Beat signal compression by loop mirror constructed with linear dispersion decreasing fiber

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A nonlinear optical loop mirror (NOLM) constructed with linear dispersion decreasing fiber (DDF) is used to compress a beat signal. Several factors impacting on quality of output pulse in this compression system, such as dispersion slope of DDF, power-splitting ratio, incident pulse shape and peak power, are analyzed numerically. The new method for selecting device characteristics is adopted to enable both good pedestal suppression and pulse compression. As a result, the output pulse train with tunable and high repetition rate, pedestal energy of 5.09%, compression ratio of 25.6 and energy transmissivity of 50.56% is obtained by using 0.524 km-long DDF with dispersion slope of 26 ps^2/km^2 and a coupler with power-splitting ratio of 0.54.

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Pulse compression has been paid considerable attention due to its extensive application in ultra-wideband communication system[1-3]. In order to obtain ultra-short signal, nonlinear optical loop mirror (NOLM) combined with Raman gain is utilized for soliton compression[4,5], in which dispersion decreasing fiber (DDF) plays a key role. The cascaded soliton compression schemes are also used for generating pulse of less than 10 fs[6-8]. Dual wavelength beat signal is used for producing pulse train with high and tunable repetition rate[9]. Tunable terahertz beat signal has been recently achieved by using mode-locked laser combined with external cavity of two fiber Bragg gratings[10] and by extracting two modes from flat comb generator[11,12]. A pulse train with high repetition rate up to 200 GHz is generated through two continuous wave (CW) lasers and highly nonlinear fiber[13], but the compression factor is less than 3. In this paper, we use a new method for compressing beat signals with low pedestal as well as good compression performance based on NOLM constructed with linear DDF.

The schematic diagram of beat signal compression by NOLM constructed with linear DDF is shown in Fig.1. The clockwise dispersion of DDF is linearly decreased while the counter-clockwise dispersion of DDF is linearly increased along the fiber. If constructive interference occurs at the center of the pulse while destructive interference occurs at the two sides of the pulse at coupler, the high repetition rate pulse train with suppressed sidelobe will be finally obtained at port 2. It is noted that the repetition rate of the pulse train is tunable by tuning the frequency difference between the two lasers.

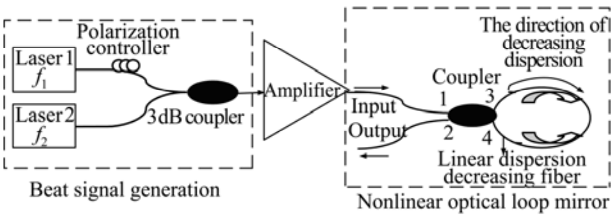

Fig.1 Schematic diagram of beat signal compression by nonlinear loop mirror constructed with linear dispersion decreasing fiber

As shown in Fig.1, the frequencies of laser 1 and laser 2 are f_1 and f_2, respectively. The optical power of the two lasers is equivalent. After the amplifier, the amplitude of beat signal is expressed as:

$$A_{in} = \sqrt{P_0}\cos[\pi(f_1 - f_2)t], \quad (1)$$

where f_1−f_2 is the beat signal frequency difference, and P_0 is the peak power of the beat signal. Then the beat signal is launched into the NOLM. After the coupler, the amplitudes of the beat signals are expressed by the following matrix:

$$\begin{pmatrix} A_1 \\ A_2 \end{pmatrix} = \begin{pmatrix} \sqrt{r} & i\sqrt{1-r} \\ i\sqrt{1-r} & \sqrt{r} \end{pmatrix} \begin{pmatrix} A_{in} \\ 0 \end{pmatrix}, \quad (2)$$

where r is power-splitting ratio of the coupler, A_1 and A_2 are the amplitudes of the beat signals at port 3 and port 4 of the coupler, respectively. The two beat signals propagate in reverse directions along DDF, which are governed by the nonlinear Schrödinger equation (in the

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anomalous dispersion regime, high order dispersion is ignored)[14]:

$$\mathrm{i}\frac{\partial A}{\partial z}-\frac{1}{2}\beta_2(z)\frac{\partial^2 A}{\partial T^2}+\frac{\mathrm{i}\alpha}{2}A+\gamma|A|^2A=0\ , \qquad (3)$$

where A is temporal electric field amplitude of the signal, z is transmission distance along the fiber, $\beta_2(z)$ is the second-order dispersion coefficient of DDF along the fiber, α is attenuation constant, and γ is nonlinearity coefficient. T is the transmission time defined from $T = t-z/v_g$ with group velocity v_g.

