Design and Construction of an Arbitrary Pulse Compressive Amplifier

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***Abstract*—Compressive pulse amplifiers are a class of amplifiers that convert long low amplitude signals into very broadband pulses of high amplitude, yielding a very high instantaneous peak power output pulse. However, in the realm of electronic immunity and susceptibility testing, very broadband short pulses are not always desired. This work presents a design for a compressive amplifier that is aimed at creating arbitrary pulsed signals of varying bandwidths. Limitations of the achievable gain and methods used are discussed.**

Keywords—Amplifier, Cavity, Compression, Compressive, Pulse, Reverberant

I. Introduction

Many works have shown the compressive amplifier to be a great tool for creating large amplitude pulses. A few different methods exist to perform the job of a compressive amplifier but cavity amplifiers such as in [1] have a relatively low production cost. The main advantage of this amplifier class is the relatively low cost in comparison to a power amplifier with the ability to create pulses at similar power levels. These high-power pulses have many different uses – from high power radar systems [5] to Ultra-Wideband (UWB) communications [6]. Another field in which high power pulses are beneficial is the area of electronic susceptibility and immunity. The main difference for the area of susceptibility is that other types of waveforms are required rather than only broadband pulses. In certain cases, such as in [4], relatively narrowband pulses are required for testing. Having the ability to increase the amplitude of arbitrary pulses using a compressive amplifier would be beneficial to any scenario needing high power pulses, especially for susceptibility and immunity testing.

Most current works on compressive amplifiers have focused solely on increasing the gain. In [2], a 130 ps pulse was generated using a compressive amplifier while achieving 19 dB of compression gain. In [1], a gain of 21.2 dB was achieved in compressing a 35 ps pulse with a bandwidth of 5 – 18 GHz. A pulse with narrower bandwidth of 300 MHz, was investigated in [3], with a stated gain of 32 dB. However, this gain appears to be calculated differently than the previous two mentioned works. Insufficient information is given to accurately calculate the gain based on the method described in the next section.

While these works show promising results in terms of gain, they require the use of broadband pulses with bandwidths of 7 GHz, [2], and 13 GHz [1]. Changing the bandwidth of the signal has been most notably discussed in [1]. The gain tended to decrease as the bandwidth of the signal decreased. While this is a negative effect, it does not conclude that pulses of an arbitrary shape and lower bandwidth cannot be achieved on the output. This work aims to look at the effects, practicality, and limitations of creating high power arbitrary signals through the use of a compressive amplifier.

II. Background Theory

The method of recreating a pulse using a reverberant cavity has been described in [1], [2], and [3]. This work uses a very similar method for recreating pulses and is expressed in the block diagram shown in Fig 1.

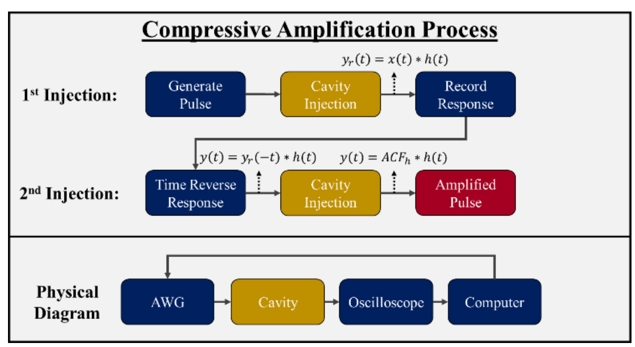

Fig. 1. Block diagrams of cavity operation. Top diagram shows the mathematical description of the compressive amplifier while the physical diagram shows the equipment used in both stages.

The method begins with acquiring the response of the cavity to the pulse that is desired for recreation. For traditional compressive amplifier applications, the desired pulse is usually a short pulse with a bandwidth of multiple GHz, which can be approximated to the Dirac Delta function, $\delta(t)$. Given that a system response is obtained with the $\delta(t)$ stimulus, the recorded response will be the impulse response of the system

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$h(t)$. Once this impulse response is recorded, it is then time-reversed (TR) using a software tool. This time reversed impulse response is then injected to the cavity much like the original pulse was, effectively convolving the impulse response with the time reversed version of itself, producing the autocorrelation function of the impulse response. For a typical reverberation chamber the autocorrelation function of its impulse response is a short pulse with large peak value compared to the peak value of the injected time reversed impulse response. The final output of the amplifier is then (in the ideal case):

$$y(t) = h(t) * h(-t) = ACF_h(t). \tag{1}$$

This relationship can also be expressed in the frequency domain (the act of time reversal is equivalent to taking the conjugate of the signal spectrum):

$$Y(j\omega) = H(j\omega)H^*(j\omega) = |H(j\omega)|^2, \tag{2}$$

where $H(j\omega)$ is the frequency response of the cavity.

