Experimental Investigation of an Optical Reservoir Computer with MZI-based Optical Mask

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***Abstract*—In this paper, we have experimentally demonstrated a novel all-optical masking solution in photonic time stretch reservoir computing to eliminate the need of high-speed signal generator for digital masks. By leveraging the high chirp rate generated through an unbalanced Mach-Zehnder Interferometer (MZI) structure, we achieved a random optical mask in the spectral domain. Optical wavelengths, acting as virtual reservoir nodes, enable spectral mixing within the reservoir layer. Thanks to time-spectrum mapping in the photonic time stretch system, equivalent temporal masking is obtained. The develop system exhibits memory capacity through delayed optical feedback process. A full photonic reservoir computing system is implemented. Two experiments of waveform and digit-spoken signal classification have been carried out. Our experimental results show that MZI-based optical mask enables superior performance in photonic time stretch reservoir computing.**

Keywords—optical mask, photonics reservoir computing, Mach-Zehnder interferometer, spectral mixing, classification

I. INTRODUCTION

Recent years have witnessed a widespread adoption of neural networks and deep learning approaches in various information and computer technologies [1]. Among these, recurrent neural networks (RNNs) stand out for sequential signal analysis as they efficiently process empirical data by utilizing self-feedback to retain information from past input signals. However, conventional RNN models suffer from time and computational inefficiencies due to training issues like the vanishing and exploding gradient problems [2], resulting in excessively long training time.

To address these challenges, Reservoir Computing (RC) has emerged as a simplified RNN variant, wherein the weights in the reservoir layer are selected randomly, and only the output weights are trained. Therefore, the overall training and computational costs are significantly lower. RC can be generally categorized into two types: spatially distributed RC and delay-based RC [3]. RC streamlines the training process, overcoming the time and computational burden associated with traditional RNNs.

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In particular, delay-based RC systems present a simplified equivalent to the traditional RC by replacing the connected nodes in reservoir layer with a nonlinear node and a delay loop, resulting in a large number of virtual nodes. Compared to spatially distributed RC, the implementation of delay-based RC is much easier, allowing for the realization of a large-scale reservoir with numerous nodes by effectively controlling the delay time between virtual nodes. This simplicity in structure has led to the emergence of numerous optoelectronic or all-optical forms of delay-based RC. Additionally, delay-based RC has found extensive applications in prediction and classification tasks, owing to its suitability for sequential time data processing.

In the context of continuous time input data streams, which are typical for RC applications, a pre-processing masking procedure is employed before feeding the input data into the reservoir layer. A temporal mask is normally applied to the input data to introduce a complex transient response. Specifically, for each sampled data point, the input state remains the constant level and is multiplied by a temporal sequence (mask). This mask sequence is then repeated for each delayed data point within the reservoir, ensuring that every virtual node can have the same connectivity with the input signal. Effectively, the mask matrix serves as the weights between the signal to be classified and the reservoir nodes, influencing the information flow and enhancing the computational capabilities of the RC system [7].

The mask matrix plays a crucial role in breaking system symmetry and enriching the dynamic states of the reservoir layer. To achieve linear independence among virtual nodes, a simple mask matrix (e.g., a constant) may not suffice. Therefore, various types of masks have been developed in the literature, including digital masks, such as binary random signals and six-level digital masks, as well as analogue masks, like chaos and coloured-noise masks [4, 5, 6]. These masks have helped to improve the performance of reservoir computing systems.

However, hardware implementations of masking signals require expensive and high-bandwidth electronics, such as a high-speed Arbitrary Waveform Generator, hence limiting the often widespread applications of such masks. To address this challenge and to enhance performance of photonic reservoir computing systems, we proposed and demonstrated an all-optical approach based on time-stretching and spectral mixing

