Chirped Microwave Pulse Compression Using a Photonic Microwave Filter With a Nonlinear Phase Response

Chao Wang, *Student Member, IEEE*, and Jianping Yao, *Senior Member, IEEE*

***Abstract*—Chirped microwave pulse compression using a photonic microwave filter with nonlinear phase response to implement matched filtering is proposed and investigated. The photonic microwave filter with the required phase response is realized based on optical phase to microwave phase conversion through single-sideband modulation and heterodyne detection. A detailed theoretical analysis on the photonic microwave filter design and the linearly chirped microwave pulse compression is developed. A photonic microwave filter having a quadratic phase response with a bandwidth of 3 GHz is implemented. An application of the photonic microwave filter for linearly chirped microwave pulse compression is investigated.**

***Index Terms*—Chirped microwave pulse, fiber Bragg grating (FBG), frequency modulation, phase response, photonic microwave filter, pulse compression, radar.**

I. Introduction

SPREAD-SPECTRUM techniques have been widely employed in modern radar systems to improve the radar range resolution [1]. A spectrum-spread signal is usually generated through pulse chirping or phase coding. Significant efforts have been directed in the past few decades to the generation and processing of chirped microwave pulses. Usually, a chirped microwave pulse can be generated and compressed in the electrical domain using analog circuitry, such as a voltage-controlled oscillator for pulse generation [2] and a surface acoustic wave (SAW) dispersive delay line for pulse compression [3]. The major limitations associated with the use of these techniques are the low central frequency and the small time-bandwidth product. With the advancement of digital electronic technologies, the generation and processing of chirped microwave signals using digital signal processing (DSP) techniques have been demonstrated [4], [5], but the performance is still limited due to the relatively low sampling speed of the state-of-the-art digital electronics. On the other hand, in a modern radar system the signals should have a central frequency up to tens or even hundreds of gigahertz with a time-bandwidth product as large as 100 [1]. Therefore, there is a continued effort in finding solutions to generate and process high frequency and large bandwidth microwave signals for modern radar applications.

An intense effort has recently been directed to the generation of high-frequency and large bandwidth chirped electrical pulses in the optical domain [6]–[10] to take advantages of the high speed and broad bandwidth offered by modern optics. In general, chirped microwave pulse generation in the optical domain can be implemented based on either free-space optics [6], [7] or guided-wave optics [8]–[10]. The key advantage of using guided-wave optics is the small size, which makes the system compact with better stability. In [9] and [10], chirped microwave pulses were generated using a pure fiber-optic system based on spectral shaping of an ultrashort optical pulse and frequency-to-time mapping in a dispersive element. The frequency of the generated chirped microwave pulses can be as high as tens of gigahertz, limited only by the bandwidth of the photodetector.

On the other hand, chirped microwave pulses at a receiver end should be compressed, which is usually realized via correlation or matched filtering [1]. To implement pulse compression for a high-frequency and broadband chirped microwave pulse, optical techniques would be utilized. To the best of our knowledge, no all-optical techniques have been reported thus far to realize chirped microwave pulse compression. In [11], a hybrid RF/laser radar system with an optical front end was reported to implement pre-dechirping of the input pulses prior to DSP. RF pulse compression with a central frequency below 1 GHz was realized, which was limited by the low sampling rate of an analog-to-digital converter.

In this paper, we propose a new technique to implement high-frequency chirped microwave pulse compression in the optical domain. This study is a continuation of our earlier research on high-frequency chirped microwave pulse generation [9], [10]. In the proposed system, a photonic microwave filter with a nonlinear phase response that is opposite to the chirp profile of the input chirped microwave pulse is used. When the input pulse is passing through the microwave filter, the pulse is compressed. The principle is similar to dispersion compensation in an optical communication system, where a chirped fiber Bragg grating (FBG) with an opposite chromatic dispersion is used to compress an optical pulse that is dispersed due to the chromatic dispersion of the fiber link [12].

We have recently proposed and demonstrated a technique to design and implement a photonic microwave delay-line filter with a nonlinear phase response based on nonuniform sampling. Complex tap coefficients are usually required in a delay-line

Manuscript received June 25, 2008; revised October 20, 2008. First published January 19, 2009; current version published February 06, 2009. This 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, ON, Canada K1N 6N5 (e-mail: jpyao@site.uOttawa.ca).

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

Digital Object Identifier 10.1109/TMTT.2008.2011189

0018-9480/$25.00 © 2009 IEEE

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

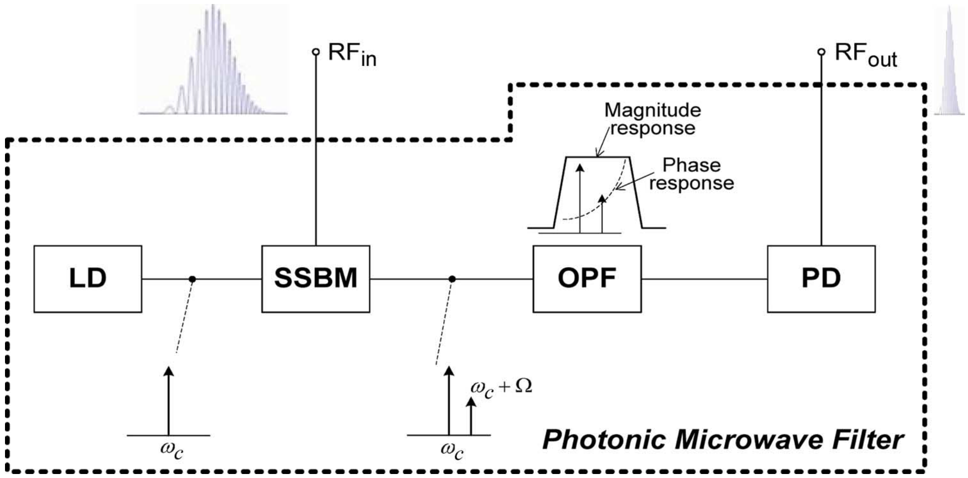

Fig. 1. Schematic diagram of the proposed chirped microwave pulse compression system. Laser diode (LD). Single-sideband modulator (SSBM). Optical phase filter (OPF). Photodetector (PD).

filter to achieve a nonlinear phase response. In the proposed system, a nonuniform sampling technique is applied to generate equivalent complex tap coefficients [13]. Since the actual tap coefficients are all-positive, a simple implementation is ensured. The major limitation of the technique is that a multiwavelength source is required, since the tap number of the filter is determined by the number of optical wavelengths, which may make the system bulky and costly.

