Tunable Optical Correlator using an Optical Frequency Comb for Generating Multiple Taps in a Tapped-Delay-Line Composed of a Single Nonlinear Element

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Abstract *We experimentally demonstrate a tunable optical correlator to search for multiple patterns among QPSK symbols in 20 Gbuad stream. We use an optical frequency comb to generate coherent signals and add them coherently using a single PPLN waveguide. Multiple patterns with different lengths are successfully searched on QPSK signals.*

Introduction

A key building block in digital signal processing is the tapped-delay-line (TDL), which can perform many important functions, including correlation, equalization, and discrete Fourier transforms.[1] Optical signal processing holds the promise of potentially performing these valuable functions at line rate on high-data-rate signals.[2] Additionally, there exists today a renewed interest in optical signal processing due to recent technical advances, such as amplitude and phase domain operations, coherent receivers, and electronic signal post-processing.[3] Specifically, optically enabled correlation can be used for header and pattern recognition, encoding/decoding, and image processing.[1,4] Finally, tunability is important for variable bit-rate systems, dynamic pattern recognition, and format transparency.[5]

Tunable TDLs typically have multiple taps to perform their specific function, with each tap having a tunable complex weight and tunable time delay.[1] For correlation, the number of taps corresponds to the number of symbols that must be matched.[5] Optical TDLs can be achieved by cascaded Mach-Zehnder interferometers (MZIs), in which each MZI represents a single tap.[4,6] However, these approaches tend to be difficult to tune in terms of the time delay.

Another approach uses a combination of two wavelength-converting nonlinear elements and one wavelength-dependent delay element to achieve a tunable TDL.[5] The operation is as follows: an incoming signal is multicasted to multiple wavelengths using a nonlinear element based on a group of pump lasers. Subsequently, these replicas experience a wavelength-dependent delay in a following stage. Finally, the differentially delayed replicas are multiplexed in a final nonlinear element. Tunability of the number of taps, complex weights and tap delays is achieved by tuning the pump lasers.

Unfortunately, this approach does not scale well with the number of taps because a large number of discrete pump lasers would be required. Moreover, it would be beneficial to reduce the number of nonlinear stages from two down to a single stage.

In this paper, we demonstrate the tunable optical correlator using an optical frequency comb for generating multiple taps in a tapped-delay-line using only a single nonlinear element. This method uses the frequency fingers of the optical frequency comb source as the correlator taps; because they are coherent, the signal does not need to be multicast in another stage of nonlinearity. We modulate our data on coherent frequency fingers and, by using one wavelength-dependent delay element and one stage of nonlinearity, the delayed signals can be multiplexed coherently. Multiple patterns of 6-taps TDL are searched successfully on 40 Gb/s quadrature phase shift keying (QPSK) signals, and correlation peaks are obtained at the matched patterns. To show the tunability of this approach to the number of taps and different patterns, we also demonstrate 2-taps, 3-taps and 4-taps of correlation with error vector magnitude (EVM) of 9.7%, 8.4% and 7.3%, respectively.

Concept

The conceptual block diagram of this optical correlator is shown in Fig. 1. As shown in Fig. 1(a), we first map the input data stream on optical QPSK signals. Then, by multiplying this optical signal with the conjugate of the target

