Clock recovery and demultiplexing performance of 160-Gb/s OTDM field experiments

Citation for published version (APA):
Turkiewicz, J. P., Tangdiongga, E., Khoe, G. D., & Waardt, de, H. (2004). Clock recovery and demultiplexing performance of 160-Gb/s OTDM field experiments. *IEEE Photonics Technology Letters*, *16*(6), 1555-1557. https://doi.org/10.1109/LPT.2004.827423

DOI:
10.1109/LPT.2004.827423

Document status and date:
Published: 01/01/2004

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 16. Nov. 2023

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.

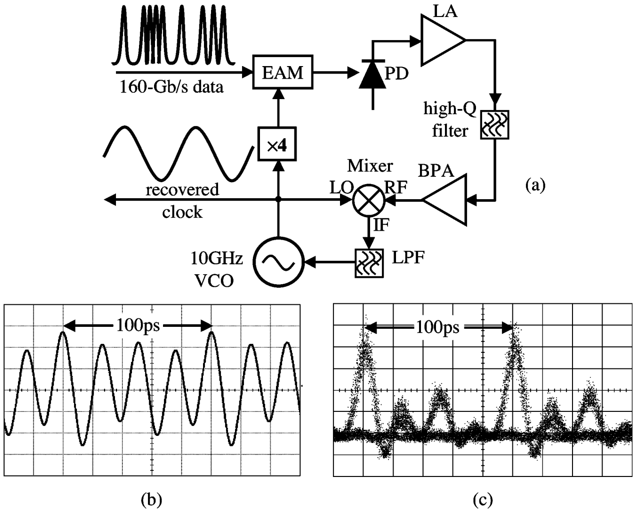


Fig. 1. Experimental setup: (a) schematic of CR, (b) response of quadrupler, and (c) response of EAM for 160-Gb/s input signal.

II. CR and Characterization

Fig. 1(a) presents the setup of the proposed CR, which is consisted 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 ($Q \sim 1000$) 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 (×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,

---

Manuscript received December 4, 2003; revised February 18, 2004. This work was supported by the European Commission under the IST-2000-28765 Project FASHION (ultraFAst Switching in HIgh-speed OTDM Networks).

The authors are with COBRA Research Institute, Eindhoven University of Technology, NL-5600 MB Eindhoven, The Netherlands (e-mail: E.Tangdiongga@tue.nl).

Digital Object Identifier 10.1109/LPT.2004.827423

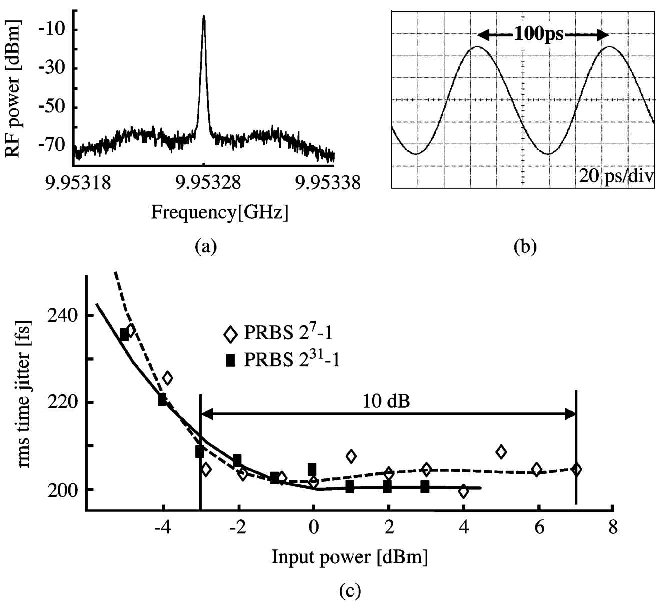


Fig. 2. Measured characteristics of the recovered clock: (a) RF spectrum, (b) waveform, and (c) rms time jitter versus input optical power.

