

SIMULTANEOUS MICROWAVE CHIRPED PULSE GENERATION AND ANTENNA BEAM STEERING

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Abstract—A new structure is suggested for simultaneous microwave chirped pulse generation and array antenna beam steering. It is based on using a multi-channel fiber Bragg grating in a photonic microwave delay-line filter. The paper presents a feasibility study of the idea, discussing the main performance parameters of both signal generation and beam steering functions. Specifically, it focuses on the effects of wavelength tuning, resolution and accuracy. The study shows that custom off-the-shelf components could be used to implement an all optical system capable of generating chirped pulses while steering the radiation pattern of a small sized antenna array. The advantages of the structure for avoiding single sideband modulation difficulties and also for the compensation of the multichannel fiber Bragg grating inaccuracies are also discussed.

1. INTRODUCTION

Photonic signal processing in microwave application has overcome many electronics' limitations in wideband applications. This synergy is reported in many areas like arbitrary waveform generation, optical beam-forming of antenna arrays and filtering [1, 2]. The trade-off between the complexity added by the photonic structure and the overall system performance is a key point in designing such mixed microwave photonic systems. In this paper we will provide a feasibility study for a microwave photonic system capable of generating chirped pulses while providing suitable time-delays for antenna beam steering.

Antenna beam steering with optical time delay elements is a rather old idea going back to 1990s [3, 4]. To reduce weight and size and also to achieve a better performance, novel integrated photonic time

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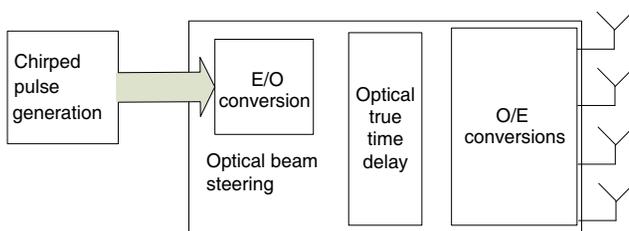
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delays are still of great interest (e.g., see [5]). A very popular method for a compact optical beam-former is to use a dispersive medium to produce increasing time delays for incremental optical carrier wavelengths/frequencies. In this method an optical carrier is assigned to each antenna, on which the transmitted/received microwave signal is modulated [6]. By tuning the optical carrier wavelengths, it would be possible to control the time delays and hence to steer the antenna array beam. On the other hand, there are a number of methods for arbitrary waveform generation using photonic devices in the literature [7]. Reference [8] provides a well-categorized discussion on these methods. Especially for wideband radar applications where electronic sampling rate is the limiting factor, optical generation is a very promising solution.

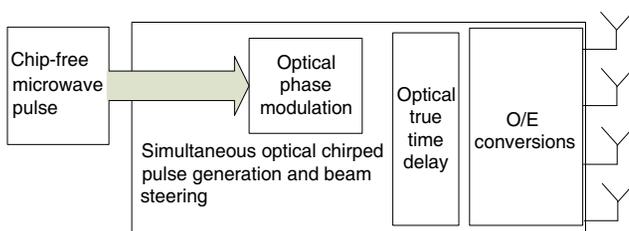
Two scenarios are possible for optical steering of an optically generated waveform. In the first scenario, depicted in Figure 1(a), an externally generated microwave signal drives a single or a series of electrical-to-optical (E/O) converters. The second scenario relies on the simultaneous generation of the waveform and antenna beam steering. This is depicted in Figure 1(b). In the first scenario when the beam-former employs a chirped fiber Bragg grating (CFBG), the dispersion limits the bandwidth for a double sideband (DSB) optical modulation [9]. As the two sidebands of the signal are delayed differently, frequency dependent power degradation at the receiver occurs. To solve this, single sideband (SSB) modulations are suggested [9]. But the generation of SSB optical modulations is not easily achieved in wideband applications. There are two methods for the generation of an SSB optical modulated signal, when the modulating signal is externally generated [5]: using optical filters and using phase shift techniques.