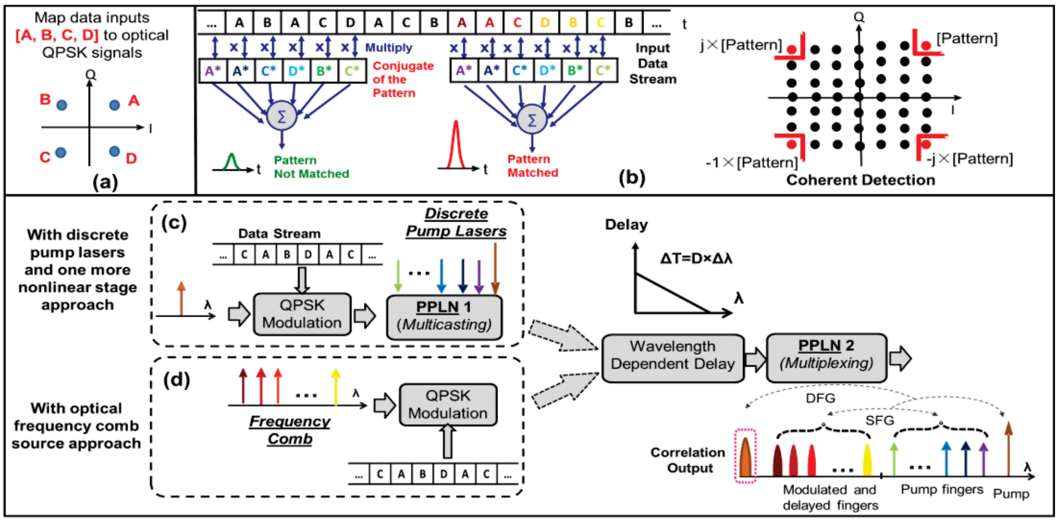


Fig. 1: Conceptual block diagram of tunable optical correlator, **(a)** mapping data stream into optical QPSK signals, **(b)** concept of correlation for matched and unmatched patterns, **(c)** optical correlator using two stages of nonlinearities and discrete pump lasers, **(d)** optical correlator using one nonlinear stage and frequency comb source

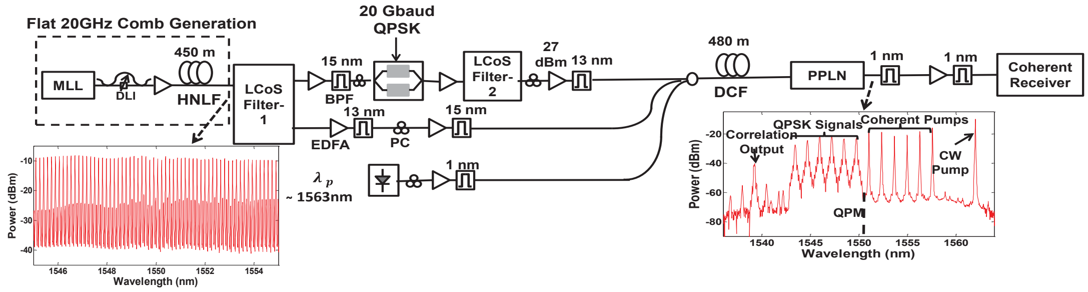
pattern, we get two types of matched and unmatched patterns that can be differentiated by coherent detection (Fig. 1(b)). To identify the appearance of a six-symbol pattern [AACDBC] in a long pattern of QPSK symbols, the correlator weights need to be set to the phase conjugate of the target pattern, *i.e.,* [A*A*C*D* B*C*]. An N-tap correlator on the QPSK signal has an output of $(n+1)^2$_quadrature amplitude modulation (QAM) constellation. The corner points, *i.e.,* upper right, upper left, lower left and lower right, which are indicated in red color in Fig. 1(b), correspond to [AACDBC], j×[AACDBC], -1× [AACDBC], and -j×[AACDBC], respectively, whereas other constellation points correspond to more than one 6-symbol patterns. By sending the result to the coherent receiver, each pattern is mapped to one constellation corner point. This is the result of their different phases, which can potentially be used to recognize simultaneously all patterns with the same correlation weights.

Fig. 1(c) depicts the concept of the optical TDL using two nonlinear elements and discrete laser pumps, which has been mentioned before. Furthermore, the block diagram of the tunable optical correlator using the frequency comb source is shown in Fig. 1(d) and is demonstrated experimentally.

In this method, we first modulate the frequency comb fingers, with the data stream in the QPSK constellation, in which the number of taps is determined by the number of fingers. Then, these modulated fingers are sent through a chromatic dispersive element to induce wavelength-dependent delays on the signal copies in the next stage. The relative delay between two adjacent replicas can be obtained by $\Delta T = D\times\Delta\lambda$, where D is the dispersion parameter and $\Delta\lambda$ is the wavelength separation between two frequency fingers. To realize a coherent correlator, the delay needs to be set to the symbol duration. Therefore, tap-delays can be continuously tuned by varying frequency comb finger spacing. These delayed signals are equivalent to OTDL taps, **which** need to be coherently combined. We also use a spatial light modulator (SLM) to put the arbitrary phase and amplitude on the fingers to tune the target pattern. In the multiplexing stage, in a periodically-poled lithium niobate (PPLN) waveguide with quasi-phase matching (QPM) wavelength of λ_{QPM}, each delayed signal mixes with another finger of frequency comb source at $\lambda = 2\times\lambda_{QPM} - \lambda_s$ through the sum-frequency-generation (SFG) process to create a signal at 1/2×λ_{QPM}. Another pump laser at λ_{Pump} is also injected into the PPLN waveguide for the difference-frequency generation (DFG) process to multiplex these signals onto λ_{out} as the output of the correlator, **which** is processed by the coherent receiver.

