Technology Overview

GaN PAs for Microwave Line of Sight Link Applications

GaN technology has proven capability for the realisation of Solid State Power Amplifiers (SSPAs). As the technology matures it is seeing increased adoption for applications requiring high linearity.

This White Paper describes the design of a PA for the 15GHz line of sight link band using Cree's 0.25µm GaN on SiC process. The performance of the initial design is optimised for IP3, the traditional microwave measure of linearity for amplifiers.

The performance of the amplifier when used with QAM 256 modulated signals is then also analysed. Spectral re-growth and Adjacent Channel Power Ratio (ACPR), distortion of the constellation and Error Vector Magnitude (EVM) are all evaluated.

Introduction

Early RF applications of GaN focused on providing high levels of saturated output power. As the technology has matured it is seeing increased adoption for a wider range of uses, including many commercial communications applications requiring high linearity to preserve modulation fidelity. This paper considers the design and analysis of a PA for the 15GHz point-to-point link band.

The initial design work focused on achieving a specific OIP3 (output Referred third order Intercept Point) performance; the traditional metric for assessing the linearity of microwave PAs. However, modern point to point links for high data rate applications, for example cellular backhaul, use complex modulation schemes, such as high order Quadrature Amplitude Modulation (QAM). In these cases the metric of OIP3 is too simple an approach for understanding how amplifiers will perform in practice.

Outline Requirements

Most PAs currently used for point to point microwave link applications are GaAs PHEMT designs. In order for GaN solutions to be adopted, they need to provide a performance advantage at a comparable cost. The outline performance specification in the table below was produced with this in mind.

Process

The design uses Cree's 0.25µm GaN on SiC process biased at 28V Vds, which is capable of delivering 4W of RF output power per mm of gate width. A layout plot of a 4-gate finger transistor is shown overleaf. The use of inter-source vias (positioned beneath each source finger) helps keep the source inductance low and the wide gate spacing provides improved thermal performance.

The high power density of GaN transistors means that careful attention to thermal performance is vital to ensure adequate reliability for the resulting amplifier.

Parameter	Target
Freq. Range	14.5 to 15.35GHz
Gain	> 20dB
OIP3	45dBm at 22dBm per tone
Psat	38dBm
PAE	35%
Chip Area	<< commercial GaAs parts

Target Spec. for 15GHz GaN PA

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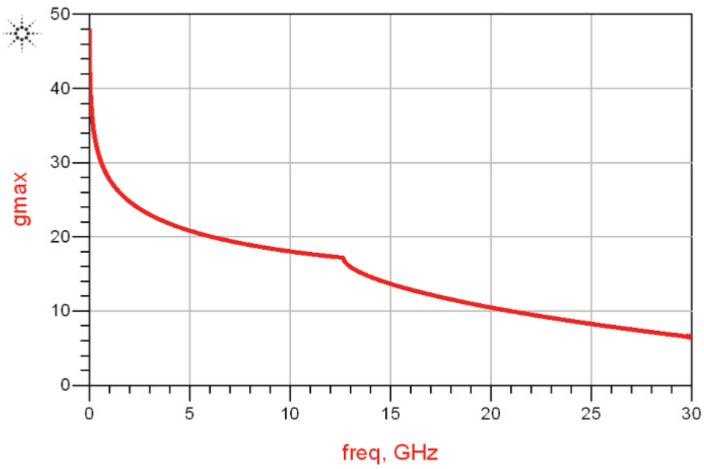
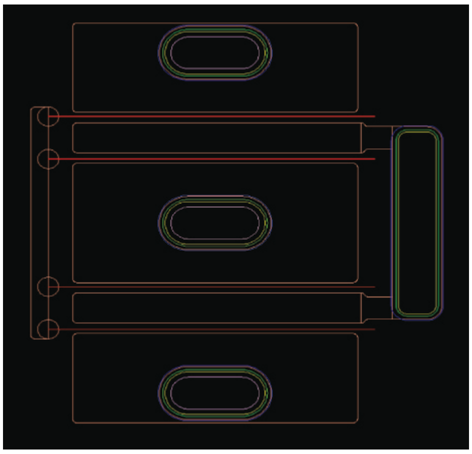
The transistor models in the Cree Process Design Kit (PDK) are able to predict junction temperature and account for the thermal effects on RF performance. To do this they require a value for the baseplate temperature (Tbase) and the thermal resistance (Rth) of the transistor from junction to baseplate. The overall thermal impedance must be determined by the designer and this will vary significantly with the baseplate temperature since the thermal conductivity of SiC reduces by a factor of 2.5 between 25°C and 200°C.



