A High-Speed Photonic Clock and Carrier Recovery Device

X. Steve Yao and George Lutes

***Abstract*—We present the experimental results of a high-speed clock and carrier recovery device based on a novel oscillator called a optoelectronic oscillator (OEO). Such a device can recover a clock signal or carrier with a frequency up to 75 GHz and can be interfaced with a photonic communication system both electronically and optically.**

I. Introduction

IN COMMUNICATIONS systems, the ability to recover the clock from incoming random data is essential. As data rates exceed 10 Gb/s, clock recovery using conventional electronic circuits based on phased locked loops [1] becomes extremely difficult, if not impossible.

Clock recovery by optically injection-locking a microwave oscillator [2] or a pulsed laser with an incoming data stream has been demonstrated by many authors [3]–[6] with varied degrees of success. In this letter, we report a different clock recovery scheme based on injection locking a novel oscillator [7] called the optoelectronic oscillator (OEO) [8]. This oscillator consists of a pump laser and a feedback circuit including an intensity modulator, an optical fiber delay line, a photodetector, an amplifier, and a filter, as shown in Fig. 1. It converts continuous wave (CW) light energy into a spectrally pure microwave signal and can operate up to 75 GHz (limited by the speed of the modulator) with a phase noise below −140 dBc/Hz at 10 kHz (limited by the relative intensity noise of the pump laser), making it attractive for high-speed and low-phase noise clock recovery.

As shown in Fig. 1, the incoming data can be injected into the OEO either optically or electrically. The free running OEO is tuned to oscillate at a nominal frequency sufficiently close (within the locking range, on the order of kHz to MHz, depending on the power of the injected clock frequency) to the clock or carrier frequency of the incoming signal. With the injection of the incoming signal, the OEO will lock to its clock or carrier frequency in a time inversely proportional to the locking range, while supressing other frequency components (harmonics and subharmonics) associated with the signal. The recovered signal can be accessed either at the optical output port or the electrical output port.

Fig. 2 shows the experimental setup used to demonstrate 100 MHz and 4.95 GHz clock recovery. Switches SW-1 and SW-2 are in the "A" position for the 100 MHz clock recovery experiment and in position "B" for the 4.95 GHz clock recovery experiment. In either experiment, using switch SW-3, we could choose to look at the OEO output in the time domain with a Tektronix 2465B oscilloscope or in the frequency domain with an HP 8562 spectrum analyzer.

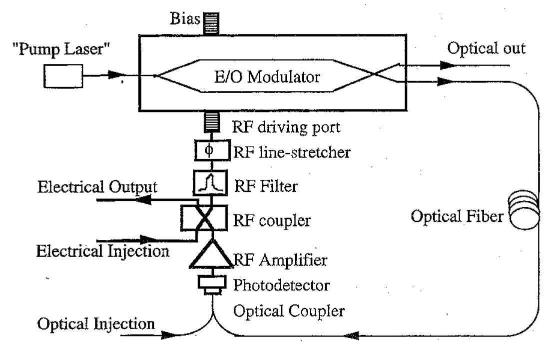

Fig. 1. The construction of the OEO. It has an optical injection port, an electrical injection port, an optical output port, and an electrical output port. The optical injection signal should be incoherent with the pump laser. The electrical injection signal can also be injected into the OEO through the bias port of the modulator. The frequency of the OEO can be tuned by changing the loop length using a line-stretcher.

In the 100 MHz clock recovery experiment, we used an HP 8080 Word Generator System to generate a stream of repetitive 64-b words at 100 Mb/s, with each word being psuedo-random in nature, and we tuned the OEO to oscillate near 100 MHz. We injected the data into the bias port of the E/O modulator through a 100-MHz filter and a bias T. The filter was used only to reduce unwanted frequency components of the input data. Its 10 MHz bandwidth was wide enough to allow multiple frequency components (11 in this case) of similar strength to be injected into the OEO. We used the first bit of each word to trigger the oscilloscope's sweep so the whole word could be displayed. The HP 8080 system's data pattern can be selected to be either return-to-zero (RZ) or nonreturn-to-zero (NRZ) so both types of data were used in our experiments. Clock recovery is independent of the word chosen, as long as it is balanced. However, for an infinitely long NRZ random data stream, the clock frequency component is zero. In order to recover the clock from such a data stream, a procedure to convert NRZ data format to RZ format is required [1].

