160-Gb/s Polarization-Independent Optical Demultiplexing in 2-m Nonlinear Fiber

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***Abstract*—We report a new method for polarization-independent optical demultiplexing that uses cross-phase modulation (XPM) in nonlinear fiber. Using this technique, we achieved error-free 160- to 10-Gb/s demultiplexing in only 2 m of highly nonlinear bismuth–oxide fiber. The demultiplexing performance is not impaired when the input data polarization state is scrambled at high speed. This method does not require circular polarization states and is shown to work even in birefringent fibers. We present a simple theoretical model that predicts the conditions under which polarization-independent XPM can be achieved, and we show numerical simulations that agree well with experimental observations.**

***Index Terms*—Demultiplexing, nonlinear optics, optical signal processing, polarization, ultrafast processes in fibers.**

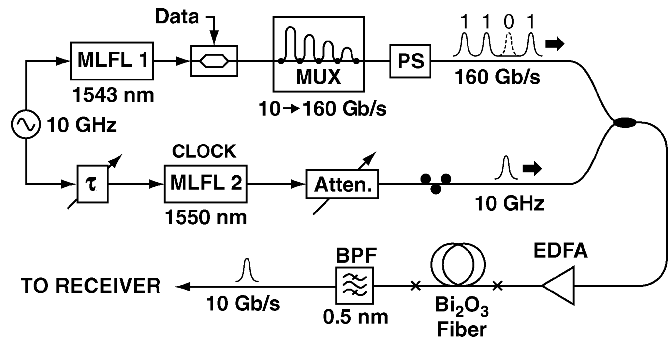

Fig. 1. Experimental setup used in polarization-independent 160-Gb/s demultiplexing. The polarization scrambler (PS) is used to evaluate the effect of polarization fluctuations.

I. Introduction

One of the key elements in high-speed optical time-division multiplexed systems is the optical demultiplexer, which extracts one tributary channel from a high-speed data stream. Among the techniques for optical demultiplexing, those that use optical fiber nonlinearities like cross-phase modulation (XPM) or four-wave mixing (FWM) are attractive because of their fast response time and low insertion loss. One problem with fiber-based nonlinearities is that the FWM or XPM efficiency depends on the polarization state of the incoming data signal, which cannot be controlled in most fiber-optic systems.

In theory, polarization-independent mixing can be achieved if the clock signal is circularly polarized, but in practice, the residual birefringence of the fiber makes it difficult to maintain a circular polarization state over the length of the fiber. One method to maintain circular polarization is to twist the fiber either during or after fabrication [1], [2], but this approach cannot be easily implemented in fibers with significant linear birefringence. Another method to overcome polarization-dependence is polarization diversity, in which the clock is split into two orthogonal states that independently interact with the data [3]–[5]. In longer fibers, the random polarization-mode dispersion can cause the polarization-dependence to average out, leading to polarization-independent operation [6]. Even in short birefringent fibers, it is possible to achieve polarization-independent XPM as long as the beat lengths are sufficiently different for the clock and data [7].

We report here a new and simple technique for 160-Gb/s polarization-independent demultiplexing that uses 2 m of bismuth–oxide fiber. By adjusting the power of the clock, it is possible to find conditions under which the XPM-induced sidebands of the data signal are polarization-independent. Unlike earlier approaches, this method does not require a prescribed clock polarization and can work even with birefringent fibers. A simple theoretical model is presented to explain the effect, and to predict the conditions under which polarization-independent behavior can be attained.

II. Polarization-Independent Demultiplexing Results

Fig. 1 shows the experiment used to demonstrate polarization-independent 160-Gb/s demultiplexing. The clock and data pulses were generated from two mode-locked fiber lasers at 10 GHz with 2.8- and 2.0-ps pulsewidths, respectively. The data signal was modulated with a 10-Gb/s $2^{23}-1$ pseudo-random data pattern and passively multiplexed to 160 Gb/s. The smallest multiplexer delay was approximately 800 ps, to ensure decorrelation between adjacent bits. The multiplexer uses polarization-maintaining fiber to guarantee that all channels of the 160-Gb/s signal are copolarized.

The data and clock signals were combined, amplified in an erbium-doped fiber amplifier, and launched into a 2-m length of bismuth–oxide fiber. The fiber has a nonlinear coefficient of $\gamma = 1100$ W$^{-1}\cdot$km^{-1}, dispersion of -260 ps/nm·km, and loss of 3 dB/m [8], [9]. The differential group delay (DGD) of the fiber was measured to be 0.15 ps. The average powers of the data and clock before entering the nonlinear fiber were 23 and

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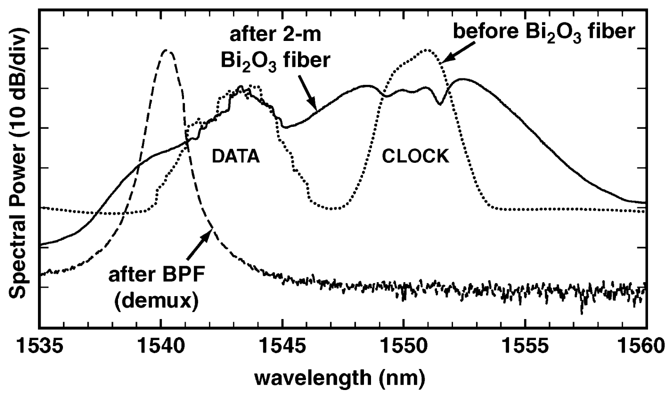

Fig. 2. Optical spectra before entering the fiber (dotted line), after 2 m of Bi_2O_3-based fiber (solid line), and after bandpass filtering (dashed line).