In the first method, one needs an optical filter to suppress one of the sidebands of a DSB modulated signal. In our application, the need for wavelength tunability makes this method extremely hard to implement. Actually we steer the antenna beam by tuning the optical wavelengths. Thus the optical filter for sideband rejection should be tunable, too. The second method is based on modulating the optical carrier with both the original signal and its Hilbert transform. A very common implementation of this technique is through using a dual drive Mach-Zehnder modulator, with the original signal applied to one drive and its Hilbert transform to the other [10]. But in wideband applications, that have led us to optical generation and optical beam steering, Hilbert transform generation in electrical domain is prohibitive.

Introduced in this work, is the second scenario that combines



(a) separate optical chirped pulse generation and optical beam steering



(b) simultaneous optical chirped pulse generation and optical beam steering

Figure 1. Two possible approaches for optical beam steering in an antenna array transmitting optically generated chirped pulses: (a) separate and (b) simultaneous generation and steering functions.

the chirped pulse microwave generation and optical beam steering. It helps to resolve the aforementioned bandwidth limitation without implementing an SSB modulation. As shown in Figure 1(b) the input to the system is a chirp-free pulse that drives a phase modulator. We will see that the phase modulation to intensity modulation (PM-IM) conversion causes power degradation in this scenario, too. But it is possible to compensate the frequency dependent power degradation by optimizing the input pulse spectrum. As will be cleared out later the simultaneous scenario needs more optical sources compared to the separate signal generation and beam steering scenario. For small antenna arrays this may be traded off for the mentioned benefit.

We found microwave waveform generation based on a photonic microwave delay-line filter suitable for the aforementioned purpose. To the best knowledge of the authors, simultaneous chirped pulse generation and antenna beam steering is not discussed elsewhere. To do this we will use a single dispersive device to act as a delay-line for the filter as well as for the beam steering function.

The structure of the paper is as follows. In Section 2, the proposed architecture is introduced. Section 3 discusses the trade-offs between

the two main functions in the selection of the dispersive medium. In Section 4, we will inspect the inaccuracies of the elements on chirped pulse generation. Section 5 concludes the paper.

2. THE PROPOSED ARCHITECTURE

A chirp-free baseband pulse passed through a photonic microwave filter with a quadratic phase response can produce a chirped microwave pulse at the filter output [11]. By choosing a delay-line structure for the filter, it will be possible to implement the quadratic phase response with non-uniform spacing of the filter tap frequencies [11]. A simple optical implementation of such a structure is obtained via phase modulating a number of non-uniformly spaced optical carriers by the input signal, passing the modulated carriers through a dispersive device and detecting the filtered output by a photo-detector.

Meanwhile, the dispersive device can be used to implement the incremental time delays required for antenna beam steering. The structure of the proposed architecture is depicted in Figure 2. A dense wavelength division multiplexing (DWDM) laser array is used to produce MN optical carriers. N is the number of filter taps required for the generation of the chirped pulse and M is the number of antennas. Using available optical telecommunication DWDM sources MN values as large as 200 can be reached in each of the C or L band ITU 25 GHz grid. N depends mainly on the time-bandwidth of the required signal but values between 10 and 40 are common. Thus

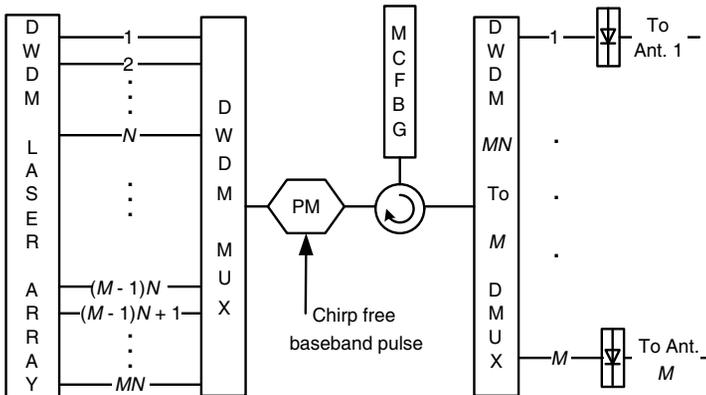


Figure 2. The proposed architecture for simultaneous generation of chirped pulses and optical beam steering. MCFBG: multichannel chirped fiber Bragg grating.

