Digital Step Attenuators for Microwave Applications in Space – AMICSA 2014

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Abstract

Digital Step Attenuators (DSA) are broadly used within Satellite Payloads to adjust signal levels either as standalone blocks or as a key part of complex systems. Wherever a DSA is employed its critical function is delivering accurate, consistent, repeatable level control in a difficult space environment. The environment in space creates additional challenges due to the wide range of temperature and radiation effects.

Commercial 7 bit/31.75dB DSA have been reported with attenuation errors in the range of (+/-0.1dB + 3% of setting) to (+/-0.15dB + 1.5% of setting) for 8GHz devices. When we investigate these numbers further we find the best attenuation accuracy is typically only achieved over the lower frequency range.

Above these frequencies there are fewer vendors and attenuation accuracy degrades significantly. A 0-13 GHz DSA has been reported with attenuation error of (+/-0.5dB +5% of setting). The attenuation error is highest for the higher attenuation values, to get around this some vendors reduce the maximum attenuation of their DSAs from 31-32dB to approximately 16dB.

The author will review the building blocks of a DSA and describe circuit solutions to improve attenuation accuracy as frequency increases.

Measured results for a 6GHz DSA and an 11 GHz DSA will be compared along with the differences in circuit topology and packaging approach. These results will demonstrate how to achieve improved high frequency attenuation error for microwave DSAs.

I. INTRODUCTION

The Satellite Market is experiencing a number of trends; in the commercial communications satellite market we see a move towards higher frequency bands, coupled with a requirement to make Satellite reconfigurable and capable of higher data rates (e.g. high throughput satellites). At the same time we see increased activity in earth observation imagery, using a range of different sensor techniques to collect high resolution images of the earth. Although these applications are very different the technical solutions result in significant overlap in the circuit blocks required to meet the market needs.

For example earth observation agencies continue to launch new, finer resolution synthetic aperture radar (SAR) while communications satellites are increasing being launched with phased arrays to create movable spot beams. Both of these applications require the phase and amplitude of signals to be accurately adjusted to many parallel paths. A typical block to adjust amplitude and phase for one antenna element is shown in Figure 1 below.

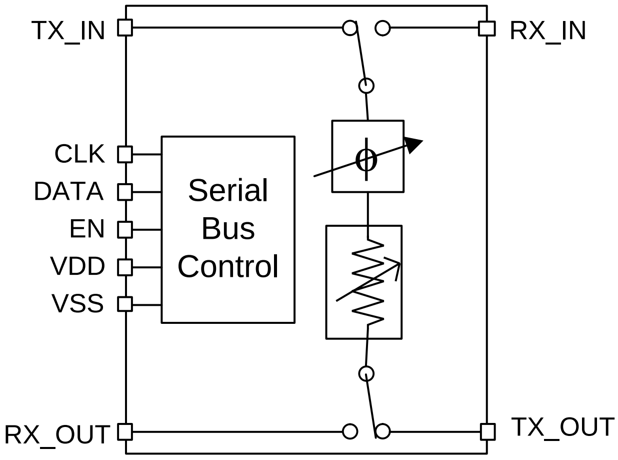


Figure 1: “Core Chip” Phased Array Building Block

The amplitude adjustment with the Core Chip is achieved with a DSA, shown as a tuneable resistor block in Figure 1.

Similarly the requirement for larger, higher data rate Communications satellites is putting pressure on the power bus of the satellite. One way to alleviate the problem is to improve the efficiency of the power amplifier, using advanced linearizers. A possible approach is a Doherty power amplifier, although this technology is not new, recent advances in asymmetric Doherty amplifiers has seen renewed interest in this approach. The Doherty PA relies on accurate adjustment of signal amplitude and phase in two independent paths. A typical Doherty PA circuit is shown below in Figure 2, with the DSA (tuneable resistor) controlling the amplitude.

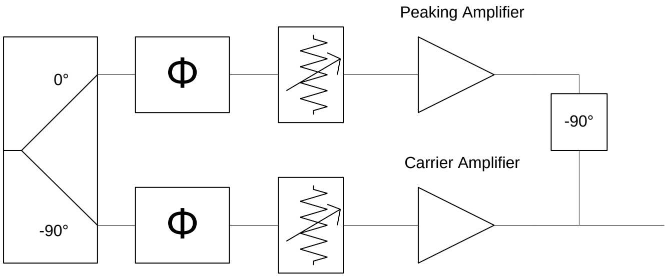


Figure 2: Doherty PA

A third application requiring accurate amplitude adjustment is navigation satellites, for example Galileo. As the system consists of a constellation of satellites, with end users receiving signals from multiple satellites it is important to radiate equivalent power from all satellites in the constellation. Failure to accurately control and balance signal levels could result in the signal exceeding the allowable maximum radiated power. A simplified Galileo RF path block diagram is shown below in Figure 3.

