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How to Design Wideband Front Ends for GSPS Converters

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INTRODUCTION

As high speed analog-to-digital converter technology improves, so does the need to resolve very high intermediate frequencies (IF) accurately at high speeds. This poses two challenges: the converter design itself and the front-end design that couples the signal content to the converter. Even if the converter's performance itself is excellent, the front end must be capable to preserve the signal quality, too. High frequency, high speed converter designs exist in many applications today, with radar, wireless infrastructure, and instrumentation pushing these boundaries. These applications demand the use of high speed, GSPS (gigasample per second) converters with resolutions of 8 bits to 14 bits; but remember, there are many parameters that need to be met in order to satisfy the "match" for your particular application.

Wide band, as defined in this paper, is the use of signal bandwidths greater than +100 MHz and ranging into the 1 GHz to 4 GHz frequencies. In this paper, what defines a wideband passive network will be discussed, and the specifications that are important when choosing a transformer or balun along with the current configuration topologies used today will be highlighted. Lastly, considerations and optimization techniques will be revealed in order to help readers realize a workable wideband solution in the gigahertz region that matches the parameters of a particular application.

LAYING THE FOUNDATION

It is natural to gravitate to GSPS converters for applications such as radar, instrumentation, and communication observation because these offer a wider frequency spectrum or Nyquist band. However, a wider frequency spectrum poses even more challenges on the front-end design. Just because you purchase a converter with a 1 GHz Nyquist band, it still means you have to wrap the right components around it and pay closer attention to the circuit's construction, i.e. front end. Challenges escalate when the application calls for +1GHz super-Nyquist sampling, where spectral information must be captured in the second, third, or fourth Nyquist zone.

QUICK NOTE ON BANDWIDTH

First, some notes on bandwidth should be discussed. Keep in mind that a converter's full power bandwidth is different from converter "useable" or "sample" bandwidth. Full power bandwidth is the bandwidth that the converter needs to acquire signals accurately and for the internal front end to settle properly. Selecting an IF and using the converter out in this region is not a good idea as performance results will widely vary in the system based on the rated resolution and performance stated in the converter's data sheet—the full power bandwidth is much bigger (possibly 2×) than the sample bandwidth of the converter itself. The design is settled around sample bandwidth. All designs should avoid using some or all of the highest frequency portions of the rated full power bandwidth; by doing so expect a derating in dynamic performance (SNR/SFDR). To determine the sample bandwidth of the high speed analog-to-digital converter, consult the data sheet or application support as sometimes this isn't specially given. Typically, the data sheet has specified or even listed production tested frequencies that guarantee delivered performance within the converter's sample bandwidth; however, better explanations about these bandwidth terms in the industry need to be specified and defined.

BALUN CHARACTERISTICS AND IMBALANCE

Once the application bandwidth and high speed analog-to-digital converter are known, choose the front-end topology: amplifier (active) or transformer (passive). The trade-offs between the two are long and depend on the application. For more information on this subject specifically, please see Reference 3. From here on out, the basis of this paper will concentrate on transformer/balun coupled front-end designs. The term "balun" will be used in the context that is referring to a transformer or balun. Even though there are differences between the two in their construction and topology, the assumption is that a passive device is used to couple and build the front end, which converts the incoming IF of interest from a single-ended signal to a differential one.

Baluns have different characteristics than amplifiers and should be considered when choosing the device. Voltage gain, impedance ratio, bandwidth and insertion loss, magnitude and phase imbalance, and return loss are some of these different characteristics. Other requirements may include power rating, type of configuration (such as balun or transformer), and center tap options. Designing with baluns is not always straightforward. For example, balun characteristics change over frequency, thus complicating the expectation. Some baluns are sensitive to grounding, layout, and center tap coupling. It is wise not to fully expect the data sheet of the balun to be the sole basis on which to choose it. Experience can play a huge role here as the balun takes on a new form when pcb parasitics, external matching networks, and the converter's internal sample and hold circuit (i.e. load) also become part of the equation.

The important characteristics of choosing a balun are summarized by the following as a guide:

Signal gain is ideally equal to the turn's ratio of the transformer. Although voltage gains within a balun are inherently noise free, using a balun with voltage gain does gain the signal noise. There can also be a significant tradeoff in bandwidth. Baluns should be viewed simplistically as a wideband pass-band filter with nominal gain. Therefore, the typical trend is the more signal gain in the balun the less bandwidth. Voltage gains with baluns can be highly variable, allowing for more significant ripple and roll-off to be obtained when it isn't wanted. Finding a 1:4 impedance ratio transformer with good gigahertz performance is difficult today. In summary, user be wary; thoughts of using 1:4, 1:8, and 1:16 impedance ratio balun to improve or optimize noise figure within the final signal chain stage should be well thought out and verified in the lab. Since bandwidth options become limited, as well as performance, the tradeoffs are significant, forcing the performance to be no better than a 1:1 or 1:2 impedance ratio design when designing in gigahertz regions.

