All-Optical Processing by Fiber Delay and Four-Wave Mixing of High-Bit-Rate Nonreturn-to-Zero Signals for Timing Extraction by Optical Injection Locking

A. Bilenca, D. Dahan, J. Lasri, and G. Eisenstein

***Abstract*—In this letter, we report an all-optical processing scheme which generates a strong spectral component at the bit rate frequency of a high-speed nonreturn-to-zero data stream. The processed signal can be used for timing extraction by direct optical injection locking. The scheme is based on multiplying the data signal by its delayed replica. A dispersion compensating fiber serves as a delay line and the multiplication is performed by four-wave mixing in a dispersion-shifted fiber. Simulated results and experimental confirmations are demonstrated.**

***Index Terms*—Carrier-to-noise ratio, nonlinear optics, timing circuit.**

BIT SYNCHRONIZATION is an inherent function in all-optical transparent networks. It requires accurate clock extraction, which is usually implemented by electrooptical or all-optical means [1]. For signals modulated in the return-to-zero (RZ) format, clock extraction is, in principle, a simple task as they contain a strong spectral component at the bit rate frequency, which can be used for optical injection locking. Timing extraction of 10 and 40-Gb/s RZ signals was recently demonstrated using direct optical injection locking of self-oscillating phototransistors [2] and self-pulsating lasers [3]. In contrast, random data sequences modulated in the nonreturn-to-zero (NRZ) format with a 50% transition density contain no spectral components at the bit rate frequency or its harmonics. In order to use NRZ signals for direct optical injection locking, some initial nonlinear processing is required so as to generate a clock frequency spectral component.

Several processing techniques have been reported in both the optical [4]–[6] and electrical [7] domains. This letter describes an all-optical version of a well-known electronics scheme known as nonlinear spectral-line self-bit synchronization [8] where clock instants are directly extracted from a noisy NRZ bit stream. It is based on multiplying the data signal by its replica, which is delayed by a fraction of the bit duration.

Fig. 1 shows the all-optical processing setup together with the signal evolution along the system described, schematically, in the time and optical frequency domains. An incoming $2^{31}-1$ pseudorandom 10-Gb/s NRZ signal centered at $\lambda_0 = 1558.73$ nm with an average power of 0 dBm is wavelength converted in a $LiNbO_3$ Mach–Zender modulator biased at V_π, and driven with a sinusoidal voltage at $\Delta f/2 = 25$ GHz. The modulator output contains a suppressed optical carrier at λ_0 [9] and two symmetric modulated sidebands separated by $\Delta f = 50$ GHz ($\Delta\lambda \cong 0.4$ nm) each carrying the 10-Gb/s NRZ data. The two signals propagate in a dispersion-compensating fiber (DCF) which serves to delay the pulses relative to each other, while at the same time it causes some pulse broadening. The two signals are optically amplified to a power level of $+1$ dBm and coupled into a long dispersion-shifted fiber (DSF) which mediates a four-wave mixing (FWM) process among them with essentially no additional pulse broadening taking place. The FWM components are proportional to the product of the data and its delayed replica and this multiplication results in an optical spectrum containing a strong spectral line at $\lambda_0 \pm (3\Delta\lambda/2)$±10 GHz [7].

The detected electrical spectrum includes, therefore, a clock component at the bit rate frequency of 10 GHz.

The DCF had a dispersion of $D_{\mathrm{DCF}} = -101$ ps/nm·km and a slope dispersion of $S_{\mathrm{DCF}} = -0.443$ ps/nm^2·km at 1550 nm. Its length was 1 km yielding a relative delay between the pulses of ∼40 ps and pulse broadening of ∼8 ps. The DSF was 10.2 km long, it had a zero dispersion wavelength of $\lambda_{\mathrm{zero\text{-}dispersion}} = 1544$ nm, and its slope dispersion was $S_{\mathrm{DSF}} = 0.078$ ps/nm^2·km. The resulting pulse broadening in the DSF was only 0.8 ps.

