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Frequency-Dependent Blanking with Digital Linear Chirp Waveform Synthesis

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Abstract

Wideband radar systems, especially those that operate at lower frequencies such as VHF and UHF, are often restricted from transmitting within or across specific frequency bands in order to prevent interference to other spectrum users. Herein we describe techniques for notching the transmitted spectrum of a generated and transmitted radar waveform. The notches are fully programmable as to their location, and techniques are given that control the characteristics of the notches.

Acknowledgements

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Contents

Foreword

This report details the results of an academic study. It does not presently exemplify any operational systems with respect to modes, methodologies, or techniques.

Classification

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

Radar systems often modulate their pulses to achieve both wide bandwidths for fine range resolution, and long pulses to maximize pulse energy and hence received Signal to Noise Ratio (SNR).

For ever finer resolutions, the radar signal requires ever larger bandwidths. Radar frequency bands are chosen to facilitate some advantage to the immediate mission, such as perhaps foliage or even ground penetration at the lower frequencies (UHF and lower) to long-range operation through adverse weather at lower microwave frequencies, to ultra-fine resolutions and narrow antenna beams at frequencies corresponding to millimeter wavelength.

As the necessary operational bandwidth increases, particularly at the lower frequencies, the radar signal must compete with other spectrum users for the specific frequency bands and sub-bands required. This manifests as interference, where the radar may act as both offender and/or victim, depending on the nature of the interference.

Regulatory limits do in fact prohibit some radar systems from transmitting in specific spectral regions. Depending on the spectral interval desired by the radar, the radar may need to ‘notch’ its transmission spectrum so as to mitigate its offense to other radio services and users.

One way to accomplish the required notching is to place electrical filters in the RF transmit signal path. Although such filters may indeed provide an adequate stopband characteristic, they often do so with some undesirable side effects. Typically, they perturb the signal in the passband so as to affect the linearity of the signal channel, thereby adversely affecting the ability of the radar to properly process the received echo signal. More specifically, they interfere with pulse compression processing, thereby adversely affecting the Impulse Response (IPR) of the processed radar data. In addition, such filters are generally not programmable, thereby limiting the ability to adjust the spectral notch characteristics to the requirements of a new locale or changing environment.

Another technique is to employ an Arbitrary Waveform Generator (AWG) for which a waveform can be created with built-in spectral notches. Essentially a general purpose processor of some sort would calculate the time samples of a desired waveform and store them in a local memory. At the time the waveform is required, the memory would be accessed and contents supplied to a Digital-to-Analog Converter (DAC). Such a system would indeed be fully programmable. The drawback is that the calculations might be fairly complex and/or require modification or updating from one pulse to the next, due perhaps to motion compensation for an airborne radar, thereby requiring prohibitive computational resources.

One technique for generating radar data while avoiding transmission in specific frequency intervals is employing a pulse modulation scheme where the total number of pulses is divided into contiguous groups of pulses, where each pulse within a group offers a small spectral width, but different center frequency. Any one pulse group, taken as a group, covers the entire required frequency spectrum except that notches are accomplished by omitting the particular pulse that would otherwise have generated energy in the forbidden spectral interval, or sub-band.

One popular mechanism for generating radar waveforms is a parametric waveform synthesizer. Such a Waveform Synthesizer (WFS) typically makes use of custom hardware to synthesize a required waveform, such as perhaps a Linear Frequency Modulated (LFM) chirp. The LFM chirp is a widely-used popular waveform with attributes well reported in the literature. The custom hardware to generate this may in fact be a specific design in a Field Programmable Gate Array (FPGA). Such a design might allow easy modification of waveform parameters to facilitate waveform length and bandwidth to the specific radar data collection requirements at hand. The advantage of a LFM chirp is that its spectral content is derived from an instantaneous frequency that sweeps with time.

We note that the correspondence of frequency to time for an LFM chirp allows a WFS to implement frequency-dependent corrections to the waveform by implementing time-dependent corrections. Such corrections might include equalizing radar phase responses and/or single-sideband mixer anomalies in the case of a WFS that generates quadrature signals.

Such LFM chirp generating WFS, along with phase error correction capabilities, are reported in the literature and in a patent.[1,2,3,4] A Quadrature WFS is also described in the literature and in several patents.[5,6,7,8,9,10]

Furthermore, for such signals, a frequency notch can be accomplished by a ‘time notch’. That is, by disabling the WFS output at a particular time for a particular interval during the chirp generation, a frequency notch is generated. Such a notch is completely controllable and programmable.

Conventionally, disabling the output of the WFS has been proposed to be accomplished by either literally switching off the signal path downstream from the WFS signal generator, or by disabling the DAC in some fashion. This approach is undesirable because switching speeds for the required components becomes problematic. Effecting a notch in the signal prior to the DAC is thus advantageous.

What is required is the ability to readily program frequency notches within the popular LFM chirp waveform generation process within the WFS itself. Furthermore, we desire to avoid switching speed issues by in turn avoiding any external (to the WFS) signal switching, or disabling the DAC. Furthermore yet, the waveform must preserve phase linearity outside of the notch.

2 Overview & Summary

We propose herein to modify the logic circuits that generate a parametric LFM chirp to include a programmable Look-Up Table (LUT) that monitors the instantaneous chirp frequency, and outputs an indication of whether that frequency is to be either passed or notched.

If the frequency is passed, then the phase of the chirp is passed to the Sin Read-Only Memory (ROM) for conversion to the desired waveform instantaneous amplitude. This ROM essentially converts phase to instantaneous amplitude of a sinusoid.

If the frequency is notched, then we interrupt the signal path in at least one of the following locations.

1. At the output of the Sin ROM, the amplitude word that is applied to the DAC is substituted with another that causes a zero signal level at the DAC output, thereby disabling the waveform for the duration of the notch.

2. At the input to the Sin ROM, the phase of the chirp is substituted with another that causes the Sin ROM to select a phase that causes the DAC instantaneous output to go to a zero signal level, thereby disabling the waveform for the duration of the notch.

To preserve phase linearity across the notch, the LFM chirp generator continues to update in the background, generally unaware whether its output is being passed to the Sine ROM and/or ultimately to the DAC or not.

Furthermore, the depth of the notch can be significantly improved in a statistical sense by randomly modulating the spectral location of the transitions between signal and notch.

Alternatively, in some systems, the notch may be implemented with a controlled gradual transition between 'on' and 'off' to similarly control notch depth.

“I don't think there is anything wrong with white space. I don't think it's a problem to have a blank wall.”-- Annie Leibovitz

3 Detailed Discussion

3.1 Basic LFM Chirp Synthesis

Conventionally, a LFM chirp may be implemented with a double-accumulator architecture, as shown in Figure 1. Recall that an accumulator is the digital equivalent of an integrator.