In this paper, we demonstrate a photonic microwave filter with a nonlinear phase response using a single wavelength. The filter is implemented based on optical phase to microwave phase conversion by using a single-sideband modulator and an FBG. The FBG acts as an optical filter that is designed to have a user-defined nonlinear phase response. The nonlinear optical phase response is then transferred to the phase response of the photonic microwave filter through single-sideband modulation and heterodyne detection at a high-speed photodetector. Therefore, by appropriately designing the dispersion characteristics of the FBG, a photonic microwave filter with the desired nonlinear phase response is realized. Note that the FBG is designed to have a unity magnitude response across the entire passband; therefore, the photonically implemented microwave filter is operating as a phase-only matched filter. In practice, the phase-only filter is the easiest filter to implement since no amplitude modulation is needed. In fact, our proposed technique enables both the amplitude and phase modulations; therefore, other types of filters, such as a complex matched filter and modified inverse filter, can also be implemented using this technique [14]. The primary motivation behind the use of a phase-only filter is not only the implementation simplicity, but also the better performance, including higher power efficiency, as well as a narrower output peak when compared with the use of a complex matched filter [14].

The proposed technique is verified by a proof-of-concept experiment. A photonic microwave filter with a quadratic phase response over a bandwidth from 2 to 5 GHz is implemented. A linearly chirped microwave pulse is compressed by the demonstrated microwave filter. The filter bandwidth has the potential to be greatly extended and will be limited only by the bandwidth of the electrooptic modulator and the photodetector utilized in the system.

This paper is organized as follows. In Section II, a theoretical analysis on the microwave filter implementation and chirped microwave pulse compression is developed. In Section III, the experimental setup is described; numerical and experimental investigations are performed with the results presented. A discussion on the filter bandwidth extension and system adaptability is presented in Section IV. A conclusion is drawn in Section V.

II. System Configuration and Theoretical Analysis

The schematic diagram of the photonic microwave filter for chirped microwave pulse compression is shown in Fig. 1. In the system, a continuous-wave (CW) light from a laser diode (LD) is fiber coupled to an optical single-sideband modulator, which is driven by an input chirped microwave pulse to be compressed. The modulated optical field has a single-sideband format. The carrier and one sideband are then sent to an optical phase filter where different phase responses are applied to the carrier and the sideband. The magnitude spectra of the optical field components and optical filter response are also schematically illustrated in Fig. 1. The output microwave signal is recovered via the heterodyne beating between the carrier and the sideband at a high-seed photodetector.

We start our analysis by assuming that the input microwave signal has a single frequency Ω, which is also appropriate for comparison with the swept-frequency measurements performed in our experiment. If the optical carrier with a frequency ω_c is modulated by the microwave signal in the single-sideband modulator, under small-signal modulation conditions, the single-sideband intensity modulation can be regarded as a narrowband linear modulation, and the spectrum of the modulated optical signal has two major frequency components: the optical carrier ω_c and one first-order sideband $\omega_c + \Omega$. The single-sideband modulated optical field can then be described by

$$E_{\mathrm{SSB}}(t) = A\exp(j\omega_c t) + B\exp\left[j(\omega_c + \Omega)t\right] \qquad (1)$$

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

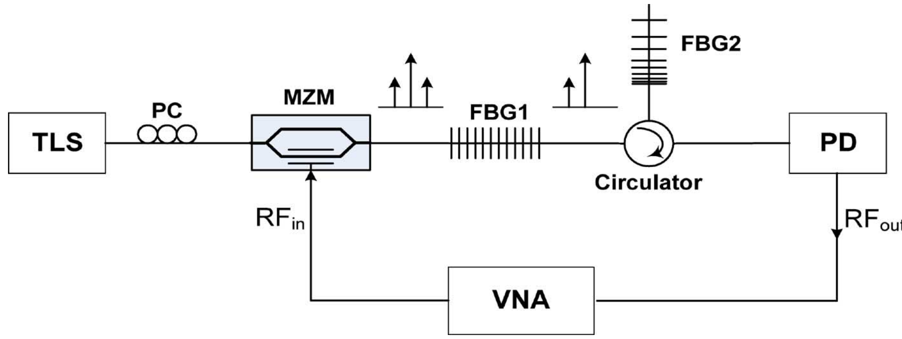

Fig. 2. Experimental setup of the proposed system. Tunable laser source (TLS). Polarization controller (PC). Mach–Zehnder modulator (MZM). Fiber Bragg grating (FBG). Vector network analyzer (VNA). Photodetector (PD).

where A and B denote the amplitudes of the optical carrier and the single sideband. Without loss of generality, the upper sideband $\omega_c + \Omega$ is chosen in our treatment.

An optical filter with a transfer function of $\rho(\omega) = |\rho(\omega)| \exp[j\theta(\omega)]$ is then used to modify the amplitudes and phases of the optical carrier and the sideband. The optical field at the output of the filter is given by

$$E_{\rm SSB}(t) = |\rho(\omega_c)|\, A \exp\left[j\omega_c t + j\theta(\omega_c)\right]\} + |\rho(\omega_c+\Omega)|\, B \exp\left[j(\omega_c+\Omega)t + j\theta(\omega_c+\Omega)\right]\} \quad (2)$$

where $|\rho(\omega)|$ and $\theta(\omega)$ represent the frequency-dependent magnitude and phase response of the optical filter, respectively.

The electrical current at the output of the photodetector is proportional to the intensity of the input electrical field

$$\begin{aligned} i(t) &\propto |E_{\rm SSB}(t)|^2 \\ &\propto \frac{1}{2}|\rho(\omega_c)|^2 A^2 + \frac{1}{2}|\rho(\omega_c+\Omega)|^2 B^2 \\ &\quad + |\rho(\omega_c)|\,|\rho(\omega_c+\Omega)|\, AB \\ &\quad \cdot \cos\left[\Omega t + \theta(\omega_c+\Omega) - \theta(\omega_c)\right]. \end{aligned} \quad (3)$$

Note that all high-order harmonic components are ignored in (3) considering the fact that the high-order harmonic components will be filtered out due to the limited bandwidth of the photodetector. It can be seen from (3) that the first and second terms on the right-hand side are dc components, and the third term is the recovered microwave signal.

