Advanced Fiber Bragg Gratings For Photonic Generation and Processing of Arbitrary Microwave Waveforms

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***Abstract* —Photonic generation and processing of microwave arbitrary waveforms has been a topic of interest recently. Compared with the electronic techniques, photonics techniques provide the capabilities of generating and processing high-frequency and large-bandwidth microwave waveforms which cannot be fulfilled by the electronic techniques, In this paper, techniques to generate and process microwave arbitrary waveforms in the optical domain using advanced fiber Bragg gratings (FBGs) are reviewed, with an emphasis on the system architectures in which FBGs are employed as spectral shapers or optical filters. The challenges in using FBGs for microwave arbitrary waveform generation and processing are also discussed.**

Index terms —**fiber Bragg grating (FBG), frequency-to-time mapping, microwave photonics, optical pulse shaping, photonic microwave filter, spectral shaping.**

I. INTRODUCTION

Photonic generation and processing of high-frequency and large-bandwidth microwave arbitrary waveforms has become an increasingly important area that can find numerous applications, such as in ultrawide-band (UWB) communication systems, radar and other warfare systems. Thanks to the advantages such as high speed and broad bandwidth, photonically assisted techniques have been proposed to generate and process high-frequency and large-bandwidth microwave arbitrary waveforms which may not be achieved by conventional electronic techniques.

Microwave arbitrary waveform generation and processing can be implemented using free-space optical devices [1-4]. The key advantage of the techniques in [1-4] is that the systems are reconfigurable thanks to the use of a spatial light modulator (SLM). These techniques, however, suffer from the difficulties such as complex alignment and high coupling loss. On the other hand, microwave arbitrary waveform generation and processing can also be implemented using pure fiber-optic devices. Compared with the approaches in [1-4], fiber-optics based approaches offer the advantages such as lower loss, better stability, and higher potential for integration. The key device in a fiber-optic based system is fiber Bragg gratings (FBGs). A FBG can be designed to have an arbitrary spectral response which is essential for microwave waveform generation and processing. In this paper, techniques to generate and process microwave arbitrary waveforms in the optical domain using advanced FBGs are reviewed, with an emphasis on the system architectures in which FBGs are employed as a spectral shaper or optical filter. The challenges in using FBGs in a microwave arbitrary waveform generation and processing system are also discussed.

II. PHOTONIC GENERATION OF MICROWAVE ARBITRARY WAVEFORMS

Basically, a microwave waveform with an arbitrary shape can be optically generated from an ultrashort optical pulse based on pulse shaping in the optical domain followed by the optical-electrical conversion in a high-speed photodetector (PD). Fig. 1 shows a generic structure for photonically assisted microwave arbitrary waveform generation.

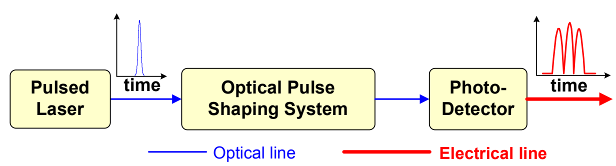

Figure 1. Diagram of a photonically assisted microwave arbitrary waveform generation system based on optical pulse shaping.

Microwave arbitrary waveform generation (AWG) using advanced FBGs can be generally achieved: 1) based on optical spectral shaping and frequency-to-time (SS-FTT) mapping, and 2) based on Fourier transform pulse shaping.

A. Microwave AWG based on Optical Spectral Shaping and Frequency-to-Time Mapping

Optical spectral shaping of an ultrashort optical pulse followed by frequency-to-time mapping in a dispersive element has been demonstrated to be a promising technique to generate high-frequency and broadband microwave arbitrary waveforms. The fundamental principle of such a microwave

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AWG system can be explained using the configuration shown in Fig. 2(a). An ultrashort pulse from a pulsed laser source is sent to an optical spectral filter. The spectrum-shaped optical pulse is then sent to a dispersive element to achieve frequency-to-time mapping. By properly designing the spectral response of the optical spectral filter, a microwave waveform with a shape identical to the shaped optical power spectrum is obtained. A key feature of this technique is that, the temporal pulse shaping is done in the frequency domain, which is easy to implement using an optical spectral filter.