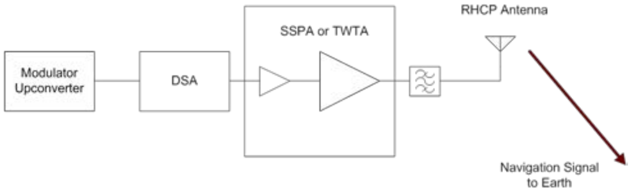
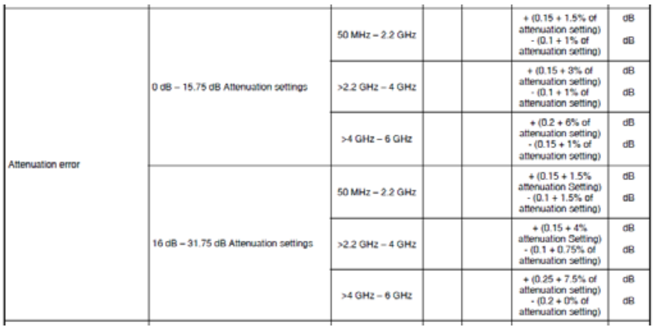


Figure 3: Galileo Navigation Satellite Simplified RF Path

II. IMPORTANT CHARACTERISTICS FOR DSAs

As reported by previous authors [1] there are several key parameters for a DSA, including power handling capability, switching speed, insertion loss, phase error and amplitude error. Generally all of these have to be balanced in the design of the DSA. For the purposes of this article we focus on Amplitude Error as there are specific challenges to achieving the required amplitude accuracy as frequency increases.

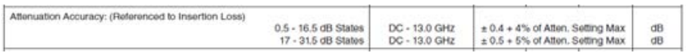
The commercial DSA market has a large number of product offerings, many reporting high attenuation accuracy. However when we review the data carefully this performance is achieved for the lower frequency of operation and rolls off quickly at higher frequency.



Attenuation error	0 dB – 15.75 dB Attenuation settings	50 MHz – 2.2 GHz			+ (0.15 + 1.5% of attenuation setting) - (0.1 + 1% of attenuation setting)	dB dB
		>2.2 GHz – 4 GHz			+ (0.15 + 3% of attenuation setting) - (0.1 + 1% of attenuation setting)	dB dB
		>4 GHz – 6 GHz			+ (0.2 + 6% of attenuation setting) - (0.15 + 1% of attenuation setting)	dB dB
	16 dB – 31.75 dB Attenuation settings	50 MHz – 2.2 GHz			+ (0.15 + 1.5% attenuation Setting) - (0.1 + 1.5% of attenuation setting)	dB dB
		>2.2 GHz – 4 GHz			+ (0.15 + 4% attenuation Setting) - (0.1 + 0.75% of attenuation setting)	dB dB
		>4 GHz – 6 GHz			+ (0.25 + 7.5% of attenuation setting) - (0.2 + 0% of attenuation setting)	dB dB

Figure 4: PE43705 Digital Step Attenuator Attenuation Accuracy

Figure 4 shows the published [2] attenuation accuracy for a commercially available 8 GHz DSA, packaged in a 32 lead 5x5mm plastic QFN package. This product offers class leading performance for a commercial part at this frequency range. However we can see that the best accuracy is achieved below 2.2GHz, particularly for the higher attenuation settings. For the maximum attenuation setting above 4GHz the attenuation accuracy, although still very good, has approximately doubled the error observed below 2.2GHz.



Attenuation Accuracy: (Referenced to Insertion Loss) 0.5 - 16.5 dB States 17 - 31.5 dB States	 DC - 13.0 GHz DC - 13.0 GHz	 ± 0.4 + 4% of Atten. Setting Max ± 0.5 + 5% of Atten. Setting Max	 dB dB

Figure 5: HMC424LH5 DSA Attenuation Accuracy

Figure 5 shows the published [3] attenuation accuracy for a commercially available 13.5GHz DSA, packaged in a leadless 5x5 ceramic package. Although this product does not specify attenuation over frequency sub-bands, we can see from Figure 6 that similar behaviour occurs versus frequency, as the 8 GHz DSA. The trend is attenuation accuracy degrades with frequency, particularly above 9GHz, and the effect is more pronounced for larger attenuation values.

