# Microwave pulse phase encoding using a photonic microwave delay-line filter

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A novel technique to perform microwave pulse phase encoding using an incoherent photonic microwave delay-line filter is proposed and experimentally demonstrated. Being different from a regular microwave delay-line filter, in which the time-delay differences are identical between any adjacent taps, the proposed filter has nonidentical time-delay differences. A phase-encoded microwave pulse with the required code pattern is generated by properly adjusting the time-delay differences. The chip number of a generated phase code is determined by the number of the filter taps, and the phase shift of each chip is determined by the corresponding time-delay difference. The proposed technique is verified by experiments. The generation of binary and quaternary phase-coded pulses is experimentally demonstrated. © 2007 Optical Society of America

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The generation of electrical signals using photonic techniques has been a topic of interest recently. Photonic approaches are particularly suitable for the generation of electrical signals at very high frequencies [1]. For many applications, such as in a modern radar system, to increase the radar range resolution, the generated electrical pulses should have a large time-bandwidth product (TBWP), realized usually through frequency chirping or phase coding [2]. Chirped or phase-coded electrical pulses can be generated using photonic techniques by taking advantage of the low loss and broad bandwidth offered by optics [3–7]. Recently, we proposed a technique to generate phase-coded microwave pulses based on linear frequency-to-time mapping in a dispersive device. In the proposed system, an optical phase modulator was incorporated in one arm of a Mach–Zehnder interferometer (MZI), to impose the phase information onto the generated microwave pulses [7]. The proposed system can operate at very high frequency. The major limitation of the approach is the high sensitivity to environmental changes since an MZI was incorporated in the system.

In this Letter, we demonstrate a new technique to generate phase-coded electrical pulses based on a photonic microwave delay-line filter (PMDLF). Being different from a regular PMDLF, in which the time-delay differences between any adjacent taps are identical, the proposed PMDLF has nonidentical time-delay differences. The phase encoding with a desired code pattern is realized by adjusting the time-delay differences, to introduce the required phase shifts. The number of code chips in the generated phase-encoded pulse is determined by the number of filter taps, and the phase shift in each chip is determined by the corresponding time-delay difference. The key advantage of the proposed technique is that microwave pulse phase coding with different code patterns could be easily achieved by adjusting the time-delay differences. The proposed technique is verified by experiments. A PMDLF with four taps is built. The generation of four-chip binary and quaternary phase-coded pulses is experimentally demonstrated.

Figure 1(a) shows the proposed PMDLF for microwave pulse phase encoding. In an $N$-tap PMDLF, the output pulse is the sum of $N$ input pulses with different time delays. In a regular PMDLF, the time-delay differences between adjacent taps are identical. It is known that the frequency response of a PMDLF is periodic with the $n$th spectral channel located at $\omega = 2\pi/\tau n$, where $\tau$ is the time delay-difference, and $n$ is an integer. For a phase-coded microwave pulse using a PMDLF, the chip number is equal to the number of the filter taps. If there are $S$ microwave cycles in each chip, then $S = \tau/T = \tau\omega/2\pi$ or $\omega = (2\pi)/(\tau)S$, where $T$ is the period of the microwave carrier. Then we have $n = S$, which means that for a chip that contains $S$ microwave cycles, the filter frequency response concerned is located at the $S$th spectral channel.

To realize phase coding using a PMDLF, the phase of the $k$th chip should be introduced by the filter with the same phase $\varphi_k$ at the $k$th tap. For example, to generate a phase-coded pulse with a code pattern of {0, $\pi$, $\pi$, 0}, the tap number $N$ should be 4, and $\varphi_k$

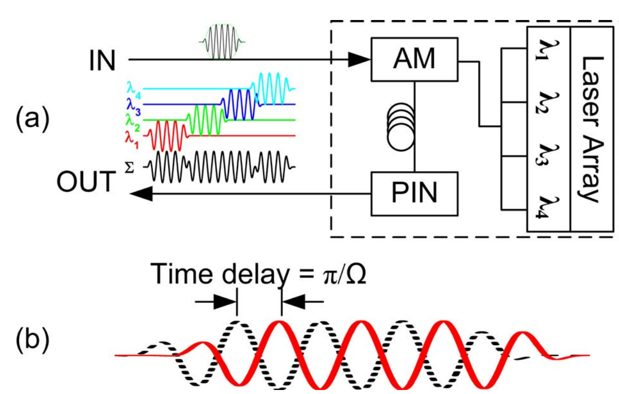


Fig. 1. (Color online) (a) Proposed PMDLF for phase coding. (b) Phase coding with the required phase shift by a time delay.

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should also be {0, $\pi$, $\pi$, 0}. Therefore, a PMDLF with both positive and negative coefficients of {1, −1, −1, 1} is required if a regular PMDLF is used. In addition, if the phase code has arbitrary phase shifts, a PMDLF with complex coefficients is required. To avoid optical interference, a PMDLF is usually operating in the incoherent regime, which leads to the filter to have all positive coefficients, or a special design is required to generate negative or complex coefficients [8,9].

