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Generating UWB and Microwave Waveforms Using Silicon Photonics

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SUMMARY We provide an overview of techniques for the photonic generation of arbitrary RF waveforms, particularly those suitable for impulse radio or multi-band ultrawideband (UWB)-over-fiber transmission, and chirped microwave waveforms, with an emphasis on microwave photonic filtering and optical spectral shaping followed by wavelength-to-time mapping. We discuss possibilities for integrating the various device and component technologies with silicon photonics.

key words: microwave photonics, silicon photonics, waveform generation

1. Introduction

Techniques for generating arbitrary RF waveforms are important for a broad range of applications from communications to imaging and sensing to instrumentation. For example, ultrawideband (UWB) has attracted interest for short-range, high-speed wireless communications and sensor networks. The use of UWB-over-fiber has recently emerged as a viable approach to extend reach and the area covered\cite{1}. In this sense, in addition to being primed for optical transmission, photonic generation of UWB signals can exploit the optical components and technologies that are already involved. Photonic approaches also provide increased flexibility, particularly with regards to reconfigurability and tunability. This is extremely valuable for generating waveforms that are suitable for impulse radio (IR) UWB, e.g., doublets or triplets, as well as multi-band (MB) UWB where the electrical spectrum is separated into multiple channels with correspondingly longer waveforms in the time domain. Finally, photonic approaches may enable different modulation formats, including pulse polarity modulation, pulse shape modulation, and bi-phase modulation.

As a second example, chirped microwave waveforms (and their subsequent compression) are useful in radar systems for increasing detection distance or resolution\cite{2}. While such waveforms can be generated in the electronic domain, their bandwidths and central frequencies are limited by the sampling rate of digital electronics. On the other hand, photonic techniques offer the possibility of achieving central frequencies of tens to hundreds of GHz as well as significant chirp rates, thereby supporting tens of GHz of bandwidth. As with UWB generation, the use of photonics also offers the possibility for tuning and reconfiguration, as well as compatibility with fiber optic transmission.

A variety of techniques for photonic generation of IR-UWB, MB-UWB, and chirped microwave waveforms have been reported. These include, amongst others, the use of optical frequency combs, nonlinear optical effects in fiber or semiconductor optical amplifiers, phase modulation-to-intensity modulation using discrimination filters, optical spectral shaping followed by wavelength-to-time mapping, direct space-to-time pulse shaping, temporal pulse shaping, and microwave photonics filters (MPFs)\cite{3, 4}.

Typically, the system implementations are based on discrete components and involve bulky (e.g., fiber-based) and/or benchtop components. In recent years, there has been a focus on integration, particularly to address issues related to compactness, stability, power consumption, and ultimately mass production for reduced cost and practical deployment\cite{5}. In this paper, we describe the use of silicon photonics (SiP) for generating UWB and chirped microwave waveforms. SiP is emerging as the platform of choice over other semiconductor technologies such as InP for photonic integration. In addition to providing a small footprint, the ability to integrate active with passive devices, and the possibility to reduce power consumption, SiP uses the same processing tools as CMOS fabrication. This has resulted in high quality control, increased yield (reliability), as well as performance of SiP integrated circuits thereby paving the pathway for commercialization\cite{6, 7}. In this paper, we consider the implementation of MPFs and optical spectral shapers in SiP.

The remainder of this paper is organized as follows. Section 2 describes MPFs for generating RF waveforms, e.g., for IR-UWB and MB-UWB transmission. Section 3 reviews optical spectral shaping followed by wavelength-to-time mapping for generating chirped microwave waveforms. Finally, perspectives and conclusions are given in Sect. 4.

2. Generating UWB and RF Waveforms Using Microwave Photonic Filters

In this section, we discuss the use of MPFs to generate UWB and RF waveforms. After illustrating the basic principle of waveform generation, we provide a brief review of MPFs. Next, we describe specific examples of generating IR-UWB and MB-UWB waveforms with MPFs. We then present an approach for generating arbitrary waveforms based on an MPF involving nonlinear mixing in a silicon nanowire (SNW). This is followed by a discussion of implementing...
MPF building blocks in SiP.

