Passive Generation of the Multi-Wavelength Parabolic Pulses in Tapered Silicon Nanowires

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ABSTRACT In this paper, passive generation of the multi-wavelength parabolic pulses (PPs) in tapered silicon nanowires (TSNs) is numerically investigated. The coupled inhomogeneous nonlinear Schrödinger equation (INLSE) is derived in the context of TSN to model the multi-wavelength PP generation. The TSN is designed based on the well-known self-similar theory that the group-velocity dispersion is decreased while the nonlinear coefficient is unchanged along the propagative direction. While the pump wavelengths for three input pulses are specially set with equal intervals of 18, 12, and 6 nm, the time-domain profiles are aligned at the same position. Simulation results show that except for wavelength interval, the waveguide length is also a critical factor that influences the quality of generated PP. Both of them reshape the pulse profile by the means of walk-off effect which depends on the cross-phase modulation between multiple pulses. By properly optimizing the input parameters of Gaussian pulses as well as the center wavelength interval and TSN length, we prove that the generation of two- or three-wavelength PPs with high-quality is feasible.

INDEX TERMS Multi-wavelength parabolic pulses, self-similar theory, tapered silicon nanowires.

I. INTRODUCTION Parabolic pulse (PP) generation has been extensively investigated in recent years [1]–[5]. The most important characteristic of PP is that its initial Gaussian form can be retained along the propagation in an optical medium with normal dispersion [6]. For this reason, PP exhibits important applications in high-power lasers [7], [8], high-speed optical communication systems [9], [10] where pulse split needs to be avoided. Up to now, PP could be acquired both from the active fibers [2] and passive media [11] when the input pulse profiles are arbitrary. Specially, PP generation has been experimentally verified in the ytterbium-doped [12]–[14], erbium-doped [15] and Raman fiber amplifiers [16]. In contrast, PP generation in a passive medium attract much less attention because the peak power is gradually reduced in the process of PP formation due to the power diffusion in the normal dispersion region. This property limits its application in which the high power is needed. However, compared to active medium, the passive medium shows two advantages in PP generation. First, the limitation of gain bandwidth [17] which often lead to pulse deformation do not exist for passive media. Second, passive medium is more beneficial to PP generation when the transverse size of used medium has to be lessened to nanometer scale.

On the other hand, on-chip nonlinear optics including pulse compression [18]–[20], supercontinuum generation [21], and optical frequency comb [22]–[24] have been attracting extensive attention. The used optical materials mainly include silicon, chalcogenide, and silicon nitride, etc. Among them, the
silicon-based waveguide demonstrates its superiority in three aspects: strong third-order nonlinear response, large refractive index difference between the waveguide and substrate, and good compatibility with complementary metal oxide semiconductor (CMOS) technology [25]. Nonlinear optical effects such as self-phase modulation (SPM) [26], [27], cross-phase modulation (XPM) [28]–[30], Raman amplification [31], [32], and four-wave mixing [33]–[35] have already been studied in silicon nanowires. Recently, nonlinear dynamics in silicon nanowires referring to PP generation from Gaussian input [36], [37], pulse collisions between two PPs [38], and self-similar propagation and compression of PP [39] are demonstrated. Nevertheless, these work only deal with the situation of single-wavelength PP generation, which in fact puts restriction to PP application especially in the dense wavelength division multiplexing and all-optical signal processing systems. For example, in Ref. [4], although the speed of regenerative wavelength converter based on single-wavelength similariton generation can be up to 40 Gbit/s, the transmission rate is actually limited by ghost pulses. The scheme of two-wavelength PP generation is expected to solve this problem through the dual-channel multiplexing. The transmission rate can be improved to 80 Gbit/s without performance degradation. This indicates the importance of multi-wavelength PP generation in the optical telecommunication. Physically speaking, the fundamental difference between single-wavelength and multi-wavelength PP generations exists in following two aspects. First, the XPM between multi-wavelength pulses could cause significant power redistribution. As a result, the pulse asymmetry in the time domain [40]–[42] can be observed. Second, the multi-wavelength pulses may suffer from free-carrier absorption (FCA) more seriously than the single-wavelength case due to the larger pulse energy within telecommunication waveband launched into silicon nanowires [43], [44].

![Conceptual diagram of the multi-wavelength PP generation in a TSN from input with arbitrary profiles at different center wavelengths.](image)

In this paper, the theoretical model for multi-wavelength PP generation is derived. With our theoretical model, the two-wavelength and three-wavelength PP generations in the tapered silicon nanowires (TSNs) are numerically investigated. The pump pulse parameters as well as waveguide length are properly adjusted to optimize the quality of generated PP. The conceptual illustration of the multi-wavelength PP generation is shown in Fig. 1. It shows multiple Gaussian pulses with different center wavelengths but the same temporal position are launched into the TSN. After propagation, they finally evolve to PPs.