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.

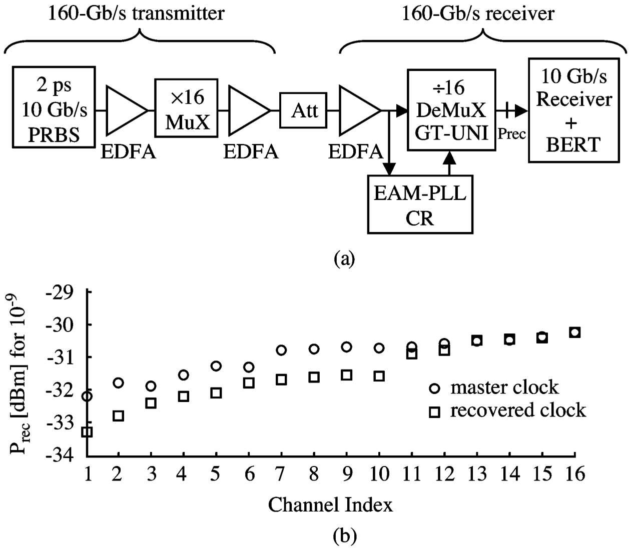
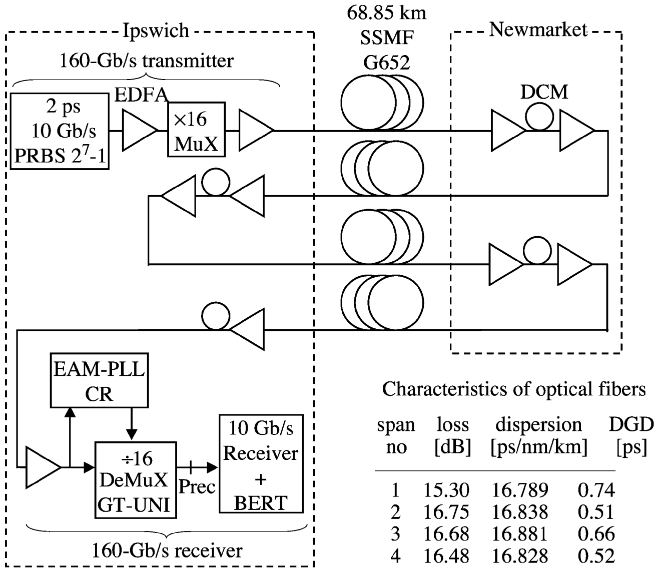


Fig. 3. Experiments on the B2B 160–10-Gb/s demultiplexing: (a) setup and (b) sensitivity values measured using master and recovered clock signal.

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 pulsewidth of 2.2 ps before the 160-Gb/s receiver. A fraction of the data signal was



Characteristics of optical fibers

span no	loss [dB]	dispersion [ps/nm/km]	DGD [ps]
1	15.30	16.789	0.74
2	16.75	16.838	0.51
3	16.68	16.881	0.66
4	16.48	16.828	0.52

Fig. 4. Transmission experiment setup using 4 × 68.85 km of commercially deployed fibers between Ipswich and Newmarket in U.K.

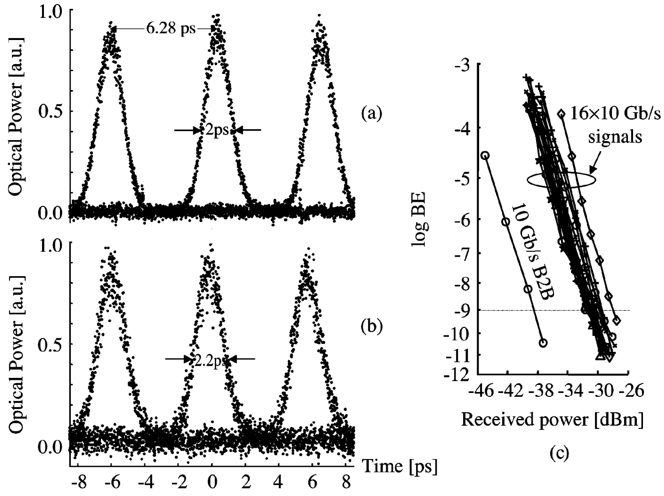


Fig. 5. Pulse performance of 160-Gb/s transmission taken with an optical sampling scope at (a) transmitter, (b) 275.4 km, and (c) BER performance of 16 10-Gb/s signals demultiplexed using a GT-UNI switch.

