Enabling 160-Gbit/s Transmitter and Receiver Designs

Lothar Möller, Yikai Su*, Chongjin Xie, Roland Ryf, Xiang Liu, Xing Wei‡, Christopher R. Doerr

Bell Laboratories, Lucent Technologies, 791 Holmdel-Keyport Rd, Holmdel, NJ 07733, USA, lmoeller@lucent.com
**State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University,*
1954 Huashan Rd, Shanghai 200030, China, yikaisu@sjtu.edu.cn
‡Bell Laboratories, Lucent Technologies, 600 Mountain Ave, Murray Hill, NJ 07974, USA

Abstract: The field of ultra high-speed (≥160Gb/s) transmission has developed rapidly over the past years from proof-of-principle demonstrations towards advanced field trial applications. We review recent trends in 160Gb/s signal generation and detection techniques.

OCIS codes: (060.2330) Fiber optics communications, (190.4380) Nonlinear optics, (060.5060) Phase modulation

1. Introduction

Today, 10 Gb/s per channel line rate is common, and several vendors offer wavelength division multiplexed (WDM) systems with overall link capacities exceeding 2 Tb/s. Recently, products have been released with channel loads of 40 Gb/s and research on the next generation networks is strongly progressing towards higher line rates. Since it is expected that the historical trend of data-rate quadrupling in optical communications will continue from one generation to the next, 160-Gb/s systems research [1,2,3] is now the major subject in the ultra high-speed field but even higher rate signals at 320 Gb/s, 640 Gb/s [4], and 1.28 Tb/s have been already demonstrated [5].

Historically the development of new optical transmission systems has been towards increasing the data rate per channel since it is anticipated that moving signal transmission and processing to higher speeds will lower the hardware costs, shrink the required equipment footprint, and reduce the power consumption per transmitted bit. However, the current 160-Gb/s research mainly deals with providing lab demonstrations for proof-of-principle purpose. Although 160-Gb/s transmission field trials have been reported, their implementations were not close to products since they are not yet competitive to WDM systems with lower data-rate channels in an economical sense.

Before reviewing the optical-time-division-multiplexing [6](OTDM) techniques applied today for generating ultra high-speed signals, it is worth taking a look at the potential of wideband electronics. It is likely that the transceiver architectures of future 160-Gb/s systems are similar to today's electrical-time-division-multiplexing (ETDM) approaches at lower speeds. Recently InP/InGaAs heterojunction bipolar transistors with a current-gain cutoff frequency f_T of more than 500 GHz have been demonstrated [7]. When applying the rule of thumb that f_T must be three to four times larger than the data rate, it becomes clear that 160-Gb/s IC designs are not unrealistic in the near future. An electrical multiplexer [8] and de-multiplexer were already demonstrated at very high speeds (144 Gb/s), and encouraging results for an 85.4-Gb/s ETDM receiver could meanwhile be obtained [9]. Other demonstrations of necessary high voltage swing components, e.g. drivers and modulators, are however difficult to fulfill the electrical bandwidth requirements of 160 Gb/s at this stage. Therefore OTDM based techniques are currently the only approaches to 160-Gb/s signaling.

Here we review key OTDM components required for transmitter and receiver designs such as pulse sources, multiplexers, de-multiplexers, clock recoveries, and dispersion compensators. However 160-Gb/s research is not limited to these fields and expands quickly to other areas, e.g., transmission properties, PMD compensation, add/drop filters, measurement techniques, performance monitoring, and all-optical regeneration.

2. Transmitter designs: phase-correlated and in-coherent signal generation

Several variations of the conventional OTDM schemes [10] were applied to form ultra high-speed data signals. They differ in pulse sources and the interleaving techniques. Fiber ring lasers are commonly used for lab applications, which output short pulses (FWHM < 3 ps) at repetition rates of 10, 20, and 40 GHz with a high power (>10dBm). Actively mode locked semiconductor diode lasers [11] (pulse width < 2 ps) at 10 or 40 GHz can generate phase coherent pulse trains (required for DPSK signaling [12]), but have weaker performance in terms of timing jitter and output power compared to fiber lasers. Laser sources with higher repetition rates offer advantages as in general it is desirable to minimize the number of required OTDM stages in order to obtain a more stable set-up. Besides mode locked lasers, CW lasers followed by periodically driven electro-absorption modulators (EAMs) at 40 GHz also serve as pulse sources but require additional pulse compression techniques [13,3].

