Photonic Synthesis of Broadband Microwave Arbitrary Waveforms Applicable to Ultra-Wideband Communication

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***Abstract*—We demonstrate photonic synthesis of broadband radio-frequency (RF) waveforms suitable for ultra-wide bandwidth (UWB) systems via open-loop reflection-mode dispersive Fourier transform optical pulse shaping. Using this technique, we synthesize broadband burst, monocycle and pulsed waveforms with RF bandwidths ranging from ∼1–8 GHz. Through appropriate optical waveform design, we demonstrate direct control over the shape of the RF spectrum—a capability that enables us to tailor our RF waveforms to conform to the low-power UWB spectral criteria.**

***Index Terms*—Arbitrary waveform generation, optical pulse shaping, pulse generators, radio-frequency (RF) photonics, ultra-wideband (UWB) systems.**

I. Introduction

In recent years, interest has rapidly increased in the area of microwave photonics—the realm where optical and radio-frequency (RF) signals and operations are combined to increase RF system performance. Specifically, optical analog-to-digital (A/D) conversion [1], [2] and microwave-photonic links [3] have garnered significant research interest. The former has been demonstrated to enable 130 GS/s A/Ds [2] and the latter has found application in data transmission as well as local-oscillator remoting operations [3].

Pulsed radar and high-frequency wireless systems applications have motivated substantial research in the area of photonic arbitrary waveform generation systems, where optical signals are used to generate arbitrary electrical waveforms. Pure narrowband microwave/millimeter electromagnetic signals have been generated (12.4 and 37.2 GHz) through heterodyning different longitudinal modes of a modelocked semiconductor laser [4]. In the millimeter band, broadband burst [5] and continuous periodic [6] signals have been synthesized in the 30–50 GHz range via a direct space-to-time optical pulse shaping technique. Arbitrary RF/microwave waveforms in the 1–12 GHz have also been demonstrated through a Fourier transform optical pulse shaping/dispersive stretching technique [7], [8].

Current interest in ultrawideband (UWB) wireless systems for communications [9], ground penetrating radar (GPR), and imaging systems also motivates novel techniques for arbitrary electrical waveform generation. Within the Federal Communications Commission-specified band of 3.1–10.6 GHz, UWB systems employ short bursts [10] of radiation to achieve material penetration (imaging, GPR) as well as to mitigate multipath interference in communications applications. In this work, we present an open-loop optical pulse shaping technique for generation of broadband sinusoidal and ultra-broadband impulsive RF waveforms [8] aimed at applications in UWB wireless communication. Examples include a chirp waveform with abrupt cycle-by-cycle frequency modulation in the 1.25–5 GHz range and ultrabroadband RF impulses and impulse sequences with temporal durations as short as 200 ps and bandwidths up to ∼8 GHz. To our knowledge, it is not possible to generate such waveforms using current commercial electronic technology.

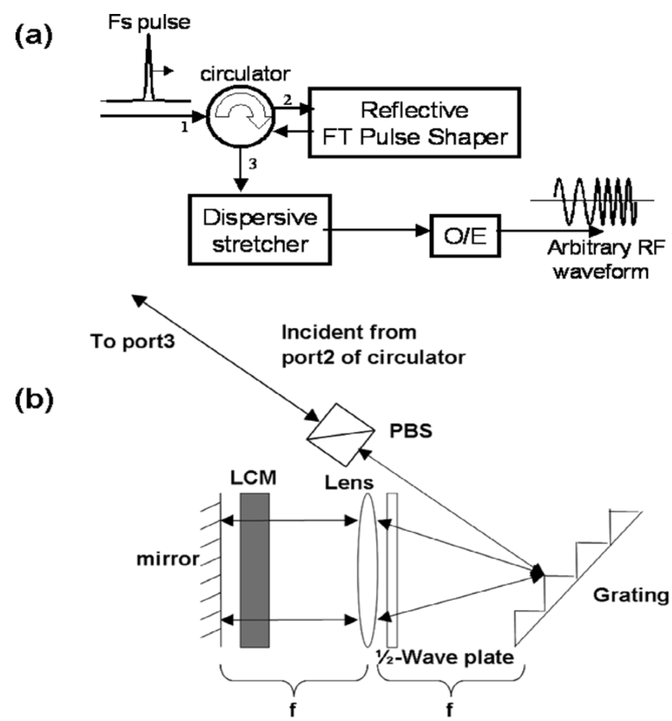

Fig. 1. (a) Experimental apparatus. (b) Reflective geometry Fourier transform pulse shaper.