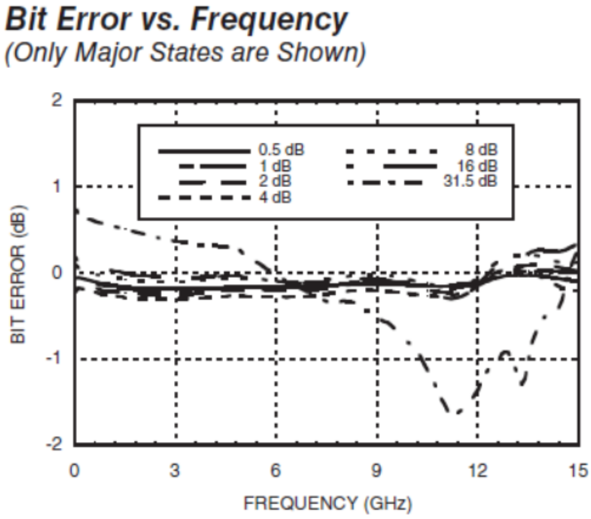
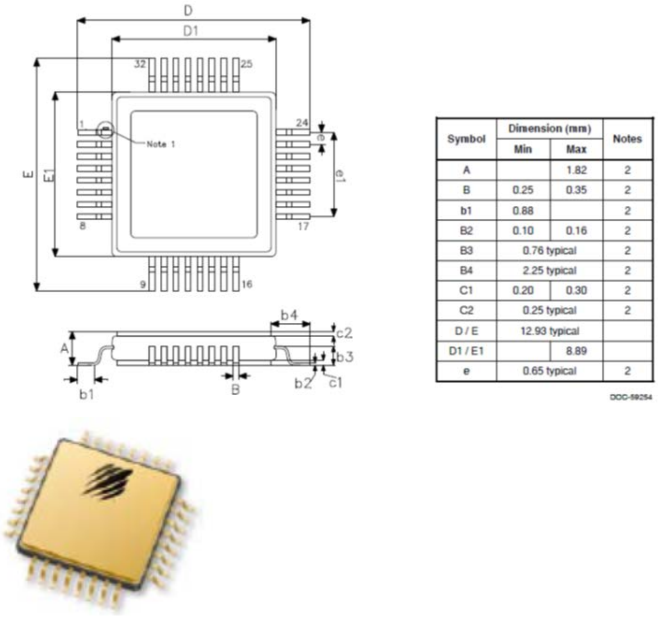


Figure 6: HMC424LH5 Bit Error

III. PEREGRINE SPACE QUALIFIED DSA EXAMPLE

Peregrine have developed a 7 bit, 0.25 dB step DSA in its proprietary 0.5um Silicon on Sapphire (SOS) process for an ESA funded project. The product is the PE43751. The aim of the project was to create a European developed, radiation hard DSA for space applications. The product was packaged in a 32 Lead CQFP package; the package can be seen in Figure 7.



Symbol	Dimension (mm)		Notes
	Min	Max	
A		1.82	2
B	0.25	0.35	2
b1	0.88		2
B2	0.10	0.16	2
B3	0.76 typical		2
B4	2.25 typical		2
C1	0.20	0.30	2
C2	0.25 typical		2
D / E	12.93 typical		
D1 / E1		8.89	
e	0.65 typical		2

Figure 7: 32 Lead CQFP Package

CQFP packages are preferred by many Space customers for several reasons: the package can be hermetically sealed, allowing parts to be placed outside of modules/hybrids; the device can be visually inspected after soldering, ensuring solder joints have formed correctly. However leaded packages introduce undesirable lead inductance, resulting in reduced performance, as will be shown later.

A. *PE43751 Attenuation Accuracy*

The PE43751 DSA is intended for applications ranging in frequency from 30 kHz to 6 GHz, although as with previous examples optimum performance is achieved at lower frequencies. Figure 8 shows the devices attenuation accuracy at 4GHz for all attenuation steps. The x-axis is the unit-less attenuation setting, as a decimal value from 0-127. Each decimal increment corresponds to a 0.25dB attenuation step. The response shows several large steps, these steps correspond to the switching of larger attenuators in the DSA. The following section will discuss the basics of how a DSA is constructed and how this influences the accuracy.

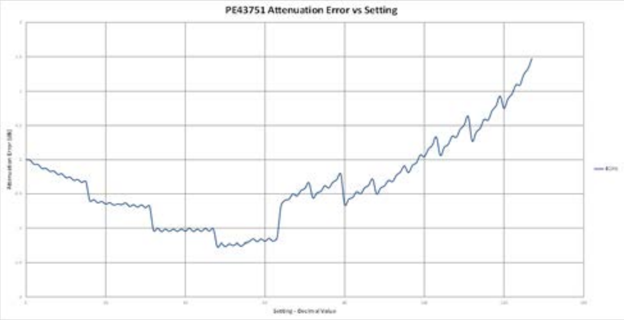


Figure 8: PE43751 4GHz Attenuation Accuracy

B. *Basic Step Attenuator Building Blocks and Construction*

A simplified block diagram of a 31.75dB DSA is shown below in Figure 9. A simplified block diagram is presented to allow the architecture to be studied without the complexity of the switches. For this discussion the switches will be considered ideal. In reality the switches will have an on resistance, a finite off isolation (off capacitance) and various parasitics. These non-ideal features will not be discussed here.

