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Combination and compression of multiple pulses with same or different wavelengths

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***Abstract*—We propose a practical scheme to demonstrate the combination and subsequent self-similar compression of two pulses with the same or different central wavelengths while propagating through a nonlinear fiber with exponentially decreasing dispersion. To initiate these processes, two raised cosine pulses with the same or different wavelengths is modulated using a phase modulator to acquire the same chirp at the input of the fiber. While propagating through the nonlinear fiber, these chirped pulses first coalesce into a single pulse and during further propagation get compressed into a single ultrashort high-power pulse. The output pulse possesses a large compression factor, high proportion of energy and peak power compared to a single input pulse. We also report the combination and compression of five raised cosine pulses with different wavelengths to achieve an appreciable compression effect, indicating that this system works well even with a small number of input pulses. The proposed scheme provides a simple way to generate high power ultrashort pulse with high energy and good quality in a short length of fiber.**

***Index Terms*—Computational modeling, fibers, pulse compression, nonlinear optics.**

I. INTRODUCTION

High-power ultrashort pulses are used in many fields, viz., micro machining [1], femto-chemistry [1], medical imaging [2] and optical communication [3]. Optical fiber lasers can produce high quality laser beams of kilowatt output power [4], [5], but this solution faces significant challenges such as gain saturation, thermal effects and deterioration of optical components [6]. Compared with generating ultrashort pulses by complicated fiber lasers, pulse compression can be considered as a more efficient way to achieve ultrashort pulses, which mainly include adiabatic pulse compression [7] and higher-order soliton compression [8]. For the adiabatic soliton compression, the highest compression factor is normally less than ~20 [9] and the adiabatically compressed pulses preserve the superiority of integrally transform-limited features in the experiment [10], [11]. In addition, complying with the strict adiabatic condition in a long fiber length is necessary that the dispersion map is monotonically decreasing along with the propagation direction [12]. In comparison, the higher-order soliton compression is a feasible way to realize a large degree of compression in a short fiber with a notable pedestal which causes the nonlinear interactions between adjacent solitons. As K. C. Chan pointed out in [8], the compression factor of a 15-th order soliton is up to 60, but the pedestal energy of compressed pulse is very large, nearly 80%. The method of nonlinear intensity discrimination is beneficial to reduce the pedestals [13], [14], but it ultimately causes wasting the pulse energy.

From literature, Moores [15] suggested the possibility of exact chirped soliton compression in nonlinear optical fibers with appropriate dispersion variation along the propagation. Since then, self-similar pulse compression has been a very attractive method to generate high quality ultrashort pulses in a short segment of fiber [10], [16]–[18]. Efficient and compact pulse compression method was proposed to generate nearly chirp-free and pedestal-free ultrashort pulses using exponentially dispersion decreasing fiber Bragg gratings (FBGs) [16]. Further, multiple pulses have been used to generate high-repetition-rate ultrashort pulse train in optical fibers and the pulses maintained self-similar evolution during the compression process [19]–[21]. The possibility of generating ultrashort pulse train by injecting multiple raised-cosine (RC) shaped or hyperbolic secant shaped optical pulses into a solid core photonic crystal fiber (PCF) and chloroform-filled PCF were also reported [19]. In another study, generation of ultrashort pulse train with high-repetition-rate was reported by pre-chirping initial optical signals in such a way that each pulse is individually chirped with the same amount of chirp and profile [21]. The final compressed pulses in the pulse train are almost transform-limited and pedestal-free [21]. These proposals [19]–[23] can achieve ultrashort pulses with large

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peak power, high-repetition-rate and good quality, but the central wavelengths of all the input pulses should be the same and hence the light pulse source is constraint to be of the same wavelength. Recently, a special optical fiber called dispersion oscillating fiber (DOF) was studied in [24]–[26], where the optical pulse propagates in media with periodic modulation of the dispersion parameter. In particular, DOF is numerically demonstrated as a fiber that can be used for the fusion of fundamental solitons into high-intensity pulse [24], but DOF has not been used for the purpose of pulse compression. To the best of our knowledge, the use of our suggested dispersion exponentially decreasing fiber for the simultaneous combination and compression of multiple pulses with same or different central wavelengths is demonstrated for the first time.

In this work, we propose a scheme that can combine and compress multiple pulses with same and different central wavelengths. A single nonlinear optical fiber with exponentially decreasing dispersion is the main component for this system. To initiate the process, pulses with the same or different central frequency must be added with appropriate initial chirp and then launched into the dispersion decreasing fiber. The required chirp is a linear profile with respect to time that covers all the pulses that are to be combined with the zero value of the chirp initially. To begin with, we use two raised cosine (RC) pulses with the same or different wavelengths that are modulated by a phase modulator to have the appropriate initial chirp. Then these chirped pulses are launched into the dispersion decreasing nonlinear fiber where they coalesce into a single pulse and during further evolution experiences efficient compression. Rapid self-similar compression can be achieved in a short length of fiber and the output single pulse contains a major portion of the energies from both input pulses. Eventually, we demonstrate that this method can compress up to five initial pulses with different central carrier wavelengths between them. The proposed system is convenient and can achieve a high-energy ultrashort pulse within a short length of fiber.

II. Theoretical Models

Pulse evolution in a nonlinear optical fiber is governed by the generalized nonlinear Schrödinger equation (GNLSE) [27],

$$\frac{\partial A}{\partial z}+\frac{i\beta_2(z)}{2}\frac{\partial^2 A}{\partial t^2}=i\left(\gamma(\omega_0)+i\gamma_1\frac{\partial}{\partial t}\right) \times\left(A(z,t)\int_0^\infty R(t')\left|A(z,t-t')\right|^2 dt'\right), \quad (1)$$

where A is the amplitude of the slowly varying pulse envelope, z is the distance variable, t is the time variable. $\beta_2(z)$ and γ are the second-order dispersion and nonlinearity coefficients of the fiber, respectively. The higher-order dispersion may be compensated by dispersion-compensation fiber, frequency-resolved programmable dispersion compensator, dispersion slope compensation or third- and fourth-order active dispersion compensation with a phase modulator [28]–[30]. We also numerically study the effect of third order dispersion on our proposed scheme, and we find that if the ratio of the second order dispersion length and third order dispersion length $L_{D2}(z)/L_{D3}(z)$ is smaller than 0.5, third-order dispersion have little influence on the combination and compression of multiple optical pulses here. Therefore, we ignore the higher-order dispersion in Eq. (1) and use it as the theoretical model and for the numerical simulations. Here $\beta_2(z)$ is assumed to decrease exponentially as $\beta_2(z)=\beta_{20}\exp(-\sigma z)$, where β_{20} is the initial second-order dispersion of the fiber and σ is the decay rate of the fiber dispersion. γ is assumed to be constant along the whole fiber. $\gamma_1 \approx \gamma/\omega_0$ and ω_0 is the center frequency of the pulse. Here ω_0 is considered as 1550 nm.

The nonlinear response function is given by

$$R(t)=(1-f_R)\delta(t)+f_R h_R(t), \quad (2)$$

where $f_R=0.18$, and the Raman response function h_R is in the form of

$$h_R(t)=\frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp\left(-\frac{t}{\tau_2}\right)\sin\left(\frac{t}{\tau_1}\right), \quad (3)$$

where $\tau_1=12.2$ fs and $\tau_2=32$ fs.

We chose two chirped raised cosine pulses as input to examine the pulse compression. Even though the proposed method is for initial pulses with different central wavelengths, we first consider the situation of input pulses with same wavelength. The chirped RC pulse on the left hand side in Fig. 1(a) is expressed as

$$\frac{\sqrt{P_0}}{2}\left\{1+\cos\left[\pi(t/T_0+1)\right]\right\}\exp\left(i\alpha_{20}t^2/2\right), t/T_0\in[-2,0], \quad (4)$$

where α_{20}, P_0 and T_0 are the initial chirp, peak power and pulse width parameters, respectively. The fiber is considered to have an exponentially decreasing second-order dispersion and constant nonlinear coefficient. The decay rate of the second-order dispersion is related to the initial chirp (α_{20}) and initial value of dispersion coefficient (β_{20}) and is given by $\sigma=\alpha_{20}\beta_{20}$. The fiber parameters are considered as $\beta_{20}=-25\ \text{ps}^2/\text{km}$, $\sigma=12.5$ /km, $\gamma=10$ /W/km and a length of $L=300$ m. This pulse central wavelength 1550 nm is the reference wavelength and is used for calculating the fiber parameters.