Considering that the input microwave signal is $\cos(\Omega t)$, we can easily get the transfer function of the system

$$|H(\Omega)| \propto |\rho(\omega_c)|\,|\rho(\omega_c+\Omega)| \quad (4a)$$

$$\Psi(\Omega) = \theta(\omega_c+\Omega) - \theta(\omega_c) \quad (4b)$$

where $|H(\Omega)|$ and $\Psi(\Omega)$ are, respectively, the magnitude and the phase responses of the developed photonic microwave filter. Since the optical filter can be designed to have a unity magnitude response across the entire passband, the implemented microwave filter can then maintain a constant amplitude transmission $|H(\Omega)| \propto |\rho(\omega_c)|^2$. Therefore, the filter is a phase-only filter. The phase response of the microwave filter, from (4b), is thus the optical phase difference between the optical carrier and the sideband in the optical phase filter. Therefore, by appropriately designing the phase or group delay characteristics of the optical phase filter, we are able to create a photonically implemented microwave filter with a desired phase response.

To compress a chirped microwave pulse, the microwave filter should have a nonlinear phase response that is opposite to the chirp profile of the input microwave pulse. The group delay introduced by the microwave filter can be obtained from the filter phase response by

$$\tau_{\rm RF}(\Omega) = \frac{d\Psi(\Omega)}{d\Omega}. \quad (5)$$

In other words, the microwave filter can be regarded as a dispersive microwave device, which has a group delay response or a chromatic dispersion that is opposite to that of the input microwave signal, leading to the pulse compression. The operation is similar to optical pulse compression by dispersion compensation in an optical communication system [12].

As a simple example, we consider the compression of a linearly frequency-modulated (or linearly chirped) microwave signal, which is the most commonly used pulsed signal in modern radar systems [1]. For a linearly chirped microwave signal with a pulsewidth of T_0 and a time-bandwidth product of P, the dispersion parameter of the microwave filter to realize an optimal compression is

$$D_{2\rm opt} = \frac{P}{1+P^2} T_0^2. \quad (6)$$

A detailed derivation of (6) can be found in the Appendix. Under the condition given by (6), the maximum pulse compression ratio is equal to the time-bandwidth product of the chirped microwave signal. Therefore, the technique presented here has an equivalent compression performance to that of a complex matched filter, which is widely used in radar systems [15].

III. Results

A proof-of-concept experiment is carried out to verify the proposed technique. The experimental setup shown in Fig. 2 is built, which consists of a tunable laser source, a Mach–Zehnder modulator (MZM), two FBGs, and a high-speed photodetector. The tunable laser source has a wavelength tunable range from 1520 to 1620 nm and a wavelength resolution of 1 pm, which is used as the optical source to produce a CW optical carrier. A polarization controller connected before the MZM is used to adjust

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

the polarization state of the optical carrier to the MZM, to minimize the polarization-dependent loss. The swept-frequency microwave signal generated by a vector network analyzer (VNA) is applied to the MZM via its RF port. At the output of the MZM, the modulated optical signal consisting of an optical carrier and two sidebands is generated. To realize single-sideband modulation, a narrowband FBG, FBG1, with very high reflectivity is used as an optical bandstop filter to suppress one sideband while transmitting both the optical carrier and the other sideband without introducing additional phase distortions. Although single-sideband modulation using a dual-drive modulator and a microwave phase shifter has been developed [16], our double-sideband modulation + FBG approach is a promising alternative with the features of low cost and easy to implement. The experimental result shows that a sideband suppression ratio as high as 50 dB is realized by using a regular MZM and a strong narrowband FBG. The second FBG, FBG2, is properly designed to have a phase response to introduce phase changes to both the optical carrier and the remaining single sideband. The microwave signal is then recovered via heterodyne detection at the high-speed photodetector. The frequency response of the photonically implemented microwave filter is characterized by the VNA.

A. Design of FBG as an Optical Phase Filter

In the proposed system, FBG2 shown in Fig. 2 is designed to have a phase response, which is transferred to the microwave filter with the desired phase response for chirped microwave pulse compression. As a simple example, to realize pulse compression of a linearly chirped microwave signal, according to (5), the microwave filter with a linear group delay is required. Equation (5) can then be rewritten as

$$\begin{aligned}\tau_{\mathrm{RF}}(\Omega) &= \frac{d\Psi(\Omega)}{d\Omega} \\ &= \lim_{\Delta\Omega\to 0} \frac{\theta(\omega_c+\Omega+\Delta\Omega)-\theta(\omega_c+\Omega)}{\Delta\Omega} \\ &= \left.\frac{d\theta(\omega)}{d\omega}\right|_{\omega_c+\Omega} \\ &= \tau(\omega_c+\Omega) \end{aligned} \tag{7}$$

where $\tau(\omega_c+\Omega)$ is the frequency-dependent optical group delay experienced by the remaining sideband in FBG2.

According to (7), FBG2 with a highly linear optical group-delay response within a narrow bandwidth from ω_c to $\omega_c+\Omega$ would enable the implementation of a microwave filter with a linear group-delay response. To efficiently compress the input linearly chirped microwave pulse, the optical group delay response, or the optical dispersion of the FBG2 must be properly designed according to the characteristics of the input microwave pulse, such as the chirp parameter u and the frequency bandwidth B. According to (7), the required optical dispersion parameter d (in picoseconds/nanometer) is determined by the microwave pulse chirp profile, and is expressed as

$$d = -\frac{c}{2\pi\lambda_c^2 n}\frac{T_0}{B} = -\frac{c}{2\pi\lambda_c^2 n}\frac{1}{u} \tag{8}$$

where λ_c is the optical carrier wavelength, n is the refractive index of the FBG, T_0 is the width of the input pulse, B is the pulse bandwidth, and $|u| = B/T_0$ is the signal frequency chirp parameter.

