First Demonstration of Real-Time 100 Gbit/s 3-Level Duobinary Transmission for Optical Interconnects

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Abstract We report on the first experimental demonstration of 100Gbit/s 3-level duobinary optical transmission enabled by in-house newly developed SiGe BiCMOS transmitter/receiver ICs. Operated in real-time, we demonstrated a 100Gbit/s data-rate over 2km SSMF without DSP.

Introduction

The continuous growth of the Internet traffic is boosting the requirement of ultra-high-speed optical interconnects for datacentres, which is largely driven by cloud computing, mobility and Internet of Things. Currently the evolution from 100Gbit/s Ethernet to 400Gbit/s is under discussion within the IEEE P802.3bs 400 Gigabit Ethernet Task Force[1]. Among different approaches, the 4-lane 100Gbit/s scheme is particularly attractive for 500m and 2km single-mode fibre applications as it allows lower lane counts and thus offering higher spatial efficiency. In research several experiments of NRZ or PAM-4 transmissions at 100-116Gbit/s were reported[2-5]. However, most of them[2-4] required heavy offline digital signal processing (DSP) to compensate the limited bandwidth of the O/E components. In reference[5] a real-time 112Gbit/s PAM-4 optical link over 2km standard single-mode fibre (SSMF) was demonstrated, with a BiCMOS transceiver (including CDR) power consumption of ~8.6 W.

Recently an alternative modulation format, 3-level duobinary (i.e. electrical duobinary EDB), is gaining a lot of attention[6,7]. Unlike optical duobinary modulation (ODB), the EDB scheme enables the usage of components and packaging technologies with lower bandwidth, reducing link cost and power consumption. The narrowed spectral bandwidth can also improve the chromatic dispersion (CD) tolerance and reduce the equalization requirements of the high-speed serial rate link[6]. In this paper, we present a newly developed EDB transmitter (TX) and receiver (RX) chipset, and experimentally demonstrate a real-time 100Gbit/s EDB optical link in C-band up to 2km SSMF.

Experimental setup

The experimental setup is illustrated in Fig. 1. A Xilinx FPGA board is adopted to generate 4 electrical 25Gbit/s NRZ shifted 2^7-1 PRBS signal streams. An EDB TX IC multiplexes 4x25G streams into a serial 100Gbit/s, and pre-equalizes the serialized NRZ signal. The pre-emphasized signal was amplified by a 50GHz RF amplifier and then used to drive a C-band 100GHz electro-absorption modulated laser

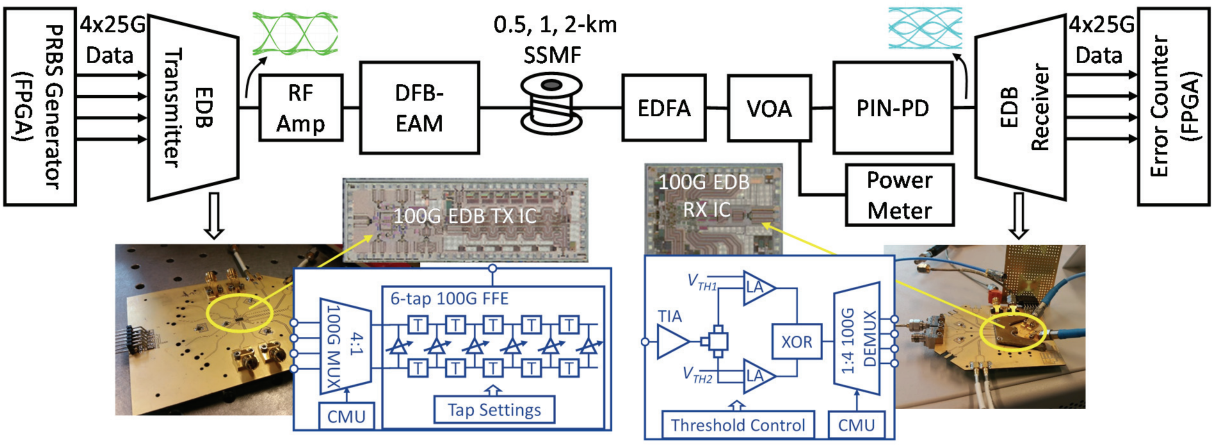

Fig. 1: Experiment setup of real-time 100Gbit/s 3-level duobinary optical link

(EML)[4]. In the experiment, the integrated distributed feedback laser (DFB) in the EML emitted at 1548.7nm and the output optical power of the EML was around 0dBm. After transmission over an SSMF, the received optical signal was detected by a PIN photodiode (PD) and a custom EDB RX IC. An Erbium doped fibre amplifier (EDFA), a variable optical attenuator (VOA) and a power meter were used before the PIN-PD to adjust/record the received optical power for measurement purpose. The EDFA can be removed from the setup when a higher power EML is available. The PIN-PD is a high-speed InP-based O/E converter packaged prototype with a responsivity of 0.5 A/W. The subsequent duobinary RX IC demodulates the 3-level eyes with two separate threshold levels. The demodulated signal is then deserialized on-chip into 4x25G NRZ outputs for real-time error detection, which is implemented in the same FPGA board as for PRBS generation.