The system parameters can be optimized to enhance the clock-to-background noise and clock-to-data ratios, CNR and CDR, respectively, of the detected FWM products. This enhancement is imperative for efficient optical injection locking and stable timing extraction, since it ensures a sufficiently wide locking range and low noise. In order to optimize the all-optical processing scheme, we simulated the experiment for a 10-Gb/s system as a function of the DCF and DSF lengths. The various system parameters and operating conditions used in the simulations were the same as in the experiments described below.

Fig. 2 shows contour plots of calculated CNR [Fig. 2(a)] and CDR [Fig. 2(b)] for DCF lengths ranging from zero to 2 km (corresponding to delays of 0 to 80 ps, 0% to 80% of the bit slot) and DSF lengths between 1and 15 km. The calculation is based on an electrical bandwidth of 1 GHz, while the resolution of the fast Fourier transform in the simulation is 10 MHz. Both CNR and CDR increase monotonically as the delay increases and peak at about 40 ps after which they decrease. The small CNR and CDR values close to zero delay result from the nonlinearity of the FWM and detection processes coupled with the

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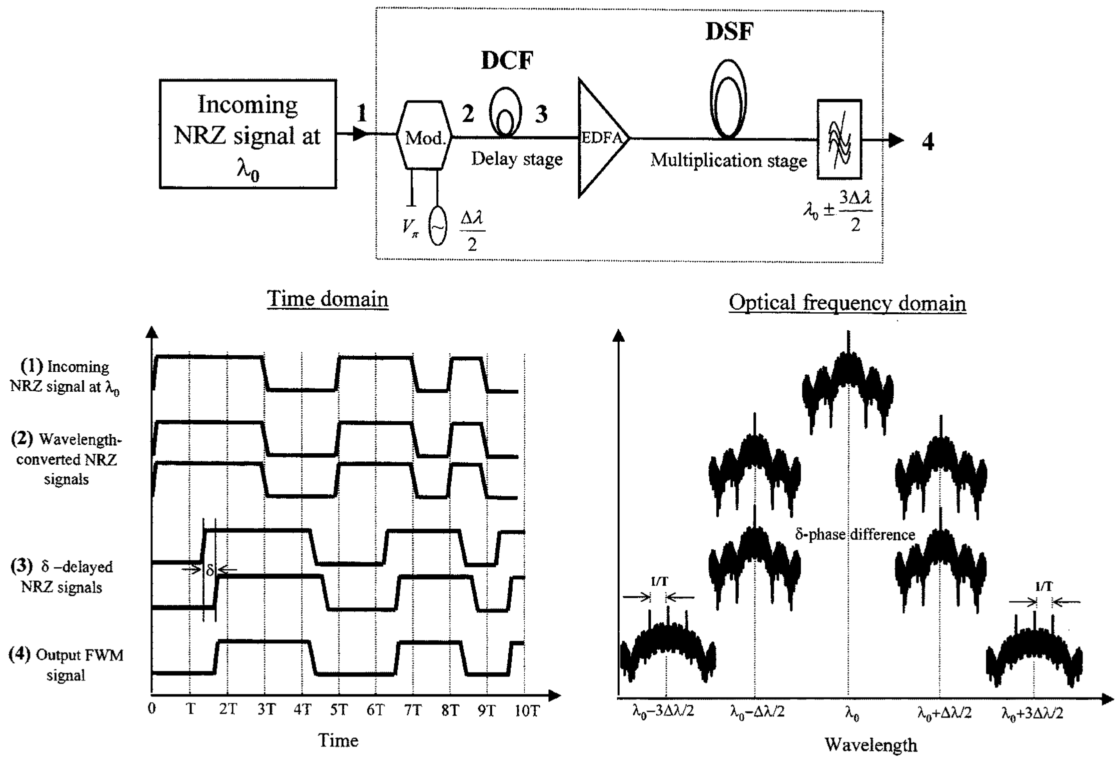

Fig. 1. Experimental schematic together with schematic time and optical frequency domain descriptions of the signal evolution along the system.