Gmax vs frequency, 1mm device biased at 100mA, 28V



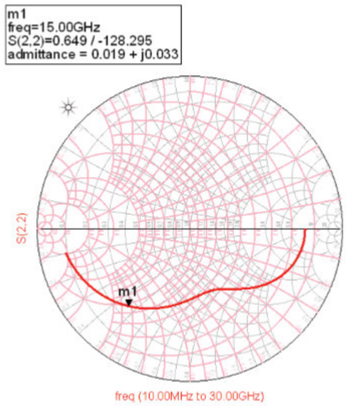
Layout of 1mm GaN Transistor

Preliminary Simulations

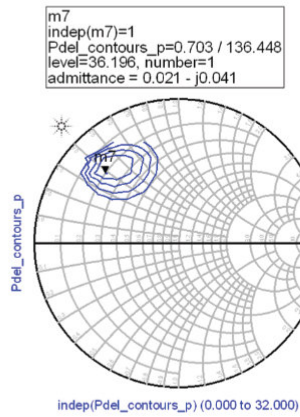
The design process commenced with preliminary simulations to select the preferred transistor size and bias point and to determine the most appropriate topology. The graph above shows a plot of the maximum available gain (Gmax) versus frequency for a 4x250µm transistor (1mm total gate width) biased at 28V Vds and 100mA Ids. The kink in the Gmax curve at around 12.5GHz corresponds to the transition between the lower frequency region of conditional stability and the region of unconditional stability (K > 1) above this. At 15GHz the Gmax is around 14dB. Allowing for implementation losses (matching networks, bias circuitry, gain flattening and low frequency stabilising networks) should still yield a gain of 11 to 12dB per stage in the operating band.

An analysis of the device S22 (see plot, right) suggests that conjugate matching to 50Ω could be conveniently achieved by the addition of a shunt inductor close to the drain. A shunt inductor of around 0.3nH would transform the impedance indicated by marker 1 to the centre of the Smith Chart. This is a benefit of the high voltage operation of GaN, which results in power transistors with a much higher output impedance than comparable devices on competing technologies.

The next step in the design process was to undertake large-signal load-pull simulations. The optimum load impedance was determined for maximum Psat (saturated output power) at 15GHz and load impedance contours were plotted as the input power was varied (see plot below, right). The maximum saturated power delivered to the load is just over 4W (36.2dBm); at this stage no allowance for output matching, combining or biasing networks has been made. A similar set of contours was also produced for Power Added Efficiency (PAE), shown overpage, indicating a maximum PAE for the single transistor of 46.8%. The two optimum impedances for these two cases are not far apart, which is a useful feature of the process.



S22 plot of 1mm device biased 100mA, 28V



Load-pull contours of 1mm device biased at 100mA, 28V

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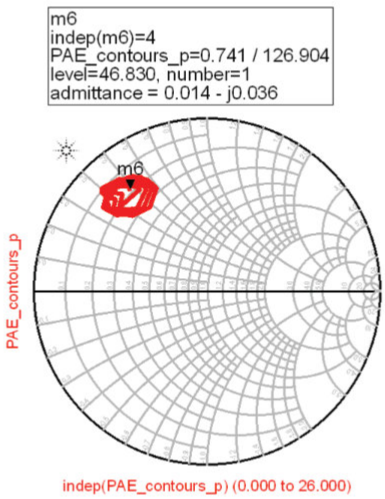
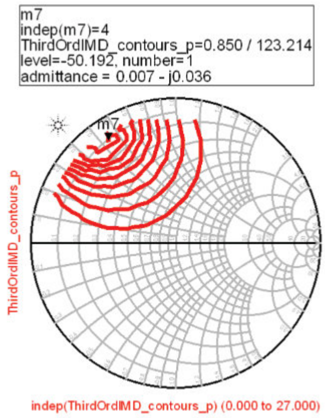
For the application under consideration, linearity rather than saturated output power performance is key. Large-signal analysis was therefore undertaken with two input tones of a specified level and the load impedance for optimum intermodulation performance was determined. This is shown right, where the different contours illustrate the degradation in intermodulation performance as the load impedance moves away from the optimum. At the optimum impedance point the two output tones are each +18dBm so the -50.2dBm third-order product level gives an OIP3 of +43.1dBm.



