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Byte-Level Parametric Wavelength Exchange for Narrow Pulsewidth Return-to-Zero Signal

Mengzhe Shen, Xing Xu, T. I. Yuk, and Kenneth K. Y. Wong, Member, IEEE

Abstract—We investigate the feasibility of switching return-to-zero signals with 3-ps pulsewidth by byte-level parametric wavelength exchange (PWE) numerically and experimentally. Square-wave modulated pumps are used in PWE for pump gating. Simultaneous bit swapping for two signals at the same time slot is achieved. Error-free operation is achieved for both signal channels with ≈3.5-dB power penalty at 10^{-9} bit-error rate.

Index Terms—Nonlinear fiber optics, optical communication, packet switching, parametric devices.

I. INTRODUCTION

A KEY function in future optical networks is the ability to switch at the router nodes in more than one physical domain to ensure high-speed and high-throughput performance [1]. Typically, switching operations are performed in either the time, wavelength, or space domain. Previously, wavelength interchange was demonstrated by using an optical parametric loop mirror based on four-wave mixing (FWM) [2]. Architectures for a wavelength interchange cross connector utilizing a parametric wavelength converter were also reported [3]. An alternative approach to achieve a wavelength interchange is parametric wavelength exchange (PWE) [4]–[6]. PWE has been proposed to manipulate the data stream in the wavelength domain due to its complete exchange characteristics. In other words, a signal wavelength at λ_{n,1} and an idler wavelength at λ_{k,1} exchange their power periodically as a function of fiber length while two strong pumps at λ_{p,1} and λ_{p,2} are copropagating in highly nonlinear dispersion-shifted fiber (HNLF-DSF). Compared with a continuous-wave (CW) pump based PWE, byte-level PWE based on a pulsed pump is more versatile in the optical network, especially when it is combined with time slot interchange [7], because the network may require the use of more than one switching domain in order to meet the increasing demand as traffic grows. Previously, we have presented a proof-of-principle demonstration of byte-level PWE with two programmable 10-Gb/s nonreturn-to-zero (NRZ) signals in [5], in which performance of exchange was quantified by the waveforms observed on oscilloscope. In this letter, we analyze the performance of byte-level PWE for 3-ps 10-Gb/s return-to-zero (RZ) signals. Experimental results show power penalties ≈3.5 dB at a bit-error rate (BER) of 10^{-9} due to PWE. Simulation suggests that the proposed setup can perform at a higher data rate, but the switching time is limited by the ON–OFF speed of the pumps.

II. BYTE-LEVEL PWE

We first introduce the principle of byte-level PWE operation as illustrated in Fig. 1. When two square pumps at λ_{p,1} and λ_{p,2} are propagating with a signal wavelength at λ_{s,1} and another signal wavelength at λ_{s,2} in HNL-DSF, data bits at λ_{s,1} and λ_{s,2} are swapped only at timeslots that the pump gates are on. The peak power of the pulsed pumps (P_{p,1} and P_{p,2}) are adjusted to follow P_{p,1} = P_{p,2} = 3\pi/4\gamma L for a fiber length L and nonlinear coefficient γ. The four waves involved in PWE are arranged symmetrically with respect to the zero-dispersion wavelength (ZDW) λ_{0} of the fiber, such that their angular frequencies (ω = 2\pi c/λ) have a relationship of ω_{s,1} + ω_{p,2} = ω_{s,2} + ω_{p,1} = 2ω_{0} [4]. Ideally, complete data bits swapping are satisfied under the wavelength allocation for a narrow linewidth signal with low transmission speed. Considering an FWM process, where ω_{j} (j = 1–4) are the frequencies of ω_{p,1}, ω_{p,2}, ω_{s,1}, and ω_{s,2}, respectively, the amplitude (B_{j}, j = 3, 4) evolution of signals at ω_{3} and ω_{4} is given by dB_{j}/dz = i[2\gamma(P_{1}P_{2})^{3/2}B_{j}/3 – \kappa B_{j}]/2]. The β is defined as Δβ = β_{1} + β_{2} – β_{3} – β_{4}, where β_{i} are the propagation constants in the fiber. The conversion efficiency for the signal at ω_{3} can be defined as η = B_{4}(z)B_{3}(z)/B_{5}(0)B_{6}(0). It shows that the maximum conversion efficiency is unity. In practical use, the conversion efficiency will be reduced by factors such...
as spurious FWM components, pump depletion, fiber dispersion slope, and ZDW fluctuation along the fiber even if the frequency relationship is satisfied. If the signal wavelength deviates from its central value which realizes unit conversion, conversion efficiency will further decrease due to the propagation constant mismatch. The larger the signal wavelength deviates from its central value, the more the conversion efficiency degrades. Since the spectrum width for narrow pulsewidth RZ signal is usually as wide as several nanometers, it is a logical question to ask if the CW or quasi-CW (such as CW pumps modulated by low-speed square waves) pumps are able to exchange short RZ pulses completely. In order to demonstrate PWE’s capability to handle a high-speed optical signal, it is thus worthwhile to investigate its signal bandwidth. This question has been partially addressed in [4], in which the analytical expression for the bandwidth of conversion efficiency was obtained.