After passing through the DDF, the amplitudes of clockwise and counter-clockwise signals turn into $A_1^{'}$ and $A_2^{'}$, respectively. They will pass through the coupler again, and output signals can be expressed as:

$$\begin{pmatrix} U_1 \\ U_2 \end{pmatrix}=\begin{pmatrix} \sqrt{r} & \mathrm{i}\sqrt{1-r} \\ \mathrm{i}\sqrt{1-r} & \sqrt{r} \end{pmatrix}\begin{pmatrix} A_2^{'} \\ A_1^{'} \end{pmatrix}, \qquad (4)$$

where U_2 is the amplitude of the output signal at port 2 of the coupler. From Eqs.(2) and (4), the coupler can cause π phase difference between the counter-propagating signals. According to the switching characteristics of loop mirror, if phase difference between the counter-propagating signals caused by DDF is zero at the sidelobe while it is π at the peak of the pulses, the sidelobe will be suppressed at port 2 due to the destructive interference, and the peak will pass through port 2 due to the constructive interference.

In order to demonstrate the output pulse quality in an overall way, it is essential to define three parameters as follows:

$$R=\frac{T_{\mathrm{FWHM}}}{T_{\mathrm{out}}},\quad Tr=\frac{E_{\mathrm{out}}}{E_{\mathrm{in}}},\quad \eta=\frac{|E_{\mathrm{out}}-E_{\mathrm{sech}}|}{E_{\mathrm{out}}}\times 100\%\ , \qquad (5)$$

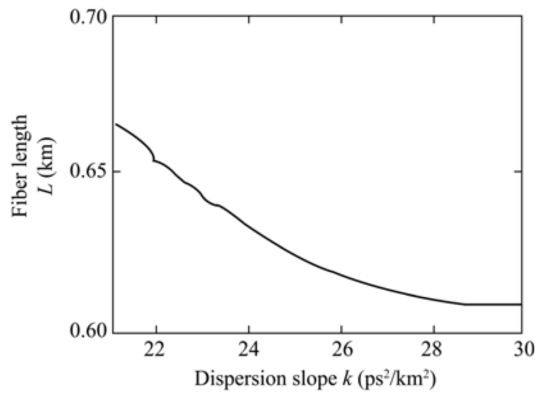
where R represents compression ratio, and T_{FWHM} and T_{out} are full widths at half maximum (FWHM) of input signal and output signal intensities, respectively. Tr represents energy transmissivity, and E_{out} and E_{in} are energy of output signal and input signal, respectively. η represents pedestal energy, and E_{sech} is energy of the hyperbolic secant pulse with the same peak power and pulse width as those of output pulse. All the simulation results are based on that the nonlinear phase shift difference between clockwise signal and counter-clockwise signal is close to π at the pulse peak and 0 at the pulse sidelobe.

In order to investigate impact of dispersion slope of DDF, we assume the second-order dispersion coefficient of DDF is linearly decreased and the initial value is β_0= -20 ps^2/km. The nonlinearity coefficient of DDF is γ = 2.6 W^{-1}km^{-1}. The power-splitting ratio of coupler is r = 0.5. The pulse width of the incident beat signal is T_{FWHM}= 12 ps (f_1–f_2 = 42 GHz) with peak power P_0 = 6.8 W.