The chirped RC pulse on the right-hand side in Fig. 1(a) is expressed as

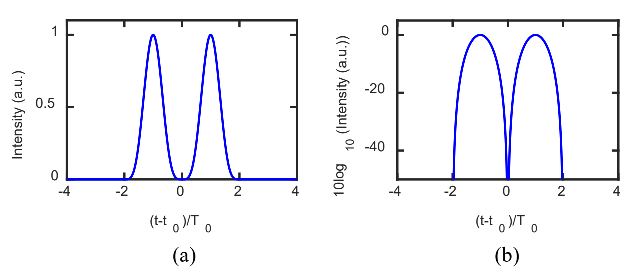
$$\frac{\sqrt{P_0}}{2}\left\{1+\cos\left[\pi(t/T_0+1)\right]\right\}\exp\left(i2\pi\Delta\nu t\right)\exp\left(i\alpha_{20}t^2/2\right),\ t/T_0\in[0,2], \quad (5)$$

where $\Delta\nu$ is the difference between the center frequencies of the two input pulses that share the common initial chirp. For the first simulation, we consider $\Delta\nu=0$ as both the pulses are considered to be of the same wavelength. Later, we will consider the $\Delta\nu=0.1247$ THz corresponding to a difference of center wavelengths $\Delta\lambda=1$ nm. Thus, the spectrum of the right-hand-side pulse given by Eq. (2) is centered at 1551 nm. Please note the bandwidth of input single RC pulse in the form of Eqs. (2) or (3) is around 4.2 nm.

III. Investigation on Combination and Compression of the Chirped RC Pulses

A. Combination and Compression of Two Chirped RC Pulses with Same Central Wavelengths

As shown in Fig. 1(a) [logarithmic scale in Fig. 1(b)], we assume that the center wavelengths of the two initial pulses are λ_0 and λ_1 corresponding to the left pulse and right pulse, respectively. We consider the combination and compression of two chirped RC pulses with the same center wavelengths with λ_0 and λ_1 both equal to 1550 nm. The two chirped RC pulses are in the form of Eqs. (4) and (5) where the $\Delta\nu = 0$ and the other pulse parameters are $T_0 = 1.374$ ps which corresponds to a full width at half-maximum (FWHM) of 1 ps, $\alpha_{20} = -0.5\ \text{THz}^2$, and $P_0 = 2.649$ W ($P_0 = 2|\beta_{20}|/\gamma/T_0^2$). The profile of the output pulse after 300 m of propagation in the dispersion decreasing nonlinear fiber is shown in Fig. 1(c) [logarithmic scale in 1(d)]. The input RC pulses eventually coalesced into a single pulse with a time bandwidth product (TBP) of 0.315, which is the value for the transform-limited hyperbolic secant pulse. This indicates that the compressed pulse is an unchirped hyperbolic secant shape. Initial chirp added across the pulses is compensated by the effects of exponentially decreasing dispersion and self-phase modulation during the propagation in the fiber. The FWHM is reduced to 61.85 fs (initial value 1 ps) which corresponds to a compression factor of 16.17. The peak power of the output pulse is 49.82 W, which is 18.81 times of a single initial pulse. Calculation of the input/output energy ratio will help to estimate the amount of energy possessed by the output pulse compared to that of the initial pulses after compression. The energy ratio is defined as the output pulse energy (calculated using a hyperbolic secant profile fit) to the total input pulses' energy. In the hyperbolic secant profile fit, we use the numerical method to calculate peak power and pulse width of the output pulse from the simulation results. The energy ratio is 64.04% implying that the compressed output pulse acquired more energy after the combination and compression of two pulses than the input single pulse. Figure 1(e) illustrates that the spectrum of the two input pulses is symmetric and the center of the spectrum is located at 1550 nm. Figure 1(f) reveals that the spectrum of the combined and compressed output pulse become asymmetric because of higher order nonlinear effects considered in the model for the propagation of the light beam in the nonlinear fiber.



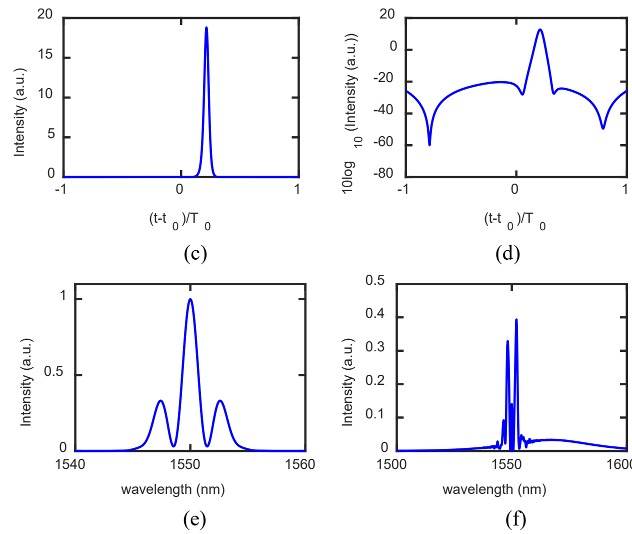


Fig. 1. The input chirped RC pulses profile with the same center wavelength in (a) linear and (b) logarithmic scales. The output compressed pulse after 300 m of propagation in (c) linear and (d) logarithmic scales. (e) The spectrum of launched chirped RC input pulses. (f) The spectrum of the combined and compressed output pulse after 300 m of propagation in dispersion decreasing nonlinear fiber.

B. Combination and Compression of Two Chirped RC Pulses with Different Central Wavelengths

Now we investigate the effectiveness of the proposed scheme for combination and compression of two RC pulses with different central wavelengths of 1550 nm and 1551 nm that can be provided from different laser sources. Figure 2(a) [logarithmic scale in Fig. 2(b)] represents the profile of two input RC pulses in the form of Eqs. (4) and (5), respectively, with $\Delta\nu = 0.1247$ THz . In order to share a common linear chirp, the pulses are to be modulated by a phase modulator. All other parameters for pulses and fiber are assumed to be the same as Section A. The output pulses after propagating 300 m in the exponentially dispersion decreasing fiber are shown in Figs. 2(c) and 2(d), respectively. Figure 2(c) indicates that the peak power of the output pulse reaches 45.41 W corresponding to about 17.14 times that of a single initial pulse. The compressed pulse contains 60.14% of the total input pulses' energies. The FWHM is reduced to 63.73 fs (initial value 1 ps) corresponding to a compression factor of 15.7, which is comparable to the compression factor of 16.17 which is the result from two RC pulses with same wavelength reported in Section A. The time-bandwidth product is calculated to be 0.260 revealing that the main portion of the compressed pulse is slightly distorted. Figure 2(e) shows the spectrum of the launched chirped RC input pulses with the different center wavelengths. Figure 2(f) depicts that the output pulse spectrum also becomes asymmetric like Fig. 1(f) because of the higher order nonlinear effects included in the nonlinear fiber model equation.