In the upper inset of Fig. 2, an estimation of the signal bandwidth is presented by using [4, eq. (18)]. The parameters are the same as those used in the experiment. It is found that there are two peaks center at 1531.9 and 1534.8 nm, both with 3-dB bandwidth of 0.5 nm. In the absence of frequency chirp, this spectral bandwidth transforms to a temporal width equal to 2.55-ps. It implies that CW and quasi-CW are capable of handling short RZ pulses in high-speed data stream up to 160 Gb/s or more. However, in an analytical approach, the neglect of spurious FWM components and the pulsed pumps’ temporal characteristic such as rise and fall time may result in a too optimistic prediction [8]. Therefore, the switching performance of the proposed PWE (the signal data rate limitation, more precisely) is investigated further by the software Optsim to perform a realistic simulation. Fig. 2 plots the variation of the exchanged signal’s Q-factor versus signal data rate. The configuration is the same as the following experimental setup except for the variable data rate. The rise and fall time of the gating pump is assumed to be 10 ps so as to largely exclude the effect of pump speed. It is found that the higher the data rate, the lower the exchanged signal’s quality, while there is a flat region between 40 to 100 Gb/s. We predict that the data rate within this region is the limitation that the proposed PWE can handle. The trace and eye diagram of the 80-Gb/s signal channel at 1532 nm when the other channel at 1535 nm is disabled is shown in the lower inset of Fig. 2.

Fig. 3 shows the experimental setup of the proposed byte-level PWE and insets are eye patterns of input signals and pumps and spectrum after HNL-DSF.
of the exchanged bits are observed to be slightly higher than that of the original ones. It is believed to be mainly caused by residual and spurious FWM components. In order to contrast the exchanged data and original data clearly, the RZ signal channel at 1532 nm is replaced by NRZ signal at 1529 nm and the pump at 1552 nm is tuned to 1555 nm correspondingly. The waveforms shown in Fig. 4(e)–(h) demonstrate a complete data swapping at bit-period timescales. In order to quantify the performance of the byte-level PWE, BER of the exchanged signals are measured and compared against the back-to-back (B2B) signal as shown in Fig. 5. It is found that for signal at 1532 nm, its power penalty is 4.5 dB, which is larger than that of 1535 nm (≈2.2 dB). In spite of the influence of PWE, it is believed to be partially caused by the original pulse quality difference that is inherited in the laser sources. Since half bits for each signal (due to the 50% duty cycle of the pulsed pump) are replaced with exchanged ones after PWE, it is reasonable that for channels originally consisting of higher quality pulses, its average BER sensitivity will degrade more after PWE, while for channels originally consisting of lower quality pulses, its BER sensitivity will degrade less. Thus, we measure sensitivity difference of the two signals in a B2B situation (≈1.0 dB) such that we are able to quantify the power penalty arising from the laser sources. Therefore, we qualitatively predict that for a signal at 1532 nm whose power penalty is 4.5 dB, a 1.0-dB penalty is inherited from the pulse quality difference between the laser sources while 3.5 dB resulted from the PWE process’s penalty. In the inset of Fig. 5, the magnified eye diagrams for the original and exchanged data are presented. It is observed that intrinsic timing jitter (≈1.2 ps) of oscilloscope (Agilent 86100C) has a severe effect on the RZ signals’ eye waveform. Besides this noise mechanism, there is no obvious signal quality degradation after the PWE process.

III. CONCLUSION

We have demonstrated byte-level PWE for 10-Gb/s RZ signals with 3-ps pulsewidths, with a power penalty of 3.5 dB for a BER at $10^{-9}$ obtained by excluding the influence of laser pulse quality. Simulation results further suggest that byte-level PWE can be a promising candidate for high data rate operation at 80-Gb/s with the help of a fast pump control.

REFERENCES