Efficient and Linear Amplification of Spectrally Confined Pulsed AM Radar Signals

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***Abstract*—This letter presents a pulsed high-efficiency power amplifier with increased spectral purity obtained by supply modulation of the pulse envelope. The PA operates at 2.14 GHz with 78% efficiency at 6 W peak power, and with 66.4% average efficiency over a 14.7 μs pulse with a 4.1 dB PAR shaped by a 90% efficient resonant-pulse envelope supply modulator. For PARs greater than 4.1 dB, the signal envelope can be split between the supply modulator and the PA drive, with up to 25% improvement in composite efficiency.**

***Index Terms*—Envelope Elimination and Restoration (EER), radar, spectral confinement.**

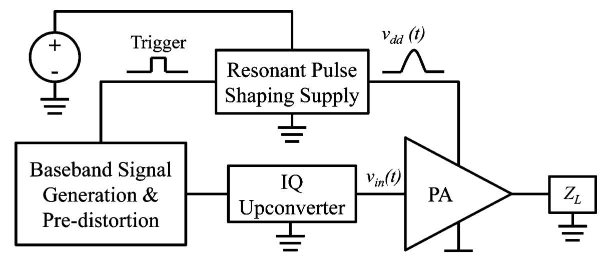

Fig. 1. Block diagram of radar transmitter with resonant pulse shaping supply for shaping the waveform envelope allowing spectral confinement of the transmitted waveform.

I. Introduction

LONG-RANGE system performance of solid-state phased array radar is enabled by a large number of transmit modules that produce very high transmit powers. A typical transmit module has an efficient nonlinear class-C power amplifier (PA) as the output stage [1]. This in turn restricts the transmitted pulse waveform to constant-amplitude rectangular envelopes with significant spectral content over a large bandwidth, which can interfere with other microwave systems. Amplitude modulation of the envelope provides a means to obtain spectral confinement, and has been experimentally investigated in [2], [3] in an out-phasing PA with a Gaussian envelope shape, with up to a 3 dB peak-to-average ratio (PAR) waveform and no system efficiency reported.

This letter presents an alternative method of creating spectrally confined radar signals based on Envelope Elimination and Restoration (EER) first introduced in [4]. Extensions of EER are extensively applied to communication signals and a good overview is presented in [5]. Typical envelope supply modulators are designed for communication signals with PARs up to 10 dB. In contrast to communications signals, a radar signal is typically well known *a priori* to transmission, allowing the use of a high efficiency resonant pulse shaping supply which shapes the signal envelope as it is amplified by a high efficiency PA. A digital pre-distortion technique is used to linearize the system in order to produce envelopes with a programmable PAR.

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II. Pulsed Radar Transmitter Architecture

Fig. 1 shows the transmitter architecture for creating spectrally confined pulsed radar waveforms. The desired waveform is generated and pre-distorted at baseband. The baseband signal is up-converted and amplified by the PA. The supply voltage of the PA is modulated by the resonant pulse shaping supply which is triggered by the baseband signal generator. Time alignment of the resonant pulse shaping supply and PA input envelope is critical to generating the desired transmitter output signal. When the PA is driven with a constant envelope, the waveform envelope is created by introducing PA gain variation via the resonant pulse shaping supply. However, the system is not limited to constant input PA drive, allowing for an additional degree of freedom in shaping the waveform envelope.

For this demonstration, a 2.14 GHz PA was designed with a TriQuint 0.25 μm GaN device, following [6]. The low-frequency stabilization capacitors on the drain bias line need to be removed to allow drain supply modulation. The PA, as shown in Fig. 2, is connected to the resonant pulse shaping supply via a low-inductance interconnect to its drain bias line.

The implementation of the resonant pulsing circuit is shown in Fig. 3. Efficient design of the pulsing circuit requires knowledge of the impedance that the PA presents to the supply, therefore characterization of the PA is required. Upon receipt of a trigger, an FPGA is used to turn on switch M_1. This produces a resonant pulse across the PA which theoretically has a raised cosine shape. Switches M_2 and M_3 are used to actively damp the pulse and improve the output wave shaping. The implemented resonant pulsing circuit has an efficiency of approximately 90% when driving a resistive load. Further detail on the implementation of the resonant pulsing circuit is given in [7]. Fig. 4 shows the measured voltage $v_{dd}(t)$ when connected

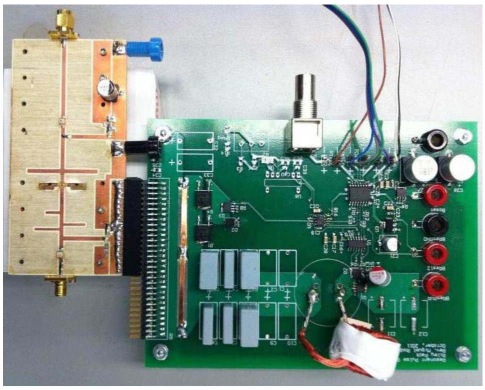


Fig. 2. Photo of the amplifier integrated with the pulsing circuit.