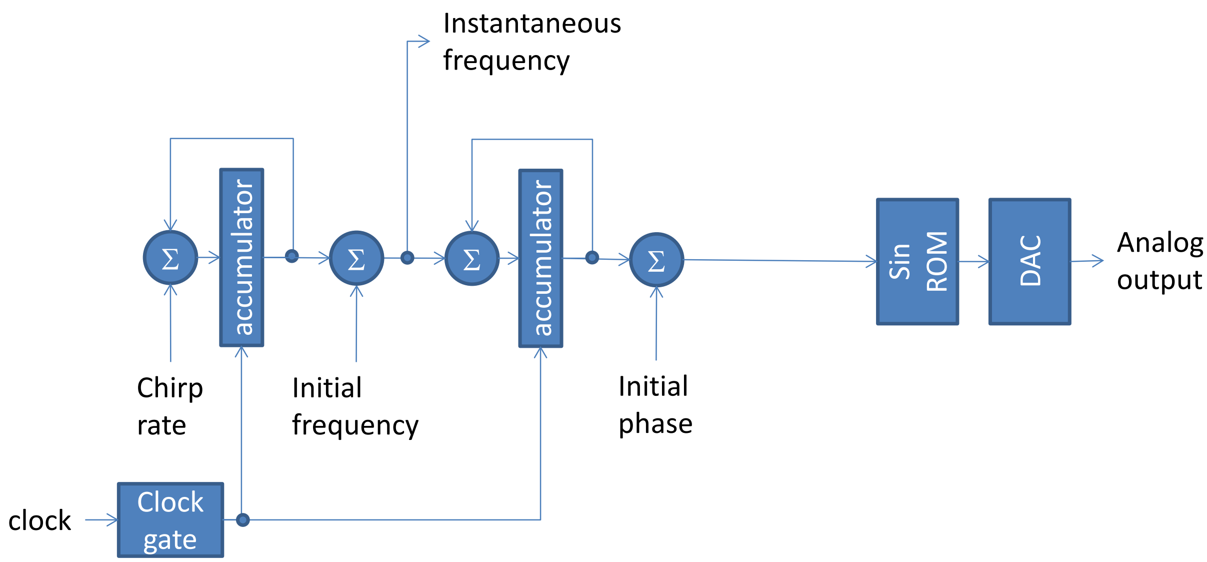

Figure 1. Double-accumulator architecture for LFM chirp generator.

In this architecture, the accumulators begin with being reset to empty, or zero. When the clock gate is enabled, the first accumulator begins to recursively add a constant chirp rate value. The accumulated value is in fact a frequency offset indication. This frequency offset is added to an initial frequency input to yield an instantaneous frequency, and then applied to the second accumulator which recursively adds the frequency value to therewith calculate a phase offset value. This phase offset value is added to an initial phase input. The resulting instantaneous phase value is converted to an instantaneous amplitude by the Sin ROM. This Sin ROM may be a simple lookup table, or may involve a more sophisticated calculation algorithm. The specific implementation is immaterial to this description. In any case, the Sin ROM output is applied to a DAC to generate an instantaneous analog signal. This process continues until the full pulse waveform is generated, at which time the clock gate is disabled, and the process repeats for the next pulse or other operation. Details for generating precision LFM chirps in this manner are discussed in a paper by Doerry, et al.[3]

The instantaneous frequency may be employed to further modify the characteristics of the output signal. For example, the instantaneous frequency may be employed to implement a frequency dependent phase error correction to equalize the subsequent RF signal channel. This is illustrated in Figure 2.

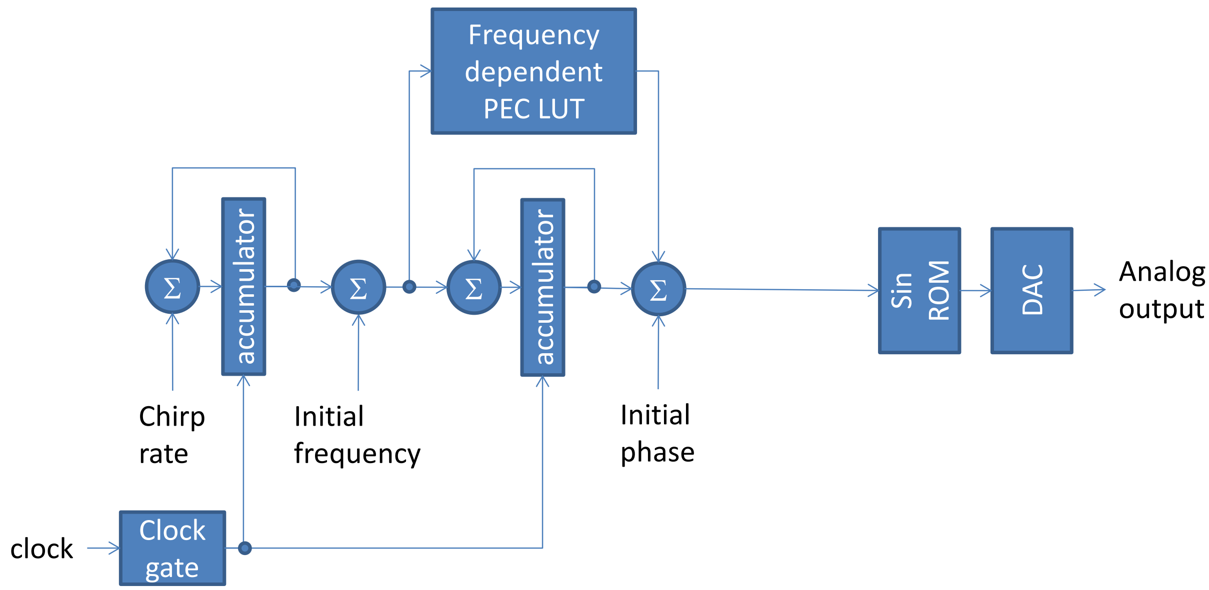

Figure 2. LFM chirp generator with frequency-dependent phase error correction.

While these examples so far have been for single-ended WFS, we can also generate a quadrature WFS capable of providing outputs for a Single-Sideband (SSB) mixer. Such a WFS is capable of double the signal bandwidth of a single-ended WFS, albeit at the cost of some increased complexity. A quadrature WFS architecture is illustrated in Figure 3. Although this figure illustrates a common Phase-Error-Correction (PEC) LUT for both output channels, separate LUTs for each of the output channels (or equivalent) would allow correcting differential channel errors as well, particularly those often manifesting in downstream SSB analog mixers.

