All-Optical 160-Gb/s Phase Reconstructing Wavelength Conversion Using Cross-Phase Modulation (XPM) in Dispersion-Shifted Fiber

Lavanya Rau, Wei Wang, Stefano Camatel, Henrik Poulsen, and Daniel J. Blumenthal, *Fellow, IEEE*

***Abstract*—Wavelength conversion using cross-phase modulation in dispersion-shifted fiber at 160 Gb/s is demonstrated. It is shown for the first time that the converter reconstructs the phase of the input signal, an important property for transmission of 160-Gb/s data. The bit-error rate of the converted channels is measured to be better than 10^{-9} with a power penalty of $<$3 dB and in some cases negative compared to the original unconverted optical time-division-multiplexing signal across all 16 $\times$ 10-Gb/s channels.**

***Index Terms*—Nonlinear fiber cross-phase modulation (XPM), optical regeneration, phase reconstruction, wavelength conversion.**

I. Introduction

TODAY'S optical transmission systems operate at data rates up to 10 Gb/s per channel and 40-Gb/s optical systems are commercially available. Transmission systems operating at 160-Gb/s systems are an area of current research focus. There is strong motivation to realize transmission and other optical networking functions that are difficult to perform electronically at data rates $>$ 100 Gb/s. Among these transmission and network functions are digital regeneration, wavelength conversion, and new signal processing and coding techniques that make transmission at 160 Gb/s more robust.

For robust transmission of high-speed signals, phase coherence is very important. The influence of phase correlation between individual channels of an optical time-division-multiplexing (OTDM) signal at 160 Gb/s in transmission was investigated in [1]. Phase correlation is also important in narrow bandwidth filtering to achieve high spectral efficiency [2]. It has been shown in [2] that coherent return-to-zero (RZ) data outperforms noncoherent RZ data in terms of narrow bandwidth filtering. Therefore, transmitters and regenerators that can reconstruct optical phase between adjacent pulses are important to 160-Gb/s systems.

Previously, wavelength conversion at 168 Gb/s was reported using a symmetric Mach–Zehnder type switch [3], however, the converted pattern lengths were severely limited and the converted channels had a power penalty of 10 dB relative to the base rate. Recently, nonlinear polarization rotation as a means of optical phase construction at a 160-Gb/s transmitter was reported in [4]. The technique utilized nonlinear polarization rotation of a copropagating continuous wave (CW) by a noncoherent data signal in highly nonlinear fiber. Highly coherent carrier-suppressed return-to-zero (CSRZ) and pair-wise alternating-phase CSRZ data formats at data rates $\geq$ 160 Gb/s are generated by filtering around the CW wavelength.

In this letter, we report the first demonstration of an all-optical nonlinear cross-phase modulation (XPM) fiber wavelength converter operating at 160 Gb/s that displays the properties of phase reconstruction on the converted data. Error-free conversion of all 16 $\times$ 10-Gb/s pseudorandom binary sequence (PRBS) data with less than 3-dB power penalty relative to the unconverted OTDM 160-Gb/s data was measured and in some cases negative power penalty was measured in the regeneration region. Previous demonstrations of fiber XPM wavelength conversion have been reported at 40 and 80 Gb/s [5], [6]. With successful operation at 160 Gb/s, we demonstrate the scalability of this technique.

II. Technique and Experimental Details

The conversion technique described here employs nonlinear phase modulation through the ultrafast Kerr effect to map RZ pulses at the input onto a highly coherent low phase noise local source tuned to the desired output wavelength. At the same time the data is converted to the new wavelength, this mapping can dramatically improve the pulse-to-pulse phase coherence as is shown in the results below. Carrier and single sideband optical filtering is employed to retransmit a copy of the input. The resulting nonlinear transfer function of the converter also equalizes pulse-to-pulse amplitude fluctuations. This combination of reconstructed phase and 2R regeneration makes this type of converter a promising candidate for 160-Gb/s optical transmission and networks.

The experimental setup shown in Fig. 1 employs a Calmar Optcom actively mode-locked fiber ring laser to generate pulses with a full-width at half-maximum of 1.5 ps at a repetition rate of 10 Gb/s at 1554.5 nm. An electrooptic modulator was used to encode 10-Gb/s $2^{31} - 1$ PRBS data on the optical pulse stream. The data encoded optical pulses were passively multiplexed using a split and interleave scheme to 160 Gb/s and the polarization states of all channels were adjusted to be equal.

At the wavelength converter, the 160-Gb/s OTDM data stream was combined with a 1547-nm CW signal before being amplified in a high-power erbium-doped fiber amplifier (hp-EDFA). The power of the CW signal in the hp-EDFA was 7.8 dB lower than the power of the 160-Gb/s data signal. It is important to maintain this ratio between the CW and the data signal to maintain a good signal-to-noise ratio of the converted

Manuscript received May 5, 2004; revised June 28, 2004.

