Clock Recovery at Multiple Bit Rates Using Direct Optical Injection Locking of a Self-Oscillating InGaAs–InP Heterojunction Bipolar Phototransistor

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***Abstract*—In this letter, we describe the use of direct optical injection locking of a self-oscillating InGaAs–InP heterojunction bipolar phototransistor to extract the clock of high-speed optical signals. We demonstrate a *single* 10-GHz oscillator, which can be locked by 10- to 40-Gb/s return-to-zero signals with high efficiency and low noise.**

***Index Terms*—Clock recovery, optical communication, heterojunction bipolar transistor, injection–locked oscillator.**

I. Introduction

As THE DATA RATES of optical communication systems reach tens to a hundred gigabits per second, timing extraction is becoming more difficult and requires complicated schemes to provide bit rate flexibility and low jitter clock synchronization. All optical techniques with mode-locked or self-pulsating lasers [1]–[3] or narrow optical filters based on stimulated Brillouin scattering [4] are used where an optical clock is needed, for example in all optical 3R processing. Electrooptic methods are usually based on phase locking of microwave oscillators, such as an injection-synchronized narrow-band ring voltage controlled oscillator [5], a HEMT-based integrated circuit [6] and an oscillator based on a resonant tunneling diode [7].

In this letter, we describe clock extraction of high-speed optical signals by *direct* optical injection locking of a microwave oscillator based on a single InGaAs–InP heterojunction bipolar phototransistor (photo-HBT) [8]. Optical injection locking of conventional [9] and heterojunction [10] bipolar transistor-based oscillators has been demonstrated previously for the purpose of controlling RF oscillations by optical means. The nonlinear nature of the HBT we use ensures multifrequency oscillations with all spectral lines being modulated or injection locked simultaneously by the optical signal [11]. Such an oscillator configuration can, therefore, be used to extract the clock of multiple rate signals. In the present experiment, we demonstrate a 10-GHz oscillator with which we extracted the clocks of both 10- and 40-Gb/s return–to-zero (RZ) data streams. Since the bandwidth of InP HBTs is very wide, the technique is suitable for bit rates even higher than 40 Gb/s. The injection locking scheme is naturally suitable for RZ data where the spectrum contain a line at the bit rate frequency. For NRZ data stream, some optical processing is required [12] prior to injection into the photo-HBT.

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II. Experimental Setup

The experimental schematic is shown in Fig. 1. The clock recovery system comprises a 10-GHz oscillator based on an InGaAs–InP photo-HBT operating in the common emitter configuration with the collector fed back to the base via a narrow-band 10-GHz filter ($Q = 1000$) and an attenuator. The electrical output is extracted via a 10-dB coupler and the optical signal is coupled to the HBT through an opening in the base electrode. A typical free-running oscillation spectrum comprises the 10-GHz fundamental line and several harmonics as shown in Fig. 2.

The timing recovery scheme was tested using RZ pulses generated by the transmitter shown in the upper part of Fig. 1. It consists of a gain switched DBR laser generating 10-GHz 30-ps-wide pulses at $\lambda = 1.55$ μm. The pulses were linearly compressed using a dispersion compensating fiber followed by amplification and soliton compression yielding pulses of $\sim$3-ps duration. The pulses were modulated using a $LiNbO_3$ Mach–Zender modulator driven by a 10-Gb/s data sequence of $2^{31} - 1$ pseudorandom binary sequence (PRBS). This 10-Gb/s RZ data stream was optically multiplexed to 40 Gb/s using the standard split and delay technique.

The 10- or 40-Gb/s signals are coupled to the photo-HBT thereby optically injection locking the appropriate oscillating line (first or fourth harmonic, respectively). The HBT output is monitored by a spectrum analyzer and in the 10-Gb/s case, it also feeds the clock input of the BER tester. The extracted clock level was $\sim$0 dBm.

