Generation of parabolic similaritons in tapered silicon photonic wires: comparison of pulse dynamics at telecom and mid-IR wavelengths

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We study the generation of parabolic self-similar optical pulses in tapered Si photonic nanowires (Si-PhNWs) both at telecom (λ = 1.55 μm) and mid-IR (λ = 2.2 μm) wavelengths. Our computational study is based on a rigorous theoretical model, which fully describes the influence of linear and nonlinear optical effects on pulse propagation in Si-PhNWs with arbitrarily varying width. Numerical simulations demonstrate that, in the normal dispersion regime, optical pulses evolve naturally into parabolic pulses upon propagating in millimeter-long tapered Si-PhNWs, with the efficiency of this pulse reshaping process being strongly dependent on the spectral and pulse parameter regime in which the device operates, as well as the particular shape of the Si-PhNW.

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Generation of pulses with specific spectral and temporal characteristics is a key functionality needed in many applications in ultrafast optics, optical signal processing, and optical communications. One type of such pulses, which can be used as primary information carriers in optical communications systems, are pulses that preserve their shape upon propagation. Solitons are the most ubiquitous example of such a pulse that form in the anomalous group-velocity dispersion (GVD) regime, whereas their counterpart in the normal GVD region are self-similar pulses, called similaritons [1–3]. Unlike solitons, which require a threshold power, no constraints have to be imposed on the pulse energy, initial shape, or optical phase profile to generate similaritons. Due to their self-similar propagation, similaritons do not undergo wave breaking and the linear chirp they acquire during their formation makes it easy to employ dispersive pulse compression techniques to generate nearly transform-limited pulses. These remarkable properties of similaritons have provided a strong incentive for their study, and optical similaritons have been demonstrated in active optical fiber systems such as Yb-doped fiber amplifiers [3, 4], using passive schemes based on dispersion-managed or tapered silica fibers [5–8], and high-power fiber amplifiers [9–11].

Driven by the ever growing demand for enhanced integration of complex optoelectronic architectures that process increasing amounts of data, finding efficient ways to extend the regime of self-similar pulse propagation to chip-scale photonic devices is becoming more pressing. One promising approach, based on silicon (Si) fibers with micrometer-sized core dimensions [12], has recently been proposed [13]. A further degree of device integration can be achieved by employing Si photonic nanowires (Si-PhNWs) with submicrometer transverse size fabricated on a silicon-on-insulator material system [14]. In addition to the enhanced optical nonlinearity and strong frequency dispersion, which allows for increased device integration, Si-PhNWs allow for seamless integration with complementary metal-oxide semiconductor technologies. Importantly, the use of Si-PhNWs can be extended to the mid-infrared (mid-IR) spectral region (λ ≥ 2.2 μm) [15], where Si provides superior functionality due to low two-photon absorption (TPA) and consequently reduced free-carrier absorption (FCA). In fact, it has already been shown that nonlinear optical effects such as modulational instability [16, 17], frequency dispersion of the nonlinearity [18], and supercontinuum generation [17, 19–21], can be used to achieve significant pulse reshaping in millimeter-long Si-PhNWs (for a review, see [22]).

In this Letter, we use a rigorous theoretical model, which describes the propagation of pulses in Si-PhNWs, and comprehensive numerical simulations to demonstrate that optical similaritons with parabolic shape can be generated in millimeter-long, dispersion engineered Si-PhNWs. In order to gain a better understanding of the underlying physics of similariton generation, we present a comparative analysis of the pulse dynamics in two spectral domains relevant for technological applications, namely telecom (λ = 1.55 μm) and mid-IR (λ = 2.2 μm) spectral regions. Thus, the pulse dynamics are described by the following equation [18, 23–25]:

\[
\frac{i}{\partial z} \frac{\partial u}{\partial z} + \sum_{n \geq 1} \frac{i^n \beta_n(z)}{n!} \frac{\partial^n u}{\partial t^n} = -\frac{i c \kappa(z)}{2 \nu_g(z)} \alphaFC(z) u \\
- \frac{\omega \kappa(z)}{\nu_g(z)} \delta n_{FC}(z) u - \gamma(z) \left[ 1 + i \tau(z) \frac{\partial}{\partial t} \right] |u|^2 u,
\tag{1}
\]