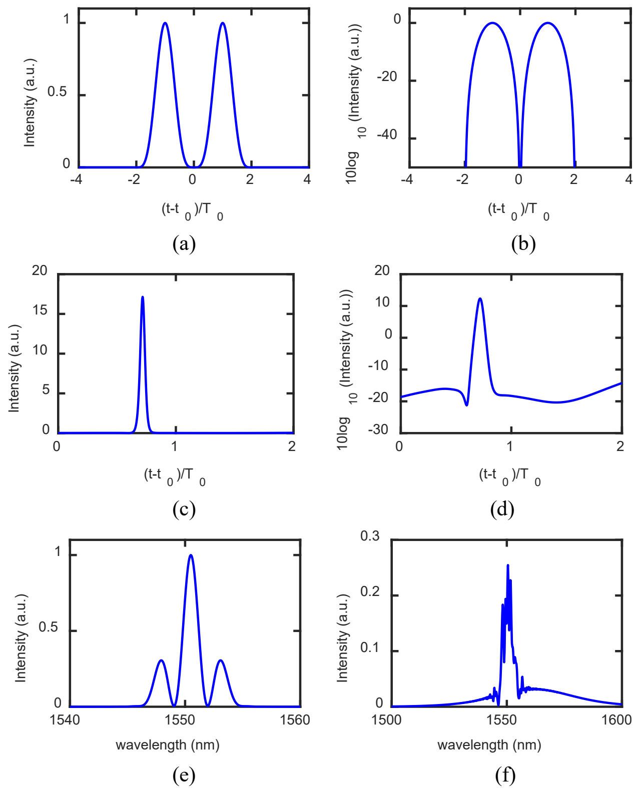


Fig. 2. The input chirped RC pulses with the different central wavelengths of λ_0 = 1550 nm and λ_1 = 1551 nm in both (a) linear and (b) logarithmic scales. The output compressed pulse at 300 m in both (c) linear and (d) logarithmic scales. (e) The spectra of launched chirped RC input pulses. (f) The spectra of the combined and compressed output pulse after 300 m of propagation in dispersion exponentially decreasing nonlinear fiber.

The pulse characteristics at the combination length have notable features. Figures 3(a) and 3(b) illustrate the combined pulse at the combination length 153 m in both linear and logarithmic scales. The combined pulse almost maintains the hyperbolic secant profile and contains 58.96% of input pulses' energies. The FWHM of the combined pulse is 0.46 ps corresponding to a compression factor of 2.17. It means that during the combination process itself, the pulse undergoes a slight compression. At this stage, the time-bandwidth product of the combined pulse is 0.403, which is lower than the value of 0.526 for the input pulses. With the interaction between decreasing dispersion and self-phase modulation effects, the initial linear chirp brings the two pulses together for the combination at a specific distance, which is the combination length. Here, the combination length is defined as the fiber length at which the peak power for the pedestal is less than 10% of the peak power for the compressed pulse. During propagation, because of the shared chirp, different spectral components of the two pulses do achieve almost the same phase shift and then coalesced into a single pulse at the combination length. In the remaining length of the fiber, the combined single pulse undergoes nearly self-similar compression because of the interaction of exponentially decreasing dispersion and self-phase modulation compensating the leftover initially added chirp that remains in the combined pulse.

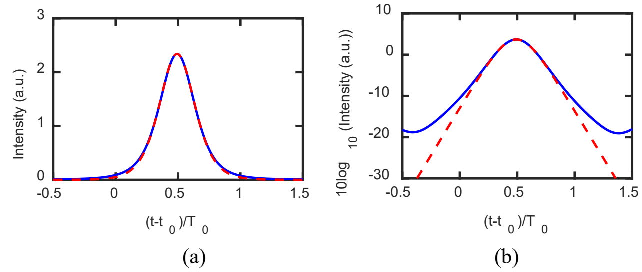


Fig. 3. The combined pulse (solid curve) for the input RC input pulses with λ_0 = 1550 nm and λ_1 = 1551 nm and curve fitted hyperbolic secant pulse (dashed curve) at 153 m in (a) linear and (b) logarithmic scales, respectively.

Table 1 compares the results of the compressed pulses with the same and different central wavelengths. Though it takes a bit longer fiber to merge the two RC pulses with different central wavelengths, the scheme works effectively for the compression of pulses as shown in Table 1. The results illustrate that two input pulses from different sources can be efficiently and compactly combined and compressed to generate single high-power ultrashort pulse by appropriately chirping the pulses and propagating them through an exponentially dispersion decreasing nonlinear fiber.

	$\lambda_0 = \lambda_1$ = 1550 nm	λ_0 = 1550 nm, λ_1 = 1551 nm
Compression Factor	16.17	15.70
TBP	0.315	0.260
Peak Power (W)	49.82	45.41
Energy Ratio	64.04 %	60.14%
Combination Length (m)	136	153

Table 1. Compression factor, time-bandwidth product, peak power, energy ratio and combination length for two RC pulses compression with initially the same and different central wavelengths.

We represent the pulse evolutions and compression factor of two chirped RC input pulses for the same center wavelength of 1550 nm and different center wavelengths of 1550 nm and 1551 nm along the propagating direction in Fig. 4. From Fig. 4(a), owing to the influence of the shared initial chirp, both pulses first move towards the zero position of the time coordinate axis and coalesce into a single pulse at the fiber length of around 136 m, leaving behind small peaks on either side of it. The peak power of the main pulse gradually increases to 2.31 times of the initial peak power during the pulse combination process. In the remaining 164 m of propagation, the combined pulse is compressed and transformed into a soliton-like pulse at the end of the fiber. Figure 4(b) shows the case of two RC pulses initially with different wavelengths. Similar to Fig. 4(a), the two input pulses first coalesce into a single pulse at 153 m (combination length) and then go through self-similar pulse compression in the rest of the fiber. Figure 4(b) shows that the compressed pulse with different central wavelength suffers more temporal shift than that of the same central wavelength (Fig. 4(a)). Figure 4(c) indicates that the evolution of the compression factor of the combined pulse varies almost exponentially as that from the theoretical self-similar model (dotted curve). The FWHM pulse width of the combined pulse at 136 m and the compressed pulse at 300 m are 0.51 ps and 61.85 fs, respectively. The final compression factor is 16.17, which is comparable to 15.32 calculated from self-similar pulse compression. Figure 4(d) illustrates that the compression factor achieved during the propagation in the last 147 m of the fiber is 15.70, which is close to the value of 14.79 calculated from self-similar pulse compression. Self-frequency shift (SSFS) induced by the Raman scattering has a notable influence on femtosecond pulses [31], and here as shown in Figs. 4(e) and 4(f), the output pulse spectrum is broadened and the energy transfer emerges as a red shift with the propagation distance increasing due to the effect of Raman scattering.

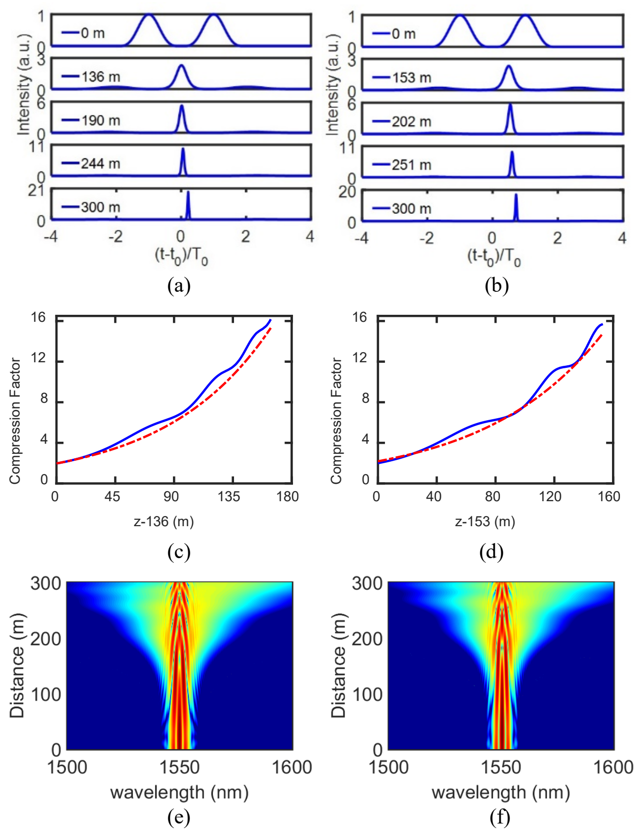


Fig. 4. Evolution of two chirped RC input pulses along the propagating direction for (a) the same center wavelength of 1550 nm and (b) different central wavelengths of λ_0 = 1550 nm and λ_1 = 1551 nm. The compression factor of the combined pulses (solid curves) and the related compression factor of theoretical self-similar compression (dotted curves) for the corresponding (c) the same and (d) different central wavelengths. Contour plot of spectral evolutions of the launched chirped RC input pulses for the corresponding (e) same and (f) different central wavelengths during propagation.