This paper is arranged as follows. In section II, the theoretical model of coupled inhomogeneous nonlinear Schrödinger equation (INLSE) is derived. In section III, TSNs are designed based on the self-similar theory when different waveguide lengths are considered. Simulation results of the two- and three-wavelength PP generations are demonstrated in section IV. In section V, we draw the conclusions.

II. MULTIPLE COUPLED INHOMOGENEOUS NONLINEAR SCHRÖDINGER EQUATION

The nonlinear dynamics of multiple pulses propagating in a TSN can be described by the coupled INLSE as [45]

\[
\frac{i}{\partial z} u_j = - \sum_{n=1}^{6} \frac{n!}{n^n} \frac{\partial^n u_j}{\partial t^n} - \frac{ic k_j(z)}{2m_{g,j}(z)} \left[ a_1 + a_{EC,j}(z) \right] u_j - \frac{\omega_j k_j(z)}{m_{g,j}(z)} \frac{\partial \alpha_{EC,j}(z)}{\partial z} u_j - \left[ \gamma_j |u_j|^2 + \rho \gamma_{kj} \sum_{j \neq k} |u_k|^2 \right] u_j, \\
\]

(1)

where \(u_j(z, t)\) and \(u_k(z, t)\) are the two carrier envelop of the slow-varying electric field, \(z\) is the propagation distance, \(t\) is the retarded time, \(\beta_n\) is the dispersion coefficient which is calculated up to six order in the simulation, \(c\) is the speed of light in vacuum, and \(k_j\) is the spatial overlap factor describing the ratio between optical mode field and whole cross-section of the waveguide, which is defined as [29]

\[
\kappa_j = \frac{n^2 \int_{A_0} \left| e(r; \omega_j) \right|^2 dA}{\int_{A_{\infty}} n^2 \left( r \right) \left| e(r; \omega_j) \right|^2 dA},
\]

(2)

where \(n\) is the refractive index of the guiding layer and \(n \approx 3.48\) at wavelength of 1550 nm for silicon, \(n(r_j)\) is the equivalent refractive index over the whole cross-section, \(A_0\) and \(A_{\infty}\) denote the transversal areas of guiding layer and whole waveguide, respectively. The \(v_{g,j}\) in Eq. (1) represents the group velocity of \(u_j, a_1 = 1\) dB/cm is the linear loss [46], and \(\alpha_{EC}\) is the loss induced by FCA, \(\omega\) is the angular frequency, and \(\delta_{nEC}\) is the change of refractive index induced by the strong field, which gives rise to the free-carrier dispersion (FCD). In the case of multi-pulse propagation in the TSN, FCA and FCD are jointly determined by the total peak power. Following the definitions of \(\alpha_{EC}\) and \(\delta_{nEC}\) in the single-pulse case [36], we delimit the \(\alpha_{EC}\) and \(\delta_{nEC}\) for multiple co-propagation pulses as

\[
\alpha_{EC,j}(z) = \frac{e^2}{\hbar \epsilon_0 c} \left( \frac{1}{\mu_e m_{e}^2} + \frac{1}{\mu_h m_{h}^2} \right) \left( \frac{N_j(z)}{\omega_j} + \sum_{k \neq j} \frac{N_k(z)}{\omega_k \omega_j} \right),
\]

(3)
2 \rho \sum_{j \neq k} \frac{\omega_j \Gamma_{jk}''(z) + \omega_k \Gamma_{jk}''(z)}{(\omega_j + \omega_k) v_{g,j}(z) v_{g,k}(z)} |u_j u_k|^2, \tag{6}
\end{equation}

where $t_c \sim 0.5$ ns is the lifetime of free carrier [47]. $\Gamma_j''$ is the imaginary part of effective third-order susceptibility of $\Gamma_j$ for $u_j$. $\Gamma_j$ is defined by the certain weighted integrals of the corresponding tensor susceptibilities between the cross-section of the guiding layer and whole transversal area, which is given by [29]

$\Gamma_j = \frac{A_0}{c} \int_A e_x^j \cdot \chi^{(3)} e_x^j e_y^j e_z^j dA \left[ \int_{\infty} n^2 (r_{\perp}) |e_y|^2 dA \right]^2. \tag{7}$

$\Gamma_{jk}$ in Eq. (6) is the imaginary part of $\Gamma_{jk}$ which is jointly determined by the distribution of electric fields for $u_j$ and $u_k$. $\Gamma_{jk}$ is given by

$\Gamma_{jk} = \frac{A_0}{c} \int_A e_x^j \cdot \chi^{(3)} e_x^j e_y^j e_z^j dA \left[ \int_{\infty} n^2 (r_{\perp}) |e_y|^2 dA \int_{\infty} n^2 (r_{\perp}) |e_y|^2 dA \right]^2. \tag{8}$