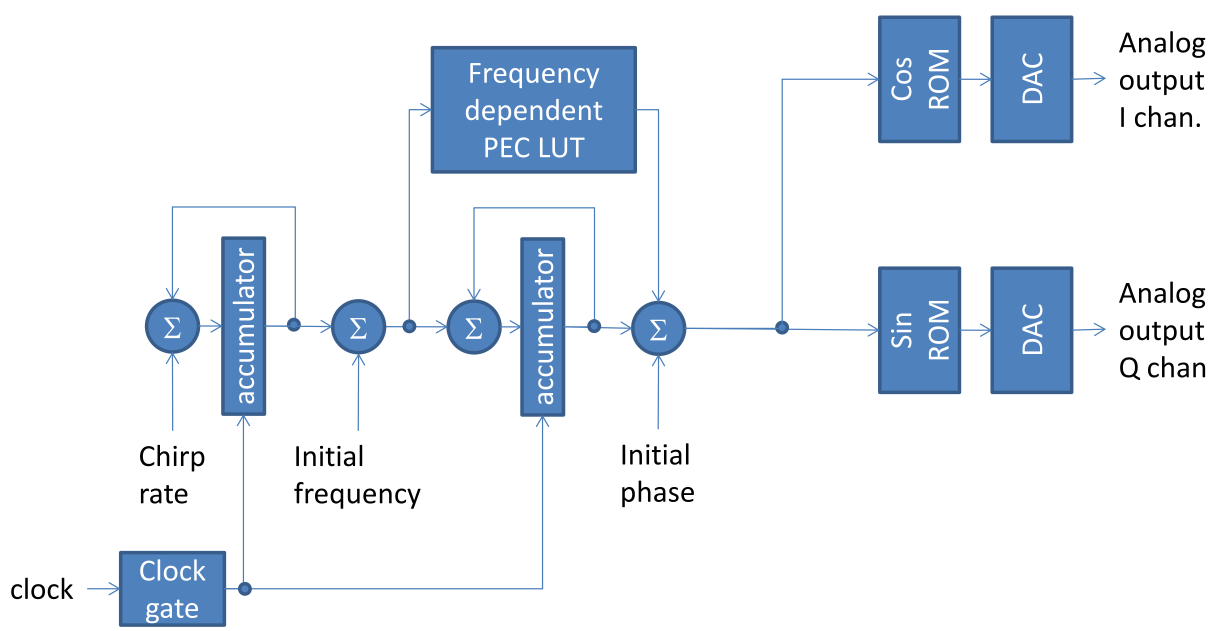

Figure 3. Quadrature LFM chirp generator with frequency-dependent phase error correction.

3.2 Spectral Notch Generation

Since the LFM chirp signal corresponds instantaneous frequency with time, any instantaneous frequency exists only once during an LFM waveform. Consequently, a LUT dedicated to the task of indicating which frequencies should be blanked, or notched, is readily constructed.

Furthermore, we note that the ROMs that convert phase to amplitude will each have at least one phase for which the output amplitude will be zero. For example, we observe that

$$\begin{aligned}&\sin(0) = 0 \text{, and}\\&\cos(\pi/2) = 0 \text{.}\end{aligned} \quad (1)$$

We shall assume that the Sin ROM implements the trigonometric sin() function, and the Cos ROM implements the trigonometric cos() function.

Nevertheless, a frequency notch can be created by either of the following two methods

1. Switching the DAC input to an alternate constant-amplitude input for each frequency for which a notch is desired. Any constant amplitude will effect a notch, but only a zero output will avoid adding a DC bias to the analog output signal. For a single-ended output, such a notch-generating modification to the WFS is illustrated in Figure 4. For a quadrature output, with both Sin and Cos ROMs, such a notch-generating modification to the WFS is illustrated in Figure 5.

2. Switching the Sin ROM input to an alternate constant phase input for each frequency for which a notch is desired. Any constant phase will effect a notch, but only those that cause a zero output will avoid adding a DC bias to the analog output signal. For a single-ended output, such a notch-generating modification to the WFS is illustrated in Figure 6. For a quadrature output, with both Sin and Cos ROMs, such a notch-generating modification to the WFS is illustrated in Figure 7.

Whether a DC bias to the DAC output signal is problematic depends on the specific RF design after the analog output.

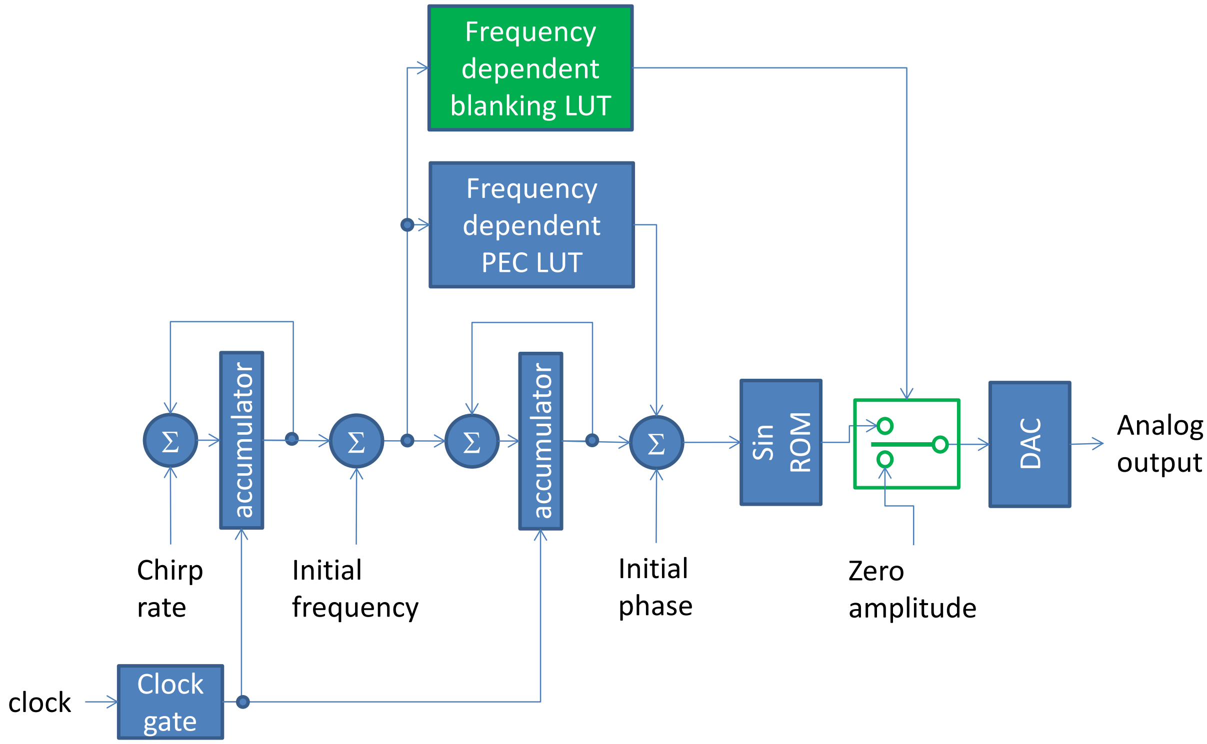

Figure 4. Single-ended LFM chirp generator with notch-generating blanking LUT.