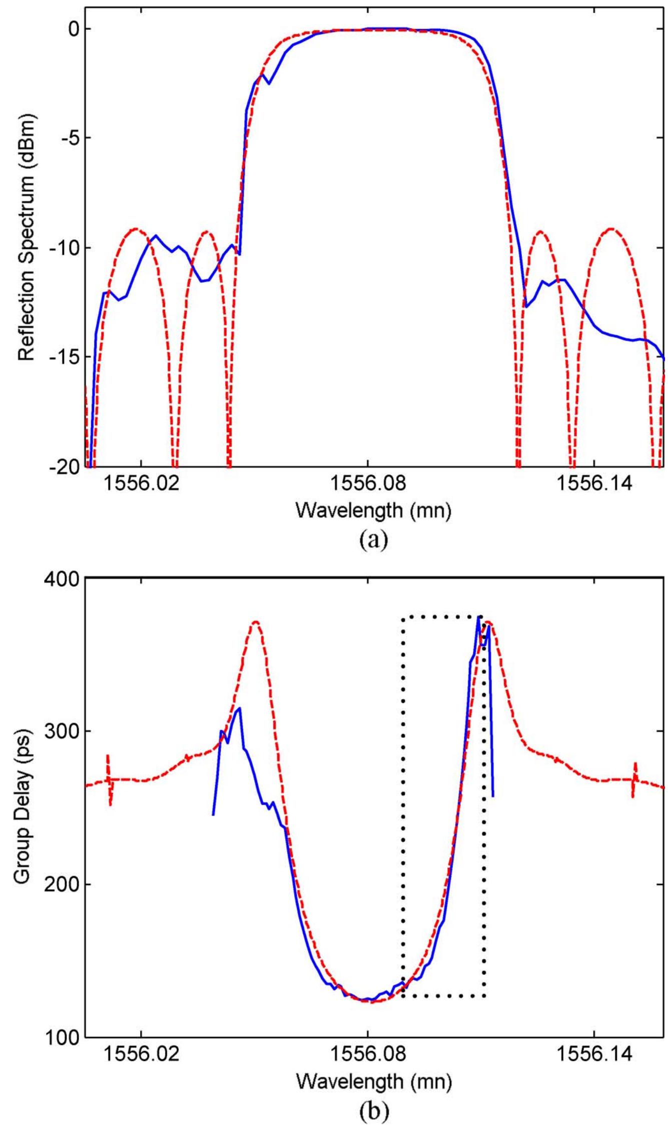

Fig. 3. Designed FBG for the implementation of the optical phase filtering. (a) Reflection sepctra. (b) Group delay responses (solid lines: experimental results; dashed lines: simulation results).

Consider an input linearly chirped microwave pulse having a bandwidth $B = 3$ GHz, a chirp parameter $u = -0.8$ GHz/ns, which corresponds to a time-bandwidth product of 11.25. Therefore, according to (8), FBG2 should have a large chromatic dispersion of 16770 ps/nm in a 0.024-nm bandwidth. This requirement can be met by using a uniform FBG. Fig. 3 shows the reflection spectrum and the group delay response of a fabricated uniform FBG. Both the simulation and experiment results are shown in Fig. 3 for comparison. The simulation results, which are obtained by solving the coupled mode equations using the piecewise-uniform matrix approach [17], are shown as dashed lines. Based on the simulation, a uniform FBG with a length of 50 mm, a refractive index modulation of 0.00008 and a central wavelength of 1556.08 nm is then fabricated using a frequency-doubled Argon-Ion laser operating at 244 nm. The measured results are plotted in Fig. 3 as

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

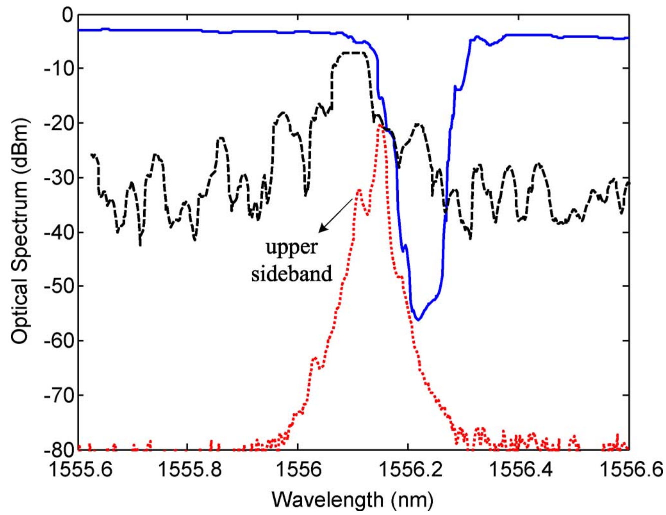

Fig. 4. Experimental results: optical spectra of the gratings and the optical signals (solid line: transmission of FBG1; dashed line: reflection of FBG2; dotted line: single-sideband modulated optical signal).

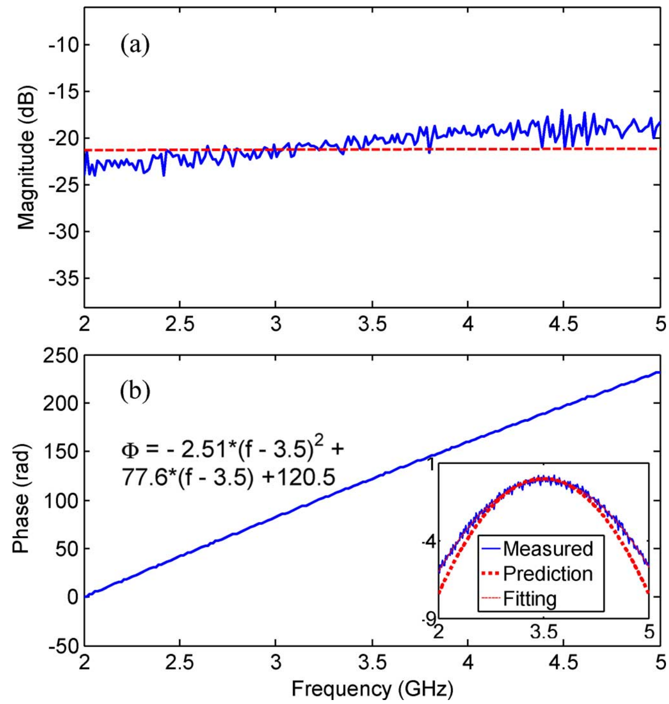

Fig. 5. Experimental results: frequency response of the microwave filter. (a) Magnitude transmission response (solid line: measured response; dashed line: desired response). (b) Measured phase response. Inset: parabolic phase response after subtracting the linear phase component (dashed line: quadratic curve-fitting; dotted line: theoretical prediction).

solid lines. From Fig. 3(b), we can see that in the spectrum down-ramp region (enclosed by a dotted rectangle, around 0.018-nm bandwidth), nearly linear group delay difference of 240 ps is achieved, which is equivalent to an optical dispersion of 13610 ps/nm. As an optical phase filter, the FBG is preferred to have a unity magnitude response. Although the magnitude spectrum is falling off rapidly within the dashed rectangle, it only has impact on the envelope of the compressed pulse. It is the group delay response that determines the microwave filter performance for pulse compression.

Such an FBG with the properly designed group delay response can then be used to build a photonic microwave filter with a quadratic phase response for linearly chirped microwave pulse compression. Note that the realized optical dispersion is not exactly identical to the designed dispersion value. The optical dispersion mismatch may reduce the filter performance for microwave pulse compression.

