Highly Coherent and Multi-Octave Mid-Infrared Supercontinuum Generations in a Reverse-Strip AlGaAs Waveguide with the Three Zero-Dispersion Wavelengths

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Abstract: In this paper, a reverse-strip AlGaAs waveguide with the three zero-dispersion wavelengths (ZDWs) is designed. The corresponding three ZDWs are located at 3.74, 6.56, and 8.89 μm, respectively. The nonlinearity coefficient of the proposed reverse-strip AlGaAs waveguide is calculated as 2.09 W−1 m−1 at wavelength 4.9 μm. The effects of the pump pulse parameters, waveguide length, and noise coefficient on the nonlinear dynamics of the supercontinuum (SC) generation are investigated. When the hyperbolic secant pump pulse with wavelength of 4.9 μm, peak power of 900 W, and duration of 100 fs is launched into the proposed waveguide and propagated after a 3 mm length, the highly coherent and multi-octave mid-infrared (MIR) SC spanning from 2.2 to 14.5 μm (more than 2.7 octaves, at −40 dB level) is generated. Finally, a possible fabrication process of the reverse-strip AlGaAs waveguide is introduced. Our research results have important applications in the MIR photonics, MIR spectroscopy, optical precision measurement, etc.

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1. Introduction

Supercontinuum generations (SCGs) spanning from the visible to near-infrared spectral region in the optical waveguides have been extensively investigated [1-7]. Recently, the SCGs in MIR spectral region have received lots of research interests due to their potential applications in molecular spectroscopy [8], gas sensing [9], medical diagnostics [10], etc. At present, some nonlinear materials including silicon and chalcogenide as the optical waveguide materials have been explored for generating the MIR SCs. Lau et al. reported the SCG on a silicon chip, spanning from the communication band of −1.5 μm to MIR spectral region beyond 3.6 μm [11]. In 2018, Karim et al. demonstrated the MIR SCG covering from 3.5 to 15 μm in a 20 mm long As2Se3 channel waveguide by using the pump source at wavelength 6 μm with the input peak power of 10 kW [12]. In 2019, Sinobad et al. reported an octave-spanning MIR SC source spanning from 2.63 to 6.18 μm by launching a pulse with peak power of 2.35 kW into a 7 cm long Si-Ge waveguide [13]. In 2020, Montesinos-Ballester et al. showed a two-octave MIR SCG on a 5.5 mm long Ge-rich graded
Si-Ge waveguides by using a pulse with 4.6 kW as the pump source [14]. Compared with the silicon and chalcogenide, GaAs, which is usually used as the substrate material in the laser devices, has remarkably advantages because of its larger nonlinear refractive index (~ 1.59×10^{-13} cm²/W) [15] and wider transparency window (up to 20 μm) [16]. In 2014, Pigeon et al. reported the SCG spanning from 2 to 20 μm in a 67 mm-long GaAs crystal by using a CO₂ laser with center wavelength of 10.6 μm [17]. However, for the bulk GaAs crystal, the undesirable self-focused filament occurs easily. Moreover, the threshold power for the SCG can be very high, so the repetition rate of the used laser source has to be very low (~kHz), which is difficult to achieve for the commercially available lasers. These disadvantages make it difficult to use the generated SC as the practical light source for the traditional Fourier transform infrared spectroscopy. AlGaAs is an alloy of GaAs and AlAs. Compared with the GaAs crystal, the key advantage of AlGaAs is that its linear refractive index can be flexibly adjusted by changing the contents of Al and Ga in the alloy. Thus, the dispersion profile of the AlGaAs-based waveguide can be easily engineered. In addition, because the AlAs has the wide transmission spectral range from 0.6 to 15 μm [18], the AlGaAs is also expected to have a wide transparency window. In 2019, Chiles et al. demonstrated the SCG spanning from 2.3 to 6.5 μm in a suspended AlGaAs waveguide [19]. In 2020, Kuyken et al. achieved the octave-spanning coherent SCG in the wavelength range from 1.055 to 2.155 μm in an AlGaAs-on-insulator waveguide [20].

