Photonic Synthesis of Spread Spectrum Radio Frequency Waveforms With Arbitrarily Long Time Apertures

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Abstract—A photonic technique is proposed to generate spread spectrum radio frequency waveforms with both high RF bandwidth and arbitrarily long temporal period. By switching the polarity of full duty cycle chirped waveforms according to a pseudo-random sequence, we can increase the waveform repetition period under electronic control while preserving RF bandwidth and average power. Proof-of-principle ranging experiments are presented to demonstrate the improvement our technique provides with respect to range ambiguity.

Index Terms—Microwave photonics, optical pulse shaping, radio frequency.

I. INTRODUCTION

CHIRPED and other spread spectrum waveforms are widely utilized in radio-frequency (RF) applications, including ultra-wideband (UWB) channel sounding [1], [2], RADAR and imaging [3], [4], and others. In contrast to direct electrical approaches for generating spread spectrum waveforms, photonic techniques offer higher bandwidth, better immunity to electromagnetic interference, and compatibility with radio-over-fiber technology. Various photonic approaches have been proposed in recent years [5]–[13]. Generally, these methods employ either direct optical pulse shaping [7] or spectral shaping in conjunction with frequency-to-time mapping (FTM) via dispersive propagation [8], [9], [12], followed in all cases by photodetection. However, techniques such as [7]–[9], [12] deliver nonrepeating waveforms only over limited time aperture (nanoseconds and below) and with limited time-bandwidth product (TBP). Ultimately in such schemes the TBP is limited by the complexity of the pulse shaping element to at most a few hundred; when the maximum TBP is reached, the time-aperture of the waveform cannot be increased without sacrificing RF bandwidth [14]. These restrictions are incompatible with established applications such as chirped radar [15], which typically employs waveforms with time apertures in the microsecond to millisecond range and much larger TBPs. Waveforms with fast chirp rates and time apertures in the microsecond range have been generated by heterodyne mixing of a fixed frequency and a rapidly frequency swept laser, e.g., [13], but the repeatability of the generated waveforms is a challenge. Another approach [10], [11], [16], which does provide a high degree of repeatability, is based on switching between multiple basis waveforms obtained via line-by-line pulse shaping of optoelectronically generated frequency combs [17]. Here waveform switching under electronic control allows for arbitrarily large time apertures without waveform repetition. However, constraints in pulse shaper resolution have limited such experiments to switching between low complexity basis waveforms, each of which has time apertures limited to a few hundred picoseconds and RF spectral features programmable only at the 5 GHz level.

In this paper, we introduce a novel photonic spread spectrum radio-frequency waveform generation technique that for the first time combines FTM and waveform switching approaches. In this work we generate basis waveforms with substantially increased complexity, with time apertures spanning several nanoseconds and RF spectral features programmable at the several hundred MHz level. By switching between positive and negative polarity versions of a basis waveform under electronic control, we are able to increase the repeat-free time aperture arbitrarily by increasing the length of the switching sequence. Such expansion could be realized by gating out pulses to directly increase the repetition period of the waveform, but at the cost of substantially reduced average power. Since our switching involves polarity-flipping only, average power is maintained.

The waveforms generated are highly repeatable and, analogous to noise radar technology [18], are characterized both by high RF bandwidth and energy spread substantially in time. Moreover, as RF bandwidth and repeat-free time aperture may be controlled independently, arbitrarily large time-bandwidth products are possible. The waveforms generated simultaneously offer several attractive features. The ability to generate large RF bandwidth supports the potential for high resolution ranging [19]. In view of the peak-voltage-limited nature of most RF photonic transmitters, increasing the time aperture provides higher average power [15], [20], boosting maximum operating distances in RF wireless applications with high path loss. Furthermore, in

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applications such as ranging and sounding of propagation channels with strong multipath, the ability to increase the repeat period of the transmit waveform to a value larger than the round-trip delay time or the maximum delay spread of the channel, respectively, avoids ambiguities. The high degree of repeatability supports signal averaging for additive noise suppression. Finally, the relatively large time aperture of individual basis waveforms offers potential compatibility with precompensation schemes applicable to multi-path RF wireless propagation, as in [21].