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 160–10-Gb/s demultiplexing in the back-to-back (B2B) scheme, i.e., -31.9 dBm [see Fig. 3(b)]. The average receiver sensitivity after transmission was measured -30.2 dBm, leading to an average transmission penalty of 1.7 dB. To quantify the total system penalty due to the multiplexing, transmission, and demultiplexing, the BER performance of the 10-Gb/s B2B signal is also depicted in Fig. 5. The receiver sensitivity shows a variation of approximately 3 dB between the best and worst channel, resulting in penalties of 7–10 dB when they are compared to the reference BER values. The OSNR requirement for a BER $< 10^{-9}$ demultiplexing performance was observed to be 3 dB higher than that for CR. We optimized the transmission line for a minimum PMD and dispersion effect. However, residual PMD and dispersion might occur during the field experiments, affecting the pulsewidth and the extinction ratio of the data pulses. The influence of these system impairments was more detrimental to the demultiplexer than to the CR circuit. If the data contrast between the main peak and the subpeaks in the EAM output [see Fig. 1(c)] remains larger than 3 dB, a 10-GHz clock signal with 205-fs time jitter can still be obtained. The results of these OTDM field experiments demonstrated the excellent performance of the proposed CR circuit in combination with the dispersion management and the time-domain demultiplexing.

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.

ACKNOWLEDGMENT

The authors would like to thank W. Schairer, H. Rohde, and G. Lehmann from Siemens AG for DCMs, and Y.R. Zhou, E.S.R. Sikora, and A. Lord from BT for the use of the transmission infrastructures.

REFERENCES

[1] O. Kamatani, S. Kawanishi, and M. Saruwatari, "Prescaled 6.3 GHz clock recovery from 50-Gb/s TDM optical signal with 50 GHz PLL using four-wave mixing in a travelling-wave laser diode optical amplifier," *Electron. Lett.*, vol. 30, no. 10, pp. 807–809, 1994.

[2] D. T. K. Tong, K.-L. Deng, B. Mikkelsen, G. Raybon, K. F. Dreyer, and J. E. Johnson, "160-Gb/s clock recovery using electroabsorption modulator-based phase-locked loop," *Electron. Lett.*, vol. 36, no. 9, pp. 1951–1952, 2000.

[3] C. Boerner, C. Schubert, C. Schmidt, E. Hilliger, V. Marembert, J. Berger, S. Ferber, E. Dietrich, R. Ludwig, B. Schmauss, and H. G. Weber, "160-Gb/s clock recovery with electro-optical PLL using a bidirectionally operated electroabsorption modulator as a phase comparator," *Electron. Lett.*, vol. 39, no. 14, pp. 1071–1073, 2003.

[4] U. Feiste, R. Ludwig, J. Berger, C. Schmidt, H. G. Weber, B. Schmauss, A. Munk, B. Buchold, D. Briggmann, F. Kueppers, and F. Rumpf, "160-Gb/s field transmission over 116 km standard single-mode fiber using 160-Gb/s OTDM and 40-Gb/s ETDM demultiplexer," in *Proc. Inst. Elect. Eng., Optoelectron.*, vol. 148, 2001, pp. 171–175.

[5] N. S. Patel, K. A. Rauschenbach, and K. L. Hall, "40-Gb/s demultiplexing using an ultrafast nonlinear interferometer (UNI)," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1695–1697, Dec. 1996.