Shaping the Power Spectrum of Ultra-Wideband Radio-Frequency Signals

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Abstract—We demonstrate the ability to tailor the power spectrum of ultra-wideband (UWB) RF waveforms via a photonics-based electromagnetic pulse shaper. We describe and experimentally demonstrate a waveform design methodology that allows us to achieve desirable power spectrum properties, such as broad bandwidth and minimal spectral ripple. As one example, we generate a 115% fractional-bandwidth impulsive waveform which spans the 3–10-GHz band, with ripple below ±1.5 dB over a 5-GHz band. Furthermore, by treating the RF spectral phase as a design parameter, we demonstrate how to achieve increased power spectral density. We illustrate the spectral design capabilities of our technique by presenting a variety of tailored UWB waveforms (including impulses, chirped signals, and arbitrary waveforms) with bandwidths that range from ∼4 to 8 GHz.

Index Terms—RF photonics, spectral engineering, ultra-wideband (UWB) signal generation.

I. INTRODUCTION

WITH THE 2002 decision by the Federal Communications Commission to allow unlicensed operation of ultra-wideband (UWB) devices in the 3.1–10.6-GHz frequency band, there has been significant interest in utilizing UWB signals for various wireless applications. For example, time-hopping impulse radio [1] and hybrid spread-time/time-hopping schemes [2] have been proposed for multiple-access wireless communication systems. In these systems, as with examples of UWB ground-penetrating radar [3], the signals frequently employed (or proposed) are monocycle waveforms. While these waveforms may be quite short in duration (and, hence, quite broadband) and easily implemented electronically [4], little attention has been paid to the spectral content of these waveforms relative to the FCC-specified spectral emissions limits [5] for UWB systems. While monocycle waveforms may certainly be designed to have spectral content in the above frequency band, their spectral shape may only be moderately controlled via electronic techniques, that is, the spectral shape is predetermined once the center frequency is chosen. Others have acknowledged it is desirable to tailor the power spectral density (PSD) of UWB signals [2]; however, there have been no hardware techniques proposed to accomplish this task.

Here, we demonstrate the ability of a photonics-based electromagnetic pulse-shaping technique [6] to tailor the PSD of UWB waveforms. This technique allows definition and control of the RF spectral amplitude, as well as the spectral phase, of UWB signals with frequency content that spans the range of ∼3–10 GHz. Here, we address the constraints inherent in this photonic technique and how these constraints may be exploited to achieve signals that exhibit extremely flat RF power spectra aimed at efficient use of the FCC-allocated UWB frequency band. This study represents the first UWB signal generation technique (either electronic or photonic) to address and demonstrate efficient use of the above frequency band.

Our paper is organized in the following manner. In Section II, we review the relevant parameters of our electromagnetic pulse shaper and introduce the constraints imposed on the electrical waveforms synthesized via our technique. Section III explains our frequency-domain waveform design methodology and provides the first rigorous discussion of how the waveform constraints inherent in our technique affect the output electrical waveforms. In addition, this section presents several examples of our technique as applied to broadband impulsive waveforms. In Section IV, we demonstrate the capability of our apparatus to control the RF spectral phase of UWB signals and demonstrate that chirped waveforms may be used in our system to increase waveform energy and the RF power spectral density. Additionally, this section provides the first theoretical analysis of the chirped waveforms that may be synthesized in our apparatus subject to a limited waveform time aperture and provides a prediction of the expected energy increase obtained by using chirped waveforms. Finally, in Section V, we conclude.

II. ELECTROMAGNETIC PULSE SHAPING BASED ON FEMTOSECOND OPTICAL PULSE-SHAPING TECHNOLOGY

In this study, we synthesize arbitrary UWB time-domain RF waveforms that exhibit user-defined RF spectral content (e.g., shape, bandwidth, and center frequency) in the 3.1–10.6-GHz frequency band while minimizing frequency content outside of this range to address the FCC-specified spectral emission limits on UWB systems. To achieve these waveforms, we utilize a photonics-based electromagnetic pulse shaper [6] that allows direct specification of arbitrary time-domain RF waveforms with frequency content in the above band. Here, we address how the above functionality may be achieved via our photonics-based approach and the relevant operational concerns that must be addressed to do so.