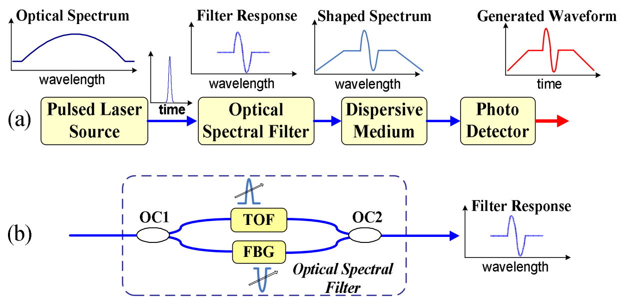

Figure 2. (a) Schematic diagram of a microwave AWG system based on optical spectral shaping and dispersion-induced frequency-to-time mapping. (b) An optical spectral filter designed for ultra-wide band pulse generation. OC: optical coupler, TOF: tunable optical filter, FBG: fiber Bragg grating.

Since the spectral characteristics (both amplitude and phase responses) of an FBG can be properly tailored, it can be employed in a photonic microwave AWG system as a spectral shaper for microwave arbitrary waveform generation. Various configurations employing an FBG-based optical spectral shaper have been proposed. For example, an ultra-wide band (UWB) pulse can be generated based on SS-FTT mapping [5]. As can be seen from Fig. 2(b), an optical spectral shaper that consists of an FBG and a tunable optical bandpass filter has a spectral response corresponding to a UWB monocycle or doublet pulse. After linear frequency-to-time mapping in the dispersive element, a temporal UWB monocycle or doublet pulse with a shape that is a scaled version of the shaped spectrum is generated. UWB pulses have found wide applications in short-range high-throughput wireless communications and sensor networks [6].

The optical spectral shaper can be designed to have a spectral response with a varying free-spectral range (FSR). After frequency-to-time mapping, a chirped microwave pulse can be generated. We have recently proposed and demonstrated such a scheme using an optical spectral filter that consists of two superimposed chirped fiber Bragg gratings (SI-CFBGs) with different chirp rates [7]. The SI-CFBGs form a distributed Fabry-Perot cavity with a cavity length that is linearly dependent on the resonance wavelength, thus a spectral response with a linearly increasing or decreasing FSR is obtained. By properly selecting the chirp rates and longitudinal offset of the two chirped FBGs, a linearly chirped microwave pulse with a high central frequency and large chirp rate could be generated after linear frequency-to-time mapping in a dispersive element. In [7], since the two chirped FBGs need to be written in a single optical fiber, the fabrication process is complicated. In addition, the longitudinal offset between the two chirped FBGs is fixed once the two chirped FBGs are fabricated; therefore the central frequency and the chirp profile of the generated chirped microwave pulse cannot be tuned. To solve these problems, we have recently proposed an all-fiber optical spectral shaper that has a varying FSR using only one single chirped FBG [8]. The optical spectral shaper is implemented based on a chirped FBG-incorporated Sagnac-loop mirror. By tuning the time delay in the fiber loop, the central frequency and chirp profile of the generated microwave pulse can be both tailored.

It is well known that a chirped FBG would exhibit large dispersion when used in reflection mode. In a SS-FTT mapping system, a chirped FBG can also act as a dispersive element to perform the frequency-to-time mapping. To perform linear frequency-to-time mapping, a dispersive element with only the group velocity dispersion (GVD) should be employed. On the other hand, a dispersive element with both the GVD and higher-order dispersion could be used to implement nonlinear frequency-to-time mapping. An important feature of using a high-order dispersive element in a SS-FTT mapping system is that a chirped microwave pulse can also be generated. In this case, a simple optical filter having a uniform sinusoidal spectral response is needed. The nonlinear frequency-to-time mapping can be achieved using a nonlinearly chirped fiber Bragg grating (NL-CFBG), as it was demonstrated in [9]. Since the value of high-order dispersion of an NL-CFBG can be controlled, the approach provides the flexibility to tailor the profile of the generated chirped pulse, such as the central frequency and the chirp rate.

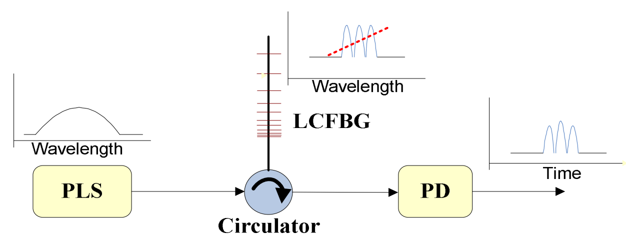

Figure 3. Schematic diagram showing a microwave arbitrary waveform generator using a single LCFBG. PLS: pulsed laser source, LCFBG: linearly chirped fiber Bragg grating, PD: photodetector.