The parameter $\rho$ in both Eqs. (1) and (6) is with the value of 2 when all waves propagating in the TSN are linearly polarized [45]. $\chi^{(3)}$ in Eq. (8) can be calculated from the following two equations once the nonlinear refractive $n_2$ and two photon absorption (TPA) coefficient, $\beta_{TPA}$, are obtained.

$$n_2 = 3 \chi^{(3)} / (4 \varepsilon_0 c n^2), \tag{9}$$

$$\beta_{TPA} = 3 \omega \chi^{(3)} \left/ (2 \varepsilon_0 c n^2) \right.. \tag{10}$$

The values of $n_2$ and $\beta_{TPA}$ have been experimentally measured and numerically fitted within a wavelength range from 1.3 to 6.2 $\mu$m [46]. Therefore, the effective third-order susceptibilities of $\Gamma_j$ and $\Gamma_{jk}$ can be also acquired within this wavelength range. Finally, the nonlinear coefficients $\gamma_j$ and $\gamma_{jk}$ in Eq. (1) can be obtained by following two equations.

$$\gamma_j (\omega_j, z) = \frac{3 \omega_j \Gamma_j (\omega_j, z)}{4 \varepsilon_0 A_0 (z) v_{g,j}^2 (\omega_j, z)}, \tag{11}$$

$$\gamma_{jk} (\omega_j, \omega_k, z) = \frac{3 \omega_j \Gamma_{jk} (\omega_j, \omega_k, z)}{4 \varepsilon_0 A_{0j} (z) v_{g,j} (\omega_j, z) v_{g,k} (\omega_k, z)}. \tag{12}$$

From Eqs. (11) and (12), it should be noted that both values of $\gamma_j$ and $\gamma_{jk}$ depend on $z$ and $\omega$. This in fact indicates that the nonlinear dynamics of pulse shaping for different center wavelengths and TSN profiles should be different, which will be demonstrated in the following sections.

**FIGURE 2.** (a) The cross-section and (b) top view of the silicon nanowire, (c) $\beta_2$ as a function of wavelength at the input (black solid curve) and output (red solid curve) ports, $\gamma_j$ as a function of wavelength at the input (black dashed curve) and output (red dashed curve) ports, the white dashed line indicates the wavelength of 1550 nm, the green bar represents the wavelength range considered, and (d) the variations of $\beta_2$ and $\gamma_j$ as functions of $W$ for wavelengths 1541 and 1559, 1544 and 1566, 1547 and 1553, and 1550 nm.

**FIGURE 3.** (a) The cross-section and (b) top view of the silicon nanowire, (c) $\beta_2$ as a function of wavelength at the input (black solid curve) and output (red solid curve) ports, $\gamma_j$ as a function of wavelength at the input (black dashed curve) and output (red dashed curve) ports, the white dashed line indicates the wavelength of 1550 nm, the green bar represents the wavelength range considered, and (d) the variations of $\beta_2$ and $\gamma_j$ as functions of $W$ for wavelengths 1541 and 1559, 1544 and 1566, 1547 and 1553, and 1550 nm.

**III. WAVEGUIDE DESIGN AND DETERMINATION OF WAVEGUIDE LENGTH**

**A. WAVEGUIDE DESIGN BASED ON THE SELF-SIMILAR THEORY**

In this subsection, the TSN design based on self-similar theory is discussed since according to self-similar theory, the PP generation can be ensured. Figure 2(a) shows the cross-section of designed TSN. The guided layer of silicon...
is buried in the SiO₂ cladding. Because of the large refractive index difference between the silicon (∼3.48) and SiO₂ (∼1.44), the optical field at 1550 nm can be well confined in the guiding layer [19]. The buried structure is chosen because it contributes to the end coupling in practice implementation. The silicon nanowire is tapered along the propagation direction and forms the TSN, as shown in Fig. 2(b). The widths (W) for the TSN are 2000 and 800 nm at the input and output ports, respectively. The height (H) is fixed at 220 nm. By using the finite element method, the group-velocity dispersion (GVD) parameter β₂ at the input and output ports are calculated as a function of wavelength ranging from 1400 to 1700 nm, as shown in Fig. 2(c). The white dashed line indicates the position of 1550 nm and the green bar represents the wavelength range from 1541 to 1559 nm which we are interested in this work. It can be seen from Fig. 2(c) that β₂ at the input port is increased as wavelength. Instead, it is decreased as wavelength at the output port. The values of γ₂ at both input and output ports are increased as wavelength. The exact value at 1550 nm for β₂ are 1.64 and 0.62 ps²/m, and γ₂ are 102.3 and 290.8 W⁻¹m⁻¹ at the input and output ports, respectively. Six input Gaussian pulses are divided into three groups according to different center wavelengths. In the case of two wavelengths, the three groups are located at 1541 and 1559 nm, 1544 and 1556 nm, and 1547 and 1553 nm, respectively. In the case of three wavelengths, the three groups are located at 1541, 1550 and 1559 nm, 1544, 1550 and 1556 nm, and 1547, 1550 and 1553 nm, respectively. Six input Gaussian pulses are divided into three groups according to different center wavelengths. In the case of two wavelengths, the three groups are located at 1541 and 1559 nm, 1544 and 1556 nm, and 1547 and 1553 nm, respectively. In the case of three wavelengths, the three groups are located at 1541, 1550 and 1559 nm, 1544, 1550 and 1556 nm, and 1547, 1550 and 1553 nm, respectively. Figure 2(d) shows the variations of β₂ and γ₂ as function of W. It can be seen that the slope of β₂ is slightly increased when W is reduced, which indicates that the group-velocity mismatch gradually increases along propagation. However, all curves for β₂ and γ₂ at different center wavelengths almost coincide with each other. This means all input pulses will show similar evolving trace in the designed TSN. Although there are three methods can be found to design TSN according to self-similar theory [39], we choose the widely used one that β₂ is decreased and γ₂ is a constant along z. This method can be mathematically described as [37]

