Research on pulse edge extraction by using nonlinear optical fiber-loop mirror*

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The output characteristics of nonlinear optical fiber-loop mirror are analyzed in detail when the pump pulses with the same wavelength are input in the both directions for recovering the clock component of the signal spectrum. It is found that the double output pulses are produced in the transmission port of the nonlinear optical fiber-loop mirror. The output pulse peaks are located in time domain at the rising and falling edges of the pump pulses. It is demonstrated that the rising and falling edges of the pump pulse can be directly extracted by this method. Through numerical simulation, the effects of the relative delay of pump pulses and the dispersion of fiber on the characteristics of output pulses are studied. By spectrum analysis, it is found that the spectrum of output pulse sequence includes the clock components of the pump pulse sequence, and a new idea is provided for all-optical clock extraction.
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To meet the demand of modern high-speed and high-capacity optical fiber transmission, all-optical re-amplifying, reshaping and re-timing (3R) regeneration based on the nonlinear effect of fiber is one of the pivotal technologies for all-optical transport networks[1-7]. Clock recovery is of the utmost importance in 3R regeneration. The clock of return-to-zero (RZ) signal can be recovered directly. But the clock component of non-return-to-zero (NRZ) signal is weak and the clock lines need to be enhanced through preprocessing. At present, there are mainly two methods to extract the clock signal of NRZ. One is direct extraction by self-pulsation laser or injection by mode-locked laser[8-10]. The second is that NRZ signal is converted to the pseudo-random RZ signal[11, 12]. Nonlinear optical loop mirror (NOLM), endowed with picosecond response speed, can all-optically implement logical operations such as all-optical XOR and all-optical AND[13, 14]. In this paper, this characteristic of NOLM is applied to preprocess RZ/NRZ signal for facilitating the clock extraction. The same input signal is splitted into two signals with a relative delay. They are input to the loop from the opposite directions as two pump signals of NOLM with the same wavelength. They acts on clockwise and counterclockwise transmission continuous waves (probe waves), respectively. At the transmission side of NOLM, pulses are output, and pulse edge is extracted. In fact, the pulse width is changed by XOR of NOLM, the NRZ signal is converted to pseudo-random RZ signal, the spectral transformation is achieved, and the clock component is recovered. This paper studies the output characteristics of NOLM in this case in detail.

The NOLM consists of a 1:1 coupler and a fiber with the length of L, and its structure is shown in Fig.1. Probe wave with the wavelength of λ_1 is input from the left end of NOLM, and is divided into two beams through the 1:1 coupler. The other input signal with the wavelength of λ_2 and pulse width of T_0 is splitted into two pump signals with relative delay T_d. They are coupled into the loop from left and right sides, respectively. It is assumed that the spectra of pump and probe light do not overlap, the polarization direction of the pump and probe light is consistent with the direction of transmission, the fiber loss is ignored, and the phase-matching conditions of four wave mixing are not satisfied[13].

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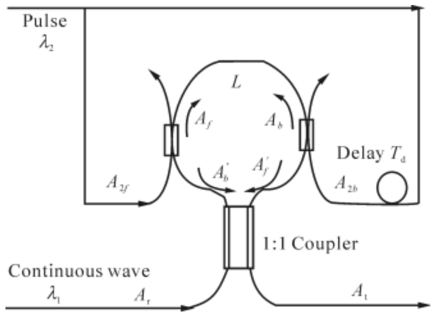

Fig.1 Schematic diagram of NOLM

Evolutions of the clockwise optical signals transmitting in the loop meet

$$\frac{\partial A_f}{\partial z} = \mathrm{i}\gamma_1(|A_f|^2 + 2|A_{2f}|^2)A_f , \tag{1}$$

$$\frac{\partial A_{2f}}{\partial z} + d\frac{\partial A_{2f}}{\partial T} + \frac{\mathrm{i}\beta_{22}}{2}\frac{\partial^2 A_{2f}}{\partial T^2} = \mathrm{i}\gamma_2(|A_{2f}|^2 + 2|A_f|^2)A_{2f} . \tag{2}$$

