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A High-Speed Demultiplexer Based on a Nonlinear Optical Loop Mirror With a Photonic Crystal Fiber

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***Abstract*—A 50-m-long photonic crystal fiber with zero-dispersion wavelength at 1552 nm is used as the nonlinear medium in a nonlinear optical loop-mirror-based demultiplexer. The successful demultiplexing of an 80-Gb/s optical time-division multiplexing signal transmitted through an 80-km span of standard single-mode fiber and the error-free demultiplexing from 160 Gb/s are achieved.**

***Index Terms*—Demultiplexing, high-speed optical techniques, nonlinear optical loop mirrors (NOLMs), optical switches, photonic crystal fiber (PCF), time-division multiplexing, transmission lines, 80 Gb/s, 160 Gb/s.**

I. Introduction

THE USE OF A Sagnac interferometer is very convenient for switching in optical communication systems. One of the first demultiplexing experiments from 160 Gb/s in an optical time-division multiplexing (OTDM) system was realized using this type of interferometer containing a semiconductor laser amplifier [1]. Generally though, optical fiber-based switches work faster than semiconductor-based ones. Using pieces of fibers as the nonlinear element in a so-called nonlinear optical loop mirror (NOLM) has, thus, been used for 640 : 10-Gb/s OTDM demultiplexing [2]. However, a NOLM usually requires a long nonlinear fiber segment to generate a sufficient phase shift in the interferometer. This long segment makes the NOLM sensitive to external environmental conditions such as temperature drift and acoustic effects, and internal conditions such as excessive walkoff between the control and data pulses and pulse broadening in the fiber loop. In [2], the effect of walkoff was suppressed by combining a number of fibers with different dispersions and dispersion slopes making the device highly complex.

Increasing the nonlinear parameter γ of the nonlinear fiber segment can help to reduce the required length of this fiber. For instance, a common highly nonlinear fiber (HNLF) with $\gamma = 10.9$ W^{-1}km^{-1} and $L = 1$ km was used for demultiplexing in a NOLM in [3]. The shortest reported HNLF ($L = 100$ m) that was used for demultiplexing with a NOLM, had $\gamma = 15$ W^{-1}km^{-1} [4].

Using photonic crystal fiber (PCF) technology allows for the tailoring of fibers with very small effective core areas, making the nonlinear parameter γ very high.

In this letter, a NOLM based on a PCF with $\gamma = 18$ W^{-1}km^{-1} and the length of only 50 m is described in its application as a demultiplexer of 80- and 160-Gb/s signals.

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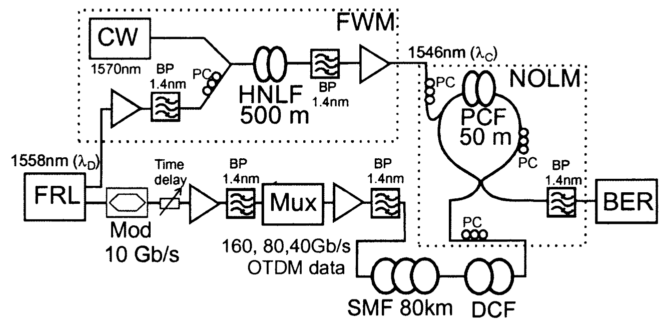

Fig. 1. Experimental setup, including the PCF-based NOLM, used for 80-Gb/s transmission and demultiplexing and for 160-Gb/s demultiplexing experiments.

II. Experimental Setup

Fig. 1 shows a schematic of the setup used for 160 : 10- and 80 : 10-Gb/s demultiplexing and 80-Gb/s transmission. The pulses are ∼2.5 ps in width with a repetition rate of 10 GHz, and are generated by a mode-locked fiber ring laser (ML-FRL) operating at a wavelength of $\lambda_D = 1558$ nm. The train of pulses is data modulated with a $2^7 - 1$ pseudorandom binary sequence by an external Mach–Zender modulator. The resulting 10-Gb/s bit stream is multiplexed to 40, 80, or 160 Gb/s by a passive fiber delay multiplexer. The multiplexed signal arrives to the input port of the NOLM after transmission through the transmission span or directly after multiplexing. The transmission span with zero dispersion at 1557 nm contains 80 km of single-mode fiber (SMF) and a dispersion compensating fiber.