antenna arrays with 5 to 20 elements (or sub-arrays) may be fed with the proposed architecture. The optical carriers are multiplexed into a single phase modulator driven by a chirp-free wideband baseband pulse. The modulated carriers are passed through a dispersive device and are de-multiplexed into M routes toward M photo-detectors before delivering the signals to the antennas. The DWDM source wavelengths are assumed to be thermally tunable around their nominal values.

The practical applicability of the microwave signal generation by a photonic microwave delay-line filter is demonstrated by others through certain experiments [8, 11, 12]. In the proposed structure, each channel may be considered as a replica of those demonstrations. Thus an approved theory is used throughout this work. In the next section a parametric analysis is presented to inspect different performance parameters of the proposed system.

3. BEAM STEERING AND PULSE SHAPING TRADE-OFFS

As the suggested structure has a single dispersive element for both beam steering and pulse shaping functions, we expect trade-offs in performance. Actually the following three items are tied together:

- A. Avoiding the PM-IM spectrum zeros to happen in the filter pass-band.
- B. The maximum and minimum beam steering angles.
- C. Wavelength tuning for beam steering.

Item A follows directly the PM-IM formula for a dispersive medium with total dispersion χ [13]:

$$H_{\text{pm-im}}(\omega) = \cos\left(\frac{\chi\bar{\lambda}^2\omega^2}{4\pi c} + \frac{\pi}{2}\right) \quad (1)$$

where $\bar{\lambda}$ is the mean value of the N wavelengths of each individual filter. Changing $\bar{\lambda}$ along the C or L band ITU grid has a negligible effect on the location of the first peak of $H_{\text{pm-im}}(\omega)$. To avoid notches, this first peak is usually designed to occur at the central frequency of the desired filter pass-band. Thus with $\bar{\lambda}_{MN}$ representing the mean value of all MN wavelengths in Figure 2 and T representing the mean time period of the chirped pulse, χ could be chosen as follows:

$$\chi = \frac{cT^2}{2\bar{\lambda}_{MN}^2} \quad (2)$$

On the other hand, the maximum and minimum achievable beam steering angles depend on the dispersive device, too. Let's assume

that the central frequency of the desired chirped pulse is $f_0 = 1/T$ and the antenna elements are spaced uniformly, half the relevant radio frequency wavelength from each other. The required time delay difference between adjacent antenna paths to steer the beam θ degrees from the array axis may be obtained as follows.

$$\Delta t = \cos(\theta)/(2f_0) \quad (3)$$

For a single channel dispersive device (or a length of optical fiber) and with DWDM optical sources with a wavelength range from λ_{\min} to λ_{\max} and spacing $\Delta\lambda$, the maximum and minimum achievable time delays are approximately given by:

$$\begin{aligned} \Delta t_{\max} &= \chi(\lambda_{\max} - N\Delta\lambda - \lambda_{\min})/(M - 1) \\ \Delta t_{\min} &= \chi(N\Delta\lambda) \end{aligned} \quad (4)$$

The maximum time delay value will exert a maximum limit on χ for a fixed f_0 value through (3) and (4):

$$2f_0\Delta t_{\max} < 1 \Rightarrow \chi < \frac{(M - 1)}{2f_0(\lambda_{\max} - N\Delta\lambda - \lambda_{\min})} \quad (5)$$

