Generation of chirped microwave signal with any central frequency based on a nonuniformly spaced finite impulse response filter

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A novel optical approach to generating a chirped microwave signal by using a nonuniformly spaced finite impulse response filter is proposed and demonstrated. In this scheme, a narrowband Gaussian pulse is used as the original chirped-free signal, which is easy to be acquired. To eliminate the need of a wideband chirped-free signal, a mixer and a radio frequency signal are used to up-convert the spectrum of the original Gaussian signal. Therefore, the required frequency response can be calculated and reconstructed by a finite impulse response filter with nonuniformly spaced taps. Besides, a dual drive Mach–Zehnder modulator is used to realize single sideband modulation of the chirped-free signal. Thus, the transfer function induced by the fiber dispersion is eliminated and the chirped microwave signal with any central frequency can be generated. In this paper, a design example of a filter with a central frequency of 10 GHz is provided, and generation of the target chirped microwave signal is also demonstrated by numerical simulations.

Keywords: microwave photonics, microwave photonic filter, chirped microwave signal, dual drive Mach–Zehnder modulator.

1. Introduction

Pulse compression is a widely used technique for increasing the range resolution in modern radar systems. Instead of transmitting sinusoidal radio frequency (RF) signals, in a pulse compression radar, the signal with large time bandwidth product is usually needed, which is usually realized by frequency chirping or phase coded [1, 2]. Based

on the advantages of the high speed and wide bandwidth provided by optics, photonic generation of the chirped microwave signals has been a hot research topic in recent years. Many schemes have been proposed to generate the chirped microwave signal, the most common photonic approaches to generating chirped microwave signals are based on optical frequency to time mapping or space to time mapping [3–9], which are always implemented by pure fiber optics with smaller size and better stability. However, the generated signal usually has an ultra-wide bandwidth, which makes it less practical in actual systems. Chirped microwave signal can also be generated by passing a chirped-free signal through a filter with a quadratic phase response [11, 12]. Since the bandwidth of the generated chirped microwave signal is limited by the filter, the signal will be more practical. The required frequency response can be achieved by constructing a finite impulse response (FIR) filter, but complex taps are usually needed, which is not easy to be realized in optical domain. To simplify the construction of the special FIR filter, the equivalent realization of the complex coefficients by nonuniformly spaced taps has been proposed in [10–14]. Since the filter has only positive coefficients, it is easy to be implemented by using a photonic delay-line structure. In [12], the chirped microwave signal with a full width at half maximum (FWHM) of 3.2 ns and a chirp rate of 1.6 GHz/ns is generated by using a 40-tap FIR filter with the required frequency response. However, in this scheme, the major power of the original Gaussian pulse cannot pass through the filter and a wideband chirped-free signal is needed for the generation of a signal with a high central frequency. Besides, if the amplitude of the filter is seriously suppressed by the transfer function induced by the phase modulation to intensity modulation (PM-IM) conversion, the chirped microwave signal cannot be generated.

In this paper, we propose a novel approach to generating a chirped microwave signal with any central frequency by using a nonuniformly spaced FIR filter. A Gaussian pulse with a narrow bandwidth, which is easy to be acquired, is used as the original chirped -free signal here. In order to eliminate the need of a wideband original chirped-free signal, the narrowband signal is firstly sent to a mixer and up-converted by mixing it with an RF signal. Then, the required frequency response can be calculated and reconstructed by a nonuniformly spaced FIR filter. Since the spectrum of the chirped-free signal has a bandpass profile, it is not necessary to use the PM-IM conversion to eliminate the baseband resonance of the FIR filter. Therefore, instead of a phase modulator (PM), a dual drive Mach–Zehnder modulator (DDMZM) can be used here to implement single sideband (SSB) modulation of the input chirped-free signal. Thus, the dispersion induced transfer function can be eliminated, which is generated by the second-order dispersion induced power penalty when double sideband (DSB) signals are used. Without the constraint by the dispersion induced transfer function, it is possible to construct a FIR filter with any central frequency in the bandwidths of the modulator and photodiode (PD) [15]. To demonstrate the advantages of employing DDMZM, the system using an ordinary Mach–Zehnder modulator (MZM) or phase modulator (PM)

is also discussed for comparison. The generation of a chirped microwave pulse with a FWHM of 3.2 ns and a chirp rate of 1.6 GHz/ns is demonstrated by numerical simulations, and the desired frequency response is also achieved by constructing a 37-tap FIR filter, which is less than the number of taps required in [11, 12].