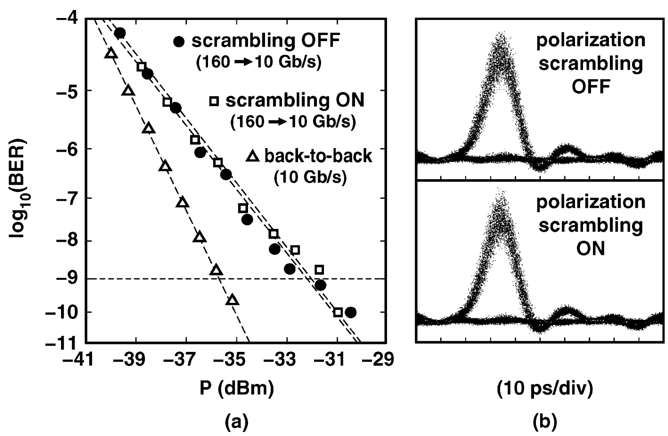

Fig. 3. (a) BER versus received power for the 160-Gb/s demultiplexer, showing little penalty when polarization is scrambled. (b) Measured eye diagrams of demultiplexed 10-Gb/s data, with and without polarization scrambling.

13 dBm, respectively. When the clock and data signals overlap, the strong clock signal causes broadening of the data signal through XPM, and a subsequent bandpass filter was used to isolate the spectrally broadened sideband [10], [11]. Fig. 2 plots data and clock spectra before entering the fiber (dotted line), after broadening in the fiber (solid line), and after bandpass filtering (dashed line). A high-speed polarization scrambler was inserted in the data path to evaluate the effect of polarization fluctuations. The clock power and bandpass filter wavelength were adjusted while monitoring the bit-error rate (BER) and eye diagram in order to achieve the lowest degree of polarization-dependence.

Fig. 3(a) plots the measured BER versus received optical power for back-to-back 10-Gb/s operation and for the 160-Gb/s demultiplexer. The circles indicate the BER obtained when the data polarization is constant, and the squares show that nearly identical performance is obtained when the data polarization is scrambled. The same behavior was observed for all 16 demultiplexed tributaries. The penalty observed between the demultiplexed and back-to-back results is attributed primarily to the extra optical amplifier required for demultiplexing, which introduces additional noise. Fig. 3(b) compares the eye diagrams of the demultiplexed data when the polarization scrambler is enabled and disabled, confirming that there is no appreciable eye closure caused by polarization scrambling.

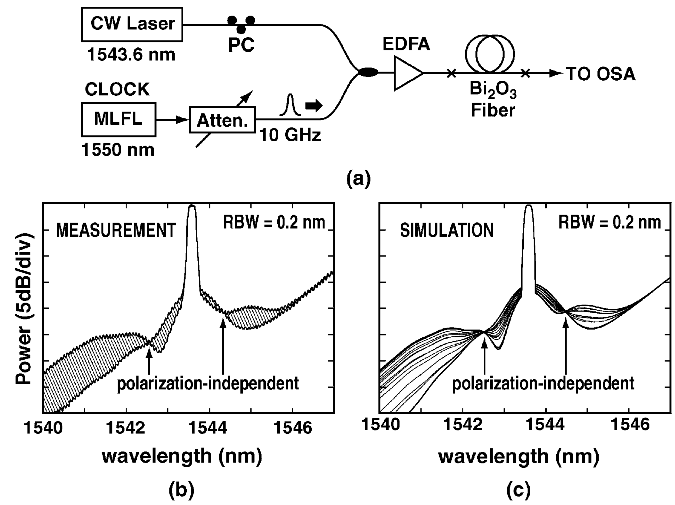

Fig. 4. (a) Experimental setup used for CW XPM measurements. (b) Measurement and (c) simulation of XPM-induced spectral broadening for different polarization states. The spectra appear tilted because of residual spectral power from the nearby pump signal (not shown).

III. Polarization-Independent XPM: Experiment and Simulation

In order to further investigate this polarization-independent behavior, we simplified the experiment by replacing the data with a continuous-wave (CW) tone, as shown in Fig. 4(a). The clock pulses were identical to those used in the demultiplexing experiment and the CW wavelength was adjusted to match the data wavelength used in the demultiplexer. In these measurements, we manually varied the polarization state of the CW signal while observing the spectrum of the XPM-broadened CW tone. The shaded region in Fig. 4(b) depicts a range of spectra that were observed experimentally while the polarization state was varied. Although the XPM spectra can differ by as much as 10 dB, all spectra were observed to intersect at one wavelength on either side of the spectrum. The XPM spectral power at these wavelengths was found to be polarization-independent. Although the clock polarization state was fixed in these measurements, we confirmed that the same behavior occurs for any input clock polarization state.

