In this paper, we numerically investigate the mid-infrared supercontinuum (SC) generation in a suspended As$_2$Se$_3$ ridge waveguide, which is designed with the two zero-dispersion wavelengths. Simulation results show that when the pump pulses at wavelength 3.3 µm with width of 100 fs and peak power of 900 W are launched into the anomalous dispersion region of the designed waveguide with a length of 0.87 mm, the SC can be generated in the wavelength range from 1.76 to 14.42 µm (more than 3 octaves), extending deep into the “fingerprint” region. The stability of the generated SC is confirmed by the first-order coherence. Moreover, we demonstrate the performance of the SC-based frequency comb by assuming a 50-pulse pump source at a repetition rate of 100 MHz. © 2019 Optical Society of America

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When the pump source at 6 μm with the pulse duration of 170-fs is used, an ultrabroadband SC covering the wavelength from 3.5 to 15 μm is shown with the largest input peak power of 10 kW [31]. When the pump pulses operate in the anomalous dispersion region, the SD and DW effects can easily happen, which is beneficial to the multi-octave MIR SC generation.

In this paper, we report the multi-octave MIR SC generation in a suspended As2Se3 ridge waveguide designed with the two zero-dispersion wavelengths (ZDWs) when pump pulses work in the anomalous dispersion region. The influences of the pump pulse parameters including the wavelength, pulse width, and peak power on the MIR SC generation are investigated. Moreover, the nonlinear dynamics for different waveguide lengths are also analyzed. Finally, the SC-based frequency comb generation is demonstrated.

2. THEORETICAL MODEL

To investigate the evolution of the short pulses in the proposed waveguide, the generalized nonlinear Schrödinger equation (GNLSE) [32] is introduced as following

\[
\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + i \sum_{n=1}^{m} \beta_n (\frac{-i \gamma_n}{m!} \frac{\partial^n A}{\partial \omega^n} + \frac{i \sum_{n=1}^{m} \gamma_n}{n!} \frac{\partial^n A}{\partial \omega^n}) A = \left[ A(z, t - \tau) \right] \left[ A(z, t - \tau_{1}) \right] dt, \tag{1}
\]

where \(A (z, t)\) is the amplitude of the SC generated with random noises, \(\alpha\) is the pump wavelength, and \(\tau_1\) and \(\tau_2\) are the time delays between the pulses. The angular brackets represent an ensemble average over independently pairs of spectra, i.e. \(A (\lambda, t)\) and \(A (\lambda, t)\), which are obtained from 50 shot-to-shot simulations with different random noises at wavelength \(\lambda\).

3. WAVEGUIDE DESIGN AND CHARACTERISTICS

The cross-section of the designed suspended As2Se3 ridge waveguide is shown in Fig. 1(a). The As2Se3 layer is suspended above the MgF2 substrate with a thick air gap. The top of As2Se3 layer is over-etched to form the ridge structure. Such a waveguide structure is beneficial to confine the propagation light field into the As2Se3 layer even at wavelength 12 μm. Meanwhile, the As2Se3 channel is covered by the air, the designed waveguide has a much larger refractive index contrast, which results in a stronger mode field confinement. The waveguide coupling can be achieved by a tapered fiber, and the coupling losses for the quasi-TE mode and quasi-TM mode are less than 1 dB. The width and height of the ridge are \(W\) and \(H\), respectively, and the height of the slab layer is \(H_2\). The suspended structure can be formed by selectively removing the buried fluoride. Traditional optical lithography with plasma reactive-ion dry etching may be used to form the air gap. In order to provide enough space between the As2Se3 and MgF2 layers, the thickness of the air gap is chosen as 2 μm.

Fig. 1. (a) The cross-section of the designed suspended As2Se3 ridge waveguide. The GVD coefficients of the quasi-TE mode as functions of wavelength when (b) \(W\) (c) \(H_2\), and (d) \(H_2\) is varied, respectively.