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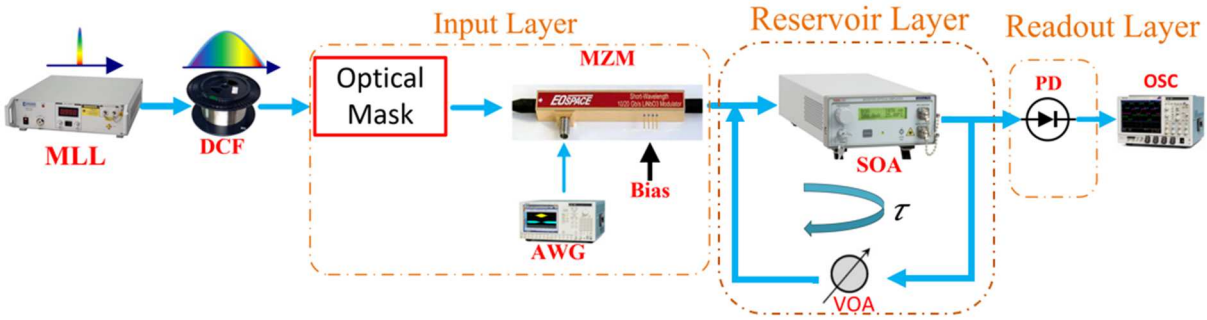

Fig. 1: The schematic of the proposed photonics reservoir computer with an optical mask. MLL: Mode-Locked Laser, DCF: Dispersion Compensating Fibre, MZM: Mach-Zehnder modulator, AWG: Arbitrary Waveform Generator, VOA: Variable Optical Attenuator, SOA: Semiconductor Optical Amplifier, PD: Photodetector, OSC: Oscilloscope.

[7]. In this method, we utilize optical means to add the mask into the system, with wavelength acting as the virtual nodes. We have verified the feasibility of this optical mask approach through numerical simulations and proposed different techniques for implementing the mask in the optical domain, such as combined diffraction gratings and a spatial mask, and an unbalanced Mach-Zehnder Interferometer (MZI) structure [8].

In this paper, we experimentally investigated the performance of a MZI-based optical mask in a photonic time stretch RC system. The MZI structure serves as the optical mask signal, added in the optical domain. We assess its impact on waveform and spoken-digit classification tasks. By overcoming existing electronic bottlenecks in digital masking, the proposed optical mask paves the way for real-time applications in photonics reservoir computing. The utilization of the MZI structure, a common optical method for adding the optical mask signal, holds promise for exploring further advancements in photonics reservoir computing applications.

II. Principle

Fig. 1 illustrates the proposed photonic reservoir computing based on time stretch and all-optical mask spectral mixing. An all-optical masking process is incorporated into the input layer using an MZI-based optical mask. Initially, an ultrashort pulse is emitted from a mode-locked laser (MLL) and then stretched using a dispersion compensating fibre (DCF) to serve as the optical carrier. Before the reservoir layer, instead of directly employing a modulation process for temporal mask implementation, an MZI-based structure is employed as an optical spectral filter to shape the spectrum of the optical carrier. Notably, a one-to-one mapping relation exists between the wavelength and time domains after time-stretching, enabling a possible approach to implement temporal masks in the optical spectral domain. This approach effectively embeds the optical mask in the temporal signal. During operation, a Gaussian pulse is multiplied with the mask on the optical link, and subsequently, the signal to be classified is modulated by a Mach-Zehnder modulator (MZM).

In the reservoir layer, our proposed RC structure incorporates a time-stretched Gaussian pulse, establishing a mapping relationship between the wavelength and time domains. Therefore, the wavelength can serve as the node within the reservoir layer. The coupling of nonlinear wavelength nodes is accomplished using a semiconductor optical amplifier (SOA), where nonlinear optical effects enable energy transfer among optical wavelengths (nodes). The spectral comb lines of input optical pulse are selected as, virtual nodes thereby facilitating spectral mixing and interaction between different neurons in the reservoir layer. This configuration enhances the dynamic capabilities of the photonic time-stretch-based RC system.

The loop updated status is accurately described by the following equation:

$$X_{n+1} = f_{NL}(WX_n + W_{in}u_n) \quad (1)$$

In the proposed RC structure, the vector of input data in the input layer is represented as u_n. To establish reservoir connections within the reservoir layer, a random square matrix W is employed. The input weights, denoted as W_{in}, are also utilized as a fixed, random matrix. The states in the reservoir are given by x_n, which undergo a nonlinear activation function denoted as f_{NL}.