If an arbitrary signal $x(t)$ is injected first instead of the short pulse representing the delta function, the response will be:

$$y_x = x(t) * h(t). \tag{3}$$

In the second injection of the time reversed copy of $y_x(t)$ the following output will be produced:

$$y(t) = y_x(-t) * h(t) = \big(h(-t) * x(-t)\big) * h(t) \tag{4}$$

or in the frequency domain:

$$Y(j\omega) = X^*(j\omega)|H(j\omega)|^2. \tag{5}$$

The frequency domain representation (5) shows that given an arbitrary signal $X(j\omega)$ injected, the output will be a filtered version of the time reversed input pulse.

Since the autocorrelation function of a typical cavity used in a compressive amplifier is a short pulse, its spectrum $|H(j\omega)|^2$ is broadband, and if it is wide relative to $X(j\omega)$ (i.e. it is approximately constant within the bandwidth of $X(j\omega)$), the output of the amplifier will be approximately a scaled (and time reversed) input signal:

$$Y(j\omega) \approx AX^*(j\omega) \tag{6}$$

$$y \approx Ax(-t) \tag{7}$$

where A is the gain of the amplifier. Because the equality in (6) and (7) is approximate, these equations cannot be used to measure the gain. The ratio of the maximum absolute values of the signals is used instead throughout the paper:

$$A \stackrel{\text{def}}{=} \frac{\max|y(t)|}{\max|x(t)|} \tag{8}$$

From (7) it might appear that the gain of the amplifier does not depend on the input signal $x(t)$. This is not the case in a practical system. The peak value of the injected signal is limited (by the generator and the preamplifier if it is used), therefore in order to achieve the maximum possible amplitude of the output signal, the signal obtained in the first injection (3) will have to be scaled to match its peak to the maximum achievable voltage at the input of the cavity. Because of this the actual output of the amplifier is

$$y \approx A_x x(-t) \tag{9}$$

with the gain specific for each signal $x(t)$.

The exact relationship between the properties of the signal $x(t)$ and the achievable gain is difficult to establish in general because the peak value of the convolution of two signals is related to the signals in a non-trivial way. This is further complicated by the nonlinear operations in (8) and the one-bit transformation of the signals needed to achieve high gain values (see below).

Because of these complications, this study is concentrated on experimental measurement of the achievable gains for three common RF signals (Gaussian pulse, exponentially decaying pulse and rectangular, or gated, pulse).

III. One-bit Signal Transformation

In order to overcome the loss in the system and achieve higher gain, One Bit Time Reversal (OBTR) can be used. The method of OBTR was used in [1] and [2] to achieve increased gain over the traditional TR technique. OBTR applies the signum function to the re-injected TR signal and effectively adds more energy to the system. Despite the fact that both the time-domain waveform and the spectrum of the OBTR signal are different from the TR waveform, the output pulse often is not significantly distorted as will be shown later. OBTR transformation for a signal $x(t)$ is defined as

$$x_{obtr}(t) = \begin{cases} 1, x(-t) \geq 0 \\ -1, x(-t) < 0 \end{cases} \tag{10}$$

Before the injection the OBTR signal is scaled to the maximum possible output level.

IV. MEASUREMENT

The setup for measuring the gain of the compressive amplifier is shown in Fig. 2. All waveforms are created using the Keysight M8190A 12 GSa/s Arbitrary Waveform Generator (AWG) and all measurements are taken in the time domain using a Keysight DSO81304B oscilloscope. The antennas contained within the cavity are 800 MHz to 6.5 GHz log periodic PCB antennas. Python code is used to interact with the AWG and oscilloscope to control the entire measurement process. The cavity dimensions are shown in Fig. 2. It is constructed using welded aluminum and contains an opening in the front for internal access. This opening is covered during testing with a fitting aluminum piece that is bolted to the main cavity and sealed with a conducting gasket. The ports into the cavity are two SMA bulkhead connectors mounted to a cavity wall for each antenna as can be seen in Fig. 2.

