

Experimental Demonstration of Flexible, Multi-Wavelength All-Optical Equalization using a Receiver-Side Integrated Photonic Reservoir

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Abstract *As IM/DD links scale, equalization across multiple wavelength channels becomes increasingly demanding. Here, we demonstrate an integrated photonic reservoir for adaptable, multi-wavelength equalization using TDM-assisted training. Results on 14–28 Gbaud/λ, 20–70km and up to four wavelengths show up to four orders BER improvement over DSP. ©2025 The Author(s)*

Introduction

Intensity-modulation direct-detection (IM/DD) links dominate short reach optical systems, including data-centers and fiber-to-the-home. However, as rates and distances increase, these links require increasingly powerful equalization while remaining subject to stringent power and cost constraints. Consequently, conventional digital signal processing (DSP)-based solutions face growing challenges in scalability and energy efficiency [1], [2].

Photonic-domain equalization offers an analog, hardware-based alternative that operates inherently at line rate and exploits passive optical interference [3]. By performing processing prior to direct detection, it also mitigates frequency fading, eliminating the need for complex DSP. Furthermore, photonic systems naturally support wavelength-division multiplexing (WDM) enabling operation of a single processing unit across multiple channels without duplicating hardware.

Among photonic approaches, reservoir computing (RC) is particularly attractive due to its simple training paradigm, where only a readout layer is optimized while the underlying recurrent neural network remains fixed [4], [5]. This enables low-complexity hardware that exploits fading memory and high-dimensional state expansion for temporal signal processing tasks such as dispersion compensation. This trainable approach also facilitates flexible operation in various transmission scenarios, as opposed to rigid compensation from fixed photonic solutions.

Prior work has demonstrated promising results for photonic RC [6–8], including high-speed operation exceeding 100 Gbaud per wavelength [9] and co-processing of both quadratures in coherent systems [10]. Multi-wavelength operation has also been explored [9], [11]. However, maintaining good performance across channels typically required additional

supporting processing (e.g., feed-forward equalizers (FFE)) or per-channel adaptation, limiting scalability within a single architecture.

In this work, we experimentally demonstrate a post-processing free, integrated photonic reservoir for multi-wavelength equalization. The reservoir is trained to operate on two or four wavelength channels, resulting in a single set of readout weights for their equalization.

The programmability of the reservoir is showcased in multiple rate-reach scenarios (14/20/28 Gbaud, 20/40/70 km SSMF) and C-band DWDM channels (192.75–193.75 THz). Adaptation across all scenarios is achieved solely through re-training the readout weights of the same reservoir. We report up to four orders of magnitude bit-error rate (BER) improvement over a 16-tap T/2-spaced FFE benchmark.

The demonstrator used is a single-wavelength prototype comprising a reservoir and a co-packaged photodiode. To enable multi-wavelength training in the absence of an on-chip demultiplexer before detection, the experimental setup is adjusted for time-division multiplexing (TDM) of the WDM channels.

Photonic Reservoir Demonstrator

The reservoir used in this work is a 16-node space-multiplexed reservoir based on the four-port architecture [12] and is depicted in Fig. 1. Multimode interferometers (MMIs) serve as reservoir nodes and spiraled delay lines between nodes introduce controlled temporal memory, critical for compensating dispersive channels. The reservoir is entirely passive: it requires no electrical power for its nodes or interconnects.

Trainable readout weights are implemented optically using Mach–Zehnder interferometers (MZIs) with thermo-optic phase shifters, enabling complex-valued weighting. The required nonlinearity for RC operation arises at the

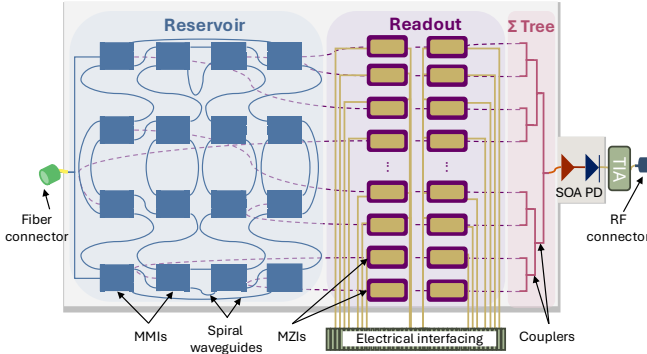


Fig. 1 schematic of reservoir - receiver demonstrator. The SiN chip includes the reservoir and readout. This is butt-coupled to the SOA-PD chip. The generated electrical signals are amplified by a TIA and routed to the RF connector. Electrical interfacing also includes DC control of readout weights. The demonstrator is a single-wavelength prototype; to enable multi-wavelength operation, the experimental setup is adjusted for time-division multiplexed wavelength-division multiplexing.

photodetector through square-law detection, avoiding the need for active nonlinear optical elements on chip.