To generate the required phase code using a PMDLF with only positive coefficients, we propose to use a PMDLF with nonidentical time-delay differences. The desired phase coding is implemented by adjusting the time-delay differences between the adjacent taps. For example, in Fig. 1(b) if a time-delay difference between two identical microwave pulses is $\tau+T/2$, a $\pi$ phase shift is thus realized. By using the time-delay-induced phase shift, the desired phase-coding pattern could be realized by setting the time delay $\tau_k$ of the $k$th tap to be

$$\tau_k = \tau_0 + \tau\left(k - \frac{\varphi_k}{2\pi S}\right), \quad k = 0,1,2, \ldots , \tag{1}$$

where $\tau_0$ is the time delay of the first tap, and $\tau$ is a constant, which is the time-delay difference for a regular PMDLF with an identical time delay. For example, for a four-tap filter we have $N=4$. If $S=4$ is selected, for a code pattern of {0, $\pi$, $\pi$, 0}, the time delays should be $\tau_0+\{0, 7/8\tau, 15/8\tau, 3\tau\}$. The phase coding based on a PMDLF having nonidentical time-delay differences and a regular PMDLF with positive and negative coefficients {1, −1, −1, 1} to generate a code pattern of {0, $\pi$, $\pi$, 0} is simulated, with the results shown in Fig. 2. A good agreement is observed. In the simulation, the input rf signal is a super-Gaussian pulse with a full width at half maximum (FWHM) of 680 ps.

A four-tap PMDLF with adjustable time-delay differences to generate tunable phase-code patterns is experimentally demonstrated. The filter consists of four tunable laser sources (TLSs), an intensity modulator, a length of single mode fiber (SMF), and a photodetector (PD). In our experiment, the input rf signal is a super-Gaussian pulse with a carrier frequency of 5.94 GHz, and an FWHM of ~680 ps. The Gaussian pulse is sent to the intensity modulator to modulate the four wavelengths from the four TLSs. The SMF in our experiment has a length of about 50 km. The time-delay difference between adjacent taps is generated due to the chromatic dispersion of the SMF, which is proportional to the wavelength spacing. Therefore, based on Eq. (1) the wavelength of each TLS is

$$\lambda_k = \lambda_0 + \Delta\lambda\left(k - \frac{\varphi_k}{2\pi S}\right), \tag{2}$$

where $\Delta\lambda = \tau/D$, and $D$ is the dispersion of the fiber link. In our experiment, $S=4$ is selected, then $\Delta\lambda$ is about ~0.8 nm.

Four code patterns are realized in our experiment. Based on Eq. (2), we calculate the wavelengths for the four code patterns, which are listed in Table 1. Note that $\lambda_0$ is 1543.184 nm in our experiment. When the wavelengths of the TLSs are tuned at one of the four sets of the wavelengths in the table, a microwave pulse with the phase-code pattern corresponding to the specific set of wavelengths is obtained at the PD, which is monitored by an oscilloscope, as shown in Fig. 3. Obviously, one can generate different code patterns by simply adjusting the wavelengths. Since the proposed PMDLF is operating in the incoherent regime, the generated signals are stable, which is also verified by the experiments.

One application of microwave pulse phase coding is to increase the range resolutions in modern radar systems. Microwave pulse phase coding can also find application in code-division multiple access (CDMA) systems to support multiuser communications. In a radar or a CDMA receiver, the code identification is performed based on matched filtering. To demonstrate the concept, in the experiment we use a simple code {0, $\pi$, $\pi$, 0}. We calculate the autocorrelation of the experimentally generated phase-encoded rf signal with the phase-code pattern of {0, $\pi$, $\pi$, 0}, as shown in Fig. 4. It is clearly seen that the generated phase-coded signals are significantly compressed, and the result is consistent with the simulation also shown in Fig. 4.

Since the phase coding in the proposed PMDLF is achieved by changing the time delays, the phase shifts are accurate only for a specific frequency and approximately accurate for a narrow bandwidth around that specific frequency due to the dependence of the phase shifts on the microwave frequency. In most of the applications; however, the frequency band concerned for the processing of microwave sig-

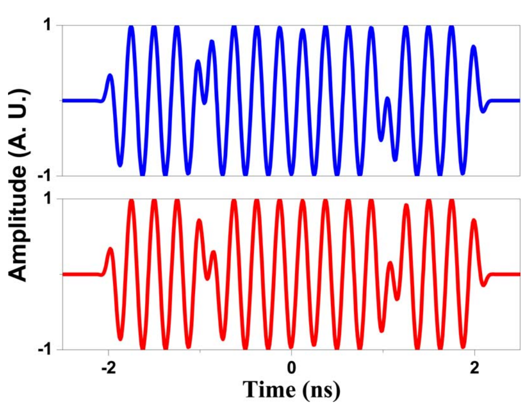


Fig. 2. (Color online) Phase-encoded microwave pulse with a code pattern of $\{0,\pi,\pi,0\}$. (a) Generated by the proposed PMDLF, (b) generated by a regular PMDLF with coefficients of $\{1,-1,-1,1\}$.