Fig. 3 is the oscilloscope display of the experimental results in the time domain that demonstrated successful clock recovery from an NRZ data stream. Fig. 3(a) shows the input data,

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The authors are with the Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109 USA.
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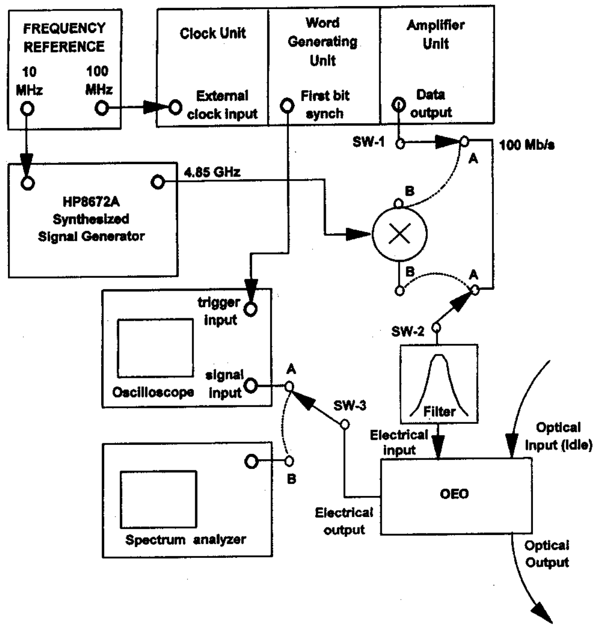

Fig. 2. Clock recovery experimental setup for both 100 MHz (switches SW-1 and SW-2 set at "A" position) and 4.95 GHz (switches SW-1 and SW-2 set at "B" position) demonstrations. The OEO is represented by a functional block diagram with two optical ports and two electrical ports.

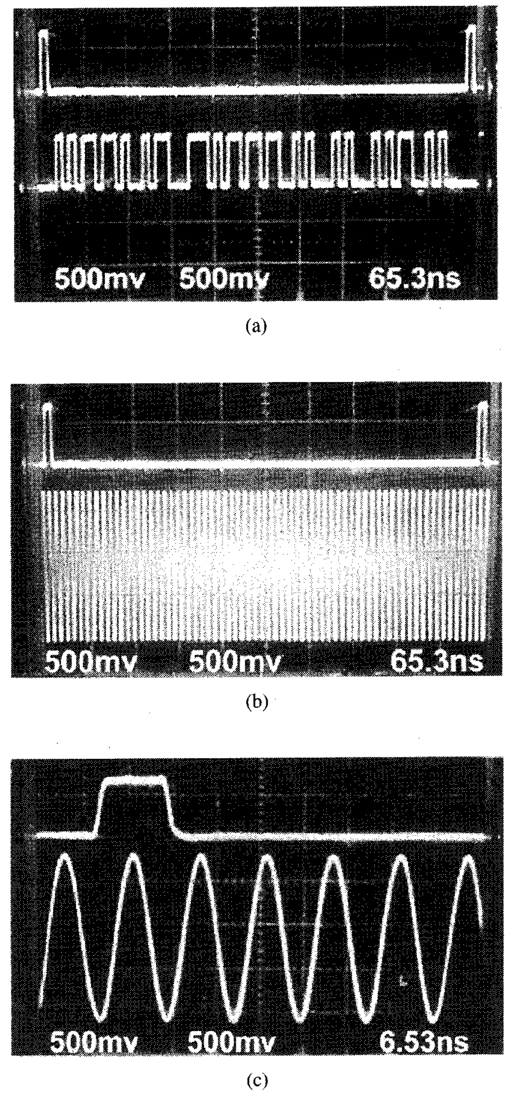

Fig. 3. Demonstration of clock recovery from an NRZ data stream measured in the time domain. (a) Input data. (b) Recovered clock. (c) Recovered clock with the time scale of (b) reduced 10 times.

while Fig. 3(b) and (c) show the recovered clock. In Fig. 3(c), the time span was reduced 10 times to show the recovered clock in more detail. In all three figures, the upper trace is the first bit of the input data used to trigger the oscilloscope. The fact that the recovered clock can be clearly displayed on the oscilloscope when the first bit of data is used as the trigger indicates that the recovered clock is synchronized with the data.

Viewed on the spectrum analyzer, the input data stream after the 100-MHz filter has some frequency components stronger than the clock frequency. After clock recovery the power of the recovered clock is more than 62 dB above the strongest frequency component of the data.

Note that the recovered clock level is almost independent of the input signal level, a feature that is desirable for clock recovery and is inherent in injection locked oscillators. Other proposed high-speed clock recovery circuits use automatic gain control and limiting amplifiers to achieve constant amplitude [9].

To extend our clock recovery experiment to higher data rates we simulated a stream of 4.95 Gb/s data by up converting a stream of 100 Mb/s RZ data using an RF mixer as shown in Fig. 2 with switches SW-1 and SW-2 in the "B" position. The OEO used in these experiments was constructed using an electro-optic modulator made by E-Tek Dynamics. We used a common reference signal from a hydrogen maser to synchronize the word generator and an HP 8672A synthesized signal generator. The frequency of the signal generator's output was chosen to be 4.85 GHz and was used to up convert the 100 Mb/s RZ data from the word generator to 4.95 GHz. The signal out of the mixer has a center band, an upper sideband and a lower sideband, which all contain the data information. We used a filter centered at 5 GHz with a bandwidth of 255 MHz to select only the upper sideband, which effectively simulated a stream of 4.95 Gb/s RZ data.