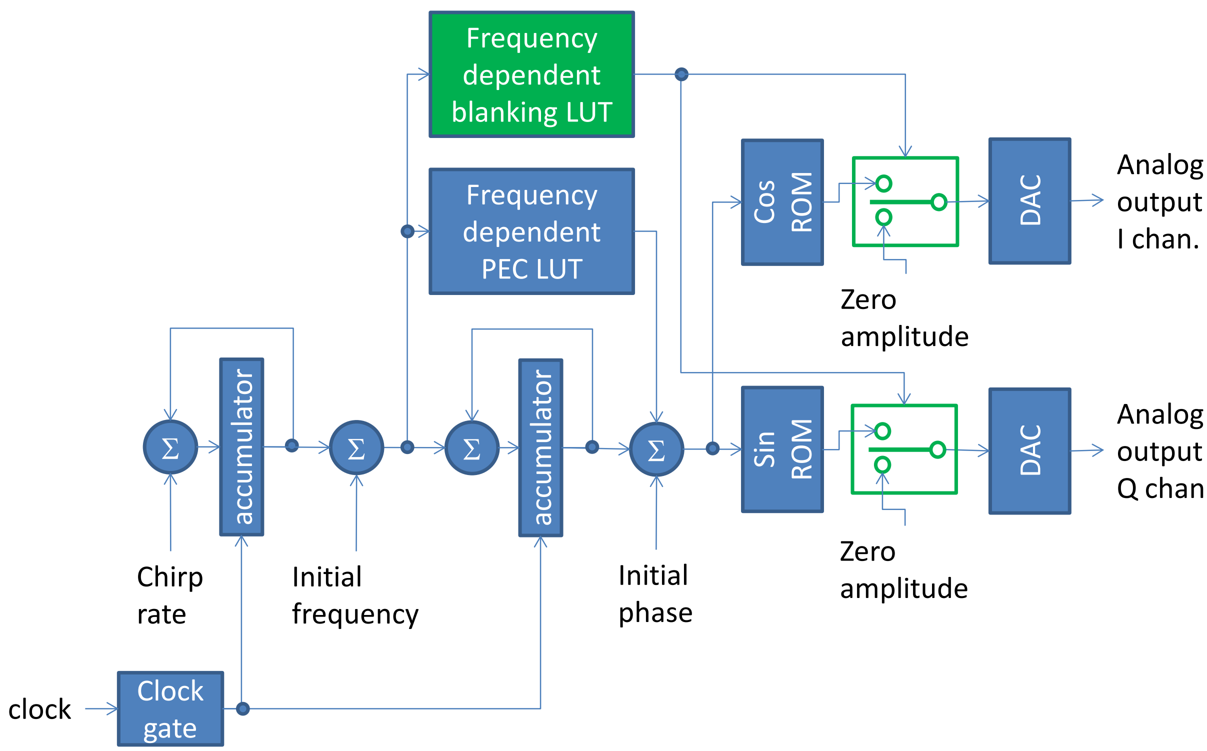

Figure 5. Quadrature LFM chirp generator with notch-generating blanking LUT.

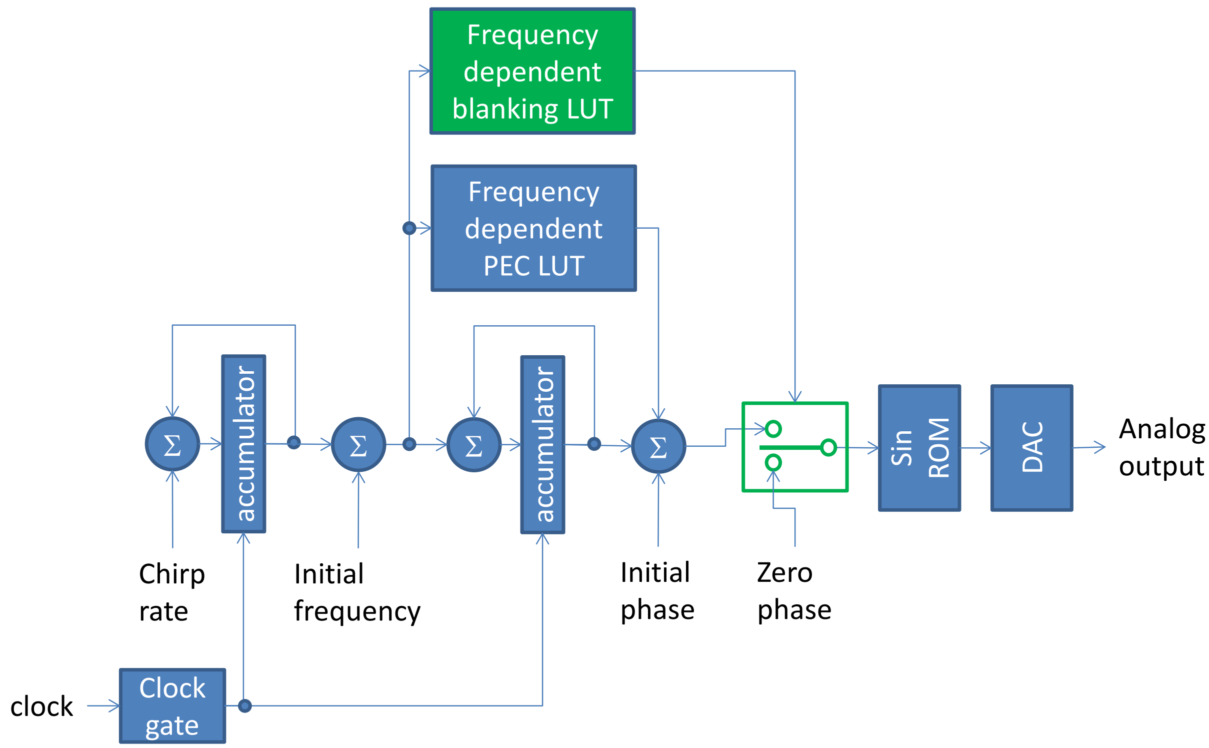

Figure 6. Single-ended LFM chirp generator with notch-generating blanking LUT.