Our apparatus is discussed in detail in [6]; here, we address the basic system functionality in relation to the RF spectral control that may be achieved in the output electrical waveforms. Our apparatus (as well as those demonstrated by others [7]) is shown...
schematically in Fig. 1. Short optical pulses (≈100 fs) from a mode-locked laser source are spectrally filtered in a Fourier transform optical pulse shaper [8]. This pulse shaper allows the user to impress an arbitrary optical filter function onto the complex amplitude spectrum of the input short pulse. Subsequently, these filtered pulses are dispersed in a length of single-mode optical fiber [length L (km) and dispersion parameter D (ps/nm/km)]. The chromatic dispersion of the optical fiber uniquely maps optical frequency to time; thus, the temporal optical intensity after the fiber stretcher is a scaled version of the power spectrum of the spectrally filtered optical pulse. The photodiode functions as an optical-to-electrical converter that yields electrical voltage waveforms whose shape is determined by the driving optical intensity waveforms. This functionality enables the user to directly specify the output electrical waveform by applying a scaled version of the desired waveform as the optical filter function in the optical pulse shaper.

In our apparatus, the time aperture (duration) of the output waveform is determined by the available optical bandwidth in concert with the frequency-to-time (F/T) constant of the fiber stretcher (the product of the length L and dispersion parameter D). The finest temporal feature in the output waveform is determined by the spectral resolution of the optical pulse shaper and the F/T conversion constant of the fiber stretcher. In our apparatus’ current configuration, the waveform time aperture is approximately 3 ns, and the finest temporal feature is ≈45 ps; the latter yields an RF bandwidth of 11 GHz. We note that these parameters may be configured by the user by adjusting the relation of the optical bandwidth and total dispersion of the fiber stretcher.

We note that other techniques for generation of arbitrary pulsed electrical waveforms have also been demonstrated [9], [10]. In these techniques, individual frequency components of an optical frequency comb (synthesized via nonlinear interactions in optical fiber in [9], derived from a mode-locked semiconductor laser in [10], or derived from a mode-locked fiber laser in [11]) are modulated in amplitude and/or phase. When these modulated frequency components are recombined and converted to an electrical waveform via a photodiode, the result is a periodic train of pulsed signals with a repetition rate determined by the element spacing in the optical frequency comb; the shape of an individual pulse is determined by the inverse Fourier transform of the frequency-domain modulation envelope sampled by the optical frequency comb. Essentially, the Fourier series of the desired pulsed waveform is synthesized. Without emphasizing the practical or complexity differences between these techniques and ours, the primary difference in functionality is the electrical frequency content that may be achieved in the output waveform. In contrast with our technique, in which the frequency content of the output electrical waveform is determined by the interplay of optical bandwidth, the F/T constant of the fiber stretcher and the resolution of the optical pulse shaper, in Fourier synthesis techniques, it is the granularity of the optical filter used to access individual optical comb elements that fundamentally determines the achievable electrical frequency content. In the Fourier synthesis systems of [9] and [10], the filter granularity is on the order of tens of gigahertz (waveform durations of ≈50–100 ps), making these techniques well suited to electrical waveforms centered in the millimeter range. However, our interest lies in UWB signals with frequency content below ≈11 GHz, which is to fine to resolve with the optical filters used in [9] and [10]. Our technique, however, is easily applied to synthesis of arbitrary waveforms in the RF and microwave frequency bands.

This technique of mapping tailored time-domain optical intensity waveforms to RF voltage waveforms offers unprecedented waveform agility. To fully utilize the flexibility provided by this technique, it is important to understand the constraints of the system and how to control the conditions these constraints impose on the output electrical waveforms (in the time and frequency domains). There are three major constraints on the waveforms achievable from this technique. The output electrical waveforms are: 1) positive definite as determined by the mapping of optical intensity to voltage; 2) of finite-duration as determined by the available optical bandwidth; and 3) peak voltage-limited as determined by the available optical energy and photodiode responsivity. In Section III, we detail how our waveform design process accommodates these constraints and how they may be utilized to tailor the spectral content of our waveforms.