Fig. 4(a) and (b) show the frequency spectrum of the data before and after clock recovery respectively. As expected, the clock frequency was strongly amplified by the OEO while other frequency components remained unchanged, resulting in a recovered clock with a signal-to-spur ratio of about 60 dB.

Although in the demonstrations the data were injected into the electrical injection port, similar results are expected if the data are in the optical domain and are injected into the OEO through the optical injection port. This is because the data in the optical domain will be automatically converted by the internal photodetector into the electrical domain before affecting the OEO. We estimate that only a few microwatts of optical signal power is required to ensure a satisfactory

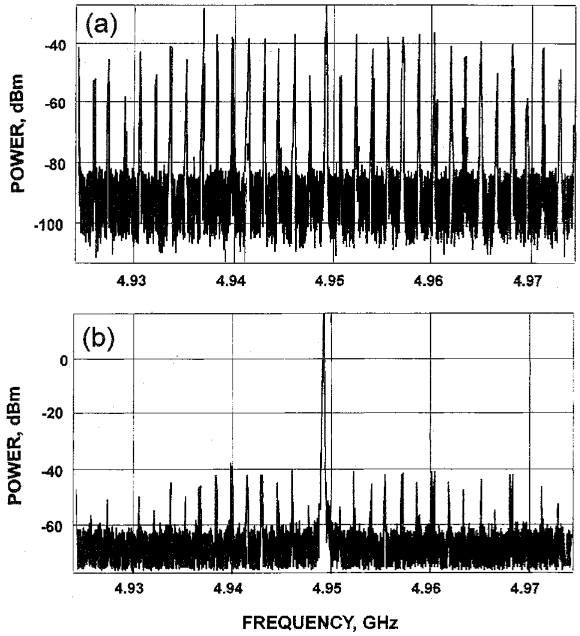

Fig. 4. The 4.95 GHz clock recovery from an RZ data stream measured in the frequency domain. (a) Data input to the OEO. (b) Recovered clock.

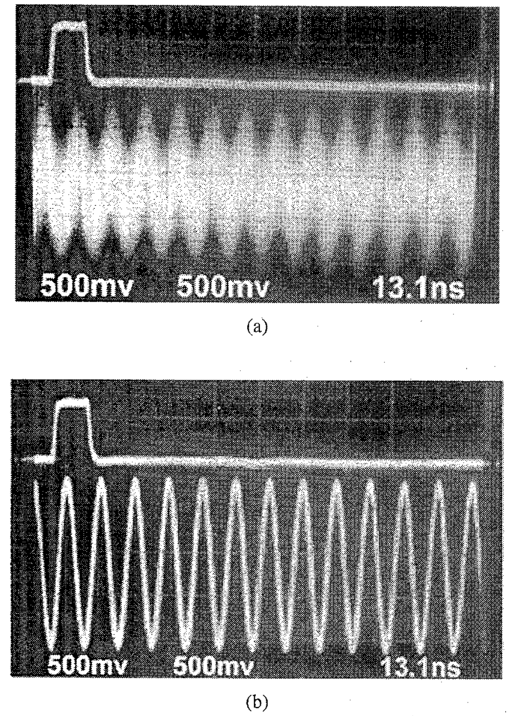

Fig. 5. Carrier recovery measured in the time domain. (a) Spoiled carrier. (b) Recovered carrier.

clock recovery for many applications. Clock recovery via optical injection is important because it enables the clock of a high-speed data stream in a fiber-optic system to be directly recovered without first converting the data to electrical pulses.

Similar to clock recovery, a carrier buried in noise can also be recovered by the OEO. In the experiment, we added noise to a clean 100-MHz test signal and adjusted the signal-to-noise-Ratio (SNR) until it was approximately 3 dB in a 100 kHz bandwidth. After carrier recovery, the SNR of the test signal was improved more than 50 dB. We also measured the spoiled carrier and recovered carrier in the time domain with an oscilloscope and the results are shown in Fig. 5. In both Fig. 5(a) and (b), the upper trace (a square pulse) is the trigger signal and the lower trace is the test signal before and after recovery. Comparison of the two figures clearly demonstrates that the recovered signal is clean and synchronized to the reference frequency.

We have demonstrated a novel photonic clock and carrier recovery device with a potential operation frequency up to 75 GHz, limited only by the speed of the modulator. It can be controlled and accessed both optically and electronically, and thus can be easily interfaced with a complex fiber-optic communication system. The amplitude of the recovered signal (clock or carrier) is virtually independent of the input power of the signal to be recovered. Other attractive properties include fast acquisition time for phase locking, wide tracking range, and wide frequency tunability.

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