where \(u(z, t)\) is the pulse envelope, \(z\) and \(t\) are the distance along the Si-PhNW and time, respectively, \(\beta_n(z) = d^n \beta/d\omega^n\) is the \(n\)th order dispersion coefficient, \(\kappa(z)\) quantifies the overlap between the optical mode and the active area of the waveguide, \(\nu_g(z)\) is the group-velocity, \(\delta n_{FC}(z) [\alpha_{FC}(z)]\) are the free-carrier...
(FC) induced index change (losses) and are given by

\[ \delta n_{\text{FC}}(z) = -e^2/2\varepsilon_0\hbar^2 \left[ N(z)/m_{\text{ee}}^* + N(z)^{0.8}/m_{\text{ch}}^* \right] \]

and

\[ \alpha_{\text{FC}}(z) = e^3N(z)/\varepsilon_0\hbar^2(1/\mu_em_{\text{ee}}^* + 1/\mu_km_{\text{ch}}^*) \]

respectively, where \( N \) is the FC density, \( m_{\text{ee}}^* = 0.26m_0 \) (\( m_{\text{ch}}^* = 0.39m_0 \)) is the effective mass of the electrons (holes), with \( m_0 \) the mass of the electron, and \( \mu_e (\mu_h) \) the electron (hole) mobility. The nonlinear properties of the waveguide are described by the nonlinear coefficient, \( \gamma(z) = 3\omega_0B_0 \Gamma(z)/4\varepsilon_0A(z)\nu_0^2(z), \) and the shock time scale, i.e. the characteristic response time of the nonlinearity, \( \tau(z) = \partial \ln \gamma(z)/\partial \omega, \) where \( B_0 \) is the peak power of the input pulse, and \( A(z) \) and \( \Gamma(z) \) are the cross-sectional area and the effective third-order susceptibility of the waveguide, respectively. Our model is completed by a rate equation describing the FC dynamics,

\[ \frac{\partial N}{\partial t} = \frac{N}{\tau_c} + \frac{3\omega_0^2\Gamma''(z)}{4\varepsilon_0\hbar A^2(z)\nu_0^2(z)} |w|^4, \]

where \( \Gamma'' \) (\( \Gamma' \)) is the imaginary (real) part of \( \Gamma. \)

The system (1)-(2) provides a rigorous description of pulse propagation in Si-PhNWs with adiabatically varying transverse size since the \( z \)-dependence of the waveguide parameters is fully incorporated in our model via the implicit dependence of the modes of the Si-PhNW on its transverse size. Thus, we consider a tapered ridge waveguide with a Si rectangular core buried in SiO_{2}, with height, \( h = 250 \) nm, and width, \( w, \) varying from \( w_{\text{in}} \) to \( w_{\text{out}} \) between the input and output facets, respectively. Using a finite-element mode solver we determine the propagation constant, \( \beta(\lambda), \) and the fundamental TE-like mode, for \( 1.3 \mu m \leq \lambda \leq 2.3 \mu m \) and for 51 values of the waveguide width ranging from 500 nm to 1500 nm. The dispersion coefficients are calculated by fitting \( \beta(\lambda) \) with a 12th order polynomial and subsequently calculating the corresponding derivatives with respect to \( \omega. \)

Using these results and the corresponding optical modes, the waveguide parameters, \( \kappa, \gamma, \tau, \) are computed for all values of \( w. \) The \( z \)-dependence of these parameters is then determined by polynomial interpolation.

The results of this analysis are summarized in Fig. 1, where we plot the dispersion maps of the waveguide parameters. Thus, Fig. 1(a) shows that if \( w < 887 \) nm the Si-PhNW has two zero GVD wavelengths, defined by \( \beta_2(\lambda, w) = 0, \) whereas if \( w > 887 \) nm the Si-PhNW has normal GVD in the entire spectral domain. In addition, if \( \lambda > 2187 \) nm the waveguide has normal GVD for any \( w. \) Important properties of the Si-PhNW are revealed by the dispersion maps of the nonlinear coefficients as well. Specifically, the strength of the nonlinearity, \( \gamma'(\lambda, w), \) decreases with both increasing \( w \) and \( \lambda, \) meaning that in the range of wavelengths and waveguide widths explored here, nonlinear effects in Si-PhNWs are stronger if narrow waveguides are used at lower wavelengths. On the other hand the TPA coefficient, \( \gamma''(\lambda, w), \) and consequently nonlinear losses, decrease with \( w \) and \( \lambda, \) which suggests that the waveguide parameters and wavelength must be properly chosen for optimum device operation. Finally, as seen in Fig. 1(e), the shock time \( \tau'(\lambda, w) \) has large values at long wavelengths but decreases with \( w. \)