In each OTDM stage, the data pulses are split into two replicas, delayed in time with respect to each other, and finally interleaved. This step doubles the data rate and has to be repeated until the final rate is achieved. The relative path delay of a OTDM module can be chosen such that for short pseudorandom bit sequences (PRBSs) (2^7-1 or 2^9-1) their pseudorandom nature is maintained but the approach becomes impractical for longer ones since it requires delays equivalent to half of the codeword length. Typically the insertion loss of commercially available multiplexers is around 5-6 dB per stage, and units that are polarization-maintaining as well as supporting both polarizations are commercially available. Beside these schemes, concepts based on parallel delay lines were reported[14]. Both architectures can be combined with polarization multiplexing at the same wavelength to achieve data rates >160Gb/s. This would additionally double the data rate or relax the duty cycle constrains for the pulse source. However, the transmission features can be significantly degraded due to coherent cross talk between both channels caused by i.e. PMD and PDL, and a polarization sensitive receiver is required. Considerable effort has been spent on integrating multiplexers into planar lightwave circuits and other compact devices in order to achieve a more stable operation and to reduce the required device foot print [15],[16],[5].

A common drawback of conventional OTDM signals is that these formats cannot be used to study the impact of bit-by-bit optical phase correlation since OTDM does not allow precise control the optical phase between adjacent bits. OTDM approaches produce random optical phase jumps between the interleaved replicas since length changes on the order of a fraction of a wavelength in the OTDM delay lines significantly affect the phase alignment of the superimposed replicas. Recently, a novel method was introduced that allows for generating ultra high-speed phase-correlated data signals [17] including DPSK [19], pair-wise alternating-phase (PAP) and group-wise alternating-phase (GAP) carrier-suppressed (CS) signals [18] etc.. This method is based on polarization dependent cross phase modulation (nonlinear polarization rotation) in a highly nonlinear fiber. Figure 1 shows qualitatively one major difference between this kind of signals and conventional OTDM-generated ones. Since the pulses of the signals are phase-correlated the corres-ponding spectrum possesses a certain frequency pattern. Meanwhile it is possible to demonstrate all important modulation formats at 160 Gb/s [18],[19],[20],[21],[34] and to experimentally study signal-dependent non-linear propagation features and filter effects[18].

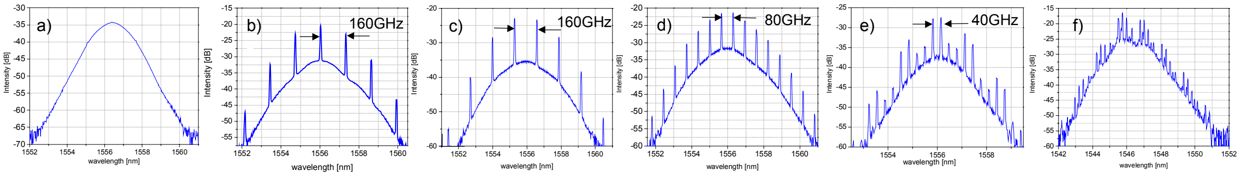

Fig.1: Measured spectra of 160Gb/s signals. a) RZ-DPSK, b) RZ, c) CS-RZ, d) PAP CS-RZ, e) GAP CS-RZ, f) OTDM.

3. De-multiplexer, clock recovery, and dispersion compensator for 160-Gb/s receiver designs

Photodiodes with up to 80-GHz bandwidth and reasonable responsivity are already commercially available that are close to the 70%-80% bandwidth requirement of 160-Gb/s signals. However, in all reported 160-Gb/s system experiments the O/E conversions at 40, 20, or 10 Gb/s were performed after demultiplexing the optical data stream in the time domain to multiple tributaries.

