LETTER

Wavelength-tunable sub-picosecond optical switch over entire C-band using nonlinear optical loop mirror

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Abstract We present a wavelength-tunable ultrafast optical switch using a nonlinear optical loop mirror (NOLM), which has a low walk-off characteristic between the signal pulse and the control pulse thanks to the use of a dispersion-flattened highly nonlinear fiber. A 400-fs switching speed and an extinction ratio of >32 dB were obtained from 1528 to 1565 nm. The NOLM was applied to the 320 to 40 Gbaud demultiplexing of DQPSK Nyquist pulse signals, and error-free operation was achieved over the entire C-band.

Keywords: optical switch, nonlinear optical loop mirror, optical time-division multiplexed transmission, highly nonlinear fiber

Classification: Optical hardware

1. Introduction

All-optical switches have many useful applications in ultra-high-speed optical communication, signal processing, and network control [1, 2, 3, 4]. For example, a high-speed optical switch is a key device for demultiplexing optical time-division multiplexed (OTDM) signals in ultrahigh-speed OTDM transmissions [5]. Among various switching devices, semiconductor optical amplifiers (SOA) [6, 7, 8, 9, 10, 11, 12] and fiber-based switches [13, 14, 15, 16, 17, 18, 19, 20, 21, 22] have attracted a lot of attention. SOAs feature compactness, high stability, and low switching power [6, 7, 8]. Although the operating speed of an SOA is limited by the slow gain recovery time, this can be cancelled by adopting a Mach-Zehnder interferometer configuration with a symmetric Mach-Zehnder (SMZ) switch [9], and a switching speed of ~ 1 ps has been demonstrated [10, 11, 12].

For fiber-based all-optical switches such as a nonlinear optical loop mirror (NOLM) [21], a subpicosecond switching speed has been achieved owing to the femtosecond response time of fiber Kerr nonlinearity [22]. By taking advantage of this ultrafast response, a NOLM has been successfully applied to a demultiplexer for ultrahigh-speed OTDM transmission at a single-channel speed of >1 Tbit/s [23, 24, 25]. In general, the switching efficiency of fiber-based switches is limited by the dispersion profile as it causes walk-off between the data and control pulses. How-

ever, the wavelength dependence of the group delay characteristics makes it difficult to realize a NOLM with wide-range wavelength tunability, which is required for OTDM demultiplexing in WDM systems.

In this paper, we describe wavelength-tunable ultrafast optical switching over the entire C-band using a low walk-off NOLM that employs a dispersion-flattened highly nonlinear fiber (HNLF). A 400-fs switching speed is obtained from 1528 to 1565 nm with a fixed wavelength control pulse in the L-band. We use the NOLM to demonstrate the error-free wavelength-tunable demultiplexing of a 320 Gbaud DQPSK signal over the entire C-band.

2. Configuration of wavelength-tunable low walk-off NOLM

Fig. 1 shows the basic configuration for OTDM demultiplexing using a NOLM. The launched OTDM signal is first divided into two parts by a 50:50 coupler. The two parts then propagate in clockwise and counterclockwise directions through an HNLF loop. The control pulse is coupled in the loop and co-propagates with the signal propagating in the counterclockwise direction, where the OTDM signal is given a phase shift of π by cross-phase modulation during propagation in the HNLF. After the circulation, the two counterpropagating signals interfere, and only the π phase-shifted tributary can be output from the NOLM. We previously demonstrated the OTDM demultiplexing of 2.56-Tbaud signals at a switching speed of 230 fs with a NOLM [25].

Fig. 1. Fundamental configuration of a low walk-off NOLM using a dispersion-flattened HNLF.

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In addition to demultiplexing a broadband OTDM signal in a single channel, the NOLM can be used to demultiplex multi-channel WDM-OTDM signals. For this purpose, the wavelength tunability of the NOLM is very important. The wavelength of the control pulse λ_c must also usually be changed for each signal wavelength λ_s to reduce walk-off. However, if the HNLF is dispersion-flattened, the

control pulse can be fixed to a single λ_c because of the low walk-off characteristics, which makes switching simple.