2.1 Basic Principle

Figure 1 (a) shows the general schematic for optical pulse shaping based on using an optical filter to tailor the amplitude and phase of the spectral content associated with an ultrashort optical input pulse (also referred to as Fourier transform optical pulse shaping) [8]. The transfer function (spectral response) of the optical filter, $H_{\text{opt}}^\text{out}(\omega)$, must satisfy the relationship

$$H_{\text{opt}}^\text{out}(\omega) = |H_{\text{opt}}^\text{in}(\omega)| \exp(j\phi_{\text{opt}}(\omega)) = \frac{E_{\text{opt}}^\text{out}(\omega)}{E_{\text{opt}}^\text{in}(\omega)}$$  \hspace{1cm} (1)

where $E_{\text{opt}}^\text{out}(\omega)$ and $E_{\text{opt}}^\text{in}(\omega)$ are the Fourier transforms of the output and input electric fields, respectively, of the desired optical waveform and input ultrashort optical pulse. Assuming that the synthesized output waveform is longer in duration than the input (which is typical in most optical pulse shaping applications), the spectrum of the output signal is given approximately by that of the filter response, $E_{\text{opt}}^\text{out}(\omega) \approx H_{\text{opt}}^\text{out}(\omega)$, i.e., the filter operates over a relatively flat (constant) portion of the input spectrum. In an analogous manner, as depicted in Fig. 1 (b), a microwave filter with frequency response $H_{\text{RF}}^\text{out}(\Omega)$ can be used to process an input RF impulse represented by its Fourier transform, $E_{\text{RF}}^\text{in}(\Omega)$, according to

$$E_{\text{RF}}^\text{out}(\Omega) = H_{\text{RF}}^\text{out}(\Omega)E_{\text{RF}}^\text{in}(\Omega)$$  \hspace{1cm} (2)

where $E_{\text{RF}}^\text{out}(\Omega)$ is the Fourier transform of the desired output waveform (we have used $\Omega$ to denote frequencies in the microwave range to distinguish them from $\omega$, which represents optical frequencies). Again, if the synthesized output waveform is long in duration compared to the input, then $E_{\text{RF}}^\text{out}(\Omega) \approx H_{\text{RF}}^\text{out}(\Omega)$. In this paper, we consider the use of MPFs to realize the desired microwave filter responses.

2.2 Brief Review of Microwave Photonic Filters

The field of MPFs is extremely rich and the design of filters with reconfiguration and/or tuning capabilities has been the subject of intense research. Indeed, many filter structures have been proposed, including those with notch responses, tailored responses involving complex tap coefficients, dispersive filters or those with specific phase profiles, and single or multiple passband responses. Excellent review articles on MPFs and microwave photonic signal processing can be found in [9]–[12]. For completeness, we provide some of their salient features.

The typical MPF structure is illustrated in Fig. 2. The input microwave signal $x_{\text{in}}(t)$ is converted to the optical domain via modulation (E/O conversion), e.g., using an electro-optic modulator (EOM) fed by a single carrier frequency or multiple carrier frequencies source. The electric field of the modulated optical signal, $e_{\text{in}}(t)$, which carries the information about the input microwave signal, is then processed in the optical domain by a photonic subsystem. The purpose of the subsystem is to take samples of the microwave signal, which are conveyed by the optical carrier(s), and weigh, delay, and combine them. The subsystem can comprise a variety of components, from passive devices such as couplers, variable optical attenuators (VOAs), fiber Bragg gratings (FBGs), and fiber delay lines to active components such as Erbium-doped or semiconductor optical amplifiers. After photonic processing, the power of the output optical signal, $|e_{\text{out}}(t)|^2$, is detected using an optical receiver (O/E conversion) to remove the optical carrier(s) and extract the processed microwave signal $x_{\text{out}}(t)$.

Generally speaking, the MPF cannot be viewed as a linear system relating $x_{\text{in}}(t)$ and $x_{\text{out}}(t)$. However, under certain conditions (see further [10]), we can consider a linear operation such that the input and output microwave signals are related by

$$x_{\text{out}}(t) = x_{\text{in}}(t) * h_{\text{MPF}}^\text{RF}(t)$$  \hspace{1cm} (3)

where $h_{\text{MPF}}^\text{RF}(t)$ is the MPF impulse response with corresponding frequency response $H_{\text{MPF}}^\text{RF}(\Omega)$. Note that the MPF frequency response does not correspond directly to the transfer function of the photonic subsystem. However, certain features of the photonic subsystem are correlated to the MPF response. For example, if the photonic subsystem involves feedback, the MPF transfer function can take on the form of an infinite impulse response (IIR) filter; on the other
hand, it will have the form of a finite impulse response (FIR) filter when there is no optical feedback. In the discussion that follows, we restrict ourselves to FIR MPFs.

Consider an optical source comprising multiple carrier frequencies that are uniformly spaced, e.g., from a bank of lasers. Assuming incoherent superposition of the carriers (samples or taps), the MPF frequency response is given by

\[ H_{\text{MPF}}(\Omega) \propto \sum_{m=1}^{N} P_m \exp[-j(m-1)\Omega \Delta \tau] \]  

(4)

where \( N \) is the number of taps, \( P_m \) is the amplitude (weight) of the \( m \)th tap, \( \Delta \lambda \) is the wavelength separation between taps, and \( \Delta \tau = D \Delta \lambda \) is the tap delay with \( D \) being the dispersion in [ps/nm] of the medium used to implement the delay. The tap amplitudes can be controlled to shape (reconfigure) the filter response while the tap delay can be varied to tune the frequency response. Note that the MPF frequency response is periodic with a period \( 2\pi/\Delta \tau = 2\pi/(D \Delta \lambda) \).