L. Rau, W. Wang, H. Poulsen, and D. J. Blumenthal are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA (e-mail: lavanya@ece.ucsb.edu).

S. Camatel is on leave from the Department of Electronic Engineering, Politecnico di Torino, Torino 24-10129, Italy

Digital Object Identifier 10.1109/LPT.2004.835187

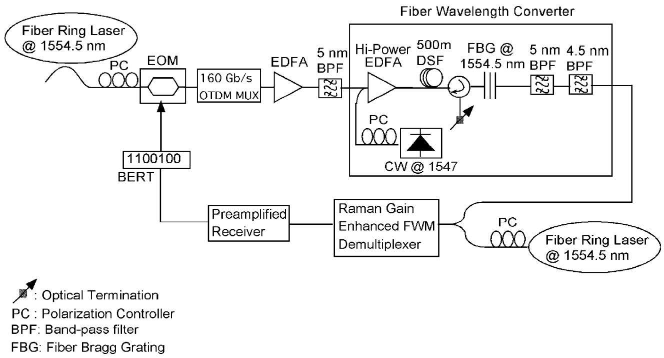

Fig. 1. Experimental setup of 160-Gb/s multiplexer–demultiplexer link with fiber XPM all-optical wavelength converter.

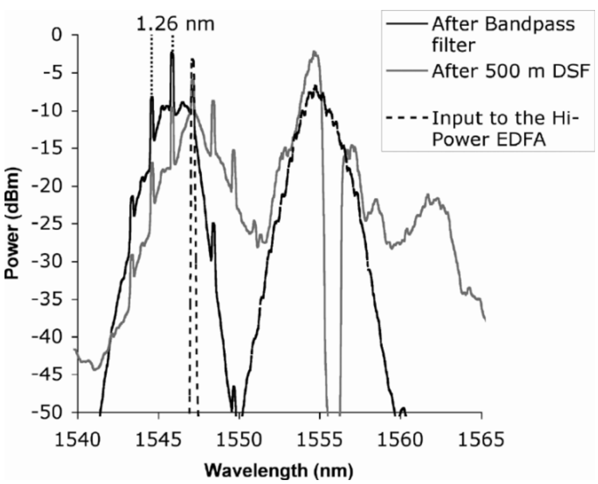

Fig. 2. Spectrum at the input to the hp-EDFA (dotted black line), after DSF (solid gray line), and after filter (solid black line).

signal. In the hp-EDFA, the CW and the data signals are amplified to 930 mW and injected into 500 m of dispersion-shifted fiber (DSF) with zero dispersion wavelength at 1559 nm. The walkoff between the data and the CW signal is less than 1 ps, a suitable value for conversion at 160 Gb/s to a new wavelength 7 nm away from the original. The data signal imposes phase modulation and generates sidebands as shown in Fig. 2. Phase modulation is converted to amplitude modulation by filtering one of the sidebands. A fiber grating and circulator is used at the output of the wavelength converter to notch out the original data signal and reduce the amount of optical power input to the optical filter. To filter the phase-broadened part of the CW, we use a combination of a 5- and a 4-nm optical filter, resulting in an effective filter bandwidth of 3.12 nm. The filter is offset from the CW signal by approximately 160 GHz to suppress the carrier to improve the extinction ratio of the converted signal.

III. Results and Discussion

The spectrum at the input to the hp-EDFA after DSF and the wavelength converted output are shown in Fig. 2. The gray solid line shows the spectrum of the combined CW and the 160-Gb/s OTDM signal at the input of the DSF. It is observed from this spectrum that the 160-Gb/s frequency tones from the original OTDM transmitter are not well defined. This is a result of poor phase correlation exhibited by pulses generated from mode-locked fiber ring lasers. The spectrum of the wavelength-converted signal shows high phase correlation at the converter output as shown by the well-defined tones spaced by 160 GHz. The improvement in phase correlation is due to phase modulation of a highly coherent distributed feedback laser as the local source of the converter.

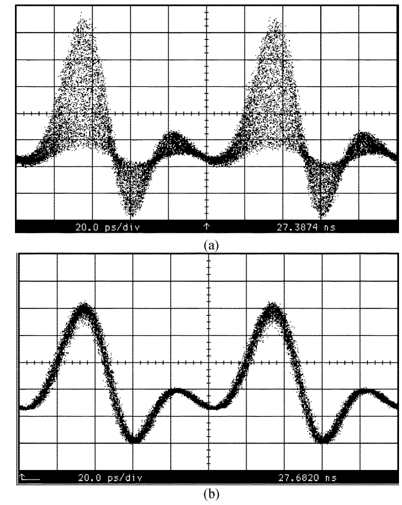

Fig. 3. (a) Pulses from fiber ring laser after the interferometer. Amplitude noise can be observed indicating insufficient phase correlation. (b) Pulses from fiber ring laser wavelength converted using fiber XPM after the interferometer. No amplitude noise can be observed indicating phase correlated output.

