Tunable optical correlator using an optical frequency comb and a nonlinear multiplexer

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Abstract: We experimentally demonstrate a tunable optical correlator to search for multiple patterns among QPSK symbols. We utilize an optical frequency comb to generate the coherent signals and multiplex them coherently in a single PPLN waveguide. Multiple patterns with different lengths are successfully searched within QPSK symbols in a 40-Gb/s signal.

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1. Introduction

All-optical signal processing is a key tool for future flexible and ultrahigh bit-rate optical communication systems. As a result, intensive research and development is being undertaken on nonlinear optics based devices to achieve the signal processing tasks [1,2]. Nonlinear optics can be used in a variety of applications such as wavelength conversion [3], add-drop multiplexing [4], and quantization [5]. Additionally, there is now a renewed interest in optical signal processing due to recent technical advances, such as amplitude and phase domain operation, coherent receivers, and electronic signal post-processing [6].

The tapped-delay-line (TDL) is a key building block in digital signal processing that can be configured to perform many important functions, including correlation, equalization, and discrete Fourier transforms [7]. Implementing the TDL in optical domain additionally has the potential to perform these functions at the line rate on high-data-rate signals [8]. Such TDLs can support optical correlation for header and pattern recognition, encoding/decoding, and image processing at the line rate [8,9].

Tunability over variable bit-rate systems and data modulation format (e.g., on-off keying (OOK) and phase-shift keying (PSK)) enables dynamic reconfigurability. Tunable TDLs typically have multiple taps to perform specific functions, with each tap having a tunable complex weight and tunable time delay [7, 10, 11]. For correlation, the number of taps corresponds to the number of symbols that must be matched [10, 11].

Several papers have reported on optical TDLs including fixed fiber-based TDLs [12], cascaded Mach-Zehnder interferometers (MZIs), in which each MZI represents a single tap [9,13], and hybrid optical and electrical approaches using microwave photonics techniques [14]. However, these approaches tend to be difficult to tune in terms of the time delay, or tend not to have independent control over the amplitude, phase and delay of each tap. Another approach uses a combination of two wavelength-converting nonlinear elements and one wavelength-dependent delay element to achieve a tunable TDL [10,11]. In this method, an incoming signal is multicast to multiple wavelengths, using a nonlinear element based on a group of pump lasers to create multiple taps in the TDL. These replicas experience a wavelength-dependent delay in a subsequent stage. Finally, the delayed replicas are multiplexed in a final nonlinear element. Tuning the pump lasers achieves tunability of the number of taps, complex weights, and tap delays. Unfortunately, this approach does not scale well with the number of taps because a large number of discrete pump lasers would be required. Furthermore, it would be beneficial to reduce the number of nonlinear stages from two to a single stage.

Mode-locked lasers producing combs of frequency fingers have resulted in many advanced technologies such as microwave photonic filters [15]. In a coherent TDL, the taps should be coherent with each other, and an optical comb source can provide these coherent taps [11,16].

In this paper, we demonstrate a tunable optical correlator using an optical frequency comb for generating multiple taps in a tapped-delay-line composed of a single nonlinear element. Instead of multicasting the signal into different wavelengths to get the replicas, we modulate our data on different frequency fingers of the optical frequency comb. Using one wavelengthdependent delay element and one stage of nonlinearity, the delayed signals can be multiplexed coherently. Multiple patterns of 6-taps TDL are searched successfully within 40 Gb/s quadrature phase shift keying (QPSK) signals, and correlation peaks are obtained at the matched patterns. To show the tunability over the number of taps and different patterns, we also demonstrate 2-taps, 3-taps and 4-taps of correlation.

2. Concept

Figure 1 shows the conceptual block diagram of our optical correlator. To implement the correlator, the data stream is composed of four values of $\{A, B, C, D\}$. To find the specific pattern on the stream, the values of $\{A, B, C, D\}$ are mapped onto the four phases of QPSK signal by an optical modulator [Fig. 1(a)]. Then, the optical signal is multiplied with the

conjugate of the target pattern to achieve the correlation output for two types of matched and unmatched patterns [Fig. 1(b)]. For instance, to identify the appearance of a six-length pattern [AACDBC] in a long stream of optical QPSK symbols, the correlator weights are set to the phase conjugate of the target pattern, *i.e.*, [A*A*C*D*B*C*]. We need to use coherent detection to differentiate between the matched and unmatched pattern at the correlator output, because our signals are mapped to the phase of the optical signal, *i.e.*, considered as a complex number. As shown in Fig. 1(c), the output of the 6-tap correlator on the QPSK signal is a 49-quadrature amplitude modulation (QAM) constellation. Thus the 6-tap QPSK signal correlation has 49 different points with different amplitude and phase, which results in the 49-QAM constellation. In general, an n-tap QSPK correlator has a $(n + 1)^2$ -QAM constellation [11]. Increasing the number of taps results in higher order OAM constellation which might need more complex coherent detection systems. Within the QAM constellation, the points with the maximum amplitude - in this case the four corner points - correspond to the target pattern and rotated versions of thereof. For example, the corner points - upper right, upper left, lower left and lower right, which are indicated in red color in Fig. 1(c) - correspond to [AACDBC], $j \times$ [AACDBC], $-1 \times$ [AACDBC], and $-j \times$ [AACDBC], respectively.