PAEload pull contours of 1mm device biased at 100mA, 28V

The imaginary parts of the optimum impedance in the large signal analyses presented above is very similar in each case and can be transformed to a real impedance by the use of a shunt inductor close to the transistor's drain. This inductive matching component essentially resonates the Cds of the transistor. The remaining real impedance is 48Ω for optimum Psat performance, 70Ω for optimum PAE and 140Ω for optimum linearity.



TOI load pull contours of 1mm device biased at 100mA, 28V

Detailed Amplifier Design and Layout

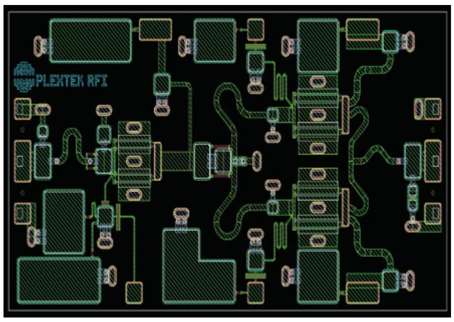
Based on the preliminary simulation work described above, a two-stage amplifier design was implemented, based on two output transistors each of 1mm gate width together with an input driver stage to provide the overall level of small signal gain.

It is important that the input stage is large enough to drive the output stage without exhibiting excessive compression. The gain of GaN transistors is high, which can lead to the conclusion that a relatively small driver stage can be used. This is a mistake as the soft compression characteristics of GaN mean that the driver stage and output stage are compressing simultaneously and the resulting amplifier linearity will be compromised.

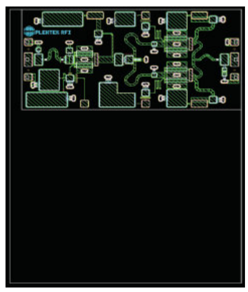
The shunt inductors used for load matching are RF grounded, which provides a convenient place to apply the drain bias. RC decoupling is also included at this point as a convenient means of adding low frequency attenuation and ensuring broadband stability. A transmission line transformer is used to combine the RF power from the two output transistors. Gate bias is applied via a high impedance transmission line, which is meandered to save die area. As with the drain bias, RC decoupling is applied to improve low frequency stability.

A low-pass interstage matching network is used to transform the output impedance of the first stage and to split the signal to drive the two output devices. The nominal quiescent bias current of the complete amplifier was increased slightly during the detailed design and optimisation, from the initial 100mA/mm to 130mA/mm. A layout of the complete two stage amplifier is shown below.

The bottom figure illustrates how the layout of the complete 15GHz amplifier compares with a commercially available GaAs part with similar linearity performance. The black area indicates the outline of the GaAs part. This clearly demonstrates the die area saving that the higher power density of GaN can offer.



Layout plot of the 2-stage GaN PA



Comparison of die area of 15GHz GaN PA and outline of commercially available GaAs part of similar linearity

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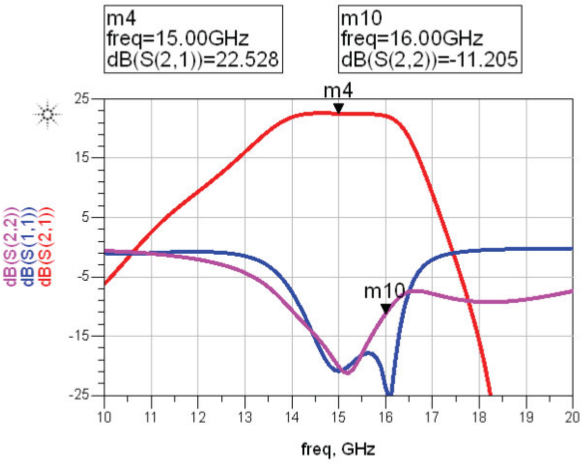
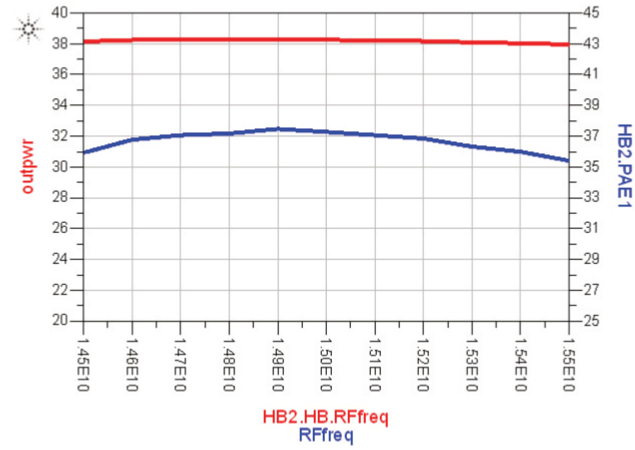