To verify that this technique improves phase correlation, we used a free-space Michelson interferometer, similar to that described in [2], to characterize the pulses before and after wavelength conversion. The delay in the interferometer was set to 1000 ps. The fiber ring laser pulses exhibited considerable amplitude noise due to poor pulse-to-pulse phase correlation, as shown in the interferometer output of Fig. 3(a). Next, a similar measurement was made on the wavelength-converted 10-GHz pulses showing extremely low amplitude noise as observed in Fig. 3(b).

To measure the digital performance of the converted 160-Gb/s data, each of the 16×10-Gb/s OTDM channels were demultiplexed down to 10 Gb/s using a Raman gain enhanced four-wave mixing demultiplexer described in [7] and detected using a preamplified 10-Gb/s receiver. Bit-error-rate (BER) measurements for each channel are shown in Fig. 4. The insets in Fig. 4(a) and (b) show the eye diagram for one of the demultiplexed wavelength-converted channels. The eye diagrams indicate clear and open eyes. All channels measured a BER better than 10^{-9} and were received with a power penalty < 3 dB power penalty relative to the unconverted OTDM 160-Gb/s data and in some cases negative power penalty when the converter was regenerating the original data. The spread in the receiver sensitivity (at 10^{-9}) is most likely due to the variation of polarization of the different time channels in the original signal resulting from the passive time multiplexer. It can be observed from Fig. 4 that the BER curves for some of the wavelength-converted channels cross the 10-Gb/s non-OTDM baseline for higher BERs which is a result of the 0.6-nm filter at the receiver not being spectrally matched to the original 10-Gb/s signal. So the receiver sensitivity of the 10-Gb/s non-OTDM signal is in

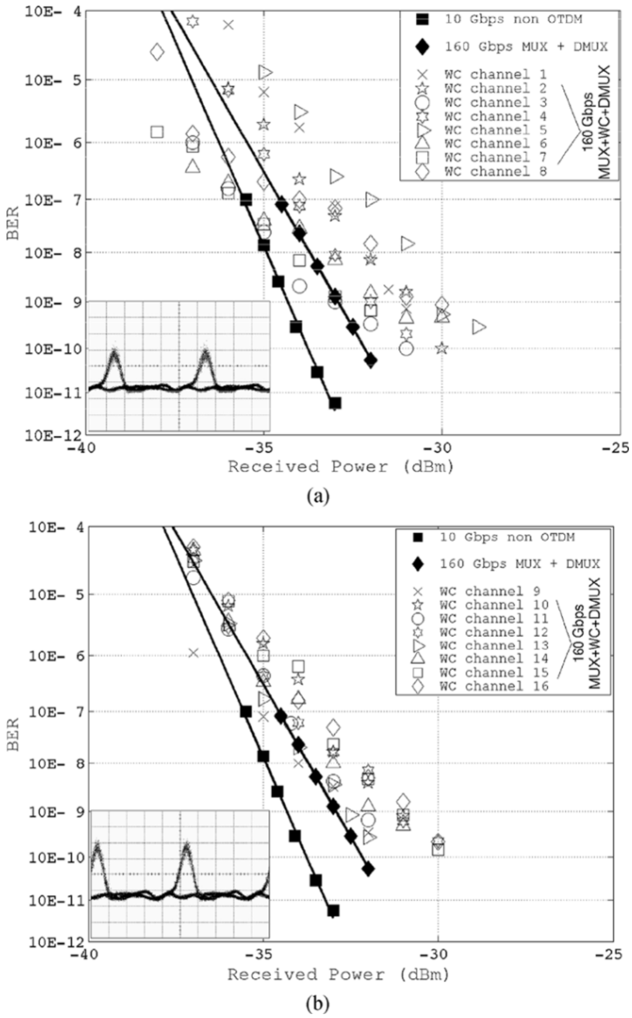

Fig. 4. BER curves for the 10-Gb/s baseline (solid squares), best 10-Gb/s multiplexed and demultiplexed channel (solid diamonds), and wavelength converted Channels (a) 1–8 and (b) 9–16.

fact better than the measured -34 dBm. It is also important to note that some of the wavelength-converted channels cross the 160-Gb/s nonconverted curves at higher BERs. We believe that the negative power penalty at these BER values is due to the ability of the converter to regenerate transmitted OTDM data. However, temperature-induced instability due to expansion and contraction of the fibers used for wavelength conversion and demultiplexing and intersymbol interference (ISI) introduced by the nonoptimized filters caused a change of slope in the BER curves and, thus, we could not obtain a negative power penalty for lower BER values. We also believe this ISI to be worse for certain channels due to the deviation from PRBS at the OTDM multiplexer output and subinterval channel misalignment in the multiplexer. There were no observed error floors for any of the 16 channels. All the channels were measured less than 10^{-12}. However, temperature-fluctuation-induced instability made it difficult to measure 10^{-11} and 10^{-12} BER over long periods of time .