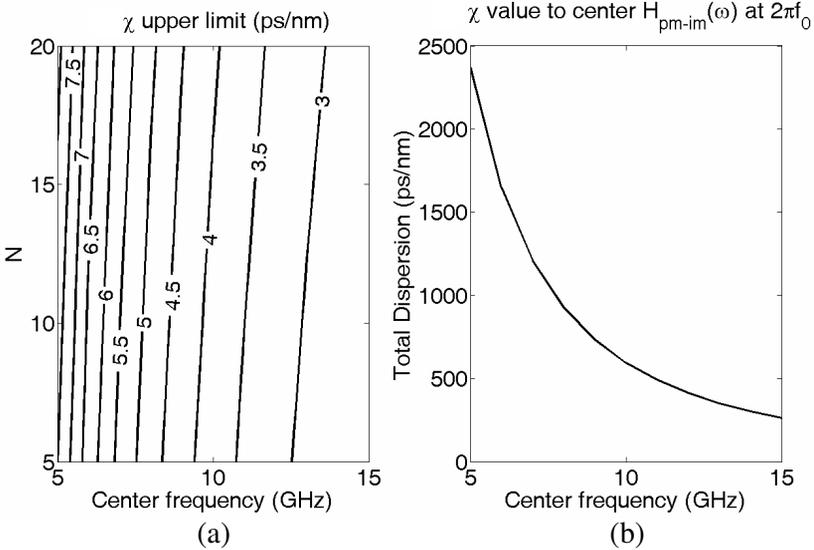


Figure 3. (a) The upper limit for χ of a single channel dispersive device for maximum steering from the array axis for different values of f_0 and N . The array is assumed to have 8 elements, (b) χ values given by (2) for different values of f_0 for the same array.

This upper limit and also the optimum value given in (2) are plotted for different center frequencies and different number of filter taps in parts (a) and (b) of Figure 3, respectively. In both parts the array is assumed to have 8 elements. The plots show that the upper limit on χ exerted by the beam steering is far smaller than the value required for avoiding $H_{pm-im}(\omega)$ zeros in the filter pass-band. It should be mentioned that it is adequate to avoid zeros of $H_{pm-im}(\omega)$ as its amplitude variation may be compensated by modifying the input chirp-free pulse spectrum [11].

Thus we suggest using a multichannel CFBG to separate the pulse generation and beam steering functions. Each channel of the multichannel CFBG should have a dispersion value given by (2). To achieve the required beam steering the following parameters should be designed:

- 1- The central wavelength and the span of channels in the MCFBG.
- 2- The wavelength tuning plan for each steering angle.

Each channel of the MCFBG should be wide enough to contain the N optical carriers plus the required wavelength tuning for beam steering. Figure 4 shows the distribution of the source wavelengths λ_m^n , $m = 1$ to M of the n th filter tap in each channel. λ_m^0 , $m = 1$ to M represents a group of reference wavelengths with identical time delays. For a certain steering angle, $\Delta\lambda = (\lambda_{m+1}^n - \lambda_{m+1}^0) - (\lambda_m^n - \lambda_m^0)$ is identical for all $n = 1$ to N and $m = 1$ to M values and is called the wavelength increment.

Figure 5(a) shows the required wavelength increment for different central frequencies and steering angles. Part (b) of the same figure, depicts the resolution required for a 1 degree rotation steps. The wavelength increment values are achievable with custom available

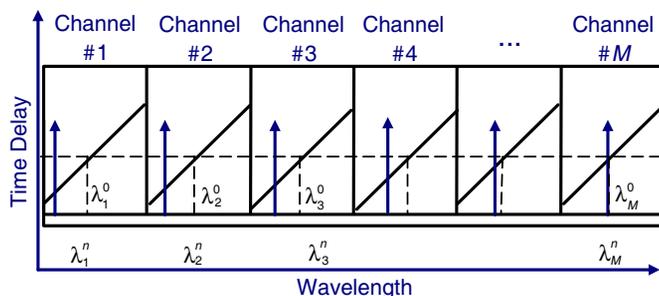


Figure 4. Distribution of the source wavelengths in a MCFBG. Only one of the several wavelengths in each channel is shown as λ_m^n , $m = 1$ to M . λ_m^0 , $m = 1$ to M represents a group of reference wavelengths with identical time delays.

