Ultralow Timing Jitter 40-Gb/s Clock Recovery Using a Self-Starting Optoelectronic Oscillator

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Abstract—We demonstrate clock recovery with ultralow timing jitter by using a novel self-starting optoelectronic oscillator that is based on an electroabsorption modulator in a fiber extended cavity. The oscillator simultaneously generates a 10-GHz-rate microwave signal and a train of 15-ps optical pulses with $\sim$40-fs timing jitter in the 100-Hz to 1-MHz range. Under direct optical-injection locking of the oscillator, we demonstrate simultaneous error-free extraction of both the electrical and the optical clocks of 10-GHz rate from either a single-channel 10-Gb/s return-to-zero data stream or a four-channel 40-Gb/s optical time-division-multiplexed data stream.

Index Terms—Electroabsorption modulator (EAM), optical clock recovery, optical demultiplexing, optical injection locking, optoelectronic oscillator (OEO), timing jitter.

A S DATA rates of optical time-division-multiplexed (OTDM) networks increase, accurate clock recovery is becoming exceedingly important with requirements for bit-rate flexibility and low-jitter synchronization of the multiplexed channels. In optical communication systems, a timing recovery device generates, out of the incoming optical data stream, either an electrical clock signal or optical clock pulses, or both. In principle, there are different purposes for an optical clock and for an electrical clock. All-optical clock recovery techniques produce an optical pulse stream on which data is reimposed by means of a decision gate to perform the retiming function of 3R (reamplification, retiming, and reshaping) regeneration for extending the distance limits on optical transmission. The optical pulse stream can also be used to control an optical switch for demultiplexing purposes. In these applications, the recovered optical clock should exhibit a lower timing jitter than the degraded optical data stream. In contrast, electrical clock recovery is used either for synchronization at the receiver or to control an optoelectronic switch for demultiplexing purposes. For these applications, the electrical clock has to follow the uncertainty in the arrival time of the noisy data. Implementation of all-optical clock recovery has been performed utilizing various techniques, including mode-locked fiber or diode lasers [1], [2], fiber-optic parametric oscillators [3], and electroabsorption-modulator (EAM)-based phase-locked loops (PLLs) [4]. On the other hand, optoelectronic techniques have been used to extract the electrical clock. Examples include narrow-band electrical filtering [5], EAM-based PLL [6], and
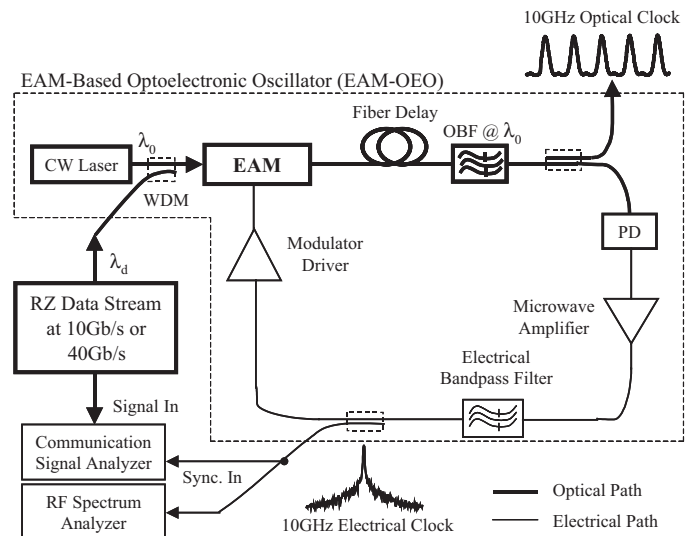
Fig. 1. Schematic of the experimental setup.

optical injection locking of an optoelectronic oscillator (OEO) [7] or a self-oscillating phototransistor [8].