The dispersion can be controlled by tailoring the geometrical parameters of the waveguide. The full-vector finite element method is used to investigate the dispersion characteristics of the waveguide with different geometrical parameters. Figs. 1(b), 1(c), and 1(d) show the calculated GVD coefficients of the quasi-TE mode when \(W\), \(H_2\), and \(H_2\) is varied, respectively. For different \(W\), \(H_2\), and \(H_2\) it is noted that all
waveguides have the two ZDWs with the flat and low anomalous dispersion. Besides, the GVD is very sensitive to both \( W \) and \( H_1 \). The second ZDW can be red-shifted by increasing \( W, H_1 \) or \( H_2 \) but the first ZDW is red-shifted slightly when only \( H_2 \) is increased. As shown in Fig. 1(b), if \( W \) is increased while \( H_1 \) and \( H_2 \) remain unchanged, the anomalous dispersion region gradually increases. In Fig. 1(c), the GVD changes very little with \( H_2 \). In Fig. 1(d), the GVD peak is red-shifted and the value increases with the increasing \( H_2 \). To make SC extend deeply into the “fingerprint” region, the pump wavelength should be located at a longer wavelength but close to the first ZDW. This can be realized by carefully selecting \( H_2 \). In addition, the GVD value in the anomalous dispersion region increases when \( W, H_1, \) or \( H_2 \) increases. However, the increment of \( H_2 \) is not beneficial to the spectral broadening because \( A_{\text{eff}} \) is increased and the nonlinear interaction becomes weak.

![Graph](image)

**Fig. 2.** (a) The calculated GVD and nonlinear coefficient \( \gamma \) as functions of wavelength, and (b) the mode field distributions of quasi-TE mode calculated at wavelengths 2, 4, 8, and 10 \( \mu \text{m} \), respectively.

According to the above analysis, the geometrical parameters of the designed waveguide are chosen as \( W=1.0 \text{ \( \mu \text{m} \)}, H_1=0.4 \text{ \( \mu \text{m} \)}, \) and \( H_2=1.0 \text{ \( \mu \text{m} \)}, \) respectively. Fig. 2(a) shows the calculated \( \beta_2 \) as a function of wavelength for the quasi-TE mode. The wavelength dependences of the As2Se3 and MgF2 materials are considered in the determination of dispersion characteristic. The two ZDWs are located at 2.43 and 8.12 \( \mu \text{m} \), respectively, with the anomalous dispersion region of 5.69 \( \mu \text{m} \). Moreover, the relationship between \( \gamma \) and wavelength is also shown in Fig. 2(a). It can be seen from Fig. 2(a) that the variation of \( \gamma \) is monotonic. Fig. 2(b) shows the mode field distributions of the quasi-TE mode, which indicates the polarization of the electric field in the \( x \) direction. And the electric field distribution is used to represent the distribution of energy. Fig. 2(b) shows the mode field distributions of quasi-TE mode calculated at wavelengths 2, 4, 8, and 10 \( \mu \text{m} \), respectively. From Fig. 2(b), the mode fields are well confined in the slab even at wavelength 10 \( \mu \text{m} \).

### 4. SIMULATION RESULTS AND DISCUSSION

In the simulation, the pump pulse is operated at the anomalous dispersion region of the waveguide, where the MIR SC generation is mainly resulted from the combined SD and DW effects. In the following, we will investigate the influences of the pump pulse parameters and waveguide length on the MIR SC generation.

When the wavelength of the pump pulse with the peak power of 900 W and width of 100 fs is changed from 2.7 to 3.6 \( \mu \text{m} \), the temporal and spectral profiles in after a propagation of 0.87 mm are shown in Figs. 3(a) and 3(b), respectively. From Fig. 3(a), some small peaks can be observed and the solitons move toward the original position in the time domain. From Fig. 3(b), the optical spectrum is gradually broadened when the pump wavelength is changed from 2.7 to 3.3 \( \mu \text{m} \). Especially for the pump wavelength 3.3 \( \mu \text{m} \), the optical spectrum width reaches its maximum. The -40 dB bandwidth of the SC generated spans from 1.76 to 14.42 \( \mu \text{m} \) (more than 3 octaves), extending deep into the “fingerprint” region. The physical mechanism on the MIR SC generation is as following. Because the pump wavelength is located at the anomalous dispersion region of the waveguide, the SD including the soliton self-frequency shift (SSFS) and soliton fission (SF) dominates the nonlinear optical process. In the process of the SSFS and SF, when the resonance matching conditions involving the higher-order dispersion are satisfied, the blue- and red-shifted DWs are generated at the shorter and longer wavelength sides due to the positive and negative dispersion slopes of \( \beta_2 \) curve with the two ZDWs. After that, the XPM which occurs between the solitons and the DWs will also further broaden the optical spectrum. However, when the pump wavelength is located at 3.6 \( \mu \text{m} \), the optical spectrum stops broadening and becomes narrower. The main reason is considered as following. First, for the longer pump wavelength, the anomalous dispersion range which the SSFS and SF are experiencing is smaller. Second, the SSFS process will be more remarkable suppressed by the second ZDW. Therefore, it is important to appropriately choose the pump wavelength for the multi-octave MIR SC generation.

