Photonically Assisted Compression of Ultra-Wideband Arbitrary Microwave Waveforms via Programmable Optical Phase Filters

Ehsan Hamidi, and Andrew M. Weiner

School of Electrical and Computer Engineering, Purdue University, 465 Northwestern Ave., West Lafayette, IN 47907-2035, USA, ehamidi@purdue.edu, amw@purdue.edu

Abstract

We experimentally demonstrate compression of ultra-wideband microwave arbitrary waveforms via programmable optical phase filters implemented in a hyperfine resolution optical pulse shaper. We synthesize arbitrary ultra-wideband radio frequency waveforms and utilize programmable microwave photonic filters to impose the opposite of a waveform spectral phase on its spectrum. This enables us to synthesize a matched filter which compresses an ultra-wideband microwave waveform to its corresponding bandwidth-limited pulse duration. As an example, we demonstrate compression of a 15 GHz bandwidth chirp with ~733 ps temporal window to a 40 ps duration pulse with more than 14 dB peak power gain. Our technique is programmable and we believe it is applicable to a wide range of arbitrary spectral phase modulated ultra-wideband radio frequency waveforms.

1. Introduction

The current interest in the area of microwave photonics has been rapidly growing in the past several years where optical techniques are utilized to enhance radio frequency (RF) systems performance [1-6]. The generation of arbitrary RF electrical waveforms using optical pulse shaping techniques has realized RF waveforms with bandwidths exceeding the few GHz values available via commercial electronic arbitrary waveform technology [5, 6]. A lot of effort has been devoted to the generation of microwave waveforms via photonic techniques; however practical techniques for processing and detection of ultra-wideband (UWB) electrical signals for applications in communication systems are still lacking. In direct sequence spread spectrum systems, a received signal is commonly correlated with a proper despreading code by using surface acoustic wave (SAW) devices and data is extracted from the resultant correlation signal; although this technique requires synchronization and suffers from timing jitter [7]. However SAW correlators have been demonstrated only for center frequencies up to 3.63 GHz with 1.1 GHz bandwidth for UWB applications [8]. This frequency bandwidth is well below the UWB frequency band (3.1–10.6 GHz) allocated by FCC and bandwidths accessible via RF photonic waveform generation techniques [5, 6]. On the other hand, UWB receivers based on a digital signal processing scheme are limited by analog-to-digital converters' speed and dynamic range [7, 9]. Electronic UWB receivers are also limited to bandwidths much less than the UWB frequency band [10]. Hence photonic processing of microwave waveforms has been becoming a distinctive candidate for processing UWB electrical signals in wireless systems [11].

In photonic processing of microwave signals, the radio frequency waveform is usually modulated on an optical carrier and the optical signal is processed in the optical domain and then converted back into the RF domain through O/E conversion [1]. In conventional technique a photonic signal processing device is implemented through multi-tap optical delay lines. This scheme enables to design discrete-time microwave photonic amplitude filters with a finite impulse response [2]. Recently programmable photonic microwave filters with arbitrary UWB phase/amplitude response were implemented via hyperfine resolution optical pulse shaping [3, 4]. This unveils a new approach for compression and detection of spread-time electrical waveforms in UWB wireless communication systems via matched filtering. Here we present a novel technique to compress UWB RF electrical waveforms through microwave photonic filters which are implemented via hyperfine resolution optical pulse shaping.

2. Experimental Setup

Our experimental setup consists of two separate subsystems: a microwave photonic filter which is programmed to function as a matched filter and a microwave photonic arbitrary waveform generator which is used to test the matched filter operation. In the following first the waveform generator and then the microwave photonic programmable filter are presented.

2.1 Microwave Photonic Arbitrary Waveform Generator

Fig. 1 shows a schematic of our microwave arbitrary waveform generator based on the method of [6]. We utilize a technique based on ultrafast optical arbitrary waveform technology for synthesis of arbitrary microwave waveforms in the arbitrary waveform generator [5, 6]. This apparatus consists of a mode-locked fs fiber laser, a Fourier transform optical pulse shaper, an optical frequency-to-time converter, an erbium-doped fiber amplifier (EDFA), an O/E converter, and an RF amplifier.

