Double Quadrature Mixer for Adaptive Spur Cancellation in Ultra-Wideband Radios

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Abstract **—Direct Digital Synthesizers (DDS) are known to be very spurious due to the use of Digital-to-Analog Convertors (DAC). This paper presents the phase behavior of spurs of the AD9912 DDS and its SpurKiller cancellation system. A great variation in spur phase and a variation in increased spurious-free dynamic range (SFDR) was observed. As a result, an adaptive system is proposed using a Double Quadrature Mixer and a variable phase LO. The system is tested at the Intermediate Frequency (IF) of 1.2 GHz, simulating an Ultra-Wideband (UWB) radio. In simulation, an increase in SFDR of 29 dB resulted. In system prototype, an increase in SFDR of 10 dB resulted.**

Index Terms- Signal synthesis, interference, cancellation, mixers, phase modulation

I. INTRODUCTION

Spurs are a significant source of interference in radios. Since wireless bands are becoming increasingly dense, improved utilization efficiency is required. Also, as UWB Software-Defined-Radios are more widely used in military applications where small signal detection is important, extremely large SFDRs are essential. A spur is a frequency component within the spectrum that is undesired and causes signal quality to degrade. Spurs, in summary, are created in the conversion process in radios.

DDSs are commonly included in UWB radios that are used in searching and tracking in the spectrum [1]. The disadvantage of DDSs is that they are quite spurious. As the DAC within the DDS has limited resolution, it introduces quantization errors, which in combination with aliasing, create harmonic spurs. Similarly, DACs have linearity errors, which create non-harmonic spurs. Additionally, their switching transients and clock feedthrough are known sources of spurs [2]-[3].

In the case of UWB radios, synthesizers are often swept so signals can be identified and locked onto [1]. In a narrowband system, mixers use a limited amount of fixed synthesizer frequencies [4]. In this case, one can simply choose a frequency where the spurs created have a large offset frequency and can be filtered out. However, in a UWB sweeping system, a band-pass filter is not the best way of reducing spurs as they are too close to the carrier. Therefore, cancellers are a better approach [5]. Knowledge about the phase of a particular spur could be used to cancel it.

II. SPUR CHARACTERIZATION

A. Spur Characterization Method

The AD9912 DDS [6] was used as an example to characterize the behavior of spurs with respect to the carrier. The LO that was designed here at D-TA Systems, has a 1 GHz system clock that the DAC uses to sample the output of the DDS for upconversion. As a result, the DDS produces a carrier from 100-400 MHz (Image 0) along with its image at 600-900 MHz (Image 1). This is explained with Nyquist Sampling Theorem in Figure 1 below.

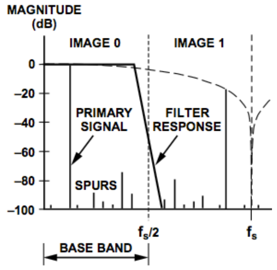

Figure 1 – DDS Carrier Image Map [6]

As the Nyquist limit in this system is 500 MHz (fs/2), the 1st image occurs below the sampling frequency of 1 GHz. As suggested in Figure 1 above, filters are used to make use of Image 0 and Image 1 frequencies for upconversion. One can also see that the harmonic and non-harmonic spurs around each image are mirrored.

To destructively cancel these spurs, the AD9912 includes a two channel harmonic spur canceller, known as "SpurKiller," with a programmable phase [6], as in Figure 2 below.

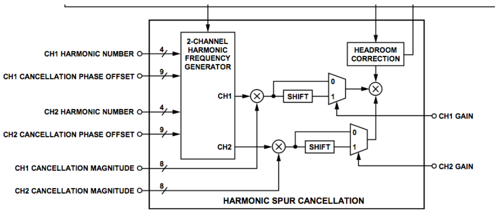

Figure 2 – SpurKiller Architecture [6]

Each SpurKiller channel digitally produces a signal aimed to deconstructively interfere with a spur. The SpurKiller is limited to harmonic spurs, and typically reduces only 2nd and 3rd harmonic numbers. The algorithm in Figure 3 below was used:

1. Determine which offending harmonic spur to reduce and its amplitude
2. Adjust the amplitude of the SpurKiller channel so that it matches the amplitude of the offending spur.
3. Adjust the phase of the SpurKiller channel so that maximum interference is achieved.

