# A Tunable Optical Tapped-Delay-Line that Simultaneously and Independently Processes Multiple Input WDM Data Signals

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**Abstract:** We demonstrate an optical tapped-delay-line that is reconfigurable with complex tap-coefficients and independently and simultaneously performs data pattern recognition, equalization, and QAM format conversion on eight B/QPSK WDM signals at both 20 and 26 Gbaud, demonstrating >400 Gbit/s processing speed.

**OCIS codes:** (070.4340) Nonlinear optical signal processing; (190.4223) Nonlinear wave mixing

## 1. Introduction

Tapped-delay-lines (TDL) are considered a basic building block in many data signal processing functions, including equalization, correlation and discrete Fourier transforms (DFT) [1]. TDLs have multiple "taps" with weights that can reconfigure the specific function being performed. Optical TDLs (OTDLs) hold the promise of higher capacities and functionality than electronic versions [2,3].

Tunable OTDLs have been shown to operate on both the amplitude and phase of the taps and, thus, the incoming data signal of a single optical channel [4]. This capability can enable signal processing operation on multiple amplitude and phase levels, such that the amount of data that can be processed per bit time is dramatically increased.

Although the tunable OTDL can operate on a single incoming optical data channel, there has not been in a report of a single OTDL that can process multiple data channels simultaneously and independently. In [2], an OTDL simultaneously equalized 16 WDM channels with a few taps, but with a similar function on all WDM channels.

In this paper, we demonstrate a single WDM-OTDL that independently and simultaneously processes multiple input WDM data signals. In our scheme, the number of input channels and the tap-coefficients are easily scalable and the number of stages determines the number of taps. Most of the time where a few taps are adequate [2], this scheme can dramatically reduce the number of elements and cost for processing of large number of WDM channels.

We utilized nonlinear wave mixings in highly nonlinear fiber (HNLF) and periodically poled lithium niobate (PPLN) waveguides together with conversion-dispersion delays [5] to realize a WDM-OTDL for independent WDM signals. We performed concurrent equalization, 2-symbol correlation on a BPSK/QPSK signal, QPSK to 16-QAM conversion, and BPSK to QPSK and 4-PAM conversion independently on each of eight WDM channels at rates of 20- and 26-Gbaud, demonstrating parallel processing at >400 Gbit/s and <1dB OSNR penalty at $10^{-4}$ BER.

## 2. Concept

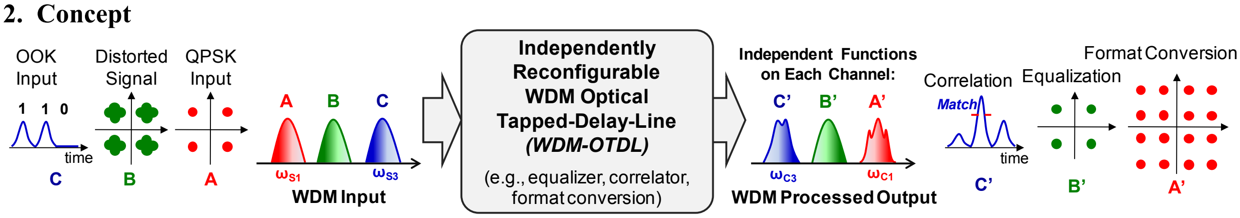


**Fig. 1.** Concept of an optical tapped-delay-line for WDM signals with independent function (e.g., equalization and correlation) on each channel.

A WDM-OTDL can perform independent functions on incoming WDM channels (Fig. 1). Fig 2 shows the principle of operation of a WDM-OTDL. Multiple WDM channels (with electrical field amplitudes $S_i(t)$ at frequencies $\omega_{Si}$) with various phase/amplitude modulation formats are sent into a nonlinear device together with a high-power continuous wave (CW) pump (with field amplitude $E_P(t)$ and frequency $\omega_P$) to produce one phase-conjugate copy of each signal, as the result of nonlinear wave mixing interactions. Such mixing can be achieved using four wave mixing (FWM) in HNLFs or cascaded second harmonic generation followed by difference frequency generation (cSFG/DFG) in PPLN waveguides. Each phase-conjugate copy is generated on a new frequency that is distinct from the original signal (i.e., $\omega_{Ci} = 2\omega_P - \omega_{Si}$) and has an amplitude proportional to $E_P^2 S_i^*(t)$. The original WDM signals