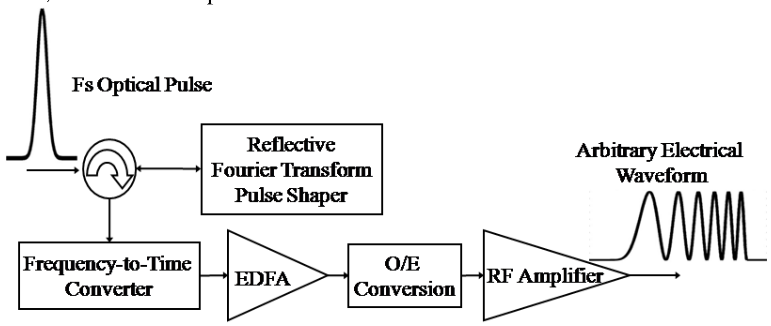

Fig. 1. Microwave photonic arbitrary waveform generator.

Ultra-short optical pulses from the mode-locked laser (~100 fs, 50 MHz repetition rate) are spectrally filtered in the reflective-geometry Fourier transform optical pulse shaper. This enables to impose a user-defined optical filter function onto the spectrum of the optical pulses. After the pulse shaper, the output pulses are dispersed in 1.6 km of single mode optical fiber. The chromatic dispersion of the fiber uniquely maps optical frequency to time; hence the temporal optical intensity of output pulses is a scaled version of the filter function applied in the optical pulse shaper. Then the optical pulse shaper output is amplified through an EDFA. The output tailored optical intensity waveforms are converted to electrical signals via O/E conversion in a photodiode with an electrical 3-dB bandwidth of ~22 GHz. After O/E conversion, the electrical waveforms also exhibit the shape of the optical filter function applied in the optical pulse shaper. This enables user-defined time-domain electrical waveforms to be directly synthesized as demonstrated in [6]. A detailed description of this apparatus is given in [6]. The RF electrical output of the photodiode is amplified with a broadband microwave amplifier (0.1-18 GHz, ~29 dB gain) to be applied to an optical intensity modulator in the next stage.

The time aperture of the generated waveforms is determined by the optical bandwidth and the length of the fiber stretcher. The time aperture and temporal resolution may be adjusted by controlling the optical bandwidth and the dispersion of the fiber stretcher [6]. The minimum temporal feature size of the RF waveform is essentially limited by the resolution of the optical pulse shaper and the dispersion constant of the fiber stretcher; however it is also limited by the photodiode and the RF amplifier electrical bandwidth (18 GHz high cut-off frequency). In our setup the length of the fiber stretcher has been chosen 1.6 km in order to obtain waveforms with about 750 ps temporal window which is the time aperture of the microwave photonic filter setup.

2.2 Microwave Photonic Matched Filter

A schematic of a microwave photonic matched filter is shown in Fig. 2. Our microwave photonic matched filter is based on programmable microwave photonic filters demonstrated in [3, 4]. This technique uses optical frequency domain filtering with O/E conversion. The frequency domain optical filtering is based on Fourier transform pulse shaping, which has been extended to hyperfine (~600 MHz) spectral resolution through the use of a virtually imaged phased array (VIPA) as a spectral disperser. In this technique, the phase/amplitude filter imposed onto the optical spectrum is directly mapped onto a microwave phase/amplitude filter at the output. As a result, a user-defined frequency domain microwave phase/amplitude filter is implemented photonically that provides essentially arbitrary phase/amplitude filter response over RF band from DC to 20 GHz with ~600 MHz programmable spectral resolution [3, 4]. The minimum spectral resolution of a pulse shaper determines the maximum temporal window of a waveform, which can be manipulated, where their relation is given by the time-bandwidth product. A spectral resolution of ~600 MHz corresponds to a temporal window of about 730 ps. In order to match the generated microwave waveforms' temporal aperture to the microwave photonic filter spectral resolution, we have adjusted the temporal window of waveforms generated in the microwave photonic arbitrary waveform generator to about 750 ps.

