Chirped Microwave Pulse Generation Using a Photonic Microwave Delay-Line Filter With a Quadratic Phase Response

Yitang Dai and Jianping Yao, *Senior Member, IEEE*

***Abstract*—We propose an optical approach to generating chirped microwave pulses using a photonic microwave delay-line filter (PMDLF) with a quadratic phase response. If a chirp-free broadband microwave pulse is inputted into the filter, a chirped microwave pulse is generated thanks to the quadratic phase response of the filter. To design a PMDLF with a quadratic phase response, complex tap coefficients are required, which is hard to implement in the optical domain. In this letter, a PMDLF with equivalent complex coefficients implemented based on a nonuniformly spaced delay-line structure is demonstrated. Since only positive coefficients are required, the filter is easy to implement. A design example is provided. A five-tap PMDLF to generate a chirped microwave pulse with a chirp rate of 13.2 GHz/ns is then experimentally demonstrated.**

***Index Terms*—Arbitrary waveform generation, chirped pulse generation, 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 [1], [2]. To achieve a large TBWP, the pulses are usually phase coded or frequency chirped. A chirped microwave pulse can be generated in the electrical domain using a voltage controlled oscillator. The major difficulty associated with the use of an electronic oscillator is that the central frequency and the bandwidth of the generated pulses are limited. An effective solution to the problem is to generate chirped microwave pulses in the optical domain, to take advantage of the high speed and broad bandwidth offered by optics. A few techniques for chirped microwave pulse generation in the optical domain have been recently demonstrated. In [3] and [4], a chirped microwave pulse is generated using a direct space-to-time optical pulse shaper. In [5], a chirped pulse is generated based on optical spectral shaping of a supercontinuum optical source followed by wavelength-to-time mapping. The techniques in [3]–[5] are all implemented based on free-space optics. Techniques based on pure fiber optics with smaller size and better stability have also been demonstrated [6], [7], in which the spectrum of an optical ultrashort pulse is shaped by a fiber-optic filter with a fixed free spectral range, and the chirped microwave pulse is then generated through nonlinear frequency-to-time mapping in a dispersive device that has high-order dispersions.

It is known that a chirped microwave pulse can be generated by passing a broadband chirp-free microwave pulse through a microwave filter with a quadratic phase response or a linear group-delay response. To implement a photonic microwave delay-line filter (PMDLF) with a quadratic phase response, complex coefficients are required, which is hard to realize in the optical domain [8], [9]. Recently, we have proposed a novel technique to implement a PMDLF with equivalent complex coefficients based on a filter structure with nonuniform spacing [10]. Based on this technique, we have demonstrated a PMDLF for microwave pulse phase coding [11].

In this letter, the generation of a chirped microwave pulse using a nonuniformly spaced PMDLF is proposed and demonstrated. The filter has a quadratic phase response, which is achieved based on nonuniform sampling with equivalent complex coefficients. Since the filter has a delay-line structure with actually all-positive coefficients, it is easy to realize in the optical domain. A design example is provided, in which a 40-tap PMDLF with a quadratic phase response is analyzed. An experiment is then performed. A chirped microwave pulse with a chirp rate of 13.2 GHz/ns is generated by a five-tap PMDLF with all-positive coefficients.

II. Filter Design

The experimental setup of the proposed PMDLF is shown in Fig. 1(a). The system consists of a multiwavelength light source, a phase modulator (PM), a length of dispersive fiber, and a photodetector (PD). The filter is designed to have a quadratic phase response with a nonuniformly spaced structure. Fig. 1(b) shows the operation of the filter in the frequency domain.

Assume that the spectrum of the input pulse is $X(\omega)$, and the spectrum of the desired chirped microwave pulse is $Y(\omega - 2\pi/T)$, where $2\pi/T$ is the central frequency of the microwave pulse and T is the mean period, then the frequency response of the PMDLF is given by $H(\omega-2\pi/T) = Y(\omega-2\pi/T)/X(\omega)$, as shown in Fig. 1(b). If the filter taps are uniformly spaced with a time delay difference of T, the coefficients of the filter are given by $\alpha_k = h(kT)$, where $h(t)$ is the inverse Fourier transform of $H(\omega)$. Since $H(\omega)$ has a quadratic phase response, the coefficients α_k should be complex valued. In this letter, to simplify the implementation, the filter is designed to have equivalent complex coefficients based on a delay-line structure with

Manuscript received November 18, 2008; revised January 18, 2009. First published February 24, 2009; current version published April 15, 2009. The work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2009.2014966