The photonic reservoir chip is fabricated on Ligentec's silicon nitride (SiN) platform [13] and co-packaged with an InP chip from III-V Lab [14] that monolithically integrates semiconductor optical amplifier and uni-travelling carrier photodiode (SOA UTC-PD), as well as a 55 nm BiCMOS transimpedance amplifier chip. This co-packaged assembly was developed within the EU Horizon 2020 NEBULA project [15]. The full assembly is discussed in detail in a complementary work [16] and a simplified schematic is shown in Figure 1.

This demonstrator is a single-wavelength prototype. To enable multi-wavelength operation, the experimental setup is adjusted for multi-wavelength TDM as discussed in the following section. This approach allows training the reservoir on all relevant wavelengths simultaneously, which ensures it can behave as a multi-wavelength processing unit.

Experimental Setup

The experimental setup is shown in Fig 2. C-band wavelengths from a multi-channel laser source are combined using a polarization-maintaining 3-dB coupler and modulated by an intensity modulator. An AWG generates bursts of OOK

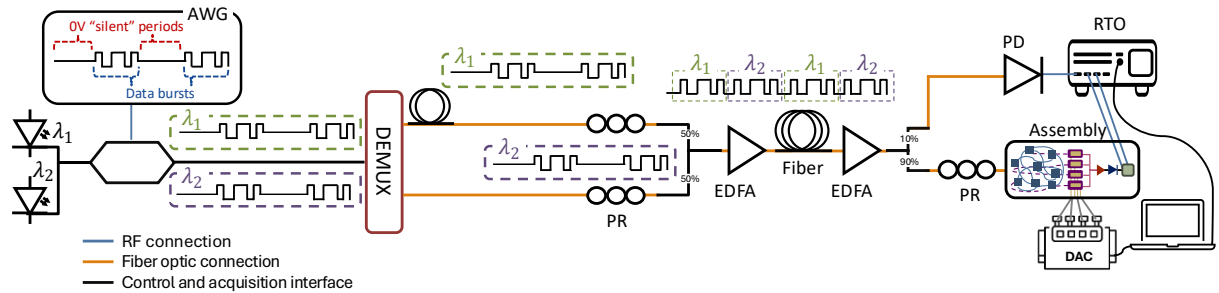


Fig. 2 Experimental setup for TDM-assisted multi-wavelength equalization. Wavelength channels are modulated, demultiplexed, temporally offset, and recombined to form a TDM-WDM signal enabling joint training across channels. The signal is transmitted over SSMF and processed by the photonic reservoir, with a reference PD and offline FFE used for benchmarking. CW: Continuous Wave, AWG: Arbitrary Waveform Generator, EDFA: Erbium-Doped Fiber Amplifier, PR: Polarization Rotator, PD: Photodiode, DAC: Digital-to-Analogue Converter, RTO: Real-Time Oscilloscope

signals to drive the modulator and in between bursts, a silent period is introduced.

The resulting modulated optical signal is then demultiplexed, and the individual wavelength channels are delayed relative to each other using calibrated fiber lengths to create a controlled temporal offset. The delayed channels are recombined after polarization alignment, which results in a time-division multiplexed and wavelength division multiplexed (TDM-WDM) signal where bursts corresponding to different wavelengths are interleaved in time. This way, each RTO acquisition window spans multiple such bursts and therefore contains data from all wavelengths, which is essential for the joint training of the reservoir. Without this, the optimization would not converge to a single set of weights that generalizes across channels.

Note that to avoid bias point drift and transients in the modulator during silent periods, 0V was applied rather than the logical 0 voltage (which would require sustained negative drive). The drawback of this is that the laser remains active during silent periods, thus reducing the available amplifier gain for data bursts. Also note that while Fig. 2 illustrates two wavelengths for simplicity, the setup is extended to four channels by incorporating additional laser lines and corresponding delay paths.

The resulting TDM-WDM signal is transmitted over SSMF, amplified, and injected into the reservoir-receiver assembly. A fraction of the signal is tapped off to a reference photodiode, where data are collected and processed offline using a 16-tap T/2-spaced FFE as a baseline for benchmarking.

Training was done for various transmission scenarios, defined by the rate, fiber length, and pairs/quadruplets of wavelength channels. Training the readout is performed using a hardware-in-the-loop approach based on a CMA-ES optimizer [17], [18]. In each iteration, candidate weights are applied to the photonic circuit, evaluated experimentally, and the resulting performance, defined as the average BER across wavelengths, is fed back to the optimizer to guide convergence.

