Microwave Correlator Based on a Nonuniformly Spaced Photonic Microwave Delay-Line Filter

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***Abstract*—We propose and demonstrate a novel technique to perform matched filtering of a phase-coded microwave signal using a photonic microwave delay-line filter. The photonic microwave delay-line filter is designed to have a frequency response that is conjugate to the spectrum of the phase-coded microwave signal. To implement the delay-line filter, the tap coefficients are usually complex, which is difficult to implement in the optical domain. In this letter, a photonic microwave delay-line filter with equivalent complex coefficients implemented using an all-positive-coefficient photonic microwave delay-line filter based on a nonuniformly spaced delay-line structure is proposed. Since only positive coefficients are required, the implementation of the filter is greatly simplified. An experiment is performed. The decoding of a 6.75-GHz binary-phase-coded microwave signal is experimentally demonstrated.**

***Index Terms*—Microwave correlator, microwave photonics, nonuniformly spaced sampling.**

I. Introduction

MICROWAVE pulses with a large time bandwidth product (TBWP) are widely used in modern radar, computed tomography, and spread-spectrum communications systems. To achieve a large TBWP, the pulses are usually phase-coded or frequency chirped. At the receiver, a matched filter is then used to detect the presence of the chirped or phase-coded signal. The decoding process can be achieved in the electrical domain using digital electronics. The major difficulty associated with the electronic approach is that the speed is limited by the sampling rate of the electronics. A possible solution to the problem is to decode a phase-coded microwave signal in the optical domain, to take advantage of the high speed and broad bandwidth offered by modern optics. Optical approaches have been recently demonstrated to generate frequency chirped and phase-coded microwave signals [1]–[4]. However, to the best of our knowledge, few techniques have been proposed to implement microwave signal decoding in the optical domain. In this letter, we propose, for the first time, a technique to implement optically a matched filter for phase-coded microwave signal decoding using a nonuniformly spaced photonic microwave delay-line filter.

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It is known that a decoding process is actually to perform the correlation between a received microwave signal and a reference signal [5]. To decode a phase-encoded microwave signal, a correlator or matched filter should have a spectral response that is a conjugate version of the spectrum of the phase-encoded microwave signal. Such a microwave correlation operation can be implemented by a photonic microwave delay-line filter. A photonic microwave delay-line filter can provide arbitrary spectral response if the filter tap coefficients can be any values including complex values, which are usually hard to implement in the optical domain [6]–[8].

Recently, we have proposed a novel technique to implement a photonic microwave delay-line filter with equivalent complex coefficients based on a delay-line structure with nonuniform tap spacing [9]. Based on this technique, we have demonstrated photonic microwave delay-line filters for microwave signal phase encoding [10] and frequency chirping [11]. In this letter, a photonic microwave delay-line filter to perform matched filtering of a phase-coded microwave signal is proposed and demonstrated. The photonic microwave delay-line filter has nonuniform tap spacing to generate equivalent complex coefficients. Since only positive coefficients are required, the implementation is greatly simplified. The detection of a 6.75-GHz binary phase-coded microwave signal is successfully demonstrated.

II. Principle

We assume that a phase-coded microwave signal is express as $W(t)\cos[\omega t+\varphi(t)]$, where ω is the angular frequency of the microwave carrier, $\varphi(t)$ is the phase coding function, and $W(t)$ is a rectangle window function which is constant for $-p/2 \le t < p/2$ while zero otherwise. At the receiver, the correlation between the phase-coded signal and a reference microwave signal, $W(t)\cos[\omega t+\theta(t)]$, is calculated. If the correlator is matched to the signal, then $\theta(t)=\varphi(t)$, an auto-correlation with a large correlation peak is achieved and the signal will be detected; otherwise, $\theta(t)$ is orthogonal to $\varphi(t)$, then we get a cross-correlation and a low correlation peak would be generated at the receiver. In the both cases, the output from the receiver should be

$$R(t)=W(t)\cos[\omega t+\varphi(t)] * W(-t)\cos[-\omega t+\theta(-t)] \quad (1)$$

where * denotes convolution operation. If the above correlation is performed by a microwave filter, then based on (1), such a filter should have an impulse response given by

$$h(t)=\frac{1}{2}W(-t)\exp[j\omega t-j\theta(-t)]+c.c. \quad (2)$$

To realize the filter in (2), a filter with a finite impulse response (FIR) can be used. Based on signal processing theory,

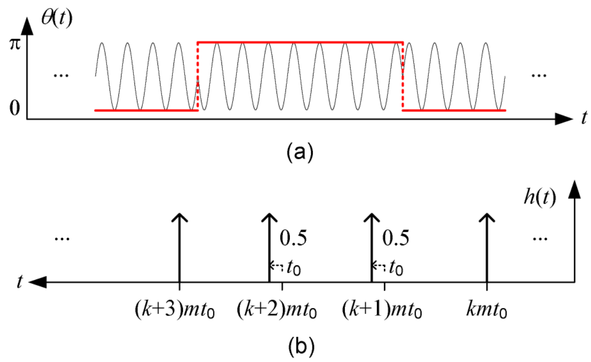

Fig. 1. (a) Phase characteristics of the microwave signal, where only biphase coding is considered. (b) Structure of the corresponding nonuniformly spaced FIR filter.

