Optical Generation of Linearly Chirped Microwave Pulses Using Fiber Bragg Gratings

Avi Zeitouny, Sander Stepanov, Oren Levinson, and Moshe Horowitz

***Abstract*—We demonstrate a new method to generate broad spectrum chirped microwave pulses using an electrooptical system. Two fiber Bragg gratings and a mode-locked fiber laser were used to generate pulses with a linear frequency chirp. The bandwidth of the microwave pulses can be significantly broader than the bandwidth that can be obtained using electronic systems. The parameters of the chirp can be easily controlled by adjusting the parameters of the optical system. The same method can be used to generate microwave pulses with a complex frequency modulation.**

***Index Terms*—Chirp modulation, gratings, interference, microwave generation.**

I. Introduction

ELECTROOPTICAL systems allow us to increase the bandwidth and to reduce the size, the weight, and the cost of microwave systems. Several methods have been used to generate continuous-wave microwave and millimeter wave signals using optical systems [1], [2]. Microwave pulses can also be generated using an optical system [3], [4]. The pulses can be generated using spectral shaping of a supercontinuum source followed by a dispersive element [4]. In a previous work [3], we have demonstrated a new method to optically generate microwave pulses with a complex amplitude profile that can be controlled in real-time by using dispersion, Kerr effect, and group velocity delay in an optical birefringent fiber or by using a fiber Bragg grating (FBG). The FBG was used to generate pulses with a constant frequency that could be simply changed by adjusting the parameters of the optical system. The optical system was based on interfering two optical pulses that propagated in a fiber system with dispersion and Kerr effect. However, since the two pulses were affected by the same effects, the system could not be used to generate pulses with a complex arbitrary profile, such as pulses with a linear chirp.

In this letter, we propose a simple and compact optical system to generate complex microwave pulses such as pluses with a linear chirp. The method is based on interfering two optical pulses that were reflected from two different FBGs. Each grating induces a different chirp in an optical pulse. The interference between the two chirped pulses induces a broad-band microwave pulse with a linear chirp. The parameters of the chirp can be easily controlled by adjusting the parameters of the optical system. For example, the frequency offset of the pulse chirp could be easily controlled by adjusting a tunable optical delay line. The bandwidth of the generated microwave pulses can be much broader than can be generated using electronic systems. The same method can be used to generate microwave pulses with a nonlinear chirp.

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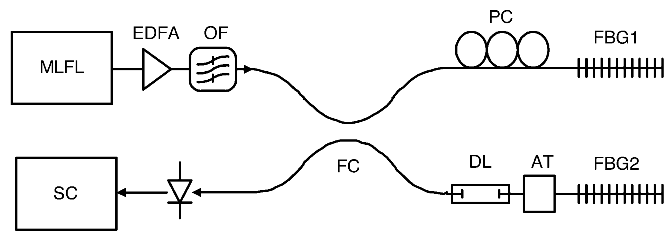

Fig. 1. Schematic description of the optical system used to generate chirped microwave pulses. MLFL is a mode-locked fiber laser. SC is a sampling oscilloscope. EDFA is an erbium-doped fiber amplifier. OF is an optical filter. FC is a fiber coupler. PC is a polarization controller. DL is a tunable optical delay line. AT is an attenuator. FBG1 and FBG2 are chirped FBGs.

The generation of broad-band pulses is important for pulse compression radars [5] and for spread-spectrum communication systems [6]. In pulse compression radars, long pulses are transmitted and then compressed at the receiver. The pulse compression enables a large radiated energy increase without causing a voltage breakdown in the transmitter while maintaining a high range resolution. Moreover, the technique also enables the reduction of the effect of clutter, multipath interference, and electronic countermeasures [5]. Microwave pulses with a linear chirp, such as demonstrated in this work, are the most popular pulses used in radars based on pulse compression [5]. The use of optical pulses to generate the pulses, as suggested in this letter, enables a significant increase in the bandwidth of the pulses and, hence, improves the performance of the radar system. The technique described in this letter can also be used to generate pulses with a nonlinear chirp. Such pulses have several distinct advantages over pulses with a linear chirp. For example, pulses with a nonlinear chirp make it possible to obtain very low sidebands after the pulse compression in the receiver. However, pulses with a nonlinear chirp attained little acceptance due to the complexity of the system [5]. The use of optical systems similar to that describe in this letter may overcome the difficulties in generating complex microwave pulses.

