Reconfigurable 2-D WDM Optical Tapped-Delay-Line to Correlate 20Gbaud QPSK Data

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Abstract *We demonstrate a 2-D optical tapped-delay-line that exploits nonlinearities and chromatic dispersion to perform 2-D correlation on 20Gbaud QPSK data with correlator results with an average EVM of ~7.8%. We successfully recognize different 2×2 target patterns in an image with 961 pixels.*

Introduction

Correlators are useful building blocks for various applications, including data decoding and pattern/header recognition[1-2].There might be benefit to performing correlation in the optical domain so that the function can be performed at the line rate at which the data is arriving. Valuable features of an optical correlator could be tunability, reconfigurable target patterns, and high bit rate[3-4].

Given the recent advances in coherent and phase-modulated systems, correlation in the amplitude and phase domains might yield higher correlation rates and efficiencies. Tunable optical correlators on a 1-dimensional data stream have been demonstrated for both amplitude modulation as well as higher-order phase modulation formats[3-6]. For phase modulated signals, tapped-delay-line coefficients are set to the conjugate of the target pattern[3,5-7]. Furthermore, a recent report showed the ability to perform correlation on different wavelengths independently[5].

However, there are applications in which there exists a 2-D data space that would require correlation, such that data has encoding or a pattern across 2 ***independent*** dimensions. Examples include: (a) coding across different domains, such as time and wavelength, and 2D image processing[1]. A laudable goal would be to show that a high-speed, tunable and reconfigurable optical correlator can function to pick out a pattern within a 2D space.

In this paper, we demonstrate a reconfigurable 2-D WDM optical tapped-delay-line (OTDL) to correlate quadrature-phase-shift-keying (QPSK) 20Gbaud data. By implementing a WDM TDL on two different signals which performs correlation over rows (inner sum), along with a coherent multiplexing of WDM channels which performs correlation over columns (outer sum), a 2-D correlator is achieved with average error vector magnitude (EVM) ~ 7.8%. Here we also search different 2×2 patterns in a 31×31 image and successfully recognize the target patterns in the image.

Concept

The conceptual block diagram of the 2-D OTDL is shown in Fig. 1. First, each image row is mapped to a WDM channel by modulating optical frequency comb fingers (phase locked sources) with QPSK symbols that correspond to the color of the image pixels. Second, a WDM-TDL is performed generating the inner sums on each of the WDM channels with the given coefficients (b_i) independently. Subsequently, these processed WDM channels - which are phase coherent - are multiplexed together with column coefficients (a_i) to generate the outer sums.

Fig. 2 shows the operational principle of these stages. To realize the inner product of the 2-D correlator, the WDM channels (which represent the image rows) are sent into a nonlinear device together with a high-power continuous wave (CW) pump, producing one phase-conjugated

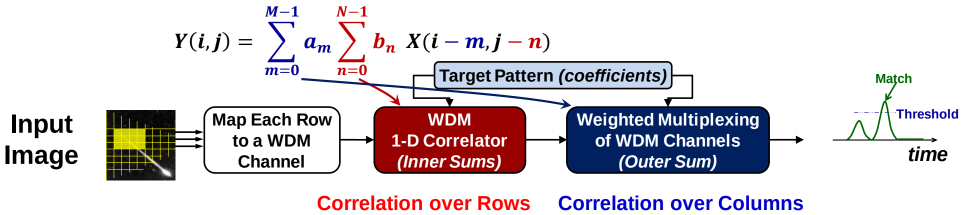

Fig. 1: Concept of how 2-D optical tapped-delay-lines perform 2-D correlation using cascaded two 1-D Correlators