III. FREQUENCY-DOMAIN WAVEFORM DESIGN METHODOLOGY FOR FINITE-DURATION UWB SIGNALS

In contrast with previous work where we directly specify arbitrary broadband time-domain waveforms in our system (such as the sinusoids and monocyte waveforms presented in [6]), here we are interested in waveforms that exhibit particular spectral characteristics. To that end, instead of directly specifying a particular time-domain waveform, we begin by numerically specifying (e.g., in MATLAB) our target complex RF spectrum in both amplitude and phase (limitations on the phase variation will be discussed in a later section). In terms of angular frequency, our target RF spectrum is expressed as

\[ V(\omega) \propto |V(\omega)| \exp\{j\phi(\omega)\}. \]  

(1)
We are interested in manipulating the spectral content of our waveforms in the 3.1–10.6-GHz frequency band; as this band is offset from dc, the resulting RF waveforms will be oscillatory in nature. As stated in the first constraint above, the mapping of optical intensity to voltage time requires that our output voltage waveforms be positive-definite. To achieve oscillatory waveforms with apparent negative voltage values, a minimal dc component \( (v_0) \) is added to our waveforms. Our target RF spectrum including this dc component is given by

\[
V_T' (\omega) \propto v_0 \delta (\omega) + V_T (\omega).
\]  

(2)

To obtain the basic time-domain waveform that will yield the desired spectrum, we perform an inverse fast Fourier transform (IFFT) of the frequency-domain data. The resulting time-domain signal is given by

\[
v'_t (t) \propto v_0 + \mathcal{F}^{-1} \{ V_T (\omega) \}
\]  

(3)

where \( \mathcal{F}^{-1} \) denotes an inverse Fourier transform. At this point, the \( \sim 3 \)-ns time aperture (the second constraint above) of our electromagnetic pulse shaper must be addressed. This time aperture constraint is included by multiplying the dc offset waveform by a rectangular window \( r (t/T) \) equal to the time aperture of our apparatus (here, \( T \sim 3 \) ns). This is equivalent to modeling the optical power spectrum in our apparatus as perfectly flat over the available optical bandwidth. Looking slightly ahead, one could envision a more general implementation of this constraint where the fixed rectangular time aperture is multiplied by a user-defined windowing function \( w(t) \). In this case, the general time-domain RF voltage waveform obtained from our apparatus is given by

\[
v_{RF} (t) \propto w(t) \times r (t/T) \times \{ v_0 + \mathcal{F}^{-1} \{ V_T (\omega) \} \}
\]  

(4)

and the RF power spectrum is

\[
|V_{RF} (\omega)|^2 \propto \left| [v_0 \delta (\omega) + V_T (\omega)] \ast W (\omega) \ast \frac{\sin(\omega T/2)}{\omega} \right|^2
\]  

(5)

where \( \ast \) denotes convolution. The finite time aperture and choice of window function contribute to the shape of the RF spectra of our waveforms in two ways. First, the baseband term in (5) shows that the window function itself contributes spectral content beyond that of the target RF spectrum \( V'_T (\omega) \) (this effect will dominate at low frequencies due to the width of the main lobe in the spectrum of \( W (\omega) \)). Second, the spectral structure of the window function will contribute to amplitude fluctuations (ripple) across the RF spectrum. In the signal processing community, these two effects are analogous to the window bandwidth and spectral leakage, respectively, in spectral analysis applications involving windowed Fourier transforms [12].