Small signal s-parameters



Output power and PAE at 3dB compression

Simulated Performance

Small signal s-parameters of the amplifier are shown above. The gain is 22.1dB ± 0.4dB from 14GHz to 16GHz providing a healthy guard band on the 14.5 to 15.35GHz operating band. The input return loss is better than 15dB across the band of interest and up to 16.2GHz. The output return loss is better than 14dB across the band of interest and up to 15.6GHz. Improved output return loss is straight-forward to achieve but results in degraded large-signal performance.

The output power and power added efficiency at 3dB compression are plotted above, right. Output power is better than 38dBm across the band and PAE is better than 36%. Further increases in both output power and PAE are possible if a higher level of compression can be tolerated.

The OIP3 versus output tone power was simulated at 15GHz and is plotted overpage, and indicates an OIP3 of 46dBm at 22dBm per output tone. The two tones were spaced 10MHz apart.

The simulations indicate that the target performance requirements of the amplifier have been met. However, investigations were undertaken to look at options for improving the OIP3. This is most conveniently achieved by increasing the quiescent bias current. The figure overleaf shows the improved OIP3 performance when the quiescent current is increased from 130mA/mm (red trace) to 160mA/mm (blue trace) and 200mA/mm (pink trace). It should be noted that appropriate consideration of thermal performance is essential when moving to a higher quiescent bias.

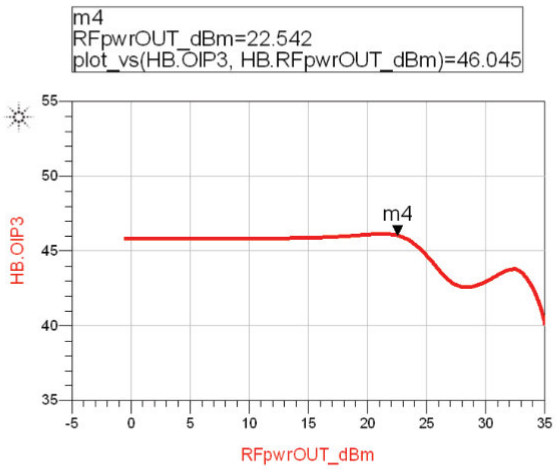
Higher Order Modulation Simulations

The 15GHz PA is intended for use in point-to-point microwave radio links. Such links are used in applications where very large amounts of data have to be conveyed; typically rates of the order of hundreds of megabits, even gigabits, per second.

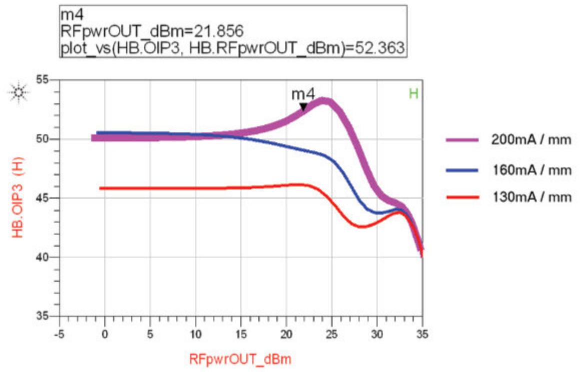
The modulation scheme used in these radio links is chosen to be spectrally efficient, in other words, chosen such that the data is carried whilst occupying the least amount of the radio spectrum necessary. The figure on page 6 presents the constellation diagram of four such schemes: QAM 64, 128, 256 & 512, where each data symbol represents 6, 7, 8 & 9 bits respectively.

