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Transmitter Passband Requirements for Imaging Radar

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Abstract

In high-power microwave power amplifiers for radar, distortion in both amplitude and phase should generally be expected. Phase distortions can be readily equalized. Some amplitude distortions are more problematic than others. In general, especially for SAR using LFM chirps, low frequency modulations such as gain slopes can be tolerated much better than multiple cycles of ripple across the passband of the waveform.

Acknowledgements

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Contents

Foreword 6
1 Introduction & Background 7
2 Discussion 9
2.1 Ideal Power Amplifier Passband 9
2.2 Non-Ideal Power Amplifier Passband 11
2.2.1 Passband Ripple 11
2.2.2 Passband Gain Slope 11
3 Summary and Conclusions 15
References 17
Distribution 18

Foreword

This report details the results of an academic study. Any resemblance to any modes, methodologies, or techniques employed by any operational system is purely coincidental, and not intended by the author.

The specific mathematics and algorithms presented herein do not bear any release restrictions or distribution limitations.

This distribution limitations of this report are in accordance with the classification guidance detailed in the memorandum “Classification Guidance Recommendations for Sandia Radar Testbed Research and Development”, DRAFT memorandum from Brett Remund (Deputy Director, RF Remote Sensing Systems, Electronic Systems Center) to Randy Bell (US Department of Energy, NA-22), February 23, 2004. Sandia has adopted this guidance where otherwise none has been given.

This report formalizes preexisting informal notes and other documentation on the subject matter herein.

1 Introduction & Background

Conventional radar systems, including conventional imaging radar systems like Synthetic Aperture Radar (SAR) require transmitting a known waveform, and then recording and processing echoes from a target. The same is true for Ground Moving Target Indicator (GMTI) systems, where although an image is not often an output data product, an image-like range-velocity map is still an intermediate data product. Physics demands that the transmitted signal contain sufficient energy for its echo to successfully compete with inherent noise. The relationship of various radar parameters to Signal-to-Noise Ratio (SNR) is calculated via the 'radar range equation'.[1,2]

Nevertheless, practical radar systems require substantial power amplification of the transmitted waveform. This is the job of the radar's 'power amplifier'. While Solid State Power Amplifiers (SSPAs) at microwave frequencies are becoming more capable, high-power microwave amplifiers are still a bastion of vacuum tube technology, particularly the Traveling Wave Transmit Amplifier (TWTA).

The general desire is that the power amplifier faithfully reproduces its input signal, only with higher power. The power amplifier characteristics, particularly its passband characteristics, can have a profound impact on the quality of radar data products, such as a SAR image. Radar systems tend to implement a matched filter as nearly as is practicable, in order to maximize signal detectability. The output of a matched filter is characterized by its Point Spread Function (PSF), also known as its Impulse Response (IPR). System nonlinearities distort the IPR.[3] Distortion is generally undesired, although some distortions may be more tolerable than others. That is, some distortions will affect the IPR more adversely than others. This distortion tolerance is often counter-intuitive, as it must take into consideration the waveform that is to be transmitted. Consequently, the radar power amplifier needs to have characteristics that do not substantially degrade the IPR of the overall SAR/GMTI system.

A popular radar waveform is the Linear Frequency Modulated (LFM) chirp signal. This waveform is heavily used in high-performance radar systems, including SAR/GMTI systems. An attractive feature of this waveform is that the modulation is entirely with the phase of the signal, and not its amplitude. This is attractive because typical power amplifiers are operated in compression to maximize their power output. Consequently, while phase modulation is preserved, amplitude modulation is not. Although we will presume henceforth the employment of a LFM chirp signal, we recognize that the fundamental concepts herein are also applicable to other waveforms as well.

The remainder of this report will discuss power amplifier passband characteristics and their influence on radar IPR.

"Experience is that marvelous thing that enables you to recognize a mistake when you make it again."

Franklin P. Jones

2 Discussion

2.1 Ideal Power Amplifier Passband

For its duration, the LFM chirp pulse ideally has constant amplitude and quadratic phase with time. This imparts a linear frequency ramp during the pulse. We shall presume the relatively typical case of a large time-bandwidth product waveform. This causes the energy spectrum to be nearly rectangular in magnitude.