Evolutions of the counterclockwise optical signals transmitting in loop meet

$$\frac{\partial A_b}{\partial z} = \mathrm{i}\gamma_1(|A_b|^2 + 2|A_{2b}|^2)A_b , \tag{3}$$

$$\frac{\partial A_{2b}}{\partial z} + d\frac{\partial A_{2b}}{\partial T} + \frac{\mathrm{i}\beta_{22}}{2}\frac{\partial^2 A_{2b}}{\partial T^2} = \mathrm{i}\gamma_2(|A_{2b}|^2 + 2|A_b|^2)A_{2b} , \tag{4}$$

where $T = t - z/v_{g1}$ is the time measured in moving frame of the reference with velocity of v_{g1}, $d = 1/v_{g2} - 1/v_{g1}$ is the measurement of group velocity mismatch between two pulses, A_j (j =1,2) denotes the amplitude of two light signals, β_{2j} (j =1,2) is the group velocity dispersion (GVD) of optical fiber at the wavelength of two light waves, $\gamma_j = (n_2\omega_j)/(cA_{\mathrm{eff}})$ (j=1,2) is the nonlinear parameter of optical fiber at the wavelength of two light waves, and n_2 is the fiber nonlinear refractive index coefficient. In Eqs.(1) and (2), the first term on the right side denotes self-phase modulation, and the second says cross-phase modulation effect between the light signals transmitting in the same direction.

Input and output characteristics of NOLM are obtained by solving Eqs.(1)−(4), which have the analytical solution under certain conditions, but there is no analysis expression under normal circumstances. At this time, researches on input and output characteristics of NOLM are carried out with the help of numerical simulation by using photonics simulation software.

The input Gaussian pulse A_{2f} and A_{2b} with the delay time of T_d and equal peak power are expressed as

$$A_{2f}(0,T) = \sqrt{P_2}\,\mathrm{e}^{-T^2/2T_0^2} ,$$
$$A_{2b}(0,T) = \sqrt{P_2}\,\mathrm{e}^{-(T-T_d)^2 2T_0^2} , \tag{5}$$

where P_2 is the peak power of pump pulse. When group velocity dispersion of optical fiber is ignored, Eqs.(1)-(4) have the analytical solution, and output characteristics of NOLM are studied by the analytical solution.

Complex amplitude of the output light of NOLM is expressed as

$$A_{\mathrm{t}}(L,T) = \frac{\sqrt{P_1}}{2}\mathrm{e}^{\mathrm{i}\gamma_1 LP_1}\begin{pmatrix} \mathrm{e}^{2\mathrm{i}\gamma_1 LP_2\exp(-\tau^2)} \\ -\mathrm{e}^{2\mathrm{i}\gamma_1 LP_2\exp(-(\tau-\tau_d)^2)} \end{pmatrix} , \tag{6}$$

$$A_{\mathrm{r}}(L,T) = \mathrm{i}\frac{\sqrt{P_1}}{2}\mathrm{e}^{\mathrm{i}\gamma_1 LP_1}\begin{pmatrix} \mathrm{e}^{2\mathrm{i}\gamma_1 LP_2\exp(-\tau^2)} \\ +\mathrm{e}^{2\mathrm{i}\gamma_1 LP_2\exp(-(\tau-\tau_d)^2)} \end{pmatrix} , \tag{7}$$

where $\tau = T / T_0$, $\tau_d = T_d / T_0$, and P_1 is the input power of continuous wave. Let $\Delta\phi = 2\gamma_1 LP_2 \mathrm{e}^{-\tau^2} - 2\gamma_1 LP_2 \mathrm{e}^{-(\tau-\tau_d)^2}$, which represents the induced nonlinear phase difference between the probe waves transmitting in clockwise and counterclockwise directions. The expressions of transmission and reflection output power are

$$P_{\mathrm{t}}(L,T) = P_1(1-\cos\Delta\phi)/2 , \tag{8}$$

$$P_{\mathrm{r}}(L,T) = P_1(1+\cos\Delta\phi)/2 . \tag{9}$$

Thus, when a time delay exists between the two pump pulses, the periodic variation of the instantaneous power difference between the pump pulses causes the cyclical change of output signal.

The parameters used in the calculations are shown in Tab.1. To compare the waveform, the power of probe wave is set at 65 mW, but it is not higher than 1 mW in simulation and practice in order to avoid stimulated Brillouin scattering.

Tab.1 Parameter list

Parameter name	Value	Parameter name	Value
f_1	193.1 THz	n_2	2.6×10^{-19} m²/W
f_2	194.1 THz	n	1.47
T_0	100 ps	P_1	65 mW
L	1000 m	A_{eff}	45×10^{-12} m²

According to Eqs.(6)−(9), the transmitted pulse is shown in Fig.2 when the relative delay is 50 ps. Fig.2 shows that output pulses are at the rising and falling edges of input pulse. The relative delay between two pulses results in a relative phase difference between the probe waves propagating in clockwise and counterclockwise directions, so NOLM can have the transmitted output.

It is can be seen from Fig.2 that there is no output at the intersection of the two input pump pulses. In other words, there is a zero minimum output amplitude trough between the two transmission peaks.