To illustrate these effects, we first analyze the two basic windows utilized in our system. Fig. 2(a) illustrates the voltage waveform obtained when our apparatus is programmed to produce a \( \sim 3 \)-ns rectangular waveform (by programming the optical filter in Fig. 1 to unity transmission for all wavelengths). This voltage waveform corresponds to the shape of the optical power spectrum from our optical pulse shaper (with no additional apodization); the dashed curve shows the ideal \( \sim 3 \)-ns rectangular time aperture. Here, the steep rising and falling edges are of most interest as these will contribute most heavily to structure in the RF power spectrum. Though there is definite structure to this waveform, i.e., the amplitude is not constant over the window duration, it is basically rectangular for our purposes. Though not performed here, the nonuniformity of this window may be addressed through equalization of the optical power spectrum in our system. In Fig. 2(b), a Gaussian window designed to reduce the steep rising/falling edges of the window in Fig. 2(a) is shown. Here, the dashed line is a numerical fit to the experimental data which yields a \( \sim 960 \)-ps full-width-at-half-maximum (FWHM) duration for the window.

The normalized RF power spectra corresponding to the waveforms of Fig. 2 are shown in Fig. 3. Here, as one would expect, the RF spectrum corresponding to the rectangular window of Fig. 2(a) [see Fig. 3(a)] shows significant spectral structure (sidelobes) arising from the steep rising/falling edges of the waveform. The location of the sidelobes agrees well with that predicted for a perfectly rectangular window of approximately 2.9 ns duration. After the first sidelobe (occurring at roughly 500 MHz with an amplitude of approximately \( -13 \) dB relative to the main lobe), the sidelobes decay more rapidly than expected for a rectangular window; this is due to the fact that the actual window is smoother than the perfect rectangular window. Even so, the sidelobes decay rather slowly, reaching a level of \( \sim 30 \) dB at a frequency of \( \sim 1.65 \) GHz and a level of \( \sim 40 \) dB at approximately 4.67 GHz.

For the Gaussian window of Fig. 2(b), one would expect the main lobe of the RF spectrum to be appreciably wider than that of the rectangular window due to the decreased window duration in the time-domain. Also, the RF power spectrum is expected to show significantly less sidelobe structure as the abrupt rising/
falling edges evident in Fig. 2(a) have been almost entirely suppressed in Fig. 2(b) (ideally, only the main lobe should exist as a Gaussian in the time-domain transforms to a Gaussian in the frequency domain). The measured RF spectrum for the Gaussian window, shown in Fig. 3(b), clearly shows both of these effects. The main lobe in the measured RF power spectrum reaches a level of $-30$ dB at a frequency of $\sim 1.03$ GHz; this value agrees well with that predicted for a perfect Gaussian window of comparable duration [dashed curve, power spectrum of the Gaussian fit in Fig. 2(b)]. The sidelobes for this window decay far more rapidly than those for the rectangular window—the sidelobes fall below $-40$ dB at a frequency of $\sim 3.57$ GHz and remain below this level. The deviation of the measured power spectrum from the ideal Gaussian shape shown by the dashed curve in Fig. 3(b) is due to the fact that the steep rising/falling edges of the underlying rectangular time-domain window [see Fig. 2(a)] have been mostly, though not entirely, suppressed [see Fig. 2(b)].

The important point here is that not only does the window contribute a low-frequency structure that is confined near dc (the main and first few sidelobes for the rectangular window and the main lobe for the Gaussian window) as shown here, but also that the sidelobe levels away from dc overlap with the desired target RF spectrum; this leads to spectral broadening (leakage) arising from the convolution $(V(f) * W(f))$ in (5). As a note, our system employs a 50-MHz laser source; the broadband RF spectral envelopes of our waveforms are, therefore, superposed with a 50-MHz frequency comb in the RF spectral measurements. For clarity, this effect has been removed in subsequent spectral measurements by plotting only the frequency bin maxima. In addition, all spectra presented here were acquired with a resolution bandwidth of 100 KHz. Since the width of an individual comb element is significantly less than this bandwidth, the measured PSD essentially corresponds to the energy of an individual comb element. As a result, our power spectra are displayed in units of dBm instead of dBm/Hz.