2.3 Review of Results Using Fiber-Based Implementations

Figure 3 illustrates several different MPF implementations and the overall system for generating IR-UWB and MB-UWB waveforms [13]–[16]. The MPFs use multiple carrier frequencies which are generated either with several discrete lasers as in Fig. 3 (a) [13] or by spectral slicing a broadband source as in Figs. 3 (b) and (c) [14]–[16]. In Fig. 3 (b), an arrayed waveguide grating (AWG) is employed to create discrete spectral slices; VOAs provide control over their amplitudes. A number of space switches and a second set of AWGs select and direct the spectral slices to one of two EOMs where E/O conversion occurs. The EOMs are biased for operation on opposite slopes of the modulator transfer function so as to obtain positive or negative taps. Note that a spectral slice can implement a positive tap or a negative tap, but not both at the same time. The MPF implementation in Fig. 3 (a) is similar except that discrete lasers replace the broadband source and AWGs to define the taps (the tap amplitudes can be set by adjusting the powers of the lasers). In all cases, a length of single mode fiber (SMF) is used as a dispersive medium to create the necessary tap delays.

The input to the MPF is a broadband RF signal, i.e., a short electrical pulse. The MPF response is then configured to shape the input RF spectrum to obtain the desired output temporal waveform as described by Eq. (2). Note that we can also interpret the system operation as generating a specific temporal waveform whose electrical spectrum satisfies a given requirement, e.g., for IR-UWB or MB-UWB transmission.

Figure 4 highlights examples of the different waveforms that can be generated. For example, pulse doublets obtained using the MPFs in Figs. 3 (a) and (b) are shown in Figs. 4 (a) and (b), respectively. In both cases, 3 taps are employed with a weight distribution of \([0.5, -1, 0.5]\). In Fig. 4 (a), the taps are based on 3 discrete lasers with a wavelength separation of 0.74 nm (centered at 1550.12 nm) and 5.43 km of SMF is used to provide a tap delay of \(-68\) ps. In Fig. 4 (b), the taps are based on 3 adjacent channels from an AWG with a 3 dB channel bandwidth of 0.4 nm and channel spacing of 0.8 nm (centered near 1547.72 nm); again 5.43 km of SMF is used to provide the tap delay (\(-74\) ps). Note that the characteristics of the waveforms—in time and in electrical spectrum—are very similar regardless of whether discrete lasers or a spectrally sliced broadband source is used (the wavelength separation between taps and tap delay are approximately the same). By increasing the number of taps and controlling their amplitudes to create an apodized profile, a Gaussian-like waveform can be generated, giving rise to a signal that is suitable for MB-UWB communications. The results obtained using the MPF in Fig. 3 (b) with a broadband source having a Gaussian-like spectrum and 3 dB bandwidth of 8 nm centered at \(-1546\) nm and 23 taps are depicted in Fig. 4 (c) [the AWG has the same characteristics as described above and 5 km of SMF is used to provide the tap delay].

The MPF shown in Fig. 3 (c) differs from those in Figs. 3 (a) and (b) in two regards. First, a periodic optical fil-
ter, here based on a Mach-Zehnder delay line interferometer (MZ-DLI), is used for spectral slicing. In this case, the resulting sinusoidal and continuous tap distribution produces a single bandpass MPF [17]. Second, a balanced photodiode (BPD) is used for O/E conversion. This allows both positive and negative portions in the generated electrical temporal waveform and differential detection removes the DC component of the signal. To control the weight of the sinusoidal and continuous taps, the spectrum of the broadband source is first shaped with an optical filter. By tuning the delay in the MZ-DLI, the free spectral range (FSR) of the periodic optical filter can be tuned. For a fixed length of SMF, this causes the tap delay to vary, which in turn tunes the passband frequency of the MPF response. Figure 5 (a) shows the generation of Gaussian-like waveforms with different periods; sample electrical spectra demonstrating tuning appear in Fig. 5 (b). These results were obtained using a broadband source with a Gaussian-spectrum and a 3 dB bandwidth of 16 nm centered at 1546.9 nm and using 5 km of SMF to set the tap delay; the delay in the MZ-DLI was tuned between 2.9 ps and 7.2 ps.