II. Experimental Setup

The experimental setup used in our system is shown in Fig. 1. A broad-band passively mode-locked fiber laser generates a train of pulses with a repetition rate of about 20 MHz, an optical bandwidth of 30 nm, and an average power of 2 mW. The pulses are filtered and amplified using an erbium-doped fiber amplifier in order to obtain pulses with a bandwidth of 0.85 nm, a central wavelength of 1548.5 nm, and an average power of about 10 mW. Two different FBGs were used. Both gratings had a center wavelength of 1548.5 nm, a maximum reflectivity of 25%, and a bandwidth of 1 nm. The first grating (FBG1) was 10 cm long and had a linear chirp of 0.072 nm/cm. The second grating was 11 cm long and had a linear chirp of 0.112 nm/cm. The relative optical delay between the pulses reflected from the two gratings was controlled using an optical delay line. The pulse duration at the output of FBG1 and FBG2 was 1150 and 750 ps, respectively. The interference between the pulses was detected by a photodetector having a bandwidth of 30 GHz and a sampling oscilloscope. An optical attenuator and a polarization controller were used in order to obtain the maximum modulation depth of the microwave pulses.

III. Theoretical Model

When the grating reflectivity is small, the Born approximation becomes accurate and the chirp of the gratings adds a second-order dispersion to the optical pulses [7]. In this case, the reflection spectrum of the jth grating $(j = 1, 2), r_j(\omega)$ is equal to

$$r_j(\omega) = |r_j(\omega)| \exp\left\{\frac{i}{2} D_j \omega^2\right\} \tag{1}$$

where ω is the frequency and D_j is the dispersion of the jth grating. After the reflection from the gratings, the pulse amplitude can be written as [8]

$$A_j(t) = F^{-1}[\tilde{A}_o(\omega) r_j(\omega)] = 2\pi G_j(t) * \left(\sqrt{\frac{i}{|D_j|}} e^{-\frac{i}{2}\frac{t^2}{D_j}}\right) \tag{2}$$

where F^{-1} is the inverse Fourier transform, $*$ denotes the convolution operator, $\tilde{A}_o(\omega)$ and $A_o(t)$ are the amplitude of the incident pulse given in the frequency and in the time domain, respectively, and $G_j(t) \equiv F^{-1}[\tilde{A}_o(\omega)|r_j(\omega)|]$. Assuming that the spectrum of the pulse is narrower than that of the grating, and assuming a grating with a uniform reflectivity at the Bragg zone, the function $G_j(t)$ can be approximated by $A_o(t)$. The interference between the two reflected pulses is given by

$$\begin{aligned} I(t) &= |A_1(t)|^2 + |A_2(t + \Delta t)|^2 \\ &+ 2|A_1(t)||A_2(t + \Delta t)| \cos[\phi_1(t) - \phi_2(t + \Delta t) + \Delta\phi_o] \end{aligned} \tag{3}$$

where Δt is the relative time delay between the two pulses and $\Delta\phi_o$ is a time independent phase.

In order to obtain implicit results, we assume that the pulses at the input of the gratings are unchirped gaussian pulses, $A(t) = \exp\{-t^2/2\tau^2\}$. In this case, (2) becomes

$$A_j(t) = \frac{\tau\sqrt{\text{sign}(D_j)}}{\sqrt{\tau^2 - iD_j}} e^{-t^2/[2(\tau^2 - iD_j)]}$$

and the interference pattern between the reflected pulses is

$$\begin{aligned} I(t) &= |A_1(t)|^2 + |A_2(t + \Delta t)|^2 \\ &+ 2|A_1(t)||A_2(t + \Delta t)| \cos[K_1 \cdot t^2 - K_2 \cdot (t + \Delta t)^2 + \Delta\phi_o] \end{aligned}$$

where $K_j = -D_j/2(\tau^4 + D_j^2)$.

The instantaneous frequency of the microwave pulse is equal to

$$f(t) = \frac{1}{\pi}(K_1 - K_2)t - \frac{1}{\pi}K_2\Delta t \tag{4}$$

where the instantaneous frequency of a function $g(t) = A \cdot \cos[\phi(t)]$ is defined as [9]

$$f(t) = \frac{1}{2\pi}\frac{d\phi(t)}{dt}.$$

Assuming that the input pulse is a chirp free Gaussian pulse, the frequency $f(t)$ changes linearly across the pulse. A delay between the two reflected pulses Δt will only add a constant value to the instantaneous frequency and will not change its linear dependence on time. A choice of a different grating rather than a grating with a linear chirp will change the frequency dependence of the microwave pulse on time. Therefore, by designing the grating structure, it becomes possible to tailor the frequency profile of the microwave pulses according to the requirements.