The nonlinear mixing process is achieved via the SOA. These optical components play crucial roles in enabling dynamic interactions and enhancing the computational capabilities of the photonic reservoir computing system.

In conventional implementations of RC systems, a digital mask, such as binary random signals and six-level signals, is typically produced using an Arbitrary Waveform Generator (AWG) and modulated onto the optical carrier. However, in our approach, we incorporate the optical mask directly in the optical domain. Specifically, we utilize a Mach-Zehnder Interferometer (MZI) structure as the optical mask in this study. The MZI structure offers the advantage of generating a high chirp rate by controlling the time-delay in one of its arms. Consequently, the resulting mask becomes an analogue optical signal, which significantly enriches the dynamic states within the reservoir layer. This innovative technique enhances the computational capabilities and performance of our photonic reservoir computing system.

III. Experiment Setup and Results

Experiments have been carried out based on the setup as shown in Fig. 1. We have employed an all-optical reservoir computer based on photonic time-stretch and spectral mixing [9]. To generate the required analogue mask, an unbalanced Mach-Zehnder Interferometer structure is utilized. The optical source is a mode-locked laser (Calmar Mendocino FP laser), producing a series of ultrashort broadband pulses (800 fs) with a repetition rate of 50 MHz. These pulses are first time-stretched to approximately 12 ns using a dispersion compensating fiber with total dispersion of -1.04 ns/nm.

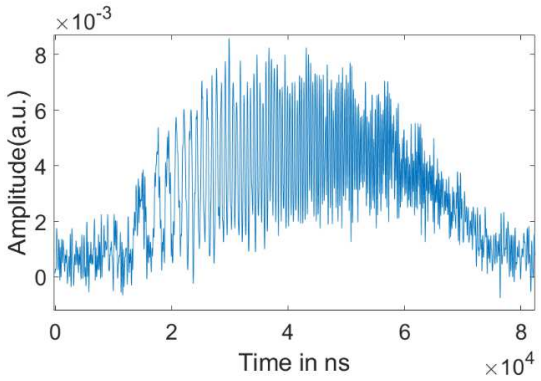

Fig. 2: The measured temporal stretched optical pulse after spectral chirp encoding. A randomly weighted mask can be obtained when uniform sampling is applied at the output layer.

Fig. 2 displays the time-stretched optical pulse after spectral chirp encoding using the MZI structure. The unbalanced MZI employs an optical delay line (General Photonics VDL001) in one arm and an extra 500 m single-mode fibre (SMF) in the other arm, leading to a linearly chirped spectral response due to unbalanced dispersion between two arms. After the dispersion compensating fibre, a frequency modulated microwave waveform with instantaneous frequency spanning from ~7 GHz to ~29 GHz within the stretched pulse window. The frequency range can be tuned by adjusting the delay line. To increase the chirp rate, the fiber length can be extended. The frequency modulated optical carrier is then modulated by the input sequential signal to be analysed before entering the Reservoir layer. Considering that at the output of system uniform sampling is always applied, a randomly weighted temporal mask can be obtained from the frequency modulated waveform, as shown in Fig. 2.

Once the optical masking process is completed, the signal to be classified undergoes modulation through an MZM, such that the input signal can be added to the reservoir.In the reservoir layer, a semiconductor optical amplifier (Thorlabs SOA1117P) serves as the nonlinear component, generating nonlinear power transfer among different wavelengths (virtual nodes). In this experiment, the driven current of the SOA is set to 250 mA.

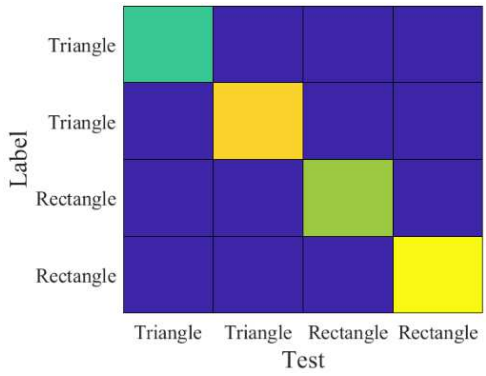

Fig. 3: Confusion matrix of waveform classification.

