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400 Gbps Net Bitrate Optical-Amplification-Free TFLN-based PAM4 Link Enabled by BU-LSTM Equalization

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Abstract *We use BU-LSTM equalization to demonstrate optical-amplification-free 400 Gbps net bitrate PAM4 link in O-band with TFLN-based MZM. BER below 6.25% overhead HD-FEC threshold for B2B and 500 m SMF transmission is achieved. ©2025 The Author(s)*

Introduction

For the upcoming 1.6 Tbps era, intensity modulation and direct detection (IM/DD) systems using pulse amplitude modulation (PAM) have become the practical choice for short-reach applications, supporting up to 200 Gbps per lane [1]. However, IM/DD systems based on electro-optic (EO) modulators with limited bandwidth struggle to achieve net 400 Gbps per lane. Optical amplification is often used to meet power and margin requirements [2], but it increases system power consumption and cost. Therefore, optical-amplification-free designs have become crucial in short-reach IM/DD deployments [3]. To date, optical-amplification-free 400 Gbps gross rate transmission has only been demonstrated using electro-absorption modulated laser (EML) [3] and net rate using thin-film lithium niobate (TFLN)-based Mach-Zehnder modulator (MZM) [4,5].

TFLN-based MZMs have emerged as a promising solution, owing to their low loss, high EO bandwidth, and exceptional modulation efficiency [6-8]. While TFLN-based MZMs offer linear modulation, chromatic dispersion (CD) still affects transmission capacity even in the O-band [9]. In addition, PAM improves spectral efficiency but at the cost of increased nonlinear distortions, further limiting transmission performance. Therefore, to mitigate the nonlinear distortions and achieve the desired performance, applying high-performance equalization techniques is crucial.

Recently, neural networks (NNs) have been widely applied in IM/DD systems for equalization, showing higher performance over traditional equalizers，such as feed-forward (FFE) and decision feedback equalizers (DFE) in compensating nonlinear impairments [10-12]. As an advanced variant of recurrent neural networks (RNN), long short-term memory (LSTM) is well-suited for sequential time-series data, making it highly effective for digital signal processing (DSP). However, most recently proposed LSTM-based models rely on shallow structures with a single hidden layer, limiting the data rate in IM/DD systems to 300 Gbps [13,14]. Deep LSTM architecture with stacked hidden layers was used for time series analysis, showing the ability to build hierarchical sequence representations progressively [15].

In this work, we use a stacked LSTM model (BU-LSTM) that combines bidirectional and unidirectional layers to enable an optical-amplification-free 400 Gbps net bitrate link. For 212.5 GBaud PAM4 signal, we achieve bit-error-ratio (BER) below 6.25% overhead (OH) hard-decision forward error correction (HD-FEC) threshold in transmission at back-to-back (B2B) and over 500 m single-mode fiber (SMF). The transmission employs PAM4 transmission using a TFLN-based MZM with 1 V_{pp} driving voltage operating in O-band. In [5], conventional FFE+DFE for B2B did not achieve BER below 6.25% OH HD-FEC threshold.

IM/DD Experimental Setup

The experimental setup is shown in Fig. 1(a). At the transmitter side, a pseudorandom bit sequence (PRBS) of over 1 million bits is generated offline using Mersenne Twister with a shuffled seed. The binary sequence is mapped to PAM4 symbols and reshaped using a root-raised cosine (RRC) filter with a 0.6 roll-off factor. The signal is
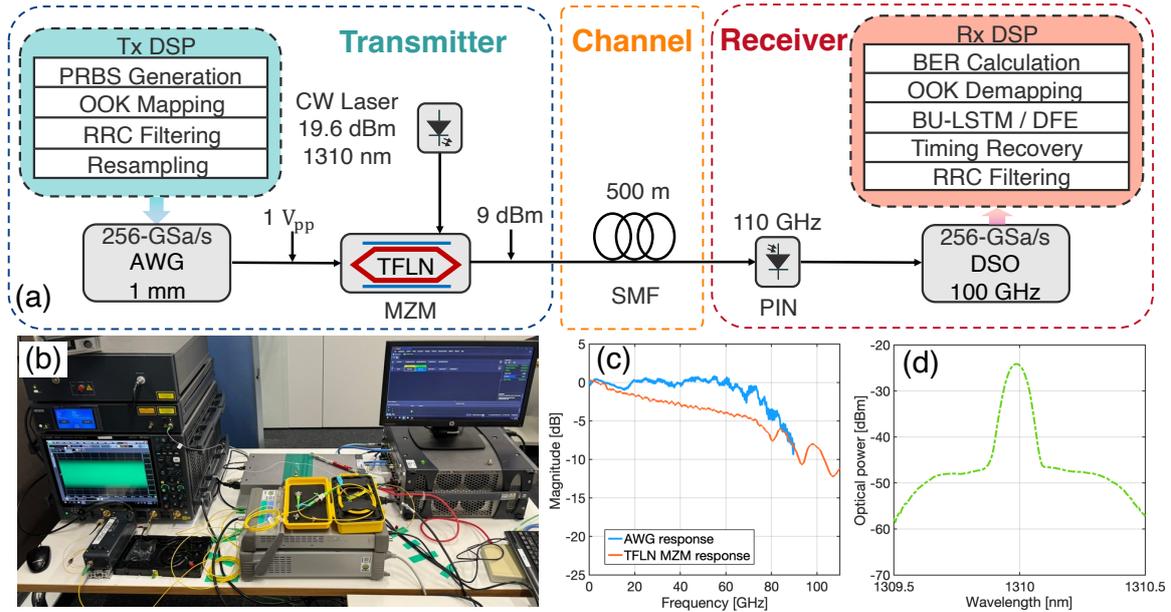
Fig. 1: (a) Experimental setup using TNLF-based MZM, (b) setup photo, (c) measured response of AWG and TFLN-based MZM, and (d) optical spectrum of 212.5 GBaud signal at 0.1 nm resolution.

