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Clock Recovery and Demultiplexing Performance of 160-Gb/s OTDM Field Experiments

J. P. Turkiewicz, E. Tangdiongga, G. D. Khoe, Fellow, IEEE, and H. de Waardt

Abstract—Clock recovery (CR) from a 160-Gb/s data signal is demonstrated using a single unidirectional electroabsorption modulator in a cost-effective phase-locked loop configuration consisting entirely of commercially available components. The CR exhibits a root mean square time jitter of 205 fs, a holding range of 10 MHz, a wavelength-independent performance of 10 nm, and an input dynamic range of 10 dB. Demultiplexing experiments of transmitted 160-Gb/s data through installed fiber links over 275.4 km verified the excellent performance of the proposed CR. All 16 10-Gb/s channels were demultiplexed error-free.

Index Terms—Demultiplexing, electroabsorption, optical switches, semiconductor optical amplifiers, time-division multiplexing, ultrafast optics.

I. INTRODUCTION

CLOCK RECOVERY (CR) is a key functionality required in any transmission system. In optical time-division-multiplexed (OTDM) networks, CR units extract a base-rate clock from the incoming high bit-rate data stream. Many CR methods have been reported. Among them, phase-locked loop (PLL)-based systems are the most established [1]. A PLL CR based on electroabsorption modulators (EAMs) has advantages in terms of stability and compactness. A tandem EAM-based CR scheme was demonstrated in [2]. A CR setup based on a differential scheme in a bidirectionally operated EAM (200-kHz holding range) was presented in [3]. In this letter, we report for the first time a PLL CR scheme based on a single unidirectional EAM that utilizes anomalous effects in a radio-frequency (RF) quadrupler. The result is a compact and simple CR setup that has several key advantages. We achieved excellent jitter and holding performance over a wide range of input powers and operational wavelengths. The number of optoelectrical components is minimized. This improves stability and significantly reduces cost of the CR. The simple nature of the proposed CR in principle allows hybrid electrooptical integration. In addition, the exclusive use of commercially available components offers immediate cost-effective applications in 160-Gb/s OTDM networks. The operation of the proposed CR was successfully tested in field transmission experiments using an installed link of 275.4-km standard single-mode fiber (SSMF). This experiment is to the best of our knowledge, the longest distance of 160-Gb/s OTDM field transmission. This letter also presents the first field demonstration of the PLL-based clock extraction from 160-Gb/s OTDM data signal.

II. CR AND CHARACTERIZATION

Fig. 1(a) presents the setup of the proposed CR, which is entirely of commercial available components. An input 160-Gb/s (16 × 10 Gb/s) OTDM signal enters an electrooptical PLL oscillator through a 40-GHz EAM. The 160-Gb/s OTDM data signal at 1551.7 nm is generated by passively multiplying 2-ps pulses from a fiber ring laser (9.953 28-GHz repetition rate), modulated with a pseudorandom bit sequence (PRBS) of $2^{7} - 1$ length. The EAM output is detected by a photodetector, amplified by a limiting amplifier, and bandpass filtered by a combination of a high-Q filter ($Q \approx 1000$) and a bandpass amplifier. An RF mixer combines the filtered data signal with a locally generated 10-GHz clock of a voltage-controlled oscillator (VCO) for phase detection. The resulting phase error is processed in an active lowpass filter (LPF), and is subsequently used to drive the VCO. The gating signal is derived from the VCO output, which is then quadrupled ($\times 4$) to 40 GHz. The quadrupler consists of two doublers in cascade, each sandwiched by high-gain amplifiers. For normal operation ($\sim 5$–$8$-dBm input power), the amplifiers produce sufficient power to saturate the doublers, resulting in a frequency multiplied output signal (40-GHz sine) with a constant amplitude. However, if the input power is below threshold (\(< 3$ dBm), the power to the first doubler is too low to switch on the amplifier,
which in turn provides too little power for the second doubler. As a consequence, we observe the fundamental input bleeding through, causing the output being an oscillating signal at 40 GHz with strong amplitude components at a 100-ps interval [see Fig. 1(b)]. This low-input power effect is further exploited by the nonlinear characteristics of the EAM to assure a narrow gating window and a high contrast ratio of the demultiplexed pulses at the data base rate. Fig. 1(c) shows a 160–40-Gb/s demultiplexed signal by the EAM, which has a strong 10-Gb/s component. The RF spectrum of the recovered clock is depicted in Fig. 2(a). We measured the carrier-to-noise ratio at 10-kHz offset 92 dBc/Hz. Integrating the single sideband phase noise over an interval 10 kHz–10 MHz results in a root mean square (rms) time jitter of around 205 fs. The time jitter measured by a digital communication analyzer with precision time base confirmed this value. Fig. 2(b) shows the recovered RF clock signal, and Fig. 2(c) the measured time jitter as a function of the EAM input optical powers. The rms time jitter decreases as the input optical power to the EAM increases due largely to better optical signal-to-noise ratio (OSNR > 15 dB). For input powers between -4 and +6 dBm, the rms time jitters are 200–210 fs, which correspond to the VCO jitter performance. We measured the time jitter of less than 210 fs over the wavelength range 1544–1554 nm. Switching the PRBS length to 2^{31} – 1 produced identical results, proving the CR scheme to be nearly pattern insensitive. The design was also verified to be polarization independent. The CR holding range is examined by adjusting the base rate once locking was achieved. We measured the holding range of 10 MHz, which we believe is limited by the bandwidth of the operational amplifiers in the LPF.

