Efficient Power Amplifiers for Amplitude-Tapered Pulses with Improved Spectral Confinement

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Abstract — This paper reviews various techniques that allow efficient amplification of amplitude-modulated radar pulses through some type of supply modulation. Examples at S and X-band with GaN PAs will be shown with efficiencies above 50% for 10-W transmitters and greatly reduced spectral sidelobes.

Index Terms — Ceramics, coaxial resonators, delay filters, delay-lines, power amplifiers.

I. INTRODUCTION

Typical radar waveforms have constant envelope pulses in order to maintain the power amplifier of the transmitter in saturated high efficiency mode resulting in spectral spreading and interference with other wireless systems. Solid state radar power amplifiers are predominantly biased in Class-C [1]. Designers prefer this class because it is biased in cut-off, allowing for two outcomes beneficial for efficiency improvement: no modulation is required on the drain to pulse the amplifier and no current is drawn between pulses. This non-linear mode of operation allows for high efficiency at fixed output power but is limited to constant amplitude rectangular pulses with only frequency or phase modulation [1]. There is interest in containing the spectral emissions of radars so that they do not interfere with other electromagnetic systems [2][3]. In addition, radars producing high spectral content increase their probability of detection from non-cooperative electronic surveillance systems.

Current radar power amplifiers (PAs) have poor spectral confinement because their rectangular pulses produce high side-lobes, and the non-linear operation of the amplifier causes high harmonic content. The side-lobes in the spectrum can be limited by using shaped pulses without fast rise-times and sharp corners as shown in Fig. 1, while the harmonics can be managed by using linear amplifiers, resulting in a lower efficiency. The approach in the work presented here is to use a transmitter with a supply-modulated PA, similar to envelope tracking (ET) transmitters. The average efficiencies of various power amplifier classes are compared for Gaussian pulses with linear frequency modulation. Simulations and measurements show that an X-Band 10W GaN MMIC power amplifier for radar with a drain supply modulator for a Gaussian pulse shape results in improved spectral confinement with improved average efficiency over the pulse duration.

Both the sensitivity and range resolution of a radar are impacted by the length of the pulse. Shorter pulses which require more spectrum [4], result in improved range resolution, but in decreased energy on target which degrades radar sensitivity.

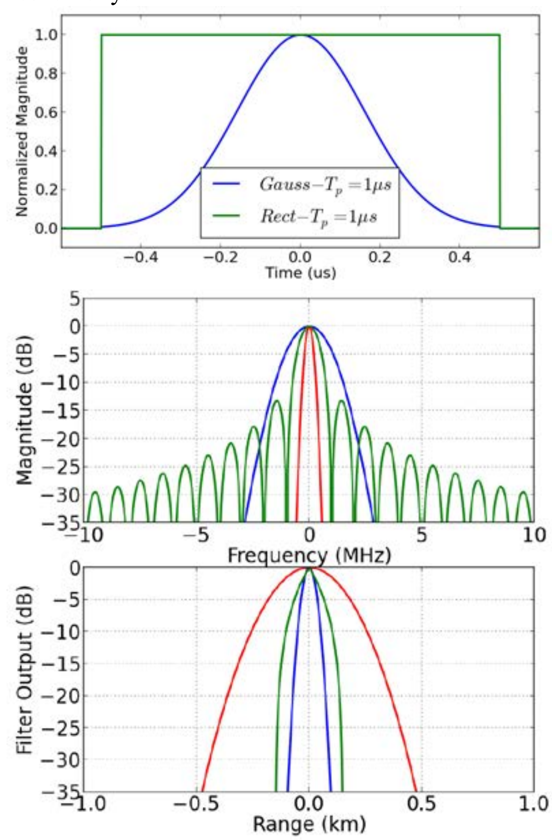

Fig. 1. Top: Envelope of a 1μs rectangular pulse (green) and 1μs Gaussian pulse containing 2.5 standard deviations on each side of the mode (blue). Spectra (middle) and range resolution (bottom) of a 1μs rectangular pulse (green), 1μs Gaussian Pulse (blue), and 5μs Gaussian Pulse (red).

