Experimental demonstration of an extreme learning machine based on Fabry Perot lasers for parallel neuromorphic processing

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Abstract: We present experimental results regarding dispersion equalization in IM-DD transmission systems with an extreme learning machine based on a Fabry Perot laser. The exploitation of two longitudinal modes yields enhanced computational power and processing speed.

1. Introduction

Reservoir computing (RC) and extreme learning machines (ELM) are two sub-classes of hardware friendly, neuromorphic computational paradigms [1], [2]. These neural networks consist of three layers, the input layer, the hidden layer and the readout layer. Information at the input layer is projected via fixed random weights to a higher dimensional output. This mechanism renders the problem solvable by a simple linear regression procedure which takes place at the readout layer. Since only the weighs at the readout layer need to be trained, these paradigms are highly effective in terms of training speed and memory footprint.

Time multiplexed RC (TMRC) and ELMs (TMELM) paved the way for efficient hardware implementations since only a single physical node is needed [3]. In TMRC/TMELM, the neurons at the hidden layer are substituted by time-multiplexed virtual nodes that span in a time period that is a multiple of the characteristic time of the incoming signal. Therefore, the price to pay for the single node is a processing speed penalty proportional to the number of virtual nodes that determine the temporal expansion of the input signal.

When real-time processing of fast signals is desired as in the case of channel equalization in optical communication systems, this bottleneck effect can pose a considerable barrier. In photonic integrated TMRC schemes, the number of virtual nodes is limited by the external cavity round trip time and the sampling speed at the output [4]. Recently, it has been shown that this trade-off can be tackled by means of a monolithic integrated Fabry Perot (FP) laser [5]. In particular, virtual nodes can be assigned to multiple longitudinal modes thus increasing the processing power of the overall system. Consequently, the performance of the signal recovering process is enhanced, without inducing any additional speed penalty. This property permits the usage of slower ADCs in TMELM/TMRC schemes, as well as a shorter external cavity length in the case of the TMRC.

In this work, we experimentally demonstrate for the first time a FP laser acting as a non-linear node to implement a TMELM for dispersion equalization in intensity modulation direct systems. Two longitudinal modes are used, leading to increased computational efficiency compared to the case of a single mode laser.

2. Experimental Setup

The experimental setup for the TMELM is illustrated in Fig. 1. The ELM aims to recover a 28 Gbaud PAM-4 signal after transmission through a 40 km fiber. The transmission process is performed numerically using the split-step Fourier method governed by Manakov equations [6]. The generated signal consists of 40000 symbols. It is down-sampled to acquire 2 samples per symbol and then it is resampled so as to form an input vector with j = 4 points per symbol. Each input is projected at a k=48 – dimensional plane (k>j) by multiplying it with a $W_{j\times k}$ matrix consisting of random fixed numbers drawn from a random uniform distribution [0, 1] (mask). The higher dimensional signal is converted from the digital to the analog domain by the arbitrary waveform generator Tektronix AWG7082C (AWG) with 4 GS/s. As a result, the time separation between virtual nodes is $\theta = 250$ ps. Although our system can operate at smaller θ values, in this experiment θ is limited by the available equipment.

Two tunable laser sources (CoBrite IDPhotonics CDx), are used as two MLs operating at different wavelengths targeting different longitudinal modes of the SL FP laser (Eblana Photonics). The first ML is modulated by an intensity modulator (Thorlabs LN81S-FC) with the PAM-4 signal of the AWG. The output from the second ML is injected to the SL without modulation (CW). The SL is biased at 9.7 mA, which is slightly below its lasing threshold (I_{thr} = 10 mA). At the output of the SL an EDFA amplifier was used alongside a tunable bandpass filter to enhance the optical signal to noise ratio (OSNR) and to isolate the output of each longitudinal mode. Finally, a 90/10 fiber coupler separates the output, feeding a 25 GHz photodiode (Thorlabs RXM25AF) and an optical spectrum analyzer (Finisar Waveanalyzer 100s). A 1 GHz / 5 GS oscilloscope (Tektronix 3-series MDO32) is used after the photodiode to record the response of the SL. The experimentally acquired symbols are used offline to train the readout layer (75% of the symbols) and to evaluate the accuracy of the system (25 %). The training is accomplished by the ridge regression procedure.

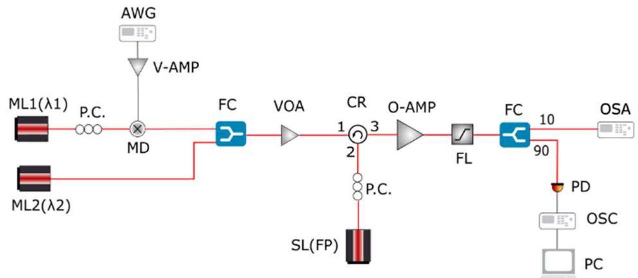

Fig. 1: The experimental setup. ML are two master single mode tunable lasers operating at different wavelengths, P.C. are the polarization controllers, FC the fiber couplers, MD the intensity modulator, AWG the arbitrary waveform generator, VOA the variable optical attenuator, CR the circulator, SL the slave Fabry Perot laser, V-AMP and O-AMP are voltage and optical amplifiers respectively, FL is a tunable filter, PD is the photodiode, OSC is the oscilloscope, OSA is the optical spectrum analyzer and PC is the personal computer used to implement the readout layer.

Due to the dispersion effects in the fiber, the information of each symbol is temporally spread to its neighboring symbols. As a result, the signal equalization task is memory dependent. Since TMELMs possess no memory, the output of each symbol is combined with the output of its 26 neighboring symbols at the offline ridge regression similarly to the operation of a typical feed forward equalizer. Thus, the system has a suitable memory capacity to tackle the signal recovering problem. Due to bandwidth limitations of the experimental setup (oscilloscope) the injected information was partially filtered out by the response of the SL. In order to amend this and without increasing the overall complexity, a typical reservoir computing approach was used, where the input is also fed to the readout layer [1].