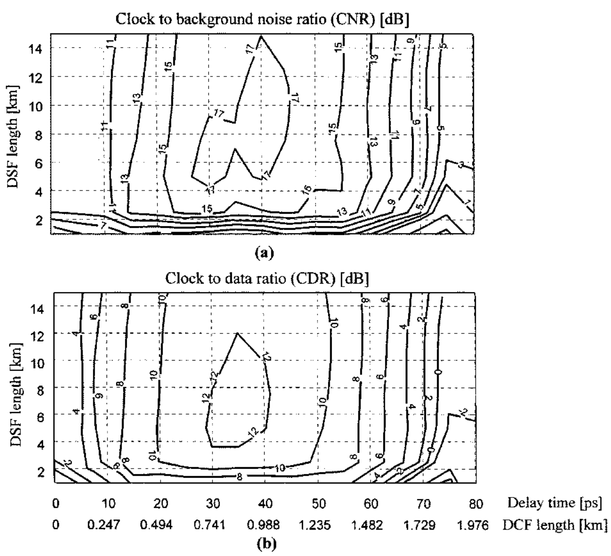

Fig. 2. Simulated results at an electrical bandwidth of 1 GHz and resolution of 10 MHz: DCF and DSF fiber length dependencies on (a) Detected clock to background noise ratio (CNR). (b) Detected clock to data ratio (CDR).

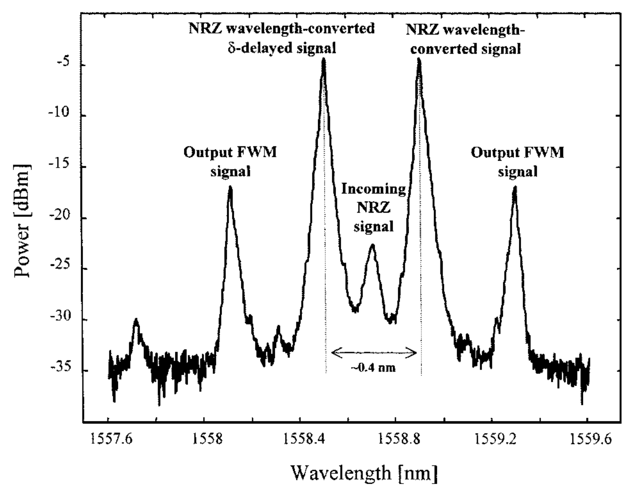

Fig. 3. Optical output spectrum measured at a resolution of 0.05 nm.

finite rise and fall times of the pulses as well as their asymmetries. At large delays, the bit overlap is small reducing the energy in the FWM products. For low DSF lengths, the parametric gain is very small and the resulting clock component in the optical domain has a very low OSNR. The electrical signal at 10 GHz, and hence, the CNR and CDR are almost independent in this case of the delay. For a sufficiently long DSF, the signal and noise at the optical frequency of the FWM products experience the same parametric gain so that the CNR and CDR have only a weak dependence on the DSF length as long as no depletion or signal walk off take place.

The experiments we performed used a 1-km-long DCF (corresponding to a delay of ∼40 ps) and a DSF of 10.2 km. The experimental results are shown in Figs. 3–5. Fig. 3 describes the optical spectrum at the DSF output measured with a resolution of 0.05 nm. We observe the two wavelength converted signals each with power of ∼−22 dBm, the imperfectly suppressed carrier (∼20 dB below the two converted signals) and the two FWM products with an OSNR of ∼17 dB. Fig. 4(a) exhibits a time domain description of the bit pattern showing very clearly the two detected NRZ signals (dotted and dashed lines) with the delay as well as their product (solid line). Fig. 4(b) illustrates

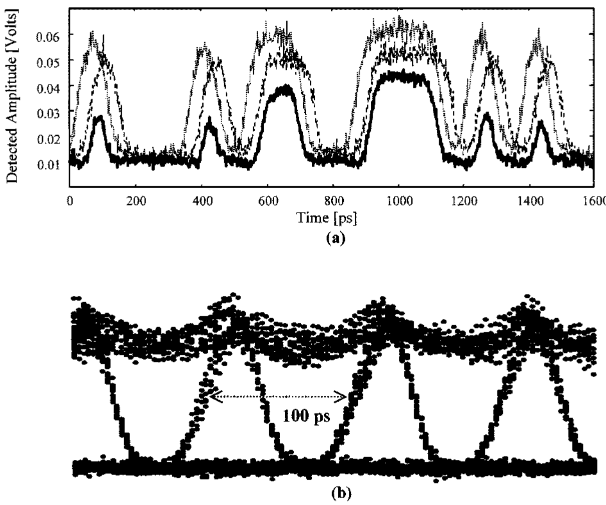

Fig. 4. Time domain description: (a) Bit patterns of the two delayed signals and their product, (b) Eye pattern of the detected FWM product.