The remainder of this paper is organized as follows: The theory of our pseudorandom modulation scheme is discussed in Section II, followed by Section III in which the experimental setup is described in detail. Waveform generation results are presented in Section IV. Then in Section V, proof-of-principle ranging experiments are presented to demonstrate the improvement our technique provides with respect to range ambiguity. In the end, Section VI presents our conclusion.

II. THEORY

In conventional photonic approaches for generating arbitrary RF waveforms, a repetitive optical pulse train from a mode-locked laser is fed into the generation apparatus. The shape of the output RF waveform can be tailored but is constrained to repeat periodically at the laser repetition rate. Thus, the temporal period of the generated waveform is always clamped to the repetition period of the source laser. Mathematically, if the RF waveform train, \( s(t) \), is expressed as

\[
s(t) = \sum_i w(t) \ast \delta(t - iT)
\]  

(1)

where \( w(t) \) denotes an arbitrary waveform having an autocorrelation function \( R_w(\tau) \), \( T \) is the repetition period, \( \ast \) denotes convolution, then the autocorrelation function \( R_s(\tau) \) equals

\[
R_s(\tau) = \sum_i R_w(\tau) \ast \delta(\tau - iT)
\]  

(2)

where \( R_w(\tau) = \int w(t) \cdot w(t + \tau) \, dt \)

Fig. 1(a) depicts a repetitive linear up-chirp waveform train with repetition period \( T \), and Fig. 1(b) shows the corresponding autocorrelation function with the same period \( T \). When a length- \( L \) binary pseudorandom sequence, also known as a PN sequence [22], is modulated onto such repetitive waveform, it can be expressed as

\[
s'(t) = \sum_i PN[i] \cdot w(t) \ast \delta(t - iT)
\]

\[
= \sum_i w(t) \ast [PN[i] \cdot \delta(t - iT)]
\]  

(3)

as illustrated by Fig. 1(c). \( PN[i] \) is the \( i \)-th element in the PN sequence and \( PN[i] = PN[i + L] \). Due to the properties of PN sequences, the autocorrelation of such a modulated waveform will have main peaks repeating with period \( T \cdot L \), while all other peaks are reduced and inverted [22], as shown in Fig. 1(d). We have found that by appropriately adjusting the amplitude of the positive polarity chips in the pseudorandom sequence modulation, it is possible in principle to completely null the unwanted peaks, as mathematically derived in Appendix I and illustrated in Fig. 1(e). The autocorrelation function of the new waveform, \( R_\omega(\tau) \), can now be expressed as

\[
R_\omega(\tau) = \sum_i R_w(\tau) \ast \delta(\tau - iT)
\]  

(4)

indicating that the modulation increases the temporal period of the new waveform by a factor of \( L \), as illustrated in Fig. 1(f). By altering the length of the PN sequence, the temporal period can be set to an arbitrarily large value. The temporal profile of the basis waveform, i.e., the temporal profile within a single period \( T \), is not disturbed, leaving the RF bandwidth preserved. Thus, the spread spectrum waveform generation which controls the temporal shape and thus the RF bandwidth, and the PN modulation which determines the temporal period as well as the time-aperture, are kept independent to realize arbitrarily large time-bandwidth product.