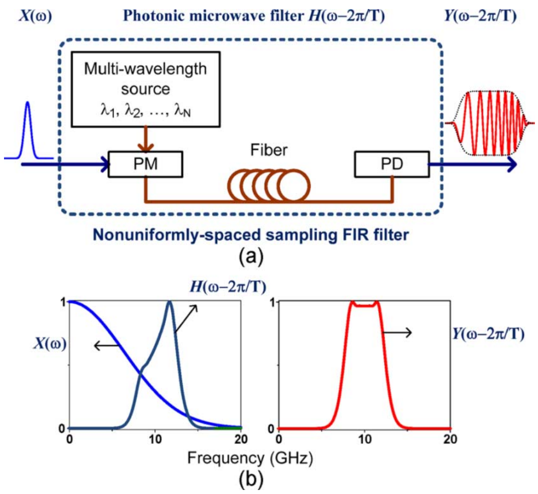

Fig. 1. (a) System setup. (b) Principle of the proposed technique for chirped microwave pulse generation.

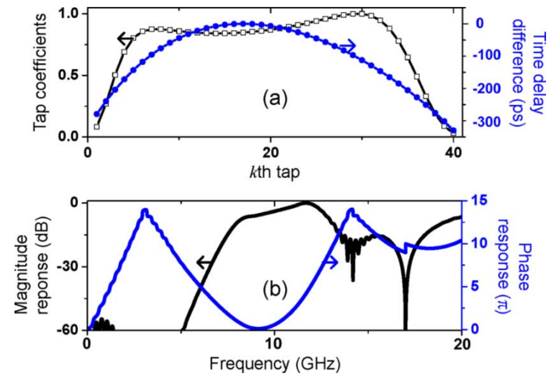

Fig. 2. (a) Filter design for the chirped microwave pulse generation. □-line: the tap coefficient profile. ●-line: time delay differences. (b) Magnitude and phase responses of the filter.

nonuniform spacing [10]. Based on the theory in [10], the time delays and the coefficients of the filter are given by

$$\tau_k + \frac{\varphi(\tau_k)}{2\pi}T = kT \quad \alpha_k = \left|\frac{h(\tau_k)}{1+T\varphi'(\tau_k)/2\pi}\right| \tag{1}$$

where τ_k is the time delay of the kth tap, and $\varphi(t)$ is the phase of $h(t)$. Since α_k is positive-only, the filter is easy to implement in the optical domain. The desired bandpass response is then obtained at the first-order channel of the spectral response of the filter designed based on (1).

It should be noted that since all the coefficients are positive, the frequency response of the filter will have a baseband at dc, which should be eliminated. To do so, we use a phase modulator instead of an intensity modulator. It has been demonstrated that phase modulation to intensity modulation (PM-IM) conversion in a dispersive fiber would generate a notch at dc [12], which can be used to eliminate the baseband resonance. Mathematically, the PM-IM conversion is given as

$$H_{\mathrm{PM-IM}}(\omega) = \cos\left(\frac{\chi\lambda^2\omega^2}{4\pi c} + \frac{\pi}{2}\right) \tag{2}$$

where c is the light velocity in free space, χ is the total dispersion of the fiber, and λ is the central wavelength of the optical carrier.

The frequency response of the PM-IM conversion is not flat at the bandpass of interest. To compensate for the nonflat frequency response, the target frequency response, $H(\omega - 2\pi/T)$, should be revised to be

$$H(\omega - 2\pi/T) = \frac{Y(\omega - 2\pi/T)}{X(\omega)H_{\mathrm{PM-IM}}(\omega)}. \tag{3}$$

In the setup in Fig. 1(a), different time delays τ_k are generated thanks to the chromatic dispersion of the dispersive fiber. To achieve nonuniform spacing, the wavelengths are nonuniformly spaced. Mathematically, the kth wavelength corresponding to the kth tap is calculated by

$$\lambda_k = \lambda_0 + \frac{\tau_k - \tau_0}{\chi} \tag{4}$$

where λ_0 is the wavelength for the zeroth tap. The values of the coefficients α_k are controlled by adjusting the output powers of the laser sources. It should be noted that the proposed filter has multiple channels, and the input pulse should be spectrally centered at the first channel. In addition, its bandwidth should be narrower than the channel bandwidth. Obviously, the maximum bandwidth is limited by the channel spacing and the maximum chirp rate is in proportion to the channel spacing, which is in inverse proportion to the pulse length. If the maximum bandwidth is the channel spacing, then the maximum chirp rate is $1/NT^2$, where N is the tap number and T is the time delay difference between two adjacent taps, which is calculated by $T = DL\Delta\lambda$, where D is the fiber dispersion parameter, L is the fiber length, and $\Delta\lambda$ is the mean wavelength spacing in the design.