We now describe an alternate implementation of a reconfigurable MPF for generating arbitrary RF waveforms [18]. Figure 6 (a) illustrates a schematic of the proposed approach. As with the systems described previously, it is based on a FIR MPF. Partially degenerated four wave mixing (FWM) in a nonlinear medium is used to increase the number of optical carriers/taps [18]–[20]. In particular, at least \( N = 2M \) taps can be obtained starting from \( M \) sources. The tap weights are adjusted using a spectral shaper in order to control the MPF amplitude response and correspondingly, the generated RF waveform. As mentioned previously, adjusting the tap delay \( \Delta \tau \) allows for tuning the central frequency of the MPF passband response. The taps are then split by a 3 dB coupler and the two copies are delayed relative to each other by an additional amount of \( \Delta \tau/2 \) before being detected with a BPD.

Figure 6 (b) depicts the experimental setup where an SNW serves as the nonlinear medium. The SNW is 20 mm in length and has a cross-section of \( W \times H = 500 \text{ nm} \times 220 \text{ nm} \) with a top oxide cladding. It is designed to have a small amount of anomalous dispersion near 1550 nm with a dispersion slope \( \sim 0 \text{ ps/(nm}^2\cdot\text{km)} \) for broadband FWM [20]. Vertical grating couplers (VGCs) are used for input and output coupling and to ensure operation with TE-polarized light in the SNW. The total fiber-to-fiber coupling loss is \( \sim 22 \text{ dB} \) and each VGC introduces \( \sim 10 \text{ dB} \) insertion loss (recent designs can reduce this loss further to \( \sim 4 \text{ dB} \) per coupler [21]).

To demonstrate the principle, we use \( M = 2 \) optical sources (at 1547 nm and 1550 nm). An electric impulse generator drives the EOM for O/E conversion (the modulated optical pulses have a FWHM duration of \( \sim 100 \text{ ps} \)); the corresponding spectrum of the electric impulses is shown in the inset of Fig. 6 (b). The modulated optical taps are amplified to an average power of \( \sim 14 \text{ dBm} \) before being coupled into the SNW. After FWM in the SNW, the 4 output taps are
amplified and their amplitudes are controlled using a benchtop spectral shaper (Finisar Waveshaper 1000-S, WS). They are amplified again before propagating through ∼5 km of SMF to provide a tap delay of Δτ = 250 ps. The taps are split equally into 2 copies with a 3 dB coupler and their relative delay is set to Δτ/2 = 125 ps using a pair of tunable optical delay lines (ODLs). The two copies are detected using a 45 GHz BPD.

Figures 7 (a)–(c) show the optical spectrum at the output of the EOM (before the SNW), after FWM in the SNW to increase the number of taps, and after the spectral shaper set to provide equal weight taps. The corresponding temporal waveform and electrical spectrum are shown in Figs. 7 (d) and (e). The RF spectrum, centered at 3.98 GHz, has a shape that is expected for an MPF comprising uniform taps and for a waveform with a constant envelope.

In all of the results shown above, shorter electrical pulses at the input to the system (equivalently with a broader input spectrum) will allow for a greater range of waveforms to be synthesized (including at higher frequencies). Moreover, increasing the number of taps will provide greater control over the MPF filter response, and hence the generated waveforms. The results also correspond to MPFs that have a linear phase response. MPFs can be designed with non-

in the sidelobe level as compared with Fig. 7 (e). By reducing the tap delay to Δτ = 180 ps, we can tune the central frequency of the MPF passband, see Fig. 8 (e) [note that the ODLs need to be re-adjusted to provide a relative delay of Δτ/2 = 90 ps between the two copies]. While the temporal waveform exhibits a ‘skew’ due to the fact that the pulses corresponding to the taps overlap slightly in time, i.e., the separation between a positive and negative pulse is 90 ps whereas the duration of each pulse is 100 ps, the RF spectrum shifts to 5.49 GHz and exhibits a similar shape to that in Fig. 8 (d). Tuning of the apodized waveforms can be useful for MB-UWB communications.

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linear phase responses [22]–[24]; in this case, we can create chirped waveforms or perform pulse compression. This provides yet another degree of freedom for waveform generation.

2.4 Towards an Integrated Solution

While the MPFs described in Sect. 2.3 involve discrete fiber and/or benchtop components, a number of these building blocks or their functionalities have been realized in SiP. First, in-line SNW VOAs with a dynamic range of 30 dB and capable of operating at speeds of up to 1 GHz [25] as well as SiP space switches integrated with CMOS drivers have been demonstrated [26]. Next, a 512 × 512 AWG router with 25 GHz channel spacing was recently reported [27]. O/E and E/O conversion with SiP technologies can be readily achieved: a number of high-performance SiP modulators exist [28], including those capable of advanced modulation formats [29], as well as PDs and BPDs [30], [31].

