An Electronic Temporal Imaging System for Compression and Reversal of Arbitrary UWB Waveforms

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***Abstract* — We describe a fully-electronic system for compressing and/or reversing arbitrarily-shaped waveforms in the time-domain using the principles of temporal imaging. The system accepts a arbitrary time-windowed broadband input and outputs a chirped waveform with the same envelope but compressed and/or reversed in time. We present a demonstration of a 3X time-compression and a basic time-reversal on a simple waveform and discuss the challenges and limitations of the proposed technique**.

***Index Terms* — Chirp modulation, microstrip filters, signal generators, pulse compression methods.**

I. Introduction

Temporal imaging is an umbrella term used to describe a system in which an arbitrary time-limited signal is magnified, compressed and/or reversed in the time-domain without distortion of the signal envelope, only a corresponding increase or decrease in amplitude in keeping with the conservation of energy. This operation can be understood as a bandwidth-converting procedure (as opposed to the single frequency-conversion of conventional mixing) based on the well-known space-time duals of diffraction and dispersion [1] by mimicking the configuration of a spatial lens-based imaging system.

Time-compression systems have attracted some interest in the optical community for use in active optical pulse-compression schemes [2]. In the microwave regime, a time-compression stage could be added to the output of an arbitrary waveform generator (AWG) to compress the output and produce waveforms with frequency content beyond the capabilities of modern commercial AWG equipment (currently limited to about 5 GHz). This technique is well-suited to creating arbitrarily-shaped, ultra-wideband (UWB) microwave pulses in the X and K-bands for wireless communication.

Compressive temporal imaging systems have seen relatively few demonstrations for input signals in the microwave regime, and those that have taken place have typically employed photonic techniques to benefit from easy access to dispersion and higher bandwidths [3], [4]. We recently demonstrated a fully-electronic implementation of 5X time-magnification for a 0.6 ns waveform [5]. Here, we propose similar configurations for performing time-compression and/or reversal instead.

II. Temporal Imaging

The theory of temporal imaging has been extensively covered in the work of Kolner [1] and revolves around the use of quadratic-phase modulation in the time domain to function as a 'time lens', so-called because it works in much the same manner as a spatial thin-lens, which imparts a quadratic-phase modulation in space on an incident wave. When bracketed by two dispersive transmission media, a time-lens can be configured to form an image of some time-apertured signal in direct analogy to the way a spatial lens between two diffractive media (such as air) forms an image of a spatially-apertured object. Kolner developed the one-to-one analogy for various aspects of such imaging in space and time domains, including the concepts of focal-time, imaging condition, and magnification [1].

As in the case of imaging an object in space, for which at the focal plane the magnification factor M is commonly known to be the ratio of image to object distance '*d*' ($M = -d_{image}/d_{object}$) [6], a corollary exists in the time-domain whereby the magnification of an imaging system is controlled by the ratio of output to input dispersion, where we restrict discussion to first-order dispersion, which results from quadratic-phase filtering in the frequency domain –not to be confused with the time lens, which is a quadratic-phase modulation in time. We will describe a first-order dispersive medium in terms of its linear group delay slope σ in s/Hz (i.e. a straight line in a frequency vs. time graph); it can be shown using this notation that the magnification factor of a temporal imaging system is $M = -\sigma_{output}/\sigma_{input}$ provided a temporal imaging condition is met that is similar to achieving proper focus in a spatial-imaging system. We observe that $|M| < 1$ is a time-compression, while $M < 0$ denotes time-reversal.

A temporal imaging system may take the form shown in Fig. 1, modeled after the original demonstration by Caputi [7], in which a time-windowed (Δt_1) RF input source on a carrier frequency is dispersed, passed to a 'time-lens' (a quadratic-phase modulation is achieved by mixing against a linear frequency sweep generated by dispersing a short-time impulse), and then passed to an output dispersive network, where the output is compressed in time to $\Delta t_2 = (-\sigma_3/\sigma_1)\cdot\Delta t_1$ and increased in magnitude by $A_{out} = |\sigma_1/\sigma_3|\cdot A_{in}$. In the frequency-mixing process, either the sum- or difference-frequency may be used; the choice will influence the condition for temporal imaging much in the same way as the choice between a convex or concave spatial-lens would [8]. Here, we will assume that the sum-frequency is of interest because a higher carrier frequency will make it easier to observe the signal envelope, thus we can use a high-pass filter (HPF) or bandpass filter in Fig. 1. The temporal imaging condition is [8]:

$$-\frac{1}{\sigma_2} = \frac{1}{\sigma_1} + \frac{1}{\sigma_3} \quad (1)$$

where σ_2 is the group-delay slope corresponding to the rate of the linear reference frequency sweep for the time-lens.