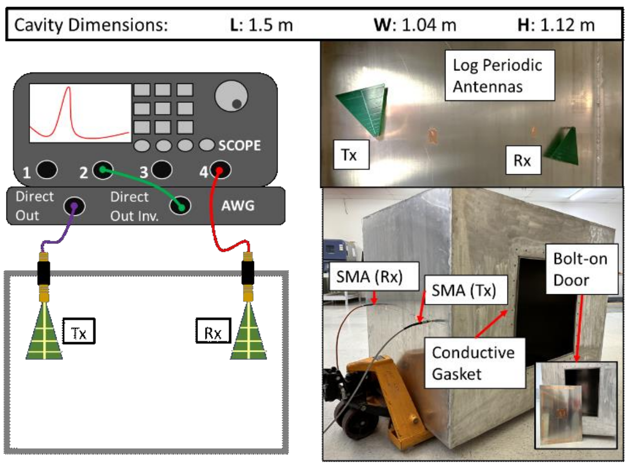

Fig. 2. Diagram showing the connections between cavity, oscilloscope, and AWG (left). Images of physical cavity (right).

To measure the gain of the amplifier, three different waveforms were used. The signals were obtained by modulating a 2 GHz carrier by three envelopes: Gaussian function, decaying exponential, and the rectangular pulse. The signals are defined by the following equations.

$$x_G(t) = \exp\left(-\frac{(t-t_0)^2}{a^2}\right)\cdot \sin(2\pi f_o t) \tag{11}$$

$$x_d(t) = \exp\left(-\frac{t}{a}\right)\cdot \sin(2\pi f_o t) \tag{12}$$

$$x_r(t) = \begin{cases} \sin(2\pi f_0 t), & 0 \le t \le \tau \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

The gaussian and damped sine waveforms are defined by a damping factor a, and the rectangular pulse by the pulse duration τ; the carrier frequency is f_0.

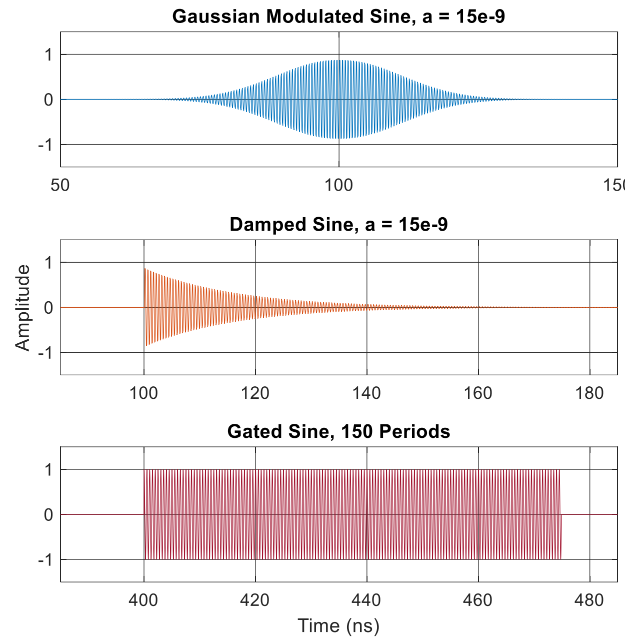

Fig. 3. The three pulses used for measurement of the compressive amplifier.

Examples of the three pulses are plotted in Fig. 3 with their respective spectrums in Fig. 4.

The bandwidth of the pulses was calculated by determining the frequency of the -3 dB level (relative to the maximum) for the envelope spectra given in Table I.