C. *Influence of Central Wavelengths Separation*

In this Section, we explore the influence of the separation between the center wavelengths based on the amount of energy acquired by the compressed pulse from the initial pulses. We report the simulation results for the compressed pulses by fixing the center wavelength of one input pulse (λ_0) to be 1550 nm and vary the center wavelength (λ_1) of the other input pulse. Figures 5(a) to 5(c) represent the variation of energy ratio, compression factor and combination length versus wavelength separation ratio (WSR), where WSR is defined as the ratio of wavelength separation $\lambda_1 - \lambda_0$ to the bandwidth of a single input pulse. In Fig. 5(a), we study the energy ratios of output pulses versus different input pulses with center wavelengths λ_1 ranging from 1548 to 1552 nm, where the corresponding WSR is from –0.48 to 0.48. The energy ratio gradually increases from 46.32% to 64.04% and the maximum of energy ratio of 64.04% is achieved when WSR is 0. There are some fluctuations on the compression factor profile while considering different central wavelengths for the two input pulses. As shown in Figs. 5(b) and 5(c), the compression factor and the combination lengths are also quite different for different WSR from –0.48 to 0.48. Within this WSR span, the minimum compression factor is 12.08 at –0.48 and the maximum value achieved is 16.17 at 0. In addition, the combination length decreases from 209 m to 136 m as the WSR increases from –0.48 to 0 and increases from 136 to 204 m as the WSR increases from 0 to 0.48. When WSR equals to –0.48, the combination length is 209 m and only 91 m length of fiber remains for the self-similar compression. From the simulations results, we conclude that within an appreciable range of central wavelengths separation, two RC pulses can be combined and compressed efficiently.

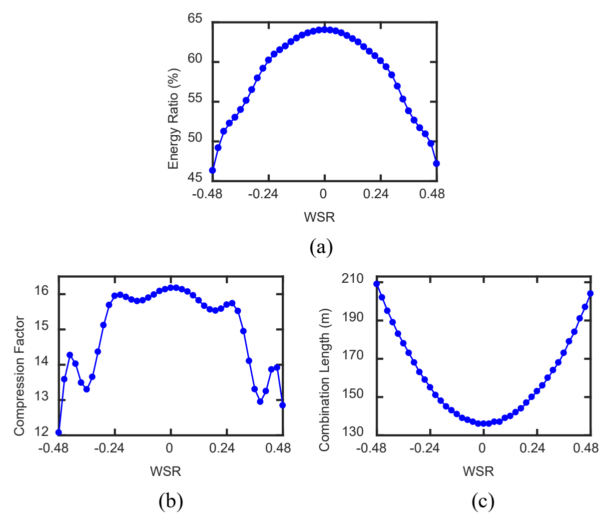
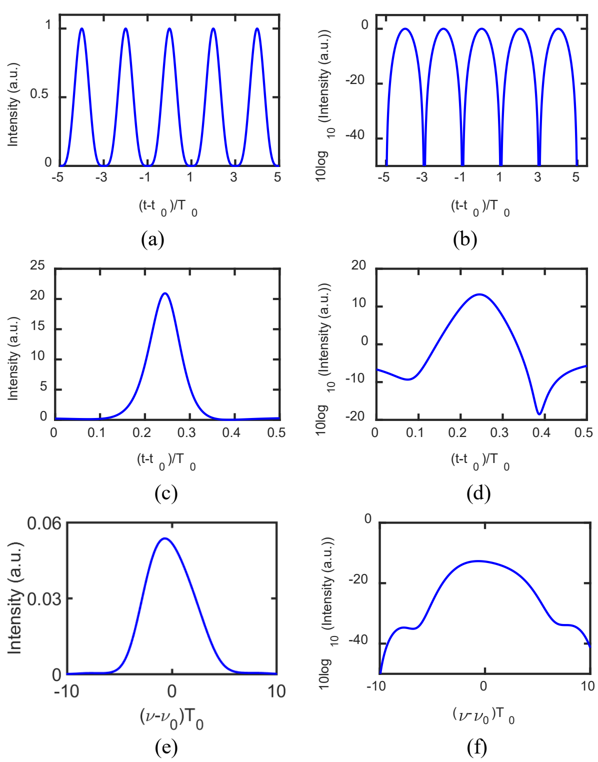


Fig. 5. (a) Energy ratio, (b) compression factor and (c) combination length of compressed output pulse at 300 m length of fiber versus different wavelength separation ratio (WSR).

D. *Combination and Compression of a few Chirped RC Pulses with Different Central Wavelengths*

We studied the combining and compressing of more than two input pulses and report the results of generating single high-power ultrashort pulse from five chirped RC pulses with different center wavelengths. In the five input pulses, the central wavelengths of five pulses are at 1550, 1550.1, 1550.2, 1550.3 and 1550.4 nm which correspond to a frequency separation of $\Delta v = 12.5$ GHz between two neighboring pulses. This situation can be considered as the five consecutive pulses are generated from different laser sources with different wavelengths. The five pulses are in the form of Eq. (1) for $t/T_0 \in [-5,5]$. Five chirped RC input pulses are chosen to have the same values for T_0 and α_{20} as in the case of two chirped RC pulses, but with optimized P_0 value of 0.662 W ($P_0 = 0.5|\beta_{20}|/\gamma/T_0^2$). The fiber parameters are the same as the case in Section A. Figures 6(a) and 6(b) represents the profile of five chirped RC input pulses of time domain in (a) linear and (b) logarithmic scales. Figures 6(c) and 6(d) depict the output pulse profile after the five chirped RC pulses propagated through the fiber length of 300 m in (c) linear and (d) logarithmic scales, respectively. The peak power of the compressed pulse is 13.86 W, which is 20.94 times that of the incident pulses. Energy ratio is calculated as 49.9%, which indicates that the compressed pulse acquired an amount of nearly 2.5 times energy as compared to the single input pulse. The initial FWHM pulse width of 1 ps decreases to 108.3 fs at the fiber output, which corresponds to a compression factor of 9.23. Figures 6(e) and 6(f) show the spectra of the main compressed pulse in $(t-t_c)/T_0 \in [-0.1,0.1]$ in (e) linear and (f) logarithmic scales, respectively. Here t_c is the central position of the output pulse at the end of the fiber. Obvious bandwidth broadening occurs during the compression process and the bandwidth-broadening factor is calculated as 7.64. Figure 6(g) illustrates the evolution of the compression factor along the fiber length during the last 37 m of the compression process for the combination pulse. In this five pulses combination and compression study, the combination length is found to be 263 m. As the number of input pulses increases, the combination length also raises for compression process.



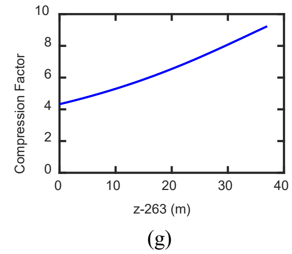


Fig. 6. Chirped five RC input pulses in both (a) linear and (b) logarithmic scales. Output pulse at fiber length of 300 m for compression of five RC pulses in (c) linear and (d) logarithmic scales. Spectra of the main pulse at 300 m in (e) linear scale and (f) logarithmic scale. (g) The compression factor of the chirped five RC pulses compression during the 37 m propagation of compression process.

IV. Conclusion

We have demonstrated that rapid combination and effective compression can be realized in a short length of dispersion decreasing nonlinear optical fiber by launching two chirped raised cosine pulses with different central wavelengths. For initial center wavelengths of 1550 and 1551 nm, the combination length for two RC pulses is 153 m and the energy ratio achieved is nearly 60.14%, implying that the input pulses coalesce into a single pulse rapidly and then experience efficient self-similar compression process. We find that the center wavelength separation between two input pulses can be up to 1.8 nm for the compressed output pulse to retain at least the energy of a single input pulse. We have also explored the combination and compression of five RC input pulses with different wavelengths, demonstrating that pulses from different lasers sources with different center wavelength could be compressed effectively. The proposed scheme is convenient and efficient and we believe that this can be practically useful for the generation of high-power ultrashort optical pulse from low power wide pulses from different wavelength laser sources.

