100 Gb/s Complete ETDM System Based on Monolithically Integrated Transmitter and Receiver Modules

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Abstract: A complete ETDM system based on monolithically integrated transmitter and receiver modules was demonstrated with BER performance below FEC threshold up to 107 Gb/s. ETDM signal at 112 Gb/s with clear eye opening was also observed.

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1. Introduction

It is a common understanding that Ethernet is the most cost-efficient transport technology in optical networks, and 100 Gigabit/s Ethernet (GbE) is the next logical step in trend. Currently, transmission technologies for 100 GbE are being developed by using multi-level modulation formats with the symbol rates up to ~ 56 Gbaud [1]. On the other hand, 100 Gb/s electrical time-division multiplexed (ETDM) transmission systems with the symbol rates at 100 Gbaud and beyond are also under investigation [2-8]. These systems are potentially low cost and may pave the way towards the next generation Terabit/s Ethernet. Nevertheless, the performance of these systems relies on the development of E/O & O/E conversion modules, as well as electrical driver amplifier and multiplexer/demultiplexer (Mux/DeMux) modules operating at 100 Gb/s and above.

Previously, an ETDM system experiment at 107 Gb/s was demonstrated by using a FIR filter to compensate the bandwidth limitation of a 30 GHz Mach-Zehnder modulator in the transmitter, and using an unpackaged integrated clock-data recovery (CDR) and demultiplexer chip in the receiver, supplied by an external voltage controlled oscillator (VCO) [2]. In [3] a 107 Gb/s ETDM system was enabled by using a 100 GHz grid for vestigial sideband filtering (VSB) at the transmitter, and separate clock recovery and demultiplexer units in the receiver. In this paper, we report, for the first time to our knowledge, complete ETDM system experiment based on a monolithically integrated distributed feedback laser and traveling-wave electroabsorption modulator (DFB-TWEAM) packaged module in the transmitter that had a smooth bandwidth response up to 110 GHz [4], and an InP-based fully packaged and monolithically integrated CDR and 1:2 demultiplexer (CDR+DeMux) module with the built-in VCO in the receiver that had the working range for input signal bit-rates between 100−107 Gb/s [5]. Bit-error-rate (BER) measurements showed that BERs below the standard forward-error-correction (FEC) threshold (2×10^{-3}) can be achieved throughout the full CDR+DeMux module working range up to 107 Gb/s. In addition, clear eye-diagram opening up to 112 Gb/s was also demonstrated.

2. Experimental setup

Fig. 1 shows the schematic experimental setup. On the transmitter side, the core part was a 16-pin module holding inside a chip with a fast TWEAM monolithically integrated in InP platform with a CW-DFB laser that emitted CW light at 1550 nm when pumped over its threshold [4]. The DFB-TWEAM module had a smooth bandwidth response up to 110 GHz, even though the 3 dB bandwidth was at ~ 75 GHz. The driving electrical data signal was obtained by using an InP DHBT-based 2:1 electrical multiplexer module [6], followed by a broadband InP DHBT-based traveling wave electrical driver amplifier (TWA) module that had a 3dB bandwidth of ~ 90 GHz and maximum peak-to-peak output voltage swing of 1.9 V [7]. The 2:1 multiplexer was supplied by two pseudorandom binary sequence (PRBS) data sequences (data & data inverted) with 2^7-1 word-length from a 56 Gb/s pattern generator.

On the receiver side, a 100 GHz photodiode was used for the O/E conversion of the received optical signal, followed by another 90 GHz broadband TWA to boost the signal eye-opening voltage swing above the input threshold of the CDR+DeMux module that had two sets of data outputs plus a recovered clock signal output at half of the input signal bit-rate [5]. The two demultiplexed tributary data channels were then directly fed into a 56 Gb/s error analyzer for the BER measurements. The CDR+DeMux module had the working range for input signal bit-rates between 100–107 Gb/s, and required negatively-biased voltage and above 200 mV eye-opening voltage swing at the input, hence an additional 65 GHz bias-T was used just before the module to lower the input DC voltage level. In addition, in order to enhance the peak-to-peak signal voltage swing after the O/E conversion with the ~ 0.5 A/W responsivity of the 100 GHz photodiode, and to facilitate the BER characterization of the ETDM signal versus its optical signal-to-noise ratio (OSNR), two cascaded EDFAs together with a variable optical attenuator were used between the transmitter and the receiver. Signal OSNR was controlled by the optical attenuator and measured by an optical spectral analyzer just before the receiver using a 20 dB optical coupler.

