40-Gb/s All-Optical Wavelength Conversion Based on a Nonlinear Optical Loop Mirror

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***Abstract*—All-optical wavelength conversion based on a nonlinear optical loop mirror (NOLM) at 40 Gb/s is demonstrated for the first time. The effect of walkoff time between control beam and signal beams is investigated when the NOLM is used as an all-optical wavelength converter or an all-optical demultiplexer.**

***Index Terms*—All-optical demultiplexing, cross-phase modulation (XPM), nonlinear optical loop mirror (NOLM), optical time domain multiplexing (OTDM), wavelength conversion, wavelength-division multiplexing (WDM).**

I. Introduction

WAVELENGTH conversion has been suggested as a method of enhancing routing options and network properties like reconfigurability, nonblocking capability and wavelength reuse [1], [2]. Cross-gain modulation (XGM) [3], [4], cross-phase modulation (XPM) [5], [6], and four-wave mixing (FWM) [7]–[9] in semiconductor optical amplifiers (SOA's) have been demonstrated for 40 Gb/s wavelength conversion. But up to now, no 40 Gb/s wavelength conversion using a nonlinear optical loop mirror (NOLM) has been reported. In fact, NOLM based on silica fiber has the potential of attaining terabits per second switching operation due to the ultrafast optical nonlinearity [10]–[13]. Reference [14] has demonstrated that the pulsewidths can be maintained, and even compressed when the walkoff between the continuous-waves (CW's) and the control pulses is small. So, wavelength conversion based on an NOLM will be suitable for return-to-zero (RZ)-based networks. In this paper, we will realize wavelength conversion based on an NOLM at 40 Gb/s, and investigate the walkoff effect when the NOLM is used as a wavelength conversion or demultiplexing media.

II. Experiment

The full-width at half-maximum (FWHM) pulsewidth of the control pulse measured by an autocorrelator is 8.2 ps, so the duty cycle is 0.33. In this case, the nonlinear phase of the counterpropagating wave will have some effect on the ER of the converted signal. Like nonreturn-to-zero (NRZ), this problem can easily be solved by adjusting the state of polarization controller in the NOLM [11], [14]. In order to obtain a switching efficiency of 1, the peak power of the control pulse should be 242 mW; it means an average power of about 40 mw. The output power of the erbium-doped fiber amplifier (EDFA) in our experiment can satisfy this requirement.

A. Experimental Setup

The experimental setup is shown in Fig. 1. It consists of two NOLM's, one is used for wavelength conversion (WC-NOLM), and the other is used for all-optical demultiplexing (D-NOLM) [15] The WC-NOLM consists of 3 km of dispersion shifted fiber (DSF) with a nonlinear index $n_2 = 2.67 \times 10^{-20}$ m^2/W, an effective cross sectional area $A_{\text{eff}} = 50\ \mu$ m^2, zero dispersion wavelength of 1550.7 nm and dispersion slope of 0.08 ps/nm^2/km. The on-off ratio defined [16] between maximum and minimum transmission of the NOLM is 30 dB without the control signal [14]. The on-off ratio between maximum and minimum transmission of the D-NOLM is 25 dB. The D-NOLM consists of 3 km of DSF with $n_2 = 2.67 \times 10^{-20}$ m^2/W, $A_{\text{eff}} = 50\ \mu$ m^2, zero dispersion wavelength of 1555 nm and dispersion slope of 0.08 ps/nm^2/km. The total dispersion and relative group delay of the DSF's in the NOLM's used as wavelength converter or demultiplexer are shown in Fig. 2(a) and (b), respectively.