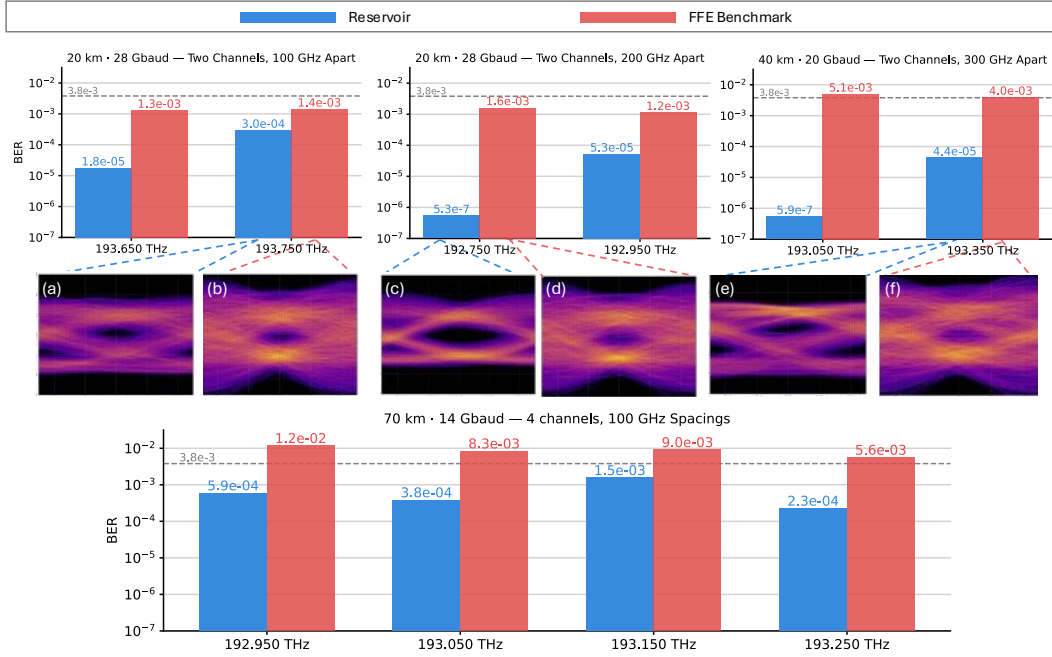


Fig. 3 BER test results for signals processed by the reservoir vs DSP for: 28 Gbaud over 20 km with two neighboring channels (100 GHz spacing) and two channels 200 GHz apart; 20 Gbaud over 40 km with two channels 300 GHz apart; 14 Gbaud over 70 km with four neighbouring channels (100 GHz spacing between each channel). Eye diagrams are shown for: 20km/28 Gbaud w/ 100 GHz spacing at 193.75 THz for (a) reservoir and (b) benchmark; 20km/28 Gbaud w/ 200 GHz at 192.75 THz for (c) reservoir and (d) benchmark; and 40km/20 Gbaud w/ 300 GHz spacing at 193.35 THz for (e) reservoir and (f) benchmark.

Results and Discussion

Test results reported in Fig. 3 are obtained by measuring over 1 million bits per wavelength. For testing, the readout weights were fixed to the values found during training for that particular transmission scenario. Wavelength channels were then activated sequentially to ensure correct labelling of the corresponding data segments, as the TDM signal contains interleaved contributions that cannot otherwise be reliably distinguished through correlation.

Fig. 3 shows transmission scenarios defined by baud rate, fiber length, and wavelength configurations. These results are selected to showcase the programmability of the reservoir across these three dimensions. At 28 Gbaud over 20 km, the case for two neighbouring channels (100 GHz apart) and for two non-neighbouring channels (200 GHz apart) are evaluated. At 20 Gbaud over 40 km, two channels 300 GHz apart are considered. Finally, four neighbouring channels at 14 Gbaud over 70 km are shown. BER is computed via direct error counting with a resolution of $1/N$, where N is the total number of transmitted bits.

Performance variations can be seen across wavelengths which stems from channel power imbalances due to the reservoir's wavelength-dependent response and reduced amplifier gain from lasers remaining active during silent periods. This left some channels in more noise-limited regimes during training, resulting in residual performance differences. This effect is implementation-related and can be mitigated

using a fully parallel WDM architecture with on-chip demultiplexing and per-channel detection. Nonetheless, all wavelength channels processed by the reservoir outperformed the FFE baseline by up to four orders of magnitude. Moreover, all the reservoir processed channels had BERs below the pre-FEC threshold of 3.8×10^{-3} .

Conclusion

We experimentally demonstrated a receiver-side integrated photonic reservoir for multi-wavelength equalization of IM/DD signals. A fixed 16-node silicon nitride reservoir was jointly trained across up to four C-band DWDM channels using a single shared set of readout weights, achieving up to four orders of magnitude BER improvement compared to a 16-tap FFE baseline. This was achieved on a prototype with a co-packaged photodiode, thus multi-wavelength training was implemented through a TDM-assisted approach.

The results covered a range of rate-reach scenarios (14/20/28 Gbaud, 20/40/70 km) and C-band DWDM channels spanning 1 THz. The results highlight three key strengths of this approach: (1) WDM scalability, enabling a single hardware to process multiple channels; (2) programmability through retraining across wavelengths, baud rates, and distances; and (3) pre-detection equalization, mitigating frequency fading and reducing FEC overhead. Future implementations with on-chip demultiplexing will enable fully parallel photonic-based WDM processing.

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