High Bit Rate Clock Recovery of NRZ Data by All-Optical Processing in a Semiconductor Optical Amplifier and Direct Optical Injection Locking of a Self-Oscillating Phototransistor

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***Abstract*—In this letter, we describe a novel all-optical processing technique of nonreturn-to-zero signals in a semiconductor optical amplifier, which enables spectral enhancement at the bit rate frequency. The processed optical signal is used for direct optical injection locking of an oscillator based on a heterojunction bipolar phototransistor. Clock extraction at 10 Gb/s and potential operation at 40 Gb/s and beyond are demonstrated.**

***Index Terms*—Injection locking, optical processing, timing jitter.**

I. INTRODUCTION

RELIABLE timing extraction of high bit rate signals is a major part of any receiver in advanced optical communication systems. Optoelectronic and electronic timing extraction techniques are common [1], [2]. All optical schemes [3], [4] have also been demonstrated, primarily for return-to-zero (RZ) data streams. The spectrum of a RZ signal contains a strong peak at a frequency equal to the bit rate and that peak can be filtered and used to phase lock an oscillator, thereby generating the timing signal. A more difficult task is timing extraction from nonreturn-to-zero (NRZ) data in which the spectrum contains, in principle, zero energy at the frequency equal to the bit rate. The NRZ format is used in all present day systems and is likely to also dominate the next generation 40-Gb/s systems. Clock extraction becomes exceedingly difficult as the NRZ bit rate increases, because it always requires some sort of electronic processing [1]. As the bit rates continue to increase, all-optical retiming techniques are likely to be widely used.

One approach is to all optically convert the NRZ signal to a pseudo-RZ (PRZ) format before optically injecting it to a phase-locked clock-generating oscillator. An all-optical version using a saturated semiconductor optical amplifier (SOA) feeding a self pulsating diode laser was demonstrated at moderate bit rates in [5]. Conversion at 10 Gb/s was recently demonstrated with two different methods. One uses a delayed Mach–Zender interferometer [6] and the second employs FM to AM conversion in a saturated (SOA) followed by a narrow filter [7].

This letter reports on a novel all-optical processing technique in a SOA of a 10-Gb/s NRZ signal to enhance both the 10-GHz spectral line and clock to data ratio. This enhancement is essential for stable clock recovery. The proposed method is based on degenerate cross-gain modulation (XGM) in a counterpropagating configuration using a single SOA. The optically processed signal is used for direct optical injection locking of a self-oscillating InGaAs–InP heterojunction bipolar phototransistor (photo-HBT), whose output is the extracted clock. Since the bandwidth of the photo-HBT and the SOA are extremely large, the scheme is applicable for signals at 40 Gb/s and beyond. The proposed method avoids the well-known stability problems of interferometric configurations [6] and is very robust. It is also advantages over the narrow-band FM to AM conversion scheme [7].

II. PRINCIPLE OF OPERATION AND EXPERIMENTS

The upper part of Fig. 1 describes the all-optical processing scheme. The incoming 0 dBm 2^{31}–1 NRZ psuedorandom bit sequence (PRBS) is split in a 10%–90% coupler. The stronger signal is delayed by a fraction of the bit slot interval relative to the 10% output signal. The signal is optically amplified, to compensate for the losses of the optical delay line, to a level of ~4 dBm. This signal feeds one port of an SOA and serves as the pump signal in a counterpropagating XGM arrangement. The second signal feeds the other port of the SOA and acts as a probe that is extracted through a circulator. Two polarization controllers, for both pump and probe signals, are used to optimize the XGM operation. The principle of the all-optical processing scheme is illustrated in Fig. 2(a). The delayed pump-and-probe signals overlap only for a fraction (τ) of the bit slot time. The leading edge of the probe signal, which precedes the pump, experiences a large gain. As the delayed pump appears, the gain saturates and the probe output decreases by ~20 dB. For a delay time that is less than half the bit duration, this configuration can be viewed as generating a clock signal by differentiating the leading edges of the incoming NRZ signal. The optimum delay was found from a theoretical calculation of the energy content in the generated spectral line to be close to half a bit period. An exemplary time domain measurement is