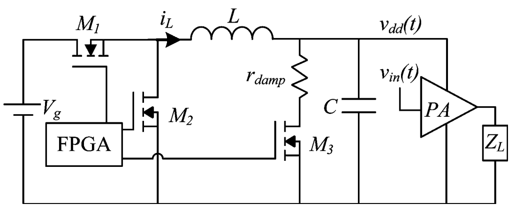


Fig. 3. Block diagram of resonant pulse shaping supply implementation.

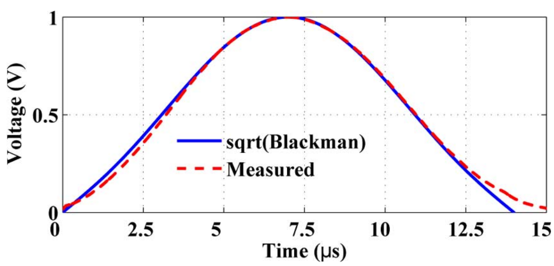
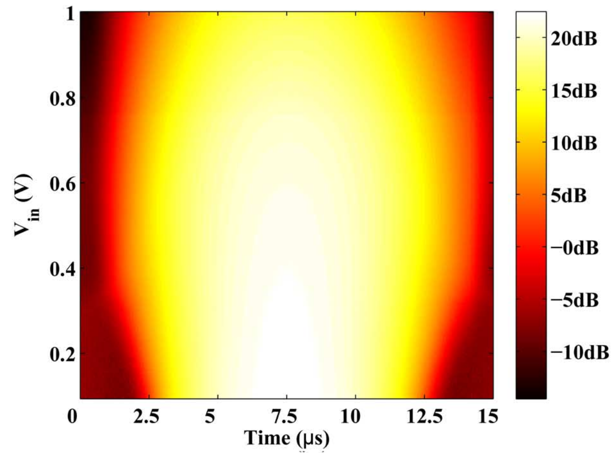
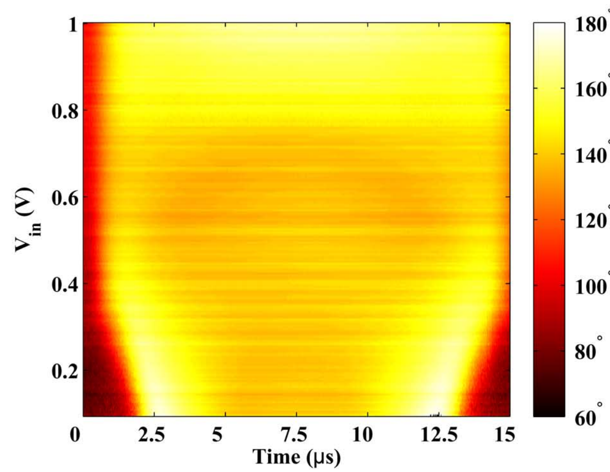


Fig. 4. Measured supply voltage versus time. The measured supply voltage is well approximated by the square root of a Blackman windowing function.



(a)



(b)

Fig. 5. (a) Gain magnitude variation as a function of input voltage and time, normalized to peak input voltage. (b) Gain phase variation as a function of input voltage and time, normalized to peak input voltage.

to the PA, which is well approximated by the square root of a Blackman window. Therefore, the power envelope of the signal may easily be shaped by a Blackman window.

For this proof-of-concept demonstration, a pulse width of approximately 14.7 μs is generated. Changing the pulse width would require modification of the lumped element values indicated in Fig. 3. However, a system implementation could include several switched resonant pulsing circuits to allow a tunable pulse width.

III. Static Digital Pre-Distortion Concept

Both the envelope shape and the phase of the pulse output from the PA need to be controlled in order to achieve spectral confinement of the radar waveform. Digital pre-distortion (DPD) using a Look-Up-Table (LUT) was applied, as a common technique for PA linearization and limiting spectral regrowth, e.g., [8]. Application of LUT-based pre-distortion to the system shown in Fig. 1 is not straightforward, since the supply modulator modifies the gain nonlinearity of the transmitter relative to that of the PA alone. Given the time varying nature of the supply waveform, a two-dimensional LUT approach was adopted. In contrast, the LUT would be a one-dimensional function of input voltage for constant $v_{dd}(t)$.

Initially, the complex voltage gain of the PA connected to the resonant pulse shaping supply as a function of time and input voltage is measured by averaging over 128 pulses. Fig. 5 shows the variation of the measured PA gain and phase over the duration of the pulse as a function input voltage. The input drive waveforms are pre-distorted using this data in order to achieve the appropriate output waveform envelope and phase from the PA based upon the programmed baseband waveform.