The corresponding eye diagrams for these schemes are also presented on page 6 and show the point in the received transmission where the signal has to be sampled to correctly determine its identity. The figure shows the eye diagram in the I (in-phase) plane and there will be a corresponding eye diagram (not shown) for the Q (quadrature) plane. Notice how there is little margin for error for the receiver symbol timing recovery loop to ensure the receiver samples the signal at the correct sampling point, namely the middle of the eye.

The occupied spectrum of QAM 64, 128, 256 & 512 modulation schemes are all virtually identical to each other and an example of an undistorted spectrum of QAM 256 is given on page 7. The rectangular-like spectrum shows it will be well confined in frequency to an allocated channel, which is a result of root-raised cosine filtering of the digital modulation. The displayed spectrum is referenced to a 1Hz bandwidth so must be scaled appropriately for the specific application. In this case, the application is for a 15GHz Class 4H transmission with a 56MHz channel spacing and a symbol rate of 46MBd.



OIP3 versus power per tone at 15GHz



OIP3 versus power per tone at 15GHz for 3 different quiescent bias currents

The class 4H transmission is one of a set of transmission standards applied to point-to-point links as specified in ETSI standard EN 302217. This standard specifies a transmit mask within which the modulated spectrum must lie and this is also depicted on page 7.

A drawback to these spectrally efficient modulation schemes is that they are corrupted by non-linearities in the transmission system and one of the largest contributors is non-linearity due to the PA when it is driven towards its maximum output. It is important not to overdrive the PA in such systems in an attempt to get more output power because this will corrupt the modulation.

The first way in which the corruption can be observed is as a distortion of the modulation constellation leading to eye closure, which in the worst case could mean one transmitted data symbol being read as a different symbol at the receiver, leading to large transmission errors. Error Vector Magnitude (EVM) is one measure of characterising this effect and specifications for radio links will have an EVM figure that the system must meet.

A second way in which PA distortion manifests itself is in the generation of intermodulation products (also known as spectral regrowth) in nearby channels. This is a spilling of the modulated spectrum into channels occupied by other users and the extent of this must therefore be restricted. The spectral mask defined by standards such as ETSI EN302217 is one example.

The impact of PA distortion on the link modulation can be predicted using a radio system simulator such as Matlab/Simulink. Such simulators can generate random data streams which can then be modulated, for instance using a QAM 256 modulator, and root-raised cosine filtered and then applied to a non-linear model of the PA. The output of the PA can then be observed and compared in terms of its spectrum, eye diagram, constellation diagram and EVM against the various mandatory and operational requirements. The major blocks of this system simulation model are shown in the final figure below.

The PA non-linearity is modelled using the level dependent magnitude and phase of the voltage transfer function for the amplifier generated using the RF circuit simulator (Agilent ADS). A sanity check must first be performed to ensure the distortion predicted by the system simulator matches with that predicted by the circuit simulator. A two-tone third order intermodulation simulation is undertaken to do this.

The results of the comparison for the OIP3 versus tone power for the two stage PA biased at 130mA/mm is presented on the last page and shows a very good match between the two simulations. This gives good confidence that the results of the system simulation will be representative of a final design.

The next step is to drive the PA with QAM 256 modulation at a level relative to a reference such as the 1dB gain compression point or the IP3 point and observe the effect of the amplifier behaviour on the constellation, eye, spectrum and EVM. The drive level into the PA is set by the "Adj. Drive Level" block and is initially set to 6dB back off with respect to the 1dB compression point, giving a mean output power of 29.4dBm.