\[ \beta_2(z) = \frac{\beta_{20}}{1 + \text{g}_{\text{eq}} z}, \quad (13a) \]

\[ \gamma_2(z) = \gamma_0, \quad (13b) \]

where β₂₀ is the value of β₂ at z = 0, g_{eq} > 0 is the equivalent gain constant depending on the TSN profile, γ₀ is the value of γ₂ at z = 0. Equation (13b) clearly indicates that the nonlinear coefficient is kept as a constant over the whole propagation.

The variations of W, β₂, and γ₂ along z are plotted in Fig. 3. In Fig. 3(a), W is decreased with z when the waveguide length L = 0.5, 1 and 2 mm, respectively. These curves in Fig. 3(a) offer theoretical guidance for practical waveguide fabrication. Figures 3(b), 3(c), and 3(d) show the variations of β₂ and γ₂ when L = 0.5, 1 and 2 mm, respectively. From Figs. 3(b) to 3(d), L and β₂ are decreased but γ₂ is increased with z, which indicates that the self-similar evolution is possible in this TSN. However, the rate of self-similar evolution for different L is slightly different. As the curves of β₂ and γ₂ for each wavelength are very close, only the design at 1550 nm is considered for multi-wavelength PP generations. This wavelength is pick up because TSN can support single-wavelength PP generation at 1550 nm when XPM effect is ignored [37]. The XPM-associated L enables us to distinguish the PP generation in single- and multi-wavelength cases. It should be noted that although Eq. (13) provides one approach to design TSN, high-quality PP can be also generated by the means of the other two [39] which we do not discuss here.

B. DETERMINATION OF THE WAVEGUIDE LENGTH

Before determining the suitable L for multi-wavelength PP generation when XPM is presented, we need to evaluate the walk-off effect between the two input pulses for different wavelength assemblies. This procedure may help us refrain from the XPM-induced walk-off effect which probably lead to asymmetries of temporal pulse. Assuming both pulse widths are the same as T₀, the walk-off distance L_W can be introduced as [45]

\[ L_W = T_0/|\beta_1(\lambda_1) - \beta_1(\lambda_2)|, \quad (14) \]
where $\beta_1 = 1/\nu_g$, $\lambda_1$ and $\lambda_2$ are center wavelengths for two injected pulses. Figures 4(a) to 4(c) show the calculated $L_W$ for different choices of $\lambda_1$ and $\lambda_2$. The full width at half maximum (FWHM) of $T_{\text{FWHM}}$ is varied from 100 to 600 fs and $W$ is decreased from 2000 to 800 nm in Fig. 4. When $\lambda_1 = 1541$ nm and $\lambda_2 = 1559$ nm, the variation of $L_W$ is shown in Fig. 4(a) in which $L_W$ is reduced when $T_{\text{FWHM}}$ is decreased or $W$ is increased. This is because when $T_{\text{FWHM}}$ is decreased, the input power will be increased to keep pulse energy as a constant. As a result, nonlinear power coupling takes place after only a short propagation. Besides, $\beta_2$ will become larger for the increased $W$ according to Fig. 2(d).

Thus, the difference between absolute $\beta_1(\lambda_1)$ and $\beta_1(\lambda_2)$ also becomes larger, which essentially decreases the $L_W$. The maximal $L_W$ appears at the upper right corner where $T_{\text{FWHM}}$ and $W$ show the maximal and minimal values, respectively. Similar pattern can be observed in Figs. 4(b) and 4(c). The difference is that as $\Delta \lambda$ is decreased, both the minimal and maximal values of $L_W$ are increased. For example, when $\Delta \lambda = 18$ nm, the maximal value of $L_W$ is 20.4 mm. However, when $\Delta \lambda = 6$ nm, the maximal value of $L_W$ is 61.2 mm. In order to get rid of the influence from walk-off effect and ensure high-quality PP generation, the condition $L \ll L_W$ should be satisfied in the simulation. From Fig. 4(a), one can clearly deduce that $L$ needs to be shorter than 7.8 mm.

