ chalcogenide fiber in anomalous dispersion region. In the investigation, the input pulse with different initial frequency chirps is considered. The simulation results indicate that positive initial chirp is beneficial for spectral broadening, while the negative chirp does the opposite. Besides, when the initial frequency chirp is lower than $30$, the SC bandwidth increases with initial frequency chirp. The maximum SC bandwidth is ~2800 nm, which spans from near-IR ($~1200$ nm) to mid-IR ($~3500$ nm). This numerical investigation can provide some reference for developing mid-IR SC in As$_2$S$_3$ chalcogenide fiber.

Acknowledgments

This work is supported by the Hunan Provincial Natural Science Foundation of China (Grant No. 2018JJ3514), the China Postdoctoral Science Foundation (Grant No. 2017M620349), the National Natural Science Fund Foundation of China (Grant No. 61605166), and the Research Foundation of Education Bureau of Hunan Province, China (Grant No. 17C1519). The authors acknowledge Wei Lin, Ph.D. (South China University of Technology) for beneficial discussion.

References

[1] Walle A, Hanna M, Guichard F, Zaouter Y, Thai A and Forget N 2015 Opt. Lett. 40 673–676
[2] Akbulut M, Davila-Rodriguez J, Ozdur I, Quinlan F, Ozharar S and Hoghooghi N 2011 Opt. Express 19 16851–16865
[3] Zou X, Qu J, Wang X, Ye Z, Sun C and Ge T 2017 IEEE Photon. 9 1–7
[4] Kedenburg S, Strutynski C, Kibler B, Froidevaux P, Désévédavy F and Gadret G 2017 JOSA B 34 601–607
[5] Qin G, Yan X, Kito C, Liao M, Suzuki T and Mori A 2010 Opt. Lett. 35 136–138
[6] Nomura Y, Nishio M, Kawato S and Fuji T 2015 *IEEE J. Sel. Top. Quantum Electron.* 21 24–30
[7] Swiderski J, Michalska M and Maze G 2013 *Opt. Express* 21 7851–7857
[8] Khalifa A B, Salem A B and Cherif R 2017 *Appl. Opt.* 56 4319–4324
[9] Marandi A, Rudy C W, Dianov E M, Vodopyanov K L, Byer R L and Plotnichenko V G 2012 *Opt. Express* 20 24218–24225
[10] Hu J, Menyuk C R, Shaw L B, Sanghera J S and Aggarwal I D 2010 *Opt. Lett.* 35 2907–2909
[11] Ahmad R, Komanec M and Zvanovec S 2016 *IEEE Photon. Technol. Lett.* 28 2736–2739
[12] Yu Y, Gai X, Wang T, Ma P, Wang R P, Yang Z Y, Choi D Y, Madden S and Davies B L 2013 *Opt. Express* 3 1075–1086
[13] Rudy C W, Marandi A, Vodopyanov K L and Byer R L 2013 *Opt. Lett.* 38 2865–2868
[14] Du Q, Huang Y, Li J, Kita D, Michon J and Lin H 2016 *Opt. Lett.* 41 3090–3093
[15] Granzow N, Stark S P, Schmidt M A, Tverjanovich A S, Wondraczek L and Russell P S J 2011 *Opt. Express* 19 21003–21010
[16] Lutherdavies B, Caillaud C, Petersen C R, Méchin D, Kubat I and Troles J 2015 *Opt. Express* 23 3282–3291
[17] Petersen C R, Moller U, Kubat I, Zhou B, Dupont S and Ramsay J 2014 *Nature Photonics* 8 830–834
[18] Cheng T, Nagasaka K, Tuan T H, Xue X, Matsumoto M, Tezuka H, Suzuki T and Ohishi Y 2016 *Opt. Lett.* 41 2117–2120
[19] Anashkina E A, Shiryaev V S, Koptev M Y, Stepanov B S and Muravyev S V 2018 *Non-Cryst. Solids* 480 43–50
[20] Zhang Z and Satpathy S 1990 *Phys. Rev. Lett.* 65 2650–2653
[21] Brabec T and Krausz F 1997 *Phys. Rev. Lett.* 78 3282–3285
[22] Blow K J and Wood D 1989 *IEEE Quantum Electron.* 25 2665–2673
[23] Dudley J M, Genty G and Coen S 2006 *Rev. Mod. Phys.* 78 1135–1184
[24] Fisher R A and Bischel W K 1975 *Appl. Phys.* 46 4921–4934