As shown in Fig. 2(a), the spectral shaping and the frequency-to-time mapping are usually implemented using two different devices. To improve the system performance, very recently, we proposed to use a single optical device to perform both functions [10]. A diagram showing the concept is illustrated in Fig. 3. The optical device that performs the two functions is a specially-designed linearly chirped fiber Bragg grating (LCFBG), which has an amplitude response corresponding to the target temporal waveform for spectral shaping. We can control the spectral response of an LCFBG by properly designing the grating refractive index modulation profile. At the same time, due to the inherent linear group delay response, the LCFBG also performs linear frequency-to-time mapping.

Most recently, an approach using a spatially-discrete chirped fiber Bragg grating (SD-CFBG) to achieve microwave AWG based on optical pulse shaping was proposed [11].

Compared to the LCFBG used in [10], the SD-CFBG provides one extra feature: the mapped temporal waveform can be further time shifted. A large time-bandwidth product arbitrary microwave waveform can be generated based on simultaneous spectral slicing, frequency-to-time mapping, and temporal shifting of the input optical pulse in the SD-CFBG [11].

B. *Microwave AWG based on Fourier Transform Optical Pulse Shaping*

As shown in Fig. 1, photonic microwave AWG is usually implemented based on optical pulse shaping. Fourier synthesis, also called Fourier transform pulse shaping, is one of the most commonly used techniques for ultrashort optical pulse shaping [12]. Fourier transform pulse shaping can be implemented in either the time domain or the frequency domain.

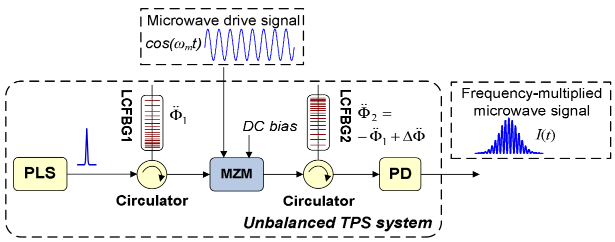

Figure 4. Schematic diagram showing an unbalanced temporal Fourier transform pulse shaping system for microwave waveform generation. PLS: pulsed laser source, LCFBG: linearly chirped fiber Bragg grating, MZM: Mach-Zehnder modulator, PD: photodetector, TPS: temporal pulse shaping.

A conventional Fourier transform temporal pulse shaping (TPS) system usually consists of a pair of dispersive elements with opposite dispersion and an electro-optic modulator that is placed between the two dispersive elements. At the output of the system, a microwave waveform that is the Fourier transform of the modulation signal applied to the modulator is obtained [13]. Recently, an unbalanced Fourier transform TPS system, which incorporates two LCFBGs having opposite dispersion but non-identical in magnitude, as shown in Fig. 4, was proposed to generate high-frequency microwave waveforms based on continuously tunable frequency multiplication [14]. The entire system can be considered as a conventional balanced TPS system for real-time Fourier transformation followed by a residual dispersive element with its dispersion being the offset of the dispersion of the two LCFBGs, to achieve a second real-time Fourier transformation. The generated pulsed microwave signal has a carrier frequency that is increased by a multiplication factor that is determined by the dispersion values of the two LCFBGs. The frequency multiplication factor can be continuously tunable by changing the dispersion values of the two LCFBGs [15].

Fourier transform pulse shaping can also be implemented in the frequency domain using an optical spectral filter. In the pulse shaping system, the optical spectral filter is usually located between two complementary dispersive elements to shape the spectrum of a dispersed optical pulse by the first dispersive element. The spectrum-shaped pulse is then completely compressed by the second dispersive element. Fig. 5 shows a simplified frequency-domain Fourier transform optical pulse shaping system in which a single LCFBG was employed [16]. The LCFBG in the system was functioning as a spectrum shaper and at the same time as a conjugate dispersive element pair to perform pulse stretching and pulse compression. The use of a single LCFBG guarantees an exact cancellation of the dispersion, making the pulse shaping system have a better pulse shaping accuracy with a simplified structure.