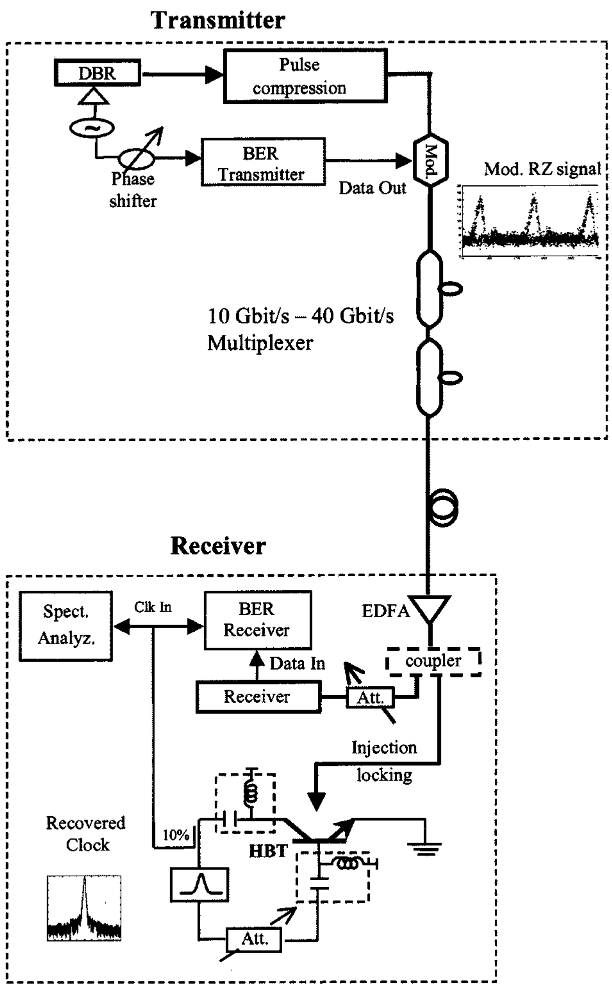

Fig. 1. Experimental schematic.

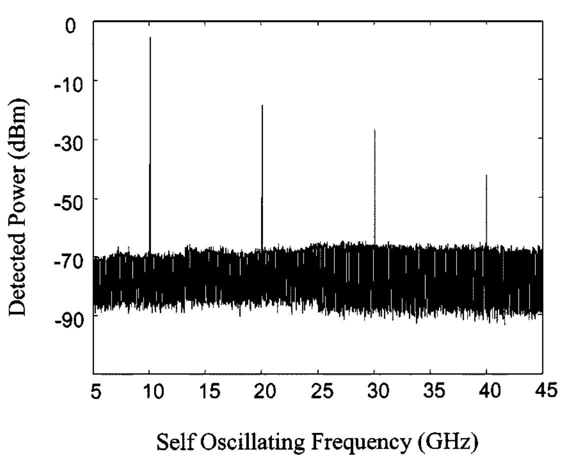

Fig. 2. Free-running multifrequency oscillation spectrum.

III. Results

Optical injection locking by the 10-Gb/s signal is described in Fig. 3. Fig. 3(a) shows the output spectrum when the injected

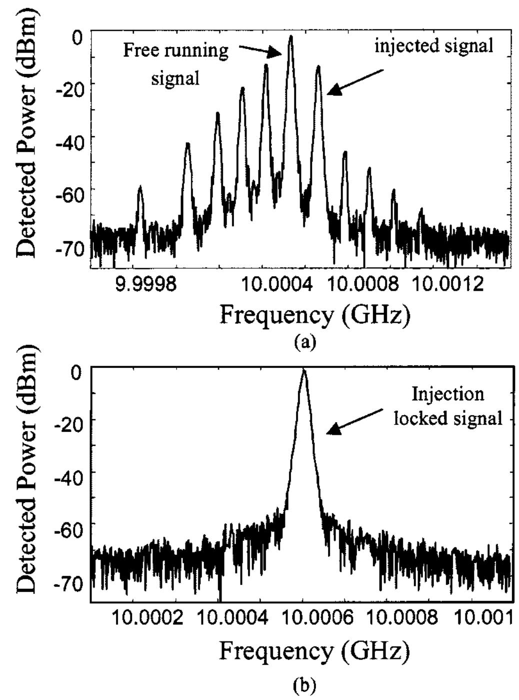

Fig. 3. Injection locking at 10 Gb/s. (a) The injected signal is outside the locking range. (b) Completely locked spectrum.

