High-speed SDM Interconnects with Directly-Modulated 1.5-µm VCSEL enabled by Low-Complexity Signal Processing Techniques

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Abstract: We report on our recent work in supporting up to 100 Gbps/λ/core transmissions with a directly modulated 1.5-µm single mode VCSEL and multicore fiber, enabled by low-compleixty pre- and post- digital equalizations.

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Vertical cavity surface emitting laser (VCSEL)-based transceivers are considered as promising candidates to support future high-performance computing (HPC) and datacenter applications, by fulfilling stringent requirements on data rate, cost, reliability, power consumption, footprint and size [1]. Among them, the VCSEL array can seamlessly extend its potential of high-density integration to space division multiplexing (SDM) to scale up the lane count per fiber and reduce cabling complexity [2]. High speed single lane transmission with short wavelength multimode (MM)-VCSELs and advanced modulation formats, and multi-lane transmissions with coupled MM-VCSEL array with multicore fibers (MCFs) for high aggregate data rates, have been reported [3-7]. For applications requiring distances more than a few kilometers, longer wavelength single mode (SM)-VCSELs with single mode fiber (SMF) links are more feasible. A few recent high-speed transmission works with 1.5-µm SM-VCSELs show promising results towards implementation [8-11]. In this abstract, we present our recent work on high-speed transmissions using 1.5-µm SM-VCSEL over 7-core fiber links of different distances [12]. We demonstrate up to 70 Gbaud PAM-4 signal generation, and 50 Gbaud PAM-4 transmissions over 1-km dispersion-uncompensated and 10-km dispersion-compensated single mode MCF links, with pre-equalization based on accurate end-to-end channel characterization, combined with low-complexity digital post-equalization.

Figure 1 shows the experimental setup, the VCSEL L-I-V characteristic, the picture of the probe station, and the S21 response curves of the chip and the transmission system before and after fiber transmission. The maximum 3-dB modulation bandwidth of the VCSEL chip is ~ 23 GHz. The PAM-4 symbols were offline generated, and pre-

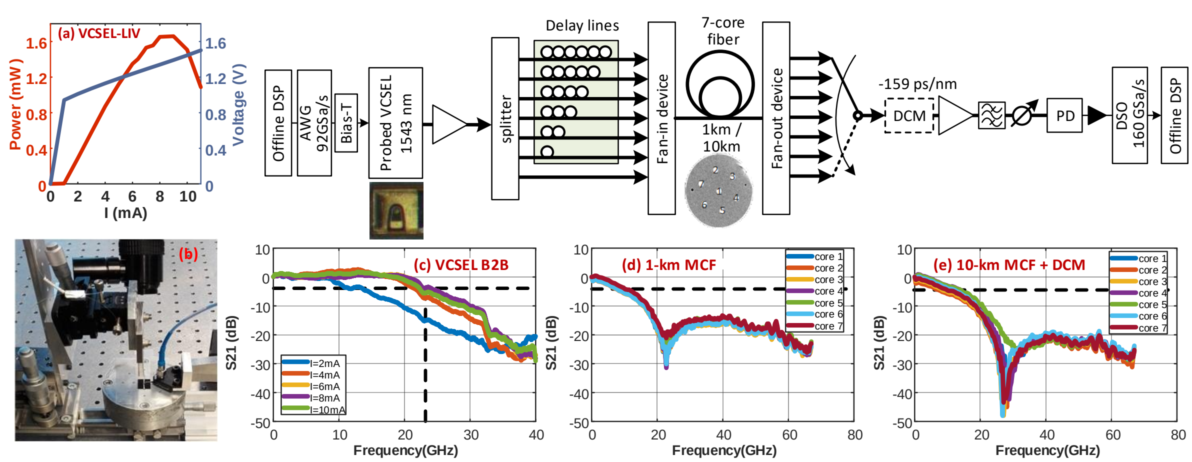

Fig. 1. Experimental setup. Insets: (a) VCSEL L-I-V curves; (b) photos of probe station; S21 response of (c) the VCSEL chip, and after transmission of each core of the (d) 1-km MCF and (e) 10-km MCF + DCM