Insertion loss of the balun is simply the loss over the specified frequency range and is the most common measurement specification found in any balun data sheet. This will definitely change when implemented in the circuit. Typically, you can expect half of the frequency range that is specified in the data sheet. Some are worse than that, depending on the balun's topology and sensitivity to load parasitics; i.e. capacitance. This is probably the most misunderstood parameter about baluns, as they are optimized without load parasitics in an ideal impedance situation; i.e. they are characterized with a network analyzer.

Return Loss is the balun's mismatch of the effective impedance of the secondary's termination as seen by the primary. For example, if the square of the ratio of secondary to primary turns is 4:1, one would expect a 50 Ω impedance to be reflected onto the primary when the secondary is terminated with 200 Ω. However, this relationship is not exact: the reflected impedance on the primary changes with frequency, as shown in the following example.

First, find the return loss at the center frequency specified for the design. In this example, 110 MHz is used. Zo is found to not be 50 Ω as assumed for an ideal transformer. It is lower, as found in Equation 3.

Eqn. 1 | Return Loss (RL) = −18.9 dB @ 110 MHz = 20 × log(50−Zo/50+Zo)

Eqn. 2 | $10^{(-18.9/20)}$ = (50−Zo/50+Zo)

Eqn. 3 | Zo = 39.8 Ω

Next, ratio the primary Zo found in Equation 3 and secondary ideal impedance. Do the same for the primary ideal and solve for the real secondary impedance.

Eqn. 4 | Z (Prim Reflected)/Z (Sec Ideal) = Z (Prim Ideal)/Z (Sec Reflected)

Eqn. 5 | 39.8/200 = 50/x

Eqn. 6 | Solving for x, x = 251 Ω

So, what this example proves is that a 251 Ω differential termination should be present on the secondary to reflect a 50 Ω load on the primary. Otherwise, the preceding stage in the signal chain ends up driving a heavier load (~40 Ω). This leads to more gain in the preceding stage; more gain and misrepresented load conditions lead to more distortion that the high speed converter will "see" and therefore limit the system's dynamic range. In general, as the impedance ratio goes up, so does the variability of the return loss. Keep this in mind when designing a "matched" front end with a balun.

Magnitude imbalance and **phase imbalance** are the most critical performance characteristics when considering a balun. These parameters provide a good measure of how each single-ended signal is off from the ideal; equal in magnitude and 180° out of phase. These two specifications give the designer a perspective on how much signal linearity is being delivered to the converter when a design calls for high (+1000 MHz) IF frequencies. In general, the more they deviate, the worse the degradation in performance. Stick to those transformers or baluns that publish this information in the data sheet as a start. If the information is not present in the data sheet, this may be a reason why this is not a good choice for this high frequency application. Remember: as frequency increases, the nonlinearity's of the balun also increases, usually dominated by phase imbalance, which translates to worse even order distortions (mainly 2^{nd} harmonic or H2) as seen by the high speed converter. Even three degrees of phase imbalance can cause a significant degradation in performance in spurious free dynamic range or SFDR. Don't be quick to blame the converter, look at the frontend design first if the expected datasheet spurious is way off, especially H2.

There are some solutions to combat against 2nd harmonic distortions when using a balun at higher frequencies; for example, try using multiple transformers or baluns in a cascaded fashion. Two, as shown in Figure 1, and in some cases, three baluns can be used to help convert the single-ended signal to differential adequately across high frequencies. The downside is space, cost, and insertion loss. The other suggestion is to try different baluns. Better single solution baluns are out there; for example, Anaren, Hyperlabs, Marki Microwave, Mini-Circuits® and Picosecond, to name a few. These have patented designs that use special topologies allowing for extended bandwidth in the gigahertz region, providing a high level of balance while only employing a single device and in some cases is smaller than the standard ferrite footprints that are commonly used today.

Remember, not all baluns are specified the same way by all manufacturers, and baluns with apparently similar specifications may perform differently in the same situation. The best way to select a balun for the design is to collect and understand the specs of all baluns being considered, and request any key data items not stated on manufacturers' data sheets. Alternatively, or in addition, it may be useful to measure their performance using a network analyzer or on the system board in front of the high speed analog-to-digital converter.

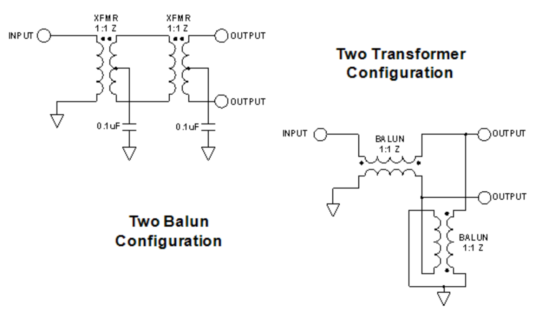

Figure 1. Double Balun/Transformer Topologies

One final note about using a single balun or multiple balun topology: layout plays an equally important role in phase imbalance as well. Keeping performance optimized at higher frequencies means keeping the layout as symmetric as possible. Otherwise, slight mismatches in traces on the front-end designs that use a balun can be proven useless (i.e. dynamic range limiting).