IV. Experimental Setup and Measurements

MATLAB is used to generate the ideal waveforms and apply pre-distortion corrections. The I and Q signals are downloaded to two Agilent 33250A arbitrary waveform generators and up-converted by an Agilent N9310A RF signal generator, whose output is amplified with a linear amplifier, providing the drive to the GaN PA. The output time-domain IQ waveforms are measured with an Agilent E4440A PSA series spectrum analyzer. Power calibration is performed by operating the PA in CW and comparing the spectrum analyzer measurements to those of a

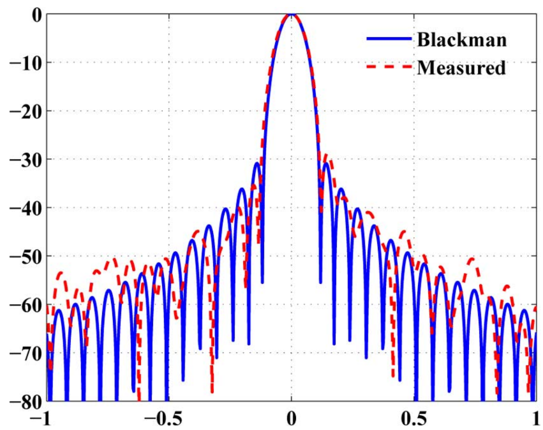


Fig. 6. Normalized frequency response of the measured power spectrum. The is consistent with the frequency response resultant from shaping the power using a Blackman power window, which is shown in the solid blue curve.

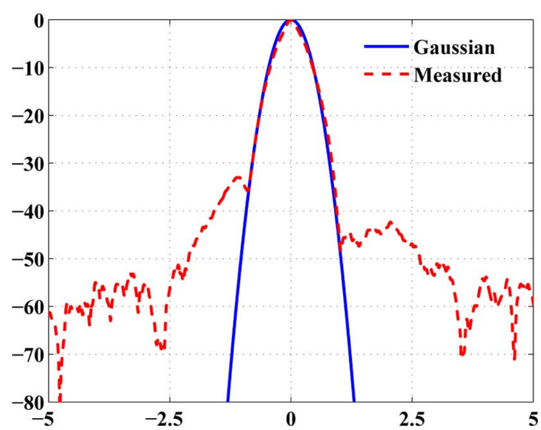


Fig. 7. Normalized frequency response of the measured power spectrum. The is consistent with the frequency response resultant from shaping the power using a 12 dB Gaussian power window, which is shown in the solid blue curve.

power meter. Average input and output power over the pulse are calculated from the spectrum analyzer measurements. Average dc power over the pulse is calculated using average current and voltage measurements input to the resonant pulse shaping supply, and scaling the power using the duty cycle. This is valid given $v_{dd}(t)$ is zero outside the pulse width and therefore the PA consumes no dc power in this region. A 14.7 μs full pulse width was used to be consistent with the approximate full pulse width of the resonant pulse shaping supply. The peak supply voltage is 30 V.

Fig. 6 shows the measured spectrum with a Blackman window applied to the power envelope, while the input drive is pulsed CW with slight pre-distortion corrections. Measured and simulated spectra are in good agreement, and the composite PAE is 66.4% with 6 W peak output power and 4.16 dB PAR. Producing the same pulse shape with the same PA at a constant

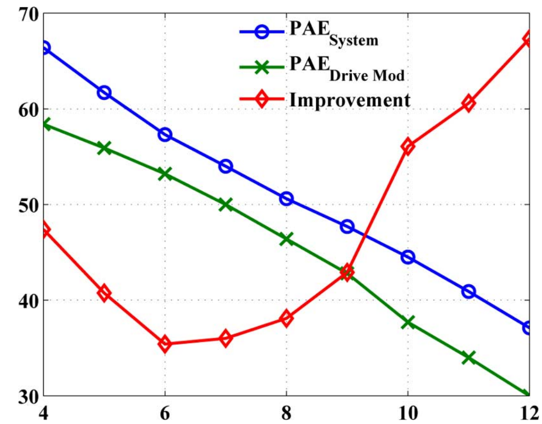


Fig. 8. Efficiency versus PAR comparison for 6 W output power.

supply voltage of 30 V results in a PAE of 58.4%, therefore the system PAE is 13.7% better than the PA alone.

Fig. 7 shows the measured spectrum with a Gaussian window with 12 dB PAR applied to the power envelope, requiring the input drive to contain some envelope variation given the resonant supply is limited to 4.16 dB. The measured and theoretical spectra show good agreement, although it is evident that the pre-distortion does not result in the ideal response. The composite PAE in this case is 37.1% which is a 23.7% increase over the value obtained using pure drive modulation. Fig. 8 shows the efficiencies as a function of PAR, with the 4 dB measurement corresponding to application of a Blackman power window and the remaining measurements corresponding to application of a Gaussian power window with variable PAR. In all cases, the first sideband in the spectrum is kept below -40 dBc and the system PAE is improved over that obtained with pure drive modulation.

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