B. Microwave Filter With a Nonlinear Phase Response

A microwave filter is experimentally demonstrated using the FBG presented above based on the setup shown in Fig. 2. The wavelength of the optical carrier is set at $\lambda_c = 1556.15$ nm. The first FBG, FBG1, which is used as an optical notch filter to filter out one sideband, has a center wavelength of 1556.23 nm, a 3-dB bandwidth of 0.04 nm, and a sideband suppression ratio more than 50 dB. The other FBG, FBG2, designed as an optical phase filter, has a center wavelength of 1556.10 nm and a 3-dB bandwidth of 0.067 nm. The measured transmission spectrum of FBG1, the reflection spectrum of FBG2, as well as the spectrum of the single-sideband modulated optical signal, are all shown in Fig. 4, where the microwave modulating frequency is $\Omega = 2\pi \times 4$ GHz. In our implementation, the upper sideband (with shorter wavelength) is selected. Note that, however, in general, either one of the two sidebands can be chosen.

Both the magnitude and phase responses of the implemented microwave filter are measured using the VNA by sweeping the modulating frequency from 2 to 5 GHz while keeping the output RF power of 5 dBm. The operational frequency range is mainly limited by the narrow operational bandwidth of the optical filter. One solution to eliminate this limitation is to develop an optical phase filter with a broader operational bandwidth. This will be discussed in more detail in Section III-C.

Fig. 5(a) shows the measured magnitude response of the implemented microwave filter. As discussed in Section II, the desired microwave filter is a phase-only filter with a flat magnitude response, as shown via the dashed line in Fig. 5(a). The measured magnitude response has a good flatness with variations limited within 4 dB. The variations in magnitude response are mainly resulted from the three sources: the electrical-optical conversion at the MZM, the optical-electrical conversion at the photodetector, and the nonflat magnitude response of the optical filter (FBG2). A theoretical analysis on the impact of optical filter magnitude response variations on a linearly chirped microwave pulse when passing through a photonic system has been reported in [18].

The measured phase response of the microwave filter is plotted in Fig. 5(b). The polynomial curve-fitting shows that the phase response is nearly quadratic. Based on the fitting result, the microwave dispersion parameter of the microwave filter can be calculated as

$$D_2 = \frac{d^2\Phi}{d\omega^2} = \frac{1}{(2\pi)^2}\frac{d^2\Phi}{df^2} = -\frac{5.02}{(2\pi)^2}\ (\mathrm{ns}^2). \qquad (9)$$

Note that the microwave filter has a strong linear phase response in addition to the desired quadratic phase response, which means that a large frequency-independent group delay is introduced in the filter. To show the nonlinear phase response

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

more clearly, the linear phase component $\Phi = 77.6f - 151.1$ can be removed from the entire measured phase response. A parabolic phase response is thus obtained after subtracting the linear phase, as shown in the inset of Fig. 5(b). A quadratic curve-fitting is also shown via the dashed line. The phase variation is limited within around 0.4 rad. The theoretical prediction of the phase response by (6) is also plotted as dotted line in the inset for comparison. Note that the difference between the phase response of the implemented microwave filter and that of the desired filter mainly comes from the optical dispersion mismatch in FBG2, as discussed in Section III-A.

Photonic microwave filter with arbitrary phase response using a spatial light modulator has been recently reported [19]. The key advantage of the approach is that the spatial light modulator can be updated in real time, which enables the filter to be reconfigurable with arbitrary phase and magnitude responses. The major difficulty associated with the use of a spatial light modulator, however, is that free-space optics is required, which involves fiber-to-space and space-to-fiber coupling, making the system bulky, lossy, and complicated. The approach presented in this paper is implemented in a pure fiber-optics-based platform, which features a smaller size, lower loss, and a better resistance to the environmental changes. In addition, the use of all fiber-based components has the potential for integration using photonic integrated-circuits techniques.

C. Linearly Chirped Microwave Pulse Compression

The compression of a linearly chirped microwave pulse using the implemented microwave filter with a quadratic phase response is investigated. Consider again the linearly chirped Gaussian microwave pulse with a bandwidth $B = 3$ GHz and a chirp parameter $u = -0.8$ GHz/ns. The original temporal waveform $s(t)$ with a pulsewidth $T_0 = 3.75$ ns is plotted as a dotted line in Fig. 6. The compressed microwave signal $r(t)$ is obtained at the output of the microwave filter, which is given by

$$r(t) = \widetilde{F}^{-1}\left[\widetilde{S}(\Omega)H(\Omega)\right] \qquad (10)$$

where $H(\Omega)$ is the transfer function (both amplitude and phase) of the implemented microwave filter, $\widetilde{S}(\Omega)$ is the Fourier transform of the input signal $s(t)$, and $\widetilde{F}^{-1}(\bullet)$ denotes the inverse Fourier transform operation.

The compressed microwave pulse calculated based on (10) is also shown as a solid line in Fig. 6. A pulse compression ratio of 5.62 is achieved. Both the desired and achieved system performances are summarized in Table I for comparison. We can see that the compression ratio is smaller than the time-bandwidth product of the input microwave pulse due to the mismatch between the phase response of the microwave filter and that of the input microwave pulse. Based on (6), the optimal microwave filter dispersion parameter should be $D_{2\text{opt}} = 0.1678$ ns^2. On the other hand, the realized microwave filter dispersion parameter is $D_2 = 0.1273$ ns^2. The microwave dispersion parameter mismatch is due to the optical dispersion mismatch. The design of an optical phase filter with more accurate group delay response would enable an improved compression performance. The inset of Fig. 6 provides a zoom-in view of the compressed microwave pulse envelope (via a solid line). The envelope of compressed Gaussian microwave pulse by an ideal phase-only filter is also plotted for comparison (via a dashed line). Note that the microwave filter magnitude response perturbations have no obvious impact on the pulse compression (even a slight improvement on the compression ratio).

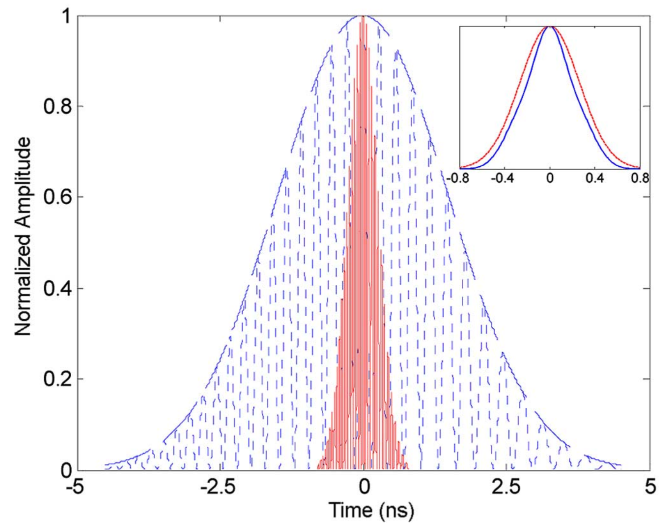

Fig. 6. Temporal waveforms (dotted line: original microwave pulse; solid line: compressed microwave pulse). Inset: zoom-in view of the envelopes of the compressed microwave pulses.