The control pulses for the WC-NOLM at 1546.8 nm (λ_1), which are generated by a gain-switched DFB-LD followed by DCF for compression, are externally modulated by a $LiNbO_3$ intensity modulator at 10 Gb/s using a $2^{31} - 1$ pseudorandom bit sequence (PRBS) before passive multiplexing to 40 Gb/s. Fig. 3 shows the eye diagrams of control signals at 10 Gb/s and the multiplexed signals at 40 Gb/s. Because the bandwidth of the optical/electrical converter in the sampling oscilloscope is only 32 GHz, the pulsewidth shown in Fig. 3 is wider than 8.2 ps. The control signals are coupled into the WC-NOLM using optical coupler (OC) 1. The CW lightwave at the center wavelength λ_2 generated by an external-cavity laser (ECL) is injected into the WC-NOLM using OC2. The tunable optical filter (TOF) 1 with 1.6 nm bandpass at the output of the WC-NOLM is used to suppress the control signals. The average power of the control signals into OC1 is 19 dBm, and the power of the CW lightwave into OC2 is 12 dBm. The converted signals at 40 Gb/s are amplified to the average power of 12 dBm, then they are injected into the D-NOLM. The control pulses for the D-NOLM are also obtained from a gain-switched laser followed by a dispersion compensated fiber (DCF) (compressed pulsewidth ~10 ps and center wavelength $\lambda_3 = 1553.0$ nm) and injected into D-NOLM from OC4. The average optical power of the control pulses for demultiplexing the optical time division multiplexed (OTDM) signals is 18 dBm; the relative timing between the control pulses and the converted signals is adjusted by using a variable optical

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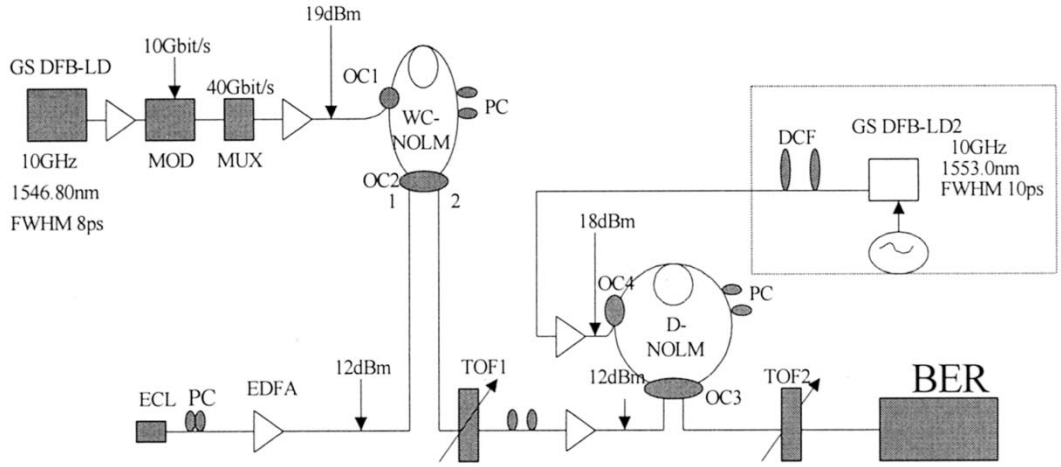


Fig. 1. Experimental setup. OC: optical coupler. EDFA: erbium-doped fiber amplifier. WC-NOLM: wavelength conversion-NOLM. D-NOLM: demultiplexing-NOLM. PC: polarization controller. TOF: tunable optical filter. ECL: external-cavity laser. DCF: dispersion compensation fiber. MOD: $LiNbO_3$ intensity modulator. PPG: pulse pattern generator. MUX: passive 10–40 Gb/s multiplexer. BER: bit-error rate detector. GS DFB LD: gain-switched distributed-feedback laser diode.