Figure 3 - "SpurKiller" User Algorithm [6]

B. *Phase Variation of Spurs*

The algorithm in Figure 3 was used to determine the SpurKiller channel phase for maximum destructive interference. The harmonic number was chosen to reduce the harmonic spur with the highest magnitude as per the algorithm. Also, the amplitude multiplier of the SpurKiller channel was found to always be the maximum value of 1, resulting in the maximum reduction. As a result, the skirt of the harmonic cancelling signal was found to additionally eliminate non-harmonic spurs [2]-[3].

In the experiment, three instances of the same AD9912 chip batch number were used in three identical instances of the DTA LO. Thus, in Figure 4 below, one notices that there is significant variation in the SpurKiller channel phase. Note that in the experiment, four individual plots were created on a per channel/per image basis, but SpurKiller Channel 1, DDS Image 0 had the widest variation. The resolution of the plot is limited as 1 MHz steps were used. Also, the sudden jumps occur as the spur harmonic number changes suddenly when the previous SpurKiller harmonic number no longer has an effect on the SFDR.

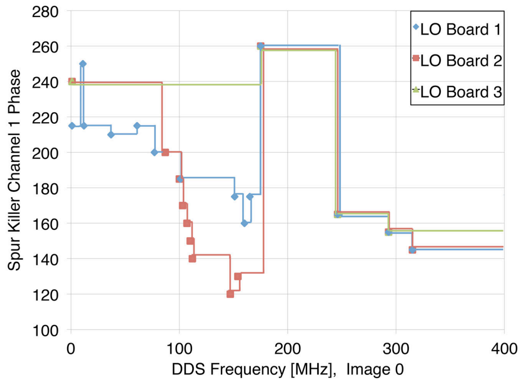

Figure 4 – Spur phase comparison vs. DDS carrier frequency

This phase variation is explained by Analog Devices:

“The actual amplitude and phase values required to destructively interfere with a harmonic spur depend upon the frequency of the primary sinusoid and any internal nonlinearities of the DAC” [3].

As a DAC is complex, there are nonlinearites throughout. Therefore, the output will always have some harmonic distortion. That harmonic distortion has a non-linear phase response, typical with microwave systems, which has been estimated empirically using the algorithm in Figure 3.

III. PROPOSED APPROACH TO SFDR IMPROVEMENT

A. *Harmonic Spur Cancellation*

The harmonic spur canceller module that is part of the IC is only limited to harmonic mutiples of the carrier. In summary, spurs are modified variably with phase and frequency. Even while using the same batch of IC, the amount of reduction as seen in Figure 5 below varies from 10-30 dB (50-70 dBc SFDR). This was achieved by trial and error and is is impractical for complex systems. An adaptive system with variable frequency is necessary to achieve a constant reduction.

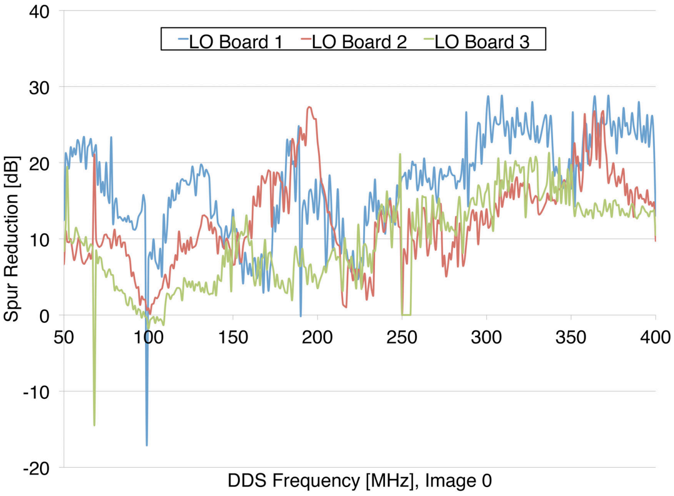

Figure 5 - Reduction acheived with Analog Devices’ "SpurKiller"

B. *FPGA Realization*

As 60 GHz radios are becoming more prevalent in society, the FPGA realization of an adaptive spur cancellation system is not possible [7] due to the limitation of clock frequencies. Xilinx produces a DDS core that claims extremely low (-100 dBc) SFDR, but only at sub-GHz frequencies. It also has poor phase noise. The best solution that can be proposed is a system that adaptively eliminates spurs.