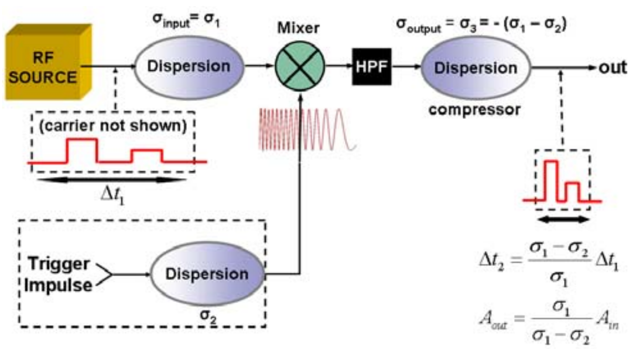


Fig. 1. Schematic of proposed time-compression system.

Photonic time-compression systems [3], [4] are able to dispense with the input dispersion entirely (a de-focused system) without significant image distortion because they use chirped optical pulses as their reference frequency sweep, and these have a much higher bandwidth than the microwave signal (the so-called "photonic time-stretch technique").

III. Electronic Time-Compression: An Example

In the broadest sense, only two elements are necessary for temporal imaging: (i) a broadband dispersive medium, and (ii) a time lens. Implementing the former in the multi-GHz regime is out of reach of traditional chirp-based surface-acoustic-wave structures. Instead, a useful substitute is the chirped electromagnetic bandgap (CEBG) structure – a 1-D chirped periodic perturbation of impedance which can easily be fabricated in conventional microstrip and other transmission line and waveguide technologies [9]. These are reflection-mode devices which are created by etching modulated width profiles. It is relatively straightforward to design CEBGs for large fractional bandwidths (>100%) and various tapering solutions exist for improving the linearity of their group-delay. Each CEBG must be paired with a broadband directional coupler to circulate the signal – fortunately, this can be readily integrated in the same technology.

What remains is to describe how to implement a broadband, electronic time lens (quadratic-phase modulation in time). One implementation is to mix the input signal with a flat-amplitude linear frequency sweep. Since active voltage-controlled oscillators under normal circumstances do not have the capacity for multi-GHz-range sweeps within a matter of nanoseconds, a better approach is to passively approximate such a sweep by dispersing a very short impulse. Although such an impulse will in practice feature a frequency roll-off, this *a priori* information can be compensated for in post-process.

Let us consider as an example a system designed using CEBG tools and assuming that local impulse-generating equipment is limited in frequency content to 15 GHz. Here, because we seek a magnification factor of $0 < M < 1$, we observe two things: σ_1 and σ_3 must have the opposite sign (we seek a non-reversed image) and we require $|\sigma_3| < |\sigma_1|$. According to (1), we see that σ_2 must therefore be of the same sign as σ_1.

Our test signal is a 1.45 ns base-band waveform: a simple, pulsed '101' signal where the second pulse is twice the height of the first. This signal has approximately 1.5 GHz single-sided bandwidth (SSB), and we seek a compressed output of 0.48 ns (a compression factor of 3 by setting M = 0.333). We first modulate the input on a 13.5 GHz carrier, which means we will be handling a 3 GHz double-sided bandwidth (DSB) and converting this to a total 9 GHz DSB at the output. If we set σ_1 = -1 ns/GHz, our dispersed input will occupy approximately (1.4 ns + σ_1·3 GHz) = 4.4 ns in the time-domain. This also sets the other CEBG group delay slopes to σ_2 = -0.5 ns/GHz, and σ_3 = +0.333 ns/GHz. We propose the frequency scheme of Fig. 2, which establishes that the input RF signal will be compressed and upconverted to fit in the 16-to-25 GHz range. The difference frequencies (being 5 to 8 GHz) are easily filtered out using an HPF, and the required CEBGs, if implemented in microstrip using the design formulae laid out in [9], would be approximately 16.4 cm in length, assuming a substrate effective permittivity 'ε_{eff}' of about 7.5. The overall proposed schematic would look like that of Fig. 3, where we have indicated that broadband directional couplers (DCs) are required.