Consequently, a matched filter to this LFM waveform will also exhibit a rectangular magnitude.

The IPR of the ideal waveform (in fast-time, normally associated with radar range) will be the autocorrelation function of the ideal waveform, namely exhibiting a sinc(x) or $\sin(\pi x)/\pi x$ characteristic, especially in the vicinity of the IPR peak or mainlobe. This is illustrated in Figure 1. Recall that the autocorrelation function is the Fourier Transform of the Energy Spectrum.

As one might expect, the IPR exhibits sidelobes as high as –13 dBc. These sidelobes can mask low level phenomena, and are typically suppressed in radar signal processing by employing sidelobe filtering via window functions in the frequency domain. Figure 2 shows the results of applying a window function for sidelobe suppression.

In any case, Figure 1 and Figure 2 presume that the waveform is amplified and transmitted without distortion, that is, with no additional spectral shaping such as ripple or gain roll-off.

Note that by using a window function, as we might expect, the mainlobe of the IPR has widened. However this is acceptable since in analyzing distortion effects we are generally more interested in anomalies in the sidelobe structure away from the mainlobe.

Note also that for a LFM chirp waveform, the signal is a swept frequency across some bandwidth. This means that any frequency-dependent distortion also becomes a time-dependent distortion. For example, a passband ripple becomes an amplitude modulation in time.

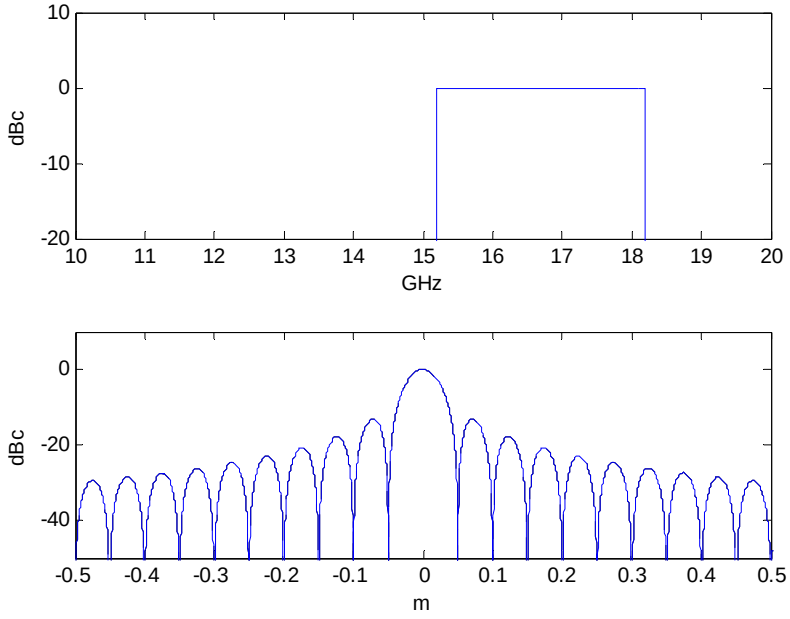

Figure 1. The top figure shows a rectangular spectrum characteristic of a large time-bandwidth product LFM chirp, with 3 GHz bandwidth centered at 16.7 GHz. The bottom figure shows the magnitude of the autocorrelation function of the waveform, or equivalently the IPR magnitude of the waveform.