TABLE I
COMPARISON OF SYSTEM PERFORMANCES

System Performances	Desired Value	Achieved Value
Optical Filter Dispersion (ps/nm)	16770	13610
Microwave Filter Dispersion (ns^2)	0.1678	0.1273
Microwave Filter Phase Response Variation (rad)	0	0.4
Microwave Filter Magnitude Response Variation (dB)	0	4
Microwave Pulse Compression Ratio	11.25 (TBWP of the input pulse)	5.62

Time-bandwidth product (TBWP).

IV. DISCUSSION

A. Bandwidth Extension

In this paper, a proof-of-concept experiment is carried out, which works within a relative narrow bandwidth (a few gigahertz), limited by the bandwidth of the optical phase filter. For many practical applications, high-frequency and broadband linearly chirped microwave pulses are usually required to be compressed. In addition, the magnitude response variations are found in the demonstrated microwave filter. Therefore, a broadband optical phase filter with a linear group-delay response and a flatter magnitude response will be required to achieve true phase-only filtering for high-frequency linearly chirped microwave pulse compression. One solution to the problem is to construct a long-length linearly chirped FBG,

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

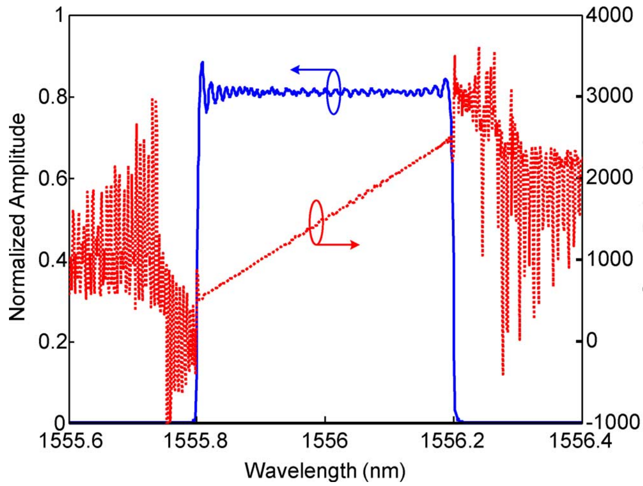

Fig. 7. Simulation results: reflection spectrum and group delay of a broadband linearly chirped FBG.

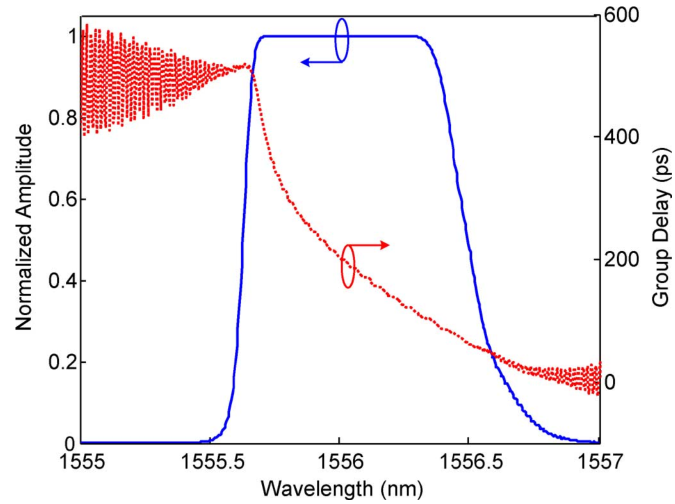

Fig. 8. Simulation results: reflection spectrum and group-delay response of a broadband nonlinearly chirped FBG.

which can provide a large linear group delay. Moreover, the linearly chirped FBG with a properly designed index modulation function would ensure the microwave filter to have a unity magnitude transmission response. Such a grating reconstruction problem can be numerically solved by using the inverse scattering algorithms, such as the discrete layer-peeling (DLP) algorithm [20].

As an example, to build a microwave filter with a quadratic phase response for the compression of a linearly chirped microwave pulse with a bandwidth of 50 GHz, and a chirp parameter $u = -2.68$ GHz/ns, the linearly chirped FBG should have an optical dispersion of 5000 ps/nm, a bandwidth of 0.4 nm, and a grating length as long as 30 cm. Since the facility currently available in the laboratory cannot fabricate such a long grating, the potential of the proposed technique for broadband operation is supported by simulations. Fig. 7 shows the simulation results of a linearly chirped FBG designed by using the DLP algorithm. Both the linear group delay and unity magnitude response are obtained. In fact, such a long grating can be easily realized with the current FBG fabrication technology. Recently, a linearly chirped FBG with a length up to 1 m has been demonstrated [21], which can be used to compress a chirped microwave pulse with a bandwidth as large as 165 GHz for the same given chirp parameter. In addition, a longer grating length would make it easier to control the magnitude response of the grating.

B. Compression of Nonlinearly Chirped Microwave Pulse

In our study, only a linearly chirped microwave signal is considered since it is the most commonly used pulsed signal for most of the applications. It is worth noting that a linear frequency chirping is not always necessary in a microwave pulse compression system. In fact, the frequency modulation can be of any form, provided that the compression filter in the receiver end is designed to match the phase of the microwave pulse to be compressed.

Here we consider the compression of a nonlinearly chirped microwave pulsed signal. The use of a nonlinearly frequency modulated signal for pulse compression has the advantage of a reduced sidelobe level if the input pulse is compressed [22]. According to the expressions in (5) and (7), to compress a nonlinearly chirped microwave signal, an optical phase filter with a quadratic group-delay response, or equivalently, a cubic phase response is required. In addition, the optical phase filter should have a broad bandwidth and a unity magnitude response. The DLP algorithm is again utilized to reconstruct the desired FBG in the numerical simulation. A nonlinearly chirped FBG with a quadratic group delay is obtained, with the reflection spectrum and group delay response being shown in Fig. 8. A simple way to fabricate such a nonlinearly chirped FBG is to use a custom-designed nonlinearly chirped phase mask [23], but at a higher cost. A low-cost solution is to generate a nonlinearly chirped FBG from a regular linearly chirped FBG by applying a strain to the grating using the strain-gradient beam tuning technique [9].