Figure 9: Simplified Digital Step Attenuator Block Diagram

The Step attenuator in Figure 9 consists of a series of resistive Pi or T pads, interconnected with a series of single pole, double throw (SPDT) RF switches. Each attenuator can be included in the overall attenuation or bypassed by the SPDT switches. In the ideal case we are able to add the attenuation of each individual attenuator to get a combined attenuation, in increments of 0.25dB, up to a maximum of 31.75dB.

In the example in Figure 9 we have shown the individual attenuators arbitrarily ordered from smallest attenuation to largest attenuation. As will be shown later this may not provide the best overall result.

Considering the DSA as the sum of individual attenuators allows us to better understand the limitations of a combined device. Reviewing the PE43751 European DSA and considering the larger attenuators in the device (4dB, 8dB, 16dB), we can see some interesting behaviour versus frequency.

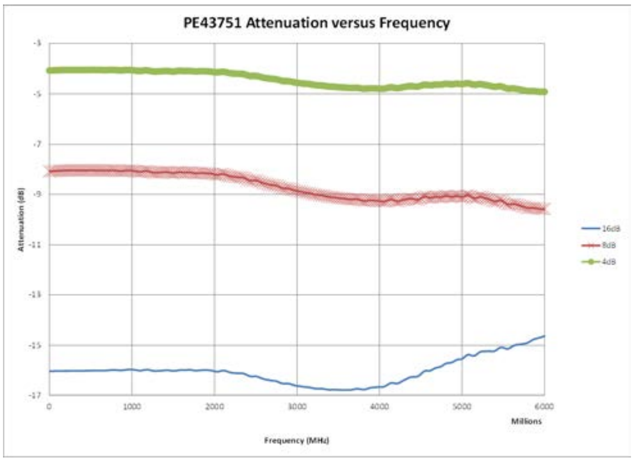


Figure 10: PE43751 Major Attenuators versus Frequency

Figure 10 shows the attenuation of the 4dB, 8dB and 16dB attenuators versus frequency. This data has been corrected for the insertion loss of the DSA, by subtracting the 0 setting insertion loss from the raw data. Considering first the 4dB and 8dB attenuators we see a general trend of the correct attenuation at low frequency, and increased attenuation as frequency increases. The responses aren't linear and don't follow a simple curve, suggesting more than one effect or root cause; this will be discussed further later.

The 16dB exhibits a different behaviour versus frequency; up to approximately 3GHz the response is similar to the smaller attenuators. Above 3 GHz the 16dB attenuators attenuation begins to reduce, leading to a large error at 6GHz. This characteristic is a well understood phenomena and is attributable to finite isolation or coupling within the device. As frequency increases a combination of ground bond coupling and limited isolation on die result in reduced attenuation. As will be discussed in the improved architecture section this effect can be reduced.

IV. IMPROVING DSA PERFORMANCE

The two frequency dependent effects on attenuation accuracy identified in the previous section were: increased attenuation versus frequency and reducing attenuation with frequency for 16dB attenuators above 3 GHz. This section will investigate these effects further and propose ways to reduce the devices sensitivity to these effects.

A. *Large Attenuator Isolation and Coupling*

The simplest and most effective way to reduce isolation and coupling effects is to physically separate the large attenuators from each other. An additional technique is to divide the large attenuator into two smaller attenuators, and to physically separate these. Dividing the large attenuator in to two with half the attenuation each reduces the isolation required per attenuator and physically separating increases the isolation. For example a 16dB attenuator can be divided in to two 8dB attenuators, which can in turn be separated from each other by the smaller attenuators. An example of this approach can be seen below in Figure 11.

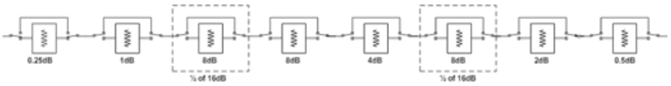


Figure 11: Improved Isolation Attenuator Architecture

In this example the 16dB attenuator is made up of two 8dB attenuators and these are in turn separated by the 4dB attenuator and the 8dB attenuator. This approach requires slightly more die area, but virtually eliminates the isolation effect. The resulting die layout can be seen below in Figure 12.

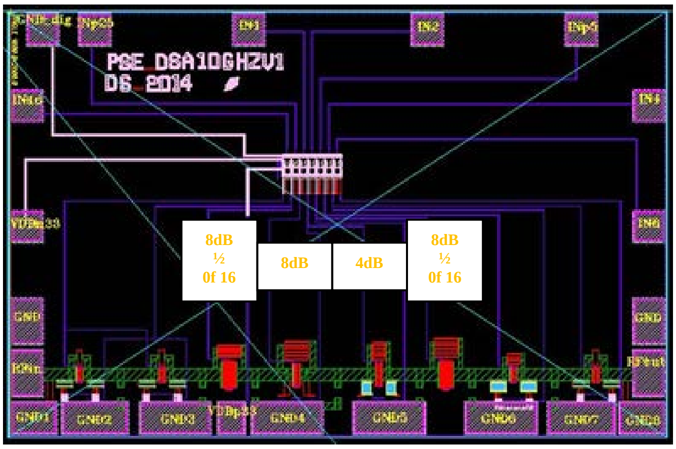


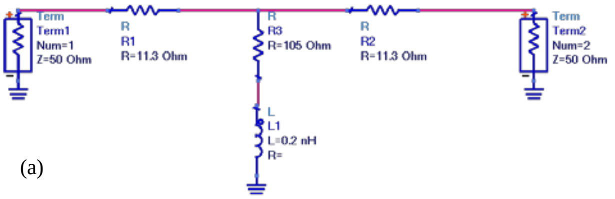
Figure 12: Die Layout for improved isolation, high attenuation accuracy