In this setup, a tunable laser with line-width below 0.1 pm centered at 1550 nm is input to a Mach–Zehnder (MZ) intensity modulator with an electrical 3-dB bandwidth of 30 GHz and a minimum transmission voltage of V_π ~4.75 V, which is driven with a microwave arbitrary waveform generated via the microwave photonic arbitrary waveform generator explained formerly. Modulating the optical carrier with a UWB RF electrical waveform in the MZ modulator transfers the RF signal into the optical domain as a double-sideband modulation about the optical carrier. The resulting double-sideband modulated signal is applied to an optical pulse shaper. In our experiment we allow both sidebands to pass through the optical pulse shaper, as opposed to [3] where one sideband is suppressed.

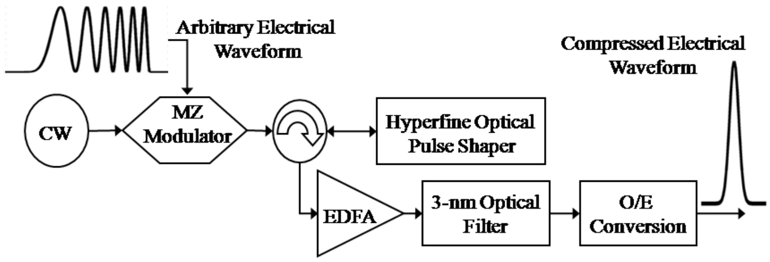

Fig. 2. Microwave photonic matched filter.

As in Fourier transform pulse shaping, different optical frequency components contained within the input signal are first separated spatially using an optical spectral disperser and a lens, and then a spatial light modulator (SLM) manipulates the phase/amplitude of the different frequency components in parallel. By using a polarizer at the pulse shaper input, simultaneous and independent amplitude and phase filtering of individual optical frequency components are enabled. A detailed description of programmable microwave photonic filters is given in [3, 4].

The output of the hyperfine optical pulse shaper is applied to an EDFA. After amplification in an EDFA, the optical signal passes through a 3-nm optical filter to reduce its amplified spontaneous emission. Then the spectrally-filtered optical signal is down-converted to baseband via a photodiode with an electrical 3-dB bandwidth of ~22 GHz. The resultant microwave signal is measured by a fast sampling scope.

The Fourier transform pulse shaper acts as a bandpass filter on the modulated optical signal. By programming the SLM, a filter can be synthesized and imposed on the optical signal. In order to synthesize a waveform compressor we program the microwave photonic filter as a matched filter. We first extract the spectrum of the output uncompressed electrical waveform when the pulse shaper is quiescent, i.e., no spectral phase is added, by taking Fourier transform of the measured output waveform. By imposing the conjugate of the output uncompressed waveform's spectrum, which reduces to only spectral phase for uniform broadband RF signals, on its corresponding optical signal spectrum the envelope of the optical carrier electric field is compressed to its transform-limited duration via matched filtering that results in corresponding output compressed transform-limited duration electrical pulse through O/E conversion.

Here we give two definitions to compare the output uncompressed and compressed voltage waveforms in order to evaluate a matched filter performance. We define a gain parameter as the ratio of the compressed pulse peak voltage, minus its dc level, to the uncompressed waveform peak voltage, minus its dc level, all measured after the photodiode which can be expressed in decibels. Since a photodiode maps optical intensity to an electrical signal, the resulting voltage signal is required to be a positive-definite quantity and has a non-zero dc level. The subtraction of the dc voltage is relevant since a dc voltage carries no information and may be easily blocked by a high pass filter. We also define a compression factor as the ratio of the uncompressed voltage waveform temporal window to the compressed voltage pulse full width at half maximum (FWHM) duration, all measured after subtraction of their dc levels.