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Combination and compression of multiple pulses with same or different wavelengths

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***Abstract*—We propose a practical scheme to demonstrate the combination and subsequent self-similar compression of two pulses with the same or different central wavelengths while propagating through a nonlinear fiber with exponentially decreasing dispersion. To initiate these processes, two raised cosine pulses with the same or different wavelengths is modulated using a phase modulator to acquire the same chirp at the input of the fiber. While propagating through the nonlinear fiber, these chirped pulses first coalesce into a single pulse and during further propagation get compressed into a single ultrashort high-power pulse. The output pulse possesses a large compression factor, high proportion of energy and peak power compared to a single input pulse. We also report the combination and compression of five raised cosine pulses with different wavelengths to achieve an appreciable compression effect, indicating that this system works well even with a small number of input pulses. The proposed scheme provides a simple way to generate high power ultrashort pulse with high energy and good quality in a short length of fiber.**

***Index Terms*—Computational modeling, fibers, pulse compression, nonlinear optics.**

I. Introduction

High-power ultrashort pulses are used in many fields, viz., micro machining [1], femto-chemistry [1], medical imaging [2] and optical communication [3]. Optical fiber lasers can produce high quality laser beams of kilowatt output power [4], [5], but this solution faces significant challenges such as gain saturation, thermal effects and deterioration of optical components [6]. Compared with generating ultrashort pulses by complicated fiber lasers, pulse compression can be considered as a more efficient way to achieve ultrashort pulses, which mainly include adiabatic pulse compression [7] and higher-order soliton compression [8]. For the adiabatic soliton compression, the highest compression factor is normally less than ~20 [9] and the adiabatically compressed pulses preserve the superiority of integrally transform-limited features in the experiment [10], [11]. In addition, complying with the strict adiabatic condition in a long fiber length is necessary that the dispersion map is monotonically decreasing along with the propagation direction [12]. In comparison, the higher-order soliton compression is a feasible way to realize a large degree of compression in a short fiber with a notable pedestal which causes the nonlinear interactions between adjacent solitons. As K. C. Chan pointed out in [8], the compression factor of a 15-th order soliton is up to 60, but the pedestal energy of compressed pulse is very large, nearly 80%. The method of nonlinear intensity discrimination is beneficial to reduce the pedestals [13], [14], but it ultimately causes wasting the pulse energy.

From literature, Moores [15] suggested the possibility of exact chirped soliton compression in nonlinear optical fibers with appropriate dispersion variation along the propagation. Since then, self-similar pulse compression has been a very attractive method to generate high quality ultrashort pulses in a short segment of fiber [10], [16]–[18]. Efficient and compact pulse compression method was proposed to generate nearly chirp-free and pedestal-free ultrashort pulses using exponentially dispersion decreasing fiber Bragg gratings (FBGs) [16]. Further, multiple pulses have been used to generate high-repetition-rate ultrashort pulse train in optical fibers and the pulses maintained self-similar evolution during the compression process [19]–[21]. The possibility of generating ultrashort pulse train by injecting multiple raised-cosine (RC) shaped or hyperbolic secant shaped optical pulses into a solid core photonic crystal fiber (PCF) and chloroform-filled PCF were also reported [19]. In another study, generation of ultrashort pulse train with high-repetition-rate was reported by pre-chirping initial optical signals in such a way that each pulse is individually chirped with the same amount of chirp and profile [21]. The final compressed pulses in the pulse train are almost transform-limited and pedestal-free [21]. These proposals [19]–[23] can achieve ultrashort pulses with large peak power, high-repetition-rate and good quality, but the central wavelengths of all the input pulses should be the same

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and hence the light pulse source is constraint to be of the same wavelength. Recently, a special optical fiber called dispersion oscillating fiber (DOF) was studied in [24]–[26], where the optical pulse propagates in media with periodic modulation of the dispersion parameter. In particular, DOF is numerically demonstrated as a fiber that can be used for the fusion of fundamental solitons into high-intensity pulse [24], but DOF has not been used for the purpose of pulse compression. To the best of our knowledge, the use of our suggested dispersion exponentially decreasing fiber for the simultaneous combination and compression of multiple pulses with same or different central wavelengths is demonstrated for the first time.

In this work, we propose a scheme that can combine and compress multiple pulses with same and different central wavelengths. A single nonlinear optical fiber with exponentially decreasing dispersion is the main component for this system. To initiate the process, pulses with the same or different central frequency must be added with appropriate initial chirp and then launched into the dispersion decreasing fiber. The required chirp is a linear profile with respect to time that covers all the pulses that are to be combined with the zero value of the chirp initially. To begin with, we use two raised cosine (RC) pulses with the same or different wavelengths that are modulated by a phase modulator to have the appropriate initial chirp. Then these chirped pulses are launched into the dispersion decreasing nonlinear fiber where they coalesce into a single pulse and during further evolution experiences efficient compression. Rapid self-similar compression can be achieved in a short length of fiber and the output single pulse contains a major portion of the energies from both input pulses. Eventually, we demonstrate that this method can compress up to five initial pulses with different central carrier wavelengths between them. The proposed system is convenient and can achieve a high-energy ultrashort pulse within a short length of fiber.

II. Theoretical Models

Pulse evolution in a nonlinear optical fiber is governed by the generalized nonlinear Schrödinger equation (GNLSE) [27],

$$\frac{\partial A}{\partial z}+\frac{i\beta_2(z)}{2}\frac{\partial^2 A}{\partial t^2}=i\left(\gamma(\omega_0)+i\gamma_1\frac{\partial}{\partial t}\right) \times\left(A(z,t)\int_0^\infty R(t')\left|A(z,t-t')\right|^2 dt'\right), \quad (1)$$

where A is the amplitude of the slowly varying pulse envelope, z is the distance variable, t is the time variable. $\beta_2(z)$ and γ are the second-order dispersion and nonlinearity coefficients of the fiber, respectively. The higher-order dispersion may be compensated by dispersion-compensation fiber, frequency-resolved programmable dispersion compensator, dispersion slope compensation or third- and fourth-order active dispersion compensation with a phase modulator [28]–[30]. We also numerically study the effect of third order dispersion on our proposed scheme, and we find that if the ratio of the second order dispersion length and third order dispersion length $L_{D2}(z)/L_{D3}(z)$ is smaller than 0.5, third-order dispersion have little influence on the combination and compression of multiple optical pulses here. Therefore, we ignore the higher-order dispersion in Eq. (1) and use it as the theoretical model and for the numerical simulations. Here $\beta_2(z)$ is assumed to decrease exponentially as $\beta_2(z)=\beta_{20}\exp(-\sigma z)$, where β_{20} is the initial second-order dispersion of the fiber and σ is the decay rate of the fiber dispersion. γ is assumed to be constant along the whole fiber. $\gamma_1\approx\gamma/\omega_0$ and ω_0 is the center frequency of the pulse. Here ω_0 is considered as 1550 nm.

The nonlinear response function is given by

$$R(t)=(1-f_R)\delta(t)+f_R h_R(t), \quad (2)$$

where $f_R=0.18$, and the Raman response function h_R is in the form of

$$h_R(t)=\frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp\left(-\frac{t}{\tau_2}\right)\sin\left(\frac{t}{\tau_1}\right), \quad (3)$$

where $\tau_1=12.2$ fs and $\tau_2=32$ fs.

We chose two chirped raised cosine pulses as input to examine the pulse compression. Even though the proposed method is for initial pulses with different central wavelengths, we first consider the situation of input pulses with same wavelength. The chirped RC pulse on the left hand side in Fig. 1(a) is expressed as

$$\frac{\sqrt{P_0}}{2}\left\{1+\cos\left[\pi(t/T_0+1)\right]\right\}\exp\left(i\alpha_{20}t^2/2\right), t/T_0\in[-2,0], \quad (4)$$

where α_{20}, P_0 and T_0 are the initial chirp, peak power and pulse width parameters, respectively. The fiber is considered to have an exponentially decreasing second-order dispersion and constant nonlinear coefficient. The decay rate of the second-order dispersion is related to the initial chirp (α_{20}) and initial value of dispersion coefficient (β_{20}) and is given by $\sigma=\alpha_{20}\beta_{20}$. The fiber parameters are considered as $\beta_{20}=-25\ \text{ps}^2/\text{km}$, $\sigma=12.5$ /km, $\gamma=10$ /W/km and a length of $L=300$ m. This pulse central wavelength 1550 nm is the reference wavelength and is used for calculating the fiber parameters.