an FIR filter can be implemented through sampling the input signal with a uniform spacing. If the sampling period is $T = 2m\pi/\omega = mt_0$, where m is an integer and t_0 is the period of the microwave carrier, then the impulse response in (2) can be obtained in the mth-order channel of the FIR filter. Since the impulse response has a nonzero phase modulation, the FIR filter has multiple complex taps, i.e., the phase of the kth tap should be $-\theta(-kT)$. An FIR filter with complex taps is difficult to realize by an optical approach.

In this letter, to simplify the implementation, the filter is designed to have equivalent complex coefficients using an all-positive-coefficient photonic microwave delay-line filter based on a delay-line structure with nonuniform spacing [9]. The filter spacing is calculated by

$$\tau_k = kT + \frac{\theta(-\tau_k)}{2m\pi}T = \left[km + \frac{\theta(-\tau_k)}{2\pi}\right] t_0 \tag{3}$$

where τ_k is the time delay of the kth tap. Clearly, the time delay difference between adjacent taps is no longer uniform. The frequency response of the filter expressed in (2) is then realized in the mth channel of the frequency response of the filter [9].

Assume that a phase-coded signal has N chips, and each chip has m cycles of the microwave carrier, then based on (3), we can get the time delays of the FIR filter

$$\tau_k = \left(km + \frac{\theta_{N+1-k}}{2\pi}\right) t_0 \tag{4}$$

where θ_k is the phase of the kth tap, $1 \le k \le N$. The structure of the nonuniformly spaced FIR filter is illustrated in Fig. 1.

As an example, we design a nonuniformly spaced FIR filter for matched filtering of a binary phase-coded microwave signal. In the example, the microwave signal is phase coded by a 13-chip Barker code, $[+1, +1, +1, +1, +1, -1, -1, +1, +1, -1, +1, -1, +1]$. Therefore, $N = 13$. The Barker codes are usually used in direct-sequence spread-spectrum communications systems and pulse compression radar systems thanks to the excellent correlation performance [5]. In the design, the carrier frequency is 40 GHz and $m = 4$, i.e., the chip rate is 10 GHz. Then t_0 is 25 ps. Based on (4), the time delays of all the taps are calculated and are given by $[4, 8, 12, 16, 20, 24.5, 28.5, 32, 36, 40.5, 44, 48.5, 52] \times 25$ ps.

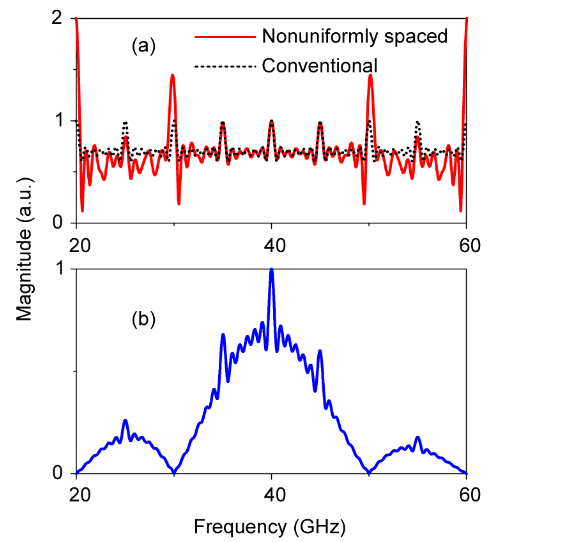

Fig. 2. (a) Frequency responses of the nonuniformly spaced FIR filter (solid) and a uniformly spaced FIR filter (dotted). The uniformly spaced FIR filter has a sampling period of $T = 100$ ps and coefficients of $[+1, -1, +1, -1, +1, +1, -1, -1, +1, +1, +1, +1, +1]$. (b) Spectrum of the input microwave signal.

The frequency response of the filter is illustrated in Fig. 2(a). For comparison, an FIR filter with uniform spacing to achieve the same matched filtering functionality using both positive and negative coefficients is also shown in Fig. 2(a). The spectrum of the input phase-coded microwave signal is shown in Fig. 2(b). It can be seen that within the effective frequency range, from 30 to 50 GHz, the frequency response of the proposed filter agrees well with that of the uniformly spaced FIR filter. Especially, in the fourth channel of the frequency response from 35 to 45 GHz, the two filters have exactly the same frequency responses. We conclude that the proposed nonuniformly spaced filter with positive-only coefficients can perform the same decoding function as a uniformly spaced FIR filter. Fig. 3 shows the input signal and correlation output in the time domain. Clearly the phase-coded microwave signal is successfully decoded.