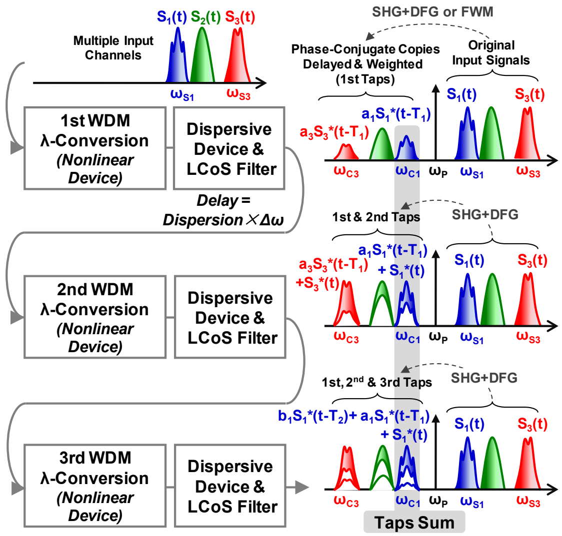


**Fig. 2.** Principle of operation of the WDM-OTDL, performing an independent and different function on each WDM channel.

and the WDM copies are sent to a dispersive element (e.g., dispersion compensating fiber, DCF), introducing a relative delay of $T_i = D \times (\lambda_{Si} - \lambda_{Ci})$ on each signal and its copy (i.e., conversion-dispersion optical delay [5]. All the signals, delayed copies, and the CW pump are then sent to an in-line phase and amplitude programmable filter to change the amplitude and relative phase of the signal copies. This is equivalent to applying a complex-coefficient of $|h_i|e^{j\measuredangle h_i}$ on the delayed and phase-conjugate signal copies $S_i^*(t - T_i)$. Because all the signals and the pump are kept on the same fiber path, phase coherency between the channels is preserved. These signals travel through a second nonlinear device (e.g., PPLN waveguide) in which the original signals again copy themselves to the $\omega_{Ci}$ frequencies (proportional to $E_P^2 S_i^*(t)$). This new copy is generated on the same frequency of the old copy and is phase-coherent with the old copy $E_P^2 h_i S_i^*(t - T_i)$, but has a different delay and amplitude. This entire path thus becomes a 2-tap TDL for each WDM data signal with independent control over the tap-coefficients. This design (i) can adapt to large number of WDM channels with no need for extra elements, (ii) is scalable to higher order taps by adding more nonlinear stages, (iii) is tunable in delays (baud rates) by tuning the CW pump and/or signal wavelengths, and (iv) requires dramatically less number of elements compared to separate single channel OTDLs. For example, 80 separate single-channel 5-tap OTDL for 80 WDM channels requires 160 nonlinear elements, where the WDM-OTDL scheme only requires 5.