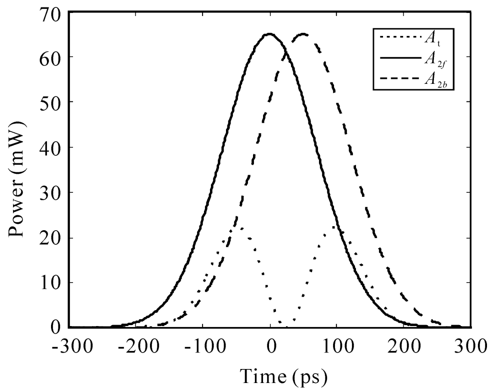

Fig.2 Waveforms of output pulses when T_d= 50 ps and P_1= P_2 = 65 mW

Output pulse amplitude changes with the amount of delay as shown in Fig.3. Fig.3 shows that the transmissivity increases as the delay time increases, the transmission output is influenced independently by the two pump pulses, and the relative magnitude of the output is 1 when two pump pulses do not overlap. Fig.3(b) shows that the time interval between adjacent output pulse peaks is equal to the delay time.

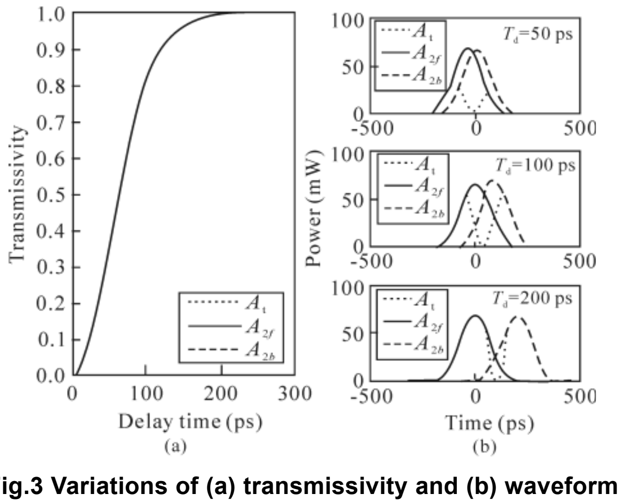

Fig.3 Variations of (a) transmissivity and (b) waveform with time delay

The results of numerical simulation are shown in Fig.4 by photonics simulation software when the input pump pulse is 40 Gbit/s pseudo-random bit sequence, the delay is 12.5 ps, and other parameters are in Tab.1.

When the fiber dispersion cannot be ignored, the pulse in the transmission is not only nonlinearly modulated, but also influenced by the dispersion effect. The output waveform and spectra of NRZ and RZ signals are shown in Fig.5 when dispersion coefficient is 2 ps/(nm·km). The output waveform and spectra of NRZ and RZ signals are shown in Fig.6 when dispersion coefficient is -2 ps/(nm·km).

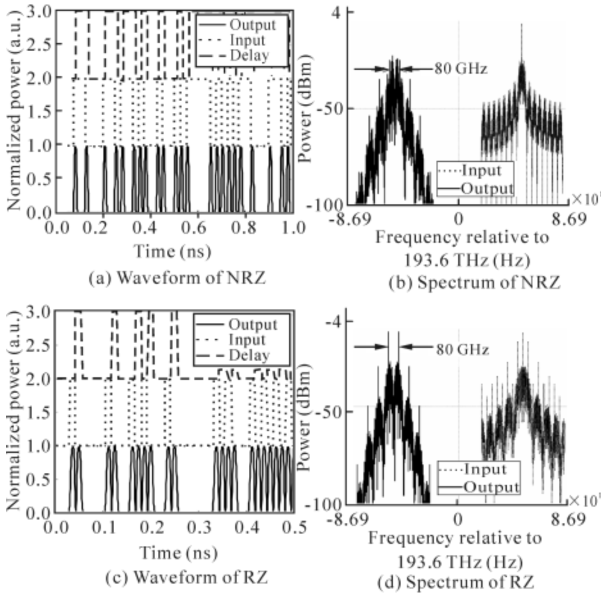

Fig.4 Input and output waveforms and spectra of NRZ and RZ signals when the fiber dispersion is ignored