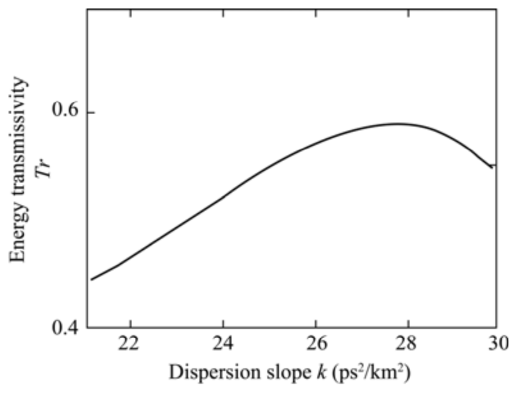
In Fig.2(a), the required fiber length decreases as the dispersion slope of DDF increases. As shown in Fig.2(b), the energy transmissivity has a maximum value at k=28 ps^2/km^2. In Fig.2(c), compression ratio increases progressively versus k. In Fig.2(d), it is clear that the pedestal energy can be controlled below 10% if 21.8 ps^2/km^2 < k < 24.2 ps^2/km^2 at the cost of low compression ratio, low energy transmissivity and long fiber length. At k=28 ps^2/km^2, the energy transmissivity achieves the maximum value, nevertheless the pedestal energy is as high as 32.64%. To sum up, the maximum energy tranmissivity, the maximum compression ratio and the minimum pedestal energy can not be obtained at the same dispersion slope of DDF. As a tradeoff, the dispersion slope around k=26 ps^2/km^2 is selected.

Considering that power-splitting ratio of coupler also influences the power of clockwise signal and counter-clockwise signal, the impact of power-splitting ratio on the quality of output pulse is analyzed. Let r range from 0.2 to 0.8, k = 26 ps^2/km^2, and other parameters are the same as those mentioned above.

In Fig.3(a), it shows that the required fiber length is short at both low and high power-splitting ratios, which results from that the different initial peak power differences between the two signals propagating in reverse directions have different contributions to the nonlinear phase shift. In Fig.3(b), it shows that energy transmissivity is higher when the power-splitting ratio is away from 0.5. In Fig.3(c), it shows that there are three maximum compression ratios at r = 0.41, 0.46, 0.55, respectively. In Fig.3(d), the pedestal energy has minimum values at 0.42/0.54. To sum up, in order to get high quality pulses, r = 0.54 is preferable, which enables great reduction of pedestal energy from 25.53% to 5.2%, and enables relatively high compression ratio as well as high energy transmissivity.



(a)



(b)

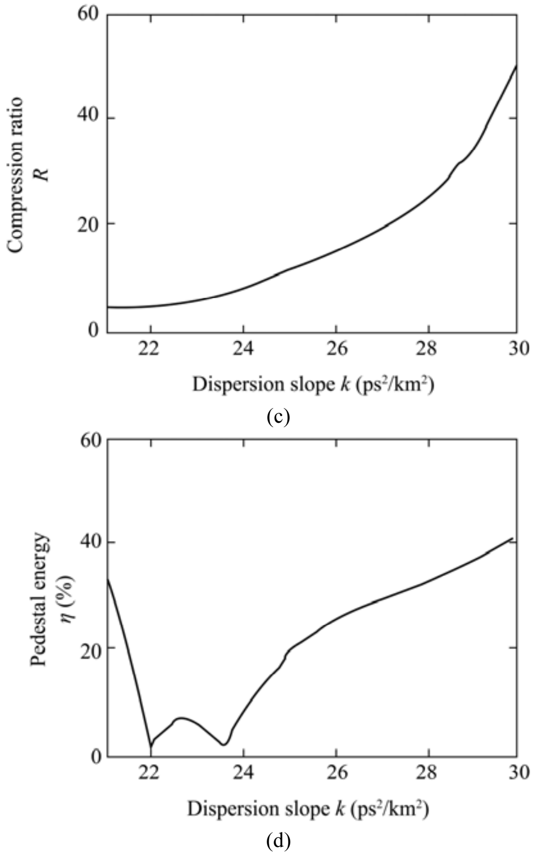
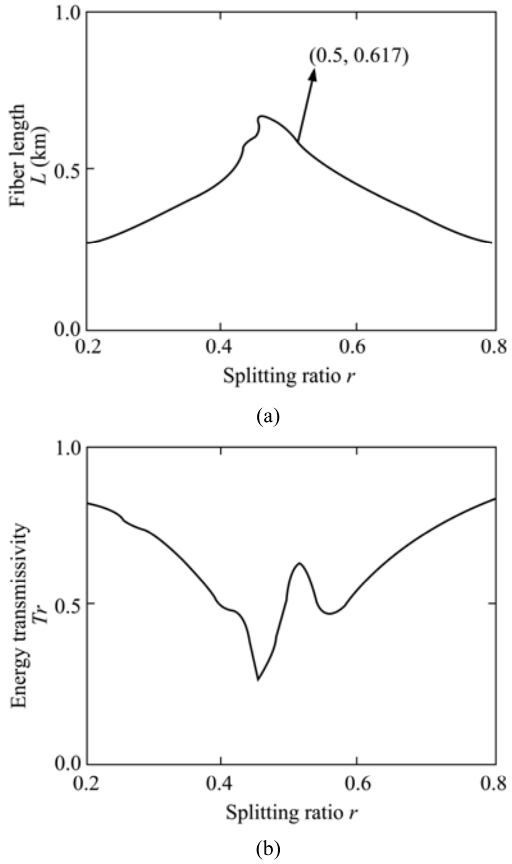