To assess the performance of the MZI-based optical mask, we conducted two classification tasks: waveform classification and spoken-digit classification. For both tasks, we employed a 'winner-takes-all' decision strategy. This means that the classification result selects the highest value from the recognition confusion matrix, indicating the most probable class.

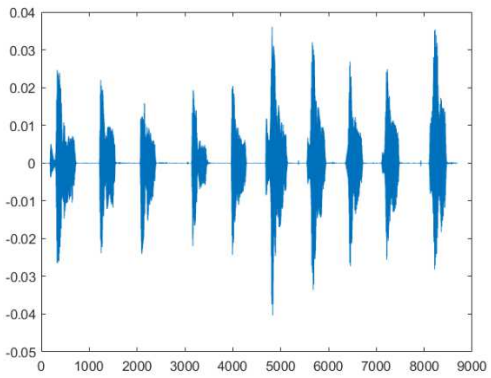

Fig. 4: Raw spoken-digit data representing 0 to 9.

Fig. 3 illustrates the waveform classification results. Here a triangle waveform and a rectangle waveform are considered. By inputting the waveforms to the developed RC system and applying the selected strategy, the two waveform signals to be classified were accurately recognized and classified correctly.

Fig. 3 displays the confusion matrix, where the colour bar represents the proportion of different possible values. The colour spectrum ranges from blue (0) to yellow (1). A higher value on the colour bar indicates a better recognition result.

Furthermore, we conducted an isolated spoken-digit recognition task and used the spoken-digit database, widely recognized for evaluating the capabilities of RC systems. The dataset comprises ten spoken digits (0-9) obtained from the NIST TI-46 corpus [10]. Each spoken digit is associated with ten different voices, and the temporal waveforms of these spoken digits are depicted in Fig. 4. During the experiment, the spoken-digit signals were fed into the reservoir, generating corresponding states in the output layer.

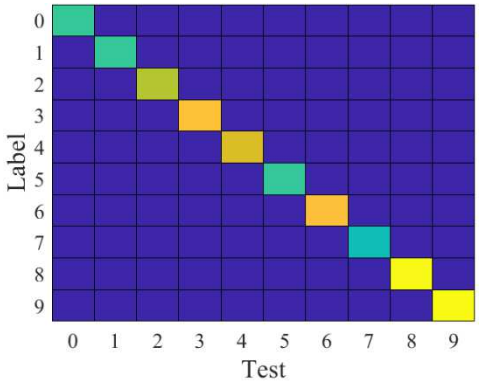

Fig. 5: Confusion matrix of spoken-digit classification task.

The classification results are depicted in Fig 5, showcasing accurate classification of spoken-digit from 0 to 9. We further evaluated the performance of our proposed RC scheme with the MZI-based optical mask by calculating the Words Correct Rate (WRR), resulting in an accuracy of approximately 95.97%. In comparison, the optical reservoir computer without the MZI-based mask achieved a WRR of approximately 80.65%. These results clearly demonstrate that

the RC system with the MZI-based mask outperforms the system without the mask.

The non-uniform mask generated by the MZI structure significantly enriches the dynamic states within the reservoir layer, leading to the observed improvement in performance. The MZI-based optical mask plays a pivotal role in enhancing the computational capabilities and accuracy of the photonic reservoir computing system.

IV. Conclusion

In this paper, we present an experimental demonstration of a photonics reservoir computing (RC) system incorporating an MZI-based optical mask. The optical mask is seamlessly integrated into the optical domain through the MZI structure. We evaluated the system's performance through waveform classification and spoken-digit classification tasks. Remarkably, the classification results reveal a high accuracy, demonstrating the effectiveness of this approach in task classification. Moreover, this novel technique effectively overcomes the electronic bottleneck, allowing for real-time classification using optical reservoir computing.

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