EAMs are often used as optical switching devices for selecting one tributary, since they allow for a relatively compact and reliable receiver design. Current high-performance EAMs exhibit low insertion loss (~5dB), high extinction ratio (>20dB), low polarization dependence (<0.2dB), and good operation performance at 40 GHz. In selection of EAMs for the optical de-mux, special attention must be paid on the extinction ratio curve versus the applied bias voltage, where not only the maximum extinction ratio but also the monotonically increasing loss with the lowering of the negative bias are desired. Applying a 40-GHz sinusoidal clock signal with a deep dc-bias to the modulator results in a short switching window (FWHM ~3.5ps) where the EAM is transparent. Since the de-mux selects only one tributary, the electrical phase of the clock tone driving the EAM needs to be swept over 2 π such that all tributaries become accessible. Hence this approach is obviously not suitable for product applications.

Nonlinear fiber devices (i.e. nonlinear fiber loop mirror (NOLM) [22]) capable of processing even higher bit rates such as 640 Gb/s [23] have been used before EAMs were applied to receiver designs. The basic idea behind these approaches is that an ultra-short control pulse co-propagates at a different wavelength with the data signal through a nonlinear fiber. Cross phase modulation will manipulate the optical phase of one tributary or the inserted control pulse. Thus the tributary can be selected based on a following interference process. Such setups provide very short switching widows and can regenerate the signal [24],[25] but have drawbacks in terms of stability and polarization sensitivity. Integrated all-optical switches based on semiconductor optical amplifiers (SOA), investigated in several different configurations, are probably more suitable for product implementation due to their compact size [26]. The operation principle (in some way similar to NOLMs) is based on refractive index changes by periodically launching control pulses into the SOA so that the input data signal experiences an optical phase shift and a following interferometric setup can filter out the tributary. Compared to NOLMs these setups are more stable since their fiber lengths are significantly shorter thus, i.e., polarization drifts are smaller. Integrated optical de-muxes, capable of delivering all tributaries simultaneously, could be prefered components for future product applications. Recently a 1:8 (160->20 Gb/s) unit was demonstrated [27].

For clock recovery (CR), various opto-electronic techniques have been proposed and demonstrated for sub-harmonic clock extraction from ultra high-speed data streams. In contrast to conventional 10 and 40-GHz CR that recover a tone equivalent to the data rate, 160-Gb/s CRs provide tones at 40 or 10 GHz for the de-mux setups mentioned before. Previously a CR was realized using a phase-locked loop (PLL) with an all-optical phase comparator based on four-wave mixing [28] or cross-phase modulation [29] in semiconductor optical amplifiers used in interferometric configurations. However, such schemes may suffer from polarization-dependent effects. In many recent 160 Gb/s experiments, EAMs were used as pre-scalers to down-convert the data to lower rates, and then the clock tone was recovered with high-Q electric filters [3], phase-locked loops (PLLs) using electronic phase comparators [30], or the combination of both [31]. Such schemes based on EAMs have advantages in terms of stability and compactness. In [32], a PLL CR scheme was reported based on a single unidirectional EAM utilizing anomalous effects in a radio-frequency (RF) quadrupler. Simultaneous demultiplexing, electrical and optical clock recovery were shown. A CR setup based on a differential scheme in a bidirectionally operated EAM was presented in [33] featuring excellent locking stability. Other CR schemes make use of optical down conversion or modulation-format specific features [34].

Active chromatic dispersion compensation in installed 160Gb/s systems will become mandatory since typical temperature changes of the fiber environment can cause significant variations of the link dispersion [35]. Also the dispersion slope in WDM systems needs to be equalized. Experimentally the need of CD compensation was shown in [36] and practical realizations of compensators are reported in [37],[38],[39],[40]. Mitigation of PMD, which is even more challenging than CD compensation due to its dynamic and stochastic nature, attracts much research attention[13].