Both EDB TX and RX ICs were designed in-house and fabricated in a 0.13um SiGe BiCMOS technology. The TX IC consists of a 4-to-1 MUX and a 6-tap feedforward equalizer (FFE) that compensates the frequency roll-off of the following components and the link. The TX IC occupies 1555um x 4567um including IOs and consumes about 1W. The measured frequency response of the E/O/E components excluding the EDB ICs is shown in Fig. 2. The frequency responses of various fibres of 500m, 1km and 2km were measured and plotted in the same figure. As can be seen in Fig. 2, in the optical back-to-back (B2B) case the bandwidth is mainly limited by the electrical amplifier and interfaces; but fibre operating in C-band will severely degenerate the flatness of the frequency response, esp. at 2km distance. Together with the bandwidth-limited components and the dispersive fibre, the real-time FFE in the TX is employed to create an equivalent channel response that transforms the NRZ from the serializer output into 3-level duobinary at the RX input.

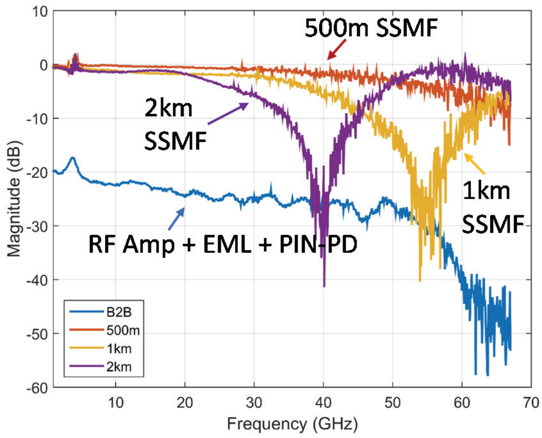

Fig. 2: Measured frequency responses of the B2B optical link and various fibres

The EDB RX IC consists of a transimpedance (TIA) input stage, two parallel level-shifting limiting amplifiers, an XOR and a 1-to-4 DEMUX. The EDB RX can be re-configured into a NRZ RX with 4 demuxed outputs, which is also used in our experiments for NRZ signalling comparison. The FFE is preferably done in TXs to avoid noise emphasis. Without the need of complex DSP, the RX IC occupies 1926um x 2585um including IOs and consumes below 1.2W.

Results and Discussion

As shown in Fig. 1, both in-house developed EDB TX and RX ICs are flip-chipped on test PCBs. Before performing the optical transmission experiment, the EDB TX/RX ICs have been first verified B2B pure electrically[8]. The electrical B2B measurement was performed continuously over 1 hour, and measured bit-error rate (BER) was less than 1E-12 for 100Gbit/s duobinary signal, which revealed a very stable performance of the EDB TX/RX ICs.

Optical performance of the link was then evaluated using the experimental setup shown in Fig. 1. To compare the performance, we first evaluated both NRZ and the proposed 3-level duobinary at various rates in optical B2B configuration. Fig. 3(a) shows the electrical 100Gbit/s NRZ eye-diagram after the TX IC

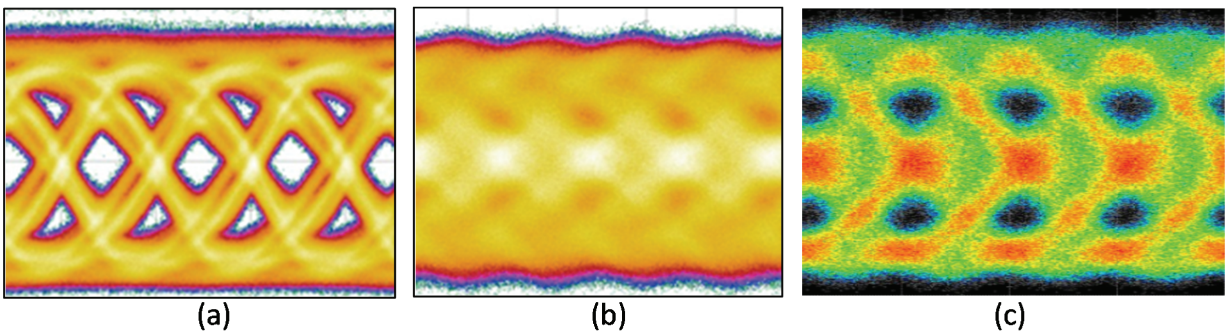

Fig. 3: Measured 100Gbit/s (a) eye-diagram at the EDB TX IC output with TX FFE disabled (b) eye-diagram at the PIN-PD output with TX FFE disabled (c) 3-level duobinary eye-diagram at the PIN-PD output with TX real-time 6-tap FFE enabled