Various forms of optical delays in silicon have also been demonstrated. These include delay lines based on photonic crystals, coupled ring resonators, and various Bragg-grating structures such as serial grating arrays, step-chirped gratings, continuously chirped gratings, and cascaded gratings. With grating structures, delays up to several hundreds of ps spanning a few nm or tens of ps spanning broader wavelength ranges are readily accessible [19], [32]–[34].

In addition to realizing discrete building blocks in SiP, there have been significant efforts at integrating various devices to increase processing capability and functionality. For example, AWG routers, modulators, and photodiodes have been integrated to implement an 8 × 8 SiP optical switch for high performance computing and data center applications [35]. The ability to integrate various building blocks will allow for the realization of compact, high performance MPFs for generating arbitrary RF waveforms for a variety of applications. Indeed, there have been recent demonstrations of integrated MPFs in various material platforms [5], [36]–[39].

3. Generating Chirped Microwave Waveforms Based on Optical Spectral Shaping and Wavelength-to-Time Mapping

In this section, we describe the generation of chirped microwave waveforms based on optical spectra shaping followed by wavelength-to-time mapping [4], [40]–[42]. We begin with a brief review of the relevant theory, followed by an overview of recently demonstrated results based on fiber implementations. We then discuss progress in developing integrated spectral shapers in SiP.

3.1 Principle of Operation

A schematic of the principle of operation is shown in Fig. 9. The system comprises a broadband source, e.g., from a mode-locked fiber laser, an optical pulse/spectral shaper, and a dispersive medium. The spectral shaper is used to modify the spectrum of the pulsed source, typically in amplitude only. The shaped spectrum then propagates through the dispersive medium where a wavelength-to-time mapping process takes place, i.e., the shape of the spectrum is mapped to the time domain. The resulting temporal signal corresponds to the microwave waveform which is detected by a PD. Note that the linearity of the system allows for the order of spectral shaping and wavelength-to-time mapping to be interchanged. The key component in the system is the spectral shaper: it must be capable of generating the desired amplitude spectrum which ultimately corresponds to the desired microwave waveform.

Wavelength-to-time mapping is based on real-time Fourier transformation of an input signal in a dispersive medium [43]. For example, consider a dispersive medium where the relative delay and frequency are related linearly by \( t = \Phi \omega \) where \( \Phi \) is the first-order dispersion coefficient (\( \Phi = d^2 \Phi / d\omega^2 \) with \( \Phi \) being the phase of the dispersive medium). Let \( a(t) \) be an input signal with pulse duration \( \Delta t_0 \) to the dispersive medium. The output signal \( b(t) \) is given by

\[
b(t) \propto A(\omega) e^{\omega t/\Phi} \quad (5)
\]

where \( A(\omega) \) is the Fourier transform of \( a(t) \) when \( \Delta t_0^2 / 8 \Phi \ll \pi \) (the input signal must be confined within a time window that satisfies this condition). The main point of Eq. (5) is that the envelope of the output signal \( b(t) \) in time corresponds to the spectrum of the input signal \( a(t) \). The linear relationship \( t = \Phi \omega \) sets a linear wavelength-to-time mapping. It is also possible to consider a nonlinear wavelength-to-time mapping, e.g., with a higher-order dispersive medium. In particular, if the relative delay can be represented as

\[
t = \ddot{\Phi} \omega + \frac{1}{2} \dddot{\Phi} \omega^2 \quad (6)
\]

where \( \ddot{\Phi} = (d^3 \Phi / d\omega^3) \) is the second-order dispersion coefficient, we obtain the following nonlinear wavelength-to-time mapping [44]:

\[
\omega = \frac{-\dot{\Phi} \pm \sqrt{\dot{\Phi}^2 + 2\dddot{\Phi} t}}{\Phi} \quad (7)
\]

To generate a uniform (sinusoidal-like) microwave waveform, we require a spectral shaper with a sinusoidal/periodic filter response, i.e., with uniform (constant) FSR, followed by a linear wavelength-to-time mapping. To
generate a chirped microwave waveform, there are two approaches: the first uses a spectral shaper with a periodic response followed by a nonlinear wavelength-to-time mapping while the second uses a spectral shaper with an aperiodic response followed by a linear wavelength-to-time mapping. Generally speaking, by controlling the FSR (or variation in FSR), as well as the first-order and/or second-order dispersion coefficients, we can tailor the central frequency and chirp rate of the generated microwave waveforms.

3.2 Review of Results Using Fiber-Based Implementations

It is relatively simple to realize (all-fiber) sinusoidal/periodic optical filters. For example, we can use a fiber-based MZ-DLI or incorporate a short length of polarization maintaining fiber (PMF) in a Sagnac loop. In these cases, the FSR of the filters are determined by the delay in the MZ-DLI or length of PMF in the Sagnac loop.