Conclusion

We reviewed various technologies for enabling 160-Gb/s transmission systems with an emphasis on the transmitter and receiver designs. System modules were discussed including transmitters, de-muxes, clock recoveries, and dispersion compensators. It is expected that future 160-Gb/s systems will be ETDM-based with the advance of wideband electronics and run on phase-correlated signals. We introduced a method to generate several different phase-correlated formats including DPSK, RZ, CSRZ, PAP-CSRZ, and GAP-CSRZ. Although 160-Gb/s research is currently not product-oriented its progress drives developments in many other areas of optical communications.

---

[1] E. Lach et al., "Advanced 160 Gbit/s OTDM system based on wavelength transparent 4 x 40 Gbit/s ETDM transmitters …" OFC'02 , 2002, pp. 2-4.

[2] U. *Feiste et al., "*160 Gbit/s field transmission over 116 km standard single mode fibre using 1…," IEE Proceedings Optoelectronics, 2001, pp.171-5.

[3] B. Mikkelsen et al."160 Gbit/s single-channel transmission over 300 km nonzero dispersion shifted fiber …," ECOC post deadline paper PD2-3, 1999.

[4] H. Sotobayashi, W. Chujo, " Inter-wavelength-band conversions and demultiplexings of 640 Gbit/s OTDM signals," OFC 2002 , 2002, pp. 261-2.

[5] M. Nakazawa et al., " Ultra high speed OTDM transmission using…," Lasers and Electro-Optics, 2001, CLEO/Pacific Rim 2001. vol.1, pp. 618-9.

[6] R.S. Tucker et al., "Optical time-division multiplexing for very high bit-rate transmission," JLT, 1988, pp. 1737-49.

[7] W. Hafez, Jie-Wei Lai, and M. Feng, "InP/InGaAs SHBTs with 75 nm collector and fT>500GHz," Electron. Lett., Vol. 39, No.20, 2003.

[8] T. Suzuki et al., "144-Gbit/s Selector and 100-Gbit/s 4:1 Multiplexer using InP HEMTs," IMS'04, TU5A-5, 2004.

[9] K. Schuh et al. "85.4 Gb/s ETDM receiver with full rate electronic clock recovery circuit," ECOC'04, Th4.1.1, 2004.

[10] D.N. Spirit, A.D. Ellis, P.E. Barnsley, "Optical time division multiplexing: systems and networks," IEEE Communications Magazine, 1994, pp. 56-62.

[11] R. Ludwig et al., "A tunable femtosecond pulse modelocked semiconductor laser for applications in …," IEICE Trans. Electron., pp 140-4, 1998.

[12] S. Ferber et al. "Comparison of DPSK and OOK modulation format in 160 Gbit/s transmission system," Electron. Lett., 2003, pp. 1458 – 9.

[13] T. Miyazaki et al."Stable 160-Gb/s DPSK transmission using a simple PMD compensator on the photonic network…," OECC/COIN 2004, July 2004.

[14] B. Mikkelsen et al., "Unrepeatered transmission over 150kmof nonzero-dispersion fibre at 100Gb/s with …," Electron. Lett.,1999, pp.1866-7.

[15] T. Ohara et al.,"160-Gb/s optical-time-division multiplexing with PPLN hybrid integrated planar lightwave circuit," IEEE PTL, pp.302-4, 2003.

[16] M. Schilling et al., "OTDM planar lightwave components (PLCs) for multiplexing from 40 Gb/s to 80-640 Gb/s," LEOS 2002, pp.887-8, 2002.

[17] L. Möller, Y. Su, X. Liu, J. Leuthold, C. Xie, "Ultra high-speed Optical Phase Correlated Data Signals," *IEEE PTL,* vol. 15, no. 11, pp 1597-9, 2003.

[18] L. Möller, Y. Su, C. Xie et al., "All-optical Phase Construction of ps-Pulses from Fiber Lasers for Coherent …," in Proc*. OFC,* 2004, paper PDP20.