V. Conclusion

We have proposed an approach to implementing microwave pulse compression using a photonic microwave filter with a nonlinear phase response. The proposed microwave filter was realized based on single-sideband modulation and heterodyne detection at a high-speed photodetector, to transfer the optical filter response to the response of the microwave filter. The key component in the proposed system is the FBG, which was designed to have a user-defined nonlinear phase response. The key advantage of this approach is that the system can be implemented using pure fiber-optic components, which has the potential for integration.

A detailed theoretical analysis on the photonic microwave filter design and the chirped microwave pulse compression was developed. A photonic microwave filter having a quadratic phase response with a bandwidth of 3 GHz was experimentally generated. The compression of a linearly chirped microwave pulse using the implemented microwave filter was investigated. A pulse compression ratio of 5.62 was demonstrated. To achieve a higher pulse compression ratio for a highly chirped microwave pulse, an optical filter with more accurately controlled phase response and a broader bandwidth is required.

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

Potential solutions were discussed and demonstrated by numerical simulations.

For an optical filter with large bandwidth, the operation frequency of the system is limited only by the bandwidth of the photodetector and the modulator. For example, to compress a chirped microwave pulse with its highest frequency of 50 GHz, both the photodetector and the modulator must have a bandwidth of 50 GHz.

The demonstrated approach offers an optical solution to the compression of a high-frequency chirped microwave signal for applications in modern radar and other civil and defense systems.

APPENDIX

Mathematically, an amplitude-normalized linearly chirped Gaussian microwave pulse can be expressed as

$$s(t) = \exp\left(-\frac{t^2}{2T_0^2}\right)\exp\left[j\left(\Omega_0 t + \frac{ut^2}{2}\right)\right] \tag{11}$$

where T_0 is the width of the pulse at the $1/e$ maximum, Ω_0 is the central microwave angular frequency, $|u| = B/T_0$ is the signal frequency chirp parameter, and B is the overall frequency bandwidth. The reason we select a Gaussian pulse rather than a normal rectangular pulse is that a Gaussian pulse has inherently low correlation sidelobes.

The frequency-domain expression of the linearly chirped Gaussian signal can be obtained by the Fourier transform

$$\widetilde{S}(\Omega) = \widetilde{F}[s(t)] = \left(\frac{2\pi T_0^2}{1-jP}\right)^{1/2}\exp\left[-\frac{(\Omega-\Omega_0)^2 T_0^2}{2(1-jP)}\right] \tag{12}$$

where $\tilde{F}(\cdot)$ denotes the Fourier transform operation. Here, for simplicity, we introduce a new notation $P = uT_0^2$, which is the time-bandwidth product of the linearly chirped microwave signal.

It is known that the group delay of the linearly chirped microwave signal is a linear function with respect to the microwave frequency. According to (5), to compress the linearly chirped signal, a microwave filter with an opposite linear group delay response, or equivalently, a quadratic phase response is required. According to (4b), this can be obtained by setting the optical phase filter with a quadratic phase response. A detailed analysis on the design of the optical filter with the required phase response for the linearly chirped microwave pulse compression has been represented in Section III. Here, we firstly consider a microwave filter with a quadratic phase response, given by

$$\Psi(\Omega) = D_2\Omega^2 + D_1\Omega + D_0 \tag{13}$$

where D_0 is a constant phase shift, $D_1 = d\Psi/d\Omega$ is a frequency-independent group delay introduced by the filter, and $D_2 \propto d^2\Psi/d\Omega^2$ is the dispersion parameter of the microwave filter. Since the last two terms will not affect the operation of the pulse compression, only the first term will be considered here.

The transfer function of the microwave filter with only the first term in (13) being considered is given as $H(\Omega) = |H(\Omega)|\exp[jD_2\Omega^2]$. When the linearly chirped signal is passing through the filter, we have the filtered microwave signal $r(t)$, which is given by

$$\begin{aligned} r(t) &= \widetilde{F}^{-1}\left[\widetilde{S}(\Omega)H(\Omega)\right] \\ &= \frac{|\rho(\omega_c)|^2 T_0}{[T_0^2 - jD_2(1-jP)]^{1/2}} \\ &\quad \times \exp\left[-\frac{(1-jP)t^2}{2[T_0^2 - jD_2(1-jP)]} + j\Omega_0 t\right]. \end{aligned} \tag{14}$$

Therefore, the filtered microwave signal maintains its Gaussian shape, but with a compressed pulsewidth. Let T_1 represent the pulsewidth of the signal after passing through the microwave filter. The pulse compression ratio γ is then given as follows:

$$\gamma = \frac{T_0}{T_1} = \left[\left(1 - \frac{D_2 P}{T_0^2}\right)^2 + \left(\frac{D_2}{T_0^2}\right)^2\right]^{-1/2}. \tag{15}$$

According to (15), the compression only occurs when the microwave filter has an opposite dispersion with respect to that of the input chirped microwave pulse $(D_2 u > 0)$. The pulse reaches the maximum compression when the chirp of the input pulse is completely cancelled by the dispersion of the filter. Mathematically, for an input chirped microwave signal with a given chirp, the maximum compression factor occurs when the following condition is satisfied:

$$D_{2\mathrm{opt}} = \frac{P}{1+P^2}T_0^2 \tag{16}$$

where $D_{2\mathrm{opt}}$ (in $\mathrm{ns}^2(10^{-18}\mathrm{s}^2)$) denotes the optimal filter dispersion parameter required for a maximum compression of a linearly chirped microwave pulse with a time-bandwidth product P and a pulsewidth T_0. Equation (16) gives us a guideline for the design of a microwave filter with an optimal phase response for a given linearly chirped microwave pulse. The maximum compression ratio can be calculated by

$$\gamma_{\max} = (1+P^2)^{1/2}. \tag{17}$$

For $P \gg 1$, which is always true for a highly chirped microwave pulse, we have $\gamma_{\max} \cong P$. This demonstrates that the maximum compression ratio is equal to the time-bandwidth product of the input linearly chirped microwave signal.