B. Minimising the Attenuation Increase with Frequency

The increased attenuation with Frequency is primarily due to lead inductance and ground bond inductance. To demonstrate the sensitivity to inductance in the series and shunt path of a high frequency attenuator a series of simple simulations were completed.

1) Pi versus T Attenuator

To optimize the Step Attenuator for high frequency operation we must consider which configuration (Pi or T) is least sensitive to package and bond wire inductances. A simulation was constructed using a 4dB Pi and 4dB T pad, with realistic inductances added to represent package and bond wire inductances. Figure 13 shows the schematics of the Attenuators.



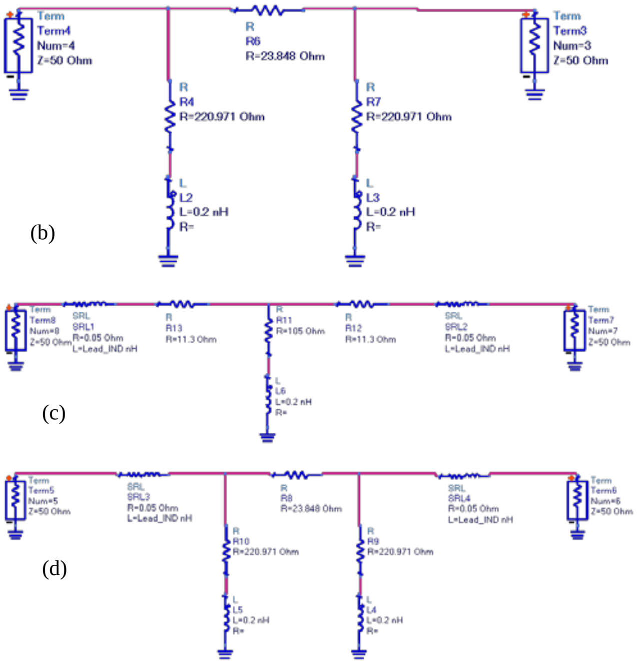


Figure 13. (a) T-pad with ground inductance. (b) Pi-pad with ground inductance. (c) T-pad with ground inductance and lead inductance. (d) Pi-pad with ground and lead inductance.

The series inductance values used in the simulation was Lead_IND=0.2nH. 0.2nH is a typical value for a short bond wire or down bond.

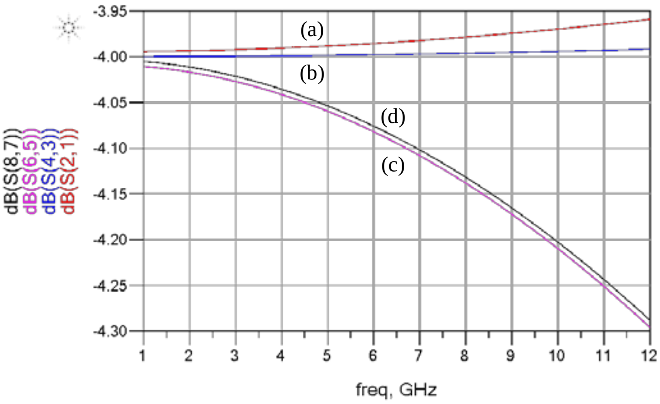


Figure 14: (a) 4dB T-pad with shunt inductance, (b) 4dB Pi-pad with shunt inductance, (c) 4dB T-pad with series and shunt inductance, (d) 4dB Pi-pad with series and shunt inductance

Figure 14 shows the results of the simulation, from these results we can see the T-pad is generally more sensitive to inductance in either the series or shunt leg of the attenuator. In both cases the series inductance has more impact than a shunt inductor.

C. Improving the 4dB Attenuator

In this section we discuss improvements Peregrine are implementing in their Space DSA for applications in X-band (8-12GHz). The improvements are contrasted with the results previous results for the PE43751 (6GHz Space DSA) and a simulation is constructed to show the impact of the package lead inductance.

Figure 15 below shows a comparison plot for the 4dB attenuator measured in the PE43751 versus a new 4dB attenuator as part of a new X-Band DSA. Both measurements are normalized by subtracting the loss of the 0dB state.