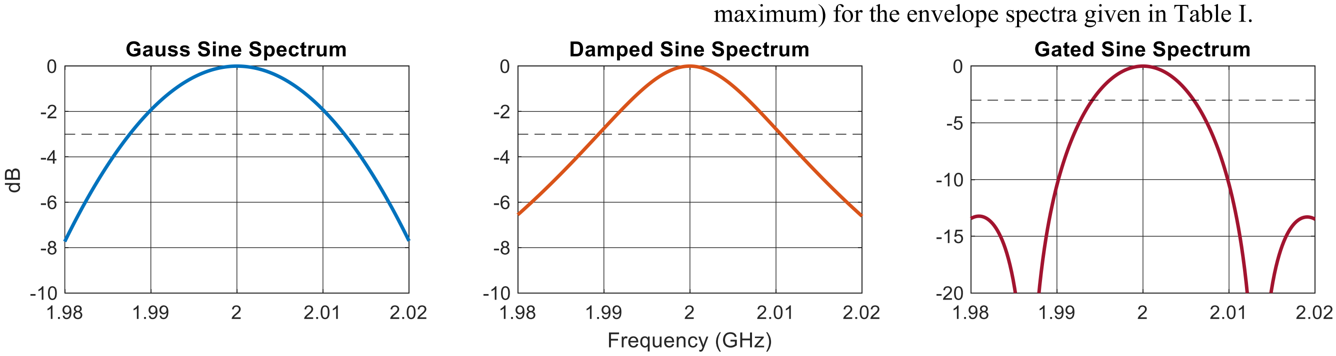

Fig. 4. Spectra of pulses used for testing narrowband operation of compressive amplifier. These spectra are much narrower than what is typically used in compressive amplifier designs.

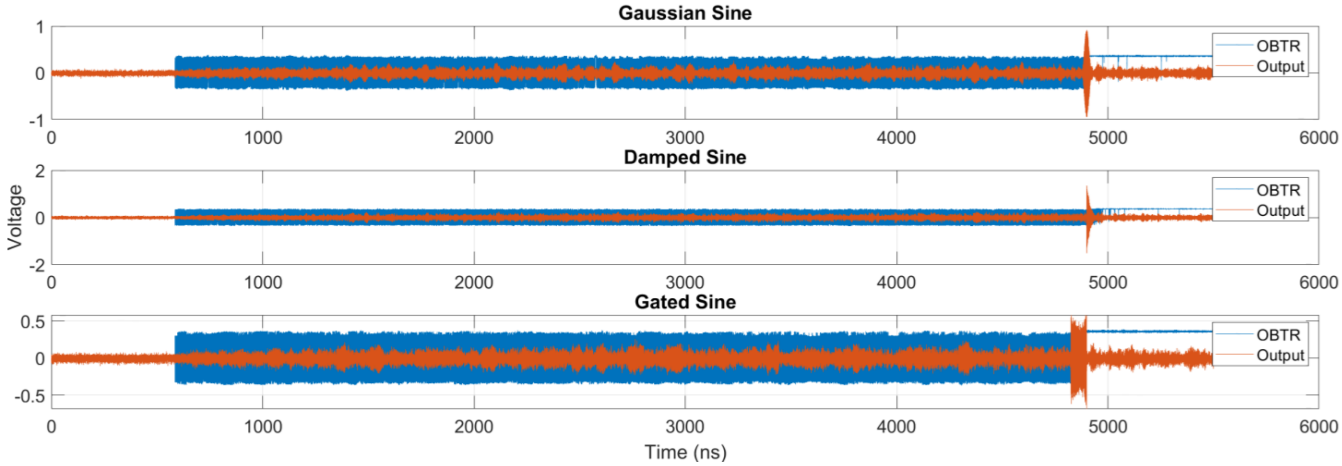

Fig. 5. Input and output waveforms from the compressive amplifier for the three pulses. The blue waveforms show the injected OBTR signal from the AWG. The signal in oragne is what the oscilloscope recorded from the cavity output. The output waveforms show that the pulses were recreated and amplified

TABLE I. SIGNAL SPECTRA ENVELOPES

	Gaussian	Damped	Gated
Spectrum envelope	$\sqrt{\pi a^2} e^{-(\pi a f)^2}$	$\left\|\frac{1}{a + j2\pi f}\right\|$	$\tau \cdot \mathrm{sinc}(\tau\pi f)$

During the gain measurement the pulses (12)-(14) were injected into the reverberant cavity and the responses to the pulses were recorded. In order to reduce the measurement noise the responses were averaged in the time domain over 1000 injections. The averaged responses were then OBTR-transformed and injected back into the reverberant cavity. An example of the output signals for each of the waveform types can be found in Fig. 5. The zoomed-in plots in Fig. 6 show relatively good correlation between the original pulse and the recreated pulse. The normalized correlation coefficient was calculated for each waveform using a 175 ns window centered at the maximum of the output waveforms. The correlation values are 94.2%, 90.8%, and 96.3% for the Gaussian, damped, and gated waveforms respectively. The gain for these pulses is 7.8 dB, 12.3 dB, and 5 dB respectively. These values are shown in Table 2.