The dispersion and group delay characteristics of the dispersion-flattened HNLF (Furukawa Electric, HNLF170407-20) that we employed for the wavelength-tunable NOLM are shown in Fig. 2(a) and (b), respectively. The dispersion-flattened HNLF was 20-m long with a non-linear coefficient of $\gamma = 22 \text{ W}^{-1} \text{ km}^{-1}$. The zero-dispersion wavelength is 1568 nm, and the dispersion slope is as low as $0.013 \text{ ps/nm}^2/\text{km}$, which is 1/6 that of standard fiber. The low dispersion slope makes it possible to reduce the walk-off between signal and control pulses as shown in Fig. 2(b). We fixed the wavelength of the control pulse at 1595 nm regardless of the signal wavelength, where the walk-off was less than 100 fs for all the wavelengths in the C-band.

Fig. 2. GVD and group delay characteristics of dispersion-flattened HNLF. (a) GVD and (b) group delay.

3. OTDM of Nyquist pulse to 320 Gbaud and its demultiplexing to 40 Gbaud using wavelength-tunable NOLM

We used this NOLM for wavelength-tunable OTDM demultiplexing from 320 to 40 Gbaud over the entire C-band. Fig. 3(a) shows our experimental setup. At the transmitter, the CW output from a tunable laser diode was launched into an optical comb generator consisting of a dual-drive LiNbO₃ Mach-Zehnder modulator driven at 40 GHz [26]. After chirp compensation with a dispersion-compensating fiber (DCF), a 320 Gbaud DQPSK signal was obtained with an IQ

modulator driven by a 40 Gbit/s, $2^{11} - 1$ PRBS and optical multiplexing from 40 to 320 Gbaud using a delay-line multiplexer. It was then shaped into a Nyquist pulse [27] with a roll-off factor $\alpha = 0$ and a bandwidth of 320 GHz using a programmable pulse shaper [28]. The waveform of the generated 320 Gbaud Nyquist OTDM signal is shown in Fig. 3(b). As shown by the white dots, the Nyquist OTDM signal is free from intersymbol interference (ISI) at each symbol location, and otherwise the pulses overlap greatly. A switching gate sufficiently narrower than the symbol period (3.13 ps) is needed to extract the ISI-free points, which exist only at the symbol period, from the overlapped Nyquist pulse train [27]. Our ultrafast NOLM is particularly advantageous for such ultrahigh-speed sampling.

Fig. 3. (a) Experimental setup for 320 to 40 Gbaud OTDM demultiplexing using the wavelength-tunable sub-picosecond NOLM. (b) Waveform of 320 Gbaud Nyquist OTDM signal.

At the receiver, the 320 Gbaud Nyquist OTDM signal and 40 GHz control pulses were coupled to the NOLM. The OTDM signal was launched at 24 dBm through a 3-dB coupler. It should be noted that SOA switches cannot generally tolerate such a high input power, and this constitutes a substantial advantage for the NOLM in terms of obtaining a high OSNR after demultiplexing. The timing offset between the signal and control pulses was optimized for each wavelength by using an optical delay line. Because of the low walk-off characteristics of the HNLF, zero timing offset is the optimum condition regardless of the wavelength. The NOLM includes polarization controllers that optimize the state of polarization of both the signal and control pulses to maximize the extinction ratio and switching efficiency. The insertion loss of the NOLM was 9.5 dB.

As a control pulse source, we used a 40 GHz mode-locked fiber laser (MLFL) operating at 1595 nm and emitting a 760-fs pulse [29], whose repetition rate was

synchronized to a 40 GHz clock extracted from the OTDM signal. To compress the pulse, the MLFL output pulse was coupled to a 10-m HNLF with a normal GVD at a launch power of 26 dBm, in which the spectrum was broadened by self-phase modulation. It was then launched into a pulse shaper, where the spectrum was shaped into a sech profile and the chirp was compensated for so that a transform-limited sech pulse with a pulse width $\tau_{FWHM} = 580$ fs was obtained. The autocorrelation waveform of the generated control pulse is shown in Fig. 4(a).