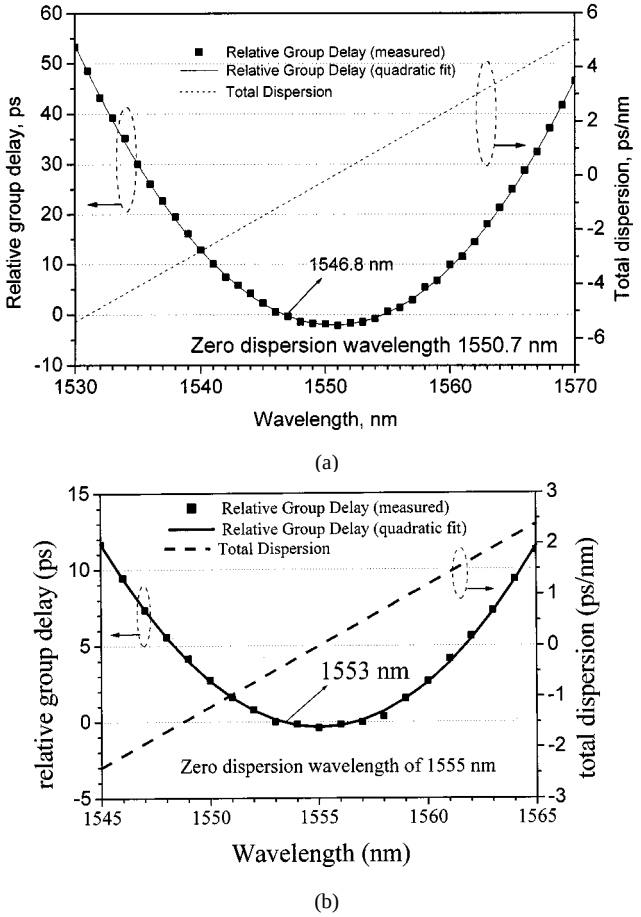


Fig. 2. Relative total group delay and total dispersion as a function of signal wavelength measured in the two DSF's. (a) DSF used for wavelength conversion. (b) DSF used for demultiplexing.

delay line. The TOF2 with 1.6 nm bandpass at the output of the D-NOLM is used to suppress the control signal (λ_3). All OC's are 2×2 couplers with power coupling ratios of 50 : 50%.

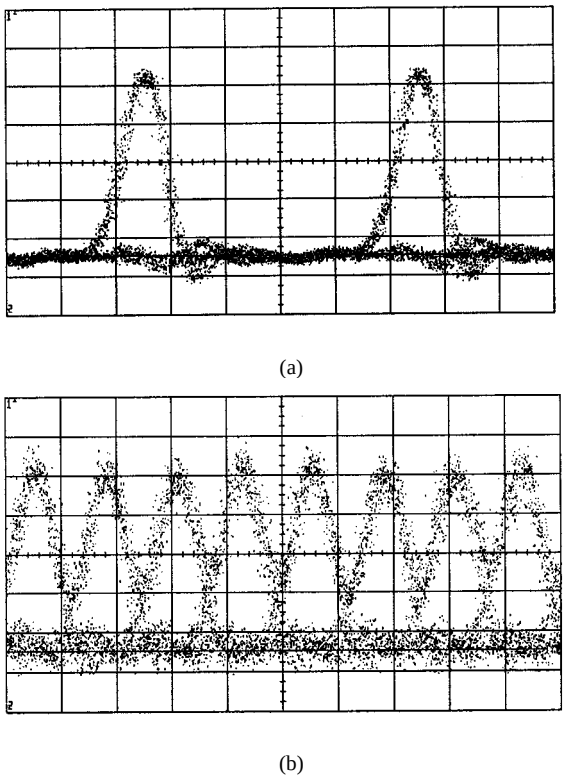


Fig. 3. Control signal at 1546.8 nm (20 ps/div). (a) 10 Gb/s and (b) 40 Gb/s.

B. Experimental Results

Fig. 4 shows some typical optical eye diagrams of the converted signals at different wavelengths. Almost the same eye diagrams are obtained at converted wavelengths from 1540 to 1563 nm. Fig. 5 shows the numerical simulation results with FWHM of control pulse of 8.2 ps; the numerical model is described in [14]. From Fig. 5, we can see that the pulsewidths of the converted signals are smaller or equal to that of the control pulses when the CW wavelengths are chosen from 1541 to