III. Design Example

The generation of a chirped microwave pulse by a PMDLF designed based on the proposed technique is first numerically studied. The desired chirped microwave pulse is expressed as

$$h_O(t) = \exp\left[-\ln(2)\left(\frac{2t}{W}\right)^8\right] \times \exp\left[j\left(\frac{2\pi}{T}t + \pi\gamma t^2\right)\right] \tag{5}$$

where $W = 3.2$ ns is the full-width at half-maximum (FWHM) of the pulse, $T = 100$ ps is the mean period, and $\gamma = 1.6$ GHz/ns is the chirp rate. The pulse has an eighth-order super-Gaussian profile. A chirped pulse with other profiles can also be realized based on the same design process. A length of 25-km standard single-mode fiber with a dispersion parameter of 17 ps/nm/km and a total dispersion of $\chi = 425$ ps/nm is used to perform the PM-IM conversion. In the simulation, we assume the chirped microwave pulse is generated from a chirp-free Gaussian pulse with an FWHM of 60 ps. Then the filter spectral response including the spectral response of the PM-IM conversion is calculated using (3).

Based on (1), the coefficients and time delays of the desired filter are calculated which are shown in Fig. 2(a). To illustrate clearly the nonuniform spacing, the time delay differences $\Delta\tau_k = \tau_k - kT$ are plotted instead of the absolute time delays.

The frequency response of the filter is calculated, which is shown in Fig. 2(b). As can be seen, the filter has a bandpass magnitude response with a central frequency at around 10 GHz and a quadratic phase response. The baseband resonance is eliminated by the PM-IM conversion. If a Gaussian pulse with an FWHM of 60 ps is applied to the input of the filter, the output pulse is chirped with a chirp rate determined by the phase response of

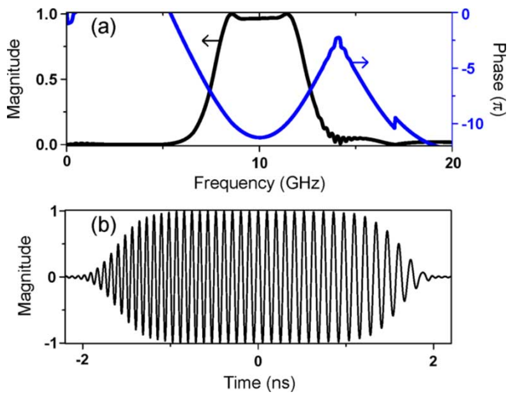

Fig. 3. (a) Spectrum of the chirped microwave pulse and (b) temporal waveform of the pulse.

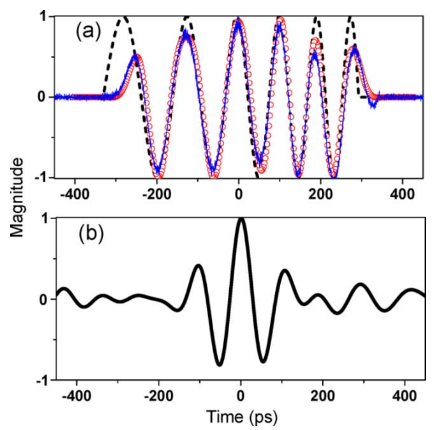

Fig. 4. (a) Solid line: the generated chirped microwave pulse. Dashed line: the desired chirped microwave pulse. Circle-line: Simulation result. (b) Correlation between the measured and the reference pulses.

the filter. The spectrum and the temporal waveform of the generated chirped microwave pulse are shown in Fig. 3. A chirped pulse with a chirp rate of 1.6 GHz/ns is generated.

IV. Experiment

To prove the concept, a PMDLF with five taps is experimentally demonstrated. In the experiment, the desired chirped microwave pulse has an FWHM of $W = 550$ ps, a mean period of $T = 110$ ps, and a chirp rate of $\gamma = 13.2$ GHz/ns. This pulse, plotted as the dashed line in Fig. 4(a), is expected to be generated from a chirp-free Gaussian pulse. The chirp-free Gaussian pulse is generated in the experiment by a bit-error-rate tester with an FWHM of 65 ps. Based on (2) and (3), $H(\omega)$ is calculated, and then the time delays and coefficients are obtained based on (1). The time delays are $T \times [-2.31, -1.08, 0.00, 0.81, 1.51]$. The wavelengths from the multiwavelength source are then calculated based on (4). In our experiment, λ_0 is 1543.30 nm. Then the five wavelengths are set as [1542.70, 1543.02, 1543.3, 1543.51, 1543.69] nm.