## 3. Experimental Setup

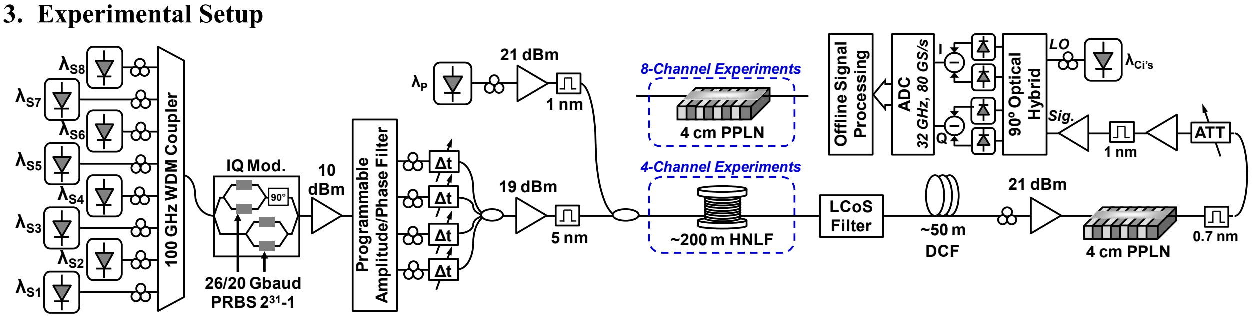


**Fig. 3.** Experimental setup. IQ: In-phase and Quadrature, HNLF: Highly Nonlinear Fiber, PPLN: Periodically Poled Lithium Niobate, LCoS: Liquid Crystal on Silicon, DCF: Dispersion Compensating Fiber, ATT: Attenuator, LO: Local Oscillator, ADC: Analog to Digital Convertor

The experimental setup for the WDM-OTDL is depicted in Fig. 3. A nested Mach-Zehnder modulator is used to generate the 20- and 26-Gbaud BPSK and QPSK data (PRBS $2^{31}$-1) on eight lasers separated by ~100 GHz. The WDM signals are decorrelated by demultiplexing them in a programmable amplitude/phase filter (using liquid crystal on silicon, LCoS) followed by different delay lines and a passive coupler. This LCoS filter can also emulate 200 nm/ps chromatic dispersion to deteriorate a channel (to be compensated using a WDM-OTDL equalizer). The resulting signals are amplified together in an EDFA, coupled with an amplified ~1551/1551.6 nm CW pump and sent to a ~200m HNLF with a zero dispersion wavelength centered at ~1560 nm to produce the copies (a PPLN waveguide is used instead of an HNLF for 8-channel experiments). All signals then travel through a ~50 m DCF and an LCoS filter to apply tap phases and amplitudes. The LCoS filter also (i) adjusts the relative delays on the input such that one (two) symbol time relative delay is achieved on the closer (farther) four WDM channels, and (ii) balances the relative power of signals and the CW pump. The signals, their copies and CW pump laser are then sent to a 4-cm-long PPLN waveguide to create the second copies. The quasi-phase-matching (QPM) wavelength of the PPLN waveguide is temperature tuned to the CW pump wavelength. For 20-Gbaud experiments, the wavelength of the CW pump and the QPM of the PPLN waveguide are increased to ~1551.6 nm to increase the symbol time from ~38 ps to 50 ps. The signals are detected coherently using a 90-degree optical hybrid and ADC to measure error-vector-magnitude (EVM) and bit-error-ratio (BER).

## 4. Results and Discussion

Fig. 4(a) depicts the output spectra of the two nonlinear stages for 26-Gbaud QPSK WDM channels. Output signals possess different shapes due to different functions implemented by the WDM-OTDL on each channel. Tap weights are applied to the WDM-OTDL to configure the desired processing of the signals. In the PPLN spectrum the first signal is fully blocked in the LCoS filter in order to make the conversion from the first copy back to the signal observable. Examples of independent and tunable WDM-OTDL functions are shown on the four WDM channels in Fig. 4(b). QPSK and BPSK signals are used to perform correlation and conversion to QAM/PAM formats. Fig. 4(c) depicts the BER measurement versus optical signal-to-noise ratio (OSNR) after the coherent detection. The generated QPSK signal has a <1dB OSNR penalty at $10^{-4}$ BER compared with a 26-Gbaud back-to-back QPSK data.