2. Principle of operation and theory

The schematic diagram of the proposed setup is shown in Fig. 1. In order to eliminate the need of the wide bandwidth of the original signal, the original narrowband Gaussian pulse is first sent to a mixer and up-converted by mixing with a RF signal. Then, the microwave signal is inputted to the two arms of the modulator after being divided by a 3-dB quadrature hybrid coupler (HC). The optical carriers with nonuniformly spaced wavelengths emitted by an array of tunable laser sources (TLS) pass through a DDMZM via a series of polarization controllers (PC), which are used for optimum modulation performances. Since different taps of the FIR filter are generated by the chromatic dispersion and the optical carriers with different wavelengths, the equivalent complex coefficients realized by the nonuniformly spaced taps can be realized after the modulated signals transmit over the dispersive fiber. And then, the expected chirped microwave signal is finally generated after photodetection via a photodiode (PD).
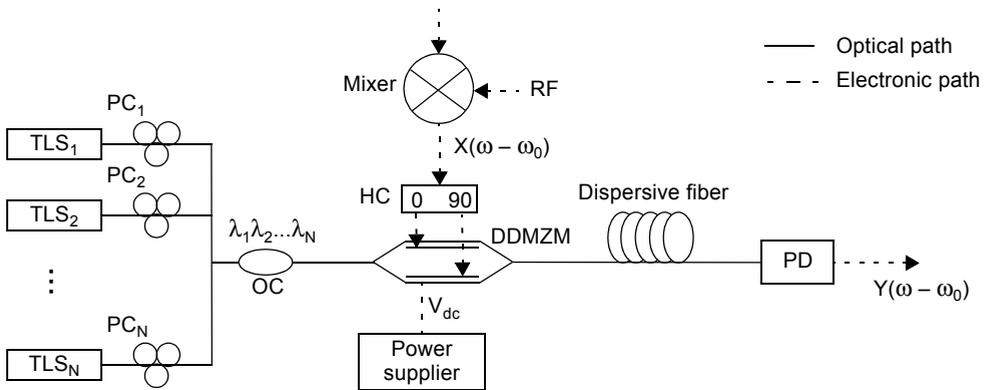
Fig. 1. Setup of the proposed system. TLS – tunable laser source, PC – polarization controller, HC – hybrid coupler, DDMZM – dual drive Mach–Zehnder modulator, OC – optical coupler, PD – photodiode, RF – radio frequency.

DDMZM has a Mach–Zehnder structure with two phase modulators in the two arms, which are driven by a 3-dB quadrature HC to generate two RF signals with the same amplitude and $\pi/2$ phase difference. A dc voltage bias exists in one arm which is used to control operating state of the DDMZM. When it is under small signal modulation, and only the first order sideband is considered, the output optical field after the DDMZM is given by [16]

$$E = E_0 \cos\left(\frac{\theta}{2}\right) J_0(m) \exp\left(j2\pi f_c t + j\frac{\theta}{2}\right) +$$

$$+ \sin\left(\frac{\theta}{2} + \frac{\pi}{4}\right) J_1(m) \exp\left[j2\pi(f_c + f_e)t + j\frac{\theta}{2} + j\frac{\pi}{4}\right] +$$

$$+ \sin\left(\frac{\theta}{2} + \frac{3\pi}{4}\right) J_1(m) \exp\left[j2\pi(f_c - f_e)t + j\frac{\theta}{2} + j\frac{3\pi}{4}\right] \tag{1}$$