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Shaped pulses without sharp edges eliminate side-lobes in the spectrum and a 1μs Gaussian pulse is compared to a 1μs rectangular pulse in Fig. 1. The Gaussian is designed to have 2.5 standard deviations on each side of the mode within the 1μs pulse. To mitigate the energy degrease of the Gaussian pulse, the length of the pulse must be increased which degrades the range resolution.

To improve the range resolution, a Linear Frequency Modulation (LFM) pulse can be used, allowing a longer Gaussian pulse to increase energy on target while maintaining a desirable range resolution. Fig. 2 shows a comparison of a 1μs rectangular pulse, a 5μs rectangular LFM with 10MHz chirp bandwidth, and a 5μs Gaussian LFM with 10 MHz chirp bandwidth. One can see that both LFMs have better range resolution than the shorter pulse without frequency modulation, but the Gaussian LFM has the cleanest spectrum.

The Gaussian LFM has the added benefit of eliminating the time side-lobes in the range resolution plot. If further improvement in range resolution is desired, more bandwidth can be used, but requires more spectrum. Since it is possible use a Gaussian pulse without losing energy on target while maintaining range resolution, we believe the Gaussian LFM is superior to the rectangular pulse or LFM; however, it must be amplified efficiently to be worth implementing.

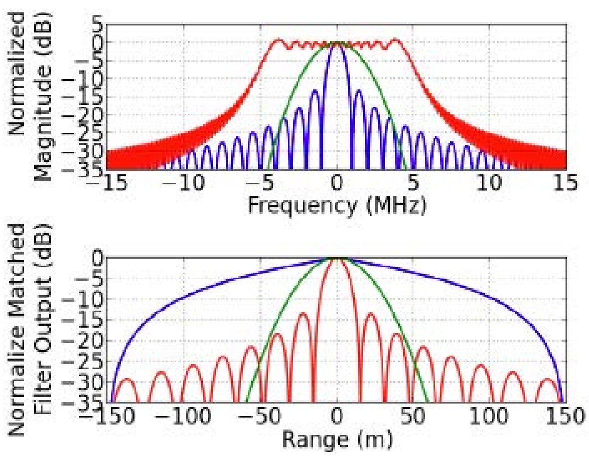


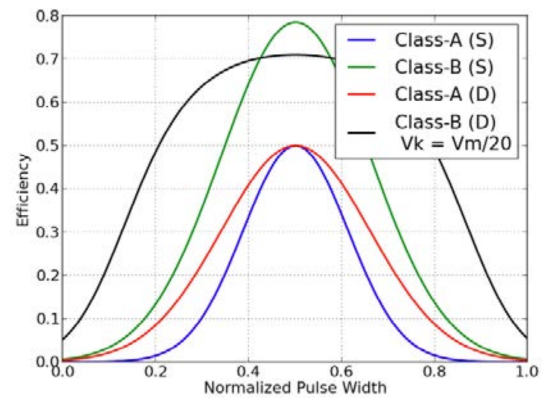
Fig. 2. Spectra (top) and range resolution (bottom) of a 1μs rectangular pulse (blue), 5μs rectangular LFM τ = 50 (red), 5μs Gaussian LFM τ = 50 (green).

II. PA Efficiency for Gaussian Pulses

To demonstrate the impact of amplifier operating class on efficiency, we consider the drain efficiency defined as

$$\eta = \frac{P_L}{P_{DC}} = \frac{I_1^2 R_L}{2V_{DD} I_0}$$

where I_1 is the magnitude of the current at the fundamental frequency, R_L is the load resistance and is set to the class-A and class-B optimal value of V_{max}/I_{max}, V_{DD} is the drain supply voltage, and I_0 is the average drain current. The current can be integrated over the period to find the efficiency, and Fig. 3 shows the resulting efficiency for class-A and B PAs. An adjustable supply voltage such that only the necessary amount was present to allow for full voltage swing at that power level, and no more, results in savings in consumed DC power and thus an improvement in efficiency, shown in Fig. 3 as class-A/B with envelope tracking (ET). The table in the figure shows calculated average efficiencies over the pulse duration for each case, as well as the required power to produce 10W of RF output power. The results show the advantage of supply modulation (ET), where the ET class-B PA consumes only 28% of the class-A PA with constant supply voltage. These results, however, assume a 100% efficient supply modulator. In [6,7], a very efficient resonant supply modulator was demonstrated with both S-band hybrid PA and an X-band MMIC PAs in GaN, as overviewed in the next section.