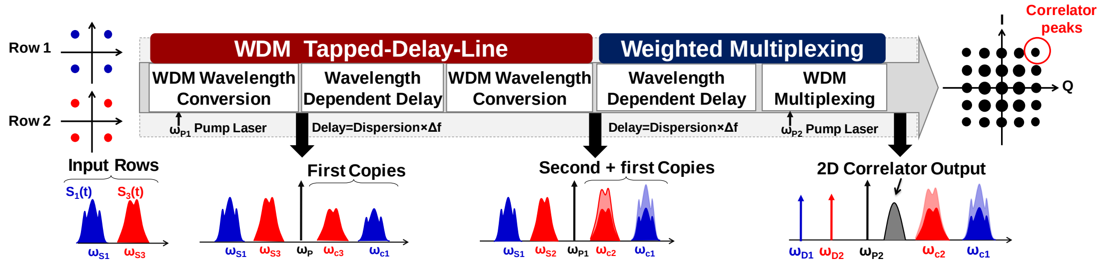

Fig. 2: Operational principle of a 2-D correlator using three nonlinear devices

copy of each signal through one of two particular nonlinear wave mixing interactions. These nonlinear processes consist either of four wave mixing (FWM) in highly nonlinear fibers (HNLFs) or cascaded second harmonic generation followed by difference frequency generation (cSHG/DFG) in periodically poled lithium niobate waveguides (PPLN). Each phase-conjugate copy lands on a new frequency that is different from the original signal (i.e., $\omega_{Ci} = 2\omega_P - \omega_{Si}$). TheBecause the WDM signals and the WDM copies are sent to a dispersive element (e.g., dispersion compensating fiber, DCF) a relative delay of $T_i = D \times (\lambda_{\mathrm{Si}} - \lambda_{\mathrm{Ci}})$ will be introduced between the signal and its copy (*i.e.*, conversion-dispersion optical delay). All the resulting 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 a complex-coefficient of $|b_i|e^{j\measuredangle b_i}$ on the signal copies. All the signals and the pump are kept on the same fiber path, preserving phase coherence between the channels. When these signals travel through the second nonlinear stage (e.g., PPLN waveguide) the original signals again copy themselves to the ω_{Ci} frequencies. This new copy, which lands on the old copy, is phase coherent with the old copy and has a different delay and different weight. This creates a 2-tap TDL for each WDM data signal with independent control over the tap-coefficients.

To realize the outer sum, all correlated rows need to be multiplexed together coherently. Thus these 1-D correlated rows, along with another set of coherent comb fingers with equal frequency spacing and a CW pump laser ω_{P2}, are injected into the third nonlinear device (a PPLN) to perform the coherent addition, which corresponds to the outer sum.

Experimental Setup

The experimental setup for the OTDL is depicted in Fig. 3. A mode-locked laser with a 10GHz repetition rate along with a DLI with FSR 20GHz is used to generate a coherent comb fingers with 20GHz frequency spacing. The 20GHz comb is then passed through an HNLF fiber to generate a flat and broad spectrum. A Liquid Crystal on Silicon (LCoS-1) filter is utilized to select and write complex weights on comb fingers and separate them into signal path and pump path. A nested Mach-Zehnder modulator is used to generate the 20Gbaud QPSK data (PRBS 2^{31}-1) on two comb fingers on the signal path separated by ~1.6nm. To make the two modulated signals as two consecutive rows in a 31×31 image, they need to be sent to DCF-1 with 12km length to induce ~969 ps/nm dispersion (31-symbols of delay). The resulting signals are amplified together in an EDFA, coupled with an amplified ~1550 CW pump and sent to a 450m An HNLF with zero dispersion wavelength of around 1555nm to produce the copies. All signals then travel through a ~70m DCF and LCoS-2 to apply tap phases and amplitudes. The second LCOS filter also (i) adjusts the relative delays on the input such that one symbol is achieved on both WDM channels, and (ii) balances the relative power of signals and the CW pump. The DCF-2 introduces one symbol time of relative delay between the taps. The signals, their copies, and

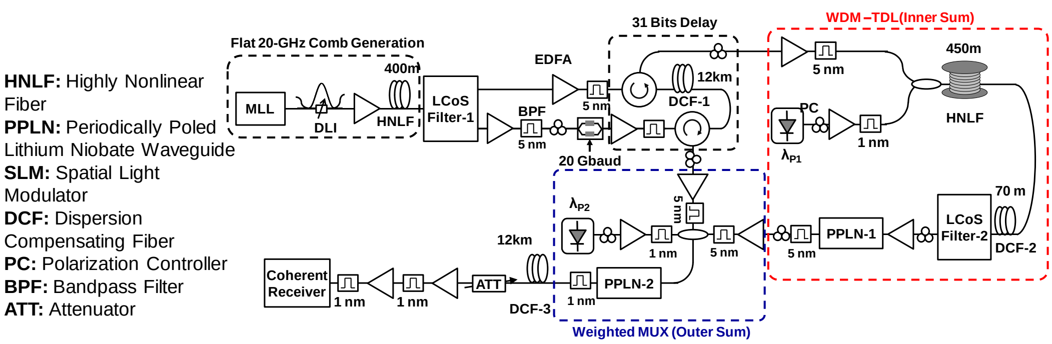

Fig. 3: Experimental setup of a 2-D Correlator

CW pump laser are then sent to a 4cm-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. These signals, along with the comb fingers selected for pump path and another CW laser at ~1548.5nm pump, are sent to the second PPLN (5cm length) after enough amplification to perform coherent multiplexing of the original signals at ~1552.5nm. The pump fingers also pass back through the DCF-1 to stabilize the generated signal. The multiplexed signal is then filtered and sent to the coherent receiver, after passing through another DCF of the same length to compensate for the induced dispersion.