TABLE II. BANDWIDTH, CORRELATION AND GAIN VALUES FOR EACH TESTED WAVEFORM

	Gaussian	Damped	Gated
Bandwidth	25 MHz	22 MHz	12 MHz
Correlation	94.2%	90.8%	96.3%
Gain	7.8 dB	12.3 dB	5 dB

A study of input pulse duration vs. output gain was performed in [1]. That study looked at signals with a minimum bandwidth of 100 MHz with a stated gain of approximately 2.5 dB and a maximum gain of 21.2 dB with a 13 GHz bandwidth. A similar study was performed for this work and the results for each waveform are shown in Fig. 7 and 8 against pulse length and bandwidth respectively. Bandwidth was changed by modifying parameters a and τ in (12)-(14) with a fixed carrier frequency (2 GHz). This differs from the study in [1] which the start and stop frequencies were varied to achieve varying bandwidth, leading to different carrier frequencies being used. The data shows a similar trend to [1]. The maximum gain values for all three signals are similar (around 22 dB). As expected, the compression gain decreases as the length of the input pulse increases, lowering the bandwidth. The plots in Fig. 7 show that positive gain can be achieved for all three pulses (with OBTR) for the pulse length of at least 100 ns. It can be seen also that the gaussian waveform showed the highest rate of gain decay. The damped sine demonstrated the least amount of gain decay. The plots in Fig. 8 provide an initial analysis into how the compressive amplifier of these dimensions will perform given an arbitrary signal of a defined bandwidth. Achieving a model for expected gain with changing cavity dimensions and input waveform is a more complicated task and may be a topic for future work.

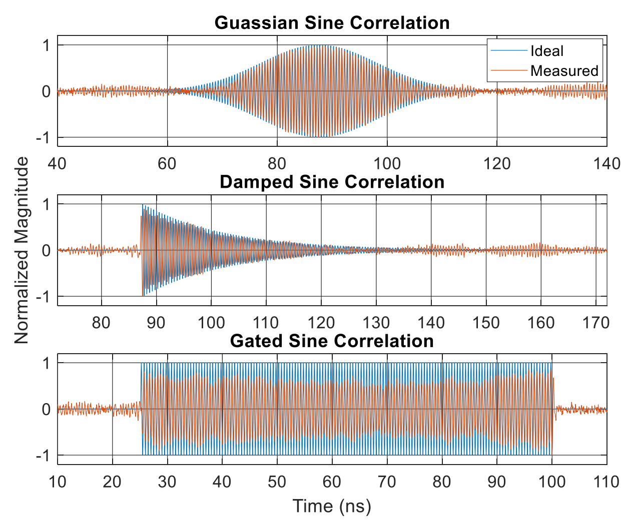

Fig. 6. Zoomed-in waveforms of Figure 4 showing correlation with the ideal waveform.

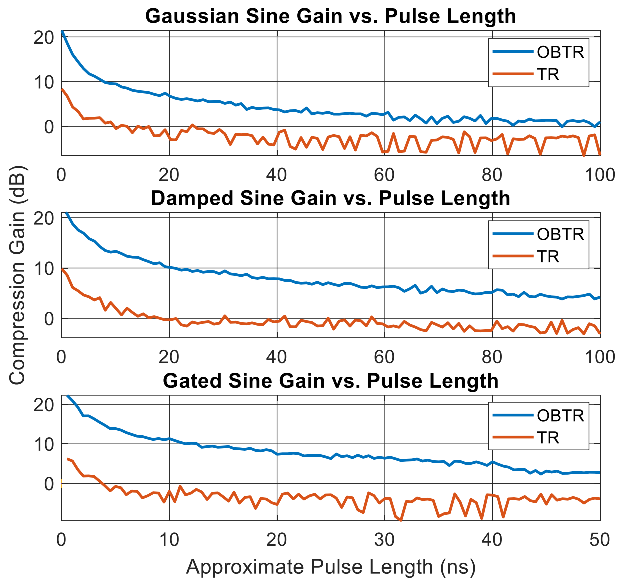

Fig. 7. Compression gain as a function of the pulse length. Results for OBTR and TR are shown. For Gaussian and damped waveforms, pulse length is approximated to *a*.

