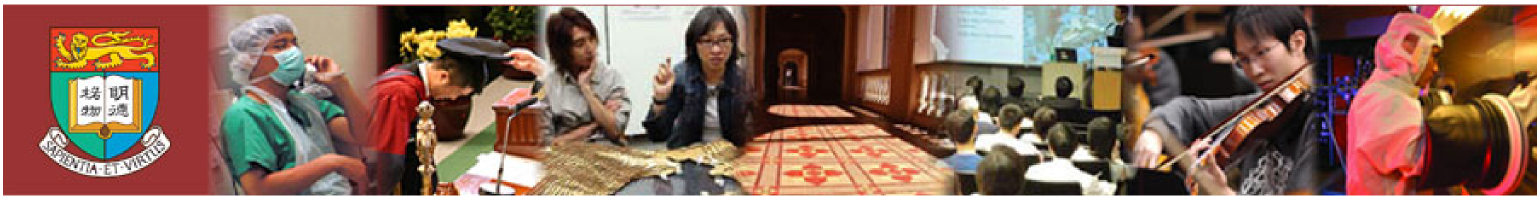

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Byte-Level Parametric Wavelength Exchange for Narrow Pulsewidth Return-to-Zero Signal

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***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 $\approx$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 convertor 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_{signal} and an idler wavelength at λ_{idler} exchange their power periodically as a function of fiber length while two strong pumps at λ_{p1} and λ_{p2} are copropagating in highly nonlinear dispersion-shifted fiber (HNL-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 $\approx$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.

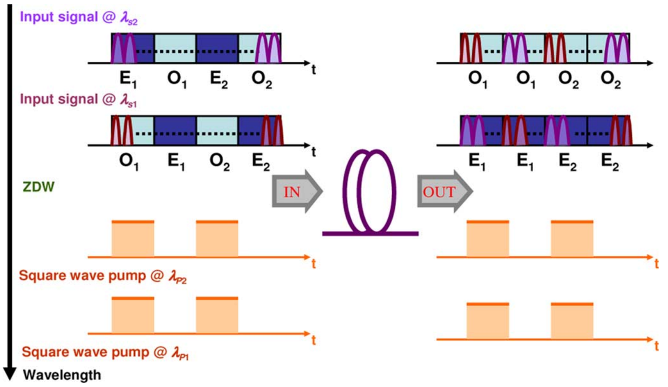

Fig. 1. Schematic illustration of byte-level PWE. Odd and even data packets at different wavelengths are swapped in compliance with synchronized pulsed pump.

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_{p1} and λ_{p2} are propagating with a signal wavelength at λ_{s1} and another signal wavelength at λ_{s2} in HNL-DSF, data bits at λ_{s1} and λ_{s2} are swapped only at timeslots that the pump gates are on. The peak power of the pulsed pumps (P_{p1} and P_{p2}) are adjusted to follow $P_{p1} = P_{p2} = 3\pi/4\gamma L$ 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 ($\omega = 2\pi c/\lambda$) have a relationship of $\omega_{s1} + \omega_{p2} = \omega_{s2} + \omega_{p1} = 2\omega_0$ [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 $\omega_{p1}, \omega_{p2}, \omega_{s1}$, and ω_{s2}, respectively, the amplitude ($B_j, j = 3, 4$) evolution of signals at ω_3 and ω_4 is given by $dB_j/dz = i[2\gamma(P_1P_2)^{1/2}B_{7-j}/3 - \kappa B_j/2]$. The $\kappa = \Delta\beta + \gamma(P_1 - P_2)/3$ describes the phase mismatch and P_1, P_2 stand for pump power at ω_1 and ω_2, respectively. $\Delta\beta$ is defined as $\Delta\beta = \beta_1 + \beta_4 - \beta_2 - \beta_3$, where β_i are the propagation constants in the fiber. The conversion efficiency for the signal at ω_3 can be defined as $\eta = B_4(z)B_4^*(z)/B_3(0)B_3^*(0)$. It shows that the maximum conversion efficiency is unity. In practical situation, the conversion efficiency will be reduced by factors such

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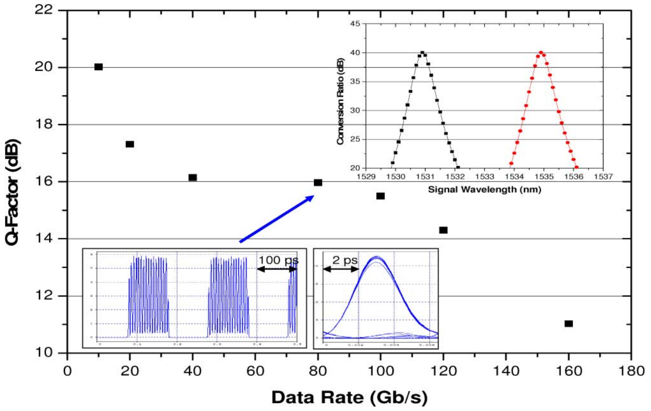

Fig. 2. Q-factors for exchanged signal at 1532 nm versus the signal data rate. Insets: signal trace and eye diagram when the other signal channel is disabled (lower); conversion ratio versus signal wavelength (upper).