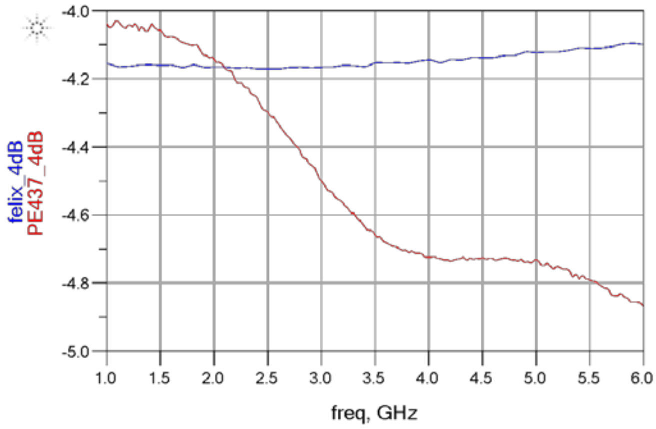


Figure 15: Comparison of 4dB attenuator accuracy versus frequency

The red curve is for the PE43751 DSA 4dB attenuator and the “felix_4dB” is the new X Band DSA 4dB attenuator. The new attenuator is tested as a bare die, probed on a carrier. The die has ground down bonds, equivalent to being bonded in a package. The “felix_4dB” results show a similar characteristic to the simulations with a small ground inductance i.e. the attenuation reduces with increasing frequency due to the inductor. The PE43751 attenuator exhibits an increase in attenuation with increasing frequency, consistent with series inductance due to a package.

A simulation was constructed using the s-parameters from the new 4dB attenuator, with the addition of a pair of series inductors and a shunt inductor. The aim of this simulation is to demonstrate addition of these inductance results in a similar response to the PE43751, and by extension these inductances are due to the choice of package.

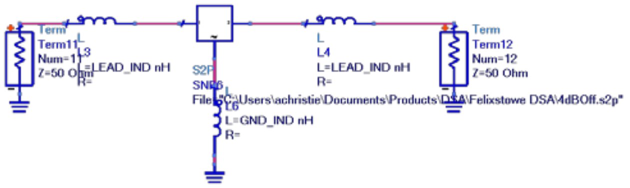


Figure 16. Schematic of New DSA with Lead and Ground Bond Inductance

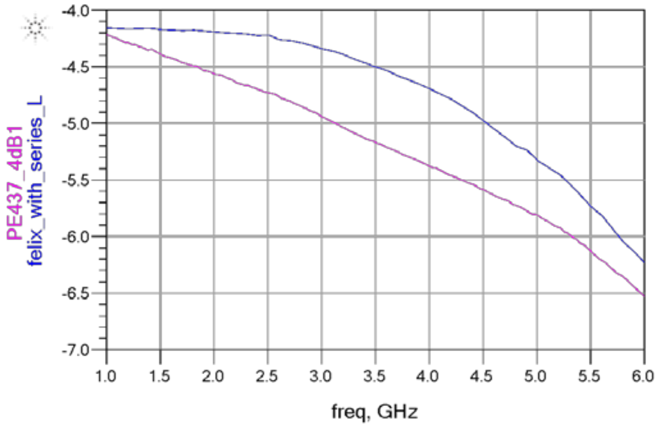


Figure 17 Impact of adding Series and Shunt Inductance

Figure 17 shows the impact of adding series inductance and shunt inductance to the improved “Felix_4dB” DSA. The new DSA response looks similar to the response of the PE43751. The inductor values used to achieve this result were 1.7nH series and 1nH shunt. The lead inductance of a CQFP package is approximately 0.9nH, while the input and output bonds for the PE43751 are relatively long (due to the package choice). The device has 2 parallel input and output bond wires, each pair approximately 1.4mm long. Assuming 1nH/mm per bond wire would introduce approximately 0.7nH of additional inductance. This would result in a total series inductance of approximately 1.6nH.

These results highlight the limitations of using a CQFP package for higher frequency applications. A better alternative for applications at 10GHz is the use of a leadless package, for example a leadless ceramic package. An example of a leadless ceramic package suitable for 10GHz is shown below in Figure 18.