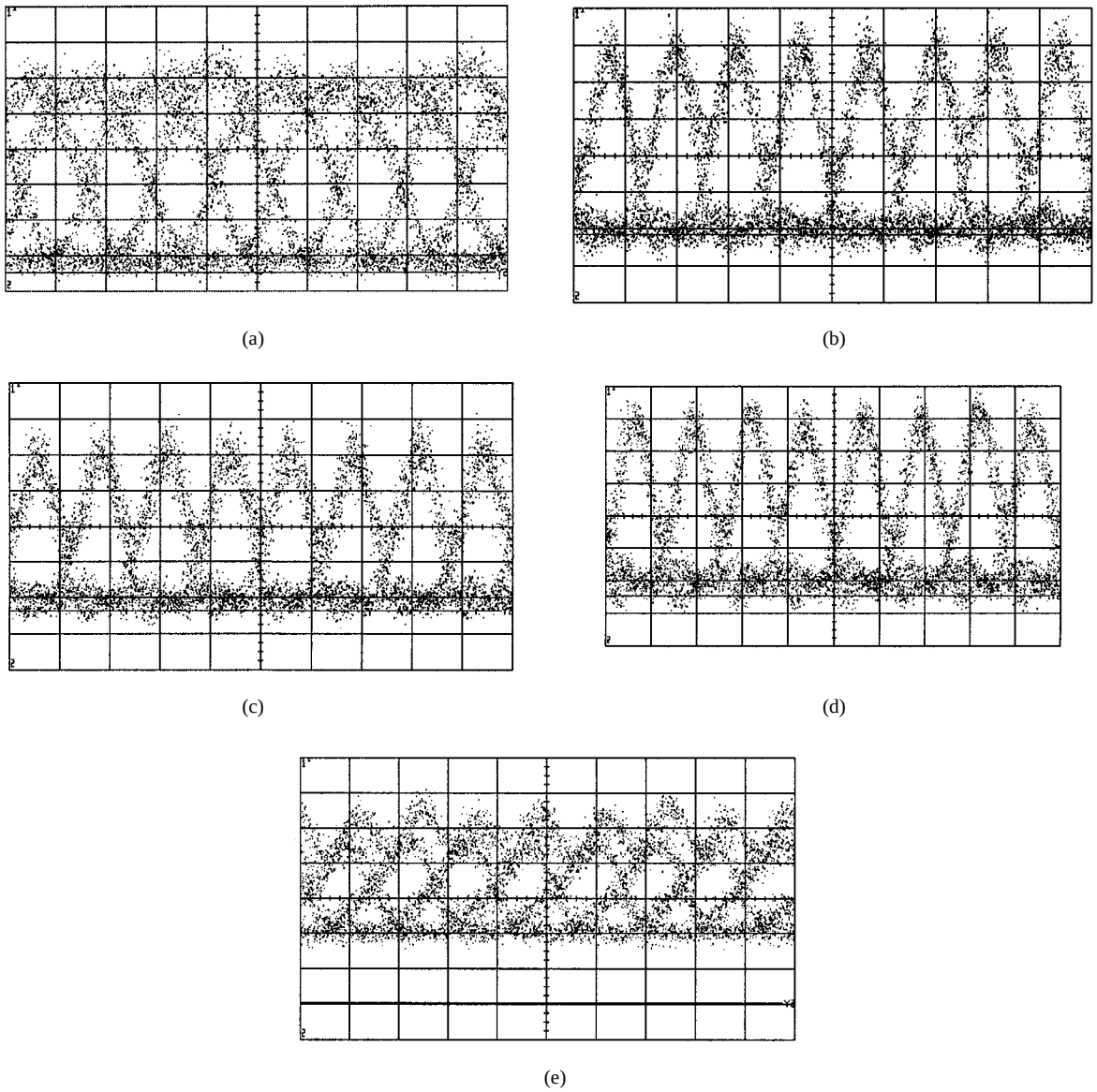


Fig. 4. Optical eye diagrams of converted signals at different wavelengths (20 ps/div). (a) 1535 nm, (b) 1540 nm, (c) 1557 nm, (d) 1563 nm, and (e) 1569 nm.