where E_0 and f_c are the amplitude and frequency of the optical carrier, $\theta = \pi V_{dc}/V_\pi$ is the phase induced by the dc voltage bias, f_e is the frequency of the input RF signal, $J_n(\cdot)$ is the n-th Bessel function with first kind, $m = \pi V_{dc}/2^{1/2} V_\pi$ is the phase induced by RF signal. From Fig. 2, it can be seen that the coefficients of the carrier and the two sidebands can be controlled, and SSB modulation of the chirped-free signal can be realized by controlling the bias voltage induced phase. Although it is not easy to generate an ideal SSB signal, which is due to the power of the suppressed sideband which cannot be completely eliminated, it is enough to make the construction of the filter free from the impact of dispersion induced transfer function [17].
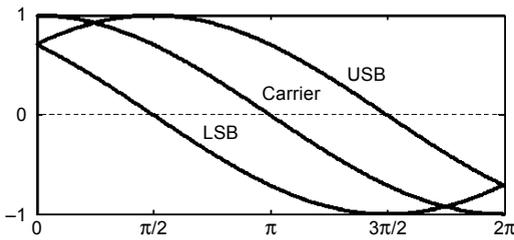
Fig. 2. Coefficients of the carrier, lower sideband (LSB), and upper sideband (USB).

According to the operation of the signal generation in the frequency domain, the required frequency response of the FIR filter is calculated by

$$H(\omega - \omega_0) = \frac{Y(\omega - \omega_0)}{X(\omega - \omega_0) H_{dispersion}(\omega - \omega_0)} \tag{2}$$

where $X(\omega - \omega_0)$ is the frequency response of the mixed chirped-free signal, $Y(\omega - \omega_0)$ is the frequency response of the desired chirped signal, $H_{dispersion}$ is the dispersion induced transfer function, T is the mean period, and $\omega_0 = 2\pi/T$ is calculated as the central frequency of the desired signal and the required filter.

Assume $h(t)$ is the inverse Fourier transform of $H(\omega - \omega_0)$. If the frequency response is reconstructed by a uniform spaced FIR filter with a sampling period of T, the coefficients of the taps are given by $\alpha_k = h(kT)$. Since $H(\omega - \omega_0)$ has a quadratic phase response, the coefficients α_k will be complex valued, which is not easy to im-

plement in the optical domain. In order to simplify the implementation of the FIR filter, according to the operation principle proposed in [10, 11], the desired frequency response can be reconstructed by a FIR filter with equivalent complex coefficients, which are realized by nonuniformly spaced taps. The time delays and the coefficients of the taps that are used for the filter construction can be calculated by

$$\tau_k + \frac{\varphi(\tau_k)}{2\pi} = kT \tag{3}$$

$$\beta_k = \left| \frac{h(\tau_k)}{1 + T\varphi'(\tau_k)/2\pi} \right| \tag{4}$$

where $\varphi(\tau_k)$ is the phase of $h(\tau_k)$, β_k and τ_k are the coefficient and time delay of the k-th tap, which are respectively realized by controlling the output power and the optical wavelength of the k-th tunable laser source (TLS). The optical wavelength required to implement the time delay of the k-th tap is mathematically given by

$$\lambda_k = \lambda_1 + \frac{\tau_k - \tau_1}{\chi} \tag{5}$$

where λ_1 is the wavelength for the first tap. Then, the frequency response of the FIR filter can be calculated by the Fourier transform, which is given by

$$H(\omega) = \sum_k \beta_k \exp(-j\omega\tau_k) \tag{6}$$

It is worth noting that the frequency response of a FIR filter has multi-channels, but the target frequency response can only be acquired in the first order channel of the filter, which is due to the nonuniformly spaced time delays of the different taps. In order to eliminate the impact of the undesired band resonances by the bandpass profile of the chirped-free signal, the frequency of the RF signal and the FWHM of the input pulse must be properly selected. Since the DDMZM is used and SSB modulation of the chirped-free signal is realized, $H_{\text{dispersion}} = 1$ in full frequency band, which makes it possible to generate a chirped microwave signal with any central frequency in the bandwidths of the modulator and PD.