To obtain a nonlinear wavelength-to-time mapping, a nonlinearly chirped FBG can be used as the dispersive medium. A number of well-established approaches exist to produce FBGs with tailored dispersive properties (in large part due to the development of FBG-based dispersion compensating modules for fiber optic communications): a nonlinear chirped phase mask can be employed or a linear strain or temperature gradient can be applied to a linearly chirped FBG. The latter approach was exploited in [44] to realize a tunable nonlinearly chirped FBG spanning a bandwidth of ~12 nm (e.g., with first- and second-order dispersion coefficients of $\Phi = 295.1 \text{ ps}^2$ and $\Phi = 20.9 \text{ ps}^3$). By using a spectral shaper based on a length of PMF in a Sagnac loop (to generate a uniform comb of slices from broadband pulses with a 3 dB bandwidth of 8 nm), chirped microwave waveforms 243 ps in duration with an instantaneous frequency varying from 25 GHz to 43 GHz, corresponding to a chirp rate of 0.074 GHz ps$^{-1}$, were obtained [44] (see Fig. 10). While the overall system is simple to implement, the use of FBGs to implement a nonlinear wavelength-to-time mapping causes several issues. First, long gratings, e.g., several cm’s to 1 m, are required to have both broad bandwidth and large dispersion. Moreover, the group delay ripple needs to be minimized to avoid degradation in the chirped microwave waveforms, especially if they are to be compressed subsequently.

The use of a spectral shaper with an aperiodic response followed by a linear wavelength-to-time mapping, e.g., in a length of SMF or dispersion compensating fiber, avoids the problems associated with nonlinearly chirped FBGs (albeit at the expense of compactness). Although more complex in design, aperiodic optical filters can nonetheless be implemented readily using FBGs or ring resonators in SiP. A simple all-fiber distributed Fabry-Pérot (FP) filter can be formed by superimposing two spatially offset and linearly chirped FBGs as shown in Fig. 11 [48]. If the FBGs have different chirp rates, the FSR becomes wavelength dependent [46]:

$$FSR(\lambda) = \frac{\lambda_0^2}{2n_{\text{eff}}(L + \frac{C_1 + C_2}{C_1 C_2}(\lambda - \lambda_0))}$$

where $n_{\text{eff}}$ is the effective index of the fiber, $C_1$ and $C_2$ are the chirp rates, $L$ is the spatial offset between the gratings, and $\lambda_0$ is the starting wavelength. To simplify fabrication, it is possible to use two identical linearly chirped FBGs with opposite orientation ($C_1 = -C_2$).

To demonstrate the principle, two 1 cm long linearly chirped FBGs were employed to realize a spectral shaper spanning a wavelength range of ~1.5 nm with variable FSR. The spectral shaper was used to shape the spectrum of broadband pulses from a mode-locked fiber laser (3 dB bandwidth of 8 nm); with 58 km of SMF as the dispersive medium, chirped microwave waveforms 1,250 ps in duration with a central frequency of 15 GHz and a chirp rate of 0.022 GHz ps$^{-1}$ were synthesized [46]. The results are summarized in Fig. 12.

Once the grating parameters are set, it is not possible to vary the FSR of the spectral shaper and as such, it is not possible to tune the chirped microwave waveform. To overcome this limitation, a spectral shaper based on incorporating a linearly chirped FBG within a Sagnac loop was proposed [47], see Fig. 13.

The transfer function (response) of a Sagnac loop incorporating an FBG can be written as [49]:

$$T = \frac{|E_{\text{out}}|^2}{|E_{\text{in}}|^2} = R_s(\lambda) \cos \left( \frac{2\pi n_{\text{eff}}}{\lambda} \frac{\Delta \lambda + \phi(\lambda) - \phi'(\lambda)}{2} \right)$$

Fig. 10 Pulse profile and instantaneous frequency vs. time for chirped microwave waveforms generated using a periodic spectral filter and a nonlinearly chirped FBG (adapted from and courtesy of J. Yao).

Fig. 11 Schematic of an all-fiber distributed FP resonator with varying FSR based on two superimposed and spatially offset linearly chirped FBGs.
where $R_g(\lambda)$ is the reflectivity of the grating, $\phi(\lambda)$ and $\phi'(\lambda)$ are the phase delays in reflection for light entering clockwise and counter-clockwise, respectively, and $\Delta L = L_1 - L_2$ is the path mismatch in the loop. For a uniform FBG, $\phi(\lambda) = \phi'(\lambda)$ and for equal path lengths, $\Delta L = 0$ such that the transfer function corresponds to the FBG reflection response: $T = R_g(\lambda)$. For a uniform grating with $\Delta L \neq 0$, the grating response is modulated sinusoidally, yielding a periodic or comb-like filter. When the grating is nonuniform, $\phi(\lambda) \neq \phi'(\lambda)$. For a linearly chirped FBG with a linear chirp rate $C$ (nm/cm), we can re-write the transfer function in Eq. (9) as:

$$T = \frac{1}{2} R_g(\lambda) \left[ 1 + \cos \left( \frac{4\pi n_{eff}}{\lambda_c^2} A \left( \Delta L + \frac{\Delta \lambda}{C} \right) \right) \right]$$