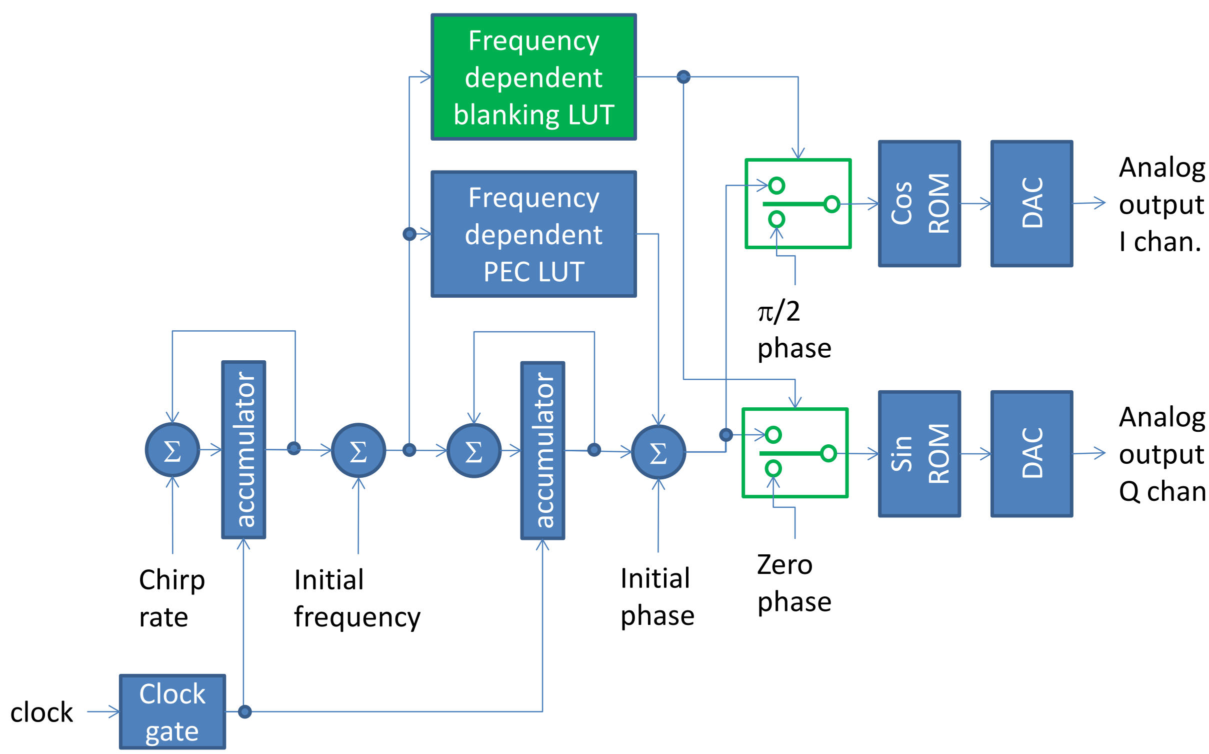

Figure 7. Quadrature LFM chirp generator with notch-generating blanking LUT.

To illustrate the utility of these architectures, we offer the following example.

WFS sampling frequency = 1 GHz
Waveform pulsewidth = 100 us
Waveform center frequency = 250 MHz
LFM chirp bandwidth = 250 MHz

Furthermore, we stipulate the following desired spectral notches

150 MHz to 170 MHz
200 MHz to 210 MHz

We will exemplify the performance of the quadrature phase-switching architecture of Figure 7. However, the other architectures will yield the same results.

Figure 8 illustrates the Blanking LUT values. Figure 9 illustrates when during the generation of the specific waveform the LUT values are accessed and applied to the switches between the chirp generation logic and the Sin (and Cos) ROMs. Figure 10 shows the resulting spectrum. Clearly we have caused the spectral notches that we desired.

As with the spectrum of a notch-free LFM chirp, the slope at the spectrum edges is a function of the time-bandwidth product of the chirp. As pulsewidth or bandwidth increase, the various edges of the waveform and notches will become steeper, and the notches will become deeper.

3.3 Randomizing Notch Edges

If increasing the time-bandwidth product of the chirp is impractical, then an alternate mechanism for deepening the notch, at least in a statistical sense, might be employed. If the desired radar data includes multiple pulses, then the edges of the notches might be modulated in some fashion to deepen the notch.

For example, the band-edge of the notch might be dithered randomly from one pulse to the next. This is illustrated for 10 pulses on the second notch of our example in Figure 11. In this case, the dithering took the form of a random adjustment of the width of the notch, with the adjustment limited to ±0.1% of the sampling frequency. In our example, the notch width was adjusted by ±1 MHz, meaning the edges were adjusted inward or outward by as much as ±0.5 MHz. The resulting mean spectrum is illustrated in Figure 12. Note how the notch depth has been improved substantially.

This would work for any of the architectures of Figure 4 through Figure 7.

Furthermore, this technique is applicable even if the downstream analog signal is substantially compressed, as with many microwave power amplifiers.

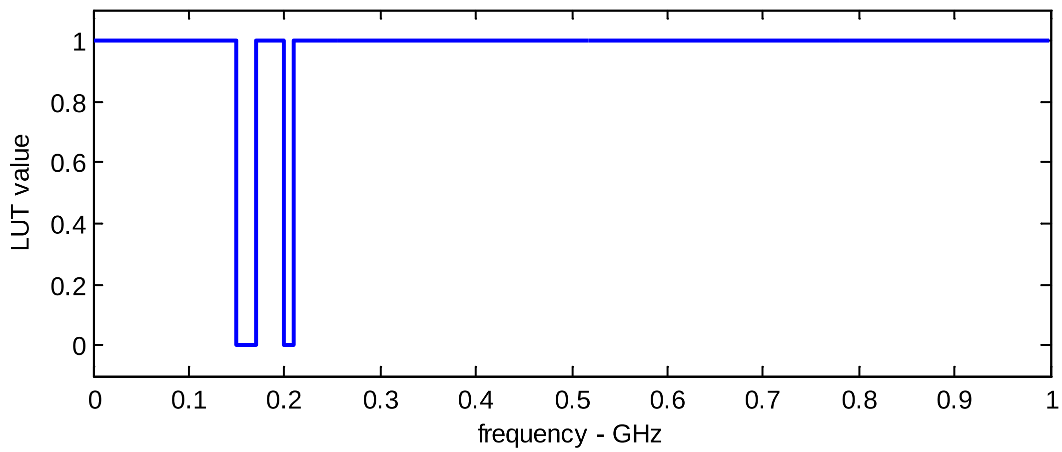

Figure 8. Blanking LUT values as a function of frequency.

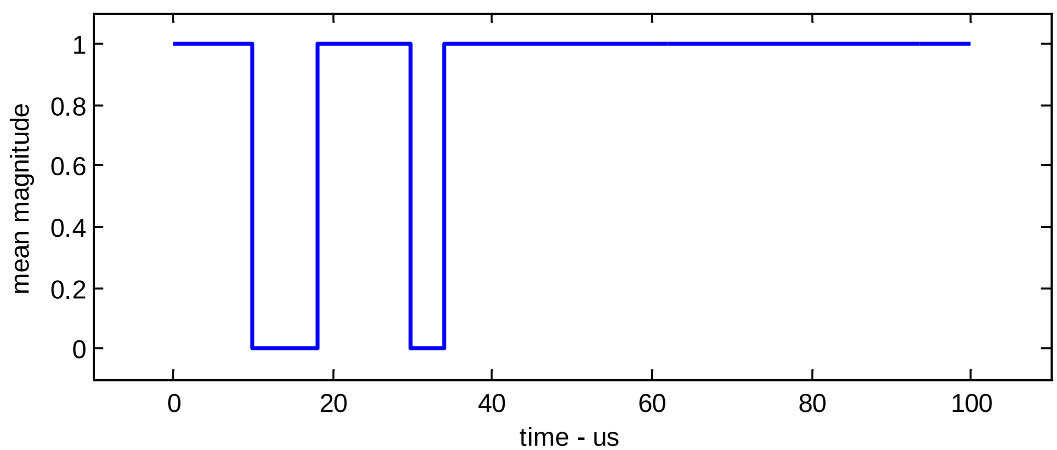

Figure 9. Blanking LUT outputs as a function of time during the waveform.