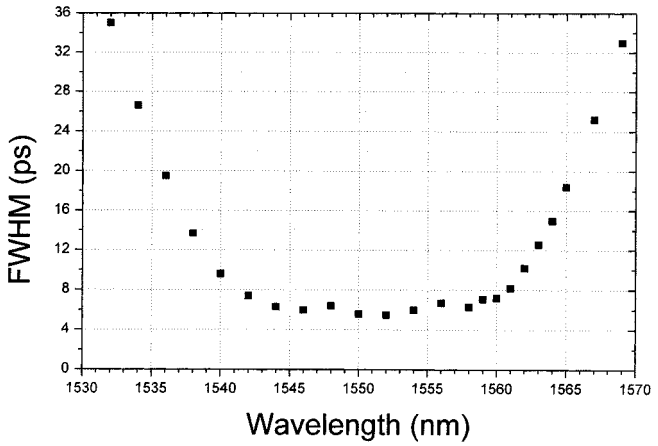
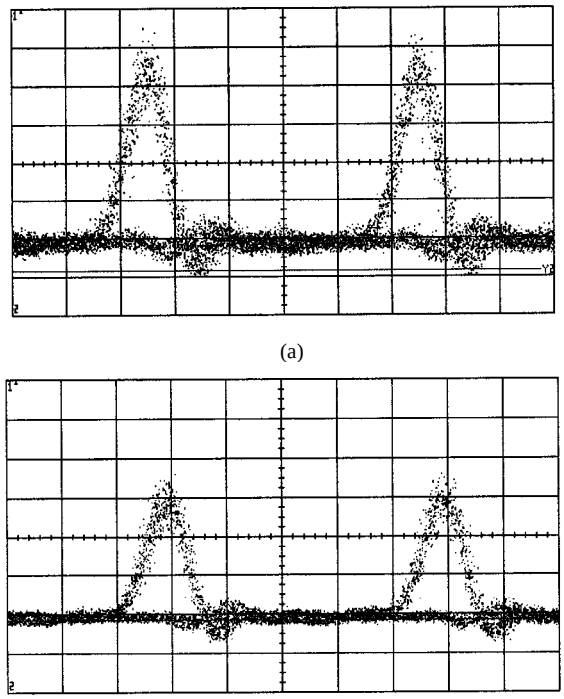


Fig. 5. Pulse FWHM for numerical simulation as a function of CW wavelength. The FWHM pulsewidth, center wavelength, and peak power of control pulses are 8.2 ps, 1546.8 nm and 150 mW, respectively.

1561 nm, and the variation of the pulsewidths in this range is small. When the CW wavelength is 1561 nm, the walkoff time is 11.8 ps. The reason for the pulsewidth compression of the converted pulses is explained in [14]. Because the pulsewidth of the converted signal is maintained or compressed, there is no intersymbol interference (ISI) as shown in Fig. 4(b)–(c). Even when the CW wavelength is 1563 nm, in which case the walkoff time is 17.7 ps, ISI cannot be observed, as shown in Fig. 4(d). This is because the pulsewidth of the converted signals is only a little wider than that of the control pulses, and the duty cycle of the control signals is small. The converted signals at 1535 and 1569 nm are severely broadened because of a large walkoff between the control signals and CW lightwaves, which leads to an obvious ISI in the converted signals, as shown in Fig. 4(a) or (e).

Without wavelength conversion means that the WC-NOLM is not used, but we demultiplex the 40 Gb/s OTDM signal (1546.8 nm) using the control pulses (1553.0 nm). The eye diagram of



(a)

(b)

Fig. 6. Optical eye diagrams of demultiplexed signals (20 ps/div). (a) 1545 nm (back to back without wavelength conversion) and (b) 1557 nm (after wavelength conversion).

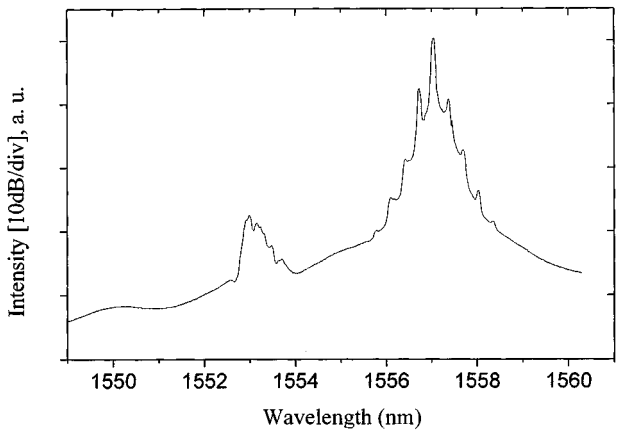


Fig. 7. Optical spectrum at 1557 nm after wavelength conversion and demultiplexing.

the demultiplexed signal is shown in Fig. 6(a). The BER performance (40 Gb/s back to back) is measured and shown in Fig. 8. As an example, Fig. 6(b) shows the eye diagram at 1557 nm after wavelength conversion and demultiplexing. The clean eye diagram of the de-multiplexed signals can be seen. Fig. 7 shows the optical spectrum around 1557 nm after wavelength conversion and demultiplexing in the time-domain; a sidemode suppression ratio (SMSR) larger than 30 dB is obtained. The second peak in Fig. 7 is the remaining control pulse at 1553 nm because of the finite suppression of the optical filter.