3. Simulation results and discussion

In this part, the generation of a chirped microwave signal with the desired parameters is verified by numerical simulation, and the desired frequency response is achieved by using a nonuniformly spaced FIR filter. By comparing with the system, in which an ordinary MZM or PM is used, the advantage of using DDMZM to eliminate the dispersion induced transfer function is clearly shown. The original signal and the waveform of the target chirped microwave signal are respectively expressed as:

$$x(t) = \exp\left[-2\left(\frac{t}{T_0}\right)^2\right] \tag{7}$$

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

where $T_0 = 120$ ps and $W = 3.2$ ns are the FWHM of the original Gaussian signal and the target signal, respectively. $T = 100$ ps and $\gamma = 1.6$ GHz/ns are the mean period and the chirped rate of the desired signal. Since the bandwidth of the original signal is not wide enough, the Gaussian pulse is firstly up-converted by mixing it with an RF signal with a frequency of 9.5 GHz. Thus, the desired frequency response can be calculated and achieved by the nonuniformly spaced FIR filter. Besides, since most of the power of the chirped-free signal can pass through the filter, the power of the generated signal can be easily increased. A length of 25 km single-mode fiber (SMF) with a total dispersion of 425 ps/nm is used to perform the time delays of the different taps. The operation of the filter without considering the fiber dispersion induced transfer function in the frequency domain is shown in Fig. 3**a**. When an ordinary PM or MZM is used in the system, the corresponding dispersion induced transfer function must be considered. As it is shown in Fig. 3**b**, the amplitude of the filter is suppressed by the dispersion
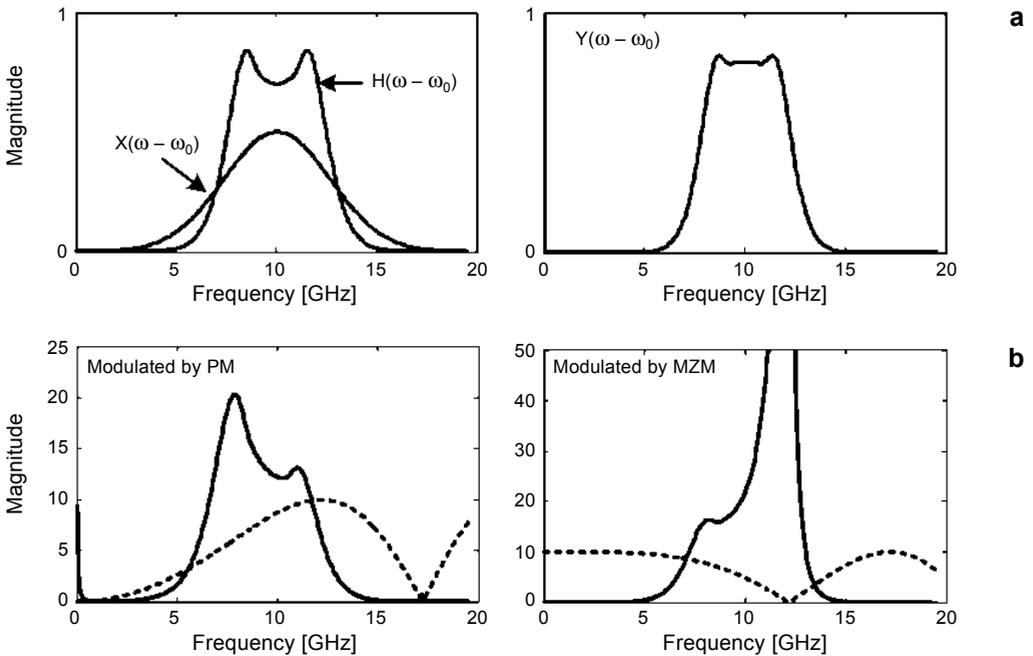
Fig. 3. The operation of the filter without considering the fiber dispersion induced transfer function in the frequency domain (**a**), the frequency response of the required filter, when PM (left) and MZM (right) are used (**b**).
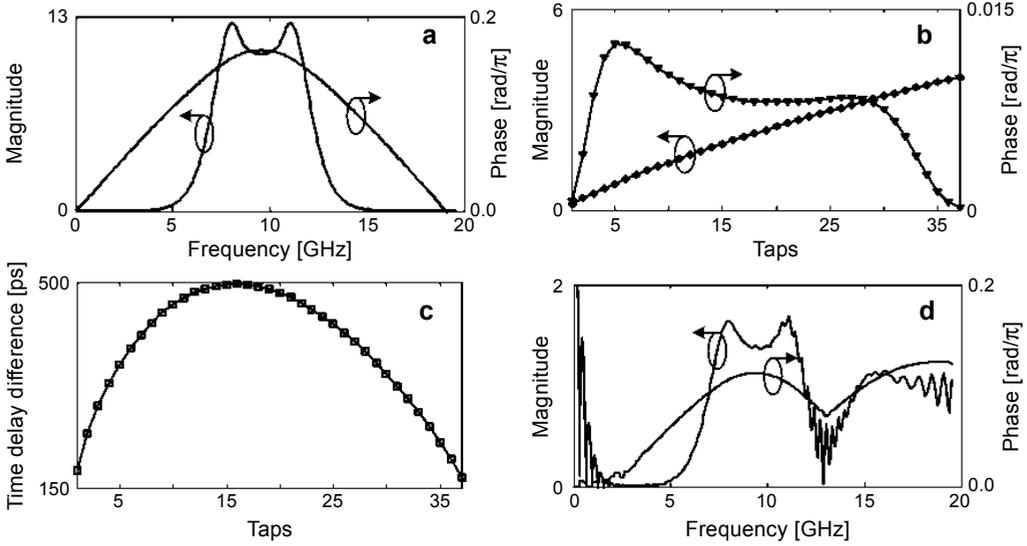
Fig. 4. The construction example of the FIR filter to generate the desired chirped microwave signal: the desired frequency response for the chirped microwave waveform generation (**a**), the time delays and coefficients of different taps (**b**), the time delay difference (**c**), and the frequency response of the nonuniformly spaced FIR filter (**d**).
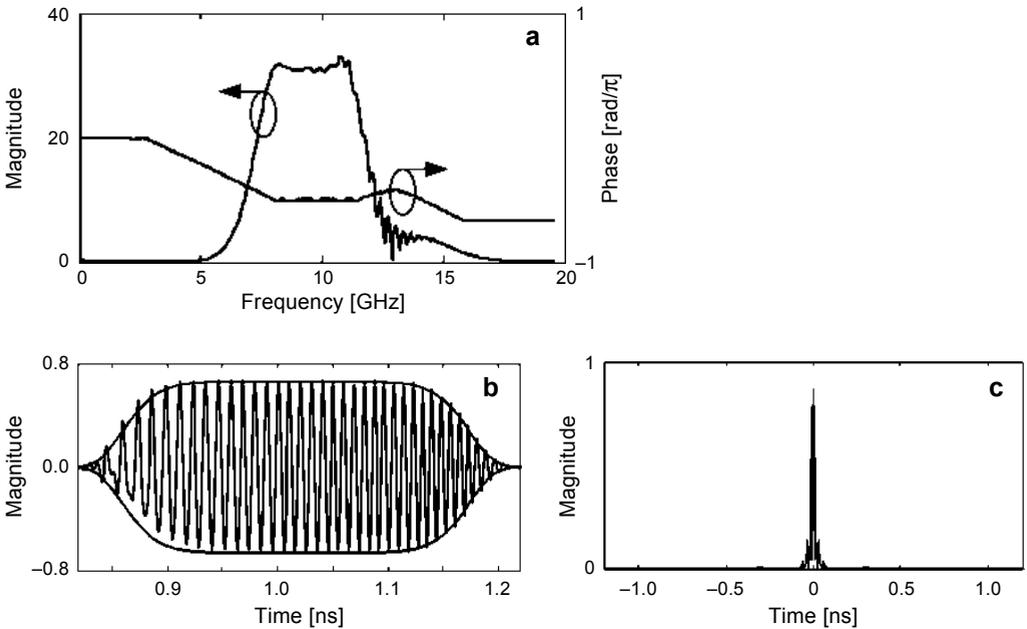
Fig. 5. The frequency response of the generated chirped microwave signal (**a**), temporal waveform of the generated pulse (**b**), and self-correlation of the generated chirped pulse (**c**).