To investigate the formation of self-similar pulses, we considered first a Gaussian pulse, \( u(t) = e^{-t^2/2T^2} \) with full-width at half-maximum (FWHM) \( T_{\text{FWHM}} = 220 \) fs \((T_{\text{FWHM}} = 1.665T_0), \) and peak power \( P_0 = 7 \) W, which is launched in an exponentially tapered Si-PhNW, \( w(z) = w_{\text{in}}e^{-az}, \) with \( w_{\text{in}} = 1500 \) nm. The remaining parameters are: \( i) \) at \( \lambda = 1.55 \mu m, \) \( w_{\text{out}} = 1080 \) nm,
becomes closer to a parabolic pulse at incidence of the formation of parabolic pulses. The pulse is almost unaffected if one neglects higher-order effects, which demonstrates the robustness against the chirp is preserved even in the presence of higher-order effects, as illustrated in the top panels of Figs. 2(a) and 2(b). These figures also show that at both wavelengths there is a band of low values of ε2 at which ε2 reaches a minimum, which is explained by the fact that the similariton formation length increases with P0. By contrast, there is no optimum value of TFWHM at which ε2 becomes minimum.

The relation between the input pulse parameters and the similariton generation can be further explored by considering pulses with different shapes. Our results regarding this dependence are summarized in Fig. 4, where we plot the evolution of ε2(z), determined for varying P0. As input pulses we considered a Gaussian pulse, a supergaussian pulse, u(t) = e−(t/τ)2m with m = 2 (TFWHM = 1.824τ0), and a sech pulse, u(t) = sech(t/τ0), where TFWHM = 1.763τ0. In all cases TFWHM = 220 fs. There are several revealing conclusions that can be drawn from the maps in Fig. 4. First, the Gaussian pulse leads to the lowest values of ε2(z), which suggests that this pulse shape is the most efficient one for generating similaritons. Second, in the case of Gaussian and sech pulses there is a band of low values of ε2(z), which is narrower at λ = 1.55 µm as compared to its width at optimum power at which ε2 reaches a minimum, which is explained by the fact that the similariton formation length increases with P0. By contrast, there is no optimum value of TFWHM at which ε2 becomes minimum.
respectively. To this end, we considered a linear taper and exponential ones with different profiles. To this end, we considered a linear taper and exponential ones, whereas in the case of supergaussian pulses two such bands exist. Finally, pulses with a supergaussian shape evolve into a similariton over the shortest distance, whereas in the case of supergaussian pulses two cases the (Gaussian) pulse parameters and its temporal profile, as well as the particular shape of the Si-PhNW taper.

\[ \lambda = 2.2 \, \mu m \] and in both cases it broadens as \( P_0 \) decreases, whereas in the case of supergaussian pulses two such bands exist. Finally, pulses with a supergaussian shape evolve into a similariton over the shortest distance, which is explained by the fact that the three pulse profiles the supergaussian one is closest to a parabolic pulse. Due to its practical relevance, we also studied the generation of similaritons in Si-PhNW tapers with different profiles. To this end, we considered a linear taper and exponential ones with different \( z \)-variation rate, in all cases the (Gaussian) pulse parameters and \( w_{in} \) and \( w_{out} \) being the same [see Fig. 5(a)]. The results of this analysis, which are presented in Fig. 5, show that although similaritons are generated irrespective of the taper profile, the efficiency of this process does depend on the shape of the taper. In particular, overall the linear taper is the most effective for similariton generation, whereas in the case of exponential tapers the steeper their profile the more inefficient they are. These conclusions qualitatively remain valid at both \( \lambda = 2.2 \, \mu m \) and \( \lambda = 1.55 \, \mu m \), although the overall pulse dynamics do depend on wavelength. In particular, \( \varepsilon^2 \) is smaller at \( \lambda = 2.2 \, \mu m \) and the pulse preserves a parabolic shape for a longer distance, in agreement with the results in Fig. 4.

In conclusion, we have demonstrated that parabolic pulses can be generated in millimeter-long tapered Si-PhNWs with engineered decreasing normal GVD. Our analysis showed that using this approach optical similaritons can be generated at both telecom and mid-IR wavelengths, irrespective of the pulse shape and taper profile. However, our investigations have revealed that the efficiency of the similariton generation is strongly dependent on the wavelength at which the device operates, pulse parameters and its temporal profile, as well as the particular shape of the Si-PhNW taper.

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