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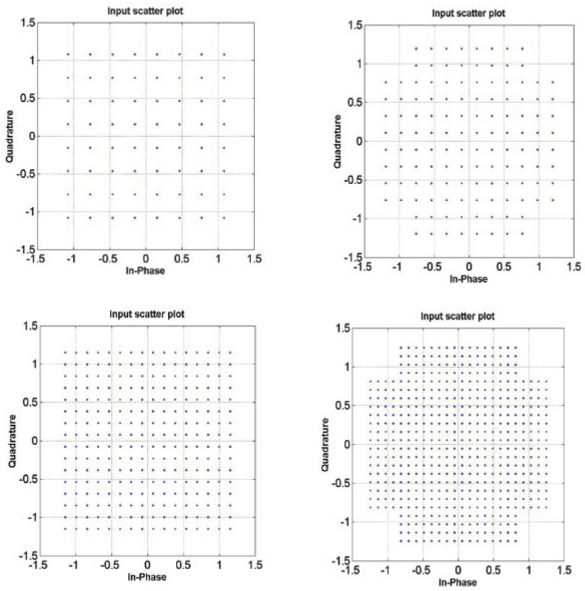
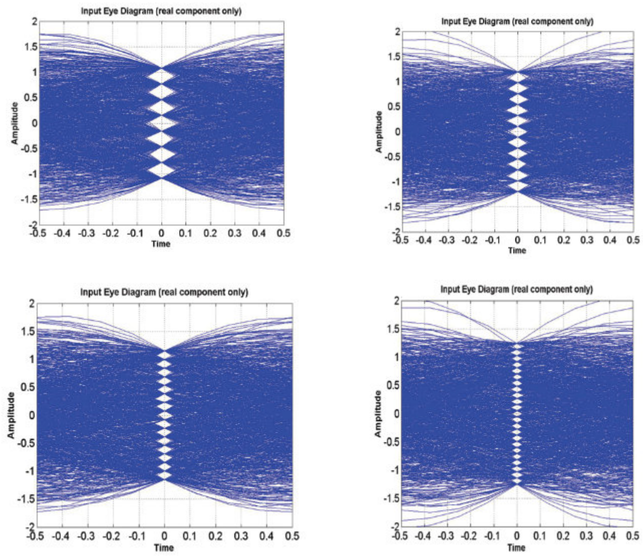


Constellation diagram of higher order modulation schemes. Clockwise from top left: QAM 64, 128, 512 & 256.



Eye diagram of higher order modulation schemes. Clockwise from top left: QAM 64, 128, 512 & 256.

The resulting output constellation, eye and spectral diagrams, presented on the last page (top), show some eye closure and constellation corruption, particularly at the extremes where the instantaneous power of the modulated signal is highest. This corruption is reflected in an EVM reading of -32.7dB, corresponding to 2.3%; a better EVM target for QAM 256 would be of the order of -38dB or 1.25%. The spectrum is just contained within the mask but only by 1 or 2dB around the 0.8 to 1Hz normalised offset point in the diagram; again more margin here would be preferred.

The system simulation was re-run at an increased current of 160mA/mm and at a drive level to give the same 29.4dBm output power. The results are presented in the final figure and the improvement to constellation and eye plots is clear with the corresponding EVM of -37.8dB (approx 1.3%) being very near target.

The spectral plot now shows greater than 7dB margin with respect to the spectral mask.

Conclusions

This case study has demonstrated the suitability of GaN technology for the realisation of a 15GHz PA MMIC for high data rate point to point link applications. Key steps in the design process, including preliminary load pull simulations, were highlighted and simulations of the complete amplifier design were presented. Good performance was achieved across the required operating band of 14.5 to 15.35GHz. Small signal gain is 22.1dB ±0.4dB, the output power at 3dB compression is better than 38dBm with corresponding PAE better than 36%.

At 130mA/mm quiescent bias the OIP3 is 46.0dBm at 22dBm per output tone, and this increases to 48.5dBm for 160mA/mm bias and 52.4dBm for 200mA/mm.

The layout of the completed GaN part showed a reduced die area compared to that of a commercially available GaAs part with similar linearity performance.

For communications applications, PAs must be driven at a level that is backed off from full compression. This is to ensure that the distortion introduced by the PA's non-linear characteristic does not excessively corrupt the signal modulation. A behavioural model of the amplifier was developed for use in a system simulator to allow analysis of key performance metrics such as adjacent channel power and EVM when driven by typical high order modulation signals such as 256 QAM. For the case of a QAM 256 application the PA met the appropriate ETSI spectral mask and achieved a 1.2% EVM with a mean output power of 29.4dBm when operated at a quiescent bias current of 160mA/mm.