In the TMELM, k defines essentially the number of neurons in the hidden layer, namely the virtual nodes. The speed penalty is defined as T/T_{symbol}, where T_{symbol} is the symbol rate of the incoming signal (35.7 ps in our case), whereas $T = k \times \theta$. The higher the value of k, the higher the processing power as more virtual nodes are used but also the higher the speed penalty. By using 2 longitudinal modes we aim to double the computational efficiency of the TMELM, while at the same time keeping the speed penalty unmodified. It is important to note that only the output of the first ML is modulated, whereas the second ML output is inserted as a continuous wave (CW) in the cavity of the SL (Fig. 1). The cross-gain mechanism inside the cavity of the SL leads to the non-linear transferring of information from the first mode to the second mode [7]. Therefore, by reading these two modes at the output of the SL separately with a tunable filter, it is possible to assume a TMELM with $2 \times k$ virtual nodes [5].

3. Experimental Results

The performance is evaluated in terms of the bit error rate (BER). The baseline is determined by using the direct input – 2 samples per symbol – in order to train the readout layer. The resulting BER is equal to 4.2×10^{-2}. First, as in the conventional TMELM, only a single longitudinal mode is used to tackle the PAM-4 equalization problem. The first ML is activated, whereas the second ML laser is deactivated. The temperature of the SL is stabilized and the ML injection locks each time a different longitudinal mode of the SL ($\lambda_x, x = 1,2,3$) so as to identify the optimum conditions, In Fig. 2(a), the optical spectrum of the optically injected SL is presented for three different modes; λ_1 = 192.7 THz, λ_2 = 193.65 THz and λ_3 = 194.435 THz. For each SL mode the frequency of the ML is tuned from -16 to 16 GHz around the corresponding SL mode, so as to identify the optimum BER performance. The results are shown in Fig. 2 (b) and they are similar to the results derived by single mode laser -based ELMs [4]. It can be seen that even for a single mode, TMELM improves the BER compared to the baseline. In terms of computational efficiency, the system is wavelength transparent which means that the performance does not depend to the selected longitudinal mode.

In order to improve the performance of the system, the fist ML is arbitrarily biased at λ_1 = 192.69 THz (-12 GHz detuning from the corresponding longitudinal mode). The second ML is also activated and it is set at the FP mode λ_2 = 194.435 THz. By using the tunable filter at the output, the outputs of the two modes are separately tracked as the second mode scans a spectral region from -16 to 16 GHz around the corresponding FP mode. The virtual nodes from the first mode are combined with the virtual nodes of the second mode in the readout layer to train the weights. A significant improvement is observed compared to the single mode case, with BER reaching 3×10^{-3}. This value is below the hard-decision forward error correction (HD-FEC) BER limit (3.8×10^{-3}) [8]. This improvement is attributed to the exploitation of 2 modes, which leads to $2 \times k = 96$ virtual nodes [5]. As a result, computational power is enhanced without imposing any further limitations on the processing speed.

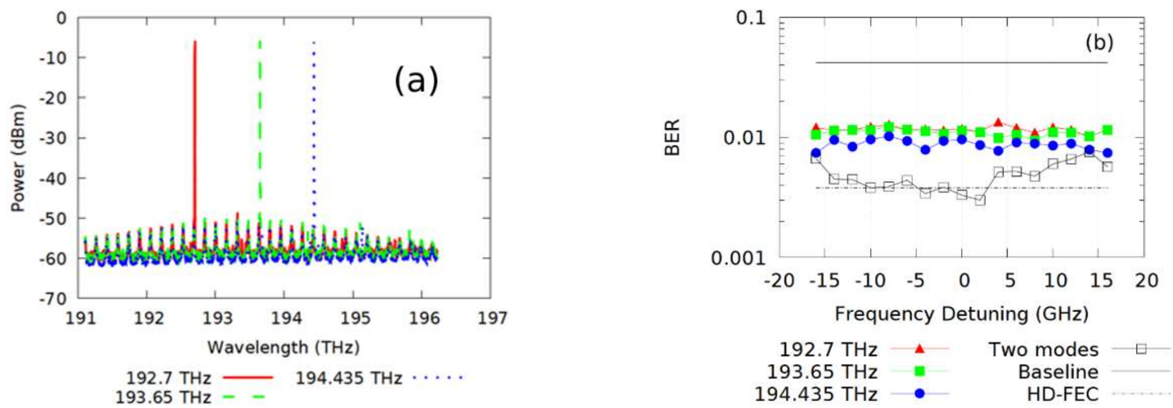

Figure 2: (a) The optical spectrum of the FP laser under three cases of single mode optical injection. (b) The BER for (a) single mode optical injection around 192.7 THz (full triangle), (b) 193.65 THz (full rectangle), (c) 194.435 THz (full circle), (d) two – mode optical injection with 192.688 fixed and 194.434 tunable (empty rectangle), (e) the baseline (dashed line) and (f) the HD-FEC.

4. Conclusions

We provide experimental results from a FP laser operating as a non-linear node in a TMELM scheme targeting the equalization of a PAM 4 signal after 40 km. Enhanced computational strength is achieved by using optical injection in two modes of the FP laser. In this case, the number of virtual nodes is doubled, without imposing any additional sped penalty. Based on these results, a FP laser with M-modes could be utilized that exploits more longitudinal modes of the SL to increase the number of virtual nodes by M times. Such an increase can naturally allow for lowering the speed penalty [5], thus paving the way for cognitive processing of high bandwidth signals in real-time.

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