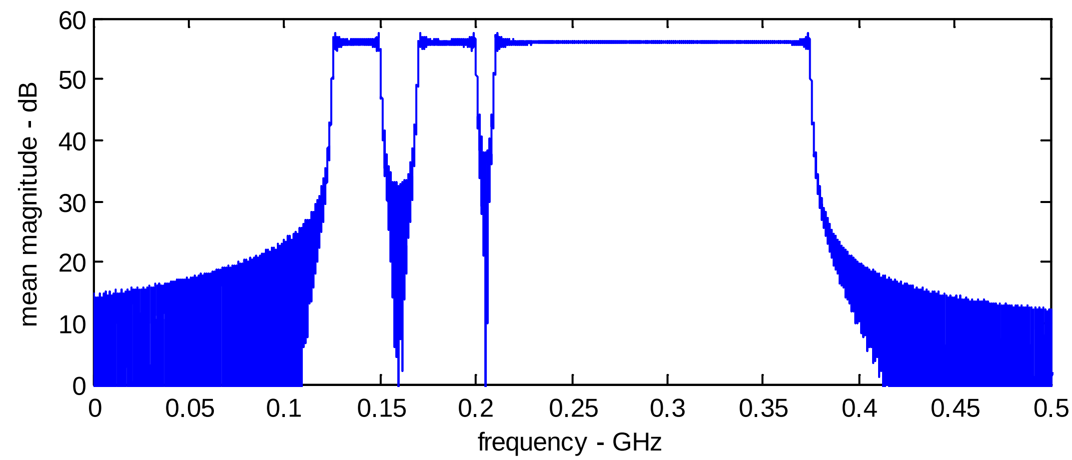

Figure 10. LFM chirp spectrum manifesting spectral notches.

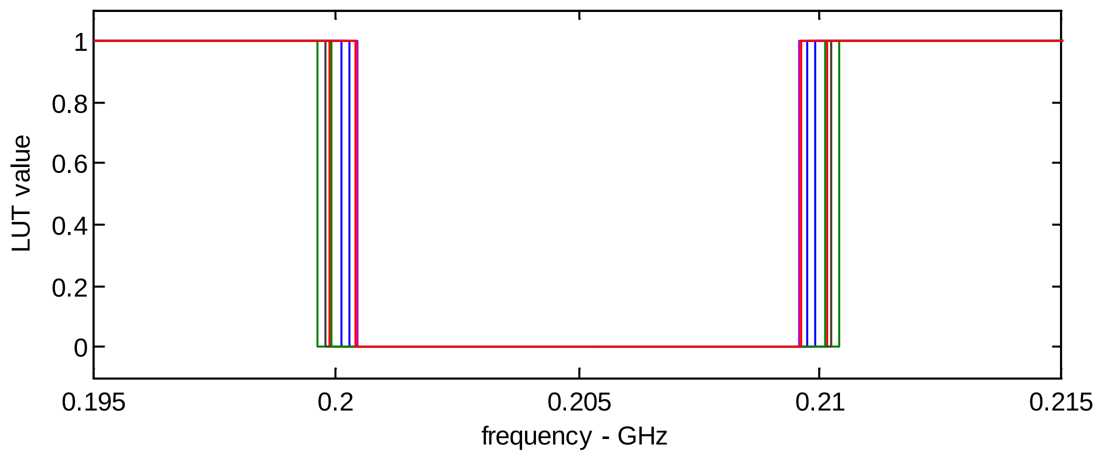

Figure 11. Dithered location of spectral notch edges for 10 pulses.

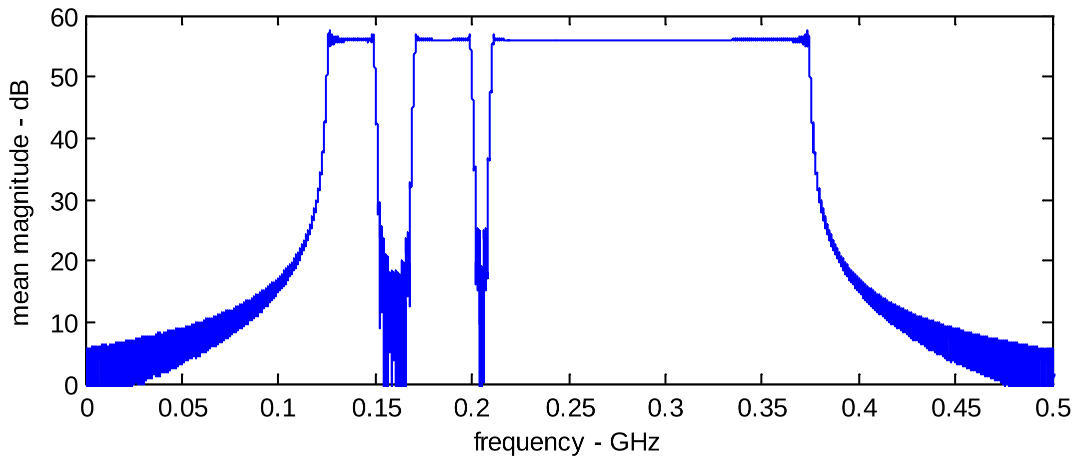

Figure 12. Mean LFM chirp spectrum manifesting spectral notches from 1024 pulses with dithered notches.

3.3.1 Tapered Notch Edges

In some cases, we can improve the notch depth even within a single pulse.

Consider now that the Blanking LUT outputs not merely an on/off indication, but rather an 'amplitude' indication that contains a sampled continuum of values between '0' and '1'. This allows the notches to be specified with gradual transitions between "on" and "off". A single-ended architecture for this is given in Figure 13, and a Quadrature architecture is given in Figure 14.

An example of tapered notch edges for the second notch is given in Figure 15. In this example, the transition region width is set to 0.1% of the sampling frequency, or 1 MHz. The corresponding spectrum is given in Figure 16. Note how the notch depth has been improved substantially from that of sharper edges.