The bandwidth and coherence are the two key parameters for evaluating the SC performance. From the previous works, the dispersion characteristic of the optical waveguide has an important effect on the bandwidth and coherence of the generated SC [21-30]. The dispersion tailoring can be achieved through choosing the waveguide materials, designing the waveguide structure, and adjusting the waveguide geometry parameters [31-38]. When the low and flat dispersion profile with the multiple zero-dispersion wavelengths (ZDWs) is achieved over a broad wavelength range, the phase-matching nonlinear effects can occur, and the SCs with large bandwidth and good coherence could be generated.

In this paper, a reverse-strip AlGaAs waveguide with the three ZDWs of 3.74, 6.56, and 8.89 μm is designed. The low and flat dispersion profile is achieved in the considered wavelength range. We also investigate the effects of the pump pulse parameters, waveguide length, and noise coefficient on the SCG. By using the waveguide proposed, the multi-octave and highly coherent MIR SC spanning from 2.2 to 14.5 μm (more than 2.7 octaves, at -40 dB level) is generated when the hyperbolic secant pump pulse with wavelength of 4.9 μm, peak power of 900 W, and duration of 100 fs is propagated after a 3 mm length. It can be found that the lower peak power and shorter waveguide length are needed for the SCG in the designed reverse-strip AlGaAs waveguide compared with other waveguide platforms [12, 14]. Finally, a possible fabrication process of the reverse-strip AlGaAs waveguide using the plasma dry etching technology and chemical vapor deposition technology is introduced.

2. Theoretical model

The propagation dynamics of the short pulse in the AlGaAs waveguide can be modelled by the modified generalized nonlinear Schrödinger equation (GNLSE) as following [39]

\[ \frac{\partial A(z,t)}{\partial z} + \frac{\alpha}{2} A(z,t) + \sum_{m=1}^{\infty} \frac{\beta_m(\omega)}{m!} \frac{\partial^m}{\partial t^m} A(z,t) = i \left( \gamma(\omega_0) + i \gamma_1(\omega_0) \frac{\partial}{\partial t} \right) \int_0^\infty R(t') |A(z,t-t')|^2 \, dt', \]

where \( A(z,t) \) is the electrical field amplitude, \( \alpha \) is the linear loss coefficient of the waveguide, \( \beta_m(\omega) \) is the m-th order dispersion coefficient calculated from the Taylor expansion of the propagation constant, \( t \) is the retarded time, \( \gamma(\omega_0) \) is the nonlinear coefficient at the center frequency \( \omega_0 \), and \( \gamma_1(\omega) \) is the first-order derivative of \( \gamma(\omega) \). \( \gamma(\omega) \) depends on the nonlinear refractive index \( n_2 \) and effective mode area \( A_{\text{eff}} \), which can be described as
\[
\gamma = \frac{2\pi n_0}{\lambda A_{eff}} = \frac{2\pi}{\lambda} \int \int n(x,y) |\vec{F}(x,y)|^2 dxdy.
\]

\(\vec{F}(x,y)\) represents the transverse distribution of the optical field [40]. The relation between \(\gamma(\omega)\) and \(\gamma(\omega_0)\) is given by [39]

\[
\frac{\gamma(\omega_0)}{\gamma(\omega)} = \frac{1}{n_0(\omega)} + \left( \frac{d n_0(\omega)}{d\omega} \right)_{\omega=\omega_0} \left( \frac{1}{A_{eff}(\omega)} \right)_{\omega=\omega_0}.
\]

Since \(n_2\) of \(Al_{0.18}Ga_{0.82}\)As changes a little after wavelength 1600 nm [41], the frequency dependence of \(n_2(\omega)\) can be neglected. In this work, \(n_2\) is taken as \(1 \times 10^{-17} \text{m}^2/\text{W}\). When an \(Al_{0.8}Ga_{0.2}\)As waveguide is used as the lower cladding material, \(\alpha\) is equal to 0.5 dB/cm [42].

