All-Optical Header Erasure and Penalty-Free Rewriting in a Fiber-Based High-Speed Wavelength Converter

Peter Öhlén, Bengt-Erik Olsson, and Daniel J. Blumenthal

***Abstract*—All-optical erasure and rewriting of 2.5–Gb/s nonreturn-to-zero (NRZ) data from high-speed return-to-zero (RZ) data has been demonstrated using a fiber-based wavelength converter. Such a wavelength converter will block the low frequencies of the NRZ data while converting the RZ pulses. This approach uses the frequency discriminating feature of the wavelength converter, and does not require active control. Penalty-free rewriting of new NRZ data was then performed.**

***Index Terms*—Cross-phase modulation, nonlinear fiber optics, optical fiber communication, optical networks, optical packet switching, wavelength converters.**

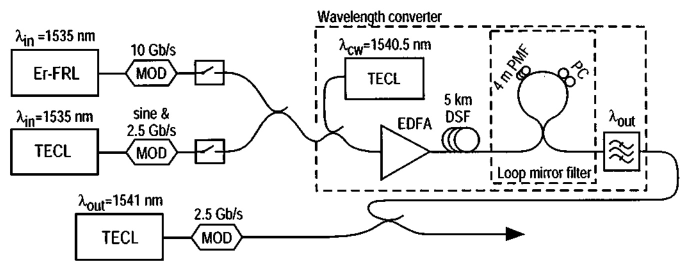

Fig. 1. Experimental setup of the XPM wavelength converter. Er-FRL: Fiber ring laser; TECL: Tunable External Cavity Laser; MOD: Mach–Zehnder modulator; EDFA: Erbium-doped fiber amplifier; PC: Polarization controller; PMF: Polarization maintaining fiber; DSF: Dispersion shifted fiber.

I. Introduction

TODAY wavelength-division multiplexing (WDM) is well established and has been able to support the increasing demand for transmission capacity. While the performance of present systems continues to improve, optical packet-switching technologies may be required to deliver low-latency packet routing and forwarding at terabit wire rates. The technologies that are being developed should also support header erasure/rewriting in order to enable next-generation IP routing approaches like all-optical label swapping (AOLS) [1]–[3] and new simpler IP routing protocols such as multiprotocol label switching (MPLS) [4] to simplify route lookup and optical implementation.

In all-optical packet switching, the header can be encoded at a lower bit rate and inserted in front of the payload [1], [5], or encoded on a subcarrier at the same wavelength, but outside the data frequency band [3]. At each node, the header is processed and replaced using relatively low-speed electronics, while the high-speed payload remains in the optical domain and is transmitted through the node. A new header is generated electronically and multiplexed with the payload to form the outgoing packet.

In an optical switching node, a tunable wavelength converter combined with a wavelength-selective element, can be used as a switching element. Here we describe how a wavelength converter based on cross-phase modulation in an optical fiber [6] can be used to passively remove a low-bit-rate nonreturn-to-zero (NRZ) header from a high-speed return-to-zero (RZ) payload. In the wavelength converter, the input data is combined with a local continuous-wave (CW) signal and launched into a dispersion-shifted fiber. The input data will impose a phase modulation on the CW light, which can be turned into an amplitude modulation by filtering out one of the generated sidebands. Such a wavelength converter has a nonlinear transfer function than can be used to suppress a header to some extent, but it also has a differentiating nature which is the main mechanism employed to remove low-frequency data used in a header. A new header can then be inserted by premodulating the local CW source in the wavelength converter [5]. If the CW source is not very stable small changes in wavelength will cause power fluctuations in the output. Here we use a separate source for the new data to overcome this problem.