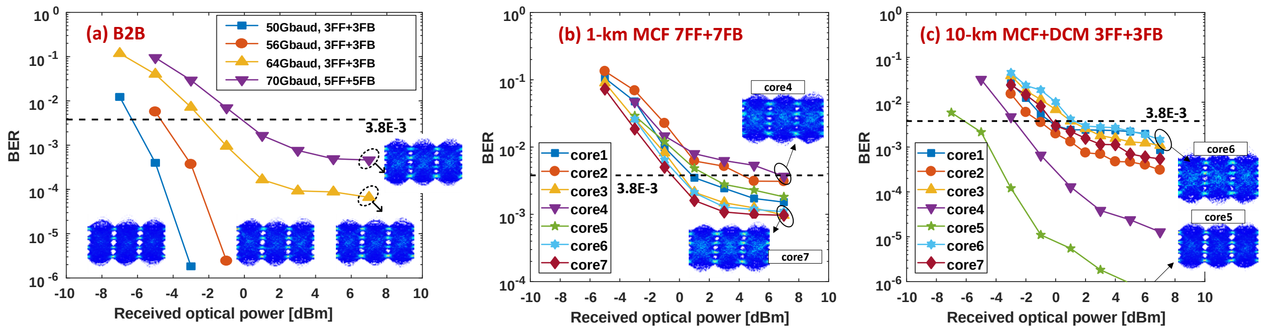

Fig.2. BER results for (a) B2B (b) 1-km MCF and (c) 10-km MCF + DCM. Selected eye diagrams are shown as insets.

equalized per the characterized S21 response (both amplitude and phase). A 92 GSa/s arbitrary waveform generator (AWG) was used to drive the VCSEL. The VCSEL was operated at room temperature without active cooling. The VCSEL output was amplified and splitted into seven lanes with proper decorrelations, to emulate parallel independent channels entering the fan-in (FI) device for the 7-core fiber. The MCF has a 150-µm cladding diameter and 42-µm core pitch, with ~ -45 dB/100 km inter-core crosstalk, 0.20 dB/km attenuation and 17.1 ps/nm/km dispersion coefficient. A fan-out (FO) device was used to split the signals to single-core fibers patch cords before the receiver. A dispersion compensation module (DCM) was used for the 10-km MCF link. The end-to-end 3-dB bandwidth after both MCF links were considerably reduced comparing to B2B due to the dispersion induced RF fading. At the receiver, we detect each FO output signal individually with a 90-GHz PIN photodiode (PD). A 160 GSa/s real-time digital storage oscilloscope (DSO) was used to capture and sample the signals. The offline DSP consists of a low-pass filter, a maximum variance-based timing recovery, a symbol-spaced decision-feedback equalizer (DFE) and an error counter. Figure 2 (a)-(c) show the BER results and selected eye diagrams for the B2B, 1-km MCF and 10-km MCF + DCM cases, respectively. For B2B, BER performance of below the 7% OH-HDFEC limit of 3.8×10^{-3} is successfully achieved at ~0 dBm received optical power (RoP) for up to 70 Gbaud PAM-4 signal, with DFE of 5 feedforward (FF) and 5 feedback (FB) taps, owning to the effective channel pre-equalization at the transmitter. After the 1-km and 10-km MCF transmissions, the BER results were measured at 50 Gbaud. The reduced baud rate compared with B2B case is mainly due to the reduced 3-dB channel bandwidth. For the uncompensated 1-km MCF cases, a DFE of 7-FF-tap+7-FB-tap can successfully recover the received signals in all the cores to reach the 7%-OH-HDFEC limit. For the 10-km dispersion-compensated MCF cases, with slight relaxed bandwidth limit, a DFE of 3-FF-tap+3-FB-tap was shown to be sufficient. Additionally, different performances between different cores can be seen in both cases. Selected eye diagrams of the best and worst cores in each case are also shown. Such performance differences are in accordance with the differences in the characterized frequency response. Due to narrow horizontal eye opening, better BER performance and/or higher baud rates can be potentially achieved after eye skew correction [10].

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