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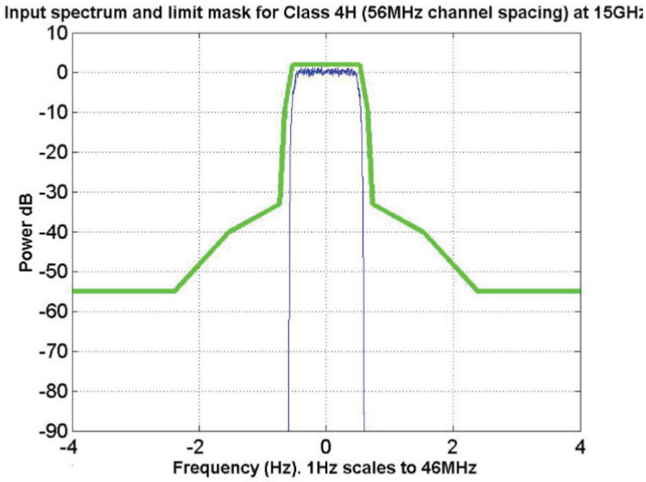
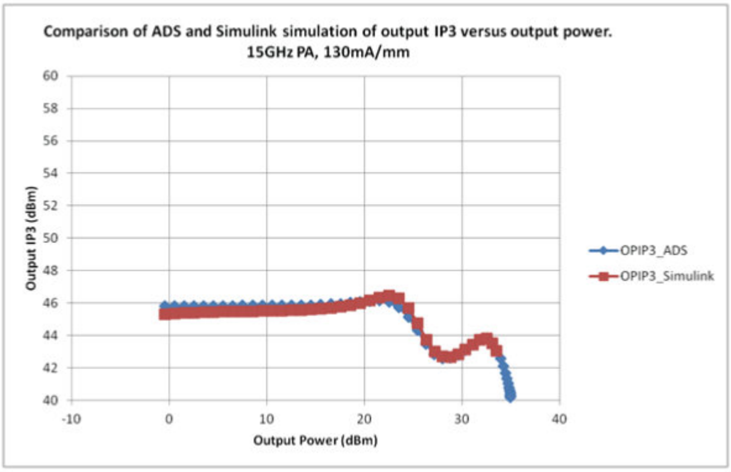
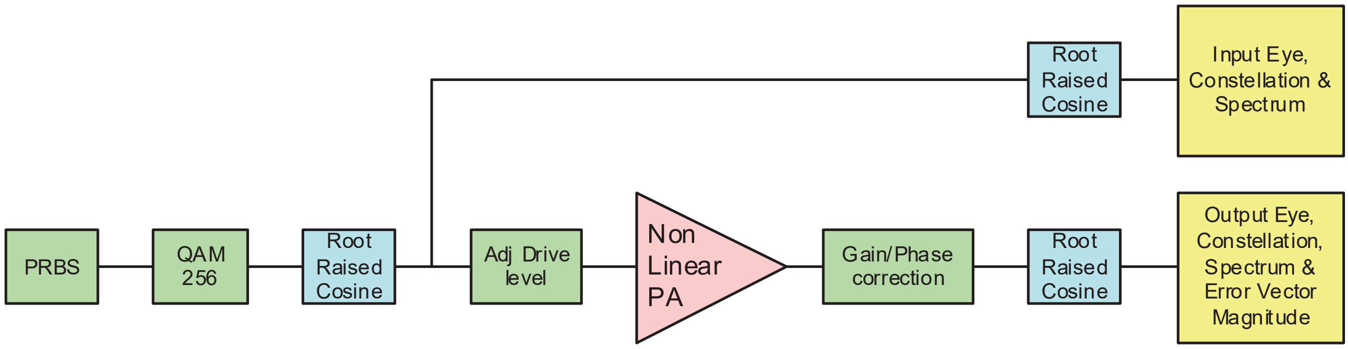