II. Experiment

In the first experiment, the wavelength converter was characterized with a sinusoidal input. Fig. 1 shows the experimental setup where 8-ps pulses with a repetition rate of 10 GHz were generated from an actively mode-locked erbium-doped fiber ring laser, and modulated with 10-Gb/s PRBS data. (This pulsewidth is suitable for optically multiplexing the 10-Gb/s data to 40 Gb/s.) A tunable external cavity laser was externally modulated with a sine signal ranging from 1 to 20 GHz. These two sources were gated with acustooptic modulators and combined to form data and sine packets as shown in Fig. 2(a). In the wavelength converter, the input signal is combined with a local continuous-wave (CW) souce, and amplified before

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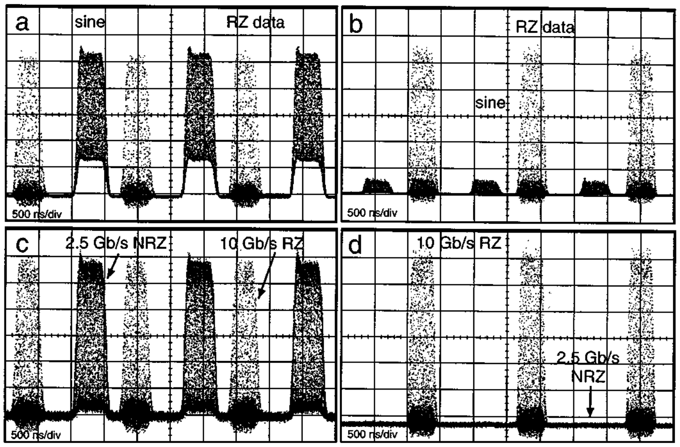

Fig. 2. Generated packets with a 10 GHz sine and 10-Gb/s RZ data before (a) and after (b) the wavelength converter. Packets with 2.5-Gb/s NRZ data and 10-Gb/s RZ data before (c) and after (d) the wavelength converter. It can clearly be seen how the RZ data is converted, while the lower frequency part is suppressed.

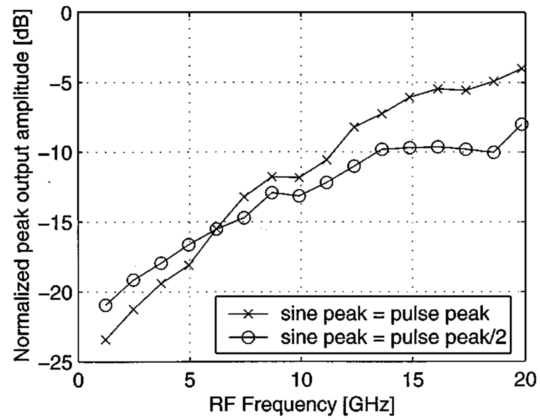

Fig. 3. Frequency dependence of the wavelength converter for a sine signal when the input sine peak power was adjusted to the input pulse power and half the input pulse power. Output powers are normalized to the output pulse peak power, and half the output pulse peak power, respectively.

entering a 5-km dispersion-shifted fiber (DSF). The local CW light is spectrally broadened by cross-phase modulation from the input signal, and will have two sidebands at the output of the DSF. A loop-mirror filter which has a sinusoidal transfer function (in the frequency domain) with repetitive notches [6] is used to remove the original CW light. Then a bandpass filter selects one of the remaining two sidebands with the wavelength converted data. (This process can be seen in Fig. 4.) Fig. 2(a) shows data packets together with 10-GHz sine packets at the input, where the peak amplitudes were adjusted to the same value. The extinction ratio of the sine signal is lower because we used the linear regime of the Mach–Zehnder transfer function. In the generation of the optical sidebands on the CW signal, the input pulse power causes a phase modulation on the CW light, and the instantaneous optical frequency deviation of the CW light is given by the derivative of the optical phase. Thus the instantaneous frequency deviation will depend on the derivative of the input pulse power, which is turned into amplitude modulation after filtering. Due to this differentiating nature, the rise and fall times determine the conversion efficiency, which means that the wavelength converter will block low signal frequencies. In Fig. 2(b), it can clearly be seen how the RZ data is converted and the 10-GHz sine is suppressed. Fig. 3 shows the output peak power, normalized to the output pulse peak power. When the frequency of the sine is decreased, the output power drops quickly to levels below −20 dB at 1.24 GHz. Fig. 3 also shows the suppression when the input sine signal was adjusted to half the RZ data amplitude, where the suppression is initially higher, but drops slower. Due to the nonlinear behavior of the wavelength converter, the output will generally not be a sine, but the peak power is still a good measure of the suppression. For pulses, the pulsewidth, and not the bit rate, will determine the conversion efficiency. It should be noted that NRZ data cannot be converted, as only the edges of a signal are converted. In a sequence of consecutive ONE's, only the first ONE would generate an output signal. However, there would still be some output that could cause crosstalk when a new header is inserted, even though the old

