Design of X-Band High Power Cascade Amplifier

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This article is the design case history of a 10-watt X-band power amplifier module for either satellite or terrestrial microwave communications

To ensure sufficient link budget of a microwave link, the high power amplifier (HPA) is of one of the essential sub-circuits used to amplify the modulated signal prior to the transmission. In the design of a high frequency HPA, the goal is to achieve sufficient power gain, output power and high PAE at the desired frequency. However, to achieve optimum electrical performance of a HPA, there are a lot of considerations that need to be taken care of such as impedance matching, DC bias network design, grounding and heat sinking of the HPA device.

Today, most semiconductor manufacturers produce internally matched HPA devices at X-band to shorten the designers' development time. Even though the device used is internally matched, ignoring the considerations mentioned above may lead to the device breakdown or oscillation. Degradations are primarily caused by insufficient device grounding and RF signal leakage to the bias network. In this paper, the design of a bias network and a simple microwave divider were evaluated. Next, a 2-watt MMIC HPA and a 10-watt HPA were designed and evaluated separately prior to integrating them with a RF detector circuit at the HPA output. The HPA housing dimension is critical, as improper design may lead to cavity resonance. Practical approaches on how to dampen the cavity resonance are presented.

HPA Design Considerations

At the initial stage of prototyping, the major constraints faced were insufficient power gain, low output power at P_{1dB} and oscillation. The reasons are identified and listed below. For all the X-band prototypes, the substrate used is the Roger RO4003 with a thickness of 0.508 mm and relative permittivity, ε_r of 3.38. The lumped elements are ceramic capacitors and resistors manufactured by ATC Inc.

HPA Device and PCB Grounding

The PCB and active device grounding of the initial prototypes relied merely on the screws. It is found that the amplifiers oscillate occasionally. Therefore the PCB and HPA device ground was then epoxied directly onto the metallic housing using thermally and electrically conductive silver epoxy, EPO-TEKH20E. This is to ensure proper electrical contact (DC and RF ground) and thermal conduction (heat sinking) of the HPA device and PCB ground plane to the aluminium housing. The chosen epoxy requires thermal curing of 20 minutes at 120°C. Higher temperature would shorten the time. However the temperature set should not exceed the absolute HPA device temperature. It has been found that the HPA without epoxy has insufficient ground contact, and leading to lower power gain and output P_{1dB} measured. In the worst case, the HPA device may become unstable and start to oscillate.

DC Blocking Capacitor

The Equivalent Series Resistance (ESR) of the capacitor has to be as small as possible to minimize the coupling loss [1]. The self-resonant frequency of the DC block capacitor should not fall near the operating frequency [2]. ATC 600F series capacitor is selected since it has very low coupling loss and high resonant frequency. The easiest way to determine the suitability of a capacitor is to measure the

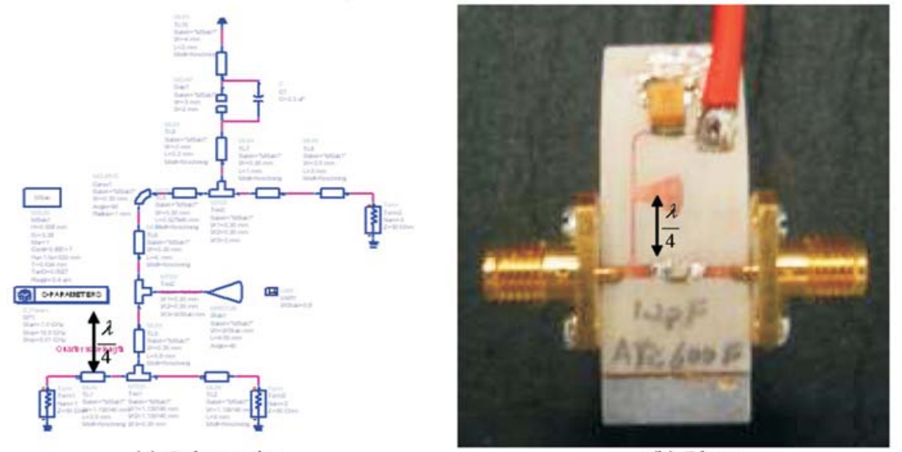

Figure 1 · The bias network consists of a quarter-wavelength radial stub and a tantalum capacitor.

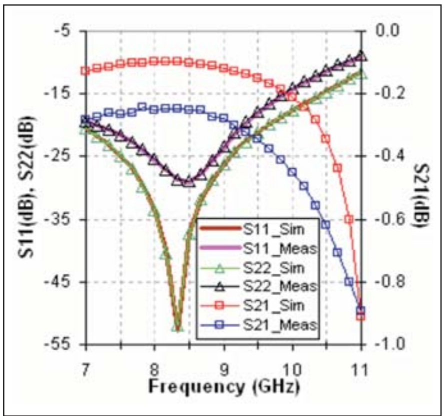

Figure 2 · Simulated and measured *S*-parameters of the DC bias network.