III. EXPERIMENTAL CONFIGURATION

Our experimental apparatus for RF arbitrary waveform generation is sketched in Fig. 2(a). Overall our setup resembles the popular approach based on pulse shaping plus frequency-to-time mapping, but modified for differential detection [23] and
polarity switching. A mode-locked fiber laser (Menlo Systems FC1500-250-WG) with 250 MHz repetition rate and \(\sim 80\) nm optical bandwidth (\(\sim 1520\) nm–\(1600\) nm) outputs an optical pulse train into a commercial pulse shaper through an intermediate fiber amplifier (not shown in the figure). The pulse shaper (FINISAR 1000S) has a resolution of \(\sim 10\) GHz and \(\sim 5000\) addressable pixels across an \(\sim 5\) THz or 40 nm wavelength range (1527 nm–1567 nm). It is programmed using the near-field frequency-to-time mapping (NFFTM) technique [14], which predistorts both the amplitude and phase of the optical spectrum to achieve target RF waveforms with high fidelity, while overcoming the “far-field” constraint which otherwise may limit the maximum attainable RF bandwidth of the generated waveform [24]. After the shaper the signal is split equally into two arms through a 50–50 optical coupler. Synchronized to the laser repetition rate, a pattern generator provides complementary drive signals to a pair of intensity modulators (IM). As a result the pulse is transmitted in one arm and blocked in the other, with the transmitting arm selected according to a pre-programmed PN sequence. The length of the dispersive fiber (\(\sim 6.6\) km of SMF-28 at \(\sim 17\) ps/nm/km) is carefully chosen so that each 40-nm bandwidth, spectrally shaped pulse is stretched to a temporal duration of 4 ns, matched to the laser period. With our differential detection geometry, it is important to ensure stable matching of both the length and the dispersion experienced in each arm. Accordingly we designed a dispersion block, illustrated in Fig. 2(b), in which both arms use the same piece of dispersive fiber, but in a counter-propagating geometry implemented using a pair of circulators. Both arms are provisioned with variable optical attenuators (not shown in the figure) to adjust the relative signal power ratio. Then the optical signal is split equally in the two arms and converted into electrical signals by two photodetectors (PD) of the same model (DSC 30S, DC-22GHz). The outputs of the PDs are differenced by a 180 degree electrical hybrid (NARDA 4346, 2–18 GHz). In the end, the pedestal of the generated waveform is removed when a high-pass filter (K&L, 2–18 GHz) is added to eliminate baseband frequencies. Background-free waveforms are then achieved. Upon differential detection our switching scheme results in signals with similar shape but complementary polarity, with the polarity determined by the photodetector onto which light is incident during that switching cycle. Generated waveforms are measured in the temporal domain by a real-time oscilloscope (Tektronix 72004B, 20 GHz, 50 GS/s) with a sampling period of 20 ps and in the frequency domain by an RF spectrum analyzer (Agilent 8565EC).

IV. WAVEFORM GENERATION RESULTS

As a first example, we program the pulse shaper to generate a linear down-chirp basis waveform covering the frequency range from \(\sim 2\) to 10 GHz and spanning the 4 ns laser repetition period. In this way, the generated waveform has a full duty cycle. Fig. 3 illustrates the great resemblance between the optical power spectrum, as shown in Fig. 3(a), and the mapped waveform in the time domain, as shown in Fig. 3(b). For this parameter range, the far-field condition is well satisfied, and FTM applies. (For higher bandwidth waveform generation, the far-field condition breaks down, and the importance of waveform predistortion via the NFFTM technique becomes more evident [14].) To demonstrate waveform switching action, we program the pattern generator with a sequence of \([11 − 1 − 1]\) and adjust both arms of the apparatus for equal amplitude. The resulting waveform is shown in Fig. 4(a) over a 16 ns time span, corresponding to four down-chirped basis waveforms. The polarity of each waveform is labeled on top; the first and second time slots have positive polarity, while the third and fourth time slot has opposite polarity. To better illustrate, the second and third waveform from Fig. 4(a) are overlapped and plotted on an expanded scale in Fig. 4(b). As clearly seen, waveforms with opposite polarities are antipodal.
over a span of 180 ns. For comparison, a waveform is recorded over the same time span without waveform switching, as in conventional FTM. Circular autocorrelations are computed offline for both cases. Such correlation measurements are relevant for pulse compression in spread-spectrum ranging and related applications. As shown in Fig. 5(a), the autocorrelation of the unmodulated waveform has a period of 4 ns, the same as the laser repetition period. In contrast, as shown in Fig. 5(b), the waveform switched according to a length-15 PN sequence has an autocorrelation with strong peaks separated by 60 ns, corresponding to an increase in period by a factor of 15. Weak peaks remain at the original 4 ns period. A magnified view of these sidelobes is shown in the inset to Fig. 5(b). The extinction ratio, defined as the ratio between the amplitude of the remaining strong peaks to the amplitude of the strongest of the residual peaks, is improved from $\sim 11$ dB, as in the case without amplitude mismatching, to $\sim 19.1$ dB, indicating strong residual peak suppression and low sidelobe level.