then resampled to 256-GSa/s to match the arbitrary wave generator (AWG, Keysight M8199B). The AWG output swing is optimized $V_{pp} = 1$ V to achieve the best linearity for the PAM4 signal. The transmitter features a 1 mm single-ended connector compatible with high-speed AWG. The signal is fed into a TFLN MZM with $V_{pi} = 2$ V, driven by a high-power tunable laser emitting up to 19.6 dBm at 1310 nm in the O-band. When biased at the quadrature point, the MZM can achieve up to 9 dBm optical power. Fig. 1(c) shows the frequency responses of AWG and TFLN MZM, measured using a lightwave component analyzer (Keysight, N4372E). The signal is then transmitted over a 500 m single-mode fiber (SMF) without any optical amplification.

At the receiver side, the optical signal is directly detected using a 110-GHz PIN photodetector (PD) and digitized using a 110-GHz real-time digital storage oscilloscope (DSO, Keysight

UXR1104A) with 256-GSa/s sampling rate. The signal is then processed offline using DSP, including RRC filtering, timing recovery, BU-LSTM and FFE+DFE equalization, PAM4 demapping, and BER calculation. The optical spectrum at 0.1 nm resolution of modulated signal is shown in Fig. 1(d).

BU-LSTM Architecture

The architecture of an LSTM cell is shown in Fig. 2(a), which x_i represents the current input symbol, C_{i-1} and C_i are previous and updated memory states, h_{i-1} and h_i are previous and current hidden states, and σ is the "*sigmoid*" activation function of the LSTM cell, respectively. The BU-LSTM model is shown in Fig. 2(b), x_i symbols are processed by a bidirectional LSTM (bi-LSTM) layer with $n_{h1} = 40$ hidden units (20 forward and 20 backward) and a "*tanh*" activation function. The
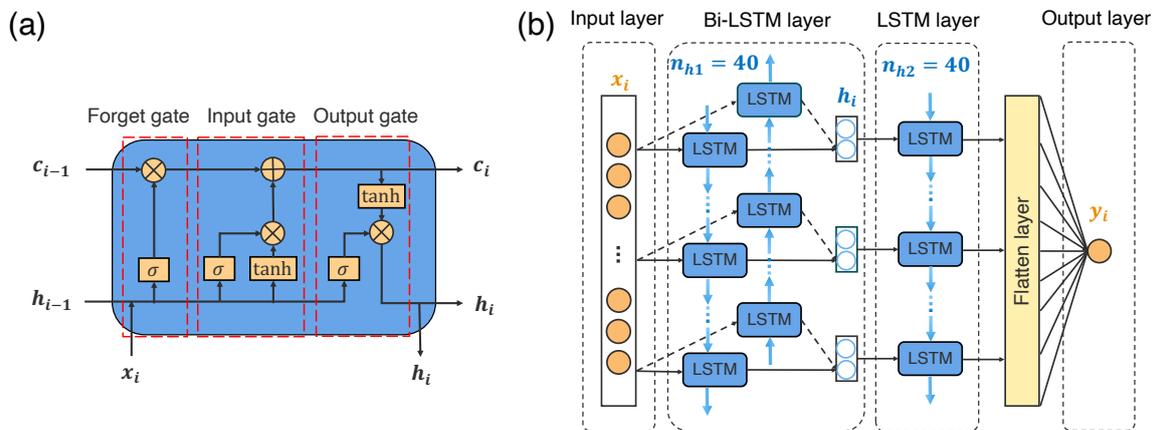

Fig. 2: Architecture of (a) LSTM cell, (b) BU-LSTM model.

hidden state h_i integrates the flow of symbol information across consecutive symbols and then passes to an LSTM layer with n_{h2} = 20 hidden units and a "*tanh*" activation function. Finally, the output is flattened to a one-dimensional array in a flatten layer and fully connected to the output layer with a "*linear*" activation function, producing a single output y_i.