induced transfer function, which will make it tougher for the achievement of the re-quired frequency response. If the amplitude in the passband of the filter is too seriously suppressed, a very high peak will exist in the desired frequency response, which cor-responds to a sinusoidal signal in time domain. Therefore, the construction of the filter cannot be realized and the target chirped microwave signal cannot be generated, unless the dispersion induced transfer function is eliminated. As it is demonstrated that SSB modulation of the chirped-free signal can be realized by bias control of the DDMZM, the signal with any central frequency can be generated, since the dispersion induced transfer function is eliminated.

The desired frequency response can be calculated based on Eq. (2) and it is shown in Fig. 4**a**. According to the principle of the filter design illustrated in Section 2, the time delays and coefficients of different taps can be calculated. From Fig. 4**b**, we can see that 37 taps are required for the filter construction, which is less than the number of taps required in [12]. Since a time delay difference of 3.7 ns exists between the 1st and the 37th tap, a total wavelength interval of 8.9 nm is required for the 37 taps. To illus-trate the nonuniform spacing clearly, the time delay differences of different taps are calculated and plotted in Fig. 4**c**, which is given by $\Delta \tau_k = \tau_k - kT$. Then, the frequency response of the FIR filter can be calculated and it is shown in Fig. 4**d**. It can be seen that the FIR filter has a frequency response almost the same as the desired frequency response in the first-order channel, and some ripples exist which are due to the wide bandwidth of the target frequency response and the nonuniform spacing taps of the FIR filter. By applying the chirped-free pulse with a central frequency of 9.5 GHz to the filter, the chirped microwave signal can be attained. As shown in Fig. 5**a**, the un-desired band resonance of the FIR filter is successfully eliminated. From Fig. 5**b**, it can be seen that the profile of the waveform is slightly distorted, which is due to the discordance between the desired frequency response and the acquired frequency re-sponse of the FIR filter.

As a chirped pulse can be compressed at a receiver using a matched filter, to demon-strate the pulse compression performance, the self-correlation of the generated chirped pulse is calculated here. It is shown from Fig. 5**c** that the microwave pulse is com-pressed, which confirms that the generated microwave signal is chirped.

4. Conclusion

We have proposed a novel approach to generating chirped microwave signals by using a nonuniformly spaced FIR filter. In this scheme, a narrowband Gaussian pulse is used as the original chirped-free signal. In order to eliminate the limitation of the narrow bandwidth of the original signal, an RF signal and a mixer were used to up-convert the spectrum of the original Gaussian pulse. Thus, the required frequency response can be calculated and reconstructed by a FIR filter with nonuniformly spaced taps. In addition, instead of an ordinary PM, a DDMZM is used and the SSB modulation of the input chirped-free signal is realized. Thus, the filter with any central frequency can be con-

structed without the constraint of the fiber dispersion induced transfer function. It should be noted that the FIR filter has multi-channels. In order to eliminate the undesired band resonances, the frequency of the RF signal and the FWHM of the original pulse should be properly selected. In this paper, the generation of a chirped microwave pulse with a FWHM of 3.2 ns and a chirp rate of 1.6 GHz/ns was verified by numerical simulations, and the required frequency response is achieved by a 37-tap FIR filter. This technique provided a solution to generate chirped microwave waveform with any high central frequency by reconstructing a nonuniformly spaced FIR filter with the desired frequency response.

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