To further reduce the selection range of $L$, we investigate the temporal evolutions at wavelengths (i) $\lambda_1 = 1541$ and $\lambda_2 = 1559$ nm, (ii) $\lambda_1 = 1544$ and $\lambda_2 = 1556$ nm, and (iii) $\lambda_1 = 1547$ and $\lambda_2 = 1553$ nm when $T_{\text{FWHM}}$ is increased from 100 to 600 fs and $W$ is changed from 2000 to 800 nm. The white dashed lines represent the location of $T_{\text{FWHM}} = 180$ fs, and the maximal and minimal $L_W$ for each white dashed line are 7.8 and 20.4 mm, 11.7 and 30.6 mm, and 23.3 and 61.2 mm in (a), (b), and (c), respectively.

Moreover, the temporal separation caused by walk-off effect between each pair of pulses is reduced at the same $z$ when the $\Delta \lambda$ is reduced from Figs. 5(a) to 5(c). Unfortunately, at the end of propagation in the three figures, flat-top pulse appears which indicates the excessively nonlinear phase. This is quite obvious for smaller $\Delta \lambda$. Therefore, it is necessary to control $L$ to prevent the possible redundant nonlinear phase.

Another important phenomenon is the drift of center position for temporal pulse, which is oscillating near $t = 0$. This oscillation is believed to originate from the unequal spectral modulation between two propagating pulses. When $\Delta \lambda$ is 12 and 6 nm, the oscillating characteristic almost disappears, as shown in Figs. 5(b) and 5(c). The reason is that the XPM-induced spectral modulation tends to the same, which give rises to the same group velocity for the co-propagating pulse. It concludes from Fig. 5 that as the pulse deformation is proportional to $z$, $L$ needs to be shorter than 3 nm to ensure high-quality two-wavelength PP generation especially for the worst case of $\Delta \lambda = 18$ nm.

To clearly demonstrate the deviations between output pulse and parabola, comparisons are plotted in Figs. 6(a), 6(b), and 6(c) when $\Delta \lambda = 18$, 12, and 6 nm,
respective. For each \( \Delta \lambda \), simulations for the cases of \( L = 0.5, 1 \) and 2 mm are conducted. The input peak power and \( T_{\text{FWHM}} \) for all cases are 400 W and 180 fs, respectively. It can be seen from Fig. 6(a) that the output pulses gradually deviate from the parabola due to the excessively accumulated nonlinear phase caused by XPM when \( L \) is increased from 0.5 to 2 mm. The most serious deviation happens for the case of \( L = 2 \text{ mm} \) because the output pulse is far away from parabolic fitting. As a result, high-quality multi-wavelength PP generation is impossible. Similar scenario can be found in Figs. 6(b) and 6(c). In another aspect, the output pulse is closer to a parabola when \( \Delta \lambda \) is reduced from 18 to 6 nm even if \( L = 2 \text{ mm} \), which can be explained by the decreased group-velocity mismatch. It is obvious that compared to \( \Delta \lambda \), \( L \) plays a more important role in making the output pulse away from desired PP.

As conclusions, we focus on designing TSN and investigating the influence of \( L \) as well the wavelength interval on the walk-off effect. It is evident that \( L \) acts as a dominant role in affecting the self-similar evolution and PP formation compared to \( \Delta \lambda \). Since in previous work [5], the input peak power and \( T_{\text{FWHM}} \) are affected to prove the PP generation as well in the single-wavelength case. In the following, the optimization of the input peak power and \( T_{\text{FWHM}} \) in the case of multi-wavelength PP generation will be discussed focally.

IV. SIMULATION RESULTS FOR MILTI-WAVELENGTH PP GENERATIONS

A. TWO-WAVELENGTH PP GENERATION

Same as above, six pulses are divided into three groups as (i) \( \lambda_1 = 1541 \) and \( \lambda_2 = 1559 \text{ nm} \), (ii) \( \lambda_1 = 1544 \) and \( \lambda_2 = 1556 \text{ nm} \), and (iii) \( \lambda_1 = 1547 \) and \( \lambda_2 = 1553 \text{ nm} \) in this subsection for two-wavelength PP generation. First, we introduce a mismatch parameter \( \sigma \) to quantality evaluate the quality of generated PP in the single-wavelength case as

\[
\sigma^2 = \frac{\int_{-\infty}^{+\infty} [P(t) - P(t)]^2 \, dt}{\int_{-\infty}^{+\infty} P^2(t) \, dt},
\]