The result obtained above can be understood intuitively by considering the effect of a grating with a linear chirp on the incident optical pulses. When the grating reflectivity is weak, the Born approximation can be used, and the optical pulse does not change significantly while propagating inside the grating [10]. In a grating with a linear chirp, the Bragg frequency changes linearly along the grating. In such a grating, each frequency component of the incident pulse is reflected from a different location along the chirped grating. Therefore, different wavelengths in the reflected pulses are linearly ordered in time, as caused by second-order group velocity dispersion. The change rate in the reflected pulse frequency in time is proportional to the chirp slope of the grating structure. The microwave pulse in the detector is the product of the interference of the pulses that were reflected by the two gratings. However, since the chirp slope of each grating is different, the instantaneous frequency of the interference pattern changes linearly in time.

Fig. 2 shows the theoretical profile of the microwave pulses for the setup described in Section II. Both the amplitude and the instantaneous frequency are plotted. As expected, the frequency changes linearly across the microwave pulse as obtained in (4). The instantaneous frequency was also calculated by using the Gabor transform [9] (denoted by squares in Fig. 2) with a Gaussian window having a full-width at half-maximum of 55 ps. In Fig. 2(a), the delay between the centers of the reflected optical pulses was zero. In this case, the frequency profile of the microwave pulse is symmetrical with respect to the center of the pulse and the instantaneous frequency changes from 15 to -15 GHz. In Fig. 2(b), the delay between the two interfering pulses was 190 ps. In this case, the microwave pulse is asymmetric, as can be seen in (4). The instantaneous frequency offset in this case is approximately 15 GHz and, therefore, the instantaneous frequency changes from about 0 to 30 GHz along the pulse. The time overlap between the interfering pulses is smaller in this case than in the symmetric case and, therefore, the pulse becomes slightly shorter. The small fluctuation in the instantaneous frequency that was calculated using the Gabor transform is caused due to the large change in the instantaneous frequency along the pulse that prevents the use of an optimal window.

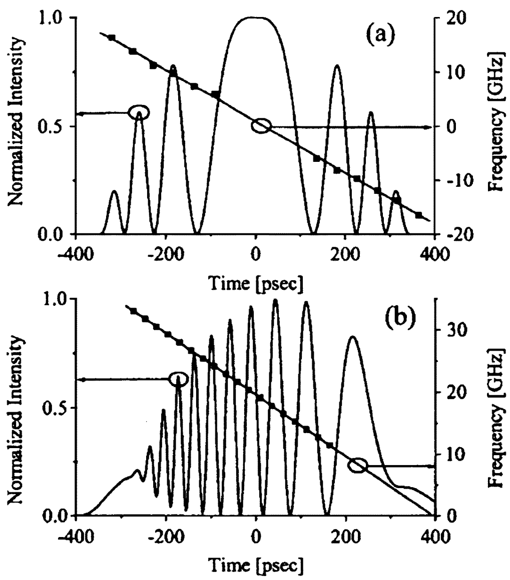

Fig. 2. Microwave pulse profile and the instantaneous frequency, calculated theoretically, for two different time delays between the two optical interfering pulses. The squares denote the instantaneous frequency calculated using Gabor transform.