The last term of the right hand in Eq. (1) represents the instantaneous and delayed third-order nonlinear effects, including the self-phase modulation (SPM), Raman effect, and self-steeping. \(R(t)\) has the following form

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

where Raman response function \(h_R(t)\) can be described as

\[
h_R(t) = \frac{r_1^2 + r_2^2}{r_1 r_2} \exp \left( -\frac{t}{r_2} \right) \sin \left( \frac{t}{r_1} \right),
\]

where \(r_1 = 18.72 \times 10^{-15}\) and \(r_2 = 750 \times 10^{-15}\) are the inverses of the phonon oscillation frequency and bandwidth of the Raman gain spectrum, respectively [43]. The fractional Raman response \(f_R\) is found to be 0.047 [44].

The degree of the first-order coherence \(g^{(1)}_{12}\) can be evaluated from the classical formula

\[
g^{(1)}_{12}(\lambda) = \frac{\left\langle E_1^*(\lambda) E_2(\lambda) \right\rangle}{\left\langle |E_1(\lambda)|^2 \right\rangle \left\langle |E_2(\lambda)|^2 \right\rangle},
\]

where \(E(\lambda)\) denotes the spectral amplitude. The noise can be described as

\[
n = \eta \hat{N} e^{i2\pi U},
\]

where \(\hat{N}\) is a normal distributed random variable with the mean value of 0 and standard deviation of 1. \(\hat{U}\) is a uniformly distributed random variable between 0 and 1. The noise factor \(\eta\) describes the noise amplitude of the input pulse. In order to quantify the coherence of the SC more intuitively, two other factors are calculated as

\[
R = \frac{\int_0^\infty g^{(1)}_{12}(\lambda) P(\lambda) d\lambda}{\int_0^\infty P(\lambda) d\lambda},
\]

\[
K = \log(1-R).
\]

where \(R\) as the weighted degree of coherence can measure the averaged coherence in the whole spectrum, and \(P(\lambda)\) describes the ensemble average power spectrum of the generated SC [45, 46]. In Eq. (9), \(K\) is used to enlarge the detail of \(R\) when the coherence of the generated SC is close to 1.

### 3. Waveguide structure and characteristics

Fig. 1(a) shows the structure of the designed reverse-strip AlGaAs waveguide, where the top-cladding is air. From Fig. 1(a), the core and substrate materials of the waveguide are \(Al_{0.18}Ga_{0.82}\)As and \(Al_{0.8}Ga_{0.2}\)As, respectively. The width of the core is \(W\), the height of the core embedded in the substrate is \(H_d\), and the height of the core exposed to the air is \(H_u\). The quasi-TE mode field distributions calculated at wavelengths 3, 5, 7, 9, 12, and 15 μm are shown in Fig. 1(b) when the geometric structure parameters of the waveguide \(W, H_u,\) and \(H_d\) are chosen as 6, 0.7, and 1.4 μm, respectively. It should be pointed out that the thickness of
the substrate is selected as 6 μm in the simulation. It can be seen from Fig. 1(b) that most of the mode field energy can be well confined in the waveguide core at the considered wavelengths.

![Image of waveguide structure](image1.png)

**Fig. 1.** (a) The structure of the proposed reverse-strip AlGaAs waveguide. (b) The mode field distributions of the quasi-TE mode calculated at wavelengths 3, 5, 7, 9, 12, and 15 μm, respectively, when $W = 6$ μm, $H_u = 0.7$ μm, and $H_d = 1.4$ μm.

![Image of dispersion curves](image2.png)