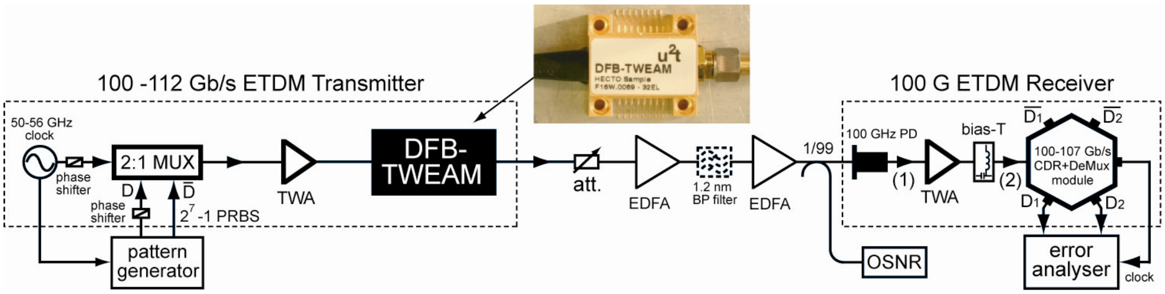

Fig. 1. Experimental setup. TWA: traveling wave electrical amplifier.

3. Experimental results and discussions

As an illustration, Fig. 2 shows the generated ETDM non-return-to-zero (NRZ) signal eye-diagrams at 100, 107 and 112 Gb/s, respectively, measured directly after the 100 GHz photodiode using a 70 GHz electrical sampling head. In the measurement, the pump current and the inverse bias voltage of the DFB-TWEAM module were adjusted so that the maximum eye-diagram opening can be achieved. This resulted in an average optical power of -1 dBm directly from the transmitter. After the amplification by the two EDFAs, the average optical signal power was enhanced to 12.5 dBm before entering the receiver. We see that clear eye-diagram opening up to 112 Gb/s can be achieved, even though the extinction ratio of the generated signals was at ~ 4 dB.

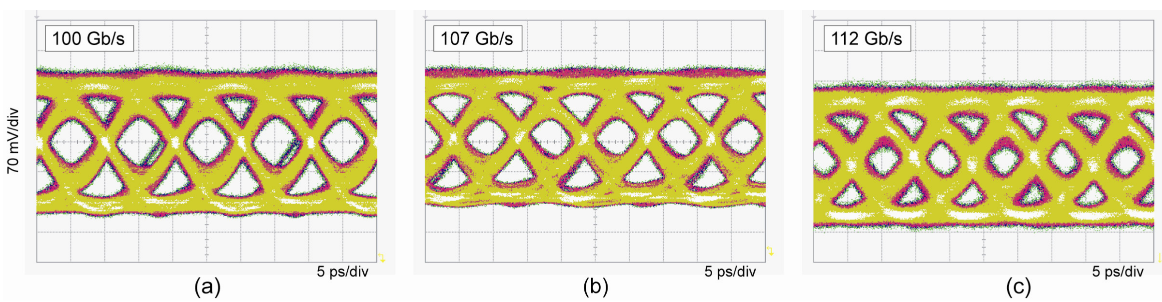

Fig. 2. ETDM NRZ data signal eye-diagrams at 100 Gb/s (a), 107 Gb/s (b), and 112 Gb/s (c), measured at point (1) in Fig. 1.

From Fig. 2 we can also see that even with 12.5 dBm average optical signal power, the signal eye-opening voltage swing was at ~ 100 mV after the photodiode, which was less than the 200 mV minimum requirement of the subsequent CDR+DeMux module. Therefore, another broadband 90 GHz TWA module was used to enhance the detected signal eye-opening voltage swing. Fig. 3 shows the corresponding eye-diagrams of the amplified signals at 100 & 107 Gb/s (that were within the working range of the CDR+DeMux module) after passing through the DC level adjusting bias-T just before the CDR+DeMux module. We can see that compared to Fig. 2, although the peak-to-peak signal voltage swing was enhanced to over 1 V, the signal eye-opening was not enhanced accordingly. This was mainly due to the 65 GHz extra bias-T before the CDR+DeMux module that limited the overall bandwidth of the receiver. Since the signal quality was degraded more significantly at 107 Gb/s, an ordinary Fabry–Perot (FP) optical filter with 1.2 nm/3dB & 7.3 nm/20dB passband was used between the two cascaded EDFAs in the characterization of the system performance at 107 Gb/s, as shown in Fig. 1 as the dashed part.