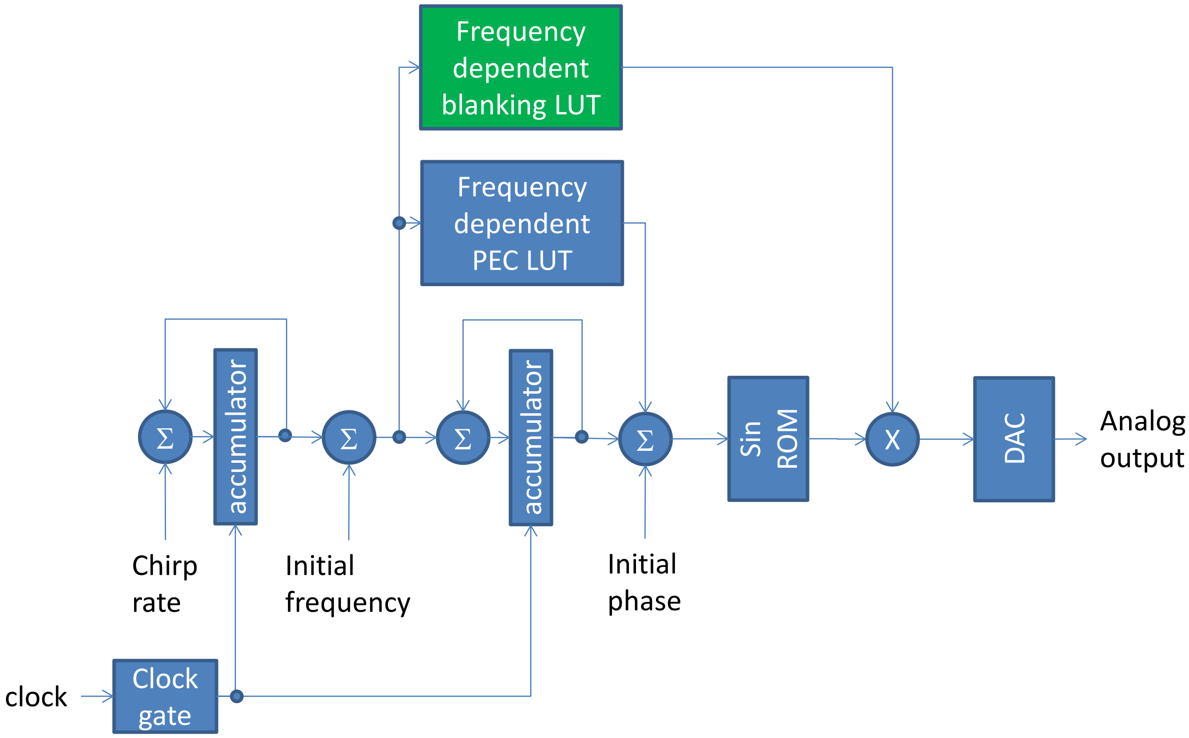

Figure 13. Single-ended LFM chirp generator with notch-generating blanking LUT and amplitude tapering multiplier.

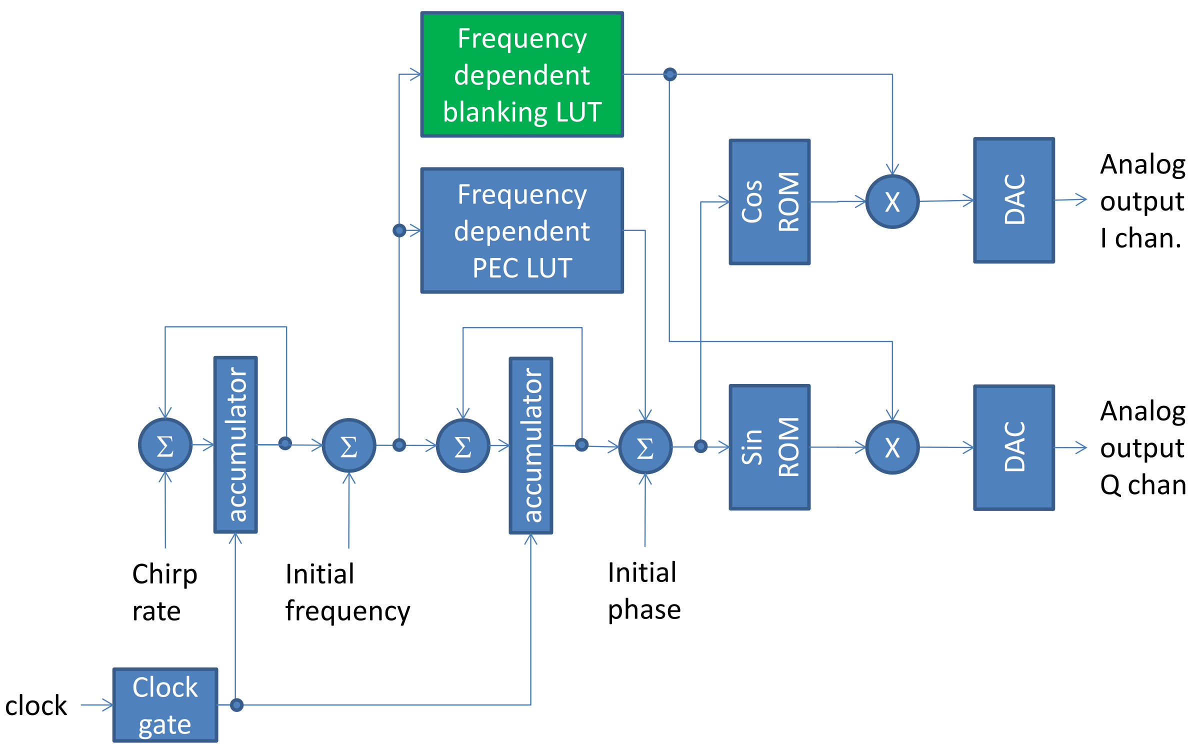

Figure 14. Quadrature LFM chirp generator with notch-generating blanking LUT and amplitude tapering multiplier.

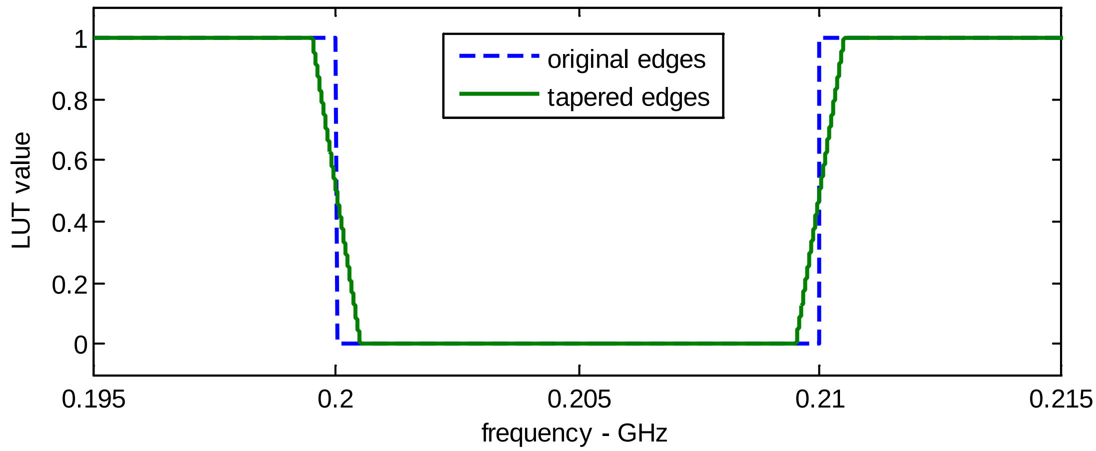

Figure 15. Original and tapered notch edges for second notch.