III. Experiment

The proposed photonic microwave delay-line filter for matched filtering of a phase-coded microwave signal is experimentally demonstrated. In the experiment, a four-chip binary phase-coded microwave signal is used as an input signal. The experimental setup is shown in Fig. 4. It consists of a four-wavelength light source, a phase modulator (PM), 25-km standard single-mode fiber, and a photodetector (PD). The light wave generated by the four-wavelength source is modulated by the four-chip binary phase-coded microwave signal at the PM. The time delays for the four wavelengths are generated due to the dispersion of the 25-km fiber. Another dispersive element such as a chirped fiber Bragg grating or a dispersion-compensating fiber can also be used, which would make the system more compact with lower loss. The entire system is equivalent to an optical microwave delay-line filter with four taps. The time delay difference between two adjacent taps is determined by the wavelength spacing of the two wavelengths. The carrier frequency of the input signal is

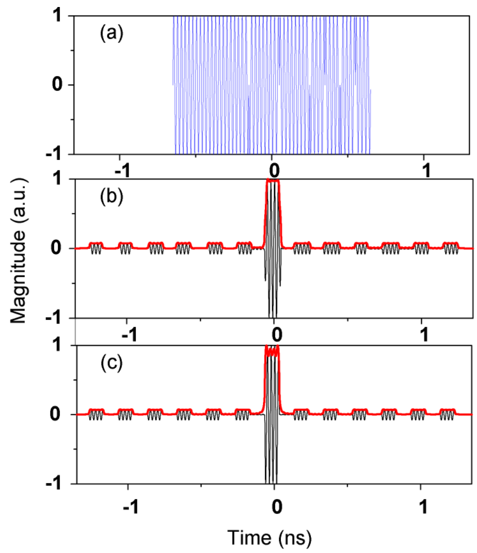

Fig. 3. (a) Input phase-coded microwave signal. (b) Correlation (with the absolute envelop) at the output of the nonuniformly spaced FIR filter. (c) Correlation (with the absolute envelop) at the output of the uniformly spaced FIR filter.

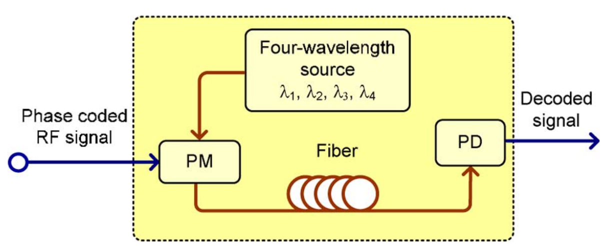

Fig. 4. Experimental setup for decoding of a phase-coded microwave signal.

6.75 GHz, which is phase coded by a four-chip Barker code, $[+1, -1, +1, +1]$. In our design, the fourth channel of the frequency response is selected, that is, $m = 4$, so that the chip rate is 1.6875 GHz. Then based on (4), the time delays for the four taps are calculated to be [0.5926, 1.1852, 1.8519, 2.3704] ns. The time delays are generated due to the chromatic dispersion of the fiber. Therefore, the four wavelengths to achieve the required time delays are calculated by [9]

$$\lambda_k = \lambda_1 + \frac{\tau_k - \tau_1}{\chi} \tag{5}$$

where λ_1 is the wavelength corresponding to the first tap, and χ is the total dispersion of the fiber. Based on (5), the four wavelengths are calculated to be [1543.10, 1544.49, 1546.06, 1547.28] nm.

Fig. 5(a) shows the generated phase-coded microwave signal. The correlation output is shown in Fig. 5(b). As can be seen a good correlation peak is observed.

In the experimental demonstration, the carrier frequency is 6.75 GHz, which is low and is limited by the equipment. For practical applications, the filter can be designed to operate at a much higher microwave frequency, limited only by the bandwidths of the PM and the PD.

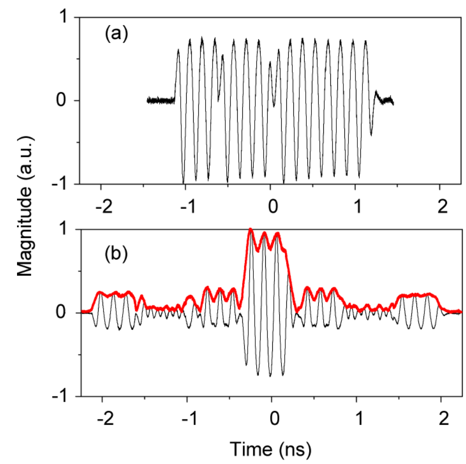

Fig. 5. (a) Input phase-coded microwave signal. (b) Measured correlation output with the calculated absolute envelop.

IV. Conclusion

We have proposed and experimentally demonstrated a new technique to implement matched filtering of a phase-coded microwave signal using a photonic microwave delay-line filter. The filter was realized with equivalent complex coefficients based on a delay-line structure with nonuniform tap spacing. Since the actual coefficients are all positive, the implementation was greatly simplified. A four-tap photonic microwave delay-line filter was experimentally demonstrated, by which a 6.75-GHz, biphase-coded microwave signal was successfully decoded.

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