FRONT-END MATCH

First off, the word "match" is a term that should be used wisely. It is almost impossible to match a front end at every frequency today with 100 MSPS converters, let alone over a 100 MHz band. The term match should be positioned to mean optimization yielding the best results given the front-end design. This would be an all-inclusive term where impedance, ac performance, signal drive strength, and bandwidth and its pass-band flatness yield the best results for that particular application.

This means each parameter should have a particular weight of importance per the application. In some cases, for example, bandwidth might be the most important spec and therefore other parameters can be allowed to suffer a bit if the right amount of bandwidth can be achieved. In Figure 2, the input network for a GSPS converter is shown. Each resistor in the network is like a variable, however as each of these resistor values is varied to create essentially the same input impedance the performance parameters will change as shown in Table 1.

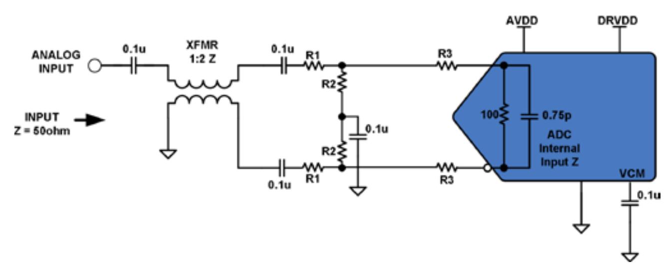

Figure 2. Generic Front-End Network

Table 1. Measured Performance Matching vs. Three Front End Case Designs

Performance Specs	**Case 1—R1 =25 Ω, R2=33 Ω, R3=33 Ω**	**Case 2—R1=25 Ω, R2=33 Ω, R3=10 Ω**	**Case 3—R1=10 Ω, R2=68 Ω, R3=33 Ω**
Bandwidth (–3 dB)	3169 MHz	3169 MHz	1996 MHz
Pass-Band Flatness (2 GHz Ripple)	2.34 dB	2.01 dB	3.07 dB
SNRFS @ 1000 MHz	58.3 dBFS	58.0 dBFS	58.2 dBFS
SFDR @ 1000 MHz	74.5 dBc	74.0 dBc	77.5 dBc
H2/H3 @ 1000 MHz	–74.5 dBc/–83.1 dBc	–77.0 dBc/–74.0 dBc	–77.5 dBc/–85.6 dBc
Input Impedance @ 500 MHz	46 Ω	45.5 Ω	44.4 Ω
Input Drive @ 500 MHz	15.0 dBm	12.6 dBm	10.7 dBm

Essentially, the impedance matching network is roughly the same but the yielded results between these three examples are different across the measured parameters needed to design the front-end network. The match here is the best result for all the parameters involved, where in this case over 2.5 GHz of bandwidth is required. This narrows the choices down to Case 1 and Case 2, as seen in Figure 3.

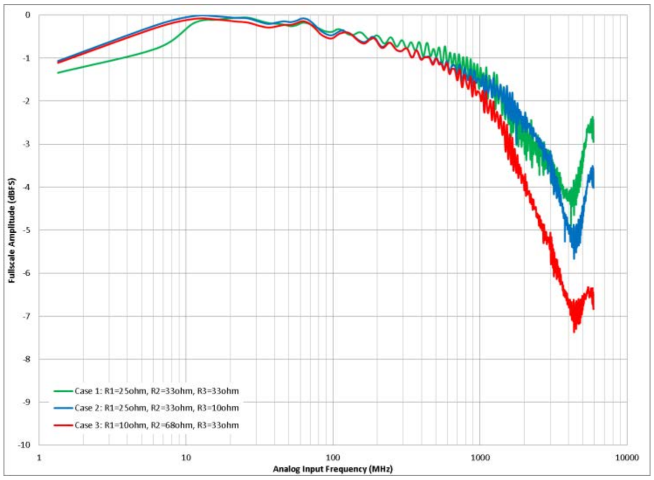

Figure 3. Bandwidth Matching.

Looking further between Case 1 and Case 2, it can easily be seen that Case 2 would be more desirable for two reasons. One, the pass-band flatness only has 2 dB of ripple across the 2 GHz region; and two, the input drive is 3 dBm less than Case 1. This puts less of a constraint on the RF gain further up the signal chain in order to achieve full scale of the high speed converter on the primary of the balun. Case 2 seems to be the best match in this example.

SUMMARY

GSPS converters offer ease of use, in theory, when it comes to sampling wider bandwidth to cover multiple bands of interest or relieve a mix down stage on the frontend RF strip; however, achieving bandwidth in the 1 GHz range can pose challenges to designing a high performance converter front-end network. Keep in mind the importance of specifying a balun where phase imbalance will become important in what the high speed analog-to-digital converter understands as optimal second order linearity, for example. Even when a balun is chosen, don't throw away its performance by using poor layout techniques and be wary of matching the network properly. Remember, there are many parameters that need to be met in order to satisfy the match for your particular application.

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