**Fig. 2.** The dispersion curves of the quasi-TE mode calculated as functions of wavelength when (a) $H_d$, (b) $H_u$, and (c) $W$ are changed, respectively.
The dispersion of the proposed waveguide can be obtained by the effective refractive index of the guided mode [47]. With the full-vector finite element method, the dispersion characteristic of the waveguide designed can be simulated. In order to investigate the sensitivity of the dispersion to the geometric parameters of the waveguide, Figs. 2(a)-2(c) show the dispersion curves of the quasi-TE mode calculated as functions of wavelength when $H_d$, $H_u$, and $W$ are changed, respectively. From Figs. 2(a) and 2(b), as $H_d$ and $H_u$ increase, the dispersion curve occurs to move up. From Fig. 2(c), the dispersion curve occurs to red-shift with the increase of $W$. When $1.1\ \mu m < H_d < 1.5\ \mu m$, $0.4\ \mu m < H_u < 0.8\ \mu m$, and $W > 5.2\ \mu m$, the dispersion curve has the three ZDWs. There is no potential to achieve more than three ZDWs through changing the $H_d$, $H_u$, and $W$ unless some extra designs are considered [34]. In order to obtain a low and flat dispersion curve with multiple ZDWs, the geometry parameters of the waveguide are chosen as $W = 6\ \mu m$, $H_u = 0.7\ \mu m$, and $H_d = 1.4\ \mu m$, respectively, and the optimized dispersion curve of the quasi-TE mode is shown in Fig. 3(a). From Fig. 3(a), the dispersion value changes between -8.2 and 14.0 ps/nm/km in the wavelength range from 3.74 to 8.89 μm, and the low and flat dispersion profile is achieved, along with the three ZDWs of 3.74, 6.56, and 8.89 μm, respectively. The three ZDWs can divide the dispersion curve into the different dispersion regions, where the normal and anomalous dispersion regions are located in the wavelength range from 3.74 to 6.56 μm and 6.56 to 8.89 μm, respectively. The presence of the third ZDW creates a rich phase-matching topology, which is beneficial to the generation of SC [48]. Moreover, the calculated nonlinear coefficient $\gamma$ of the

\begin{table}[h]
\centering
\caption{The dispersion coefficient $\beta_m$ calculated at wavelength 4.9 μm.}
\begin{tabular}{|c|c|}
\hline
$m$ & $\beta_m$ \\
\hline
2 & -0.1801 ps²/m \\
3 & 7.3813x10⁴ ps²/m \\
4 & 2.9958x10⁵ ps²/m \\
5 & -5.0993x10⁶ ps²/m \\
6 & 5.1635x10⁷ ps²/m \\
7 & -2.7913x10⁸ ps²/m \\
8 & 2.9710x10⁹ ps²/m \\
9 & 3.5379x10¹⁰ ps²/m \\
10 & -7.8861x10¹¹ ps²/m \\
11 & 1.5407x10¹² ps²/m \\
12 & 5.2536x10¹³ ps²/m \\
\hline
\end{tabular}
\end{table}
waveguide are also shown in Fig. 3(b). It can be seen from Fig. 3(b) that $\gamma$ is calculated as 2.09 W$^{-1}$m$^{-1}$ at wavelength 4.9 $\mu$m. As shown in Table 1, up to 12-th order dispersion coefficients of the quasi-TE mode at wavelength 4.9 $\mu$m are considered in the following simulation.

4. Simulation results and discussion

By numerically solving Eq. (1) using the Runge-Kutta algorithm, the nonlinear dynamics of SCG in the proposed reverse-strip AlGaAs waveguide can be studied. When the wavelength is longer than 1.5 $\mu$m, the two-photon absorption (TPA) effect of Al$_{0.18}$Ga$_{0.82}$As can be neglected [49]. Moreover, when the wavelength is longer than 2.2 $\mu$m, the three-photon absorption (3PA) effect of Al$_{0.18}$Ga$_{0.82}$As can be beyond consideration [50]. In order to optimize the performance of the generated SC, we will investigate the effects of the pump pulse parameters on the SCG.

![Fig. 4](image)

Fig. 4. (a) and (b) show the temporal and spectral expansions with different pump wavelengths in the proposed reverse-strip AlGaAs waveguide. The pump peak power is 900 W, pump duration is 100 fs, and pump wavelengths are chosen as 3.9, 4.4, 4.9, and 5.4 $\mu$m, respectively.

