288 Gb/s 850 nm VCSEL-based Interconnect over 100 m MMF based on Feature-enhanced Recurrent Neural Network

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Abstract: We experimentally demonstrate an ultra-high speed record of single-lane 288 Gb/s PAM-8 signal transmission over 100 m MMF attributed to the proposed design-optimized 850 nm VCSEL and feature-enhanced RNN equalization.

1. Introduction

The vast majority of optical links within data centers are based on vertical cavity surface emitting lasers (VCSELs) operating at 850 nm over multimode fiber [1]. They have proven to be very reliable and VCSELs have been the key component in determining the performance of short reach optical communication. To better meet the explosive increase in data traffic, a lot of efforts have been made to improve the capacity of VCSEL-MMF based systems. In [2], 140 Gb/s signal transmission over 100 m OM-5 MMF was enabled by applying VCSEL with bi-layer oxidized aperture. A demonstration of 200 Gb/s PAM-4 transmission over 100 m MMF using a prototype VCSEL of ~30 GHz bandwidth was reported in [3]. 224 Gb/s transmission for the discrete multitoned format at 10 m-MMF link case with a bit error ratio (BER) below the soft-decision forward error-correction (SD-FEC) was demonstrated based on an anti-waveguiding VCSEL at 850 nm [4]. Rapid development of VCSELs is driving the continuous improvement of optical interconnection transmission rates.

Meanwhile, advanced digital signal processing (DSP) techniques are required to compensate for signal impairments in high-speed transmission systems. Deep learning (DL) has drawn widespread attention due to its excellent capability to deal with high-complexity, high-dimensionality and nonlinear mapping problems. In [5], a deep neural network (DNN) is implemented for dispersion mitigation in optical fibers, however they do not address bandlimited channel. A convolutional neural network (CNN) based nonlinear classifier was realized for 112 Gb/s optical link which shows better performance than DNN in the same scenario [6]. In [7], a recurrent neural network (RNN) architecture is used to combat inter-symbol interference (ISI) induced by a Poisson channel with performance approaching maximum likelihood sequence estimate (MLSE). Our team has proposed a low-complexity Half-RNN structure for high speed optical transmission in the former work [8].

In this paper, single-lane 288 Gb/s PAM-8 signal transmission over 100 m OM-4 MMF is experimentally demonstrated with measured BER below the SD-FEC threshold of 2.7×10^{-2} [9]. We optimize epitaxial structure of 850 nm VCSEL to improve bandwidth performance and propose a feature-enhanced RNN equalization structure for high-speed optical communications. To the best of our knowledge, it is the highest single-lane bit rate record for 100 m transmission based on a ~23 GHz 850 nm VCSEL.

2. VCSEL Characteristics and Feature-enhanced RNN Equalization

The 850 nm VCSELs are grown on GaAs substrates. N-type AlGaAs distributed bragg reflectors (DBRs) with over 99.99% reflectivity are deposited as bottom reflector, followed by strained AlGaAs/InGaAs multiple quantum wells (MQWs) as active region. One single high Al content AlGaAs layer is used as oxide layer for the thermal oxidation process in the fabrication. Then p-type AlGaAs DBRs are deposited as top reflector. In the fabrication, the oxide layer is oxidized to approximately 6-7 μm size aperture for lateral current confinement. P&N metal contact pads are evaporated on the same side of chip to reduce parasitics while 2.5 μm thick benzo-cyclo-butene (BCB) is used under the p-contact pad to reduce capacitance. Fig. 1(a) displays the die picture of our optimized 850 nm VCSEL and the frequency response under different current is shown in Fig. 1(b). We choose 8 mA as the operating bias to obtain a wide ~23 GHz 3-dB bandwidth.

Neural networks hold the potential to learn the channel indirectly during the training stage without any explicit need of channel state information (CSI). We propose a feature-enhanced RNN equalization structure, as shown in Fig. 2, to deal with severe ISI and nonlinear impairments in high-speed VCSLE-MMF based communications. Fig. 2 (a) illustrates the approach to feature enhancement process, which consists of Sinc-interpolation on the original data and a linear convolution of the data feature vectors. The weights are trained by the gradient method under the mean square error criterion. It is beneficial because differential equations have been indispensable for modeling neural networks and convolution process approaches the smooth condition for accelerating convergence. This can help the multi-layer RNN structure, including three hidden layers and one output layer as shown in Fig. 2 (b), achieve better performance.