(15)

where \( P(t) \) and \( P(t) \) are the powers of output pulse and fitted parabola, respectively. To understand the impacts of input peak power and \( T_{\text{FWHM}} \) on the two-wavelength PP generation, \( \sigma \) under different input peak powers and \( T_{\text{FWHM}} \) are calculated when \( L = 0.5, 1 \), and 2 mm, respectively. The symbol of \( \sigma \) at \( \lambda_1 \) and \( \lambda_2 \) are reset as \( \sigma_1 \) and \( \sigma_2 \). Two new variables are introduced to quantality evaluate the quality of generated PP in the two-wavelength case as

\[
\begin{align*}
\sigma^2_{\text{sum}} &= \sigma_1^2 + \sigma_2^2, \\
\sigma^2_{\text{diff}} &= \left| \sigma_1^2 - \sigma_2^2 \right|.
\end{align*}
\]

(16a), (16b)

For the minimal value of both \( \sigma_{\text{sum}} \) and \( \sigma_{\text{diff}} \), the output two pulses can be very close to PP. The effective mismatch parameter is defined as

\[
\sigma_{\text{sd}}^2 = 1000 \times \left( \sigma^2_{\text{sum}} + \sigma^2_{\text{diff}} \right) / n_w,
\]

(17)

where \( n_w \) is the number of input center wavelengths. For the two-wavelength case, \( n_w = 2 \). It is clear that smaller value of \( \sigma_{\text{sd}} \) means better quality of output two pulses. This definition provides a useful approach to quantality assess the quality of output two pulses with only one parameter.

Figure 7 shows the distribution of \( \sigma_{\text{sd}}^2 \) when input peak power and \( T_{\text{FWHM}} \) change from 100 to 600 W and from 100 to 600 fs, respectively. The step sizes in peak power and FWHM are 10 W and 10 fs. The input peak power and \( T_{\text{FWHM}} \) for two pulses are the same. Figure 7(a) to 7(c) demonstrate that the values of \( \sigma_{\text{sd}}^2 \) from 100 to 200 fs are increased with \( L \) because of the increased pulse deformation caused by the walk-off effect. Similar scenario can be found from Figs. 7(d) to 7(f) and
Figs. 7(g) to 7(i) in which the \( \Delta \lambda \) are 12 and 6 nm, respectively. Yet, the distinction is that the increasing rate for \( \sigma_{sd} \) is slowed down as \( \Delta \lambda \) is reduced from 18 to 6 nm. In Figs. 7(a), 7(d), and 7(g) in which the \( L \) are fixed at 0.5 mm, \( \sigma_{sd} \) is also decreased as \( \Delta \lambda \) is reduced from 18 to 6 nm. In addition, when \( L \) is fixed at 1 and 2 mm, the similar trends are observed, which corresponds to Figs. 7(b), 7(e) and 7(h), and Figs. 7(c), 7(f) and 7(i), respectively. All these results point to one fact that smaller \( \Delta \lambda \) shows great advantage in self-similar evolution. For the fixed \( \Delta \lambda = 18 \) nm, the maximal values of \( \sigma_{sd}^2 \) are 27, 168, and 618, and the minimal value of \( \sigma_{sd}^2 \) are 2.9, 3.1 and 3.7 when \( L = 0.5, 1 \) and 2 mm, respectively. These minimal values are marked by yellow crosses as shown in Fig. 7. It can be seen that suitable input peak power as well \( T_{FWHM} \) strongly determine the high-quality multi-wavelength PP generation. The corresponding value of \( T_{FWHM} \) for three minimal \( \sigma_{sd}^2 \) are 170, 310, and 550 fs, respectively. It shows longer TSN requires larger \( T_{FWHM} \) to achieve high-quality PP for given input peak power.

The exact waveforms and their parabolic fittings for the output two-wavelength pulses at \( \Delta \lambda = 18, 12 \), and 6 nm are shown in Figs. 8(a), 8(b), and 8(c), respectively. The parabolic fittings are conducted under the condition that the values of \( \sigma_{sd}^2 \) in Fig. 7 are minimal. From Fig. 8, all pulses can be well fitted by the parabolas which means the pulse deformation can be relieved to some extent by matching the XPM, SPM and GVD after optimizing the input peak power and \( T_{FWHM} \). That is to say, the inherent balance between nonlinearity and dispersion required by two-wavelength PP generation is satisfied. Different from the case of single-wavelength PP generation, XPM provides another free degree to control the PP generation in the two-wavelength case. It is evident that the two-wavelength PPs with high quality have been generated by optimizing the input peak power and \( T_{FWHM} \) in the TSNs when \( \lambda = 0.5, 1 \), and 2 mm, respectively.