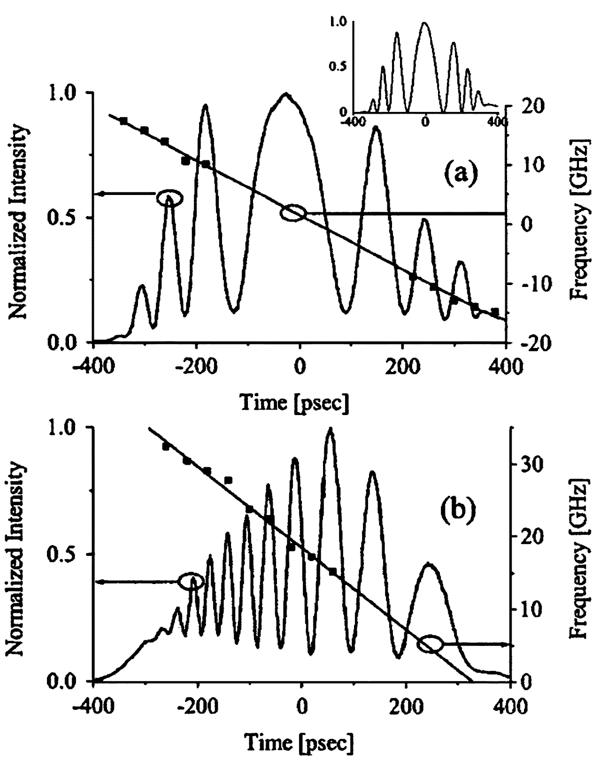

Fig. 3. (a) Symmetric and (b) asymmetric microwave pulse profiles measured experimentally (slid line) and the instantaneous frequency calculated using Gabor transform (squares). The change in the microwave pulses was simply obtained by adjusting the delay line (DL) in the experimental setup.

IV. Experimental Results

The two typical theoretical interference patterns that were shown in Fig. 2 were demonstrated experimentally and are shown in Fig. 3. The change in the interference pattern was simply obtained by controlling the optical delay line, shown in Fig. 1. The results shown in Fig. 3 are in a good quantitative agreement with the theoretical results shown in Fig. 2. The inset of Fig. 3(a) shows the interference pattern calculated using the measured complex spectrum of the gratings, measured using the method given in [11]. The inset of Fig. 3 shows that imperfections in the gratings slightly change the generated pulse. In a radar system, such deviations may reduce the signal-to-noise ratio and distort the sidelobes of the compressed signal at the receiver. However, since the measured distortion of the pulse is small, the performance of the radar is not expected to significantly deteriorate. As opposed to the theoretical results, the modulation depth in the experimental results was limited. This effect is partly caused due to slow measurement time of the sampling oscilloscope. Small changes in environmental conditions during the measurement slightly change the interference pattern and cause a decrease of the modulation depth. Another cause for the smaller modulation depth obtained in the experiments is the polarization mode delay in the optical fibers. The use of polarization-maintaining fiber and controlling the temperature of the experimental setup may increase the modulation depth of the electrical pulse.

V. Conclusion

We have demonstrated theoretically and experimentally a new method to generate linearly chirped broad-band pulses by using FBGs. The bandwidth of the microwave pulses can be significantly broader than the bandwidth that can be obtained using electronic systems. The frequency offset of the instantaneous frequency chirp could be easily controlled by adjusting an optical delay line. The technique can also be used to generate broad-band microwave pulses with a nonlinear chirp that can be tailored according to specifications and can be easily controlled by adjusting the parameters of the optical system.

References

[1] C. H. Lee, "Optical generation and control of microwave and millimiter waves," in *1987 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. II, Jun. 1987, pp. 811–814.

[2] A. Bilenca, J. Lasri, G. Eisenstein, D. Ritter, V. Sidorov, S. Cohen, P. Goldgeier, and M. Orenstein, "Optoelectronic generation and modulation of millimeter waves in a single InP–GaInAs photo heterojunction bipolar transistor," *IEEE Photon. Technol. Lett.*, vol. 12, no. 9, pp. 1240–1242, Sep. 2000.

[3] O. Levinson and M. Horowitz, "Generation of complex microwave and millimiter-wave pulses using dispersion and kerr effect in optical fiber systems," *J. Lightw. Technol.*, vol. 21, no. 5, pp. 1179–1187, May 2003.

[4] 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.

[5] *Radar Handbook*, 2nd ed. New York: McGraw-Hill, 1990. M. I. Skolnik.

[6] J. P. Proakis, *Digital Communications*, international, 4th ed. New York: McGraw-Hill, 2001.

[7] F. Ouellette, "Dispersion cancellation using linearly chirped Bragg grating filters in optical waveguides," *Opt. Lett.*, vol. 12, no. 10, pp. 847–849, 1987.

[8] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. New York: Academic, 1995.

[9] S. Mallet, *A Wavelet Tour of Signal Processing*. San Diego, CA: Academic, 1999.

[10] A. Rosenthal and M. Horowitz, "Inverse scattering algorithm for reconstructing strongly reflecting fiber Bragg gratings," *IEEE J. Quantum Electron.*, vol. 39, no. 8, pp. 1018–1026, Aug. 2003.

[11] M. Zaacks, A. Zeitouny, M. Horowitz, and U. Mahlab, "Measurement technique of phase abberation induced by fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 14, no. 3, pp. 352–354, Mar. 2002.