A hyperbolic secant pump pulse with peak power of 900 W and duration of 100 fs is launched into the designed reverse-strip AlGaAs waveguide. When center wavelength of the pump pulse is increased from 3.9 to 5.4 $\mu$m, the simulation results of the temporal and spectral evolutions in 3-mm long AlGaAs waveguide are shown in Figs. 4(a) and 4(b), respectively. From Figs. 4(a) and 4(b), some split peaks are observed when the pump wavelength is increased, accompanying with a narrower temporal pulse. The corresponding optical spectrum is gradually broadened when the center wavelength is increased from 3.9 to 4.9 $\mu$m due to the enhanced dispersion with the increase of $\beta_2$. The spectral broadening mechanisms is considered as following. Because the first ZDW of the waveguide is located at 3.74 $\mu$m, the pump pulse works in the anomalous dispersion region. The higher-order soliton (the calculated soliton order $N = 10$) will be formed because of the interplay between the negative dispersion and SPM. Under the effects of the higher-order dispersion and intrapulse Raman scattering, the higher-order soliton splits into the fundamental solitons and occurs to red-shift. During the process, the blue-shifted dispersion waves (DWs) are generated at the shorter wavelength side when the resonance matching condition is satisfied (calculated at wavelength around 3 $\mu$m) [51]. The red-shift process of the soliton will be suppressed by the
existing second ZDW (6.56 μm) [52]. At this time, the cross-phase modulation (XPM) effect between the residual pump, soliton, and DWs can further broaden the optical spectrum through generating the new spectral components at the shorter and longer wavelength sides. In addition, the spectral broadening may be enhanced by the four-wave mixing (FWM) effect due to the existing third ZDW (8.89 μm). When center wavelength of the pump pulse is located at 4.9 μm, the -40 dB bandwidth of the generated SC spans from 2.2 to 14.5 μm (more than 2.7 octaves). In contrast, when the center wavelength of the pump pulse is increased to 5.4 μm, the overall optical spectrum moves toward the longer wavelength side without obvious further broadening. The main reason is considered that the red-shifted soliton is suppressed because the wavelength of 5.4 μm is close to the second ZDW. Considering the small difference between the SCs generated by the pump pulses at wavelengths 4.9 μm and 5.4 μm and the difficulty in obtaining the longer wavelength pump sources, we choose 4.9 μm as the optimized pump center wavelength in the following investigations.

The influence of pump peak power on the SCG is studied. The simulation results of the temporal and spectral evolutions are shown in Figs. 5(a) and 5(b), respectively. For all cases, the pump wavelength is 4.9 μm and duration is 100 fs, and the peak power is increased from 500 to 1100 W. These power levels will not damage the facet of the used waveguide [19]. From Figs. 5(a) and 5(b), the pulse duration gradually becomes narrower when the peak power is increased. Remarkably, the peaks occur to split when peak power exceeds 700 W. The corresponding optical spectrum is broadened obviously. When peak power of the pump pulse is chosen as 500 W, the spectral broadening is dominated by the SPM effect. As peak power of the pump pulse increases to 700 and 900 W, the soliton dynamics and XPM effect play important role, and the optical spectrum is further broadened. Especially when peak power increases up to 900 W, the generated MIR SC can be more than 2.7 octaves (from 2.2 to 14.5 μm). As peak power of the pump pulse is further increased to 1100 W, the spectrum becomes flat and has not been further broadened. Considering that the spectral bandwidth exceeding 2.7 octaves and the kilowatt level peak power being easy to damage the waveguide, we choose 900 W as the optimized pump peak power.
Fig. 6. (a) and (b) show the temporal and spectral expansions with different pump durations in the proposed reverse-strip AlGaAs waveguide. The pump wavelength is 4.9 μm, pump peak power is 900 W, and pump durations are chosen as 100, 150, 200, and 250 fs, respectively.

To determine the appropriate pump duration, 100, 150, 200, and 250 fs are chosen to investigate the nonlinear evolution dynamics in a 3-mm long waveguide, as shown in Figs. 6(a) and 6(b), respectively. It can be seen from Fig. 6(a) that as duration of the pump pulse increases from 100 to 250 fs, the pulse duration gradually becomes wide, and the split peaks gradually disappear when duration of the pump pulse is larger than 200 fs. As pump duration increases, the bandwidth of the generated SC decreases obviously, as shown in Fig. 6(b). The main reason is considered as following. As pump pulse duration increases, the pulse energy is increased, and the initial bandwidth gradually becomes narrower. The narrower initial bandwidth may cause the number of frequency components participated in the initial SPM stage less than the shorter duration pulse with a larger initial bandwidth, so the larger pump pulse duration will limit the broadening of spectrum. The largest bandwidth of the generated SC can be up to more than 2.7 octaves when the pulse duration of 100 fs is used. Therefore, 100 fs is the best choice for the pump pulse duration.