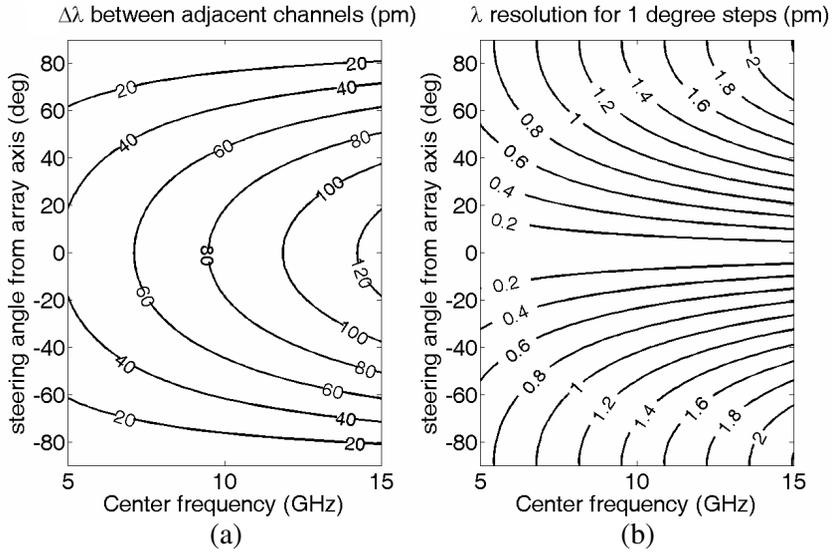


Figure 5. (a) Wavelength increment for different steering angles and central wavelengths. (b) Wavelength tuning required for a 1 degree rotation steps.

DWDM lasers, but the resolutions seem too fine and may lead to beam steering steps coarser than 1 degree. In both plots the total dispersion is assumed to follow (2).

It is worth mentioning that the combined signal generation and beam steering has another advantage in compensating for different group delay responses of the multi-channel delay element. Each of the channels shown in Figure 4 could have slightly different but measurable group delay responses. The proposed structure in Figure 2, facilitates to compensate for such inaccuracies by tuning the optical wavelengths in each channel independently. This is not possible when the chirped pulse is generated before entering an optical beam-former as in Figure 1(a).

4. INACCURACIES IN CHIRPED PULSE GENERATION

In Section 3, we decoupled the beam steering and pulse generation functionalities by using a multichannel CFBG. We also quantified the effects of wavelength tuning range and resolution on beam steering. Here we will inspect the effects of limited wavelength tuning resolution on the quality of the generated signal, numerically. We assume the

Table 1. Parameter values for the chirped pulse.

W	γ	T
825 ps	3.2 GHz/ns	110 ps

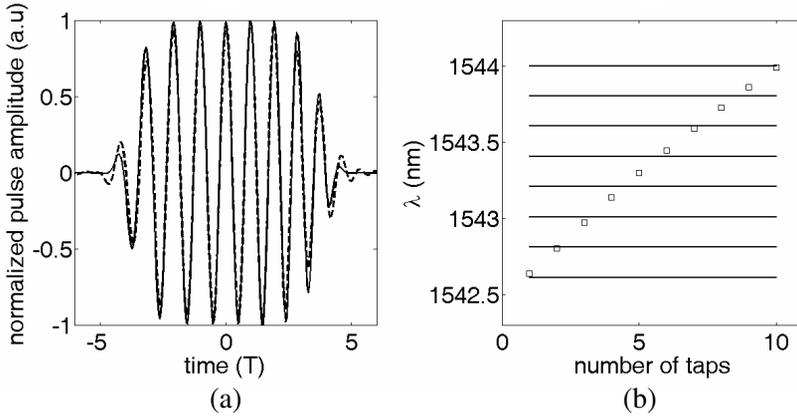


Figure 6. (a) Solid line: the desired pulse, dashed line: the synthesized pulse with a 10 tap delay line filter. (b) Squares: the non-uniformly spaced source wavelengths required for the delay line filter, lines: the nearest 25 GHz ITU grid wavelengths.