Experimental Setup

The experimental setup for the tunable optical correlator using an optical frequency comb is shown in Fig. 2. A mode-locked laser with a 10GHz repetition rate and a 2ps pulse width is used to generate a coherent frequency comb with a 10-GHz frequency spacing. To increase the frequency spacing, this optical frequency comb is passed through a DLI with a free spectral range (FSR) of 20-GHz. Then, we pass the 20-GHz frequency comb through an HNLF to generate a flat and broad spectrum, as is shown in the figure. We utilize a Liquid Crystal on Silicon (LCoS-1) filter to select and write complex weights on the comb fingers and



MLL: Mode Lock Laser, **DLI**: Delay Line Interferometer, **HNLF**: Highly Nonlinear Fiber, **BPF**: Band Pass Filter, **PC**: Polarization Controller, **EDFA**: Erbium Doped Fiber Amplifier , **DCF**: Dispersion Compensating Fiber, **PPLN**: : Periodically Poled Lithium Niobate

Fig. 2: Experimental setup for tunable optical correlator using an optical frequency comb

separate them into the signal path and the pump path. For each path, we select six comb fingers with a spacing of 1.28 nm. After pre-amplification, a nested Mach-Zehnder modulator is used to generate the 40- Gb/s QPSK data (PRBS 2^{15}-1) on the comb fingers. Then, we pass the signals through another programmable LCoS filter to fine-tune the delay on signals and balance their relative amplitude and phase. After being amplified together in an EDFA, all signals travel through a ~480 m DCF to introduce one symbol-time of relative delay between them. For a more stable result, we pass the amplified pumps through another path with another amplified continuous wave (CW) laser pump at ~1563 nm through the same DCF. All the signals and pumps are then sent to a 4-cm PPLN waveguide to create the correlator output signal with the spectrum shown in the figure. The QPM wavelength of the PPLN waveguide is temperature-tuned to the wavelength of ~1550.5 nm. The output signal is then filtered and sent to the coherent receiver to be analyzed.

Results and Discussion

Fig. 3 shows the coherent correlator output results. The 49-QAM correlator output for 6-taps TDL is shown in Fig. 3(a) for two different patterns. As can be seen, all output symbols in all four corner points of the IQ-plane can be individually detected as the target pattern with 0^0, 90^0, 180^0, and -90^0 rotations, for which, in these cases, we either have just one match or no matched patterns. In Fig. 3(b), the correlator peaks on 4096 QPSK symbols to target patterns of [DBCDCC] and [BBCADB] are shown. The phase of the mapped data stream is also shown in Fig. 3(c) to highlight the corresponding patterns in our data stream that match with the peak level.

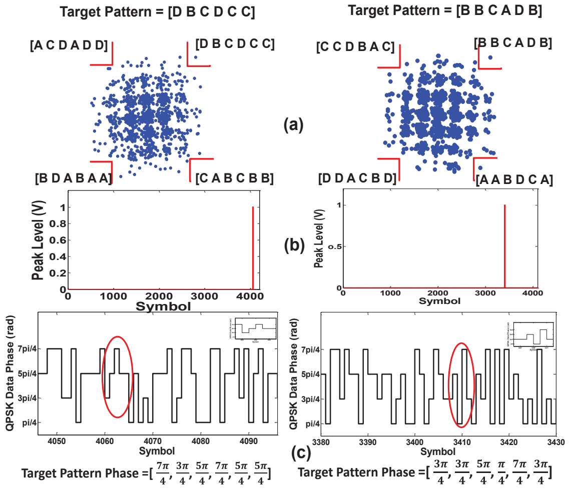
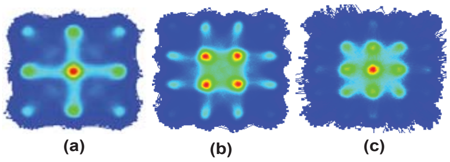


Fig.3: Experimental result for coherent correlator **(a)** 6-tap correlator output for two different patterns, **(b)**correlator peak for matched pattern **(c)** phase of mapped data stream and target pattern phase which matches with the peak level



(a) (b) (c)

Fig.4: Experimental result for coherent correlator output of different patterns **(a)** 2-taps TDL for pattern [AC] with EVM 9.7%, **(b)** 3-taps TDL for pattern [ABD] with EVM8.4% **(c)** 4-taps TDL for pattern [ABBD] with EVM 7.3%

Lastly, the optical correlator output for different patterns is shown in Fig. 4, and represents the possibility of finding those specific patterns in our PRBS data stream.

Acknowledgements

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

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