The control pulses to the NOLM are obtained by wavelength conversion of a branch of the pulse train from the ML-FRL. The 10-GHz pulse train at $\lambda_D = 1558$ nm is coupled with the l570-nm light from a continuous-wave (CW) laser and injected into a HNLF, where four-wave mixing generates a spectral component at $\lambda_C \approx 1546$ nm [5]. This component is filtered, amplified, and launched into the NOLM as a control signal. The resulting control signal has a pulsewidth of 3.6 ps

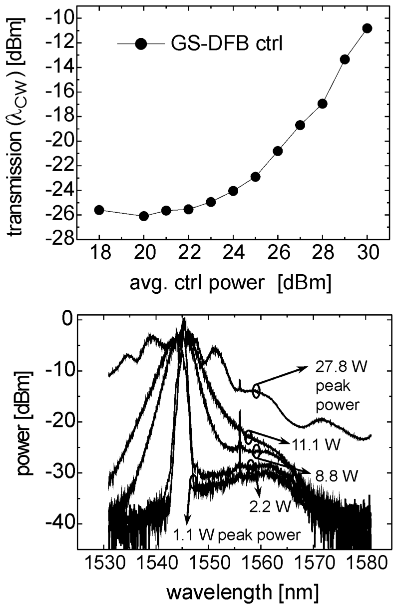

Fig. 2. Switching characteristics of the PCF-based NOLM. Top: Power of transmitted CW light as function of the GS-DFBL-CF (12-ps pulsewidth) control power. Bottom: Spectra at the output of the NOLM for different levels of control power of ML-FRL.

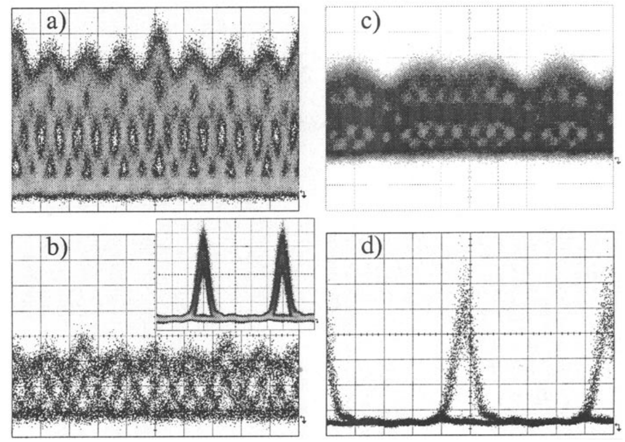

Fig. 3. Eye diagrams of 80-Gb/s signal (a) before and (b) after transmission through the span. Inset in (b): demultiplexed 10-Gb/s eye diagram. (c) 160-Gb/s eye diagram and (d) demultiplexed 10-Gb/s eye.

and a power of 17 dBm. The data signal is split into the two arms of the NOLM interferometer. The control pulses with a repetition rate of 10 GHz introduce a phase shift of the copropagating pulses through cross-phase modulation due to the optical Kerr effect in the PCF. As a result, the demultiplexed 10-Gb/s data signal is obtained at the output of the NOLM. A preamplified bit-error-rate (BER) receiver is used to evaluate the demultiplexed data channel.

The PCF has a slightly elliptical microstructured region (the birefringence is $1.1 \cdot 10^{-4}$) with air-filled holes surrounding a 2.3-μm-diameter solid silica core with an 0.8-μm-diameter Ge-doped center [6]. This results in a small effective core area and, thereby, a high nonlinear parameter ($\gamma = 18\ \mathrm{W}^{-1}\mathrm{km}^{-1}$). The PCF has a zero-dispersion wavelength of ≈1552 nm and dispersion slope of ≈ -0.25 ps/nm^2/km, so at the wavelength interval of 1546–1558 nm, the total accumulated dispersion of the 50-m PCF does not exceed 0.1 ps/nm. This means that a pulse with an initial width of 2.5 ps should not suffer a broadening exceeding 1%. Furthermore, the control and data wavelengths are placed symmetrically around the zero-dispersion wavelength, so the walkoff time is negligible. The total loss of the PCF including splicing and coupling losses is 4.7 dB. High γ, combined with polarization matched control and signal in the entire fiber (due to the birefringence), reduce the required fiber length to only 50 m.

III. Result and Discussion

The switching characteristics of the PCF-based NOLM are shown in Fig. 2. First, a gain-switched distributed feedback (GS-DFB) laser followed by a segment of compressive fiber (CF) yielding 12-ps-wide pulses at 1556 nm was used to generate the control pulses. A CW beam with wavelength of $\lambda_{CW} \sim 1549$ nm acts as a probe–data signal and is sent to the input port of the NOLM. As the pulses are relatively broad, the spectrum of the GS-DBF is narrow, and the spectral separation between control and signal is sufficiently large to reduce the spectral overlap of the control spectrum on the transmitted signal, thus improving the range over which the switching characteristics can be determined. Fig. 2 (top) shows how the probe transmittance increases as the pump power increases. A switching contrast of more than 15 dB is obtained when changing the average pump power from 20 to 30 dBm (~0.8- to 8-W pulse peak power), which should be adequate for demultiplexing. This demonstrates the potential for demultiplexing. Furthermore, an investigation of the switching characteristics corresponding to the subsequent demultiplexing experiment was carried out, by using an ML-FRL as pump. In this case, the control pulses are about 3.6 ps wide allowing peak powers of as high as ~27.8 W with an average power of 30 dBm. The ML-FRL has a wavelength at 1545 nm and the CW beam is at $\lambda_{CW} \sim 1556$ nm. Note that the wavelength and the pulsewidth of the control signal in these measurements and in the subsequent demultiplexing experiment are identical.