(10)

where $\Delta \lambda$ represents the wavelength detuning from the center wavelength $\lambda_c$. For $\Delta L = 0$, the spectral response is symmetric about $\lambda_c$ and the FSR decreases with increased wavelength detuning (from $\lambda_c$). For $\Delta L \neq 0$ (the value of mismatch must be sufficiently large), the spectral response is no longer symmetric about $\lambda_c$ and we can control the variation in FSR, i.e., with a monotonic increase or decrease in FSR over the grating bandwidth, by tuning $\Delta L$ (the sign of $\Delta L$ determines whether there is a monotonic increase or decrease in FSR).

To verify the principle, a Sagnac loop incorporating a tunable delay to control the value $\Delta L$ and a 1 cm long linearly chirped FBG with a chirp rate of 2 nm/cm was constructed. The spectral shaper was used to filter the spectrum of a broadband pulsed source (3 dB bandwidth of 8 nm); in particular, the path mismatch $\Delta L$ was tuned to create a monotonic increase or decrease in FSR (corresponding to a negative or positive chirp rate in the generated waveform). Chirped microwave waveforms 1,150 ps in duration with a central frequency and chirp rate of 20.2 GHz and 0.02 GHz/ps or 24.5 GHz and $-0.022$ GHz/ps were generated after linear wavelength-to-mapping in 30.8 km of SMF [47]. The results are shown in Fig. 14. The instantaneous frequency vs. time shows that the chirp is quite linear. These chirped waveforms can be compressed by a factor of $\sim 55$ and the compressed pulses exhibit relatively low side-lobes (see [47] for further details).

3.3 Towards Integration in SiP

The results shown in Sect. 3.2 demonstrate the capabilities of optical spectral shaping followed by wavelength-to-time mapping for generating chirped microwave waveforms. We now discuss recent progress on developing integrated spectral shapers.

We have fabricated Sagnac loops incorporating uniform and linearly chirped Bragg gratings in SiP, see Fig. 15. The devices were fabricated using electron beam litho-
phy and a full etch. The Si waveguides have a thickness of 220 nm on top of a 3 μm buried oxide (BOX) layer on a Si substrate. The Bragg gratings are based on sidewall corrugations [50] with a depth ΔW = W1 − W2. For the uniform Bragg grating, we use a period Λ = 320 nm, a waveguide width W1 = 500 nm, a corrugation depth ΔW = 10 nm, and 3,000 periods. The chirped Bragg grating is based on tapering the waveguide width [32]. We also use Λ = 320 nm, ΔW = 10 nm, and 10,000 periods; the waveguide width W1 varies linearly from 500 nm to 510 nm from one end of the grating to the other (corresponding to a grating chirp of C ∼ 0.26 nm/mm). A 10 μm long taper is used to bring the waveguide width from 510 nm at one end of the grating back to 500 nm. The multimode interference (MMI) coupler is 6 μm wide and 127 μm long and the input or output waveguides (each 500 nm in width) are separated by 3 μm. All waveguides and gratings are covered by an index-matched 2 μm top oxide cladding layer. VGCs, which couple light into and out of the chip, also ensure TE mode operation.

Figure 16 (a) shows the measured response in which a uniform Bragg grating is located symmetrically within the Sagnac loop. The passband has a bandwidth of 3.2 nm and exhibits an out-of-band rejection (OBRR) of ∼15 dB. The response is shown normalized to that of the VGCs, which are obtained via separate measurements on a test structure comprising the VGCs and a short length of waveguide only; the fiber-to-fiber insertion loss is 25 dB so that the insertion loss of the passband is estimated to be 2 dB. Apodization can be used to reduce the sidelobes in the grating response [51]. Figure 16 (b) shows the measured response when a chirped Bragg grating is located near the center of the Sagnac loop (∆L = 100 μm only). The response is nearly symmetric about the center wavelength with an FSR that decreases with increasing wavelength detuning from λc (the response will become more asymmetric, i.e., with a monotonic increase or decrease in FSR over the entire bandwidth, if the path mismatch is made much larger). Note that the visibility of the fringes is quite high (typically ∼20 dB).