[19] L. Möller, Y. Su, C. Xie et al. "Generation of a 160-Gb/s RZ-DPSK Signal and Its Detection with a One-Bit …," ECOC'04, post deadline paper, 2004.

[20] L. Möller, Y. Su et al., "Narrow bandwidth filtering of coherent and OTDM-generated 160 Gb/s data signals" OFC'04, ThN2, 2004.

[21] H. Murai et al., "Single channel 160 Gbit/s carrier-suppressed RZ transmission over 640 km with EA modulators …," ECOC'03, 2003, pp.52-3.

[22] N.J. Doran and D. Wood, "Nonlinear-optical loop mirror," Opt. Lett., 1988,13, pp.56-58.

[23] T. Yamamoto et al., "Ultrafast nonlinear optical loop mirror for demultiplexing 640 Gbit/s TDM signals," Electronics Letters, 1998, pp. 1013 -14.

[24] M. Meissner. K. Sponsel, K. Cvecek, "3.9-dB OSNR Gain by an NOLM-Based 2-R Regenerator," IEEE PTL, 2004, pp. 2105-7.

[25] A. *Bogoni et al., "*All-optical regeneration and demultiplexing for 160-gb/s …," IEEE J. Selected Topics in Quantum Electronics, 2004, pp.192-6.

[26] C. Schuber et al.," Comparison of interferometric all-optical switches for demultiplexing applications in high-speed OTDM …" JLT , 2002, pp.618-24.

[27] I. Shake et al., "160 Gbit/s full optical time-division demultiplexing using FWM of SOA-array integrated on PLC," Electronics Letters , pp.37-8, 2002.

[28] S. Kawanishi et al., "Single channel 400 Gbit/s time-division-multiplexed transmission of 0.98 ps pulses …," *Electron. Lett.*, vol. 32, 1996, pp. 916-7.

[29] T. Yamamoto et al., "Clock recovery from 160 Gbit/s data signals using phase-locked loop with …," *Electron. Lett*. vol., 2001, pp. 509-10.

[30] D.J.K. Tong et al., "160 Gbit/s clock recovery using electroabsorption modulator-based phase-locked loop," *Electron. Lett.*, 2000, pp. 1951-52.

[31] J.P. Turkiewicz et al., "Clock recovery and demultiplexing performance of 160-Gb/s OTDM field experiments," *IEEE PTL*, 2004, pp. 1555-7.

[32] Hsu-Feng Chou et al., "Simultaneous 160-Gb/s demultiplexing and clock recovery by utilizing microwave harmonic …," IEEE PTL, 2004, pp. 608-10.

[33] C. Boerner et al., "160 Gbit/s clock recovery with electro-optical PLL using bidirectionally operated …," Electron. Lett., 2003, pp. 1071-72.

[34] Y. Su et al., "Demonstration of a 160-Gb/s Group-Alternating Phase CSRZ format Featuring Simplified Clock …," submitted to OFC'05, 2004.

[35] S. Vorbeck et al., "Dispersion and dispersion slope tolerance of 160-Gb/s systems, considering the temperature …, "IEEE PTL, 2003, pp.1470 – 2.

[36] M. Daikoku et al., "160-Gb/s four WDM quasi-linear transmission over 225-km NZ-DSF with 75-km spacing," IEEE PTL, 2003, pp.1165-7.

[37] B.J. Eggleton et al., "Tunable dispersion compensation in a 160-Gb/s TDM system by a voltage controlled chirped …, " IEEE PTL, 2000, pp. 1022-4.

[38] S. Wielandy et al., "Demonstration of automatic dispersion control for 160 Gbit/s transmission over 275 km of …," Electron. Lett., 2004, pp.690 – 1.

[39] E. Hellstrom et al., "Third-order dispersion compensation using a phase modulator," JLT, 2003, pp. 1188 – 97.

[40] S. Matsumoto et al., "Tunable dispersion slope compensator with a chirped fiber grating and a divided thin-film heater …," IEEE PTL, pp. 1095 – 7.