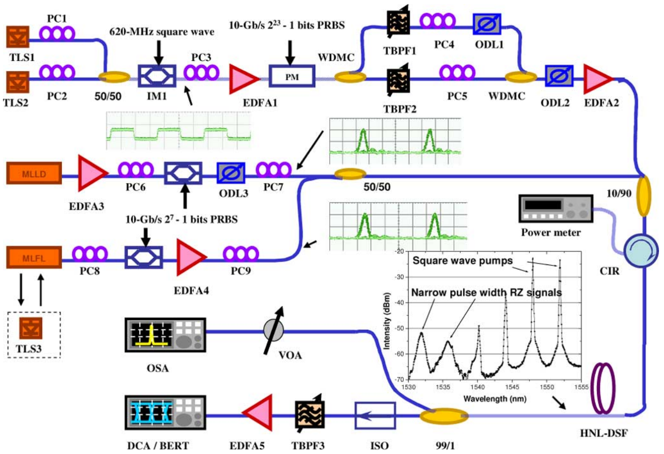

Fig. 3. Experimental setup for the byte-level PWE and insets are eye patterns of input signals and pumps and spectrum after HNL-DSF.

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 for narrow pulsewidth RZ signals. It is similar to the setup used in [5]. The two pumps are chosen at 1548 and 1552 nm, respectively. They are intensity modulated with a 620-MHz gating quasi-square-pulse with a pulsewidth of 800-ps and a duty cycle of 50% through the intensity modulator (IM), to provide 0.2 W of peak power after erbium-doped fiber amplifier (EDFA 2). The rise and fall times for the gating pumps are 14.2 and 18.1 ps, respectively, which correspond to above 40-Gb/s switching speed. Optical delay lines (ODL 1 and ODL 2) are used to synchronize the gating pumps and the pumps with signals. The input 10-Gb/s RZ signals at 1532 and 1535 nm are generated by intensity-modulating a 2-ps 10-GHz pulse train from a mode-locked fiber laser (MLFL) and a mode-locked laser diode (MLLD) with two IMs. The pseudorandom binary sequence (PRBS) length of the resultant 10-Gb/s signal is $2^7 - 1$ bits and they are further amplified to -0.5- and -1.5-dBm average power before HNL-DSF, respectively. The wavelengths of the two RZ signals are relatively close to each other because 1532 nm is the lower wavelength bound of our MLFL. In order to measure the BER for packet swapped data stream after the PWE process, we must ensure that the swapped data packets carry exactly the same 0 or 1 as in the input. It means that the RZ data stream at two channels must be synchronized in the time domain. Thus, we add 1-m-long single-mode fiber (SMF) and an ODL 3 in the fiber path of signal at 1535 nm to provide synchronization.

To demonstrate the completeness of exchange for each signal at the time slots synchronized with pulsed pumps, we first enable only one signal channel at 1532 or 1535 nm passing through the fiber with pulsed pumps. Corresponding eye waveforms for two signal wavelengths are shown in Fig. 4(a) and (c). The small amount of residual power level incurs a low crosstalk between the residual data and swapped ones. In Fig. 4(b) and (d), the eye diagrams for composite data stream at both signal wavelengths combining original bits and exchanged bits after PWE are demonstrated. The space levels

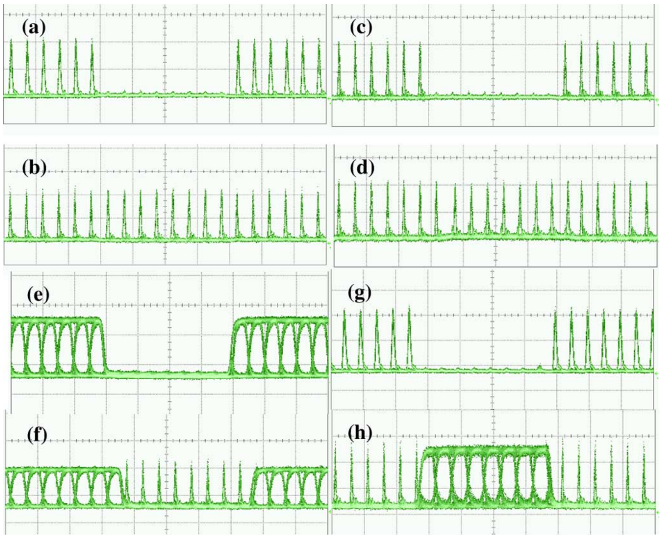

Fig. 4. (a), (b) RZ signal at 1532 nm; (c), (d) RZ signal at 1535 nm; (e), (f) NRZ signal at 1529 nm; (g), (h) RZ signal at 1535 nm after HNL-DSF when the other signal branch is OFF and ON. Time base: 200 ps/div.

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. Indeed, this claim can be verified by the fact that the signal at 1535 nm experiences 2.2-dB penalty after the exchange since the penalty inherited from the source compensates for 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.

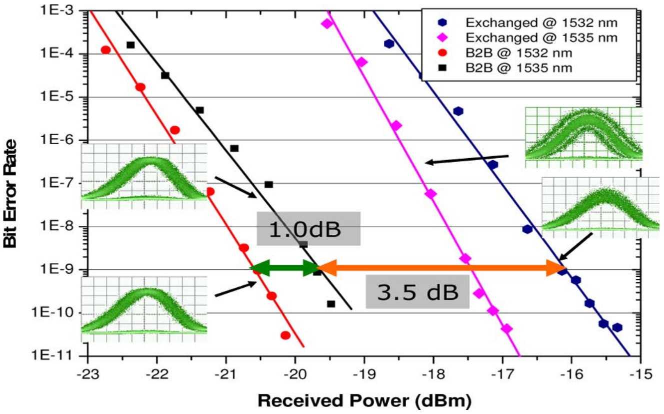

Fig. 5. BER plots of the B2B and exchanged signals. Inset: magnified eye diagrams before and after exchange.

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.

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