In conclusion, a hyperbolic secant pulse with center wavelength of 4.9 μm, peak power of 900 W, and duration of 100 fs is chosen as the pump source. In the following, the nonlinear dynamics for SCG under different waveguide lengths will be investigated. When the waveguide lengths are 2, 3, 4, and 5 mm, the temporal and spectral profiles at the output end of the designed reverse-strip AlGaAs waveguide are shown in Figs. 7(a) and 7(b), respectively. The temporal pulse becomes narrower, and split peaks appear when waveguide length is 3 mm, as shown in Fig. 7(b). When the waveguide length is increased from 3 to 5 mm, the pulse duration gradually becomes wider. It can be seen from Fig. 7(b) that when the waveguide length is changed from 2 to 3 mm, the spectral bandwidth is increased. However, the continuous broadening is not observed after the waveguide length of 3 mm, and the spectral flatness becomes worse. This is mainly due to the fact that at initial propagation, the SPM, soliton fission, XPM broadens the optical spectrum. When the waveguide length is longer than 3 mm, the accumulated dispersion and increased propagation loss degrade the spectral flatness and restrict the extension of the optical spectra.
Fig. 7. (a) and (b) show the temporal and spectral expansions with different waveguide lengths in the proposed reverse-strip AlGaAs waveguide. The pump wavelength is 4.9 μm, pump peak power is 900 W, and pump duration is 100 fs. The waveguide lengths are chosen as 2, 3, 4, and 5 mm, respectively.

Fig. 8. (a) Spectral profiles and (c) \( g_2^{(1)} \) of the SC generated at the output end of the designed reverse-strip AlGaAs waveguide with \( \eta = 0.0001 \). (b) Spectral profiles and (d) \( g_2^{(1)} \) of the SC generated at the output end of the designed reverse-strip AlGaAs waveguide with \( \eta = 0.01 \). The grey and red lines in (a) and (b) represent the overlapped spectra of the 50 shots and average values of the 50 shots, respectively.
Finally, we will investigate the effect of noise on SCG in the proposed waveguide. Figs. 8(a) and 8(b) show the averaged spectra (red lines) and overlapped spectra (gray lines) of 50 shots for the same pump condition and waveguide length when \( \eta \) is chosen as 0.0001 and 0.01, respectively. The spectral fluctuation in Fig. 8(a) is very slight while the spectral fluctuation in Fig. 8(b) becomes very obvious. Figs. 8(c) and 8(d) show the calculated \( g^{(1)}_i \) with 50 shots when \( \eta = 0.0001 \) and \( \eta = 0.01 \), respectively. It can be seen from Figs. 8(c) and 8(d) that in the considered wavelength range, \( g^{(1)}_i \) is equal to 1 when \( \eta = 0.0001 \). In contrast, \( g^{(1)}_i \) is seriously degraded when \( \eta = 0.01 \). In order to quantitatively compare the value of coherence for different \( \eta \), the weighted degree \( R \) as a function of lg(\( \eta \)) in the whole spectra is shown in Fig. 9(a). It can be seen from Fig. 9(a) that when lg(\( \eta \)) \( \leq 3 \) (\( \eta \leq 0.001 \)), \( R \) is close to 1. However, \( R \) drops quickly from 1 to 0.49 as lg(\( \eta \)) increases from -3 to -1 (that is, \( \eta \) increases from 0.001 to 0.1). In Fig. 9(b), \( K \) as a function of lg(\( \eta \)) is also calculated since \( R \) is very close to 1. In Fig. 9(b), \( K \) is increased with increasing lg(\( \eta \)). Therefore, good coherence of the generated SC can be obtained when lg(\( \eta \)) \( \leq 3 \) (\( \eta \leq 0.001 \)).