REFERENCES

[1] A. W. Rihaczek, *Principles of High-Resolution Radar*. Norwood, MA: Artech House, 1996.
[2] H. Kwon and B. Kang, "Linear frequency modulation of voltage-controlled oscillator using delay-line feedback," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 6, pp. 431–433, Jun. 2005.
[3] A. M. Kawalec, "SAW dispersive delay lines in radar signal processing," in *IEEE Int. Radar Conf.*, May 1995, pp. 732–736.
[4] H. D. Griffiths and W. J. Bradford, "Digital generation of high time-bandwidth product linear FM waveforms for radar altimeters," *Proc. Inst. Elect. Eng.*, vol. 139, no. 2, pt. F, pp. 160–169, Apr. 1992.
[5] S. G. Qadir, J. K. Kayani, and S. Malik, "Digital implementation of pulse compression technique for X-band radar," in *Int. Appl. Sci. Technol. Bhurban Conf.*, Jan. 2007, pp. 35–39.
[6] 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.

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.

[7] 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.
[8] A. Zeitouny, S. Stepanov, O. Levinson, and M. Horowitz, "Optical generation of linearly chirped microwave pulses using fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 660–662, Mar. 2005.
[9] 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.
[10] C. Wang and J. P. Yao, "Photonic generation of chirped microwave pulses using superimposed chirped fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 20, no. 11, pp. 882–884, Jun. 2008.
[11] C. Allen and S. Gogineni, "A fiber-optic-based 1550-nm laser radar altimeter with RF pulse compression," in *Proc. Int. Geosci. Remote Sens. Symp.*, Hamburg, Germany, Jun. 20–Jul. 2 1999, vol. 3, pp. 1740–1742.
[12] R. L. Fork, C. H. Brito-Cruz, P. C. Becker, and C. V. Shank, "Compression of optical pulses to six femtoseconds by using cubic phase compensation," *Opt. Lett.*, vol. 12, no. 7, pp. 483–485, Jul. 1987.
[13] Y. Dai and J. P. Yao, "Nonuniformly-spaced photonic microwave delay-line filter," *Opt. Exp.*, vol. 16, no. 7, pp. 4713–4718, Mar. 2008.
[14] C. Wang and J. P. Yao, "Photonic microwave matched filters for chirped microwave pulse compression," in *Proc. IEEE Int. Top. Microw. Photon. Meeting*, Sep. 30–Oct. 3 2008, pp. 47–50.
[15] M. I. Skolnik, *Radar Handbook*, 2nd ed. New York: McGraw-Hill, 1990.
[16] M. Izutsu, S. Shikama, and T. Sueta, "Integrated optical SSB modulator/frequency shifter," *IEEE J. Quantum Electron.*, vol. QE-17, no. 11, pp. 2225–2227, Nov. 1981.
[17] M. Yamada and K. Sakuda, "Analysis of almost-periodic distributed feedback slab waveguides via a fundamental matrix approach," *Appl. Opt.*, vol. 26, no. 16, pp. 3474–3478, Aug. 1987.
[18] R. Rotman, O. Raz, and M. Tur, "Analysis of a true time delay photonic beamformer for transmission of a linear frequency-modulated waveform," *J. Lightw. Technol.*, vol. 23, no. 12, pp. 4026–4036, Dec. 2005.
[19] S. Xiao and A. Weiner, "Programmable photonic microwave filters with arbitrary ultra-wideband phase response," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 11, pp. 4002–4008, Nov. 2006.
[20] R. Feced, M. N. Zervas, and M. A. Muriel, "An efficient inverse scattering algorithm for the design of nonuniform fiber Bragg gratings," *IEEE J. Quantum Electron.*, vol. 35, no. 8, pp. 1105–1115, Aug. 1999.
[21] M. Ibsen, M. K. Durkin, M. N. Zervas, A. B. Grudinin, and R. I. Laming, "Custom design of long chirped Bragg gratings: Application to gain-flattening filter with incorporated dispersion compensation," *IEEE Photon. Technol. Lett.*, vol. 12, no. 5, pp. 498–500, May 2000.
[22] M. Pollakowski and H. Ermert, "Chirp signal matching and signal power optimization in pulse-echomode ultrasonic nondestructive testing," *IEEE Trans. Ultrason. Ferroelecrt. Freq. Control*, vol. 41, no. 5, pp. 655–659, Sep. 1994.
[23] S. Lee, R. Khosravani, J. Peng, V. Grubsky, D. S. Starodubov, A. E. Willner, and J. Feinberg, "Adjustable compensation of polarization mode dispersion using a high-birefringence, nonlinearly chirped fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 11, no. 10, pp. 1277–1279, Oct. 1999.

Chao Wang (S'08) received the B.Eng degree in opto-electrical engineering from Tianjin University, Tianjin, China, in 2002, the M.Sc degree in physics from Nankai University, Tianjin, China, in 2005, and is currently working toward the Ph.D. degree in electrical engineering in the School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada.

His current research interests include microwave signal generation, radio-over-fiber systems, FBGs, and applications in microwave photonics systems.

Jianping Yao (M'99–SM'01) received the Ph,D, degree in electrical engineering from the Université de Toulon, Toulon, France, in 1997.

In 2001, he joined the School of Information Technology and Engineering, University of Ottawa, ON, Canada, where he is currently a Professor, Director of the Microwave Photonics Research Laboratory, and Director of the Ottawa–Carleton Institute for Electrical and Computer Engineering. From 1999 to 2001, he held a faculty position with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He holds a Yongqian Endowed Visiting Chair Professorship with Zhejiang University, Zhejiang, China. He spent three months as an Invited Professor with the Institut National Polytechnique de Grenoble, Grenoble, France, in 2005. He was named University Research Chair in Microwave Photonics in 2007. He has authored or coauthored over 110 papers in refereed journals and over 100 papers in conference proceeding. He is an Associate Editor of the *International Journal of Microwave and Optical Technology*. His research has focused on microwave photonics, which includes all-optical microwave signal processing, photonic generation of microwaves, millimeter waves, and terahertz, radio-over-fiber, ultra-wideband (UWB) over fiber, FBGs for microwave photonics applications, and optically controlled phased array antennas. His research interests also include fiber lasers, fiber-optic sensors , and bio-photonics.

Dr. Yao is a Registered Professional Engineer in the Province of Ontario. He is a member of The International Society for Optical Engineering (SPIE), the Optical Society of America (OSA). He is a Senior Member of the IEEE Lasers and Electro-Optics Society (LEOS) and the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He is on the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He was the recipient of the 2005 International Creative Research Award of the University of Ottawa and the 2007 George S. Glinski Award for Excellence in Research. He was a recipient of a 2008 Natural Sciences and Engineering Research Countil of Canada (NSERC) Discovery Accelerator Supplements Award.

Authorized licensed use limited to: University of Ottawa. Downloaded on February 6, 2009 at 20:14 from IEEE Xplore. Restrictions apply.