Fig. 1. Conceptual block diagram of a tunable optical correlator. (a) Mapping data stream into optical QPSK signals. (b) Concept of correlation for matched and unmatched patterns. (c) Coherent detection of optical correlator for 6 taps. (d) Optical correlator using two stages of nonlinearities and discrete pump lasers. (e) Optical correlator using one nonlinear stage and optical frequency comb source.

Figures 1(d) and 1(e) show the concept of an optical TDL using two approaches. The first uses two nonlinear elements and discrete laser pumps to implement the correlator [Fig. 1(d)]. A laser is modulated with the QPSK data stream and combined with discrete pump lasers in periodically poled lithium niobate (PPLN)-1 to multicast the signals in different wavelengths. These replicas are sent through a wavelength-dependent delay element, such as a dispersion compensating fiber (DCF), to result in different wavelengths, in which the number of taps of the correlator corresponds to the number of replicas. Finally these replicas are combined with specific tap weights corresponding to the target pattern conjugate. To achieve coherent addition, the same discrete pump lasers with desired amplitude and phase are combined with

the delayed replicas of the signal in the second stage of nonlinearity (PPLN-2) to generate the correlation output [10,11]. As mentioned before, this approach requires two nonlinear stages and discrete pump lasers. This thus does not scale well with the number of taps.

As a result, we propose another approach using a frequency comb source to implement the tunable optical correlator, and demonstrate this experimentally herein [Fig. 1(e)]. In this scheme, the fingers of frequency comb source are used as the pump lasers. The fingers are modulated with the QPSK data stream, $A_S(t)$, to generate replicas of the data on different wavelengths, and these replicas are sent through a chromatic dispersion element to induce relevant delays. The relative delay between two adjacent replicas can be obtained by $\Delta \tau = D$ $\times \Delta \lambda$, where D is the dispersion parameter and $\Delta \lambda$ is the wavelength separation between two frequency fingers. A coherent correlator is created by setting the delay to the symbol duration, *i.e.*, $\Delta \tau = T$, where T is the symbol duration. By tuning the frequency comb finger spacing or varying the length of the DCF, the tap-delays can be continuously tuned, which provides tunablity over different data rates. The delayed signals $A_{s,i} = A_s(t-iT)$, i = 0, 1, ..., N (N = number of taps) are equivalent to the optical TDL taps that need to be coherently combined. To multiplex the delayed versions of signal coherently, a different set of fingers of the frequency comb source are combined in a PPLN waveguide with a quasi-phase matching (QPM) frequency of f_{OPM} . Each of the new set of fingers is chosen such that for each delayed version of signal, $A_{s,i}$, at frequency $f_{s,i}$, a frequency finger $A_{D,i}$ is placed at f_i such that $f_i = 2 \times f_i$ f_{OPM} – $f_{s,i}$. A spatial light modulator (SLM) filter (based on liquid crystal on silicon (LCoS) technology) places arbitrary phase and amplitude on each finger $A_{F,i}$ to tune the target pattern. Each pair of signal and pump finger generates a signal with value of $A_{s,i} \times A_{D,i} \times A_{F,i}$ at frequency of 2 \times f_{QPM} through the sum-frequency generation (SFG) process in the PPLN waveguide. Because the delayed signals and set of frequency comb fingers are coherent with each other, all the generated signals at $2 \times f_{QPM}$ are added together coherently. This results in the signal $\sum_i (A_{s,i} \times A_{D,i} \times A_{F,i})$ at frequency $2 \times f_{QPM}$. Another pump laser, A_P , at f_{pump} , is injected into the PPLN waveguide for the difference-frequency generation (DFG) process to convert the multiplexed signals back to the frequency of $f_{out} = 2 \times f_{OPM} - f_{pump}$. Thus;

$$A_{out} \propto \sum_{i=1}^{N} A_{pump}^{*} A_{D,i} A_{F,i} A_{S}(t-iT)$$
(1)

is the output of the optical correlator in which A_{pump}^* is the complex conjugate of the pump signal. Changing the phase and amplitude of programmable filter $A_{F,i}$ tunes different terms in Eq. (1) to the target pattern to generate the correlation output processed by the coherent receiver.