### B. THREE-WAVELENGTH PP GENERATION

For the case of three-wavelength PP generation, the six pump wavelengths are also divided into three groups as (i) \( \lambda_1 = 1541, \lambda_2 = 1550 \) and \( \lambda_3 = 1559 \) nm, (ii) \( \lambda_1 = 1544, \lambda_2 = 1550, \) and \( \lambda_3 = 1556 \) nm, and (iii) \( \lambda_1 = 1547, \lambda_2 = 1550 \) and \( \lambda_3 = 1553 \) nm. The maximal and minimal values of \( \Delta \lambda \) in this case are the same as those in the two-wavelength case. However, the nonlinear interaction in the three-wavelength case is more complicated than the two-wavelength one because each optical spectrum will be simultaneously modulated by the other two via XPM. For the three-wavelength case, the quality of generated pulses can be quantified by evaluating the following two equations as

\[
\begin{align*}
\sigma_{sum}^2 &= \sigma_1^2 + \sigma_2^2 + \sigma_3^2, \\
\sigma_{diff}^2 &= |\sigma_1^2 - \sigma_2^2| + |\sigma_2^2 - \sigma_3^2| + |\sigma_1^2 - \sigma_3^2|,
\end{align*}
\]

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the mismatch parameters of the three output pulses from one TSN at center wavelengths of \( \lambda_1, \lambda_2, \) and \( \lambda_3, \) respectively. Similar to the two-wavelength case, \( \sigma_{sd} \) in the three-wavelength case can be calculated after \( \sigma_{sum} \) and \( \sigma_{diff} \) defined by Eqs. (18) and (19) are determined. The calculated distribution of \( \sigma_{sd}^2 \) are shown in Fig. 9 when the input peak power and \( T_{FWHM} \) are varied from 100 to 600 W and from 100 to 600 fs, respectively. It can be seen that \( \sigma_{sd} \) is increased with \( L \) and decreased with \( \Delta \lambda, \) which exhibits the same trend as the two-wavelength case in Fig. 7. The first difference manifests in that the maximal value of \( \sigma_{sd}^2 \) in Fig. 9 is 213, but in Fig. 7 it is only 27 when \( \lambda = 0.5 \) mm. The same situations can be also found for \( \lambda = 1 \) and 2 mm. Therefore, the quality of generated three-wavelength PPs is worse than that of two-wavelength case. The reason is that the three-wavelength pulses at telecommunication band suffer
from stronger nonlinear absorption including the TPA and FCA than that of two-wavelength case in the TSN. It has been proved that TPA allows significantly degradation in quality of generated PPs [37]. Another difference is that the growth rate of $\sigma_{sd}$ from 100 to 200 fs in Fig. 9 is faster than that in Fig. 7 when $L = 0.5$, 1 and 2 mm. This is because the self-similar evolution for three-wavelength case experiences stronger obstruction due to the presence of nonlinear absorption. The positions where the minimal values of $\sigma_{sd}^2$ are located are marked by yellow crosses, as shown in Figs. 9(a) to 9(i). The corresponding $T_{FWHM}$ for the minimal $\sigma_{sd}$ is increased with $L$ increasing from 0.5 to 2 mm. Although most values of $\sigma_{sd}$ for three-wavelength case are larger than that of two-wavelength case, the minimal value of $\sigma_{sd}^2$ for the two cases are almost the same. For example, when $L = 0.5$ mm and $\Delta \lambda = 6$ nm, the minimal $\sigma_{sd}^2$ are 2.89 and 2.95, respectively, which are very close to each other. In a word, the generation of three-wavelength PPs with high quality has been achieved.

![FIGURE 10. When $\sigma_{sd}^2 = 3.35$ and $L = 2$ mm, the output pulses and their parabolic fittings at (a) $\lambda_1 = 1541$, (b) $\lambda_2 = 1550$, and (c) $\lambda_3 = 1559$ nm. When $\sigma_{sd}^2 = 2.82$ and $L = 1$ mm, the output pulses and their parabolic fittings at (d) $\lambda_1 = 1547$, (e) $\lambda_2 = 1550$, and (f) $\lambda_3 = 1553$ nm.](image)

The exact waveform of individual output pulse and its parabolic fitting in the time-domain are shown in Figs. 10(a) to 10(f) for the three-wavelength case. The corresponding values of $\sigma_{sd}^2$ are 3.35 for $L = 2$ mm and 2.82 for $L = 1$ mm. These two values of $\sigma_{sd}^2$ correspond to the maximal and minimal values among all $\sigma_{sd}^2$ marked by yellow crosses in Fig. 9. In Figs. 10(a) to 10(c), the three output pulses are well fitted by its parabolic counterpart at center wavelengths of $\lambda_1 = 1541$, $\lambda_2 = 1550$, and $\lambda_3 = 1559$ nm. However, smaller value of $\sigma_{sd}^2$ in Figs. 10(d) to 10(f) means that the output waveforms under reduced $\Delta \lambda$ are closer to parabolas. This can be attributed to the approximately equal group velocity between the three co-propagating pulses. The corresponding physical mechanism is similar to the two-wavelength case. It should be noted that although only two output waveforms for $L = 2$ mm and 1 mm are shown

in Fig. 10, the minimal values of $\sigma_{sd}^2$ in all nine subfigures in Fig. 9 are very close to each other.