The sech pulse was then coupled into the NOLM through a WDM coupler at an input power of 24 dBm as a control pulse. It should be noted that the wavelength of the control pulse ($\lambda_c = 1595$ nm) is in the anomalous dispersion regime ($D = 0.35$ ps/nm/km) as shown in Fig. 2(a), and thus the sech-shaped control pulse can propagate in the NOLM as a soliton [30]. In this case, the peak power of the control pulse is $P_c = 4.0$ W, while the peak power required for a fundamental soliton is calculated to be $P_{N=1} = 0.776 (\lambda_c^3 |D| A_{eff} / \pi^2 c \tau_{FWHM}^2 n_2) = 200$ mW and the soliton period becomes $z_0 = 0.332 (2\pi c \tau_{FWHM}^2 / \lambda_c^2 |D|) = 405$ m. Here, n_2 is the nonlinear coefficient, A_{eff} is the effective core area, and c is the speed of light. This indicates that the control pulse propagates as a higher-order soliton with a soliton order $N = (P_c / P_{N=1})^{1/2} = 4.5$, and since the soliton period is much longer than the HNLF length of 20 m in the NOLM, soliton compression occurs during propagation in the NOLM. An autocorrelation waveform of the control pulse measured at the output of the 20-m HNLF is shown in

Fig. 4. Autocorrelation waveform of the control pulse measured at the input (a) and output (b) of the NOLM, respectively.

Fig. 4(b). It can be seen that the pulse is compressed to 370 fs inside the NOLM. This offers an advantage in terms of ultrafast NOLM operation.

At the output of the NOLM, the demultiplexed 40 Gbaud DQPSK signal was separated from the control pulses with an optical bandpass filter, and then demodulated with a one-bit delay interferometer (DI) and detected with a 40 GHz balanced photo-diode (PD). Finally, the bit error rate (BER) was measured online with an error detector.

4. NOLM performance

Fig. 5(a) shows the extinction ratio of the NOLM for various wavelengths in the C-band. An extinction ratio as high as 32 to 37 dB was obtained over the entire C-band, where a longer wavelength has a higher extinction ratio. We next measured the switching gate width of the NOLM by launching a CW probe light instead of an OTDM signal. The switching gate width for each wavelength is shown in Fig. 5(b), and a switching gate waveform measured at 1548.11 nm is shown in the inset. A switching gate width as narrow as 390~450 fs was successfully achieved for all the wavelengths. Such a narrow switching gate despite a control pulse width of 580 fs is a consequence of the soliton effect as described earlier. It can be seen that the gate width is broader for shorter and longer wavelengths because of the residual walk-off. The gate width is sufficiently narrower than the symbol period of 3.13 ps and

Fig. 5. Wavelength dependence of the extinction ratio (a) and the switching gate width (b) of the NOLM.

applicable to the ultrafast sampling of the 320 Gbaud Nyquist OTDM signal shown in Fig. 3(b).

Fig. 6 shows the demultiplexing characteristics of the present NOLM, where the BER characteristics are plotted against the received optical power for three wavelengths in Fig. 6(a) and the received power of each wavelength required for a BER of 10^{-9} is shown in Fig. 6(b). The demultiplexed waveform for a signal wavelength of 1548.11 nm is also shown in Fig. 6(c). After the demulti-

plexing, the signal pulse broadened due to the 5 nm optical filter after the NOLM, which was used for removing the control pulses. As shown in these figures, we achieved error-free demultiplexing operation at all the channels in the C-band. Also, at a shorter wavelength, where the signal and the control pulses are sufficiently separated, there is no crosstalk and the receiver sensitivity is high as shown in Fig. 6(b). However, the power penalty incurred by demultiplexing was larger at shorter wavelengths. This is because the gain of the EDFA preamplifier installed at the NOLM output was lower at shorter wavelengths.

5. Conclusion

We demonstrated wavelength-tunable ultrafast optical switching using a NOLM with a low walk-off characteristic. We achieved the error-free demultiplexing of a 320 Gbaud DQPSK Nyquist pulse signal from 1528 to 1565 nm by using a NOLM with fixed control pulses located in the L-band. The NOLM allows us to realize the ultrahigh-speed demultiplexing of OTDM-WDM signals and is expected to have the potential for applications to ultrafast optical networks and signal processing over a wide wavelength.

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Fig. 6. Demultiplexing characteristics of the NOLM. (a) BER performance for 320 to 40 Gbaud demultiplexing plotted against the received power at signal wavelengths of 1528.77, 1548.11, and 1565.09 nm, (b) the receiver sensitivity of each wavelength required for a BER of 10^{-9} , and (c) the demultiplexed waveform at 1548.11 nm.

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