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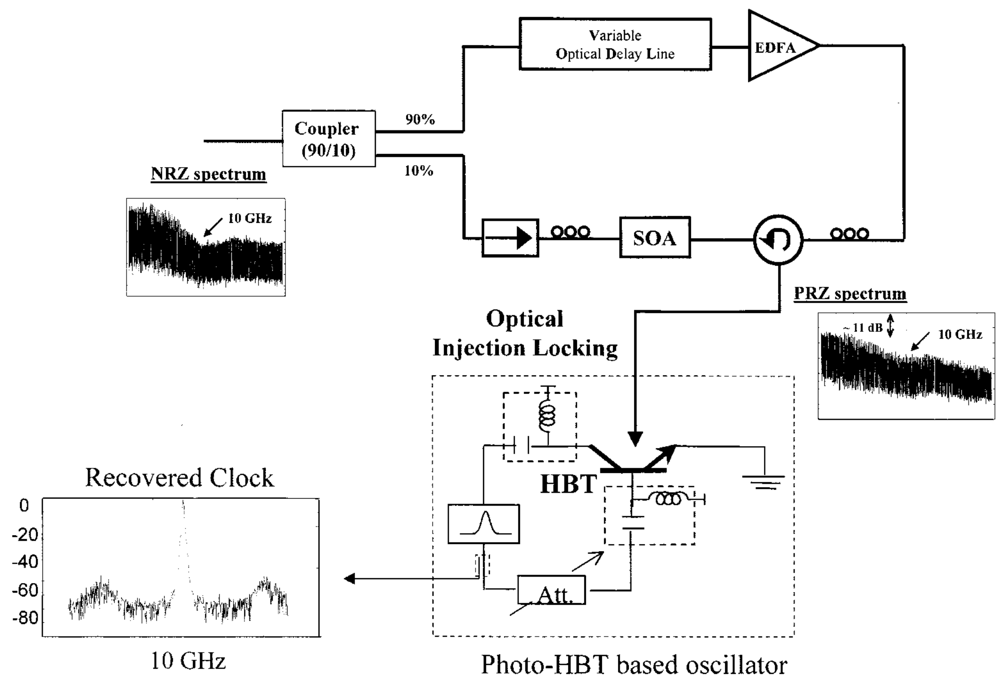

Fig. 1. Experimental schematic of the all-optical processing system and the photo-HBT- based oscillator.

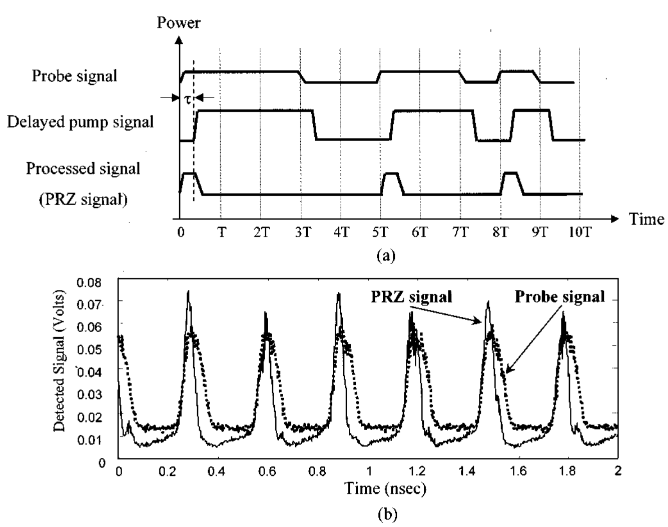

Fig. 2. (a) Time domain all optical processing principle of operation. (b) Measured example with a 10-Gb/s "100" sequence.

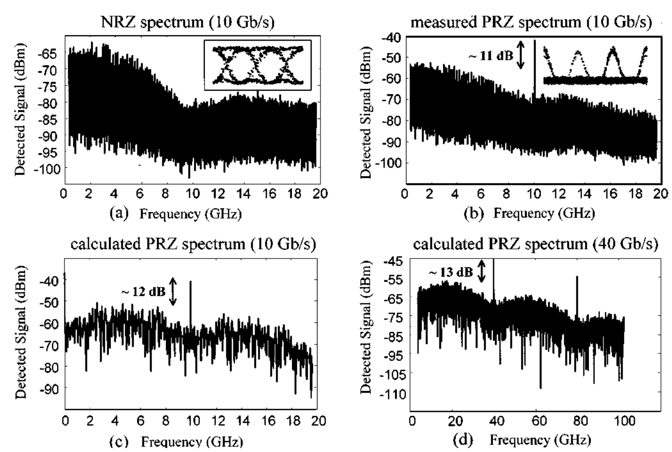

Fig. 3. Detected spectra: (a) Spectrum of the incoming 10-Gb/s NRZ signal. (b) Measured spectrum of the all optically processed signal. (c) Simulated spectrum of the all optically 10-Gb/s processed signal. (d) Simulated spectrum of the all optically processed 40-Gb/s signal.

shown in Fig. 2(b) which shows the leading edge differentiation in a simple 10-Gb/s "100" sequence.

The photo-HBT-based oscillator is shown in the lower part of Fig. 1. It comprises a 10-GHz oscillator based on an InGaAs–InP photo-HBT operating in a common emitter configuration with the collector fed back to the base via a narrow-band 10-GHz filter and an attenuator. The output of the oscillator contains several harmonics of the fundamental 10-GHz oscillating line and each of those harmonics can be optically injection locked.