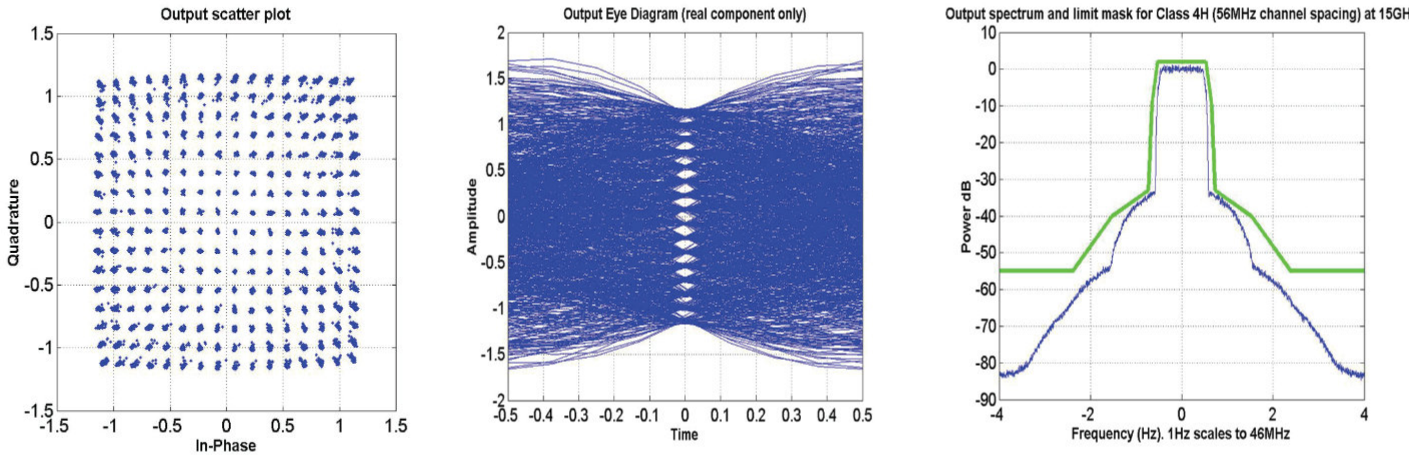


QAM 256 modulation spectrum and associated transmit spectral mask for point-to-point links using EN 302217 Class 4H transmissions.

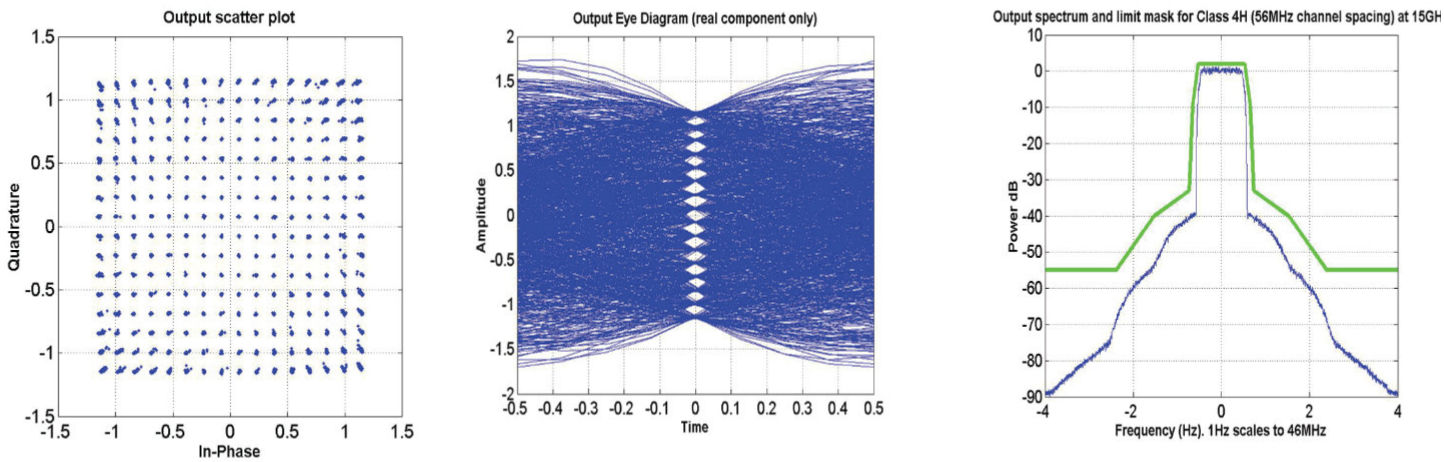
Comparison of ADS and Simulink simulation of output IP3 versus output power. 15GHz PA, 130mA/mm



Radio system simulator block diagram for observing the effects of drive level into a non-linear PA on its output



Constellation (left), eye (middle) and spectrum (right diagrams for 15GHz QAM 256 PA at 130mA/mm driven 6dB backed off from P1dBc. Output power is 29.4dBm.



Constellation (left), eye (middle) and spectrum (right) diagrams for 15GHz QAM 256 PA at 160mA/mm driven. Output power is 29.4dBm

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