The spectra of both waveforms, measured by the RF spectrum analyzer with a frequency resolution of 100 kHz, are plotted in Fig. 6(a) and (b). Two principal effects are evident. First, Fig. 6(a) shows a clear comb structure, which reflects the 250 MHz waveform repetition frequency. The spectrum fills in in Fig. 6(b), consistent with the 15-fold decrease in waveform repetition frequency. Second, we observe that the envelope of the RF spectrum is largely unaffected by the increase of the temporal period. As stated previously, basis waveform generation and PN-modulated waveform switching are separated in our technique. This enables us to increase the time-aperture and the RF bandwidth simultaneously. By setting the length of the PN sequence to 1023 and programming a higher rate chirp modulation on the optical power spectrum, we are able to generate a waveform with more than 4 microseconds time aperture (see autocorrelation in Fig. 5(c)) and a RF bandwidth of $\sim 20$ GHz (see RF spectrum in Fig. 6(c)). The resulting TBP exceeds 80000. The autocorrelation peaks have a width of $\sim 50$ ps, making the ratio of peak spacing to peak-width $\sim 80000$. The suppressed autocorrelation peaks, with an extinction ratio of $\sim 21$ dB, are too small to discern given the linear scale of Fig. 5(c).

Our technique also exhibits excellent stability and repeatability. Because our hybrid optical-electrical design combines signals in the electrical domain rather than the optical domain, the system is insensitive to the relative optical phases of the two generation arms in Fig. 2. Moreover, the dispersion block described in Fig. 2(b) provides signals from either arm with the same fiber propagation environment, eliminating an important source of potential instability. To quantify the stability and repeatability performance, we conduct a long-term measurement in which 336 real-time oscilloscope measurements of the signal described in Fig. 5(b) are recorded over one hour. The first measurement is chosen as the reference, and cross-correlation
Fig. 7. (a) Autocorrelation of the reference measurement; (b) Cross-correlation functions between reference and all other measurements. 335 traces overlapped in a same temporal frame of 4 ns.

functions between the reference and all other measurements are computed off-line. All 335 cross-correlation functions are overlapped in the same 4 ns temporal frame in Fig. 7(b). Clearly, all the cross-correlations are very similar. Compared with the autocorrelation of the reference measurement, as shown in Fig. 7(a), the curve in Fig. 7(b) is slightly thicker because of the amplitude differences between each cross-correlation. Minor distortions may also be seen at both main negative sidelobes. These results provide compelling evidence of stable waveform generation. Thus, data averaging can be implemented to reduce the additive noise in channel sounding and other applications. Furthermore, the reference waveform may be stored and used in later experiments as a template for pulse compression via offline correlation processing.

V. PROOF-OF-PRINCIPLE RANGING EXPERIMENT

A simple 1-D ranging experiment is conducted to illustrate one of the applications of our technique. The experimental schematic involving a pair of horn antennas (DORADO, 1–12 GHz) is described in Fig. 8. The transmit antenna is located at position P0. The receive antenna is located either at position P1 (\(\sim 1.22\) m away from P0) or position P2 (\(\sim 2.43\) m away from P0). Assuming a propagation speed of light, relative temporal delay between P1 and P2 is \(\sim 4\) ns.