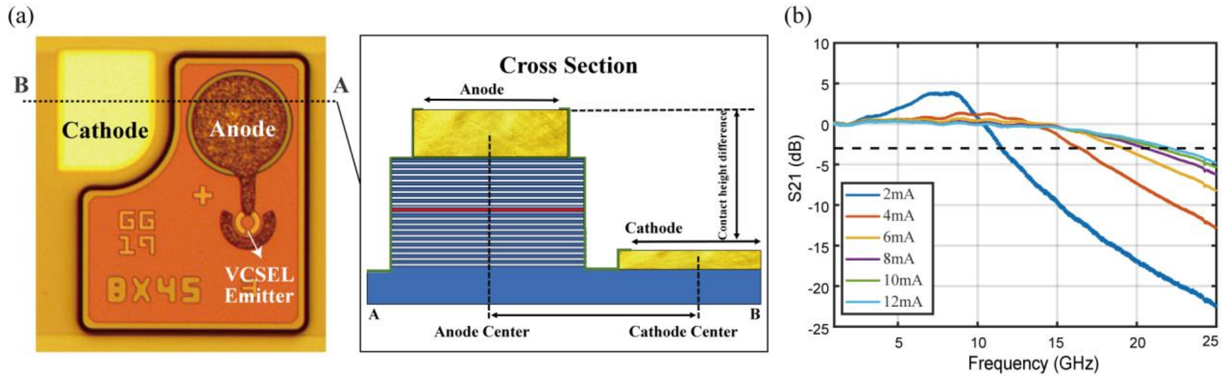

Fig. 1. (a) Micrograph of the 850 nm VCSEL and the corresponding cross section schematic (b) S21 characteristic of the VCSEL.

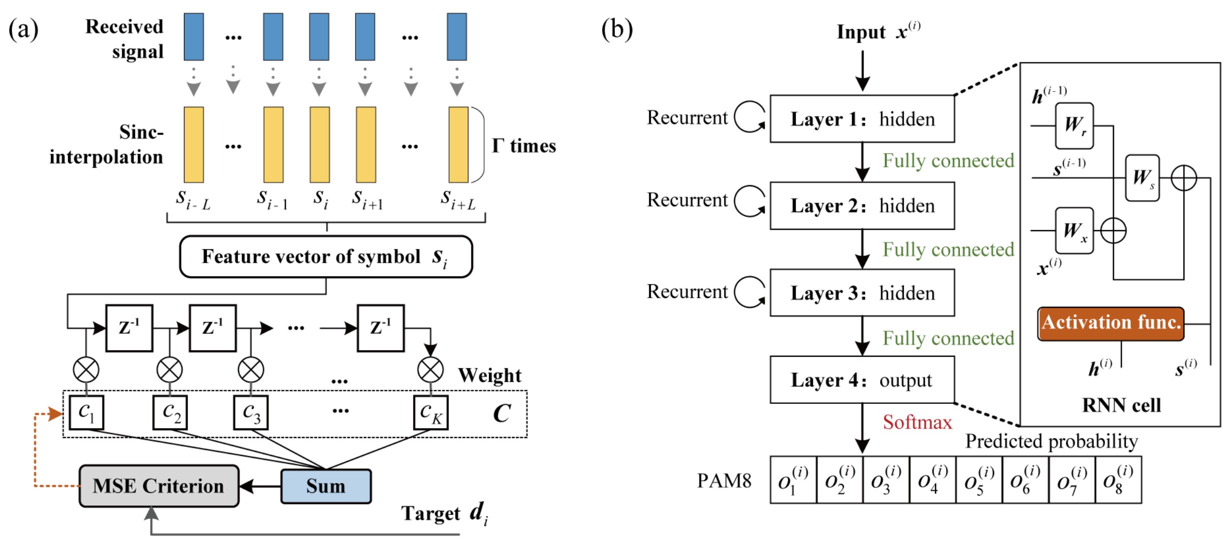

Fig. 2. (a) Feature enhancement process of proposed equalization. (b) RNN structure consisting of three hidden layers and one output layer. W_x, W_r, W_s : trainable fully-connected weights, recurrent weights and state weights. $h^{(i)}$: hidden vector. $x^{(i)}$: feature vector. $s^{(i)}$: state vector.

3. Experimental Demonstration and Results

The experimental setup and DSP diagram are depicted in Fig. 3 (a). At the transmitter, the PAM-8 electrical symbols are generated by an arbitrary waveform generator (AWG, Keysight M8194A) with 120 GSa/s sampling rate. Following [10], we do not use PRBS pattern. Instead, a binary sequence is first generated by applying sign(.) function to an Gaussian noise sequence generated in MATLAB, then converted into PAM-8 sequence. After up-sampling, the signal is digitally shaped via a root raised cosine (RRC) filter with roll-off factor of 0.4 and resampled to the suitable rate for AWG transmitting. The operating bias is set through a bias-T (SHF BT65R, up to 65GHz) with current supplied by a precision source (Keysight, B2911A). We drive the VCSEL through 67 GHz ground-source (GS) probes. The signal is coupled into the 100 m OM-4 MMF using a lensed fiber and we obtain the optimal coupling angle by careful adjustment. The optical output power is maintained at 2.3 mW. At the receiver side, the optical signal is directly detected by a photoreceiver with 22 GHz bandwidth (New Focus, 1484-A-50). After a 22dB electrical amplifier (SHF S804B), it is sampled by a real-time digital storage oscilloscope (DSO, DSAX-96204Q) operating at 160GSa/s to perform off-line DSP.