	Average Efficiency	Power Needed of P_{out}=10W
Class-A (Static)	14.1%	70.4 W
Class-B (Static)	31.4%	31.8 W
Class-A (ET)	20.0%	50.0 W
Class-B (ET)	48.9%	20.4 W

Fig. 3. The efficiencies of different amplifier classes over the duration of a Gaussian pulse. The table shows calculated average efficiencies and required power for a 10W output, assuming an ideal envelope tracking circuit.

III. Supply Modulated PA Results

The improvement in efficiency and spectral confinement was demonstrated for several PAs and an overview is presented here, along with some new results and future outlook. In most envelope-tracking transmitters for communication signals, a switching dc-dc converter (Buck) is used together with a linear amplifier, which limits the total efficiency [5]. For Gaussian-type radar signals, a simpler type

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of supply modulator can be used, as shown in Fig. 4. This modulator is a resonant circuit which is damped so that the first half-period resembles a Gaussian shape, though it is more similar to a square-root of a Blackman filter [6]. The timing is controlled via an FPGA.

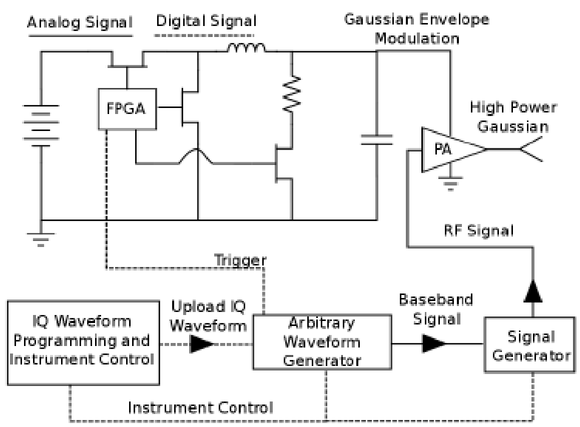

Fig. 4. Block diagram of resonant supply pulse modulator (top) and variable pulse widths enabled by FPGA timing control (bottom).

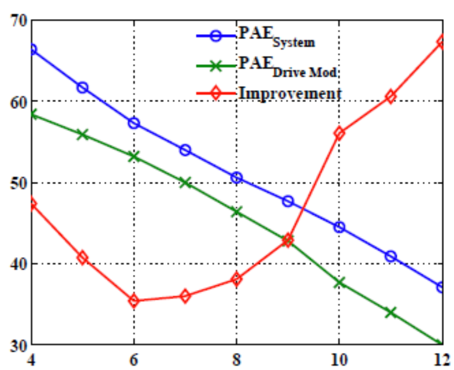

Fig. 5. Efficiency improvement for a 6-W S-band PA using a supply modulator, as a function of peak-to-average ratio of the pulse. The first sideband of the output spectrum for this transmitter for a 14µs full pulse width was below -30dBc, compared to -13dBc for a rectangular pulse [6].

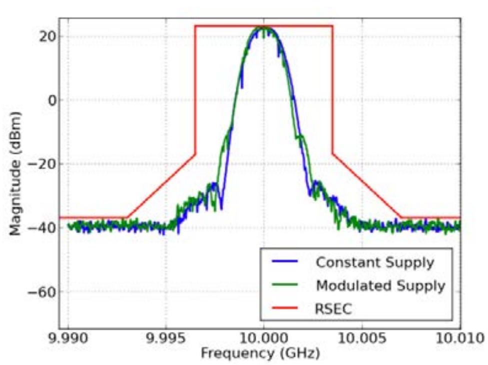

Fig. 6. Measured spectra for both driven and supply modulated 5-W 10-GHz MMIC PA using a resonant supply modulator [8].