This technology is scalable from 40 to 160 Gb/s. The pulsewidth and the filter bandwidth requirements for operation from 40 to 160 Gb/s are shown in Fig. 5. While the pulsewidth and the filter bandwidth requirement scale commensurate with

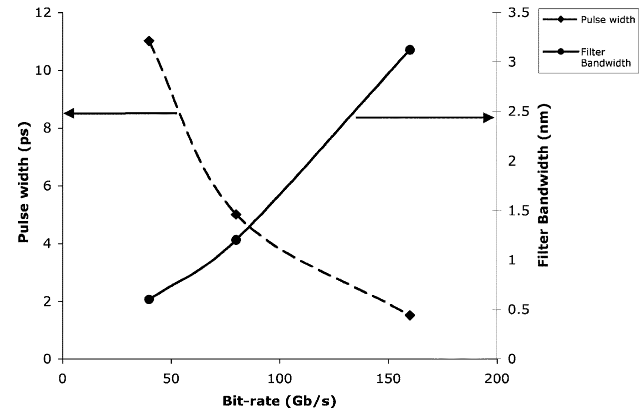

Fig. 5. Pulsewidth and filter bandwidth requirement for operation from 40 to 160 Gb/s.

the bit rate, the required power per channel is constant around 100 mW per channel.

IV. Summary and Conclusion

We have demonstrated for the first time that wavelength conversion at 160 Gb/s using XPM in 500 m of DSF exhibits the desirable property of improving the phase coherence of a signal with poor phase coherence. This property coupled with the 2R regenerative operation makes this technique a promising future candidate for 160-Gb/s transmission and networks. The converted signals are received with about 3-dB power penalty compared to the nonconverted signal. The measured sensitivities for all channels at 10^{-9} ranges from -30 to -33 dBm which can be improved by using a polarization-maintaining OTDM and obtaining a higher extinction ratio with an optimal filter design. Using a highly nonlinear fiber can further lower the power requirement.

References

[1] I. Morita and N. Edagawa, "Study on optimum OTDM signals for long-distance 40 Gbit/s transmission," in *Postconf. Tech. Dig. Optical Fiber Communication Conf. (OFC 2002)*, Washington, DC, 2002, Paper TuA4.

[2] L. Möller, Y. Su, R. Ryf, C. Xie, and X. Liu. Narrow bandwidth filtering of coherent and OTDM-generated 160 Gb/s data signals. presented at *Optical Fiber Communication Conf.*. [CD-ROM]Paper ThN2

[3] S. Nakamura, Y. Ueno, and K. Tajima, "168-Gb/s all-optical wavelength conversion with a symmetric-Mach–Zehnder-type switch," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1091–1093, Oct. 2001.

[4] L. Möller, Y. Su, C. Xie, R. Ryf, X. Liu, X. Wei, and S. Cabot, "All-optical phase construction of ps-pulses from fiber lasers for coherent signalling at ultra-high data rates," in *Optical Fiber Communication Conf.*, Washington, DC, 2004, Postdeadline Paper PDP20.

[5] B. E. Olsson, P. Ohlen, L. Rau, and D. J. Blumenthal, "A simple and robust 40-Gb/s wavelength converter using fiber cross-phase modulation and optical filtering," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 846–848, July 2000.

[6] L. Rau, S. Rangarajan, D. J. Blumenthal, H. F. Chou, Y. J. Chiu, and J. E. Bowers, "Two-hop all-optical label swapping with variable length 80 Gb/s packets and 10 Gb/s labels using nonlinear fiber wavelength converters, unicast/multicast output and a single EAM for 80- to 10 Gb/s packet demultiplexing," in *Postconf. Tech. Dig. Optical Fiber Communications Conf. (OFC)*, vol. 2, 2002, Postdeadline Paper 02CH37339, pp. FD2–1–FD2-3.

[7] W. Wang, L. Rau, H. Poulsen, and D. Blumenthal, "Raman gain enhanced FWM 160 Gb/s OTDM demultiplexer with highly-nonlinear-fiber," in *Optical Fiber Communication Conf.*, Washington, DC, 2004, Paper ThN3.