Fig.8 shows further the bit-error rate (BER) performance. τ represents the walkoff time between control pulses and signals in D-NOLM. There is a power penalty of 3.2 dB for the 40-Gb/s

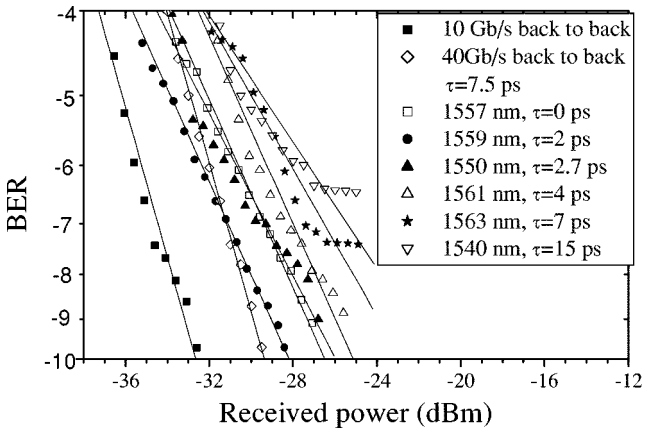


Fig. 8. BER versus received power for control signal (back-to-back) and converted signals.

OTDM signal without wavelength conversion (40 Gb/s back to back). The penalty is due to a large walkoff between the control pulses (1553.0 nm) and the 4×10 Gb/s signals (1546.8 nm). The power penalties are dependent on the wavelengths of the converted signals, because there is a different walkoff time when signals at different wavelengths are demultiplexed in the D-NOLM. Because there exists a timing jitter in both control pulses and signals, and the D-NOLM uses the interaction between control pulses and signals through the optical Kerr effect, timing errors result in fluctuations in the switching efficiency and thus degradation of the BER performance. One effective way to improve the jitter tolerance is to take advantage of the walkoff between control pulses and signals. Reference [18] has found that a proper walkoff time can suppress the BER degradation due to timing jitter, and the optimal walkoff depends on the value of pulse timing jitter. The eye diagrams in Fig. 4(b)–(e) are almost the same, demonstrating that the converted signals at 40 Gb/s in Fig. 4(b)–(e) have almost the same performance. From Fig. 8, we can see that when the walkoff time between the control pulses and signals is 2 ps, then the power penalty is smallest and equal to 4 dB at BER of 10^{-9}. It shows that the optimal walkoff is 2 ps. When the walkoff is 0 ps and 2.7 ps, there is almost the same power penalty, and that power penalty is approximately 6 dB at BER of 10^{-9}. When the walkoff is 7 ps and 15 ps, error floors appear at BER's of $\sim 10^{-7}$ and 10^{-6}, respectively, although the eye diagrams of the converted signals at the wavelengths of 1540 nm and 1563 nm are very clear. It shows that the walkoff plays an important role when the NOLM is used as a demultiplexer. Because of the SNR reduction of converted signals, the tolerance of the walkoff time will be reduced when the OTDM signals are demultiplexed by the D-NOLM. Even if there is a walkoff time of 7.5 ps between the original OTDM signals (1546.8 nm) and control pulses (1553.0 nm), the original OTDM signals can be demultiplexed, however, after wavelength conversion, the OTDM signals with a walkoff time of 7 ps can not be demultiplexed and there is an error floor at BER of 10^{-7}.

III. Conclusion

We have demonstrated 40-Gb/s RZ wavelength conversion based on an NOLM. Because the pulsewidths of the converted

signals can be maintained and even compressed, there is no evident ISI in the converted signals at center wavelengths from 1540 nm to 1561 nm. The pulsewidth of the converted signals can be maintained even if the walkoff time is 11.8 ps when the CW wavelength is 1561 nm. However, when the NOLM is used as a demultiplexer and when the walkoff time is larger than 4 ps, there is an obvious effect on the demultiplexed signals, which shows that the walkoff plays a more important role when the NOLM is used as a demultiplexer.

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