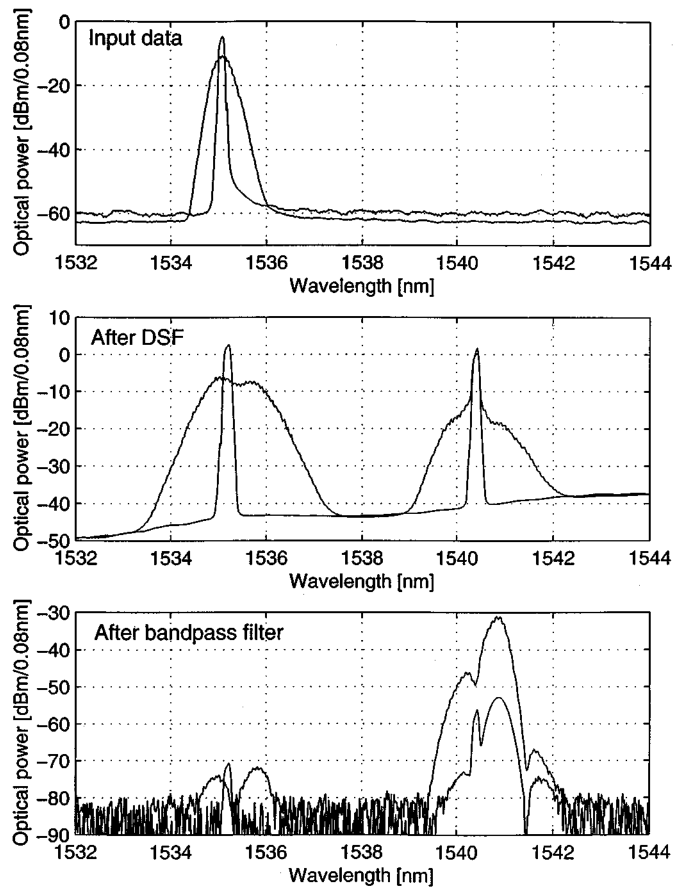

Fig. 4. Optical spectra for the 10-Gb/s RZ and the 2.5-Gb/s NRZ, at the wavelength converter input, after the dispersion-shifted fiber, and after the wavelength converter.

header data has been corrupted. Fig. 2(c) and (d) shows the situation for packets of 2.5-Gb/s NRZ and 10-Gb/s RZ, before (c) and after (d) the wavelength converter. On the oscilloscope, the remainder of the 2.5-Gb/s NRZ data was totally hidden in the detector noise. By averaging the signal, the suppression was estimated to around −23 dB, which agrees with the sine measurements.