In the Rx-side DSP, the captured signal is resampled to the same samples per symbol as that at the Tx-side. After the matched RRC filter, synchronization and normalization, the signal is equalized based on the proposed feature-enhanced RNN structure. A dataset containing 510, 0000 PAM-8 symbols are obtained following [10]. We have extracted 450, 0000 of the whole dataset to construct the training set, while the rest are put into the test set. During the feature enhanced process, Γ is set at 2 while the number of convolution taps is set at 81. The feature vectors of training data are subsequently fed into the multi-layer RNN. We design the structure with three hidden layers and one output layer, allowing self-learning and extraction of optimal data features by multiple layers. The number of neurons adjusts depending on link rates, with a general number around 400. Rectified linear unit (ReLU) and cross entropy are chosen for the loss function and activation function respectively. Fig. 3 (b) shows the bit error ratio (BER) under different data rates. The measured BER for 288 Gb/s PAM-8 transmission over 100 m OM4 MMF is well below the SD-FEC threshold [9]. Meanwhile, it can be seen that 261 Gb/s date rate transmission can reach the 20% hard-decision forward error-correction (HD-FEC) threshold [11] under comparable complexity. It is attributed to the smooth condition gain from feature enhancement.

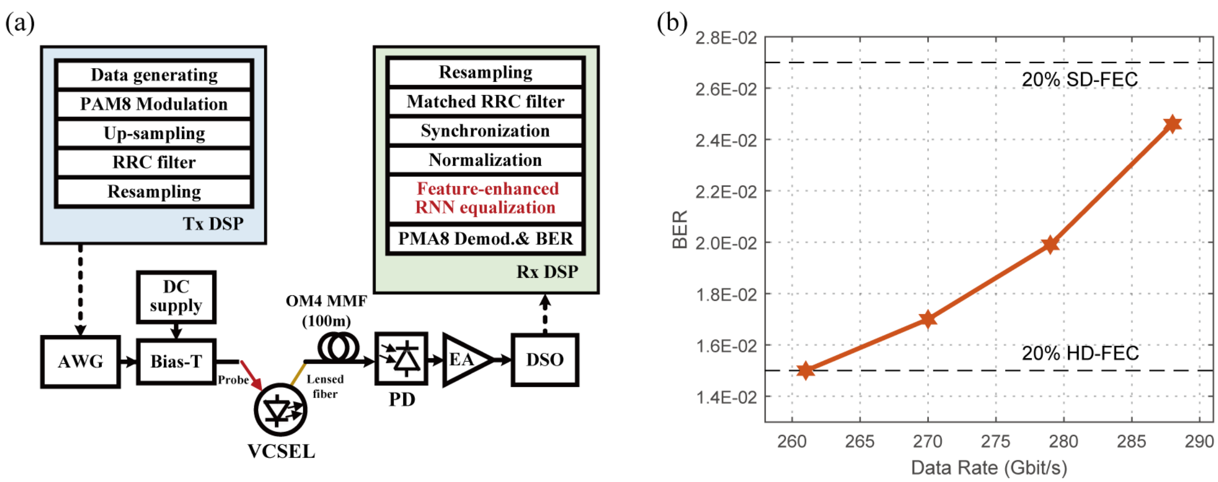

Fig. 3. (a) The experimental setup and DSP program. AWG: arbitrary waveform generator; MMF: multimode fiber; PD: photodiode; EA: electrical amplifier; DSO: digital storage oscilloscope; Tx: transmitter; Rx: receiver; RRC: root raised cosine. (b) Measured BER performance of proposed feature-enhanced RNN equalization as a function of different data rates for 850 nm VCSEL over 100 m MMF transmission.

4. Conclusions

In this paper, we experimentally demonstrate single-lane 288 Gb/s PAM-8 signal transmission over 100 m MMF by utilizing design-optimized 850 nm VCSEL and proposed feature-enhanced RNN equalization. The measured BER of 288 Gb/s rate transmission is well below the 20% SD-FEC threshold while 261Gb/s link reaches the 20% HD-FEC threshold. To our best knowledge, we report the highest single-lane transmission rate in 100 m interconnect utilizing cost-effective 850nm VCSEL.

5. Acknowledgement

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6. References

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