The use of frequency-swept or chirped waveforms is prevalent in many radar systems [1–2]. Chirped waveforms are of constant magnitude, and they are relatively simple to generate and process. A matched filter at the receiver end of the radar system compresses the entire energy of a long chirped waveform into a sharp and narrow virtual peak with low sidelobes. The duration of the obtained peak is inversely proportional to the broad bandwidth of the waveform. In this manner, high ranging resolution may be obtained, alongside a large signal-to-noise ratio (SNR), without resorting to short and intense isolated pulses.

The most straightforward chirped waveforms are linear-frequency-modulated (LFM) signals, in which the instantaneous frequency is swept at a fixed rate [2, 3]. Although simple to analyze and process, the compressed form of LFM signals exhibits relatively high sidelobes, which could lead to false detection. The sidelobes can be reduced substantially through careful optimization of the chirped waveform’s power spectral density (PSD) [3]. An optimized PSD would require, however, that the instantaneous frequency of the signal is swept at a non-constant rate, resulting in a more general, nonlinear-frequency-modulated (NLFM) waveform [3].

The incorporation of elaborate NLFM waveforms in advanced radar systems is both attractive and challenging [3].

Many modern radar systems rely on phased-array antennas (PAA s) for angular beam steering. The spatial steering of broadband waveforms in PAs requires variable group delay increments, often referred to as true time delays (TTD), to avoid spatial distortion [4]. The extent of the necessary delay scales with the time of flight across the PAA aperture, and could reach tens of nanoseconds. The realization of TTD elements using microwave photonic (MWP) methods provides several potential advantages over radio frequency (RF) techniques [5], such as low propagation loss in optical fibers, broadband width of several terahertz, and immunity to electromagnetic interference. Over the last two decades, much effort has been invested in the research of optical delay lines (ODLs) for beam steering within PAs [6–12].

The primary figure of merit of a TTD element is the product of the maximum achievable delay times the bandwidth of the processed waveform. Most continuously variable ODLs struggle to retain the necessary quality of the processed waveform while operated at delay-bandwidth products above unity.

The application of ODLs to the TTD of NLFM chirped waveforms is of particular interest, due to the complexity of such waveforms and their significance in radar systems. Previous works, however, are largely restricted to the specific case of LFM. In a series of works by Tur and co-authors [10, 13, 14], discrete delays of LFM waveforms were demonstrated through wavelength-selective switching among different paths. A continuously variable TTD of LFM waveforms was reported based on stimulated Brillouin scattering “slow light” [9]; however, the obtained delay of 230 ps is insufficient for large PAs. In our earlier works, the TTD of LFM waveforms by as much as 100 ns was reported [15, 16]. Due to the fixed sweep rate of LFM signals, it was shown that the application of a frequency offset to an LFM waveform is nearly analogous to its TTD [15, 16]. The necessary frequency offset was conveniently implemented through acousto-optic modulation of a single LFM optical sideband [16]. A simple frequency offset is inapplicable, however, to NLFM waveforms, as their sweep rate varies in time.

In this work, the MWP processing scheme is extended to provide the TTD of chirped pulses having arbitrary pre-designed sweep rate profiles. The method relies on the application of a carefully timed phase correction term to an NLFM optical sideband. The continuously variable delay of 500 MHz wide waveforms by as much as 20 ns is experimentally demonstrated. The method allows for the variable delay of general NLFM waveforms with the necessary fidelity and range. It is applicable to the processing of chirped pulses having arbitrarily high central RFs.

A general chirped pulse of fixed magnitude \(A_0\) and duration \(T\) (that is typically microseconds long) is expressed as

\[
A_{FM}(t) = A_0 \cos(\phi(t)) \cdot \text{rect}(t/T),
\]

where \(t\) denotes time, and \(\text{rect}[x]\) equals 1 for \(|x| \leq 0.5\) and equals zero elsewhere. The instantaneous phase \(\phi(t)\) of an \(n\)th-order NLFM waveform is designed using the
algorithm of [2], so that the PSD of the waveform (1) would best approximate a target function of order \( n \):

\[
V(\Delta f) = V_0 \left[ k + (1 - k)\cos \left( \frac{\pi \Delta f}{B} \right) \right]^{1/2} \cdot \text{rect} \left( \frac{\Delta f}{B} \right). \tag{2}
\]

Here \( V_0 \) is a constant PSD value, \( \Delta f \) is a variable of spectral detuning from the central RF of the waveform, \( B \) is the waveform bandwidth, and \( 0 \leq k \leq 1 \) is a design parameter [2]. The waveform reduces to the basic LFM form for \( k = 1 \). Figure 1 (top) shows an example of the instantaneous frequency \( (\text{d} \phi / \text{d}t) / 2 \pi \) of LFM and 16th-order NLFM waveforms. Figure 1 (bottom) shows the corresponding calculated impulse responses. The sidelobe suppression of the impulse response function is quantified in terms of the ratio of the correlation peak power to that of the highest sidelobe (PSLR), and the ratio of energy within the correlation main lobe to the energy outside it (ISLR). The sidelobe suppression is more effective in higher-order NLFM waveforms. The simulated PSLR and ISLR of a 500 MHz wide, 5 \( \mu \)s long LFM waveform are 17.8 and 15.7 dB, respectively, whereas the corresponding metrics of a 16th-order NLFM waveform of equal bandwidth and duration are 45.7 and 40.8 dB, respectively. Sidelobe suppression, however, comes at the expense of lower resolution: the full width at half-maximum (FWHM) of the main lobe of the NLFM impulse response is 6.8 ns, as opposed to 2 ns for the LFM waveform.