Such a supply modulator can be up to 98% efficient, as demonstrated in [8]. When used with a S-band PA, a resonant supply resulted in an improved efficiency as well as reduced spectral spreading. The summary measured data is shown in Fig. 5. A similar resonant supply was coupled to an X-band MMIC amplifier, and resulted in close to 40% average efficiency over the duration of the pulse, with a measured spectrum as shown in Fig. 6, where it is compared to the spectrum of a lower-efficiency directly-driven case [8].

In resonant supplies, the pulse shape is limited in PAR and in duration. In order to be able to change the pulse shape, a high efficient, digitally controlled, multilevel supply modulator was implemented with GaN on Si power devices, as detailed in [9] and was exploited for radar pulse shaping with a 10-W GaN MMIC at 10 GHz as described in [10]. The topology of this supply modulator is described in Fig. 7, along with the entire transmitter setup. This topology enables the binary-coded sum of three input voltage sources, implementing a power-DAC (pDAC) with a discretized output waveform with 8-levels resolution. The direct digital control of the pDAC, along with its wide bandwidth, give complete flexibility in the synthesis of the pulse profile, allowing arbitrary PAR and duration of the transmitted pulse shape.

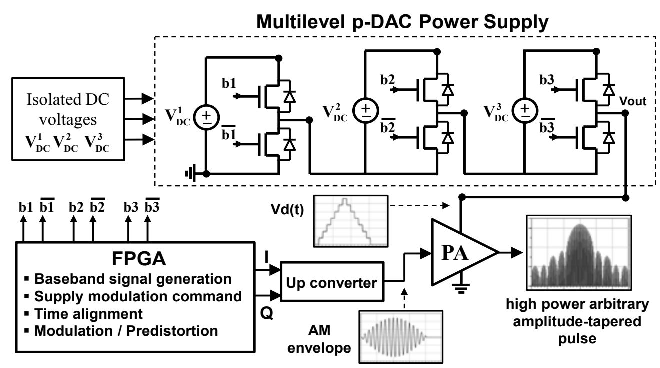

Fig. 7. Block diagram of the radar arbitrary pulse shape transmitter with pDAC supply modulator and an FPGA for signal generation, supply-modulator control and predistortion.

Fig. 8 shows several tested pulse profiles described in detail in [10]: the use of the pDAC allows to operate the desired tapering of the RF output signal with considerable power saving, compared to a traditional rectangular bias pulse. Fig. 9 shows the measured spectrum with a triangular pulse (rectangular pulse as reference). In this case, some digital predistortion (DPD) is required because of the sharp changes in discrete voltage levels of the pDAC. The effectiveness of the DPD, provided by the same FPGA that controls the pDAC (Fig. 7), can be appreciated comparing the two spectra of Fig. 9 (DPD is off in the upper spectrum and on is the lower one). The total average efficiency, including the PA, the supply modulator and the averaging over the pulse, is demonstrated to be over 58% [10].

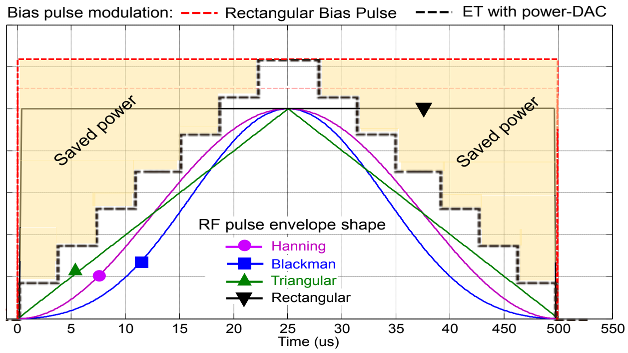

Fig. 8. Several pulse profiles tested with the pDAC transmitter setup: the discretized shape of Vd(t) synthesized by the pDAC enables power saving (light yellow area) with respect to rectangular bias pulse.