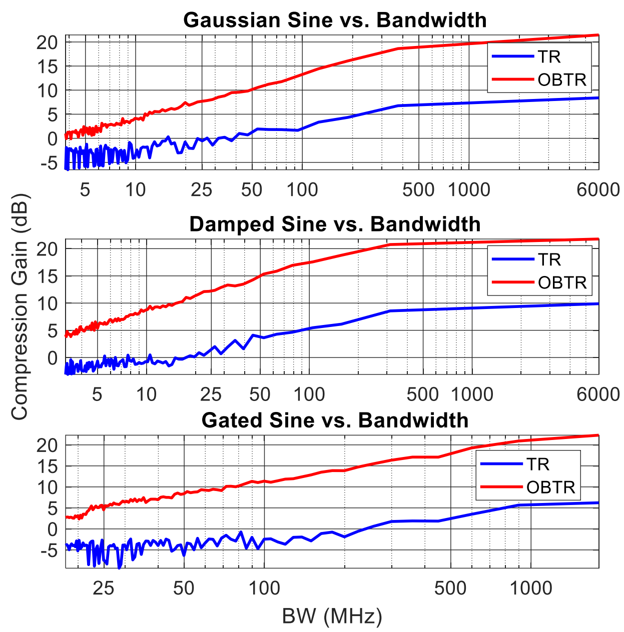

Fig. 8. Gain vs. bandwidth curves for all three pulses. Both OBTR and traditional TR methods are shown.

The maximum gain (22.3 dB) waveform obtained for the gated sine pulse of 0.5 ns duration (one period at 2 GHz) can be seen in Fig. 9. Correlation analysis was performed using a 10 ns window yielding a value of 90.4%.

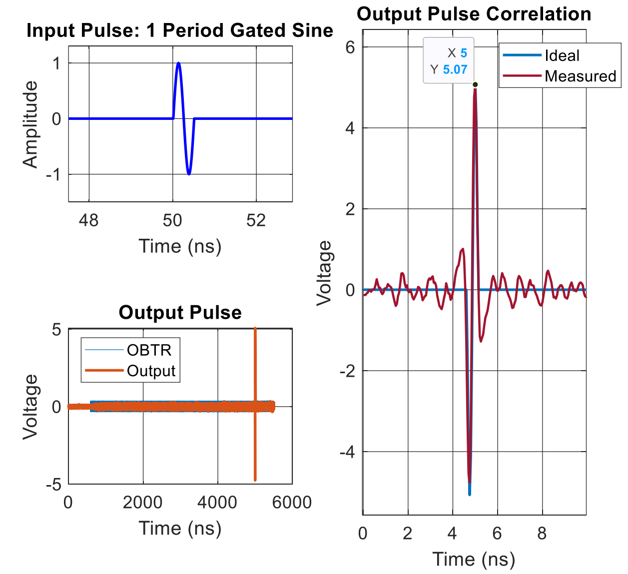

Fig. 9. Maximum gain achieved with a 1 period gated sine pulse (22.3 dB). Ideal waveform is in top left. Gain is calculated off the bottom left plot.

V. Conclusions

The compressive amplifier was investigated for its usefulness in immunity and susceptibility testing to generate arbitrary waveforms. Pulse reconstruction and compression gain was studied for Gaussian sine, damped sine, and gated sine waveforms. The pulse reconstruction of the amplifier performed well even for relatively narrowband signals of approximately 22 MHz reaching 12 dB gain for the damped sine pulse. A maximum gain of 22.3 dB was observed for a gated sine waveform. Work will continue to investigate increasing the gain when using the compressive amplifier together with relatively narrowband power amplifiers.

VI. References

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