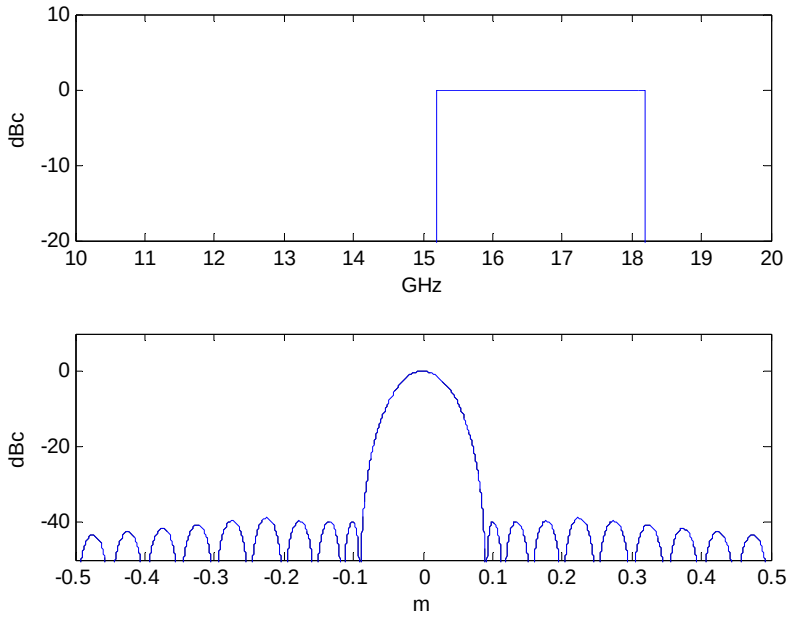

Figure 2. The top figure shows the same rectangular spectrum of Figure 1. The bottom figure shows the IPR magnitude of the waveform after sidelobe mitigation by using a –40 dB Taylor window with nbar=4.

2.2 Non-Ideal Power Amplifier Passband

High-power microwave power amplifier design and construction is a difficult endeavor, requiring highly specialized skills, and entails complicated performance parameter compromises. This also extends to the high voltage power supplies required of TWTA amplifiers. Invariably the power amplifier subsystem will distort the waveform during its amplification. Indeed these amplifiers are often designed to operate in compression, but in addition will exhibit passband ripple and gain roll-off. We now examine the effects of these distortions on the radar system IPR.

First, however, we acknowledge that distortion will occur generally both in amplitude and phase. Of these, the phase errors can be fairly easily corrected by characterizing the distortion, and predistorting the LFM waveform phase in the opposite direction, such that the net effect is a compensated waveform exhibiting ideal phase characteristics. This is also called phase equalization, and works quite well. Applying a similar strategy to amplitude distortion is generally not viable, since the power amplifier is typically operated in compression, that is, not in a linear manner.

2.2.1 Passband Ripple

A LFM waveform transmogrifies a passband ripple into a time-domain amplitude modulation. As communication theory suggests, sidebands (sidelobes) will be generated whose amplitude depends on the ripple magnitude, and position with respect to the mainlobe will depend on the number of ripple cycles across the bandwidth of the signal.[4]

Figure 3 shows 1 dB peak-to-peak ripple with 6 cycles across the waveform bandwidth.

Figure 4 shows 1 dB peak-to-peak ripple with 2 cycles across the waveform bandwidth.

In general, near-in sidelobes are less objectionable than far-out sidelobes.

2.2.2 Passband Gain Slope

Gain slope can be considered a low-frequency modulation. A such we can expect its effects on the IPR to be near-in to the mainlobe. Furthermore, we should be able to tolerate a greater gain variation than an equivalent amount of ripple.

Figure 5 shows a linear (in dB) gain slope with 3 dB of gain variation.

Figure 6 shows a linear (in dB) gain slope with 10 dB of gain variation.

Clearly, even a substantial gain slope will yield virtually negligible degradation of the IPR.