3. Experimental and Numerical Results

To test our compression technique, we have synthesized a linear frequency-modulated (chirp) electrical waveform via the microwave photonic arbitrary waveform generator and used it as an input to the microwave photonic matched filter. First the uncompressed output waveform that is obtained from the microwave photonic filter, when the pulse shaper is quiescent, is measured using a fast sampling scope. Then the spectral phase of the output RF baseband waveform is extracted through Fourier transform. By programming the pulse shaper to apply the opposite spectral phase function; the output electrical waveform is compressed to a short bandwidth-limited electrical pulse.

Fig. 3 shows compression of a UWB RF electrical chirp waveform, with ~15 GHz bandwidth centered at ~7.5 GHz with ~733 ps temporal window. Fig. 3(a) shows the microwave photonic filter output electrical waveform when the pulse shaper is quiescent. The blue curve in Fig. 3(b) shows the compressed electrical waveform at the output after the conjugate spectral phase, i.e. the matched filter, is applied through the microwave photonic filter. A 14.2 dB gain parameter has been achieved, and the output electrical voltage pulse FWHM duration is 40 ps which corresponds to a compression factor of 18.3. A calculation of the electrical waveform of Fig. 3(a) processed through an ideal conjugate spectral phase optical filter which is numerically performed through FFT in MATLAB is shown by red curve in Fig. 3(b). For the ideally compressed waveform, a 15.1 dB gain parameter and a 38 ps FWHM electrical voltage pulse duration, which corresponds to a compression factor of 19.3, are expected. In each trace the dashed line shows the dc level of the photodiode output voltage waveform averaged over its 733 ps temporal window from 147 to 880 ps. The excellent agreement between experiment and simulation suggests that the uncompressed RF waveform spectral phase is being corrected with a high degree of precision.

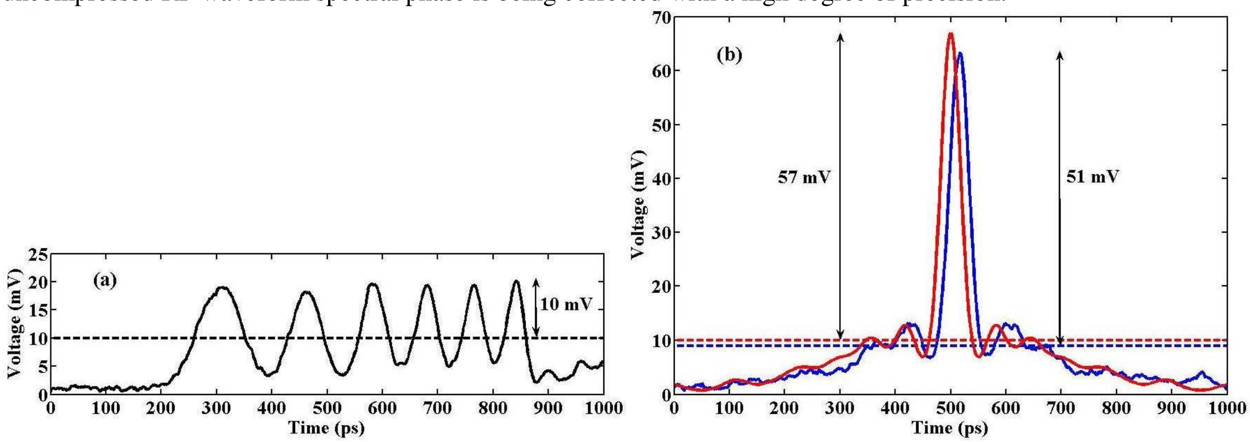

Fig. 3. (a) Output linear chirp electrical waveform with ~15GHz bandwidth centered at ~7.5GHz when the pulse shaper is quiescent. (b) blue: output compressed electrical waveform after the matched filter is applied, red: ideally matched filtered electrical waveform.

4. Conclusion

Compression of UWB RF spread-time arbitrary electrical waveforms via programmable microwave photonic phase filters implemented in an optical pulse shaper is experimentally demonstrated. A new approach to compress and asynchronously detect RF electrical waveforms in UWB communication systems via matched filtering is proposed. This enables to asynchronously detect UWB spread-time electrical waveforms, to recover a synchronizing signal, and to compensate a channel response in a multi-path environment.

5. References

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