In this letter, we describe a new scheme to simultaneously extract both the electrical and the optical clocks of 10-GHz rate from either a single-channel 10-Gb/s return-to-zero (RZ) data stream or a four-channel 40-Gb/s OTDM data stream for demultiplexing purposes. The scheme utilizes a new type of compact self-starting EAM-based optoelectronic oscillator (EAM-OEO) that incorporates an EAM, an optical-fiber delay line, and optical detection in a closed-loop resonating configuration. Under direct optical injection, the 10-GHz spectral component of the injected data stream creates periodic switching windows in the EAM for the self-starting EAM-OEO signal to lock to. Within the locking range, the EAM-OEO output tracks the clock of the injected data stream, which is useful for electrical clocking applications. Outside the locking range, however, the recovered clock's jitter follows the very quiet spectrum of the EAM-OEO, which is useful for optical clocking applications. Therefore, our scheme offers a simple and scalable solution for timing extraction with error-free synchronization and excellent jitter-transfer capabilities for use in future OTDM networks.

The experimental schematic is shown in Fig. 1. The EAM-OEO configuration is similar to the scheme suggested in [7], the main difference being the use of an EAM instead of an electrooptic Mach–Zehnder modulator, which allows for generation of not only a low-phase-noise electrical signal but also a very low-jitter optical pulse train. Light from a continuous-wave (CW) laser $(\lambda_0 \sim 1550 \text{ nm})$ is injected into a 14-GHz bandwidth InGaAsP EAM, whose output after passing

through a long fiber is converted to an electrical signal by a photodetector. The output of the photodetector is amplified, filtered by a 10-GHz microwave bandpass filter of ~10-MHz bandwidth, and fed back through a driver to the electrical input of the EAM. This configuration supports self-sustained oscillations at a frequency determined by the bandpass characteristics of the electrical filter, the bias setting of the EAM, and the length of the fiber. High stability and spectral purity are a consequence of the large energy stored in the optoelectronic cavity and the low round-trip loss due to propagation in the fiber. As we have recently demonstrated [9], the high-Q electrical bandpass filter together with the sharp rectangular-shaped transmittance window of the EAM allows up to 3000 m of fiber to be used in the loop, yielding a 10-GHz-rate optical pulse stream with >90-dBc/Hz sidemode suppression and 42-fs timing jitter over 100-Hz to 1-MHz range (or 19 fs in the 1-kHz to 1-MHz range) along with a 10-GHz electrical signal having a relatively low phase noise (−115 dBc/Hz at 10-kHz offset). Note that the 42-fs timing jitter could not be reduced further with longer lengths of fiber in the OEO cavity because of the limit imposed by random fiber-length fluctuations due to environmental effects. However, to the best of our knowledge, 42 fs is the lowest jitter obtained for a self-staring 10-GHz-rate optical pulse source.

To test the clock recovery scheme, we used either a 10-Gb/s RZ data stream or a 40-Gb/s OTDM data stream. To obtain the former, we encoded using a Mach–Zehnder LiNbO$_3$ modulator 10-Gb/s data with a word length of $2^{31} − 1$ onto 8-ps-wide optical pulses at $\lambda_d = 1565$ nm generated by a sinusoidally driven mode-locked fiber laser (MLFL). To obtain the 40-Gb/s RZ data, we time-multiplexed the 10-Gb/s optical stream by bit interleaving through two stages of optical fiber delay lines.

The 10- or 40-Gb/s signal is divided into two portions; one feeds the communication signal analyzer (CSA) and the other is coupled using a wavelength-division multiplexer to the optical input of the EAM for clock recovery. The 10-GHz-rate switching windows in the EAM, created by the 10-GHz spectral component of the input data, allow the self-starting EAM-OEO signal to be injection-locked to the input stream. Gating of the CW light by the EAM with the synchronized electrical signal as a drive generates the optical clock.