We can see in Fig. 3(b)&(c) that by slightly detuning the center wavelength of the optical bandpass filter, a certain eye-opening improvement can be obtained, due to a slight signal carrier suppression. This was verified by the BER measurement, as shown in Fig. 4, by using the two 50 & 53.5 Gb/s tributary channels of the data signals from the CDR+DeMux module. The corresponding eye-diagrams of the demultiplexed tributary channels are also shown as the insets in the figure. We see that on the one hand at 100 Gb/s, BERs of the two tributary channels approaching 10^{-7} can be achieved without any optical filtering. On the other hand, when the signal bit-rate was increased to

107 Gb/s, the BERs of the two tributary 53.5 Gb/s channels were above the $2{\times}10^{-3}$ FEC threshold without optical filtering. By further inserting the 1.2 nm optical bandpass filter with a slight detuning of the center wavelength, BERs below $2{\times}10^{-3}$ can be achieved at the signal OSNR above 33.5 dB. Nevertheless, worth noting here is that although at 107 Gb/s the signal BER below the FEC threshold was achieved by resorting to optical filtering, the bandwidth limitation in the receiver induced by the extra bias-T is not intrinsic and can be overcome by removing the bias-T using a bias-feeding photodetector [8], or an improved CDR+DeMux module DC control board. These measures would allow a direct compatibility of the photodetector DC output level with the input level of the CDR+DeMux module.

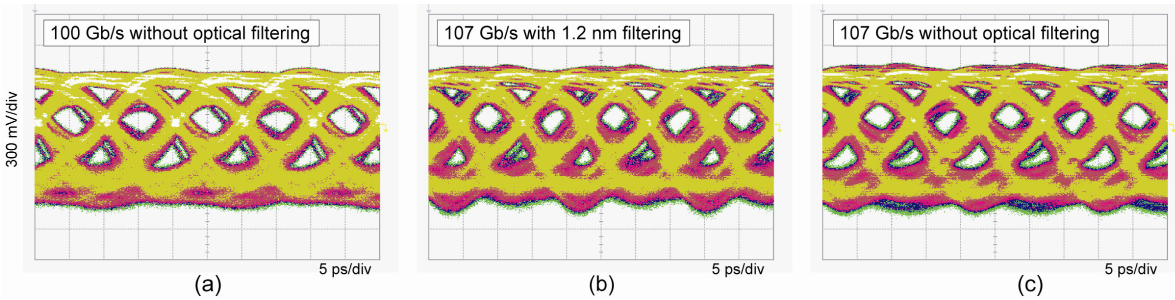

Fig. 3. CDR+DeMux input signal eye-diagrams at 100 Gb/s without optical filtering (a), and at 107 Gb/s with (b) & without (c) optical filtering, measured at point (2) in Fig. 1.

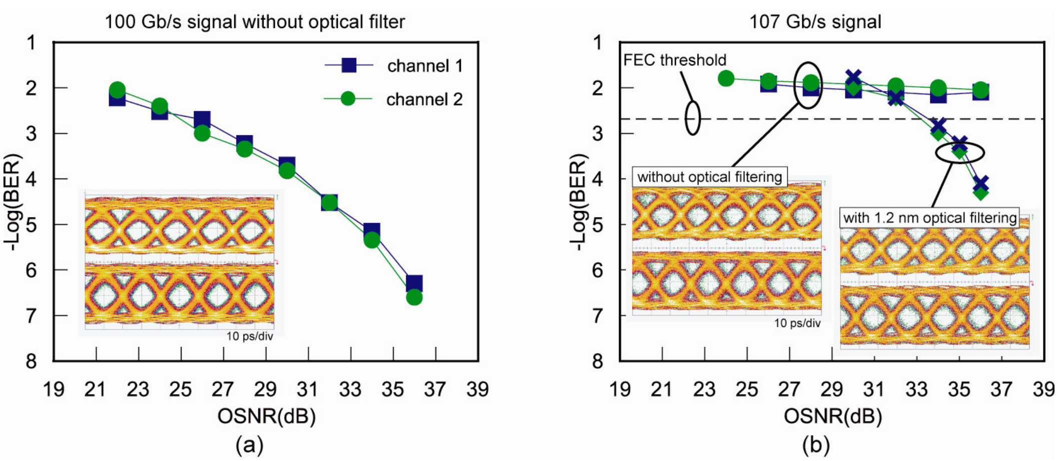

Fig. 4. BER versus signal OSNR at 100 Gb/s (a), and at 107 Gb/s (b). Insets: the corresponding demultiplexed tributary eye-diagrams.

4. Conclusion

In this work, we successfully have demonstrated a complete working ETDM system based on monolithically integrated transmitter and receiver modules with BER performance below FEC threshold up to 107 Gb/s, and clear signal eye-diagram opening up to 112 Gb/s. Our results show that directly modulated high-speed ETDM transmission systems with the symbol rates at 100 Gbaud and beyond are promising candidate for cost-effective 100 GbE applications and may even pave the way towards the next generation Terabit/s Ethernet.

5. Acknowledgement

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