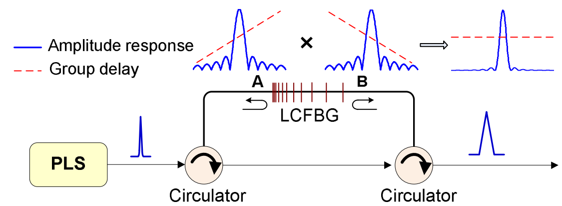

Figure 5. Schematic diagram showing the simplified frequency-domain Fourier transform optical pulse shaping system using a single LCFBG. PLS: pulsed laser source, LCFBG: linearly chirped fiber Bragg grating.

III. PHOTONIC PROCESSING OF MICROWAVE ARBITRARY WAVEFORMS

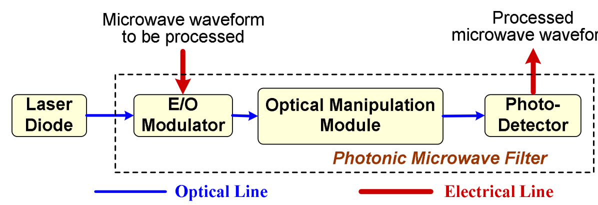

Figure 6. General diagram of a photonic microwave filter for microwave waveform processing. E/O: electro-optic.

It is also desirable that the optically generated microwave waveforms can be processed in the optical domain, to take advantage of the high speed and broad bandwidth offered by optics. A photonic microwave filter (PMF) is usually used to process microwave signals in the optical domain. Fig. 6 shows a generic structure of a PMF for microwave waveform processing. A microwave waveform is first converted to the optical domain using an electro-optic (E/O) modulator, and then an optical manipulation module is used to process the modulated signal in the optical domain. The processed microwave waveform is converted back to the electrical domain by a high-speed PD.

One of the most important microwave waveform processing functions is matched filtering. In a radar system, for example, a chirped waveform can be compressed at the radar receiver to increase the radar range resolution. We have recently proposed and demonstrated a PMF to implement matched filtering for chirped microwave pulse compression [17]. It is known that to compress a linearly chirped microwave pulse, the microwave matched filter should have a quadratic phase response, which is complementary to the chirp profile of the chirped microwave pulse to be compressed. Fig. 7 shows a PMF with a desired phase response for chirped microwave pulse compression. Different from a conventional multi-tap delay-line PMF [18], where a multiwavelength optical source is required, the proposed PMF uses only one single optical wavelength, and is realized based on optical filter response to microwave filter response conversion by using a single-sideband (SSB) modulator and an FBG. The FBG acts as an optical spectral filter that is designed to have a user-defined amplitude and phase response. The optical filter response is then transferred to the response of the PMF through SSB modulation and optical heterodyne detection at a high-speed PD. Therefore, by appropriately designing the reflection response and the dispersion characteristics of the FBG, a PMF with the desired amplitude and phase response is realized. A comprehensive study on the performance of different forms of matched filters for microwave pulse compression was reported in [19].

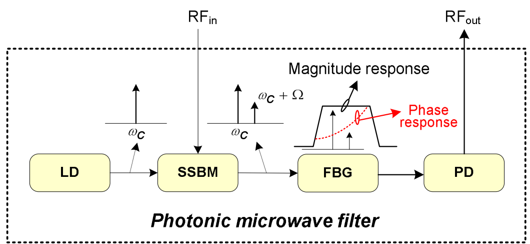

Figure 7. Schematic of a microwave waveform processing system for chirped microwave pulse compression. LD: laser diode; SSBM: single sideband modulator; FBG: fiber Bragg grating; PD: photodetector.

IV. Discussion and Conclusion

Techniques to generate and process microwave arbitrary waveforms in the optical domain using advanced FBGs have been reviewed. The unique filtering properties and versatility as an in-fiber device of an FBG have been illustrated by its use in a variety of microwave photonic applications [20]. The key advantages of an FBG-based system for microwave arbitrary waveform generation and processing are the small size, low loss, good stability, and high potential for integration.

Compared with the photonic microwave arbitrary waveform generation and processing techniques based on free-space optics, the FBG-based methods have the key limitation of poor reconfigurability since the spectral response of an FBG is hard to be altered once it is fabricated. The currently available methods for FBG tuning are mainly based on mechanical and thermal tuning, which are relatively slow. Although the use of a piezoelectric device or a divided thin-film heater could improve the tuning speed, the performance is still limited. In addition, the systems based on fiber-optic devices are costly due to the use of discrete optical devices, such as modulators and PDs. A solution to reduce the cost is to use photonic integrated circuits (PICs). A silicon-based PIC was recently demonstrated to generate microwave arbitrary waveforms with a center frequency up to 60 GHz [21].

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