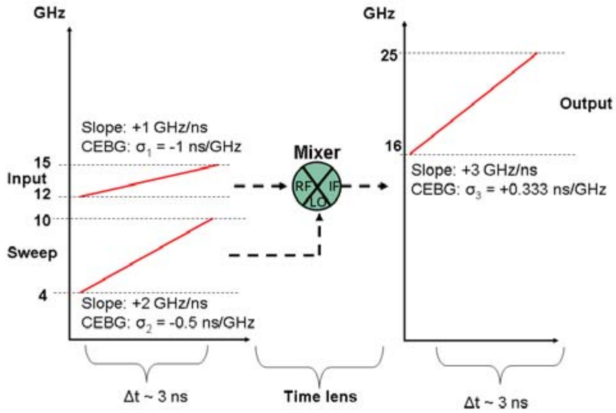


Fig. 2. A frequency vs. time representation of the time-lens process for our demonstration system.

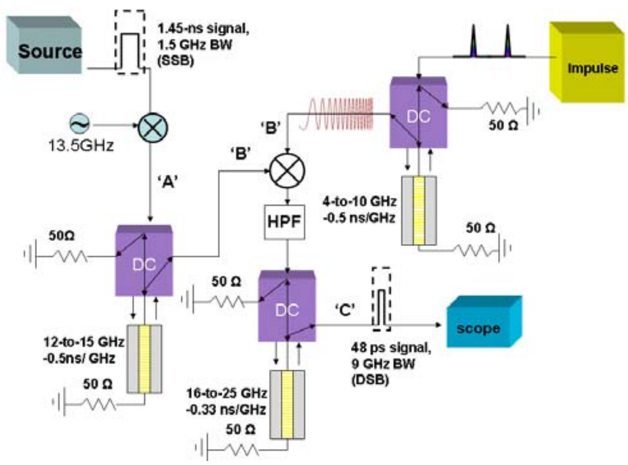
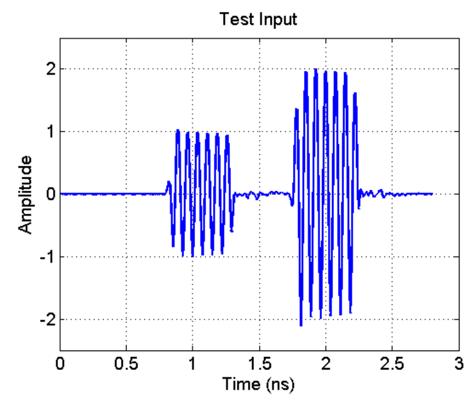


Fig. 3 Detailed schematic of the proposed system, showing all CEBGs, directional couplers (DCs) and target frequencies.

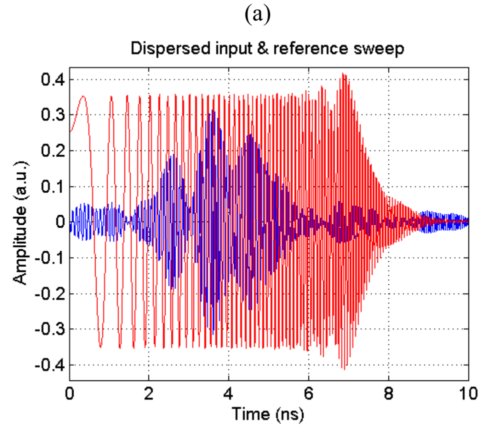
Using MatLAB to predict the expected theoretical results of the system, we show the signals at each of the labeled points of Fig. 3 (points 'A', 'B' and 'C'), assuming ideal CEBGs (rectangular bandpass, quadratic-phase filters), and lossless mixing and coupling operations, as well as a flat-amplitude reference frequency sweep (DC-to-15 GHz) generated by applying dispersion to a sinc function, thus avoiding the frequency roll-off of a practical impulse for purposes of illustrating the concept.

In Fig. 4a, we show the input waveform at point 'A', where it spans 1.45 ns, and in Fig. 4b after the first dispersion element (point 'B'), where it is shown in temporal alignment with the reference frequency sweep. The product of these signals is shown in Fig. 4c in the frequency domain where sum and difference frequencies are evident and occupy different bandwidths.