Experimental confirmation of the all-optical processing scheme are described in Figs. 3 and 4 together with simulated predictions. Fig. 3(a) shows a detected spectrum of a 2^{31}–1 PRBS NRZ signal at 10 Gb/s, with the typical spectral skirt and zero energy at 10 GHz. Fig. 3(b) shows a measurement of the detected spectrum following the all-optical processing with a clear peak at 10 GHz extending more than 10 dB above the signal level. The inserts in Fig. 3(a) and (b) show, respectively, the measured eye diagram for the NRZ signal and the all-optically processed signal, with a full-width at half-maximum duration of about 40 ps. Fig. 3(c) shows a simulated spectrum of an all-optically processed 10-Gb/s NRZ signal which is essentially identical to the measured spectrum. The all-optical processing scheme was also simulated for higher bit rates. The simulation predicts easy operation at 40 Gb/s and beyond as described in Fig. 3(d). The spectral line at 80 GHz [see Fig. 3(d)] is the second harmonic generated due to the nonlinear nature of the XGM process. The lack of an NRZ data source at bit rates higher than 10 Gb/s prevented experimental confirmations at 40 Gb/s,

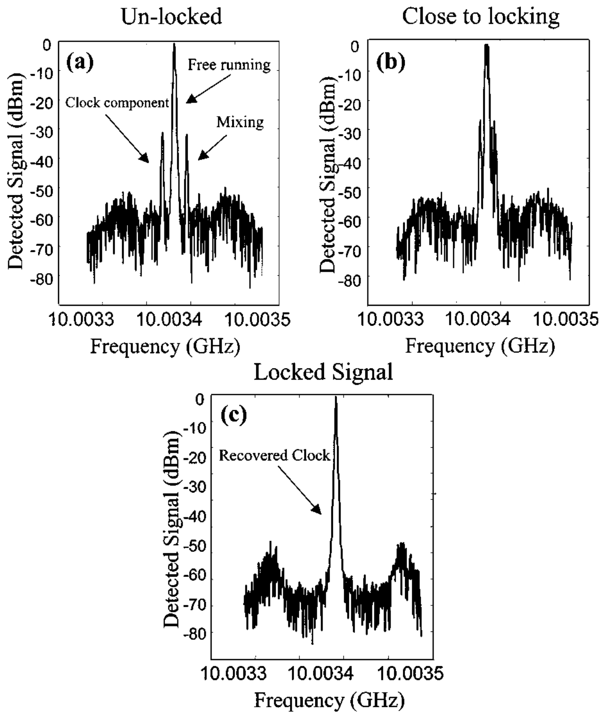

Fig. 4. Optical injection locking sequence. (a) Unlocked case. (b) Close to locking. (c) Locked case.

but published results on XGM in an SOA at rates as high as 100-Gb/s support the simulated prediction [8].

Fig. 4 shows the injection locking process with the signal at the all-optical processor output feeding the optical input port of the photo-HBT. The power level of the incident processed signal was -4 dBm. Fig. 4(a) shows the unlocked case with the free running signal, the 10-GHz input and the mixing product all appearing. Fig. 4(b) shows the situation close to locking and Fig. 4(c) shows a completely locked 10-GHz signal, which represents the extracted clock of the 10-Gb/s NRZ input signal. The locking range was measured to be $\sim$250 KHz for -4 dBm optical power. This locking range can be increased using a higher optical power as we have previously demonstrated in [9]. In a separate experiment [10], we have demonstrated optical injection locking of the fourth harmonic of this 10-GHz oscillator using a 40-Gb/s RZ input.

A high-quality extracted clock signal is synchronized well to the data stream. Its phase uncertainty (jitter) should follow that of the input. Any deviation in the respective phases stems from the noise at the oscillator input together with the oscillator internal noise and the loop bandwidth. In the present experiment, we observed completely open eyes when triggered by the extracted clock suggesting that the scheme had negligible jitter, consistent with bit-error-rate measurements using the same oscillator [10].

III. Conclusion

We have demonstrated an all-optical processing scheme using counter propagating XGM in a SOA, which enhances the spectral component at the bit rate frequency. The resulting signal is used to optically injection lock a photo-HBT based oscillator thereby extracting the clock from the NRZ signal. Operation at 10 Gb/s was demonstrated experimentally and the potential for 40 Gb/s and beyond has been shown in simulations. Since SOAs have been proven to operate at rates up to 100 Gb/s [8], and since InGaAs–InP photo-HBTs have been demonstrated with $f_{\max}$ (the highest possible oscillation frequency) of more than 150 GHz [11], the configuration proposed here has the potential to operate as an efficient timing extraction system for data rates well beyond 40 Gb/s.

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