This behavior was confirmed by numerical simulations, using a vector split-step propagation code. Fig. 4(c) plots the calculated XPM-broadened spectrum of the CW tone for 16 different input polarization states. All 16 spectra converge at two wavelengths, and show excellent agreement with the experimental measurements. Although the CW measurements provide insight into the mechanism of polarization-independent behavior, because of the very different spectral shapes for 160-Gb/s data and the CW tone, one should not rely on the CW measurements to predict the wavelengths at which polarization-independent demultiplexing occurs.

IV. Discussion

To estimate the conditions under which polarization-independent performance can be attained, we consider the XPM of a weak CW probe signal by a strong Gaussian pump pulse described by

$$P(t) = P_0 e^{-t^2/T^2}. \tag{1}$$

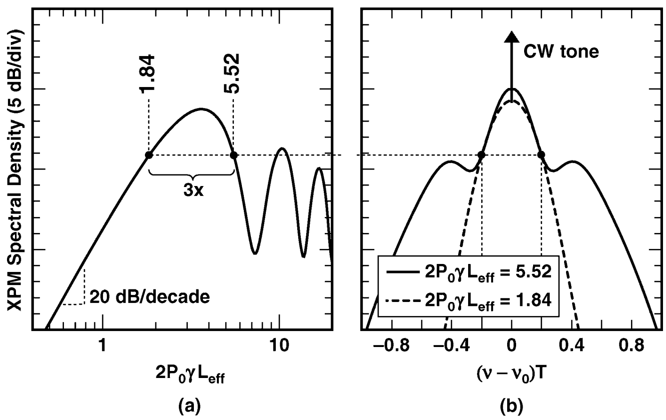

Fig. 5. (a) Calculated XPM spectral power at an offset frequency of $(\nu - \nu_0) = \pm 0.2/T$, as a function of $2P_0\gamma L_{\text{eff}}$. The two labeled points show that γ can change by $3\times$ without changing the XPM spectral power. (b) Calculated XPM spectra for the two points labeled in (a), showing the crossing points at $(\nu - \nu_0) = \pm 0.2/T$.

If we neglect the effects of pulse dispersion, FWM, and group velocity walkoff, the XPM spectrum of the probe signal depends only upon the dimensionless quantity $\phi_0 \equiv 2P_0\gamma L_{\text{eff}}$, where P_0 is the peak power of the Gaussian pump pulse, γ describes the nonlinearity, and $L_{\text{eff}} = (1 - e^{-\alpha L})/\alpha$ is the effective length.

The spectrum of the modulated CW tone cannot be expressed analytically, but it can be readily computed numerically. When ϕ_0 is small, the XPM spectrum grows in proportion to ϕ_0^2, but as the peak phase shift approaches π, the XPM spectrum begins to exhibit oscillations. This effect is shown in Fig. 5(a), which plots the calculated XPM spectral power at an offset frequency of $\Delta\nu = \pm 0.2/T$ away from the CW tone, as a function of $2P_0\gamma L_{\text{eff}}$.

The foregoing analysis assumed that the pump and probe signals were linearly copolarized. If the CW probe signal is instead polarized orthogonal to the pump, then the nonlinearity γ will decrease by a factor of $1/3$. The two points marked in Fig. 5(a) show that for a given peak power P_0, the nonlinear coefficient γ can decrease by a factor of $1/3$ without changing the XPM spectral power. Under this condition, the two orthogonal polarization states will produce the same XPM spectral power at the offset frequency, leading to polarization-independent operation. Fig. 5(b) plots the XPM spectra corresponding to the points labeled in (a), showing the distinct crossing points analogous to those observed experimentally.

For the selected offset frequency of $\Delta\nu = \pm 0.2/T$, polarization-independent behavior is predicted when $2P_0\gamma L_{\text{eff}} = 5.5$, whereas for the actual parameters reported here we instead calculate $2P_0\gamma L_{\text{eff}} = 10.9$. The discrepancy arises because the simple theory does not account for dispersion and signal walkoff, which can significantly decrease the XPM efficiency. As demonstrated in Fig. 4(c), more exact agreement between theory and experiment can be obtained by including the measured dispersion and DGD in the simulation. Nevertheless, the dispersion-free theory illuminates the underlying physical principle and provides a useful order-of-magnitude estimate of the power needed to obtain polarization-independent behavior.

As with other demultiplexing schemes that use XPM, the cumulative DGD and pulse walkoff from chromatic dispersion should be smaller than the pulsewidth. The technique could potentially be applied in a wavelength-division-multiplexed system, provided the 160-Gb/s channel of interest is first spectrally separated.

V. Conclusion

We report a new method for polarization-independent demultiplexing at 160 Gb/s using 2 m of bismuth–oxide nonlinear fiber. Error-free performance is obtained even when the polarization state is randomly scrambled. Numerical simulations confirm the nature of the the polarization-independent XPM, and a simple theoretical calculation is provided to predict the conditions required for polarization-independent behavior.

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