Fig.2 (a) The fiber length *L* of DDF, (b) energy transmissivity *Tr*, (c) compression ratio *R*, (d) pedestal energy *η* of output pulse versus the dispersion slope of DDF



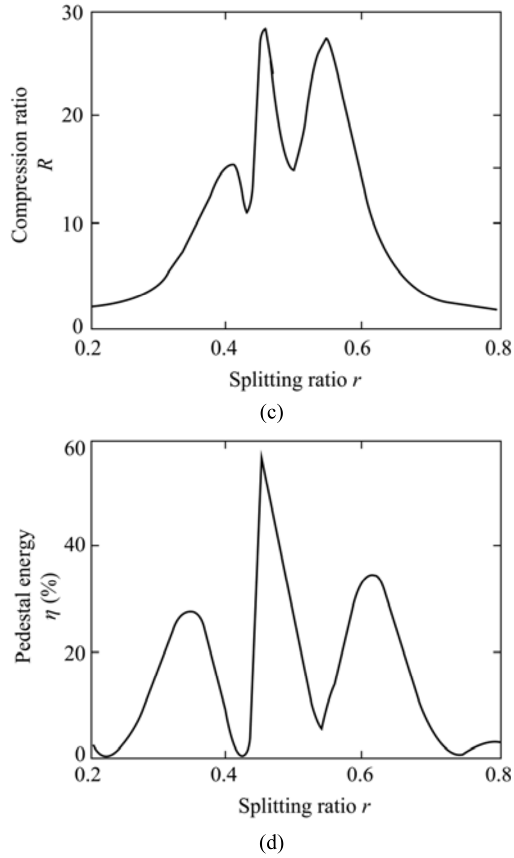
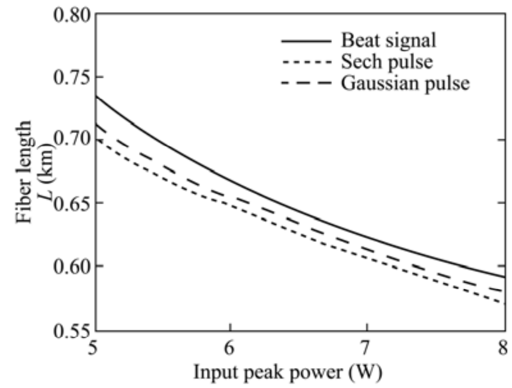