The recovered electrical clock, which is monitored by an electrical spectrum analyzer (ESA) at the output of the electrical filter, also serves as the trigger for the CSA. Fig. 2 shows evolution of the optical injection-locking process on way to the 10-GHz electrical clock recovery. The main body of Fig. 2(a) is the electrical spectrum of the output clock in the vicinity of 10 GHz when the injected signal is outside the locking range. One sees peaks due to the free-running OEO and the bit-rate spectral component of the injected signal, along with several other peaks generated by the nonlinear mixing process in the EAM. In this case, the incoming data monitored with the CSA cannot be synchronously triggered by the unlocked clock output and, therefore, the CSA shows nothing but noise for the 10- and 40-Gb/s traces, as plotted in the left and right insets of Fig. 2(a), respectively. Fig. 2(b) shows the case when the injected signal is at the edge of the locking range. In this case, the shape of the 10- or 40-Gb/s eye pattern for the injected data has become
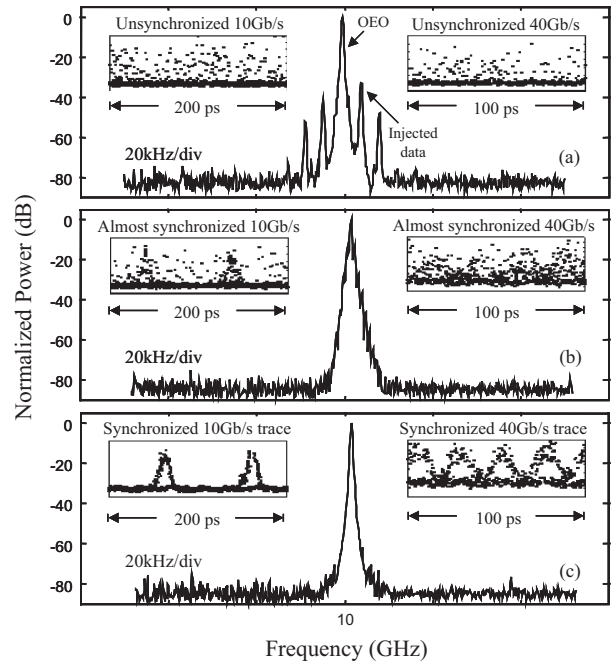

Fig. 2. Normalized spectra showing the optical injection-locking process with 300-Hz resolution bandwidth as the clock rate of the injected data stream is varied. (a) Injected signal is outside the locking range. (b) Injected signal is at the edge of the locking range. (c) The OEO has latched on to the injected signal. Insets: CSA traces of 10- and 40-Gb/s data, respectively.

observable through the noise on the CSA, as shown by the insets of Fig. 2(b). Fig. 2(c) shows the case when the injected signal is inside the locking range and the incoming data stream is synchronized to the recovered clock. In this case, the eye patterns of the 10- and 40-Gb/s signals are clearly seen in the left and right insets of Fig. 2(c), respectively, which demonstrate the error-free capabilities of the recovered clock. Note that for the demonstration of the locking process shown in Fig. 2, the frequency of the RZ data source was varied. However, for a given input data stream, one can also bring the free-running OEO into the locking range by adjusting the bias of the EAM. To further confirm the timing extraction operation, we measured the bit-error-rate (BER) performance using the recovered clock and obtained error-free operation with no power penalty when compared to the back-to-back BER measurements using the transmitter's clock. Note that for the results in Fig. 2, the average power of the injected data streams was chosen to be −15 and −9 dBm for the 10- and 40-Gb/s signals, respectively, resulting in only 12-kHz locking range. However, the locking range can be increased by increasing either the injected optical power, the bandwidth of the microwave bandpass filter, or the gain of the microwave amplifier [10]; for example, we obtained ~200-kHz locking range when the power was ~12 dB higher in both cases.