A. Impulsive UWB Waveforms and the Frequency-Domain Effects of Time-Domain Apodization

To illustrate how the choice of time-domain apodization window affects spectral broadening, we analyze the effects of the two windows above on a broadband impulse. The desired waveform is an impulse tailored to have a super-Gaussian spectral shape with a $\sim 4$-GHz bandwidth (full width at $1/e^2$ power level) at a center frequency of approximately 5 GHz. This target spectrum is designed to exhibit a fractional bandwidth ($\%\text{ BW} = -10$ dB full-width/center frequency) of approximately 80.4%. A super-Gaussian spectral shape was chosen to achieve an extremely flat RF power spectrum subject to the $\sim 3$-ns time aperture of our apparatus. The target spectrum for this waveform—which corresponds to (1) in our design method—is given by (frequency is expressed in gigahertz)

$$V_i(f) = \exp \left\{- \left[\frac{f - 5}{2}\right]^2 \right\}. \quad (6)$$

Fig. 4(a) illustrates the impulse achieved from our apparatus with no additional time-domain apodization (rectangular window) and Fig. 4(b) shows this impulse after apodization with the Gaussian window of Fig. 2(b). The ideal impulse (without the dc pedestal) has a calculated rms full-width duration of $\sim 216$ ps—the value of 228 ps shown in Fig. 4(b) was obtained by filtering the fast Fourier transform (FFT) of the time-domain data to remove the dc pedestal. Fig. 5 compares the measured RF power spectra (normalized to the power spectral density at
Fig. 5. Measured RF power spectra (normalized) for the impulses in Fig. 4 illustrating the effect of the window function on the RF power spectrum. (a) Power spectrum for the impulse synthesized with a rectangular window and the target RF spectrum (dashed line). Significant spectral broadening and distortion is observed due to the sidelobe structure of the rectangular window. (b) Power spectrum for the Gaussian-apodized impulse and the predicted power spectrum resulting from the convolution of the target spectrum with that of the Gaussian fit in Fig. 2(b) (dashed line). Apodization of the time-domain impulse significantly decreases spectral broadening and distortion. Over the range of 3.5–6.5 GHz, the spectral amplitude fluctuations have been reduced by ~4.7 dB as compared with the spectrum in (a).

5 GHz of ~57 dBm) for these waveforms. In Fig. 5(a), the power spectrum of the nonapodized impulse is highly structured due to the approximately rectangular temporal window. The desired target spectrum described previously falls in the range of ~3–7 GHz, where there is clearly a less structured portion of the spectrum; for illustration, the calculated target spectrum is shown by the dashed line. From dc to approximately 1 GHz, the baseband structure of the rectangular window dominates as evidenced by the ~13-dB relation between the main lobe and first sidelobe occurring at roughly 500 MHz. In the frequency range from 1 to 3 GHz, spectral broadening due to the sidelobe structure of the window leads to significant spectral content with power levels either equal to (or only modestly below) that in the 3–7-GHz range. Moreover, within the bandwidth of the target spectrum, the spectral amplitude varies over ±3.35 dB in the range of 3.5–6.5 GHz—which is a significant departure from the target RF spectrum. After a sharp decrease of roughly 10 dB near 7 GHz, the PSD gradually decays, falling below −20 dB of the 5-GHz power level at approximately 12.5 GHz.