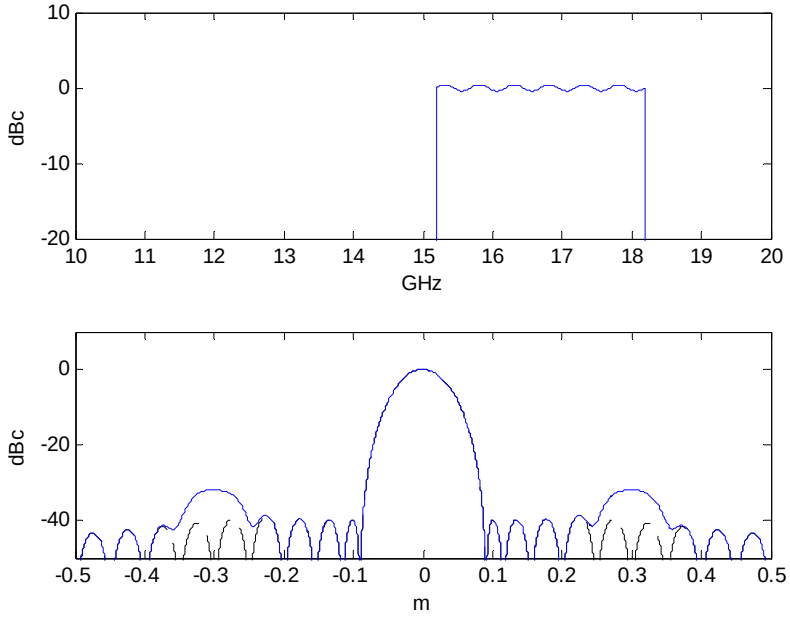

Figure 3. Signal magnitude spectrum and IPR for 6 cycles of 1 dB peak-to-peak sinusoidal ripple. Sidelobes are elevated to – 32 dBc. Ideal response is represented by dashed lines.

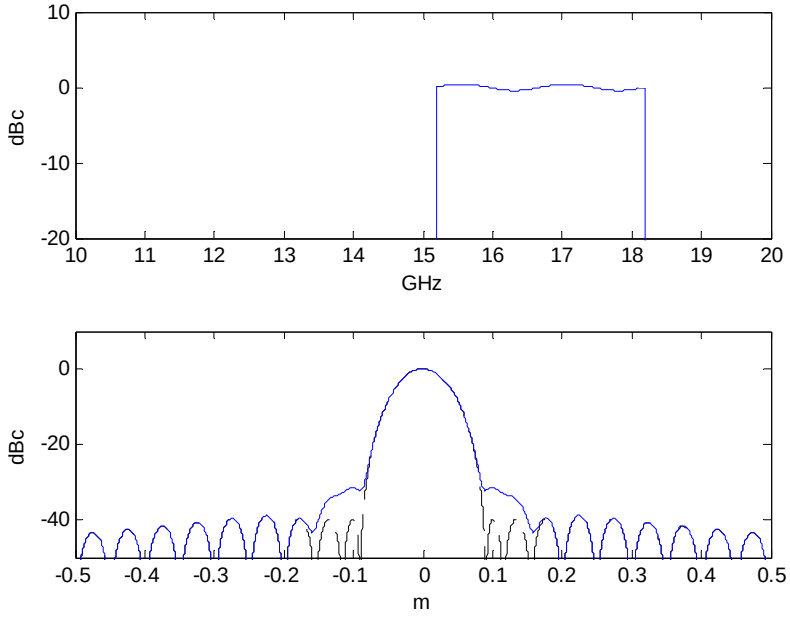

Figure 4. Signal magnitude spectrum and IPR for 2 cycles of 1 dB peak-to-peak sinusoidal ripple. Sidelobes are elevated to – 31 dBc. Ideal response is represented by dashed lines.