The equalizer was trained on 2^{17} symbols and tested on 2^{15} symbols per each received optical power (RoP) value in a regression fashion. A Bayesian optimizer is used to select input normalization, activation functions, and batch size. The mean squared error is used as the loss function, and the Adam optimizer is applied with an adaptive learning rate ranging from 0.0001 to 0.04. The equalization is performed at one sample per symbol. The BU-LSTM is pre-trained at 8.5 dBm RoP in B2B and fine-tuned using transfer learning for other RoP levels.

Results and Discussion

Fig. 3(a) shows the BER as a function of input tap number for 212.5 GBaud PAM4 signal. Increasing taps improves BER but also raises the required training and inference time. To balance performance and computing time, 31 taps are selected for our model.

Fig.3(b) shows the BER results for different equalizers across various RoPs in B2B transmission. As a benchmark, the 31-tap BU-LSTM equalizer is compared with conventional 55-tap FFE + 55-tap DFE, 31-tap LSTM and 31-tap bi-LSTM. FFE + DFE achieves a BER of 8.1×10^{-3} 8.6 dBm RoP, failing to meet the 6.25% OH HD-FEC threshold. The LSTM and bi-LSTM show comparable suboptimal performance with BERs of 4.95×10^{-2} and 5.64×10^{-2}, respectively. This is because LSTM lacks access to future symbols, while bi-LSTM does not maintain causal structure during inference. In contrast, BU-LSTM significantly outperforms all baselines, achieving a BER of 4.18×10^{-3}, which is below the 6.25% OH HD-FEC threshold of 4.5×10^{-3}. By combining a bidirectional layer with a unidirectional layer, BU-LSTM enables more effective mitigation of inter-symbol interference and nonlinear distortion.

BER versus RoPs after 500 m SMF transmission is shown in Fig. 3(c). Like B2B, FFE+DFE achieves a BER of 6.8×10^{-3} at 8.5 dBm RoP, while LSTM and bi-LSTM show BERs of 4.83×10^{-2} and 4.44×10^{-2}, respectively. The BU-LSTM maintains the lowest BER of 3.44×10^{-3} at 8.5 dBm RoP. The improvement in 500 m case is because the inherent chirp in the modulator interacts with chromatic dispersion in the system.

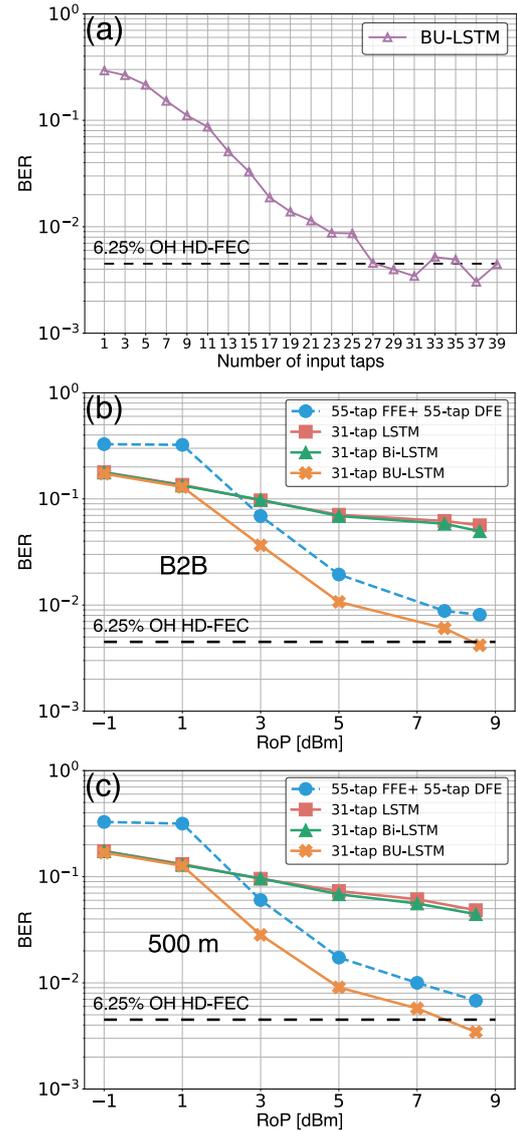This work aims to show the effectiveness of our proposed BU-LSTM equalizer for assisting in

Fig. 3: BER versus (a) input taps number of BU-LSTM. (b) RoPs in B2B, and (c) RoPs after 500 m SMF transmission.

enabling 400 Gbps per lane IM/DD transmission. Complexity analysis, including hardware-specific considerations [16], is planned for future work.

Conclusions

In this work, we demonstrate a TFLN-based optical-amplification-free 212.5 GBaud PAM4 link, achieving a net bitrate of 400 Gbps with BER below the 6.25% OH HD-FEC threshold. The proposed BU-LSTM equalizer outperforms both conventional FFE+DFE and shallow LSTM models (LSTM and bi-LSTM), achieving BERs of 4.18×10^{-3} in B2B and 3.44×10^{-3} over 500 m SMF, respectively. Our work highlights the effectiveness of deep LSTM architecture in enhancing TFLN-based PAM4 IM/DD for ultra-high-speed transmission, enabling it as a promising low lane count solution for 1.6 Tbps short-reach interconnects.

Acknowledgements

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