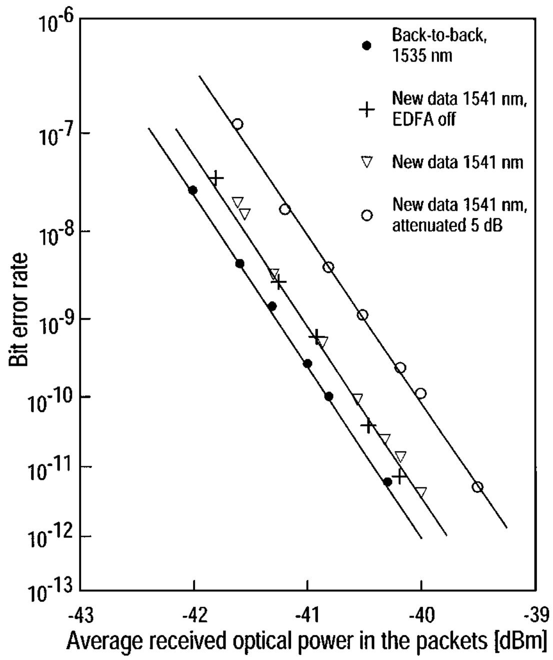

Fig. 5. BER measurements: (•) the original 2.5-Gb/s NRZ data at 1535 nm; (+) new 2.5-Gb/s NRZ data at 1541 nm with EDFA in the wavelength converter turned off; (▽) new 2.5-Gb/s NRZ data with the wavelength converter turned on; and (○) new 2.5-Gb/s NRZ data attenuated 5 dB, otherwise as ▽.

In the second experiment, the 10-Gb/s RZ data and the 2.5-Gb/s NRZ data were switched manually, to measure the optical spectra, and to measure the penalty for rewriting new 2.5-Gb/s data where the original data was erased. At the input to the wavelength converter, the average power of the NRZ and the RZ data were equal. Fig. 4 shows the optical spectra as measured with an optical spectrum analyzer at the input to the wavelength converter, after the DSF, and after the wavelength converter. It can clearly be seen how the RZ data significantly broadens the CW source in the WLC, whereas no broadening can be noticed in the diagrams for the 2.5-Gb/s data.

Then the bit-error rate (BER) was measured for the original and rewritten header data using continuous $2^{31} - 1$ pseudo-random data. Fig. 5 shows the back-to-back measurements for the original transmitter at 1535 nm (•) as well as for the new transmitter at 1541 nm with the EDFA in the wavelength converter turned off (+). The small difference in sensitivity of 0.2 dB could be due to minor differences in the transmitters and the wavelength. The average power of the new data was adjusted to the same average power as the converted RZ data. The bit-error rate when the wavelength converter is turned on (▽) shows no penalty compared to the case with the amplifier turned off. The new data is offset by 0.5 nm, which means that the crosstalk will not be interferometric. With a suppression of around −20 dB, one should not see a penalty and the experimental result is expected. When the power of the new data is attenuated by 5 dB (○), keeping everything else constant, a penalty of 1 dB can be seen, which increases to 5-dB penalty with 10-dB attenuation of the new data. This is probably due to noise from the amplifier in the wavelength converter. In this experiment, no BER measurements were made for the 10- and 40-Gb/s data, which have been reported elsewhere for packets [5] and continuous data [6].

III. Conclusions

From the measurements it is clear that this type of wavelength converter can be used to passively erase a 2.5-Gb/s NRZ header from a high-speed RZ payload. Compared to other approaches using time-domain header [1], [2], no timing control is required to erase the header. To insert a new header timing control would be necessary to align the new header to the wavelength converted payload. New 2.5-Gb/s data can then be rewritten in different ways. Here a separate transmitter was used for the new data, which showed no crosstalk penalty from the previously erased data. This makes the system more stable compared to the approach of premodulating and slightly detuning the local CW light in the wavelength converter as demonstrated in [5], but requires a high extinction ratio of the new header source when the payload is present. Otherwise, the local header source would cause the payload data to be degraded due to interferometric crosstalk. A third option which has not been experimentally investigated, is to encode the new header by frequency-modulating the local CW laser in the wavelength converter. With the present tuning speed of about 5 ns this would limit the bit rate to a maximum of 100 Mb/s, but with further advances in tunable laser technology this could be an interesting option.

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