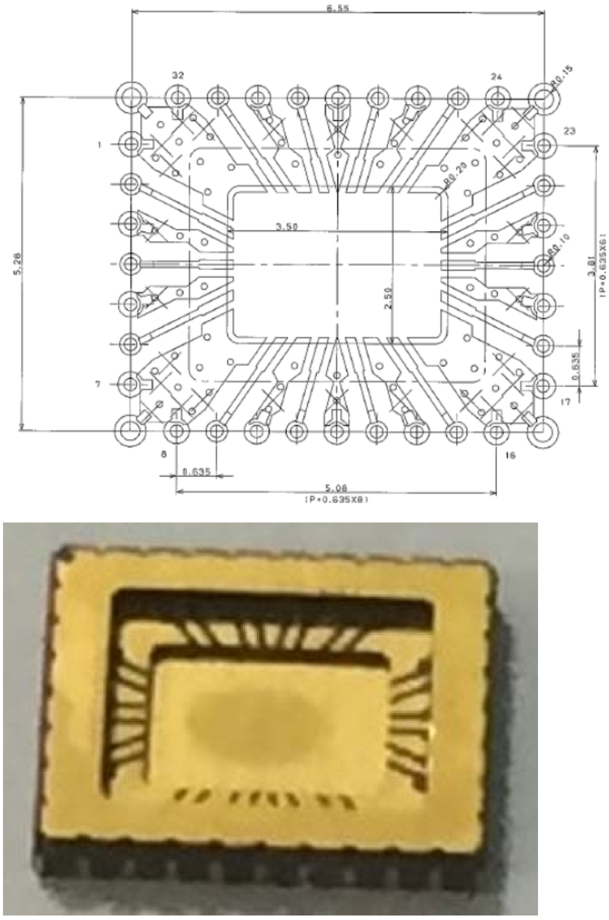


Figure 18: Leadless Ceramic Package

This package has been specifically designed for high frequency operation and uses alternate ground and signal pins, allowing Co-planar wave (CPW) techniques to be used. This coplanar wave approach minimizes the lead inductance and simplifies the transition to a circuit board. Additionally laying out the die to position the input and output bond pads to have the shortest possible bond wire lengths will further improve performance.

D. 4dB Attenuator in leadless ceramic package

The leadless ceramic package in Figure 18 minimises the inductance of the packaged device and allows us to improve DSA performance at higher frequencies. In addition to eliminating the lead inductance associated with a CQFP package the leadless package contains a shelf to reduce bond wire inductance. A partial cross section of the package is shown in Figure 19

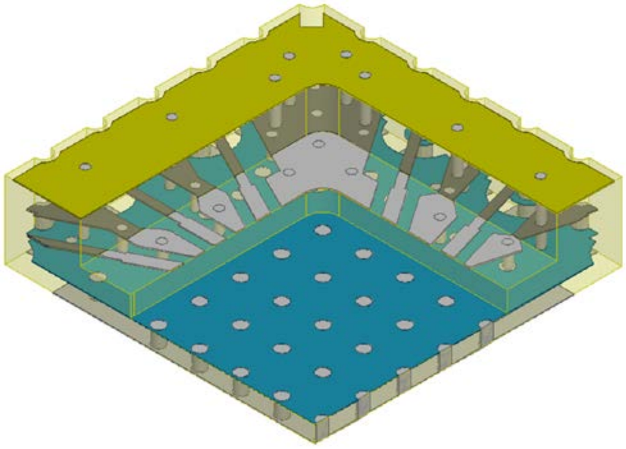


Figure 19: Leadless package cross section

The shelf allows the top of the die to be co-planar to the package bonding area. A simplified cross section comparison between the leadless package and a CQFP can be seen in Figure 20

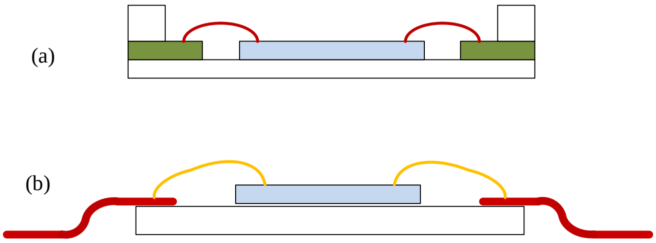


Figure 20: Bonding benefits of leadless package (a) leadless package bonding, (b) CFQP package bonding

Figure 20 (a) shows the bond wire length and shape for the leadless package; Figure 20(b) is the equivalent bond for the CQFP package. The co-planar die and package bond pad significantly reduces the bond loop height and overall length compared to the CQFP package. This results in a significant reduction in the series inductance for the attenuator and DSA.

1) Results for 4dB attenuator in leadless package

To demonstrate the performance improvement of the leadless package compared to the CQFP package the “felix_4dB” (new 4dB attenuator RF probe measurements) was combined with the vendor provided package model in the simulator. The package vendor model consists of a 28 port S-parameter file to model every package I/O from the outside of the package to the bonding area.