II. Experimental Apparatus

Our method relies on the ability to shape the optical power spectrum in a Fourier transform (FT) pulse shaper [11] followed by frequency-to-time conversion in a dispersive medium as demonstrated previously [7], [8]. A block diagram of our experimental apparatus is illustrated in Fig. 1(a). Short pulses from a modelocked erbium fiber laser (∼100 fs, ∼30 nm bandwidth) are spectrally filtered in a reflective FT pulse shaper. This allows

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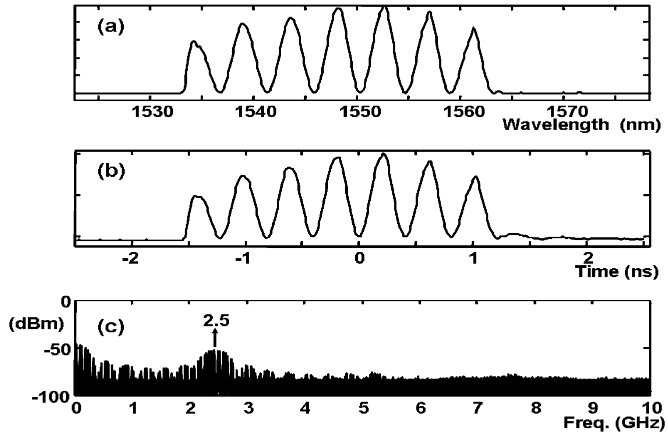

Fig. 2. 2.5 GHz sinusoidal burst. (a) Filtered optical spectrum with periodic 4.2 nm amplitude modulation. (b) $\sim$2.5 GHz time-domain RF waveform. (c) RF power spectrum clearly showing the peak at $\sim$2.5 GHz.

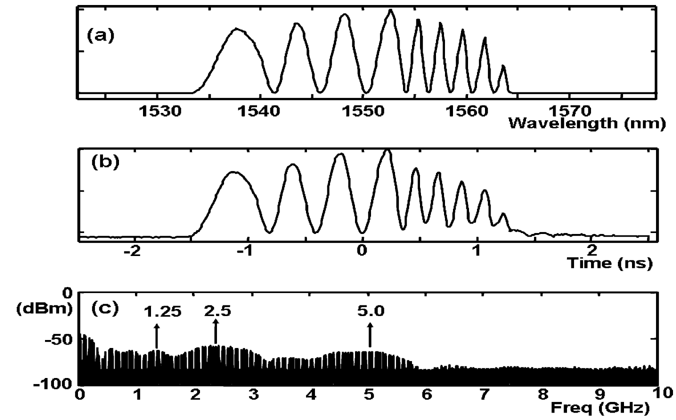

Fig. 3. Broadband frequency modulated waveform. (a) Filtered optical spectrum showing chirped modulation. (b) Time-domain RF waveform showing cycles at $\sim$1.25, $\sim$2.5, and $\sim$5 GHz. (c) Broadband RF power spectrum.

us to impress an arbitrary filter function onto the optical spectrum. These shaped pulses are then dispersed in 5.5 km of single mode fiber. The chromatic dispersion of the fiber gives us a frequency-dependent linear time delay that results in a time-domain optical waveform exhibiting the shape of the optical filter function applied in the pulse shaper. Thus, after optical-to-electrical (O/E) conversion of the time-domain optical waveform, the measured RF waveform exhibits the shape of the filter function applied to the optical power spectrum. By manipulating the optical filter function of the pulse shaper, we directly modulate the optical spectrum and, hence, the time-domain RF waveform.