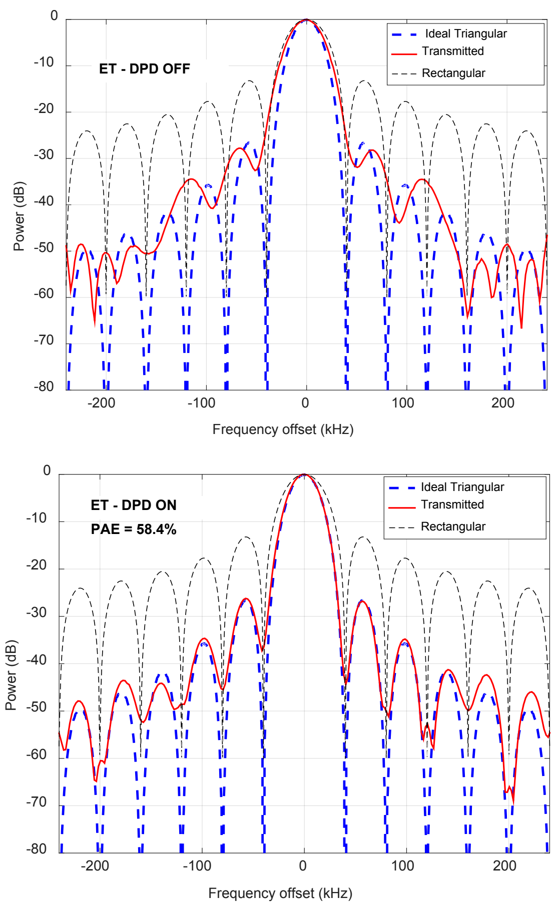

Fig. 9. Measured spectra with an 8-level discrete supply modulator resulting in >58% total efficiency for an X-band 10-W MMIC PA

In summary, this paper presents an overview of supply modulation for Gaussian-type amplitude modulated radar pulses, which allows for reduced spectral emissions, while the supply modulation maintains high. Other interesting future topics include pulse-to-pulse modulation in addition to amplitude modulation at each pulse level.

IV. Acknowledgments

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References

[1] M. Skolnik, Radar Handbook (Third Edition). McGraw-Hill, 2008

[2] J. A. J. de Graaf, et al. “Generation of spectrally confined transmitted radar waveforms: Experimental results,” *2006 IEEE Conf. Radar*, Apr. 2006.

[3] C. Baylis, et al. “Solving the spectrum crisis: Intelligent, reconfigurable microwave transmitter amplifiers for cognitive radar,” *IEEE Microw. Mag.*, vol. 15, no. 5, pp. 94–107, July 2014.

[4] R. Chen and B. Cantrell, “Highly bandlimited radar signals,” in *Proc. IEEE Radar Conference*, 2002., 2002, pp. 220–226.

[5] D. Kimball, et al. “High-efficiency envelope-tracking W-CDMA basestation amplifier using GaN HFETs,” *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 11, pp. 3848–3856, Nov 2006.

[6] M. Roberg, et al., “Efficient and linear amplification of spectrally confined pulsed am radar signals," *Microwave and Wireless Components Letters, IEEE*, vol. 22, no. 6, pp. 279-281, june 2012.

[7] M. Rodriguez, et al., “Resonant Pulse-Shaping Power Supply for Radar Transmitters," *IEEE Trans. Power Electronics*, pp. 707-718, Feb. 2014.

[8] A. Zai, et al. "Supply-Modulated Radar Transmitters With Amplitude-Modulated Pulses," in *IEEE Trans. on Microwave Theory and Techniques,* vol.63, no. 9, pp. 2953-2964, Sept. 2015.

[9] C. Florian, et al. “Envelope Tracking of an RF High Power Amplifier With an 8-Level Digitally Controlled GaN-on-Si Supply Modulator”, *IEEE Trans. Microwave Theory Techn.,* vol. 63, issue 8, pp. 2589-2602, Aug. 2015.

[10] C. Florian, T. Cappello, D. Niessen, R. P. Paganelli, S. Schafer, Z. Popovic, “Efficient Programmable Pulse Shaping for X band GaN MMIC Radar Power Amplifiers,” submitted to *IEEE Transaction on Microwave Theory and Techniques*.