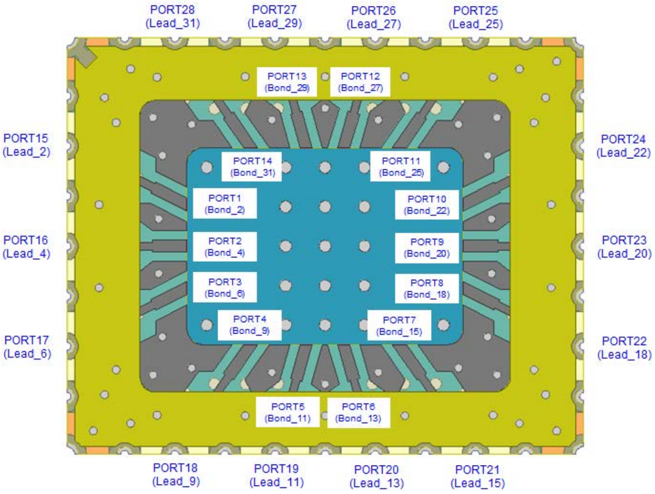


Figure 21: Leadless package 28 port model ports

Figure 21 shows the port numbers for the leadless package. The model can be understood in the following way: alternate pins on the package are ground and RF to create a CPW transition; leads 2, 4, 6, 9, 11, 13, 15, 18, 20, 22, 25, 27, 29 and 31 are the RF connections; all other leads are ground. The S-parameter S(16,2) provides a model for Lead 4 and S(9, 23) provides the model for Lead 9.

Combining the leadless package model and the probed data for the 4dB attenuator we created the following model for the packaged attenuator.

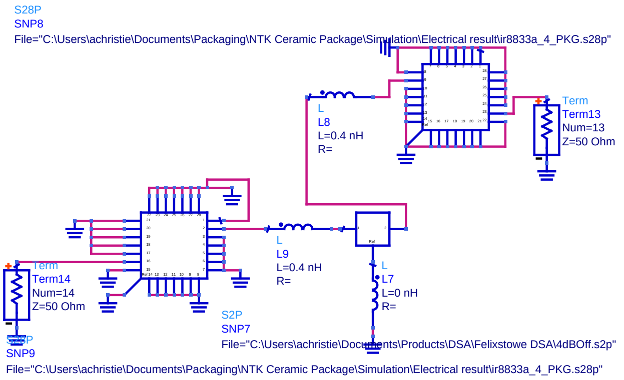


Figure 22: Model for 4dB attenuator and leadless package

The combined model in Figure 22 consists of the package model (S28P file) followed by 0.4nH for the input bond wire, the probe data (S2P file), 0.4nH for output bond wire and the package model. The ground inductance for the probe data (L7) was set to zero as the probe data already includes down bonds. The input and output bond wire lengths are <0.6mm and each consist of a pair of bond wires. 0.4nH is a worst case estimate for the bond wire inductance.

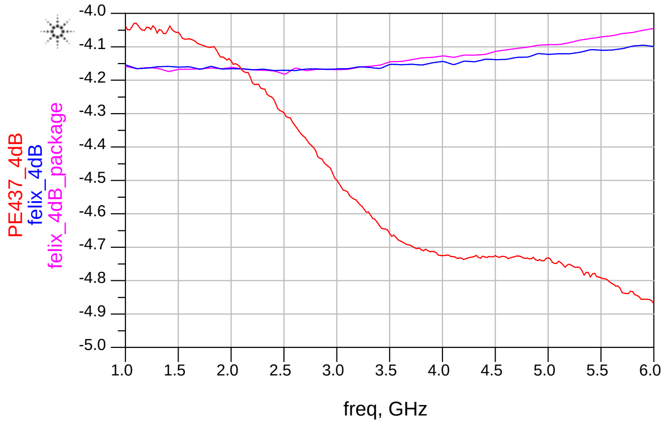


Figure 23: Improved 4dB Attenuator response in leadless package

Figure 23 shows the attenuation of the 4dB attenuator (felix_4dB_package) in the leadless package compared to the improved attenuator probe data (felix_4dB) and the existing PE43751 DSA. The leadless package creates a slight increase in attenuation variation versus frequency compared to the probe data, but the effect is small. When compared to the CQFP packaged PE43751 the leadless package shows a significant improvement in attenuation accuracy and consistency versus frequency.

V. CONCLUSION

This paper presented a 6 GHz Space qualified DSA fabricated in 0.5um SOS CMOS technology. The performance of this DSA was reviewed and used to highlight the challenges of developing high frequency DSAs. DSA architectures were reviewed and a series of simple simulations were constructed to demonstrate how to improve high frequency performance. A method of improving attenuation accuracy was demonstrated using a combination of an improved 4dB attenuator and a new ceramic leadless package. The paper shows that by minimising inductance outside of the die performance significantly improves. This resulted in a 1.8dB improvement in attenuation accuracy for the 4dB attenuator at 6GHz.

VI. ACKNOWLEDGEMENTS

The author would like to thank the following people: Vikas Sharma for technical inputs and suggestions regarding content of this article; Daoud Salameh for developing the improved DSA and sharing measured probe data; John Dench for collecting and post-processing data for the PE43751 DSA and Mark Moffat for editorial comments.

VII. REFERENCES

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[2] PE43705 Data Sheet. http://www.psemi.com/pdf/datasheets/pe43705ds.pdf

[3] HMC424LH5 Data Sheet. http://www.hittite.com/content/documents/data_sheet/hmc424lh5.pdf