Fig. 1(b) shows our reflective geometry FT pulse shaper configuration. Short pulses from the laser source enter the pulse shaper from a circulator through a polarizing beamsplitter. Individual frequency components of the input pulse are angularly dispersed by an 830 l/mm diffraction grating. A 190 mm focal length lens stops this dispersion and focuses the dispersed frequency components along the retroreflecting mirror at the back focal plane of the lens. A 128 pixel, single-layer liquid crystal modulator (LCM) is placed immediately before the mirror. The dispersed frequency components are amplitude modulated in parallel under voltage control by the combination of the 128-pixel LCM and the polarizing beam splitter at the output. After modulation, the frequency components are recombined by the lens/grating combination, and exit the pulse shaper through the polarizing beamsplitter/circulator. The source laser bandwidth ($\sim$30 nm) and the total chromatic dispersion of the fiber stretcher ($\sim$96 ps/nm) enable a time aperture of approximately 3.0 ns for our RF waveforms. After O/E conversion with a 22-GHz photodiode, our temporal RF waveforms are measured with a 50-GHz sampling oscilloscope and the RF spectra of these waveforms are measured with a 50-GHz RF spectrum analyzer. The key difference between our work and previous demonstrations of this technique [7] is that our system operates in an open-loop configuration. Thorough characterization of our pulse shaper and dispersive stretcher enable real-time arbitrary RF waveform realization, without the need for iteration.

III. Measurement and Results

We now present several representative waveforms generated in our system. As a first simple example, Fig. 2 shows a burst sinusoidal RF waveform. In Fig. 2(a), we show the filtered optical spectrum which exhibits a sinusoidal amplitude modulation with a period of $\sim$4.2 nm. After dispersive stretching and O/E conversion the measured RF waveform shows the shape of the optical power spectrum as clearly illustrated in Fig. 2(b). The $\sim$400 ps period of the time domain waveform agrees quite well with the value predicted by the total fiber dispersion and the applied periodic spectral filter function. In the frequency domain, a peak is quite evident at $\sim$2.5 GHz in the RF spectrum of Fig. 2(c). Nice correspondence between optical spectrum and time domain RF waveform is illustrated. The roll-off in the time domain waveform is due to the underlying shape of the optical spectrum and can be eliminated through proper equalization. The noise floor of the RF spectral measurement is approximately -84 dBm and our signal peak is ~ -50 dBm showing a signal-to-noise ratio of $\sim$34 dB. Sidelobes in Fig. 2(c) are due to the roughly square time aperture of the sinusoidal waveform. We obtained similar results (not shown) for burst sinusoidal waveforms with center frequencies throughout the 1–5 GHz range.

We also demonstrate the ability to modulate our waveforms on a timescale not achievable via electronic techniques. Fig. 3 shows an example of a broadband frequency-modulated waveform composed of $\sim$1.25/2.5/5 GHz cycles. The top trace, Fig. 3(a), again shows the filtered optical spectrum which has been patterned with a sinusoidal shape varying discretely in period from $\sim$8.4 nm (0.5 cycle) to $\sim$4.2 nm (2.5 cycles), to $\sim$2.1 nm (four cycles). After stretching, this spectrum gives rise to an RF waveform [Fig. 3(b)] with abrupt frequency modulation, exhibiting 0.5 cycles at $\sim$1.25 GHz, 2.5 cycles at $\sim$2.5 GHz, and four cycles at $\sim$5 GHz. In the RF spectrum [Fig. 3(c)], three main peaks centered at $\sim$1.25/2.5/5 GHz are clearly seen. The broad RF spectral bandwidth shown here is achieved by our ability to change frequency on a cycle by cycle basis—an ability not achieved with current electronic techniques.

To further illustrate the capability to generate extremely broadband RF waveforms in our system, we turn now to demonstration of impulsive waveforms geared for ultrabroadband RF systems applications, such as UWB communications. An example of an ultra-broadband impulsive waveform is shown in Fig. 4. Here, we specifically appeal to UWB applications by demonstrating a burst of monocycle waveforms

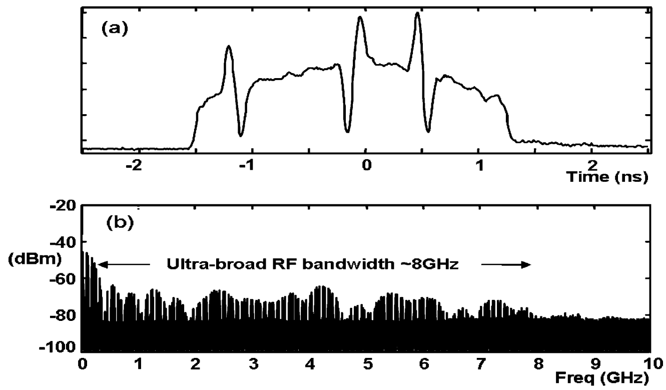

Fig. 4. Ultra-broadband monocycle burst waveform. (a) Time-domain waveform. (b) RF power spectrum.