C. *Adaptive Double Quadrature Mixer*

To cancel spurs more effectively, a second IF stage is introduced with variable LO phase, as in Figure 6 below, known as the Double Quadrature Mixer [8]. A fixed LO requires a very high SFDR so that more spurs aren’t introduced, for example a PLL. This architecture makes use of two stage I and Q channels that are mathematically operated on so that the spurs are substracted and filtered at the output. The last mixing stage upconverts the output so that the original IF frequency is maintained.

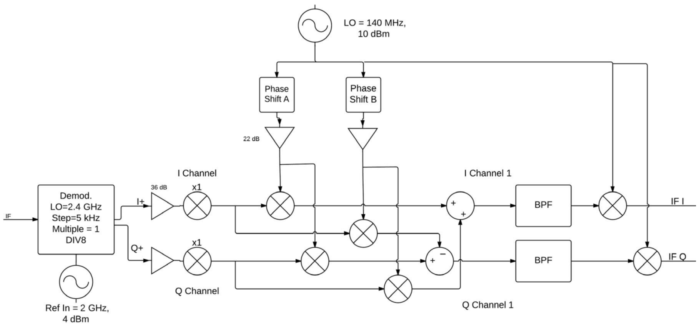

Figure 6 – Modified Double Quadrature Achitecture for improved SFDR [8]

Suppose at IF, in the ideal case, the spurs are 90° phase offset from the carrier as in (1)-(2) below. Note that the demodulation is repesented by (2) which is (1) phase shifted by 90°:

$$IF_I = \sin(\theta_{spur\_low}) + \cos(\theta_{carrier}) + \sin(\theta_{spur\_high}) \qquad (1)$$

$$IF_Q = \cos(\theta_{spur\_low}) + \sin(\theta_{carrier}) + \cos(\theta_{spur\_high}) \qquad (2)$$

where $\theta_X = 2\pi * f_X$ *and the phase offsets are embedded in the use of* sin *and* cos.

$$IF\_1_I = \sin(\theta_{LO}) * IF_Q + \cos(\theta_{LO}) * IF_I \qquad (3)$$

$$\begin{aligned}&= \frac{1}{2}\sin(\theta_{LO} + \theta_{spur\_low}) + \frac{1}{2}\sin(\theta_{LO} - \theta_{spur\_low}) + \frac{1}{2}\cos(\theta_{LO} - \theta_{carrier}) \qquad (4)\\ &-\frac{1}{2}\cos(\theta_{LO} + \theta_{carrier}) + \frac{1}{2}\sin(\theta_{LO} + \theta_{spur\_high}) + \frac{1}{2}\sin(\theta_{LO} - \theta_{spur\_high})\\ &+\frac{1}{2}\sin(\theta_{LO} + \theta_{spur\_low}) - \frac{1}{2}\sin(\theta_{LO} - \theta_{spur\_low}) + \frac{1}{2}\cos(\theta_{LO} - \theta_{carrier})\\ &+\frac{1}{2}\cos(\theta_{LO} + \theta_{carrier}) + \frac{1}{2}\sin(\theta_{LO} + \theta_{spur\_high}) - \frac{1}{2}\sin(\theta_{LO} - \theta_{spur\_high})\end{aligned}$$

$$IF\_1_I = \sin(\theta_{LO} + \theta_{spur\_low}) + \cos(\theta_{LO} - \theta_{carrier}) + \sin(\theta_{LO} + \theta_{spur\_high}) \qquad (5)$$