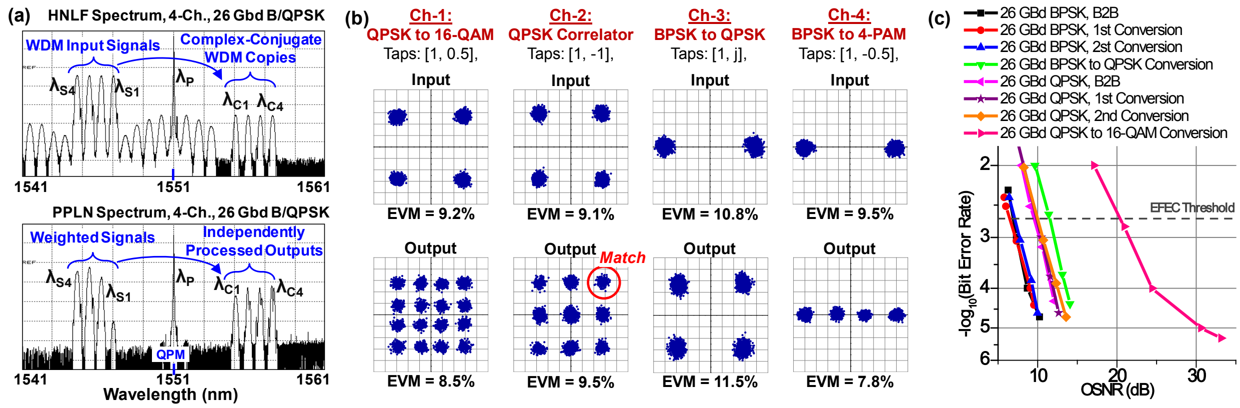


**Fig. 4.** (a) Spectra after the nonlinear stages. (b) Independent output constellations for four 26-Gbaud WDM channels. (c) BER measurements.

Because many signals are amplified in one EDFA, Fig. 5(a) characterizes the effects of channel phases and the power trade-offs on the output signal quality of a 26-Gbaud BPSK to QPSK conversion on Ch1. The system is twice as sensitive to CW phase compared to the input signal phase. Increasing the WDM power deteriorates the output more than decreasing it, we believe due to self phase modulation. Fig. 5(b) shows sample results on 20-Gbaud channels to demonstrate baud-rate tunability of the system. Fig. 6 depicts the results of a 32-bit parallel correlation using eight 26-Gbaud QPSK signals, resulting in 416-Gbit/s throughput. In Fig. 6(c), a 2-tap equalizer is applied to channel-8 to partially equalize a 200 ps/nm dispersed signal.

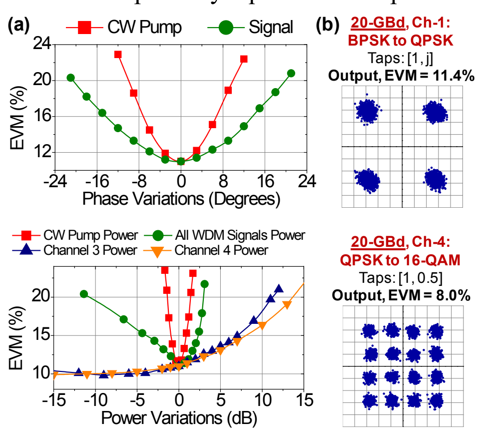


**Fig. 5.** (a) Sensitivity of the 1st channel (BPSK to QPSK) to variations in power and phase. (b) Sample outputs for 20-Gbaud signals on channels 1 and 4.

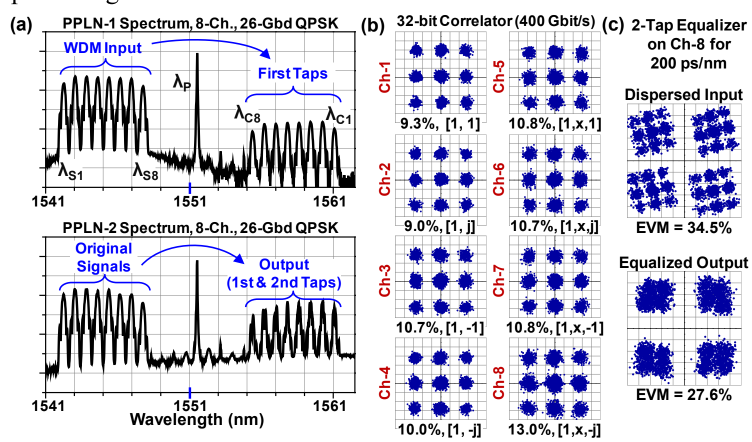


**Fig. 6.** (a) Spectra of the 8-channel WDM-OTDL. (b) WDM output constellations, where 2-symbol correlation is performed. x: don't care. (c) 2-tap equalization results.

## Acknowledgements

This work is partially supported by the NSF Center for Integrated Access Networks (CIAN) under contract 0812072, DARPA, and Cisco Systems.

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