The chirped RC pulse on the right-hand side in Fig. 1(a) is expressed as

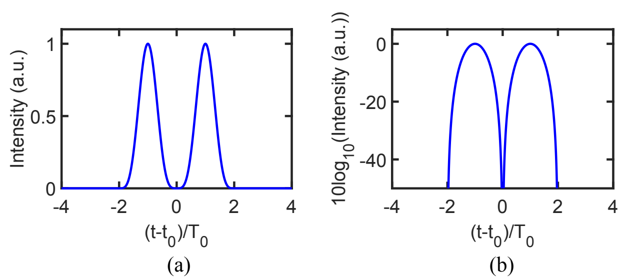
$$\frac{\sqrt{P_0}}{2}\left\{1+\cos\left[\pi(t/T_0+1)\right]\right\}\exp(i2\pi\Delta\nu t)\exp\left(i\alpha_{20}t^2/2\right),\ t/T_0\in[0,2], \quad (5)$$

where $\Delta\nu$ is the difference between the center frequencies of the two input pulses that share the common initial chirp. For the first simulation, we consider $\Delta\nu=0$ as both the pulses are considered to be of the same wavelength. Later, we will consider the $\Delta\nu=0.1247$ THz corresponding to a difference of center wavelengths $\Delta\lambda=1$ nm. Thus, the spectrum of the right-hand-side pulse given by Eq. (2) is centered at 1551 nm. Please note the bandwidth of input single RC pulse in the form of Eqs. (2) or (3) is around 4.2 nm.

III. Investigation on Combination and Compression of the Chirped RC Pulses

A. Combination and Compression of Two Chirped RC Pulses with Same Central Wavelengths

As shown in Fig. 1(a) [logarithmic scale in Fig. 1(b)], we assume that the center wavelengths of the two initial pulses are λ_0 and λ_1 corresponding to the left pulse and right pulse, respectively. We consider the combination and compression of two chirped RC pulses with the same center wavelengths with λ_0 and λ_1 both equal to 1550 nm. The two chirped RC pulses are in the form of Eqs. (4) and (5) where the $\Delta v = 0$ and the other pulse parameters are $T_0 = 1.374$ ps which corresponds to a full width at half-maximum (FWHM) of 1 ps, $\alpha_{20} = -0.5\ \text{THz}^2$, and $P_0 = 2.649$ W ($P_0 = 2|\beta_{20}|/\gamma/T_0^2$). The profile of the output pulse after 300 m of propagation in the dispersion decreasing nonlinear fiber is shown in Fig. 1(c) [logarithmic scale in 1(d)]. The input RC pulses eventually coalesced into a single pulse with a time bandwidth product (TBP) of 0.315, which is the value for the transform-limited hyperbolic secant pulse. This indicates that the compressed pulse is an unchirped hyperbolic secant shape. Initial chirp added across the pulses is compensated by the effects of exponentially decreasing dispersion and self-phase modulation during the propagation in the fiber. The FWHM is reduced to 61.85 fs (initial value 1 ps) which corresponds to a compression factor of 16.17. The peak power of the output pulse is 49.82 W, which is 18.81 times of a single initial pulse. Calculation of the input/output energy ratio will help to estimate the amount of energy possessed by the output pulse compared to that of the initial pulses after compression. The energy ratio is defined as the output pulse energy (calculated using a hyperbolic secant profile fit) to the total input pulses' energy. In the hyperbolic secant profile fit, we use the numerical method to calculate peak power and pulse width of the output pulse from the simulation results. The energy ratio is 64.04% implying that the compressed output pulse acquired more energy after the combination and compression of two pulses than the input single pulse. Figure 1(e) illustrates that the spectrum of the two input pulses is symmetric and the center of the spectrum is located at 1550 nm. Figure 1(f) reveals that the spectrum of the combined and compressed output pulse become asymmetric because of higher order nonlinear effects considered in the model for the propagation of the light beam in the nonlinear fiber.



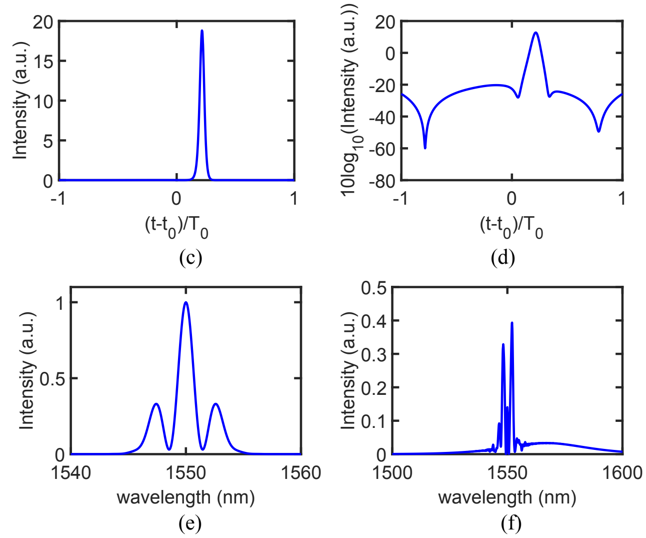


Fig. 1. The input chirped RC pulses profile with the same center wavelength in (a) linear and (b) logarithmic scales. The output compressed pulse after 300 m of propagation in (c) linear and (d) logarithmic scales. (e) The spectrum of launched chirped RC input pulses. (f) The spectrum of the combined and compressed output pulse after 300 m of propagation in dispersion decreasing nonlinear fiber.

B. Combination and Compression of Two Chirped RC Pulses with Different Central Wavelengths

Now we investigate the effectiveness of the proposed scheme for combination and compression of two RC pulses with different central wavelengths of 1550 nm and 1551 nm that can be provided from different laser sources. Figure 2(a) [logarithmic scale in Fig. 2(b)] represents the profile of two input RC pulses in the form of Eqs. (4) and (5), respectively, with $\Delta v = 0.1247$ THz. In order to share a common linear chirp, the pulses are to be modulated by a phase modulator. All other parameters for pulses and fiber are assumed to be the same as Section A. The output pulses after propagating 300 m in the exponentially dispersion decreasing fiber are shown in Figs. 2(c) and 2(d), respectively. Figure 2(c) indicates that the peak power of the output pulse reaches 45.41 W corresponding to about 17.14 times that of a single initial pulse. The compressed pulse contains 60.14% of the total input pulses' energies. The FWHM is reduced to 63.73 fs (initial value 1 ps) corresponding to a compression factor of 15.7, which is comparable to the compression factor of 16.17 which is the result from two RC pulses with same wavelength reported in Section A. The time-bandwidth product is calculated to be 0.260 revealing that the main portion of the compressed pulse is slightly distorted. Figure 2(e) shows the spectrum of the launched chirped RC input pulses with the different center wavelengths. Figure 2(f) depicts that the output pulse spectrum also becomes asymmetric like Fig. 1(f) because of the higher order nonlinear effects included in the nonlinear fiber model equation.