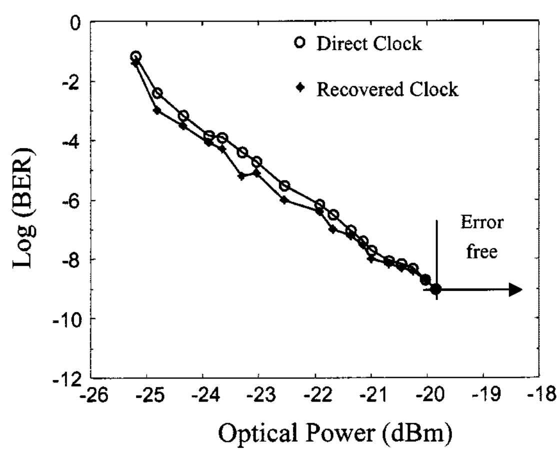

Fig. 4. BER measurements at 10 Gb/s.

signal is outside the locking range. Shown are the free running signal, the injected signal and several mixing products generated by the nonlinear mixing process. Fig. 3(b) shows in contrast a completely locked spectrum. The locking range was measured to be ~250 kHz for a −4-dBm optical input power. This locking range can be increased with a higher optical power [13].

To confirm the timing extraction operation, we measured the bit-error rate (BER) performance using the recovered clock and compared it with a back-to-back measurement, which used the clock signal from the BER tester transmitter. For this measurement, the power to the receiver was varied, while the power feeding the photo-HBT was held constant at −4 dBm. The two BER curves shown in Fig. 4 are essentially identical proving the low jitter performance of the proposed timing extraction scheme.

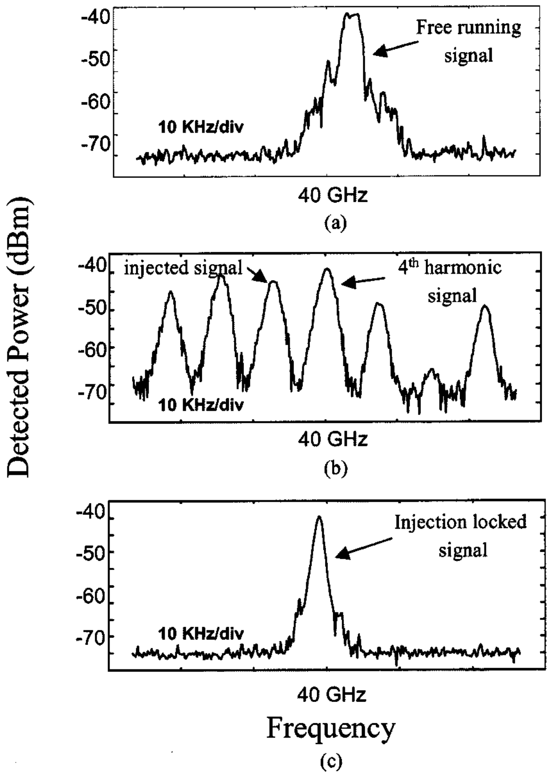

Fig. 5. Injection locking at 40 Gb/s. (a) Free running oscillation spectrum. (b) The injected signal is outside the locking range. (c) Completely locked spectrum.

At 40 Gb/s, the RZ signal optically injection locked the fourth harmonic of the *same* 10-GHz oscillator. Since no 40-Gb/s data source was available, we could only measure the spectral characteristics of the multiplexed case. Fig. 5(a) shows the free-running spectrum, while Fig. 5(b) describes the situation when the injected signal is outside the locking range. The locking range of the fourth harmonic depends linearly on the ratio between the amplitude of the injected signal and that of the harmonic. Since this ratio slightly decreases with frequency (corresponding to the frequency response of the HBT) the locking range of the fourth harmonic decreased somewhat (compared to the 10-GHz case) to 100 KHz at the same −4-dBm optical power. Fig. 5(c) shows the oscillator spectrum when it is completely locked to the incoming 40-Gb/s data stream. The locked spectrum exhibited the expected linewidth narrowing and stability.

IV. Conclusion

To conclude, we have described direct optical injection locking of a self-oscillating InGaAs–InP photo-HBT to extract the clock of a multirate digitally modulated optical data stream. Error-free performance at 10 Gb/s was demonstrated proving the extremely low jitter characteristic of the extracted clock. The 10-GHz oscillator was used to extract the 40-GHz clock of a 40-Gb/s optical signal by injection locking the fourth harmonic of the oscillator, proving the potential of this kind of configuration for tens of gigabytes systems.

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