The spectral response of the NOLM is shown in Fig. 2 (bottom). It is seen that when the control pulse peak power exceeds about 8 W, the spectrum broadens into a supercontinuum and thereby drowns the switching window. Thus, the maximum usable contrast is obtained for peak powers less than 8 W. This measurement further reveals the versatility of the used nonlinear crystal fiber in that it may also be used for supercontinuum generation.

The eye diagrams evaluating the setup in Fig. 1 at 80-Gb/s transmission and 160-Gb/s demultiplexing are shown in Fig. 3. The eye diagrams of Fig. 3(a) and (b) show no visible broadening of the 80-Gb/s pulses after transmission. This means that the transmission span is dispersion compensated at the operating wavelength and that nonlinearities do not affect the transmission performance significantly (the input power at the beginning of the span is ≈10 dBm). The high bit-rate eye diagrams (80 and 160 Gb/s) are not resolved due to the limited bandwidth (50 GHz) of the oscilloscope used for the measurements. The demultiplexed 10-Gb/s eyes, however, are clear and open

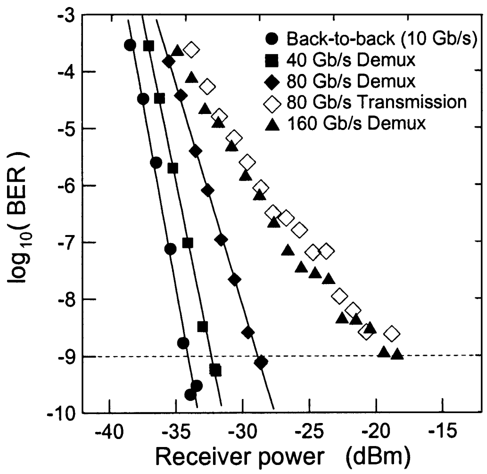

Fig. 4. BER measurements for demultiplexing to 10 from 40, 80, and 80 Gb/s; after transmission through 80 km, 160 Gb/s.

with no offset [Fig. 3(d) and inset in 3(b)]. Both the 80-Gb/s [Fig. 3(a)] and the 160-Gb/s signal [Fig. 3(c)] show some amplitude variation in the different OTDM channels (about 1 dB), which is due to an imperfect multiplexer.

The BER curves characterising the quality of the 10-Gb/s channels demultiplexed from 40, 80, and 160 Gb/s without transmission are shown in Fig. 4 together with the 80/10-Gb/s BER curves after transmission with no clock recovery. In all cases, error-free operation is obtained.

The receiver has a 10-Gb/s back-to-back sensitivity of -34.2 dBm and, with respect to this BER curve, the other curves have penalties arising from a combination of the multiplexing, transmission, and demultiplexing functions as well as pulse broadening through filters. The 40/10-Gb/s curve has a penalty of 1.7 dB, which is due to the pulse broadening from 2.5 to 3.8 ps in the 1.4-nm-wide filters used in the setup (wider pulses require more average power to maintain the same SNR [7]). Consequently the demultiplexing in itself does not generate any significant penalty.

The 80/10 Gb/s has a penalty of 5.1 dB compared with the back-to-back, which apart from the filter-induced pulse broadening stems from intersymbol interference (ISI) in the multiplexed data stream.

This ISI is significantly stronger in the case of 160/10-Gb/s demultiplexing and it leads to the error floor on the BER curve. But an error-free demultiplexing was nevertheless obtained; the measured penalty is 15.5 dB.

In order to characterize the overall system including the fiber transmission span, an 80-Gb/s data signal was transmitted and demultiplexed. A BER of 2.6×10^{-9} is obtained. The setup did not include a clock recovery, so there is a synchronization penalty after the 80-km transmission span. This is the reason for the error floor on the BER curve and the degradation of the receiver sensitivity of 8 dB in comparison with 80-Gb/s demultiplexing without transmission. The BER curves for the signal demultiplexed from 40 and 80 Gb/s without transmission show no presence of an error floor. The timing jitter makes it impossible to transmit faster signals (e.g. 160 Gb/s) using the present setup.

IV. Conclusion

In this letter, demultiplexing of an up to 160-Gb/s OTDM data signal using a 50-m-long piece of PCF as the nonlinear medium in a NOLM has been demonstrated. Furthermore, an 80-Gb/s OTDM signal is transmitted through 80 km of standard SMF and demultiplexed in this NOLM. The performance is error free but might be considerably improved by the use of narrower pulses and synchronization of the transmitted data to the receiver (e.g., by clock recovery).

The highly nonlinear PCF can produce a sufficient phase shift for demultiplexing with the NOLM yielding a 15-dB switching contrast. At the same time, due to the short length of the PCF, the walkoff effect and pulse degradation in the NOLM are minimized. The short length also reduces any sensitivity of the NOLM to environmental disturbances. The high nonlinearity of the PCF paves the way for a promising compact, fast, and stable optical switching device.

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