**TABLE 1. The minimal values of $\sigma_{sd}^2$ for different cases.**

| $L$ (mm) | Two-wavelength case | Three-wavelength case |
|---------|---------------------|-----------------------|
| $\Delta \lambda$ (nm)| 0.5 | 1 | 2 | 0.5 | 1 | 2 |
| 18 | 2.95 | 3.08 | 3.68 | 2.89 | 2.87 | 3.35 |
| 12 | 3.19 | 3.33 | 2.99 | 3.03 | 2.88 | 3.12 |
| 6 | 3.27 | 2.89 | 2.92 | 2.86 | 2.82 | 3.08 |

The minimal values of $\sigma_{sd}^2$ for different $L$ and $\Delta \lambda$ are given in Table 1 in order to clearly manifest the quality of generated two-wavelength and three-wavelength PPs. From Table 1, the minimal values of $\sigma_{sd}^2$ for the two-wavelength and three-wavelength cases are 2.89 and 2.82, respectively when $\Delta \lambda = 6$ nm and $L = 1$ mm. However, among all minimal $\sigma_{sd}^2$ marked by yellow crosses in Figs. 7 and 9, the maximal values are 3.68 in Fig. 7 and 3.35 in Fig. 9, respectively. At this time, $\Delta \lambda = 18$ nm and $L = 2$ mm. These results again confirm that both $\Delta \lambda$ and $L$ significantly affect the quality of generated PPs. Therefore, to obtain high-quality multi-wavelength PPs in designed TSN, it is necessary to optimize all parameters including the input peak power and $T_{FWHM}$, as well as the waveguide length $L$ and wavelength interval $\Delta \lambda$.

The time-domain characteristics of output pulses have been demonstrated in above section. Now we will investigate the frequency-domain characteristics which can be measured by the frequency-resolved optical gating (FROG). For this purpose, the time-frequency map is adopted because it can reflect the time-domain as well as frequency-domain information at the same time. The time-frequency map can be described as [48]

$$S(\omega, \tau) = \left| \int_{-\infty}^{\infty} u(t) g(t-\tau) e^{-i\omega t} dt \right|^{2}, \quad (20)$$

where $g(t-\tau)$ is the variable-delay gate function with a Gaussian shape of 200-fs width and $\tau$ is the delayed time. Fig. 11 shows the resulted time-frequency maps in which Figs. 11(a) and 11(b) demonstrate the output $S$ for $L = 2$ mm when $\lambda_1$ and $\lambda_2$ are chosen as 1541 and 1559 nm, respectively. Figs. 11(c) to 11(e) show the output $S$ for $L = 2$ mm when $\lambda_1$, $\lambda_2$, and $\lambda_3$ are 1541, 1550, and 1559 nm, respectively. Obviously, all optical spectra are stretched around its center wavelength because of the spectral broadening under XPM and SPM. The two ends of stretched spectra are thicker than the middle portions, suggesting higher energy distribution at both ends than the middle portion. This is also indicated from the optical spectra plotted by white solid curves. All spectral curves in Figs. 11(a) to 11(e) have a nearly symmetrical bimodal structure, which is similar to the spectral profile only caused SPM. This allows temporal pulses do not manifest any asymmetric deformation. Furthermore, the spectral intensities in Figs. 11(a) and 11(b) are higher

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than those in Figs. 11(c) to 11(e) because the two-wavelength pulses are subject to a lower nonlinear absorption than the three-wavelength one. More importantly, the nonlinear absorption not only reduces the output spectral intensity, but also deteriorates the quality of generated multi-wavelength PPs. Further simulation results show that by using suitable optical filters, an individual temporal component for each center wavelength among all output PPs can be perfectly extracted and reproduced.

It should be noted that in this work, although we only show the generation of two-wavelength and three-wavelength PPs, PPs with more than three wavelengths can also be generated with high quality as long as the walk-off effect can be effectively restrained. This can be realized by appropriately optimizing $L$ and $\Delta \lambda$, as well as the input peak power and $T_{\text{FWHM}}$. This work provides a general scheme for multi-wavelength PP generation in passive media.

V. CONCLUSIONS

In summary, the theoretical model for multi-wavelength PP generation in designed TSNs is derived. It shows small $L$ and $\Delta \lambda$ can weaken the walk-off effect and improve the quality of generated multi-wavelength PPs. To obtain high-quality multi-wavelength PPs, the maximal values for $L$ and $\Delta \lambda$ are chosen as 2 mm and 18 nm. Simulation results show that two-wavelength and three-wavelength PPs can be generated with high quality after optimizing the input peak power and $T_{\text{FWHM}}$ of Gaussian pulses. The minimal values of $\sigma_{\text{sd}}^2$ for the two-wavelength and three-wavelength cases are 2.89 and 2.82, for two-wavelength and three-wavelength cases are 2.89 and 2.82, respectively. It is believed that the proposed scheme of multi-wavelength PP generations has important applications in the on-chip dense wavelength division multiplexing and all-optical signal processing systems.

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