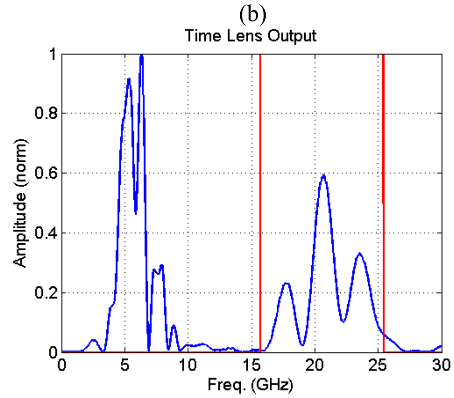
When the sum-frequency is band-passed (using an ideal, rectangular filter), the output after the final dispersion is shown in Fig. 5a to be 0.53 ns in length –a time-compression factor of 2.8, just shy of the target of 3. The limited system resolution (which can only distinguish a few elements in the original window) still produces a recognizable '101' sequence, although the edges have been rounded, highlighting the loss of detail. This is in part due to the limited bandwidth assumed to be available for the presumed output CEBG. If the output CEBG were a true all-pass quadratic-phase modulator, the output is somewhat better at retaining the pulse shape, using both sum and difference frequencies (Fig. 5b).



(a)



(b)



(c)

Fig. 4 (a) The input signal at point 'A'. (b) The signal at point 'B' after dispersion (solid) along with the reference frequency sweep (dash) aligned in time as inputs to the mixer. (c) The output of the mixer in the frequency domain, showing sum and difference frequencies, and the ideal bandpass filter used to isolate the sum frequency in simulation.

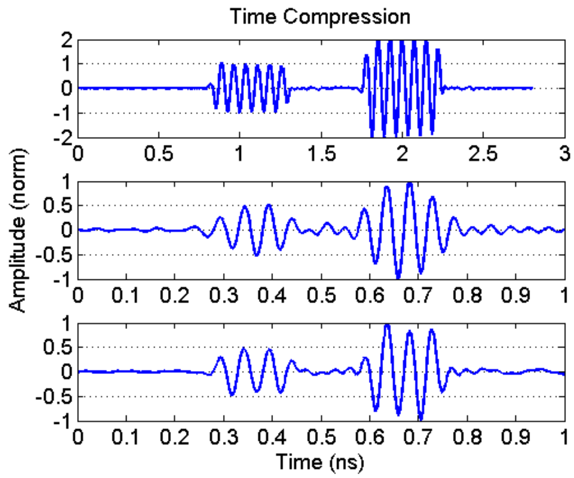


Fig. 5 Electronic time-compression. The input (top) is shown for comparison with the 3X compressed output (note the change in x-axis), both with (middle) and without (bottom) filtering to isolate the sum-frequency.

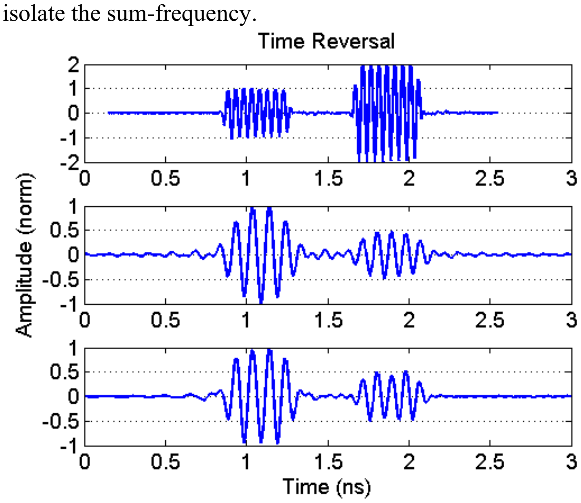


Fig. 6 Electronic time-reversal. The input waveform (top) is reversed using difference-frequency mixing (middle) and assuming no filtering (bottom, requires much broader CEBG).

IV. Electronic Time-Reversal

A simple change of dispersion slopes and frequency ranges is enough to modify the system to demonstrate time-reversal, which is potentially interesting for antenna arrays, acoustic and sonar [3]. Here we will target the difference-frequency and can set M = -1 by choosing σ_1 = -1ns/GHz, σ_2 = -0.5 ns/GHz and σ_3 = -1 ns/GHz, respecting the imaging condition (1) except that, since we seek a difference frequency, we reverse the sign of σ_2 [7].

For an input signal of 1.45 ns spanning 15-20 GHz, we can assume the same 15 GHz reference frequency sweep is available to achieve time-reversal. Using the same pattern as before, now slightly shorter in time we can see in Fig. 6 the output signal has reversed in time, again both with and without an assumed bandpass filter from the final CEBG. The output frequency range here is from 8 to 13 GHz, although this is at the discretion of the designer.

V. Conclusion

We have demonstrated that a fully-electronic system for time-compression and time-reversal of UWB microwave waveforms are feasible using broadband electronic dispersion and mixing techniques. This approach, although featuring some resolution limitations [1], is nevertheless easy to implement in mature technology. Further research into reducing the required dimensions of the dispersive bandgap structures involved should be a target of interest in furthering this research.

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