Results and discussion

Fig. 4(a) depicts the output spectra of all three nonlinear stages for a 20Gbaud QPSK 2-D WDM correlator. At the first stage, a CW laser creates a conjugate copy for each WDM signal. At the second stage, on both rows, a 2-tap correlation is performed independently. As dshown, the two 9-QAM -quadrature-amplitude-modulation- signals (9 possible correlation results) are thus generated. At the last stage, these two signals are multiplexed coherently with the column coefficients to realize a 2-D correlator. In Fig. 4(b), different 2-D patterns are searched for within random data and a 25-QAM

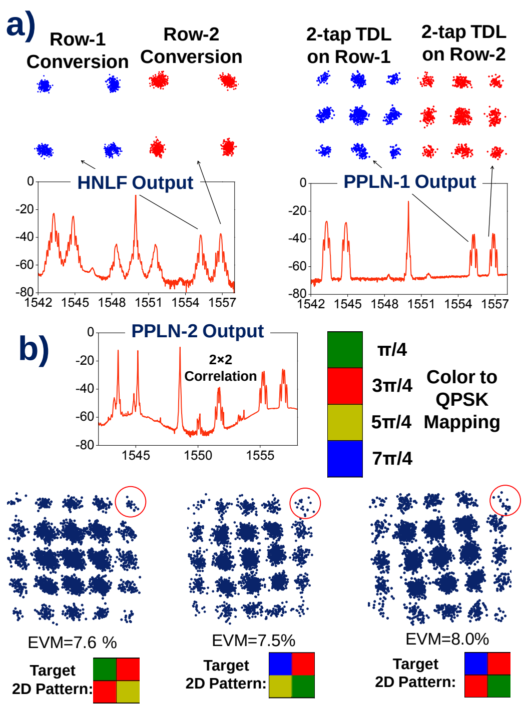

Fig. 4: a) The Spectra of all three nonlinear stages along with the constellation of generated signals b) the 25-QAM correlation results for three 2×2 target patterns with their corresponding EVMs.

constellation (25 possible correlation results) is generated for each target pattern. The upper right corner point of the IQ plane corresponds to the correlator peaks[4]. The EVM of each correlation result is also shown. As shown in the figure, an average EVM of ~7.8% is achieved.

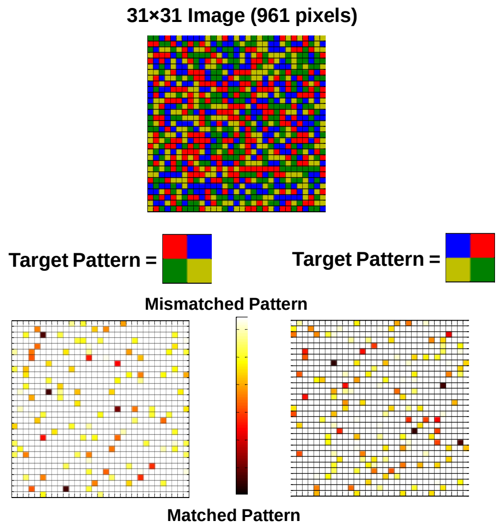

Fig. 5: Searching two different 2×2 target patterns in an image with 961 pixels. The correlation peaks are obtained with respect to the upper right corner of 25-QAM constellation. The dark squares correspond to the target patterns.

In Fig. 5, a 31×31 image (961 pixels) is searched for two different patterns. The matched patterns are located in upper-right corner of IQ plane, so the inverse of the distance between correlation results and the upper-right point in the IQ plane determines the amount of similarity between each 2×2 section of the image and the 2×2 target pattern. These results are depicted for two target patterns. As also shown, the experimental results for both patterns exhibit 4 peaks (dark points) in each table at the 2×2 sections that are matched to the target patterns.

Acknowledgements

This work is partially supported by Cisco Systems, DARPA and the NSF (0812072).

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