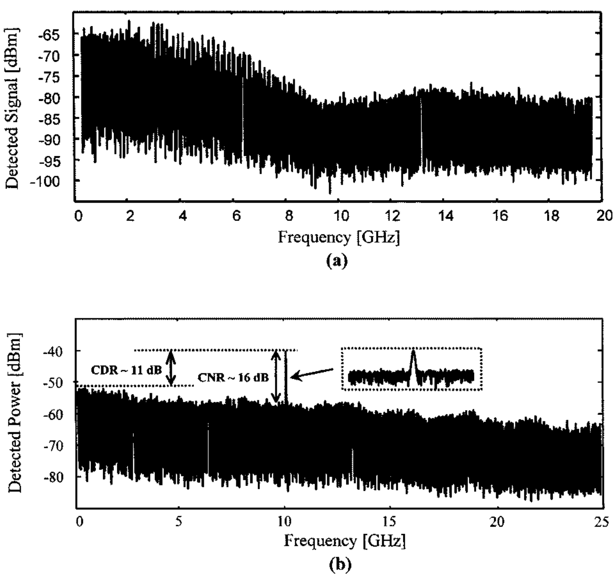

Fig. 5. Detected spectra measured at a resolution bandwidth of 1 MHz. (a) NRZ input signal. (b) All optically processed signal.

the eye pattern of the detected FWM product which comprises a quasi-sinusoidal signal (which is a time domain manifestation of the 10-GHz spectral component) and two constant values corresponding to consecutive sequences of ones or zeros.

Fig. 5 compares the detected NRZ spectrum at the input [Fig. 5(a)] with the detected spectrum of one of the FWM products [Fig. 5(b)], both measured at a resolution bandwidth of 1 MHz. The NRZ input signal contains no energy at 10 GHz, as expected, while the all optically processed signal exhibits a large peak at 10 GHz with a CNR of 16 dB and a CDR of 11 dB consistent with the simulated predictions of Fig. 2. The inset shows a zoom description of the discrete 10-GHz component measured over a frequency span of 1 MHz at a resolution bandwidth of 30 KHz. The processed signal (i.e., one of the FWM components) can easily serve to optically injection lock a self-oscillating photo-HBT [2] or a different oscillator [3], and hence, to enable efficient and reliable clock recovery.

To conclude, we have demonstrated an all-optical processing scheme to transform a high-speed NRZ data stream into a signal whose detected spectrum contains a strong peak at the bit rate frequency to be used for optical injection locking in timing recovery systems. The processing includes wavelength conversion using a Mach–Zender modulator, a DCF delay line and FWM in a DSF. Simulated results and an experimental confirmation were demonstrated. The choice of DCF DSF length combination determines the CDR and CNR and these in turn dictate the minimum required performance of the oscillator to be injection locked.

We note that the use of a highly nonlinear fiber instead of the DSF can reduce the power requirements to the point where no optical amplifier is needed. That means that with a properly chosen length of highly nonlinear fiber, the conversion efficiency may increase by more than an order of magnitude. Also, for multiwavelength input signals at arbitrary bit rates, the proposed technique generates several FWM components containing spectral lines at the corresponding bit rate frequencies. Hence, multiwavelength clock extraction is possible using only one device. Finally, as the FWM nonlinearity is an instantaneous phenomenon, it is possible to derive a clock tone from very high-bit-rate signals. Such high frequency clock signals may be used to optically injection lock fast InGaAs–InP photo-HBT- based oscillators, which can operate at frequencies well beyond 100 GHz [10].

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