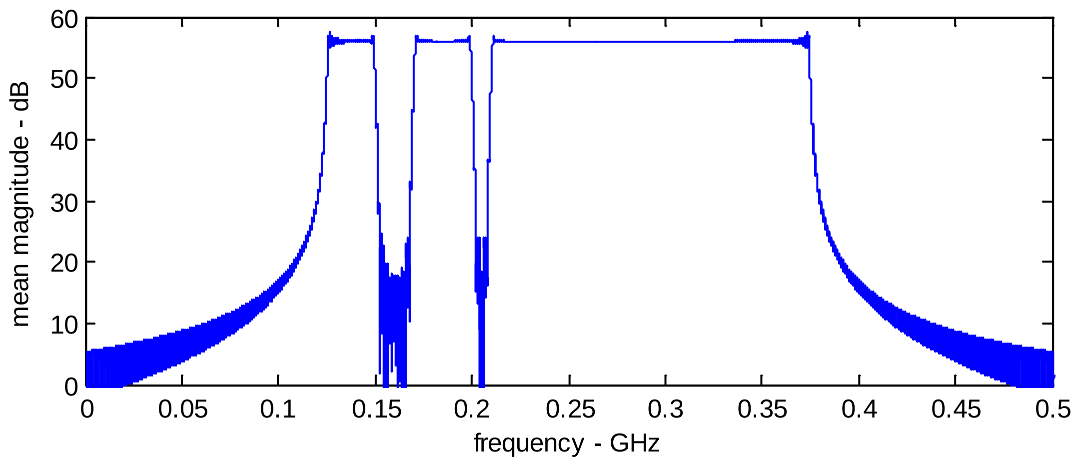

Figure 16. LFM chirp spectrum manifesting spectral notches with tapered edges.

While we have exemplified a linear transition at the notch edges, we note that other transition functions also can be employed with similar results.

However, for this spectrum to be maintained between WFS output and transmitted signal, a tacit assumption is that the analog signal channel is strongly linear, that is, the amplitude scaling holds. Since this spectrum is based on amplitude scaling, any signal path amplitude compression, such as is often exhibited by many components including power amplifiers, will alter the amplitude scaling and thereby alter the spectrum characteristics.

Depending on the specific magnitude compression characteristics exhibited by the analog RF components in the signal path, and the specific notch-edge tapering employed, the notch characteristics might be either degraded or even improved in some cases. One might even consider selecting tapering to specifically compensate subsequent analog component linearity, and achieve a more precise transmitted spectrum.

3.3.2 Extensions

It should be obvious to the radar designer that the basic techniques described herein can be applied to any other waveform for which an instantaneous frequency can be associated with a specific waveform time point or interval. This includes, but is not limited to, Non-Linear FM (NLFM) chirp waveforms,[11,12] constrained random-phase waveforms,[13,14] stepped frequency waveforms, and compound waveforms.[15,16]

“There is no such thing as an empty space or an empty time. There is always something to see, something to hear. In fact, try as we may to make a silence, we cannot.”
-- John Cage

4 Conclusions

The essential elements presented herein include the following.

- Spectral notches can be created by suitable controlling either amplitude or phase as a function of instantaneous frequency.
- This can be implemented as a LUT controlling either a digital amplitude or a phase switch within a multiple-accumulator architecture.
- The notch depth can be controlled by modulating the notch edges from pulse to pulse.
- One suitable modulation scheme is randomizing the notch edges from pulse to pulse.
- The notch depth can also be controlled by controlling the taper of the amplitude modulation.

“The ability to change constantly and effectively is made easier by high-level continuity.”
-- Michael Porter

References

[1] Bruce Walker, Grant Sander, Marty Thompson, Bryan Burns, Rick Fellerhoff, and Dale Dubbert, "A High-Resolution, Four-Band SAR Testbed with Real-Time Image Formation", Proceedings of the 1996 IEEE International Geoscience and Remote Sensing Symposium, IGARSS '96, Vol. 3, pp. 1881-1885, 27-31 May 1996.

[2] Lars Wells, Kurt Sorensen, Armin Doerry, Brett Remund, "Developments in SAR and IFSAR Systems and Technologies at Sandia National Laboratories", Proceedings of the 2003 IEEE Aerospace Conference, Vol. 2, pp. 2_1085-2_1095, 2005.

[3] A. W. Doerry, J. M. Andrews, S. M. Buskirk, "Digital synthesis of linear-FM chirp waveforms – comments on performance and enhancements," SPIE 2014 Defense & Security Symposium, Radar Sensor Technology XVIII, Vol. 9077, Baltimore MD, 5–9 May 2014.

[4] Peter Dudley, Bert Tise, "Multiplexed Chirp Waveform Synthesizer", US Patent 6,614,813, Sep., 2, 2003.

[5] Lars Wells, Armin Doerry, "Synthetic aperture radar: not just a sensor of last resort", Proceedings of the SPIE 2003 International Symposium on Aerospace/Defense Sensing, Simulation, and Controls, Airborne Reconnaissance XXVII, Vol. 5109, pp. 98-109, Orlando FL, 21-25 April 2003.

[6] A. W. Doerry, D. F. Dubbert, "Digital Signal Processing Applications in High-Performance Synthetic Aperture Radar Processing", Conference Record of the IEEE Thirty-Seventh Asilomar Conference on Signals, Systems and Computers, Vol. 1, pp. 947-949, November, 2003.

[7] George R. Sloan, Dale F. Dubbert, "Affordable, miniaturized SAR for tactical UAV applications", Proceedings of the SPIE 2004 International Conference on Airborne Intelligence, Surveillance, Reconnaissance (ISR) Systems and Applications, Vol. 5409, pp. 74-83, August 30, 2004.

[8] Peter A. Dudley, Armin W. Doerry, Dale F. Dubbert, Bertice L. Tise, "Waveform synthesis for imaging and ranging applications", US Patent 6,825,800, November 30, 2004.

[9] Dale F. Dubbert, Peter A. Dudley, Armin W. Doerry, Bertice L. Tise, "Waveform synthesis for imaging and ranging applications", US Patent 6,836,240, December 28, 2004.

[10] Armin W. Doerry, Peter A. Dudley, Dale F. Dubbert, Bertice L. Tise, "Waveform synthesis for imaging and ranging applications", US Patent 6,828,933, December 7, 2004.

[11] Armin W. Doerry, "Generating Nonlinear FM Chirp Waveforms for Radar", Sandia Report SAND2006-5856, Unlimited Release, September 2006.

[12] A. W. Doerry, "Generating precision nonlinear FM chirp waveforms", SPIE 2007 Defense & Security Symposium, Radar Sensor Technology XI, Vol. 6547, Orlando FL, 9-13 April 2007.

[13] Armin W. Doerry, Brandeis Marquette, "Shaping the Spectrum of Random-Phase Radar Waveforms", Sandia Report SAND2012-6915, Unlimited Release, September 2012.

[14] A. W. Doerry, B. Marquette, "Random-phase radar waveforms with shaped spectrum", SPIE 2013 Defense, Security & Sensing Symposium, Radar Sensor Technology XVII, Vol. 8714, Baltimore MD, 29 April – 3 May 2013.

[15] Armin W. Doerry, Brandeis Marquette, "Compound Multi-Frame Radar Waveforms", Sandia Report SAND2012-6965, Unlimited Release, September 2012.

[16] A. W. Doerry, B. Marquette, "Compound radar waveforms with multiple frames", SPIE 2013 Defense, Security & Sensing Symposium, Radar Sensor Technology XVII, Vol. 8714, Baltimore MD, 29 April – 3 May 2013.

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