![Fig. 9. The weighted degree of coherence (a) R and (b) K calculated in the whole spectra versus the random noise level lg(\( \eta \)) for the generated SC.](image)

By optimizing the pump parameters, waveguide length, and \( \eta \), multi-octave and highly coherent MIR SC can be obtained. When pump pulse with center wavelength of 4.9 \( \mu \)m, peak power of 900 W, and duration of 100 fs is launched into the proposed reverse-stripe AlGaAs waveguide with a length of 3 mm and \( \eta \) is chosen as 0.0001, the temporal and spectral evolutions of the pump pulse along the waveguide length are shown in Figs. 10(a) and 10(b), respectively. Correspondingly, the bottom and top in Figs. 10(a) and 10(b) also show the temporal and spectral profiles at the input and output ends of the reverse-stripe AlGaAs waveguide, respectively. From Fig. 10(a), with the increase of waveguide length, pulse becomes narrower gradually. The pulse occurs to split starting at the waveguide length of 2 mm. In Fig. 10(b), the optical spectrum is symmetrically broadened by SPM when the waveguide is shorter than 2 mm. After the wavelength length of 2 mm, the soliton dynamics and XPM effect make the optical spectrum further extend toward the shorter and longer wavelength sides. What’s more, because of the existence of the third ZDW at 8.89 \( \mu \)m, the FWM effect may further enhance the spectral broadening at the longer wavelength side. Fig. 10(c) shows the evolution of \( g^{(1)}_i \) along the waveguide length. It can be seen from Fig. 10(c) that \( g^{(1)}_i \) is always remains 1 in the considered wavelength range, showing a good coherence of generated SCs. The main reason is considered that the modulation instability could be effectively depressed by the relatively small \( \beta_2 \). Therefore, with the designed reverse-stripe AlGaAs waveguide, we can generate the multi-octave and highly coherent MIR SC, whose -40 dB bandwidth spans from 2.2 to 14.5 \( \mu \)m (more than 2.7 octaves).
Fig. 10. (a) and (b) show the temporal and spectral evolutions along the waveguide length, respectively, the bottom and top figures showing the temporal and spectral profiles at the input and output ends of the designed reverse-strip AlGaAs waveguide. $I$ in (a) represents the intensity. $S$ in (b) represents the spectrum. (c) shows the evolution of $g_\text{th}$ along the waveguide length.

At present, the plasma etching technology and atmospheric chemical vapor deposition technology can be used to fabricate the proposed reverse-strip waveguide [53]. Figs. 11(a)-11(f) show the possible essential fabrication process of the proposed waveguide. First, the surface of the Al$_{0.8}$Ga$_{0.2}$As substrate was cleaned and covered with a layer of SiN mask by the plasma enhanced chemical vapor deposition (PECVD) [Figs. 11(a) and 11(b)] [19, 54]. Second, a micro-trench was fabricated by ultraviolet lithographic patterning and plasma dry etching [Figs. 11(c) and 11(d)]. Third, a Al$_{0.18}$Ga$_{0.82}$As layer was grown on the trench with the PECVD technology [Fig. 11(e)]. Finally, the reverse-strip waveguide was formed by using the phosphoric acid to remove the SiN mask [Fig. 11(f)].
5. Conclusions

In summary, we design a reverse-strip AlGaAs waveguide with three ZDWs for generating the MIR SC. The effects of the pump pulse parameters, waveguide length, and $\eta$ on the SCG are investigated. The MIR SC with good coherence and more than 2.7 octaves (at -40 dB level) is obtained with the designed reverse-strip AlGaAs waveguide when a hyperbolic secant pulse with center wavelength of 4.9 $\mu$m, peak power of 900 W, and duration of 100 fs is used as the pump source. In addition to generating such a broadband SC, the designed reverse-strip AlGaAs waveguide itself shows more solid and simpler fabrication process when compared with the suspended structure of AlGaAs on silicon waveguides proposed in ref. [19]. The proposed waveguide also can generated polarization-insensitive SC by changing the $H_0$, $H_u$, and $W$ [55]. It is believed that our research results can find significant applications in the MIR photonics, MIR spectroscopy, optical precision measurement, etc.

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Disclosures

The authors declare that there are no conflicts of interest related to this article.

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