**Table 1. Four Sets of Wavelengths for Four Different Code Patterns**

| Code Pattern | Wavelength Set (nm) | | | |
|---|---|---|---|---|
| {0, 0, 0, 0} | 1543.184 | 1543.984 | 1544.784 | 1545.584 |
| {0, $\pi$, $\pi$, 0} | 1543.184 | 1543.884 | 1544.684 | 1545.584 |
| {0, $\pi$, 0, $\pi$} | 1543.184 | 1543.884 | 1544.784 | 1545.484 |
| {0, $\pi$/2, $\pi$, 3$\pi$/2} | 1543.184 | 1543.934 | 1544.684 | 1545.434 |

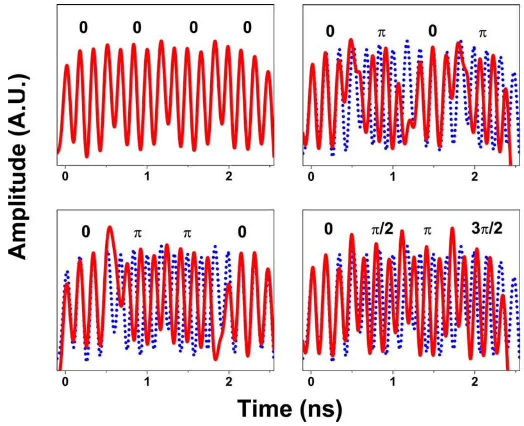


Fig. 3. (Color online) Solid curve: experimentally generated phase-coded rf pulses. Dotted curve: rf signals without phase coding.

nals is very narrow. Therefore, it is feasible to use this equivalent phase shift technique to generate the required frequency response at the specific frequency band. The key advantage of this technique is that we can generate a frequency response employing an all-positive-coefficient PMDLF with nonidentical time delays, which can only be generated using a PMDLF with true negative and even complex coefficients [10]. For example, if $N=4$, the code pattern is {0, $\pi$, $\pi$, 0}, and $S=4$ is selected; the frequency responses of the proposed system and that of a regular PMDLF with coefficients of {1, −1, −1, 1} are plotted in Fig. 5, where $\tau$ is 680 ps in our simulation. One can clearly see that the proposed filter has the exact frequency response at the fourth spectral channel as that using a regular microwave delay-line filer with true negative coefficients. In the proposed system, the time delays are introduced by a length of fiber. If a double sideband modulation scheme is employed, the chromatic dispersion of the fiber would lead to dispersion-induced power fading [9]. A solution to the problem is to use single sideband modulation.

In summary, a novel technique to perform microwave pulse phase encoding using an incoherent PM-

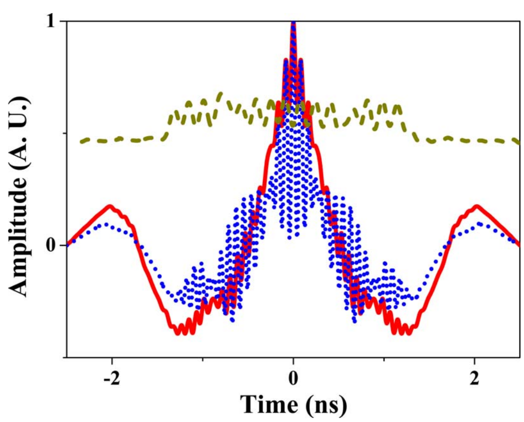


Fig. 4. (Color online) Calculated autocorrelations of the experimentally generated phase-coded microwave signal (solid line), and the simulated signal corresponding to Fig. 2 (dotted line). Dashed line: the experimentally generated phase-coded rf signal.

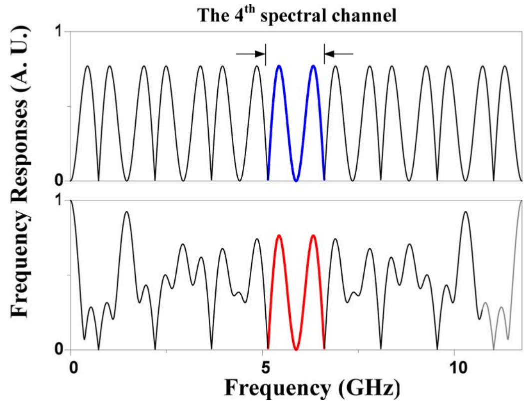


Fig. 5. (Color online) Simulation results of frequency responses of the proposed filter (down) to generate a phase code of $\{0,\pi,\pi,0\}$, and a regular PMDLF (up) with coefficients of $\{1,-1,-1,1\}$.

DLF with nonidentical time-delay differences was proposed and experimentally demonstrated. A phase-encoded microwave pulse with the required code pattern was generated by properly adjusting the time-delay differences, to introduce the required phase shifts. The key advantage of the technique is that a frequency response, which could only be generated by a PMDLF with true negative and complex coefficients, can be simply realized by using the proposed filter with nonidentical time-delay differences. Different code patterns were experimentally achieved by adjusting the wavelengths of the TLSs. Binary and quaternary phase-coded pulses were generated. Pulse compression using the generated phase code was also demonstrated.

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