In the experiment, the output power of each laser is controlled so that the tap coefficients α_k are optimized to minimize the error between the generated and the desired chirped pulses. The tap coefficients are calculated to be [1.0, 1.0, 1.0, 1.5, 1.4]. The generated pulse is then measured by a high-speed oscilloscope (Agilent 86100C), which is shown as a solid line in Fig. 4(a). The generated pulse is in good agreement with the simulation result, which is also close to the targeted pulse. A visible discrepancy at the leading and tailing edges is due to the limited number of taps in the implementation. To demonstrate the pulse compression performance, we calculate the correlation between the measured and the reference chirped microwave pulses [the solid line and dashed line in Fig. 4(a)], and the correlation result is plotted in Fig. 4(b). It is clearly seen that the microwave pulse is compressed, which demonstrates that the generated microwave pulse is chirped.

V. Conclusion

We have proposed a new optical approach to generating chirped microwave pulses using a PMDLF with a quadratic phase response. The proposed filter was realized with equivalent complex coefficients using an optical microwave delay-line filter with nonuniformly spaced taps. Since the tap coefficients are all positive, the implementation of the filter was greatly simplified. A design example was provided. A five-tap PMDLF to generate a chirped microwave pulse with a chirp rate of 13.2 GHz/ns was then experimentally demonstrated. The technique provides a simple solution to generate high-frequency and broadband chirped pulses which can find applications in modern radar and communications systems.

References

[1] A. W. Rihaczek, *Principles of High-Resolution Radar*. Norwood, MA: Artech House, 1996.

[2] M. Bertero, M. Miyakawa, P. Boccacci, F. Conte, K. Orikasa, and M. Furutani, "Image restoration in chirp pulse microwave CT (CP-MCT)," *IEEE Trans. Biomed. Eng.*, vol. 47, no. 5, pp. 690–699, May 2000.

[3] S. Xiao, J. D. McKinney, and A. M. Weiner, "Photonic microwave arbitrary waveform generation using a virtually-imaged phased-array (VIPA) direct space-to-time pulse shaper," *IEEE Photon. Technol. Lett.*, vol. 16, no. 8, pp. 1936–1938, Aug. 2004.

[4] J. D. McKinney, D. E. Leaird, and A. M. Weiner, "Millimeter-wave arbitrary waveform generation with a direct space-to-time pulse shaper," *Opt. Lett.*, vol. 27, no. 15, pp. 1345–1347, Aug. 2002.

[5] J. Chou, Y. Han, and B. Jalali, "Adaptive RF-photonic arbitrary waveform generator," *IEEE Photon. Technol. Lett.*, vol. 15, no. 4, pp. 581–583, Apr. 2003.

[6] H. Chi and J. P. Yao, "All-fiber chirped microwave pulse generation based on spectral shaping and wavelength-to-time conversion," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 9, pp. 1958–1963, Sep. 2007.

[7] C. Wang and J. P. Yao, "Photonic generation of chirped millimeter-wave pulses based on nonlinear frequency-to-time mapping in a nonlinearly chirped fiber Bragg grating," *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 2, pp. 542–553, Feb. 2008.

[8] J. Capmany, B. Ortega, and D. Pastor, "A tutorial on microwave photonic filters," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 201–229, Jan. 2006.

[9] R. A. Minasian, "Photonic signal processing of microwave signals," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 832–846, Feb. 2006.

[10] Y. Dai and J. P. Yao, "Nonuniformly-spaced photonic microwave delay-line filter," *Opt. Express*, vol. 16, no. 7, pp. 4713–4718, Mar. 2008.

[11] Y. Dai and J. P. Yao, "Microwave pulse phase encoding using a photonic microwave delay-line filter," *Opt. Lett.*, vol. 32, no. 24, pp. 3486–3488, Dec. 2007.

[12] F. Zeng and J. P. Yao, "Investigation of phase modulator based all-optical bandpass microwave filter," *J. Lightw. Technol.*, vol. 23, no. 4, pp. 1721–1728, Apr. 2005.