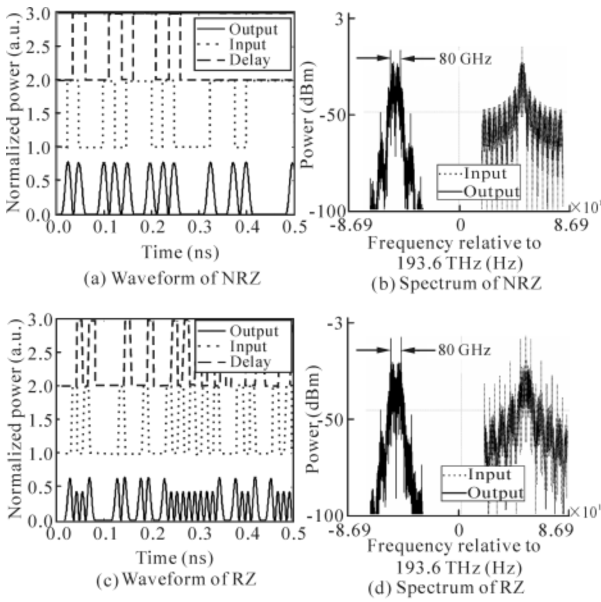

Fig.5 Input and output waveforms and spectra of NRZ and RZ signals when GVD is 2 ps/(nm•km)

Figs.5 and 6 show that the output pulse is produced respectively in leading and trailing edges of each input pulse. When the dispersion coefficient is positive, the output pulse is ahead of the input pump pulse. The output pulse has a certain delay when the dispersion coefficient is negative. Dispersion causes the walking-off between the pump and probe waves, and the output pulse width increases, which can affect the NOLM logic operation speed. So the impact of fiber dispersion should be fully taken into account in case of using NOLM as all-optical logic devices. If the normal and anomalous dispersion fibers are used in loop, the total dispersion of the loop is zero, and the impact of dispersion can be reduced.

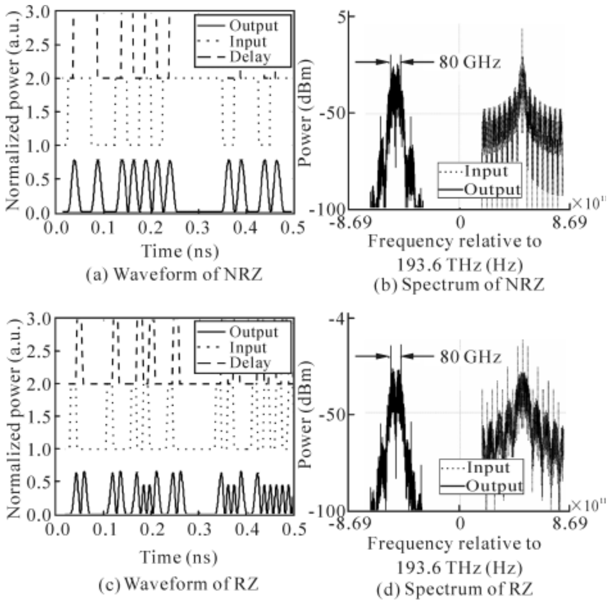

Fig.6 Input and output waveforms and spectra of NRZ and RZ signals when GVD is -2 ps/(nm•km)

It can be seen by comparing the relative output amplitudes that the relative amplitude of output pulse declines, because the action time shortens and the action intensity weakens between pump pulse and probe wave due to dispersion.

Figs.5 and 6 show that the clock spectral lines of NRZ and RZ signals are generated, whose frequency equals the input signal bit rate. It helps to extract the clock of input signal. In particular, it is conducive to the clock recovery of NRZ signal. It can be seen that RZ clock spectral line is stronger by comparing the output spectra of NRZ and RZ signals. Figs.5 and 6 also show that the carrier is suppressed in the output spectrum. It is because the transmitted adjacent pulses have a constant phase difference π.

In summary, the same input signal is splitted into the two signals with relative time delay. The two signals are coupled into the NOLM from the opposite directions as they have the same wavelength, and they are acting on clockwise and counterclockwise probe waves. The output pulse is generated at the NOLM transmission port. The time-domain positions of output pulse peaks are at the rising edge and falling edge. The characteristics of output pulse, such as amplitude and time-domain location of pulse peak, are influenced by relative delay of the pump pulse and the fiber dispersion. When the delay time relative to the pulse width is larger, the output pulse amplitude is larger. When the delay is small, although the output pulse amplitude decreases, the time domain positions of pulse peaks are closer to the rising or falling edge of pump pulse. When the delay exceeds the pulse width, the output positions of pulse peaks are determined only by the peak positions of two pump pulses, the time difference between the adjacent output pulses is equal to the delay time, and the output pulse peak does not change. The fiber dispersion weakens the cross-phase modulation, resulting in output pulse amplitude decreasing, meanwhile causes walking-off effect between the pump and probe waves, and the width of output pulse increases. It can be seen from the output spectra that a clock frequency component exists, and the effect provides a new way for extracting the clock of the NRZ signal.

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