The optical clock is extracted at the output of the OBF and characterized by an optical spectrum analyzer and a 45-GHz bandwidth photodetector followed by both a CSA and an ESA. Fig. 3(a) shows the CSA trace for the wavelength-converted optical clock, where the width of the peaks is measured to be 20 ps, giving a pulsewidth $\Delta\tau$ of 15 ps after deconvolving the photodetector's impulse response. The optical spectrum of the clock pulses [Fig. 3(b)] is very symmetric with more than 20-dB deep
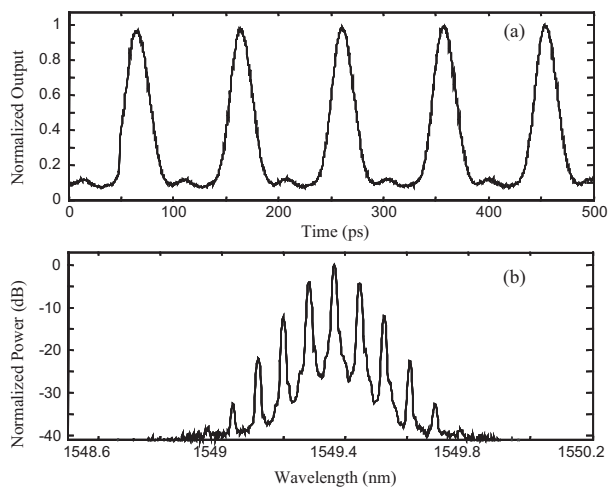
Fig. 3. Optical clock characterization. (a) Time-domain measurement. (b) Optical spectrum with 0.01-nm resolution.
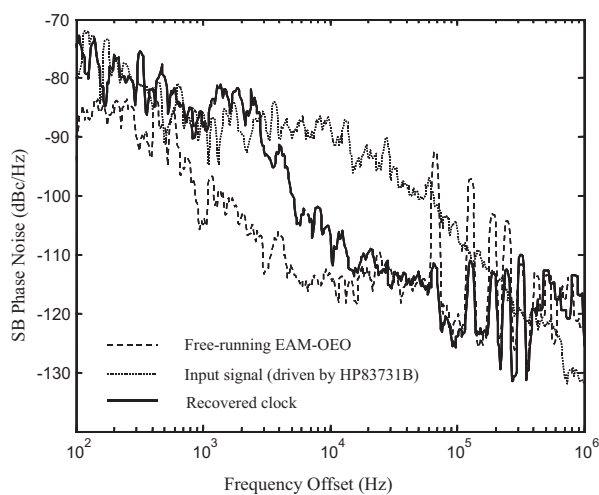

Fig. 4. Phase noise characteristics of the recovered clock, the EAM-OEO, and original pulses from the MLFL.

modulation of the 0.08-nm-spaced peaks corresponding to the 10-GHz pulse rate. The width of the modulation envelop $\Delta v = 0.18$ nm, which gives a time-bandwidth product of $\Delta v \Delta \tau \sim 0.34$ that is almost transform limited for an assumed sech^2 pulse shape.

Fig. 4 shows the results for the single-sideband (SSB) phase-noise spectrum of the detected 10-GHz injection-synchronized tone (recovered clock). Also plotted are the corresponding results for the tones detected at the outputs of the MLFL (which uses an HP83731B as the driving source) and the EAM-OEO. The figure illustrates three important features. 1) The SSB phase-noise spectrum of the free-running EAM-OEO contains a series of peaks with $\sim$67-kHz separation that correspond to the nonoscillating sidemodes of the 3000-m-long OEO cavity. As shown, these sidemodes are suppressed by >90 dBc/Hz. 2) The SSB phase-noise spectrum of the locked signal shows that the optical injection-locking process further suppresses the sidemodes by more than 20 dB. 3) The capability of the recovered optical clock to track the

timing noise of the incoming data inside the $\sim$5-kHz locking range (corresponding to an average input power of -19 and -13 dBm for the 10- and 40-Gb/s signals, respectively), i.e., it follows the uncertainty in the arrival time of the data, which is useful for applications of the electrical clock (as analyzed in [10] for a different kind of OEO). Outside the locking range, however, the timing noise of the recovered optical clock is lower than that of the incoming data, i.e., it has less timing jitter and, therefore, the recovered optical clock can be simultaneously useful for all-optical 3R regeneration purposes. It is worth noting that when the SSB phase-noise spectrum of the detected signal is used to characterize optical pulses, the integration band plays an important role. For clock recovery applications, the ITU standards for SONET OC-192 specify the requirements for jitter transfer (i.e., the ratio of the jitter on the output of the regenerator compared to that on the input) for an offset only up to 10 MHz. Within this frequency band, the jitter transfer should be $\sim$0 dB inside a 120-kHz range (the locking range), whereas, outside the locking range it must be attenuated by 20 dB/decade.

In conclusion, we have demonstrated direct optical-injection locking of a novel EAM-based self-starting OEO for ultralow-timing-jitter 40-Gb/s clock recovery. When the recovered electrical clock was used to monitor the incoming pseudorandom stream, we obtained error-free performance with no power penalty.

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