desired signal at each antenna to be an 8th order super-Gaussian chirped pulse with the following format [12]:

$$y(t) = \exp\left(-\ln(2) \left(\frac{2t}{W}\right)^8\right) \times \exp\left(j \left(\frac{2\pi}{T}t + \pi\gamma t^2\right)\right) \quad (6)$$

where W is the full-width at half-maximum (FWHM) of the pulse, T is the mean period and γ is the chirp rate. Table 1 lists the values of these parameters for the numerical example considered here. Figure 6(a) shows the produced chirped pulse using the method described in [13] with a 10 tap filter, compared to the desired chirped pulse. Figure 6(b) depicts the non-uniformly spaced wavelengths of the DWDM sources and the nearest standard ITU 25 GHz grid. The input pulse is a chirp-free baseband Gaussian pulse with a FWHM of 20 ps.

Very often, a matched filter structure is used for the detection of a back-scattered chirped pulse. Thus the output of a matched filter is a good benchmark for evaluating the optically generated pulse. Figure 7(a) shows the output of a matched filter for an ideally

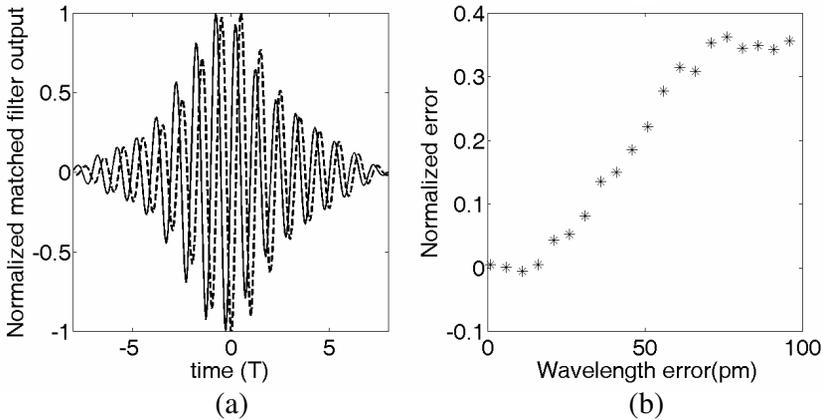


Figure 7. (a) The output of the matched filter for the pulse generated with exact wavelengths (dashed) and with wavelengths having an error with 100 pm RMS error (solid). (b) Normalized error of the matched filter output vs. wave length RMS error.

generated pulse and also a pulse generated with a set of sources having 100 pm RMS wavelength errors. To quantify this we will define the following normalized error:

$$\text{Normalized Error} = 1 - \frac{\int z_2(t)z_1(t)dt}{\int (z_1(t))^2 dt} \quad (7)$$

where $z_1(t)$ and $z_2(t)$ are the matched filter outputs for the ideal and erroneous pulses, respectively.

Sweeping the RMS error from a few picometers to 100 pm, this normalized error is plotted in Figure 7(b). Wavelength error RMS values up to about 20 pm do not produce significant errors. This is already achieved in many available DWDM sources. Of course the acceptable matched filter output is determined by the specific application of the total system. Results of Figure 7 are obtained from Monte-Carlo simulations with 50 iterations.

5. CONCLUSION

We have proposed a structure for simultaneous optical generation of chirped microwave pulses and small antenna array beam steering. It is beneficial in wideband applications that SSB modulation is hard to implement. It was shown that a single channel dispersive element

cannot fulfill the required performance. A multichannel CFBG was suggested to decouple the performance of the two functionalities. The required range of wavelength tuning, resolution and accuracies of a series of DWDM laser sources were also investigated.

The proposed structure relies mainly on custom off-the-shelf optical elements. DWDM laser sources, DWDM multiplexers and de-multiplexers, MCFBG, circulators and phase modulators are all available in the whole C or L band range. Thermally tuning the source wavelengths will allow steering the antenna array beam in space, while generating a modulated chirped pulse optically.

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