P1 (\(\sim 1.22\) m away from P0) or position P2 (\(\sim 2.43\) m away from P0). The ca. 4 ns propagation delay between positions P1 and P2 is intentionally chosen to match the laser repetition period in order to highlight the range ambiguity issue. The transmit signal (described below) is launched into the channel through a cascaded pair of RF amplifiers (Picosecond 5828A, 0.05–14 GHz, 10 dB gain; Minicircuits ZVA-183, 0.7–18 GHz, 26 dB gain), and the received signal is amplified by a low noise amplifier (B&Z 110UC1, 0.1–10 GHz, 34 dB gain). The input signal and the received signal at position P1 and P2 are recorded using the real-time oscilloscope. All measurements are triggered by the same clock signal from the pattern generator. Cross-correlation functions between the input signal and both received signals are computed off-line and plotted in the same temporal frame. As discussed in [25], the signal received in such a system can be severely distorted due to the frequency dependent delay of the antennas. To cancel such distortion, we implement post-compensation. The system impulse response (including RF amplifiers, antennas and free-space propagation) is obtained from the input signal and the received signal at position P1 by applying deconvolution, an algorithm in which the frequency response of the channel is determined by dividing the frequency profile of output signal by that of the input one [2], [26]. Both frequency profiles are obtained by Fourier transforming the corresponding temporal measurements. The impulse response is employed to modify both received signals using a phase compensation algorithm through which frequency dependent spectral phase distortion introduced by the system is subtracted. This compresses the cross-correlation peak to the bandwidth limit [27], [28]. By evaluating the relative temporal delay between the cross-correlation peaks for both received antenna locations, the difference in range between P1 and P2 can be determined.

We compare ranging with three different RF transmit waveforms. In the first scenario, the input signal is a chirped waveform train as sketched in Fig. 9(a), generated by conventional FTM without waveform switching. Each chirped waveform spans from \(\sim 2\) to 12 GHz, with a 4 ns periodicity and 100% duty cycle. The peak-to-peak voltage level right after the PD is \(\sim 8\) mV. The cross-correlation functions obtained for receive antenna positions P1 and P2 are overlaid in the same 60 ns temporal frame in Fig. 10(a). The amplitude of the signal from P2 is less than that from P1 because of a longer propagation distance.
where $U$ is an integer \[22\]. Such sequences $U^2$ ONCLUSION \[2\] such as UWB channel sounding, wireless communications and RADAR.

APPENDIX I

Pseudorandom (PN) sequences are certain binary sequences of length $2^m - 1$ where $m$ is an integer \[22\]. Such sequences have two key properties:

- There are $2^{m-1}$ “1”s and $2^{m-1} - 1$ “0”s in any PN sequence (A.1)
- Their circular (periodic) autocorrelation, defined for any discrete length-$L$ sequence $f[i], 1 \leq i \leq L$ as

$$(f \star f)[n] = \sum_{i=1}^{L} f[i] f[(i + n) \mod L]$$ (A.2)

where $\star$ denotes correlation operator, is given by

$$(PN \star PN)[n] = \begin{cases} L & n = 0, \pm L, \pm 2L, \ldots \\ -1 & \text{elsewhere} \end{cases}$$ (A.3)

To get rid of the non-zero floor in Equation (A.3), we found that the amplitude of all $\frac{1}{2^n}$ “1”s can be adjusted to $1 + p$, where $p$ is a positive number. This new pseudorandom sequence $PN'$ with amplitude mismatching can be expressed as

$$PN' = \left( 1 + \frac{p}{2} \right) PN + \frac{p}{2} \cdot U$$ (A.4)

where $U$ is an unit sequence of length $L$ defined as $U[i] = 1$ for $1 \leq i \leq L$.

Computing the circular autocorrelation function of such a sequence reveals that

$$(PN' \star PN') = \left( 1 + \frac{p}{2} \right)^2 PN \star PN + \left( \frac{p}{2} \right)^2 U \star U + 2 \cdot (1 + \frac{p}{2}) (\frac{p}{2}) PN \star U$$ (A.5)

The first correlation on the right hand side of Equ. (A.5) is defined in Equ. (A.3). The second correlation is the summation of the unit sequence and thus equals to $L$ for all delays. The last correlation is the summation of the PN sequence, which

Because the propagation delay between P1 and P2 positions matches the laser repetition period, the P1 and P2 correlation peaks overlap. This clearly illustrates the ambiguity in range position that results when time delays greater than or equal to the 4 ns repetition period are considered.