![Graph](image)

**Fig. 3.** (a) Temporal and (b) spectral profiles of the SC when the pump pulse wavelength is located at 2.7, 3.0, 3.3, and 3.6 \( \mu \text{m} \), respectively.

When the pump pulse at 3.3 \( \mu \text{m} \) with the widths of 100, 150, 200, and 250 fs is launched into a 0.87-mm long waveguide, the temporal and spectral profiles are shown in Figs. 4(a) and 4(b), respectively. It should be noted that the micron-scale length is not difficult to achieve by using the current waveguide fabrication technique. As the pulse width is increased from 100 to 250 fs, the soliton order, which is related to the pulse width and peak power \([8,40]\), is calculated as 11.2, 16.8, 22.5, and 28.1, respectively. When the pump pulse width is chosen as 100 fs, the soliton separation distance is 0.76 mm. At this time, the soliton fission occurs evidently, and the number of the small peaks increases and the solitons move toward the right side of the original position in the time domain. The corresponding optical spectrum is greatly broadened. When the pump pulse width is chosen as 150, 200, and 250 fs, the soliton separation distance is 1.13, 1.15, and 1.89 mm, respectively. At this time, the apparent soliton fission cannot be observed because of the shorter waveguide length. The optical spectrum has multi-peaks and the spectral bandwidth is 40 dB becomes narrower. Therefore, the pump pulse with width of 100 fs is more favorable for the generation of multi-octaves MIR SC in the designed waveguide.
In the following, we will investigate the influence of the pump peak power on the MIR SC generation. Figs. 5(a) and 5(b) show the temporal and spectral profiles when the peak power of the pump pulse at 3.3 μm with the width of 100 fs is changed from 300 to 900 W. The soliton order is calculated as 6.5, 8.4, 9.9, and 11.2 as the peak power is increased from 300, to 500, to 700, and to 900 W, respectively. From Fig. 5(a), the satellites become larger and the solitons move toward the original position at the same time as the peak power increases. From Fig. 5(b), the corresponding bandwidth of the optical spectrum is increased since the nonlinear effects can be enhanced by the higher peak power. When the peak power is increased up to 900 W, the MIR SC generated can be more than three octaves.

Fig. 5. (a) Temporal and (b) spectral profiles of the SC generated when the pump peak power is chosen as 300, 500, 700, and 900 W, respectively.

We will demonstrate the nonlinear dynamics of the MIR SC generation for different waveguide lengths. When the width and peak power of the pump pulse at 3.3 μm are chosen as 100 fs and 900W, the temporal and spectral profiles for the waveguide lengths of 0, 0.61, 0.87, and 1 mm are shown in Figs. 6(a) and 6(b), respectively. From Fig. 6(a), many small peaks emerge and the solitons move toward the right side of the original position in the time domain as the waveguide length increases. From Fig. 6(b), when the waveguide length is increased from 0 to 0.87 mm, the spectral bandwidth is also increased. Especially for the waveguide length of 0.87 mm, the spectral range spans from 1.76 to 14.42 μm. However, when the waveguide length is increased up to 1 mm, the optical spectrum does not continue to widen. Figs. 6(c) and 6(d) show the corresponding temporal and spectral evolutions. From Figs. 6(c) and (d), the SPM causes the obvious spectral broadening at the beginning stage. As the waveguide length increases, the temporal pulse is significantly compressed due to the relatively low and flat dispersion. But the propagation loss restricts the extension of the optical spectrum for the longer waveguide length.

Fig. 6. (a) Temporal and (b) spectral profiles of the SC generated when the waveguide length is 0, 0.61, 0.87, and 1 mm, respectively. The evolution of (c) temporal and (d) spectral profiles in the designed waveguide when the pump pulse with width of 100 fs and peak power of 900 W is used.

The degree of coherence $\xi^{(1)}$ is calculated to confirm the stability of the generated MIR SC. The pump peak power and propagation length are chosen as 900 W and 0.87 mm, respectively. For the SC generated with the picosecond pulse, the unavoidable intrinsic noise degrades the coherence of the SC. To investigate the effect of the noise, the following optical pulse with shot noise is injected into the designed waveguide:

$$A(t) = P_0^{1/2} \sec h \left( \frac{t}{T_0} \right) \left[ \exp \left( \frac{i2\xi^2}{2} \right) + \eta \tilde{N} \exp \left( i2\pi \tilde{U} \right) \right].$$

where $\tilde{N}$ is a normally distributed random variable with mean value of 0 and standard deviation of 1, and $\tilde{U}$ is a uniformly distributed random variable between 0 and 1. The noise factor $\eta$ indicates the amplitude of the noise relative to the pulse amplitude. In the simulation, $\eta = 1 \times 10^{-2}$ and $\eta = 1 \times 10^{-4}$ are used, respectively. A pulse train including 50 pulses with a repetition rate of 100 MHz is launched into
the waveguide for generating the SC-based frequency comb. The pump pulse train has periodicity in the time domain. According to the theory of Fourier transform, the spectrum of pulse train in the frequency domain is discrete. Due to the influence of the nonlinear and dispersive effects, the output pulse is compressed greatly in the time domain. In our simulation, the launched 50 pulses are the same except the imposed random noise.