$$IF\_1_Q = \cos(\theta_{LO}) * IF_Q - \sin(\theta_{LO}) * IF_I \qquad (6)$$

$$\begin{aligned}&= \frac{1}{2}\cos(\theta_{LO} - \theta_{spur\_low}) + \frac{1}{2}\cos(\theta_{LO} + \theta_{spur\_low}) + \frac{1}{2}\sin(\theta_{LO} + \theta_{carrier}) \qquad (7)\\ &-\frac{1}{2}\sin(\theta_{LO} - \theta_{carrier}) + \frac{1}{2}\cos(\theta_{LO} - \theta_{spur\_high}) + \frac{1}{2}\cos(\theta_{LO} + \theta_{spur\_high})\\ &-\frac{1}{2}\cos(\theta_{LO} - \theta_{spur\_low}) + \frac{1}{2}\cos(\theta_{LO} + \theta_{spur\_low}) - \frac{1}{2}\sin(\theta_{LO} + \theta_{carrier})\\ &-\frac{1}{2}\sin(\theta_{LO} - \theta_{carrier}) + -\frac{1}{2}\cos(\theta_{LO} - \theta_{spur\_low}) + \frac{1}{2}\cos(\theta_{LO} + \theta_{spur\_low})\end{aligned}$$

$$IF\_1_Q = \cos(\theta_{LO} + \theta_{spur\_low}) - \sin(\theta_{LO} - \theta_{carrier}) + \cos(\theta_{LO} + \theta_{spur\_high}) \qquad (8)$$

Then, mathematically modelling the architecture in Figure 6, (3) and (6) represent the addition and subtraction following the double mixing stage. As the spurs are 90° offset from the carrier, maxium cancellation occurs when the Phase Shift A = 0° and B = 90°. The resulting mixing products in (4) and (7) result in an upconverted ($\theta_{LO} + \theta_X$) spectrum where the carrier is eliminated by destructive inteference. Similarly, a downconverted spectrum also results where the spurs are eliminated. This destructive interference is a result of phase shifts caused by sin and cos multiplication [9]. As a result, the spurs are completely cancelled out at the I Channel 1 and Q Channel 1 (see Figure 6) downconverted frequency and remain only at the upconverted frequency as in (5) and (8). Now they can then be easily filtered out as they are far enough away from the carrier.

IV. RESULTS

The system in Figure 6 was prototyped using Mini-Circuits and Analog Devices components. The spurious IF spectrum (1.2 GHz carrier, downconverted from 4.5 GHz, unmodulated) of D-TA's 9590 UWB radio was used as input. The last mixing stage was omitted, and only Q was plotted for simiplicity. Overall, as in Figure 7 below, a 10 dB improvement in SFDR is achieved (A = 0°, B = 190°), based on the reduction of a non-harmonic input spur at 83 MHz offset. The high-side spur is reduced by 20 dB resulting in the low-side spur dictating the new SFDR. A 29 dB improvement in SFDR was achieved in simulation.

This difference is due to the poor demodulator PLL phase noise, and LO injection, even after minimization. As development continues, LOs at higher frequencies and simple 90° phase shifters will be compared for phase noise and LO injection improvement. Phase and frequency variation will be studied as well.

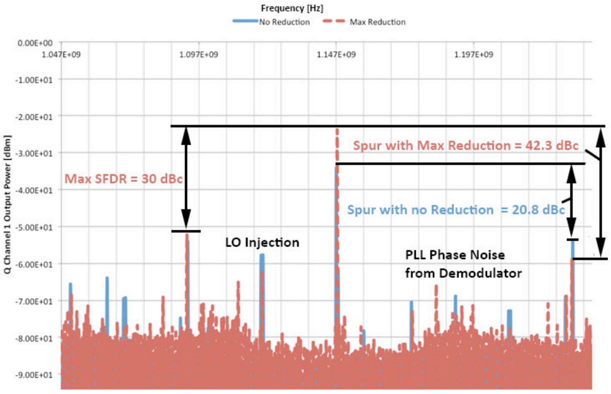

Figure 7 - Comparison in SFDR Reduction in Prototype

V. CONCLUSION

On a spurious IF spectrum at 1.2 GHz, a 29 dB increase in SFDR was observed in simulation, and 10 dB in practice, but was limited by the quality of phase-shifters, demodulation, and frequency planning.

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