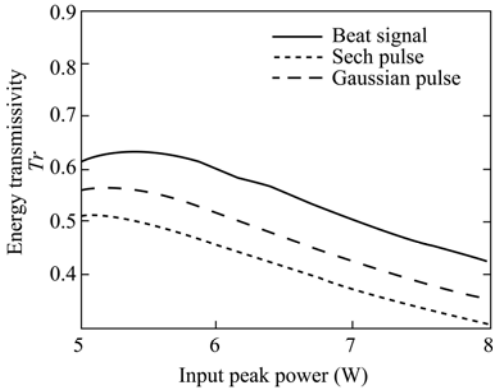
Fig.3 (a) The fiber length *L* of DDF, (b) energy transmissivity *Tr*, (c) compression ratio *R*, (d) pedestal energy *η* versus the power-splitting ratio *r*

The shape of incident pulse will also affect the quality of output pulses. In order to select the optimal peak power for beat signal, let P_0 range from 5 W to 8 W, k = 26 ps^2/km^2, r = 0.5, and other parameters are the same as those mentioned above.

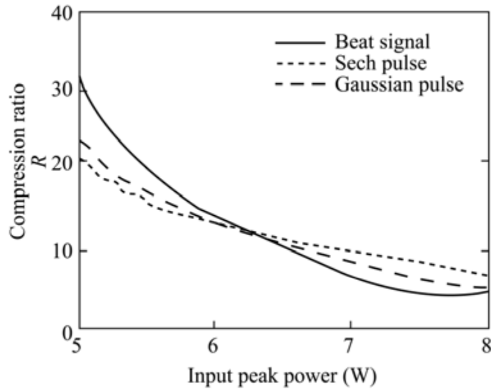
In Fig.4(a), it shows that the required fiber length has a little difference for three signals at the same input peak power. In Fig.4(b), it shows that beat signal has the highest energy transmissivity and the hyperbolic secant pulse has the lowest one at the same input peak power. In Fig.4(c), it can be seen that the compression ratio has a little difference for three signals at the same input peak power. In Fig.4(d), it shows the pedestal energy of beat



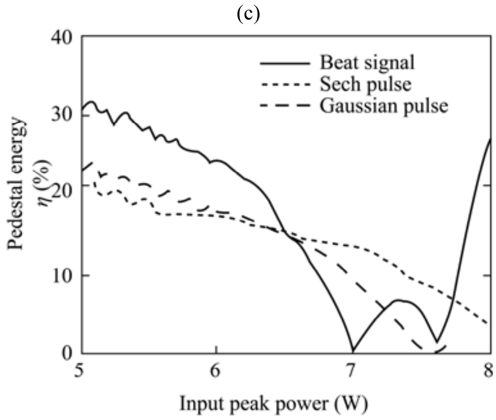
(a)



(b)



(c)



(d)

Fig.4 (a) Fiber length *L*, (b) energy transmissivity *Tr*, (c) compression ratio *R*, (d) pedestal energy *η* of beat signal, hyperbolic secant pulse and Gaussian pulse versus input peak power P_0

signal is the lowest compared with the other two pulses as 6.6 W < P_0 < 7.2 W. To sum up, it is easy to find that the beat signal has the highest energy transmissivity and the lowest pedestal energy at P_0 = 7 W compared with the other two pulses.

Considering all the factors mentioned above, the beat signal with peak power P_0 = 7 W is incident into NOLM system with dispersion slope k = 26 ps^2/km^2 and power-splitting ratio of coupler r = 0.54. Consequently, the pedestal energy decreases to 5.09% while compression ratio and energy transmissivity are still as high as 25.6 and 50.56%, respectively. Moreover, the required fiber length is merely 0.524 km. Compared with soliton-based compression, beat signal shows better quality with low pedestal energy as well as high compression ratio and energy transmissivity in the optimized compression system. Furthermore, it is numerically proved that beat signal with tunable high repetition rate shows better performance than hyperbolic secant pulse and Gaussian pulse at higher input power. The output compressed beat signal from NOLM system is very suitable for ultra-wideband communication system.

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