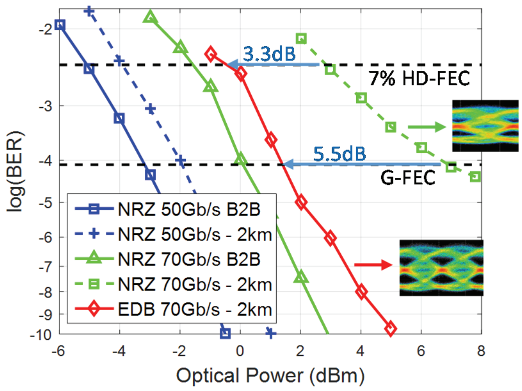

Fig. 4: Measured NRZ BER curve up to 70Gbit/s and 2km SSMF, compared to 70Gbit/s EDB modulation

without FFE, which is clearly open. However, the received optical eye at the PIN-PD (Fig. 3(b)) was completely closed due to the component bandwidth limitation as indicated in Fig. 2. As shown in Fig. 3(c), by enabling the real-time 6-tap FFE in the EDB TX IC, the received optical eye has been shaped into 3-level duobinary and two separate eyes were clearly formed after the PIN-PD. For fair comparison, the TX FFE is always enabled in the experiment and separately optimized for each rate.

The measured BER curves for 50Gbit/s and 70Gbit/s NRZ signals are shown in Fig. 4. The optical power shown here is measured at the input of the PIN-PD (after the VOA). The NRZ signaling works relatively well in B2B up to 70Gbit/s. However, after 2km of SSMF, we noticed a decreased performance at 70Gbit/s (4.4 dB penalty compared to the B2B). As clearly indicated by the received eye-diagram, the CD introduces significant inter-symbol interference (ISI) and closes the NRZ eye. In contrast, we can utilize this ISI effect and create 3-level duobinary signal by optimizing the TX FFE. The optimized 3-level duobinary eye in Fig. 4(a) shows two widely open eyes. The measured BER for 70Gbit/s EDB link over 2km can reach a BER of ~1E-10, which is well below the hard-decision forward error correction (HD-FEC) with 7% overhead (BER=3.8E-3) or G-FEC threshold (BER=8E-5). In addition, using EDB modulation, we obtained a sensitivity improvement of 3.3 dB at 7% HD-FEC limit (or 5.5 dB at G-FEC limit) with respect to the 70Gbit/s NRZ transmission over 2km distance.

Next, 100Gbit/s EDB measurements were performed with different fibre lengths. The resulting eye-diagrams for B2B, 500m, 1km, and 2km SSMFs are depicted in Fig. 5(a). The real-time BER measurements are shown in Fig. 5(b). For 500m applications, no noticeable penalty was observed. Over 2km SSMF, 100Gbit/s EDB signal can still be received with BER of 3.7E-3, below 7% HD-FEC threshold.

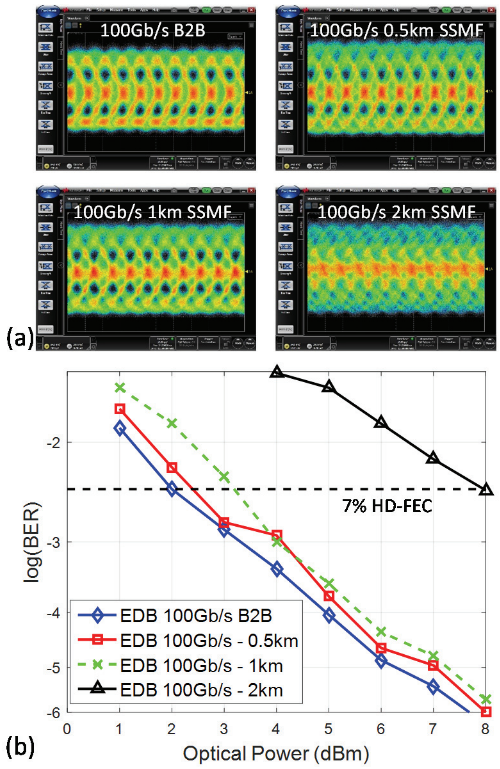

Fig. 5: Measured (a) eye-diagrams of 100Gbit/s EDB transmission at different fibre lengths (b) BER curves of 100Gbit/s EDB transmission at different fibre lengths

Conclusions

For the first time, we have demonstrated optical signalling in 3-level duobinary format at line rates up to 100Gbit/s. The measured BER is below the threshold of HD-FEC with 7% overhead up to a 2km SSMF link without any offline DSPs.

Acknowledgements

The authors would like to thank the support from the Industrial Research Fund (IOF) of Ghent University, National Natural Science Foundation of China, Natural Science Foundation of Guangdong Province, Swedish Research Council, the Swedish Foundation for Strategic Research, and Göran Gustafsson Foundation, and EU MC ICONE project.

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