3. Experimental setup

Figure 2 shows the experimental setup for the tunable optical correlator using an optical frequency comb. A mode-locked laser with 10GHz repetition rate and 2ps pulse width generates a coherent frequency comb with 10-GHz frequency spacing. The optical short pulse is passed through a delay line interferometer (DLI) with free spectral range (FSR) of 20-GHz to increase the frequency spacing of optical comb. Then, to generate a flat and broad spectrum, the 20-GHz frequency comb is passed through a highly nonlinear fiber (HNLF) (shown in the Fig. 2). A programmable filter based on Liquid Crystal on Silicon (LCoS-1) is used to select and write complex weights on comb fingers and separate them into signal path and pump path. For each path, six comb fingers with a spacing of 1.28 nm are selected. After pre-amplification, a nested Mach-Zehnder modulator generates the 40- Gb/s optical QPSK data on comb fingers. Then the signals are passed through another programmable LCoS filter to fine-tune the delay on signals and balance their relative amplitude and phase. All the signals are amplified in an Erbium-doped fiber amplifier (EDFA) and sent through a \sim 480 m DCF to introduce one symbol-time relative delay between two adjacent signals. The DCF could also disperse the signal which might be compensated in the receiver side. However, for the length of the DCF and the baud rate used in the experiment, the amount of dispersion on

the signal would be negligible. For a more stable result, the amplified pumps with another amplified continuous wave (CW) laser pump at ~1563 nm are passed through the same DCF. All the signals and pumps are sent through a 4-cm-long 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, which is at the center of the tapped signals and pump fingers frequency. The output signal is then filtered and sent to the coherent receiver to be analyzed.



Fig. 2. Experimental setup for tunable optical correlator using an optical frequency comb. (MLL: Mode Lock Laser, DLI: Delay Line Interferometer, HNLF: Highly Nonlinear Fiber, BPF: Band Pass Filter, PC: Polarization Controller, EDFA: Erbium Doped Fiber Amplifier)

4. Results

Figure 3(a) shows the experimental result for the two-tap tunable correlator. As shown in the optical spectrum, there are only two signals and two comb fingers as pumps. Two taps creates three levels of amplitude for each of in-phase and quadrature-phase of the output, resulting in a 9-QAM constellation. The constellation corner points, shown in a red circle on the constellation, indicate matches to the target pattern in the data stream. The specific pattern that is searched for this two tap is [CC] in a pseudo random binary sequence (PRBS) data stream of four words of {A, B, C, D}. This pattern results in an error vector magnitude (EVM) of 9.8%. After post processing on the constellation, we could get the pattern peaks as shown in the figure. The correlation eye diagram which is the output of direct detection of the correlator is also shown in the figure.



Fig. 3. Experimental result for coherent correlator output of different patterns. (a) 2-tap for pattern [CC] with EVM 9.8%. (b) 3-tap for pattern [ADB] with EVM8.3%. (c) 4-tap correlator for pattern [CCXXAA] with EVM 7.4%

Figure 3(b) shows the output constellation spectrum, optical frequency spectrum, eyediagram, and pattern peaks for a three-tap correlator. EVM of 8.3% for the specific pattern of [ADB] is measured.

In addition to searching based on the number of taps, it is sometimes useful to analyze correlation in a data stream that has redundant data. Consider searching for the pattern [CCXXAA], in which the double [XX] in the middle of the pattern represents the redundant data in the stream. This can be implemented easily by turning off the fingers of the corresponding redundant pattern, as shown in the optical spectrum at Fig. 3(c). This figure also shows the eye-diagram and constellation of 25-QAM with EVM of 7.4% for the four-tap correlator as well as pattern peaks.



Fig. 4. Experimental results for 6-tap coherent correlator output with the pattern peaks and corresponding optical data phase for (a) Pattern [DBCDCC]. (b) Pattern [BBCADB].

Furthermore, increasing the number of taps, this configuration can also demonstrate a 6tap optical QPSK correlator, which results in a 49-QAM matching pattern. Figure 4(a) shows the coherent correlator result for the specific pattern of [DBCDCC]. All output symbols in all four corner points of the IQ-plane can be detected as the target pattern with 0°, 90°, 180°, and -90° rotations, separately - which, in this case, will be the patterns [DBCDCC], [ACDADD], [BDABAA] and [CABCBB], respectively. Analyzing the upper right corner of the constellation yields the location of the matched patterns in a 4096 QPSK symbol stream, shown as the correlator peaks in Fig. 4(a). The phase of the mapped data stream is also shown in Fig. 4(a) to highlight the corresponding patterns in the data stream that matched with the peak level. The pattern of [BBCADB] in the data stream is also searched and the results are shown in Fig. 4(b).

5. Conclusion

We have demonstrated an optical correltor using an optical frequency comb source and a single nonlinear element. Optical frequency comb source was used to achieve the high number of coherent taps in the correlator. We have used a wavelength dependent delay to achieve the tunable delays. A PPLN crystal was used to multiplex the tapped delays of the signal utilizing the nonlinear wave mixing of SFG and DFG. We have analyzed the output of the correlator by coherent detection and successfully searched multiple patterns with different lengths in a data stream at the rate of 40 Gb/s. In order to have a correlator with a high number of taps, a PPLN crystal with a high conversion efficiency would be required as well as an advanced coherent receiver which could detect high order QAM constellations.

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