III. DEMULTIPLEXING EXPERIMENTS

We investigated the performance of the recovered clock signal for demultiplexing 160–10 Gb/s in a field trial condition. The experiment setup is given schematically in Fig. 3(a). The receiver consists of an optical amplifier, a 160–10-Gb/s demultiplexer, a 10-Gb/s optical receiver, and a 10-GHz CR setup. Bit-error-rate (BER) values are evaluated by a BER tester. We related the sensitivity performance to the input power to the optical receiver for which BER = 10^{-9}. For demultiplexing to 10 Gb/s, we used the drop output of an ultrafast nonlinear interferometer (UNI) in a gain transparent (GT) operation, as it was used in [4]. The switch is an improved version of the UNI which was first proposed in [5]. The input signal was +10 dBm for the GT-UNI switch and +3 dBm for the CR setup. The results of using a master and recovered clock are depicted in Fig. 3(b). The sensitivity values of the master clock are observed to be 1 dB worse than those of the recovered clock because the master clock was not always phase-matched to the data coming from the fiber-based transmitter and the Er-doped fiber amplifiers (EDFAs). We believe that this difference is insignificant if the complexity and the large variation of the ambient condition of the experimental setup during laborious and time-consuming BER measurements are taken into account.

IV. TRANSMISSION EXPERIMENTS

Fig. 4 shows the transmission setup. The transmission line consists of four 68.85-km spans of SSMF, dispersion compensation modules (DCMs) and EDFAs to compensate for the losses in the SSMF and the DCMs. The fibers have been buried in the ground for more than five years and are connecting Ipswich and Newmarket in the U.K. The 160-Gb/s transmitter and receiver were sited in Ipswich. EDFAs and DCMs were colocated in Ipswich and Newmarket. Degradation due to polarization-mode dispersion (PMD) was minimized by coupling the data signal to the principal states of polarization of the fiber link. Chromatic dispersion of the link was completely compensated and dispersion slope was kept small. This dispersion management resulted in an optical pulse train with a pulselength of 2.2 ps before the 160-Gb/s receiver. A fraction of the data signal was
Fig. 4. Transmission experiment setup using 4 × 68.85 km of commercially deployed fibers between Ipswich and Newmarket in U.K.

coupled to the CR unit. This scheme differs from the one applied in [4], where the clock signal was transmitted in an auxiliary wavelength channel. The recovered clock signal has a carrier-to-noise ratio at 10-kHz offset of more than 90 dBc/Hz. This value corresponds to a rms time jitter of less than 210 fs.

Fig. 5 presents the BER values of all 16 demultiplexed 10-Gb/s signals as a function of the input power to the receiver. All channels were detected error free and no error floors were observed. For comparison, we used the average receiver sensitivity of the 160-Gb/s signals demultiplexed using a GT-UNI switch.

V. CONCLUSION

We have demonstrated a simple and compact subharmonic 10-GHz CR setup using a single unidirectional EAM. The recovered clock signal exhibited a low rms time jitter of around 205 fs over a wide range of the optical input powers and wavelengths. The characterization and 160-Gb/s transmission experiments using a commercially deployed fiber link of 275.4 km confirmed error-free demultiplexing using this CR circuit.

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REFERENCES