Finally, we will analyze the influence of the random noise factor $\eta$ on the MIR generation. Figs. 7(a), 7(b), 7(c), and 7(d) show the generated MIR SC and coherence calculated with the 50 shots for different $\eta$. The blue lines are the averaged spectrum of 50 shots, and the grey lines are the overlapped spectra of 50 shots with the random noise. When the pump pulse with the width of 100 fs and peak power of 900 W is launched into a 0.87-mm long waveguide, the overlapped and averaged spectra and coherence for $\eta = 1 \times 10^{-4}$ are shown in Figs. 7(a) and 7(c), respectively. It can be seen from Figs. 7(a) and 7(c) that the spectral fluctuation is very slight and the corresponding $g^{(2)}(t)$ is close to 1 within the considered wavelength range. In contrast, under the same pump condition and waveguide length, the overlapped and averaged spectra and coherence for $\eta = 1 \times 10^{-2}$ are shown in Figs. 7(b) and 7(d), respectively. From Figs. 7(b) and 7(d), the spectral fluctuation becomes very evident and $g^{(2)}(t)$ is seriously degraded.

Fig. 7. (a) The spectra and (c) degree of coherence of the SC generated with $\eta = 1 \times 10^{-4}$. (b) The spectra and (d) degree of coherence of the SC generated with $\eta = 1 \times 10^{-2}$. The grey and blue lines in (a) and (b) represent the overlapped spectra of the 50 shots and average values of the 50 shots, respectively.

In order to generate the SC-based frequency comb, a pulse train included 50 pulses with a repetition frequency of 100 MHz is launched into the waveguide. The pump pulse train with the width of 100 fs and peak power of 900 W is used. Fig. 7(a) shows the SC-based frequency comb structure. Fig. 7(b) clearly shows the zoom-in view of the frequency comb generated at 90.85 THz/3.3 μm with a sampling bandwidth of 500 MHz. The comb line structure can be clearly seen from the zoom-in view with a frequency interval of 100 MHz.

For the problem of practical fabrication, some previous works were concentrated on the integrated chalcogenide glass. One of the works reported that a 30-μm-radius and 450-nm-thick microdisk resonator pulley coupled to an 800-nm-wide channel bus waveguide [41]. In another work, attention was paid to the mask fabrication. The photo-mask has a measured line edge roughness on straight waveguides of 6 nm RMS for a spatial fluctuation wavelength range of 0.6 to 62 μm [42]. Figs. 9(a)–(e) show a possible fabrication process of the designed waveguide. Firstly, the As$_2$Se$_3$ layer is grown on a MgF$_2$ substrate by the atmospheric chemical vapor deposition (CVD) technology [43], and then invert carefully the formed die as shown in Fig. 9(a). Secondly, we can form a suspended trench (Fig. 8(b)) by the traditional optical lithography with plasma reactive-ion dry etching [44,45]. Thirdly, the hydrophobic bonding techniques are used to make the etched die be directly bonded onto the MgF$_2$ wafer (Fig. 8(c)). The detailed bonding process is introduced in Ref. [46]. Finally, a metal mask is used to protect the ridge structure from etching, which is patterned by i-line lithography and lift-off [47]. The CF$_4$:O$_2$ plasma etching can be used to make sure the As$_2$Se$_3$ ridge layer is accomplished, and hydrofluoric acid dip is used to remove the metal mask (Fig. 8(d)).
5. CONCLUSION

In summary, we design a suspended As$_2$Se$_3$ ridge waveguide with the two ZDWs. With the designed waveguide, we investigate the influences of the pump pulse parameters and waveguide length on the MIR SC generation. When the pump pulse at wavelength 3.3 µm with width of 100 fs and peak power of 900 W is launched into a 0.87-mm long waveguide, the MIR SC with the bandwidth of more than 3-octaves can be generated. Moreover, the performance of the SC-based frequency comb is demonstrated. It is believed that the proposed waveguide structure paves the way for obtaining the MIR SC source which would be highly desirable for the applications in the MIR photonics and spectroscopy.

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References