In the second scenario an intensity modulator is added immediately after the laser. The intensity modulator blocks 14 pulses out of every 15, increasing the waveform repetition period to 60 ns while keeping the same energy per basis waveform. Each pulse is shaped the same as in the first scenario, resulting in a 4 ns long chirped waveform repeating every 60 ns, as sketched in Fig. 9(b). Although the temporal period is increased to 60 ns, extending the range over which unambiguous measurements can be made, the average power is reduced 15-fold. Although the cross-correlation peaks corresponding to positions P1 and P2 are now distinct (see Fig. 10(b)), the amplitudes of the peaks are attenuated by approximately this same factor of 15 compared with those in (a). Magnification from 2 to 10 ns horizontally and −0.1 to 0.1 vertically is shown on right. (c) Length-15 PN modulated chirps as in Fig. 9(c) are transmitted. ∼4.04 ns between peaks of P1 and P2, corresponding to ∼1.2 m assuming a propagation speed of light. Horizontal magnification from 2 to 10 ns is shown on right.

VI. CONCLUSION

To sum up, we propose and demonstrate a novel photonic radio-frequency waveform generation technique which is able to create spread spectrum waveforms with arbitrarily long temporal period. In addition, independent control of time-aperture and RF bandwidth is realized and thus arbitrarily large time-bandwidth product can be obtained. The RF bandwidth reaches as high as ∼20 GHz and is just limited by available RF bandwidth of O/E conversion. Our generated RF waveforms, with arbitrarily long temporal period, high RF bandwidth and average power, can be implemented in a wide range of applications such as UWB channel sounding, wireless communications and RADAR.

Fig. 10. Cross-correlations obtained by transmitting three different waveforms sketched in Fig. 9. Normalized to 3.2 V^2^-ps. (a) Unmodulated chirps as in Fig. 9(a) are transmitted, 4 ns between peaks of P1, 4 ns between peaks of P2. Horizontal magnification from 2 to 10 ns is shown on right. (b) Repetition period increased chirps as in Fig. 9 (b) are transmitted, ∼4.04 ns between peaks of P1 and P2. Peaks are attenuated by a factor of ∼15 compared with those in (a). Magnification from 2 to 10 ns horizontally and −0.1 to 0.1 vertically is shown on right. (c) Length-15 PN modulated chirps as in Fig. 9(c) are transmitted. ∼4.04 ns between peaks of P1 and P2, corresponding to ∼1.2 m assuming a propagation speed of light. Horizontal magnification from 2 to 10 ns is shown on right.
according to (A.1), equals 1 for all delays. Then Equ. (A.5) can be further simplified to
\[
(PN' \ast PN'') [n] = \begin{cases} 
\frac{L+1}{2} p^2 + (L+1) p + L, & n = 0, \pm L, \pm 2L \ldots \\
\frac{L+1}{4} p^2 - 1 & \text{elsewhere}
\end{cases}
\]
(A.6)

Then floor of the autocorrelation becomes zero when
\[
p = \frac{2}{\sqrt{L+1}}.
\]
(A.7)

When the conventional pseudorandom sequence in Equ. (3) is replaced by an amplitude-mismatched pseudorandom sequence \(PN'\) of length \(L\), the autocorrelation of such signal can be expressed as
\[
R_{sw}(\tau) = \int s'(t) s'(t + \tau) dt
\]
\[
= \sum_{j} \sum_{k} PN'[j] PN'[k] \int w(t-jT) \cdot w(t-kT+\tau) dt
\]
\[
= \sum_{j} \sum_{k} PN'[j] PN'[k] R_w ((j-k)T+\tau)
\]
Replacing \(j-k\) with \(i\)
\[
= \sum_{i} R_w (\tau + iT) \sum_{j} PN'[j] PN'[j-i]
\]
(A.8)

Notice that the second summation on the right hand side of Eq. (A.8) is a time-reversed version of the autocorrelation of the amplitude-mismatched pseudorandom sequence and thus only has non-zero value at \(i = mL\), where \(m\) is an integer and \(L\) is the sequence length. Therefore Eq. (A.8) can be rewritten as
\[
R_{sw}(\tau) \sim \sum_{m} R_w (\tau + mL) = \sum_{i} R_w (\tau) \ast \delta (\tau + mL)
\]
(A.9)

Equation (A.9) clearly demonstrates that when a pseudorandom sequence with amplitude mismatching is modulated onto a repeating waveform at the same rate, the separation of the auto-correlation peaks, and thus the non-repeating time-aperture, will be expanded by a factor of the length of the sequence.

REFERENCES


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