An NLFM waveform delayed by \( \Delta t \) is given by

\[
A_{\text{FM}}(t - \Delta t) = A_0 \cos[\phi(t - \Delta t)] \cdot \text{rect}[t - (t - \Delta t) / T]. \tag{3}
\]

Consider now the introduction of an instantaneous phase correction term \( \Delta \phi(t) \):

\[
A_{\text{FM}}^{\text{shifted}}(t) = A_0 \cos[\phi(t) + \Delta \phi(t)] \cdot \text{rect}[t / T]. \tag{4}
\]

The phase-corrected waveform could well approximate the delayed one, \( A_{\text{FM}}^{\text{shifted}}(t) = A_{\text{FM}}(t - \Delta t) \), provided that \( \Delta t \ll T \) and

\[
\Delta \phi(t) = \phi(t - \Delta t) - \phi(t). \tag{5}
\]

Differences between the truly delayed signal and the phase-shifted one are confined to the edges of the rectangular temporal window, which is not delayed by the phase correction process. Note that the compensating waveform is low-rate, and independent of the central frequency of the chirped waveform, which may be arbitrarily high. The phase correction term can be applied to an NLFM optical sideband using a phase modulator.

Figure 2 presents the experimental setup for the TTD of the impulse response of arbitrarily chirped waveforms [15,16]. The output of a CW laser source is split in two paths. Light in the upper path is modulated by an electro-optic intensity modulator, driven by RF NLFM waveforms. The waveforms \( (T = 5 \mu \text{s}, B = 500 \text{ MHz}) \) are generated by a programmable, high-rate arbitrary waveform generator (AWG) at a central intermediate frequency (IF) of 1 GHz, and they are upconverted to a central frequency of 7.5 GHz using an RF mixer. A fiber Bragg grating is then used to filter out the optical carrier and one modulation sideband, retaining only the other modulation sideband. The remaining sideband passes through a phase modulator, which is driven by the appropriate phase correction function [see (5)]. The correction term is generated electrically by a low-rate arbitrary function generator (AFG). Unlike the previously reported TTD of LFM waveforms, careful synchronization between the NLFM pulses and the phase correction term is necessary.

Prior to detection, the optical carrier that is retained in the lower path is reintroduced and combined with the processed sideband (see Fig. 2). A phase-offset RF waveform is reconstructed through the beating of the carrier and the single sideband on a broadband photodetector [6]. Using a second RF mixer, the photodetected signal is downconverted to the original IF, and sampled by a real-time oscilloscope of 6 GHz bandwidth. Finally, the impulse response of the detected waveform is calculated by cross-correlating it with a reference signal, which was acquired at the output of the high-rate AWG.

The ISLR of the impulse response of a nondelayed, 4th-order NLFM waveform was 23 dB. This value comes close to the 26 dB ISLR of a corresponding RF-only
processed waveform, in which the two RF mixers were connected back-to-back without optical processing.

Experimental impulse responses of 4th-order NLFM waveforms, delayed by 0–50 ns, are shown in Fig. 3. The FWHM of the delayed impulse response functions were 4 ns. The PSLR and ISLR for a 20 ns delay were 28 and 16 dB, respectively. The impulse responses of 8th-order and 16th-order NLFM waveforms were also successfully delayed by 20 ns, with PSLR and ISLR values of 24.4 and 16.7 dB, respectively, for 8th-order NLFM, and 27 and 18 dB, respectively, for 16th-order NLFM (see Fig. 4). The longer delay of higher-order NLFM waveforms would be limited by the relatively narrow bandwidth of the AFG used in the generation of the phase correction term. Note that the phase bias was not controlled in the experiments. Control over the phase bias would be necessary in beam steering experiments involving multiple elements [6].

In summary, a continuously variable ODL setup accommodating chirped waveforms of arbitrary sweep rates, durations, and central RFs has been introduced and demonstrated. The method relies on the application of a low-bandwidth correction term to the instantaneous phase of a single modulation sideband. The technique extends, for the first time, the MWP TTD of chirped waveforms beyond the processing of the fundamental LFM signals. The reported scaling toward general, high-frequency NLFM waveforms is significant in two respects: (a) NLFM waveforms improve the SNR and power budget of advanced, broadband, and low-sidelobe radar systems [2]; and (b) the relatively complex sweep rates of NLFM signals makes the electrical generation of their delayed replicas more difficult.

The reported delays are sufficient for beam forming in PAAs that are several meters wide. Comparable delays using slow-light-based TTD, for example, would exceed the delay-bandwidth product limitations, or would require the use of frequency-swept pump sources [17]. The method can be extended further to the TTD of chirped pulses whose amplitudes are temporally varying as well, with the application of an electro-optic intensity modulator in series.

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References