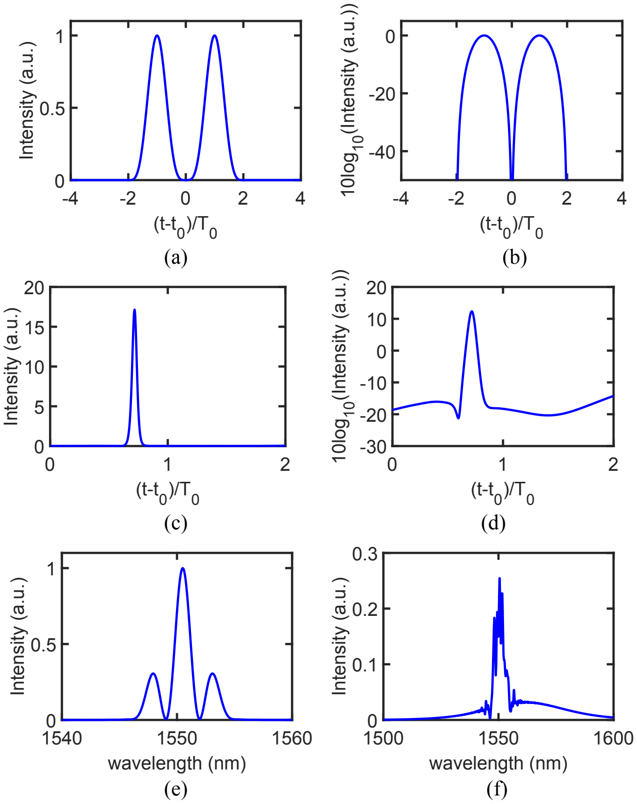


Fig. 2. The input chirped RC pulses with the different central wavelengths of λ_0 = 1550 nm and λ_1 = 1551 nm in both (a) linear and (b) logarithmic scales. The output compressed pulse at 300 m in both (c) linear and (d) logarithmic scales. (e) The spectra of launched chirped RC input pulses. (f) The spectra of the combined and compressed output pulse after 300 m of propagation in dispersion exponentially decreasing nonlinear fiber.

The pulse characteristics at the combination length have notable features. Figures 3(a) and 3(b) illustrate the combined pulse at the combination length 153 m in both linear and logarithmic scales. The combined pulse almost maintains the hyperbolic secant profile and contains 58.96% of input pulses' energies. The FWHM of the combined pulse is 0.46 ps corresponding to a compression factor of 2.17. It means that during the combination process itself, the pulse undergoes a slight compression. At this stage, the time-bandwidth product of the combined pulse is 0.403, which is lower than the value of 0.526 for the input pulses. With the interaction between decreasing dispersion and self-phase modulation effects, the initial linear chirp brings the two pulses together for the combination at a specific distance, which is the combination length. Here, the combination length is defined as the fiber length at which the peak power for the pedestal is less than 10% of the peak power for the compressed pulse. During propagation, because of the shared chirp, different spectral components of the two pulses do achieve almost the same phase shift and then coalesced into a single pulse at the combination length. In the remaining length of the fiber, the combined single pulse undergoes nearly self-similar compression because of the interaction of exponentially decreasing dispersion and self-phase modulation compensating the leftover initially added chirp that remains in the combined pulse.

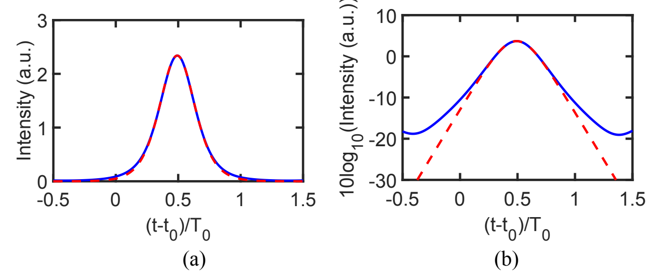


Fig. 3. The combined pulse (solid curve) for the input RC input pulses with λ_0 = 1550 nm and λ_1 = 1551 nm and curve fitted hyperbolic secant pulse (dashed curve) at 153 m in (a) linear and (b) logarithmic scales, respectively.

Table 1 compares the results of the compressed pulses with the same and different central wavelengths. Though it takes a bit longer fiber to merge the two RC pulses with different central wavelengths, the scheme works effectively for the compression of pulses as shown in Table 1. The results illustrate that two input pulses from different sources can be efficiently and compactly combined and compressed to generate single high-power ultrashort pulse by appropriately chirping the pulses and propagating them through an exponentially dispersion decreasing nonlinear fiber.

	$\lambda_0 = \lambda_1$ = 1550 nm	λ_0 = 1550 nm, λ_1 = 1551 nm
Compression Factor	16.17	15.70
TBP	0.315	0.260
Peak Power (W)	49.82	45.41
Energy Ratio	64.04 %	60.14%
Combination Length (m)	136	153

Table 1. Compression factor, time-bandwidth product, peak power, energy ratio and combination length for two RC pulses compression with initially the same and different central wavelengths.

We represent the pulse evolutions and compression factor of two chirped RC input pulses for the same center wavelength of 1550 nm and different center wavelengths of 1550 nm and 1551 nm along the propagating direction in Fig. 4. From Fig. 4(a), owing to the influence of the shared initial chirp, both pulses first move towards the zero position of the time coordinate axis and coalesce into a single pulse at the fiber length of around 136 m, leaving behind small peaks on either side of it. The peak power of the main pulse gradually increases to 2.31 times of the initial peak power during the pulse combination process. In the remaining 164 m of propagation, the combined pulse is compressed and transformed into a soliton-like pulse at the end of the fiber. Figure 4(b) shows the case of two RC pulses initially with different wavelengths. Similar to Fig. 4(a), the two input pulses first coalesce into a single pulse at 153 m (combination length) and then go through self-similar pulse compression in the rest of the fiber. Figure 4(b) shows that the compressed pulse with different central wavelength suffers more temporal shift than that of the same central wavelength (Fig. 4(a)). Figure 4(c) indicates that the evolution of the compression factor of the combined pulse varies almost exponentially as that from the theoretical self-similar model (dotted curve). The FWHM pulse width of the combined pulse at 136 m and the compressed pulse at 300 m are 0.51 ps and 61.85 fs, respectively. The final compression factor is 16.17, which is comparable to 15.32 calculated from self-similar pulse compression. Figure 4(d) illustrates that the compression factor achieved during the propagation in the last 147 m of the fiber is 15.70, which is close to the value of 14.79 calculated from self-similar pulse compression. Self-frequency shift (SSFS) induced by the Raman scattering has a notable influence on femtosecond pulses [31], and here as shown in Figs. 4(e) and 4(f), the output pulse spectrum is broadened and the energy transfer emerges as a red shift with the propagation distance increasing due to the effect of Raman scattering.

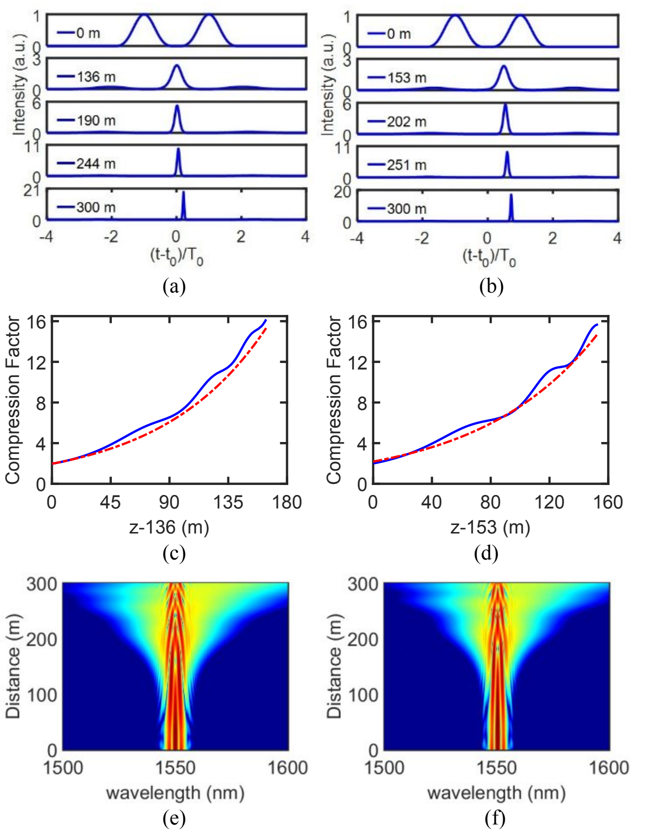


Fig. 4. Evolution of two chirped RC input pulses along the propagating direction for (a) the same center wavelength of 1550 nm and (b) different central wavelengths of λ_0 = 1550 nm and λ_1 = 1551 nm. The compression factor of the combined pulses (solid curves) and the related compression factor of theoretical self-similar compression (dotted curves) for the corresponding (c) the same and (d) different central wavelengths. Contour plot of spectral evolutions of the launched chirped RC input pulses for the corresponding (e) same and (f) different central wavelengths during propagation.