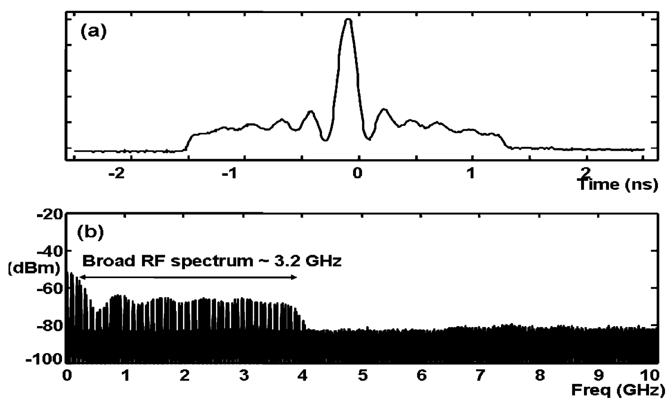

Fig. 5. Impulsive RF waveform. (a) Time-domain waveform. (b) RF power spectrum. Here, the RF spectral shape closely matches the target super-gaussian form.

[Fig. 4(a)] similar to those frequently used in UWB systems. Several unique capabilities are illustrated in Fig. 4. First, our monocycles are on the order of $\sim$200 ps in duration, already shorter than those typically generated electronically [10]. Additionally, the time resolution of our system enables the spacing between adjacent pulses to be controlled to within approximately 30 ps; this enables pulse-position modulation encoding with a much finer resolution than is available from current electronic devices. Another capability unique to our system is the potential for arbitrary polarity reversals as illustrated by the second monocycle in the sequence. We expect this could enable the use of phase-shift keying in UWB systems, again with more flexible control than provided by purely electronic techniques. From Fig. 4(b), the ultra-broad bandwidth of the monocycle sequence is clearly evident—the measured RF spectrum shows nonzero spectral content ranging from dc to $\sim$8 GHz.

With careful waveform design, we can further tailor the spectrum of our RF signals. Specifically, we aim to generate ultra-broadband signals conforming to the power and spectral content limits specified for UWB communication applications. Fig. 5 shows an example of an RF waveform illustrating this concept. Here, our goal is to generate an extremely flat RF spectrum. We first select a super-Gaussian as the target RF spectrum. The requisite filter function applied in our pulse shaper is then determined by sampling the inverse Fourier transform of the target RF spectrum. Fig. 5(a) shows the measured RF temporal waveform resulting from this operation. The impulsive waveform is approximately 450 ps (between first two nulls) and rides on a small dc pedestal (again, we are shaping the optical intensity). As shown in Fig. 5(b), the RF power spectrum is very broad and shows a nearly super-gaussian shape with a bandwidth of $\sim$3.2 GHz. The flatness is within 6.78 dB over spectral range from 0.59 GHz to 3.77 GHz, and the majority of this fluctuation results from the square-like dc pedestal in the time domain. This clearly illustrates our ability to tailor the RF spectrum of our waveforms to conform to the spectral requirements of a particular RF system. All waveforms exhibit peak amplitudes of $\sim$14.0 mV as determined by the input optical power ($\sim$ 5 μW, average), photodiode responsivity, and 20 dB (power) electrical amplification.

IV. Conclusion

In conclusion, we demonstrate an efficient open-loop optical-to-electrical technique for generation of ultra-broadband arbitrary RF waveforms. Our technique, based on Fourier transform optical pulse shaping and subsequent frequency-to-time conversion, allows direct specification of the time-domain RF waveform. Here, we demonstrate application of our technique to broadband frequency-modulated sinusoidal waveforms, in addition to the first demonstration of ultra-broadband impulsive waveforms. Our open-loop technique could provide the means to rapidly prototype UWB wireless systems by providing real-time waveform design capability—an ability not offered by current electronic techniques.

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