The power spectrum for the Gaussian-apodized impulse [see Fig. 5(b)] shows marked improvement with regard to both spectral broadening and spectral flatness. Again, below approximately 1 GHz, the spectral structure is dominated by the baseband spectral structure of the Gaussian apodization window. The spectral broadening in the range from ~1–2.2 GHz is again due to the sidelobe structure of the apodization window; however, given that this sidelobe structure decays far more rapidly than the rectangular window does [see Fig. 2], this additional spectral content is, at its highest level, roughly 12 dB below (~1.4 GHz) the power level of the target spectrum and is suppressed to a level of −20 dB at 2.2 GHz. In the region of the target spectrum, the measured power spectral density is extremely flat—in the range of 3.5–6.5 GHz, the spectral amplitude variations have been reduced to approximately ±1 dB—which is a reduction of 4.7 dB in total amplitude fluctuation compared with the spectrum for the nonapodized impulse. The measured spectrum, though slightly broader than the target spectrum (dashed line in Fig. 5(a)) shows excellent agreement with the power spectrum predicted using the ideal time-domain impulse (IFFT of the target spectrum) and the fit to the Gaussian window shown in Fig. 2(b), shown here by the dashed line. Here, the measured spectrum has a ~10-dB width of ~4.3 GHz, which yields a fractional bandwidth %BW ≈ 86% (only ~7% larger than the %BW of the target spectrum). The measured spectrum rolls off smoothly to 8 GHz, and, above this frequency, undesirable spectral content remains below 20 dB of the target spectral amplitude and is largely suppressed below ~30 dB of this power level.

Here, we utilize a simple time-domain apodization window to suppress unwanted frequency content in our waveforms. Alternatively, more complex apodization windows could be designed by utilizing iterative optimization techniques—such as those employed in the design of optical fiber Bragg grating filters [13]—to further suppress frequency content outside of the desired target spectrum.

By utilizing proper apodization in the time domain, we are able to synthesize extremely broadband signals that exhibit excellent spectral amplitude uniformity. An intriguing example of this capability is the broadband impulse shown in Fig. 5(a). This impulse is designed to exhibit a super-Gaussian spectral envelope which spans the entire 3.1–10.6-GHz frequency band. In the time domain, the measured impulse shows an rms duration of ~183 ps. The measured RF power spectrum (Fig. 5(b), normalized to the ~62-dBm PSD at ~6.7 GHz) shows a ~10-dB bandwidth of ~7.7 GHz at a center frequency of approximately 6.7 GHz, which yields a %BW of 115%. Over the central frequency band of 4–9 GHz, spectral amplitude fluctuations are limited to approximately ±1.4 dB.

Our goal in these experiments was to synthesize RF waveforms that achieve a high degree of spectral flatness. To that end, our examples emphasize a super-Gaussian shape for our target spectra. This technique may be applied to other spectral shapes as well. As another example, the time-domain waveform shown in Fig. 7(a) is tailored to have a 4-GHz bandwidth target spectrum centered at ~8 GHz that has a steep increase (~9 dB) in PSD. As with the impulse examples above, the time-domain waveform to achieve this spectrum does not have a closed-form expression; the appropriate optical filter function must be calculated from the target frequency-domain data. The measured power spectrum shown in Fig. 7(b) exhibits a ~7.6-dB increase over an approximately 540-MHz frequency range near 8 GHz and shows good agreement with the target spectrum.

IV. ACHIEVING INCREASED RF ENERGY AND PSD BY UTILIZING CHIRPED WAVEFORMS

Given the operation of our system, i.e., mapping of the optical intensity to a time-domain electrical waveform, and assuming that the system is set for a fixed time aperture, the quantity that fundamentally determines the attainable RF energy and PSD in the output electrical waveform is the per-pulse energy from the
optical source. To see this, again consider the voltage waveform shown in Fig. 2(a). As described previously, this waveform results when the optical filter function in our apparatus is set to unity amplitude transmission for all wavelengths; this waveform then shows the shape of the optical power spectrum in our system. More importantly, this waveform represents the peak voltage that may be achieved at any instant in the ~2.9-ns time aperture of our apparatus. Thus, for a particular target RF power spectrum, the time-domain electrical signal that most efficiently utilizes the available optical energy will result in the largest RF PSD and waveform energy. Here, we show that the RF PSD and waveform energy may be increased on the order of 8 dB—for a given RF spectral shape and fixed input optical energy—by utilizing smoothly chirped waveforms instead of UWB impulses. This concept is similar to the use of chirped waveforms to avoid peak power limitations in optical or microwave amplifiers (e.g., optical chirped pulse amplification [14] or chirp radar applications [15]). For systems where the RF spectral content is of more importance than a minimal temporal duration, this provides a simple technique for increasing the RF energy without adding additional electronic amplification.