We then used the device to spectrally shape the output pulses from a passively mode-locked fiber laser. The pulses have a Gaussian-like spectrum with a 3 dB bandwidth of 1.5 nm which we tune to different locations to capture increasing or decreasing FSR. For example, using 24 km of SMF as the dispersive medium, we generated a chirped microwave waveform with a total duration of ∼1,000 ps and chirp rates of ∼ ±0.02 GHz/ps. The results are summarized in Fig. 17.

We have also implemented a distributed FP filter in SiP based on two spatially offset Bragg gratings with opposite chirp, see. Figure 18. As before, the Si waveguides have a thickness of 220 nm on top of a 3 μm BOX layer on a Si substrate and are covered by an index-matched 2 μm top oxide cladding. Each chirped Bragg grating has Λ = 315 nm, ΔW = 10 nm, and 500 periods; the waveguide width W varies linearly from 500 nm to 520 nm from one end of the grating to the other (corresponding to a grating chirp of |C1| = |C2| = 12.2 nm/mm). The two gratings are separated by a length L = 457.5 μm. We use the reflection response, which is extracted via a Y-splitter. Again, VGCs are used to couple light into and out of the chip.

Figure 19 shows the measured response of the distributed FP filter in SiP; the FSR clearly increases with increasing wavelength. We then implemented the filter in the waveform generation system. Pulses from a passively mode-locked fiber laser are filtered so that we operate over a wavelength range of ∼16 nm of the distributed FP filter response. We used 5 km of SMF as the dispersive medium for wavelength-to-time mapping. This results in a chirped microwave waveform with a total duration of ∼1,100 ps and a chirp rate of 0.012 GHz/ps, see Fig. 19.

Integrated spectral shapers based on ring resonators have also been proposed and realized. For example, Fig. 20...
Fig. 17 Generating chirped microwave waveforms with an integrated spectral shaper based on a Sagnac loop incorporating a chirped Bragg grating. Response of the spectral shaper showing input optical pulses tuned to capture (a) increasing and (b) decreasing FSR. Corresponding temporal waveforms after linear wavelength-to-time mapping and instantaneous frequency vs. time.

Fig. 18 Schematic of distributed FP filter in SiP.

Fig. 19 Spectral response (in reflection) of distributed FP filter in SiP. Corresponding temporal waveform after wavelength-to-time mapping and instantaneous frequency vs. time.

Fig. 20 Schematic of tunable integrated spectral shaper in SiP based on cascaded microring resonators with additional MZ structures (courtesy of M. Qi).

Fig. 21 Schematic of integrated spectral shaper in SiP based on cascaded microring resonators embedded within an MZI (courtesy of J. Yao).

Recently, a different version of an integrated spectral shaper using cascaded microring resonators was reported in [53]. In this case, the microring resonators are embedded in an MZI. Moreover, the microring radii differ substantially in order to provide a larger variation in the spectral separation between rings (see Fig. 21). The device operates in reflection mode so that the input and output can share a common VGC and the MZI configuration increases stability. As a proof-of-principle demonstration, devices based on 4 or 5 rings were fabricated and tested. Chirped microwave waveforms with bandwidths of 8.5 GHz and 15.5 GHz with chirp rates of 0.012 GHz/ps and 0.017 GHz/ps were achieved after linear wavelength-to-time mapping in a dispersive medium with −948 ps/nm dispersion. These chirp rates are ten times greater than those obtained in [52]. While this prototype device was static, it can be readily adapted to allow for reconfigurable operation using thermal tuning as in [52]. Note that in both approaches, the number of cycles in the waveforms is constrained to the number of cascaded microrings. In many practical applications, a larger number of cycles is necessary which in turn, requires the addition of
microrings.

In Sect. 2, we described some recent developments for implementing tunable delays in SiP; these can be readily combined with the spectral shapers described here to realize a fully integrated chirped microwave waveform generation system. However, the main challenge resides in obtaining the necessary dispersion and/or bandwidth for appropriate wavelength-to-time mapping.

4. Summary and Perspectives

We have described the generation of UWB and RF waveforms based on microwave photonic filtering as well as chirped microwave waveforms using optical spectral shaping followed by wavelength-to-time mapping. It should be noted that many of the MPF structures described in the review articles [9]–[12] can be employed for waveform generation; we have presented only results in which the filters were used explicitly for such a purpose. We have also described briefly the implementation in SiP of a number of critical building to realize MPFs or spectral shapers. While several challenges still remain, e.g., the development of delay lines with larger bandwidth-delay products or filters that can process a larger number of taps, integrated microwave photonics is still an emerging field. SiP holds significant promise to realize a number of component technologies and integrated systems for demonstrating enhanced capability or functionality which, in turn, will pave the way for new applications that will make the technology further commercially viable. Combined with recent advances in graphene microwave photonics [54], an exciting future undoubtedly lies ahead.

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References