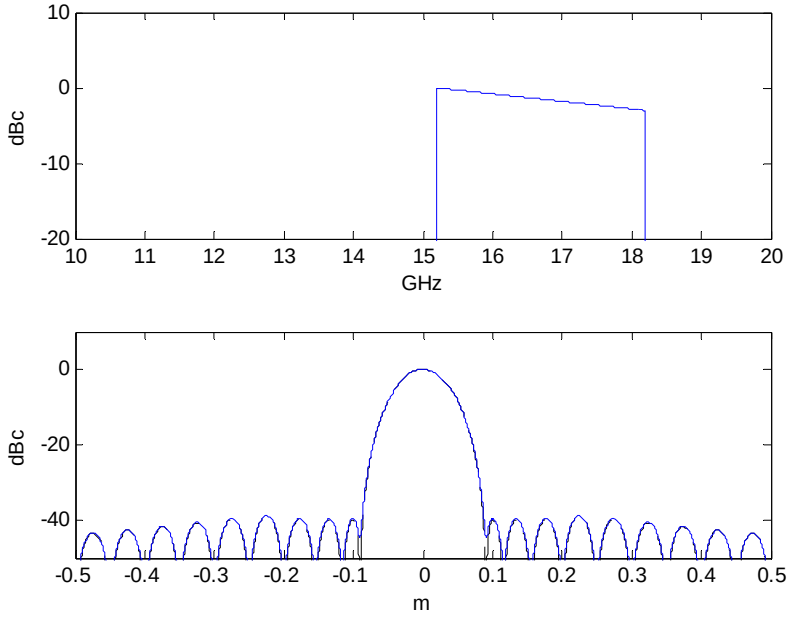

Figure 5. Signal magnitude spectrum and IPR for linear (in dB) gain slope with 3 dB gain variation. Ideal response is represented by dashed lines.

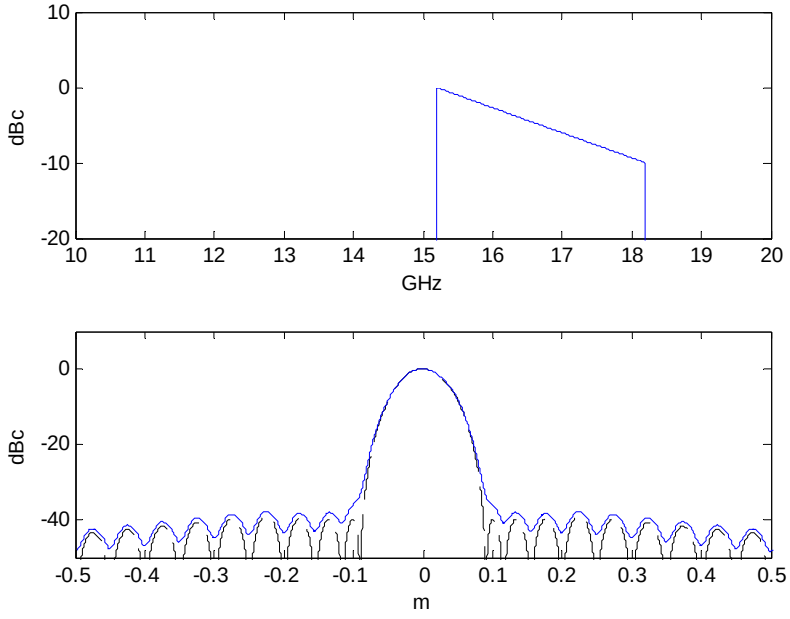

Figure 6. Signal magnitude spectrum and IPR for linear (in dB) gain slope with 10 dB gain variation. Ideal response is represented by dashed lines.

“I'm a great believer in luck, and I find the harder I work the more I have of it.”

Thomas Jefferson (1743 - 1826), (attributed)

3 Summary and Conclusions

In high-power microwave power amplifiers for radar, distortion in both amplitude and phase should generally be expected. Phase errors can be corrected via waveform predistortion or equalization. Amplitude distortions are not as easily mitigated.

Some amplitude distortions are more problematic than others. In general, especially for SAR/GMTI using LFM chirps, low frequency modulations such as gain slopes can be tolerated much better than multiple cycles of ripple across the passband of the waveform. This is at odds with amplifier requirements in other applications.

These effects and their significance are readily observed in the calculated IPR corresponding to the distorted waveform. This suggests the IPR calculation as the appropriate measure for acceptable power amplifier performance for SAR/GMTI systems.

“Everything should be made as simple as possible, but not one bit simpler.”

Albert Einstein (1879 - 1955), (attributed)

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[1] A. W. Doerry, "Performance Limits for Synthetic Aperture Radar – second edition", Sandia Report SAND2006-082, Unlimited Release, February 2006.

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[3] Armin W. Doerry, "Anatomy of a SAR Impulse Response", Sandia report SAND2007-5042, Unlimited Release, August 2007.

[4] R. E. Ziemer, W. H. Tranter, *Principles of Communications – Systems, Modulation, and Noise*, Fourth Edition, ISBN 0-471-12496-6, John Wiley & Sons, Inc., 1995.

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