To achieve linearly chirped waveforms in our system, we may directly specify a chirped sinusoid in the time domain and apply this waveform as the optical filter function in our apparatus [16]. An alternative method is to define a target RF spectrum as described above and to specify the RF spectral phase to be a quadratic function of frequency. In (1) then, the phase function becomes

$$\phi(\omega) = \alpha \omega^2. \quad (7)$$

The appropriate optical filter function to achieve the chirped waveform is then determined as previously described—by sampling the IFFT of the practical RF amplitude spectrum [see (4)].

To achieve appreciable pulse broadening and the concomitant increase in waveform energy in our system for a waveform with bandwidth $\Delta \omega$, the chirp rate ($\alpha$) must satisfy the condition [15], [17], [18]

$$\alpha \gg \frac{1}{\Delta \omega^2}. \quad (8)$$

Practically, this condition means that two frequencies $\Delta \omega$ apart may be resolved in the time-domain waveform (i.e., that it is fairly heavily chirped). There is also an upper bound on the chirp rate that may be achieved which is dictated by the time aperture ($T$) of our apparatus. To see this, consider the frequency-dependent delay that arises from the spectral phase variation $\phi(\omega)$

$$\tau(\omega) = \frac{d\phi(\omega)}{d\omega} = -2\alpha \omega. \quad (9)$$

For a signal with bandwidth $\Delta \omega$: if the chirp rate $\alpha$ is chosen such that the delay spread across the signal bandwidth is greater than the time aperture $|\tau(\Delta \omega)| > T$, frequencies falling outside the time aperture $T$ are filtered from the waveform. The

$$\text{This assumes exp}(j\omega t) \text{ time dependence.}$$

Figure 6. Ultrabroadband ~183 ps impulse designed to exhibit an extremely flat super-Gaussian power spectrum which spans the frequency band of ~3–10 GHz (115% BW). (a) Measured time-domain waveform. (b) Measured RF power spectrum (normalized) and that predicted using the ideal Gaussian window and target RF impulse (dashed line).

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$$\text{This assumes exp}(j\omega t) \text{ time dependence.}$$
in (10). Therefore, in this technique, the benefits of increased waveform energy and PSD are achieved at the expense of PSD uniformity. The amplitude variations across the rectangular window (optical power spectrum) [see Fig. 2(a)] will introduce additional spectral distortions on chirped waveforms given the time-dependent frequency variation of these waveforms (whereas this effect is quite small for impulses that utilize only a fraction of the window)—these distortions may be removed through equalization of the optical power spectrum, although this is not performed in the current study.

When a quadratic spectral phase variation (\( \alpha \sim 0.03 \text{ ns}^2/\text{rad} \)) is applied to the \( \sim 4 \) GHz bandwidth super-Gaussian spectrum corresponding to the impulse in Fig. 4(b), the chirped waveform of Fig. 8(a) results. Here, the chirped waveform is clearly broader (\( t_{\text{rms}} \approx 880 \) ps) and spends a longer time near the peak voltage level of \( \sim 80 \) mV than the impulses of Fig. 4.

In Fig. 8(b), the bold curve shows the measured power spectrum of the chirped waveform in Fig. 8(a); the spectrum has been normalized to the PSD of the impulse Fig. 5(b) at \( \sim 5 \) GHz (\( \sim 57 \) dBm). Clearly, the PSD of the chirped waveform has been increased relative to that of the impulse (shown here by the light curve). Assuming that the chirp-rate \( \alpha \) is chosen such that no spectral narrowing occurs, the bandwidth of these two waveforms remains the same. Therefore, the energy increase achieved by utilizing a linearly chirped waveform is linearly proportional to the waveform duration. Additionally, any peak voltage variations between the waveforms will contribute quadratically to the waveform energy. Therefore, as a predictor of the increase in energy (in decibels) for the chirped waveform, we use the following relation:

\[
\Delta W = 10 \log \left( \frac{t_c v_c^2}{t_p v_p^2} \right) \tag{12}
\]

where \( t_c, v_c, t_p, \) and \( v_p \) are the full-width rms durations and peak voltages amplitudes of the oscillatory portions of the chirped and impulsive waveforms, respectively. Based on this relation, the predicted energy increase for the chirped waveform in Fig. 8(a) (\( t_c \approx 880 \) ps, \( v_c \approx 37.6 \) mV) relative to that of the impulse in Fig. 4(b) (\( t_p \approx 228 \) ps, \( v_p \approx 35.4 \) mV) is approximately 6.4 dB. This value agrees quite well with the 6.3-dB increase in waveform energy (calculated by integrating the magnitude squared of the FFT of the time-domain data over the 3–7-GHz frequency range). If we make the (idealized) assumption that this energy is distributed uniformly over the signal bandwidth, the increase in signal energy also corresponds to the increase in the PSD for the chirped waveform. The measured average increase in PSD of 6.2 dB over the 3–7-GHz band again agrees quite well with the measured increase in energy, as well as that predicted from (12). As described earlier, the use of a (nonuniform) rectangular window will decrease the uniformity of the PSD for the chirped waveform. Here, the measured PSD variation is approximately \( \pm 3.1 \) dB over the 3.5–6.5-GHz range.

As another example, when we apply a quadratic spectral phase (\( \alpha \sim 0.016 \text{ ns}^2/\text{rad} \)) to the target spectrum corresponding to the impulse of Fig. 6(a) the up-chirped waveform of Fig. 9(a) results. The measured power spectrum for this waveform is shown by the bold curve in Fig. 9(b) (normalized to the PSD of the impulse in Fig. 6—shown by the light curve—at a frequency of \( \sim 6.7 \) GHz). Here, the rms time duration of the waveform has increased to approximately \( t_c = 1927 \) ps and the peak oscillatory voltage value is \( v_c \approx 33 \) mV. The predicted energy increase [see (12)] over the impulse of Fig. 6(a) (\( t_p = 183 \) ps and \( v_p = 35.6 \) mV) is \( \Delta W \approx 6.4 \) dB. The measured energy increase over the 3–11-GHz band is approximately 7.7 dB, which agrees well with the predicted value. The \( \sim 1.3\)-dB discrepancy between the predicted and actual energy increase is attributed to spectral broadening and distortion due...
to the rectangular waveform window—(12) does not account for this effect. The average PSD increase across the 3–11-GHz band is \( \sim 8 \) dB, which again agrees well with the measured energy increase. Over the range of 4–9 GHz, the spectral amplitude variation is approximately \( \pm 2.8 \) dB.

As these examples illustrate, control of the RF spectral phase in addition to the spectral amplitude enables broadband time-domain waveforms to be tailored to maximize the RF energy and PSD. Here, we have demonstrated that our apparatus enables energy increases on the order of 8 dB for waveforms that exhibit up to 115% fractional bandwidths. Larger energy increases could be achieved by increasing the time–bandwidth product of our apparatus by lengthening the time aperture \( T \)—this would enable larger chirp rates to be utilized for a fixed RF bandwidth. For a fixed bandwidth of 11 GHz, a factor-of-two increase in time aperture is a reasonable estimate for our current apparatus.

V. CONCLUSION

We have demonstrated the capability of our photonics-based electromagnetic pulse shaper to tailor the power spectral density of UWB RF signals. We demonstrate that proper time-domain apodization enables us to control out-of-band frequency content and to achieve extremely flat PSDs for signals exhibiting up to 115% fractional bandwidth. In addition, we demonstrate that the use of chirped waveforms allows us to circumvent the peak voltage limitation of our apparatus to achieve increased waveform energy and PSD. We expect that our technique could prove quite useful as a signal conditioning element or signal prototyping apparatus for a variety of UWB systems.

ACKNOWLEDGMENT

This work was performed at Purdue University, West Lafayette, IN.

REFERENCES


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