C. *Influence of Central Wavelengths Separation*

In this Section, we explore the influence of the separation between the center wavelengths based on the amount of energy acquired by the compressed pulse from the initial pulses. We report the simulation results for the compressed pulses by fixing the center wavelength of one input pulse (λ_0) to be 1550 nm and vary the center wavelength (λ_1) of the other input pulse. Figures 5(a) to 5(c) represent the variation of energy ratio, compression factor and combination length versus wavelength separation ratio (WSR), where WSR is defined as the ratio of wavelength separation $\lambda_1 - \lambda_0$ to the bandwidth of a single input pulse. In Fig. 5(a), we study the energy ratios of output pulses versus different input pulses with center wavelengths λ_1 ranging from 1548 to 1552 nm, where the corresponding WSR is from –0.48 to 0.48. The energy ratio gradually increases from 46.32% to 64.04% and the maximum of energy ratio of 64.04% is achieved when WSR is 0. There are some fluctuations on the compression factor profile while considering different central wavelengths for the two input pulses. As shown in Figs. 5(b) and 5(c), the compression factor and the combination lengths are also quite different for different WSR from –0.48 to 0.48. Within this WSR span, the minimum compression factor is 12.08 at –0.48 and the maximum value achieved is 16.17 at 0. In addition, the combination length decreases from 209 m to 136 m as the WSR increases from –0.48 to 0 and increases from 136 to 204 m as the WSR increases from 0 to 0.48. When WSR equals to –0.48, the combination length is 209 m and only 91 m length of fiber remains for the self-similar compression. From the simulations results, we conclude that within an appreciable range of central wavelengths separation, two RC pulses can be combined and compressed efficiently.

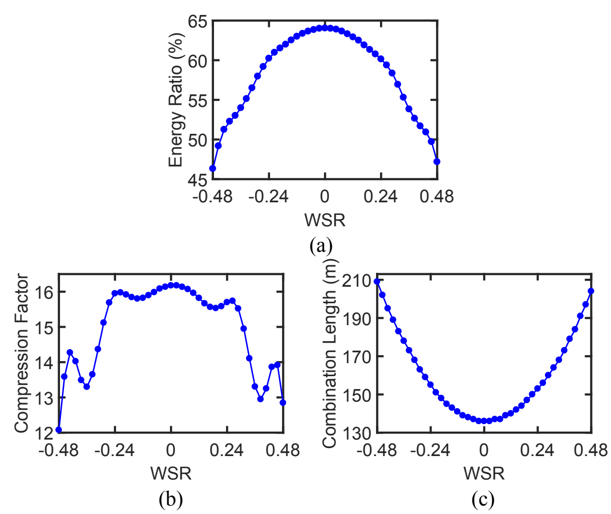
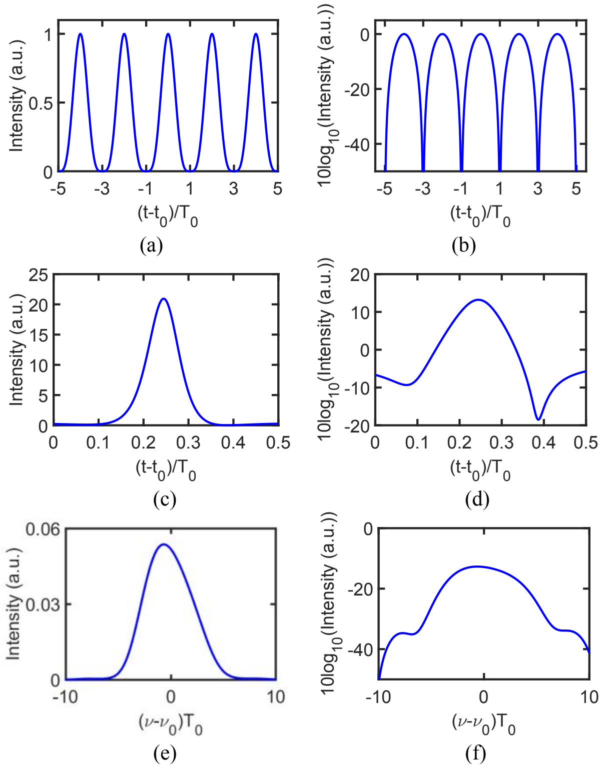


Fig. 5. (a) Energy ratio, (b) compression factor and (c) combination length of compressed output pulse at 300 m length of fiber versus different wavelength separation ratio (WSR).

D. *Combination and Compression of a few Chirped RC Pulses with Different Central Wavelengths*

We studied the combining and compressing of more than two input pulses and report the results of generating single high-power ultrashort pulse from five chirped RC pulses with different center wavelengths. In the five input pulses, the central wavelengths of five pulses are at 1550, 1550.1, 1550.2, 1550.3 and 1550.4 nm which correspond to a frequency separation of $\Delta v = 12.5$ GHz between two neighboring pulses. This situation can be considered as the five consecutive pulses are generated from different laser sources with different wavelengths. The five pulses are in the form of Eq. (1) for $t/T_0 \in [-5,5]$. Five chirped RC input pulses are chosen to have the same values for T_0 and α_{20} as in the case of two chirped RC pulses, but with optimized P_0 value of 0.662 W ($P_0 = 0.5|\beta_{20}|/\gamma/T_0^2$). The fiber parameters are the same as the case in Section A. Figures 6(a) and 6(b) represents the profile of five chirped RC input pulses of time domain in (a) linear and (b) logarithmic scales. Figures 6(c) and 6(d) depict the output pulse profile after the five chirped RC pulses propagated through the fiber length of 300 m in (c) linear and (d) logarithmic scales, respectively. The peak power of the compressed pulse is 13.86 W, which is 20.94 times that of the incident pulses. Energy ratio is calculated as 49.9%, which indicates that the compressed pulse acquired an amount of nearly 2.5 times energy as compared to the single input pulse. The initial FWHM pulse width of 1 ps decreases to 108.3 fs at the fiber output, which corresponds to a compression factor of 9.23. Figures 6(e) and 6(f) show the spectra of the main compressed pulse in $(t-t_c)/T_0 \in [-0.1,0.1]$ in (e) linear and (f) logarithmic scales, respectively. Here t_c is the central position of the output pulse at the end of the fiber. Obvious bandwidth broadening occurs during the compression process and the bandwidth-broadening factor is calculated as 7.64. Figure 6(g) illustrates the evolution of the compression factor along the fiber length during the last 37 m of the compression process for the combination pulse. In this five pulses combination and compression study, the combination length is found to be 263 m. As the number of input pulses increases, the combination length also raises for compression process.



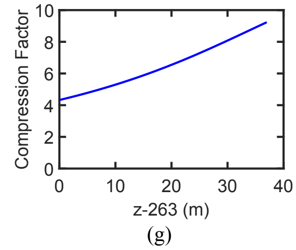


Fig. 6. Chirped five RC input pulses in both (a) linear and (b) logarithmic scales. Output pulse at fiber length of 300 m for compression of five RC pulses in (c) linear and (d) logarithmic scales. Spectra of the main pulse at 300 m in (e) linear scale and (f) logarithmic scale. (g) The compression factor of the chirped five RC pulses compression during the 37 m propagation of compression process.

IV. CONCLUSION

We have demonstrated that rapid combination and effective compression can be realized in a short length of dispersion decreasing nonlinear optical fiber by launching two chirped raised cosine pulses with different central wavelengths. For initial center wavelengths of 1550 and 1551 nm, the combination length for two RC pulses is 153 m and the energy ratio achieved is nearly 60.14%, implying that the input pulses coalesce into a single pulse rapidly and then experience efficient self-similar compression process. We find that the center wavelength separation between two input pulses can be up to 1.8 nm for the compressed output pulse to retain at least the energy of a single input pulse. We have also explored the combination and compression of five RC input pulses with different wavelengths, demonstrating that pulses from different lasers sources with different center wavelength could be compressed effectively. The proposed scheme is convenient and efficient and we believe that this can be practically useful for the generation of high-power ultrashort optical pulse from low power wide pulses from different wavelength laser sources.

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