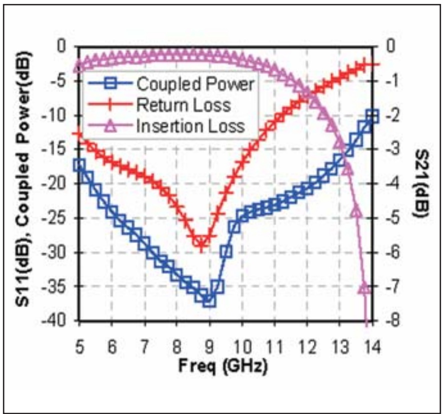

Figure 3 · Measured insertion loss, return loss and coupled power of the X-band power divider.

insertion loss of the capacitor. Since the *S*-parameters of each capacitor value are available from the ATC Web site, any simulation tool can be used to predict the insertion loss and resonant frequency of a capacitor.

DC Bias Network

Most designers do not spend much time to characterize the performance of the bias network. Improper design of a DC bias network may lead to oscillation if the RF signal leaks to the DC supply. Hence it is worthwhile to evaluate the bias network before designing the HPA. The objective of the bias circuit design is to minimize the insertion loss while pertain high RF isolation to the DC source. The design of bias network is well known by using a high impedance quarter-wavelength transformer with either a radial stub [3] or chip capacitors [4]. As part of the investigation, the biasing network was epoxied onto an aluminium block. The bias network consists of a quarter-wavelength transformer at 8.3 GHz and a radial stub as shown in Figure 1. The length of the stub is slightly shorter than quarter-wavelength and the angle subtended by the stub is 45°. A 15 µF tantalum capacitor is added as a bypass capacitor. The circuit was simulated in the ADS 2003 and measured using the Anritsu VNA. Figure 2 shows that the insertion loss of the bias circuit measured is less than 0.4 dB from 7 to 9 GHz with a return loss of –20 dB. Note that the insertion loss measured includes the coupling loss introduced by the DC block capacitor.

Design of the Microwave Divider

A directional coupler is usually used to couple forward and reverse power at the output of a HPA. In fact, the coupler can be replaced by a simple power divider circuit. The divider is modified and realized based on the bias network described in previous section. It can be designed to have a coupling power of 25 dB to 35 dB. By using a quarterwavelength transformer and a radial stub, the measured leakage signal to the bias network is approximately 30 dB at 8.3 GHz (leakage power is therefore 30 dB). To further reduce the RF signal leakage, placing a high capacitance tantalum as shown in Figure 1(b) is recommended to achieve an isolation of up to 35 dB (coupled power will be 35 dB in this case). Thus the leakage power in a bias network is similar to the forward coupled power in a conventional 4-port coupler. With this topology, the insertion loss of the divider is significantly lower than a conventional coupler because the insertion loss of the divider is independent of the coupling ratio. The leakage power is adjustable by optimizing the stub dimension or by using tantalum capacitor with the right capacitance. The only disadvantage of such configuration is that the "coupled" power is not flat across a wideband of frequency as shown in Figure 3. This is because the stub is a narrowband, frequency dependent element. In addition, it may be also due to the parasitic introduced by the tantalum capacitor. For the current application, it is not a serious concern since the objective is to ensure that the divider contributes the lowest insertion loss. The insertion loss mea-

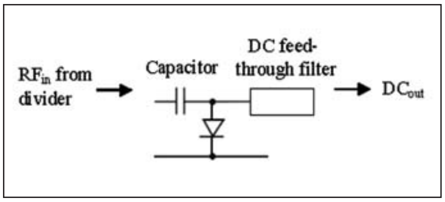

Figure 4 · Detector circuit.

sured is less than 0.4 dB with 35 dB of "coupled" power at 8.3 GHz.

RF Detector Circuit

The RF detector is incorporated at the output of the divider. The RF detector used is a surface mount Schottky mixer diode, HSMS-8202, manufactured by Agilent Technologies. The approach used is the self-biased (zero bias) single diode detector [5] as shown in Figure 4. Such detector could be realized either by placing it in series or in shunt. In this project, the Schottky diode was shunted across the microstrip to the ground. When RF power is coupled to the divider, the diode will convert the RF power to a DC voltage. Hence different RF power level at the HPA output will generate a DC level. A capacitor is placed in series to block the converted DC from flowing back to the divider. A DC feed through filter (similar to LPF) is added to filter out analogue signal at the output.

The Cascade HPA Module

The HPA1 is a MMIC, Fujitsu FMM5057VF, which has a typical gain of 26 dB and P_{1dB} of 34 dBm while the HPA2 is a GaAs FET, Fujitsu FLM 7785-12F, which has a typical gain of 8.5 dB and P_{1dB} of 40.5 dBm. Both devices are hermetically sealed package and internally matched to 50 ohm at the input and output. HPA1 is biased at VDS of 10 V, 1.1 A and VGS of –5 V, 20 mA. HPA2 is biased at VDS of 10 V, 2.9 A and VGS of –0.5 V, 1 mA. The small signal gain of HPA1 and HPA2 measured using VNA is 26 dB and 9.5 dB respectively. The HPA2 is cascaded after the HPA1. An isolator is placed after the HPA2 so that the HPA device can be protected from damage if there is any reverse power from the antenna unit. The isolator used has an insertion loss of 0.7 dB and isolation of 34 dB at 8.3 GHz. The detector is incorporated at the divider output. It is worthwhile to note that it is important to power on and off the HPA devices in a proper sequence to avoid the device burnout due to transient. A good recommendation of proper bias sequences is available in [6].

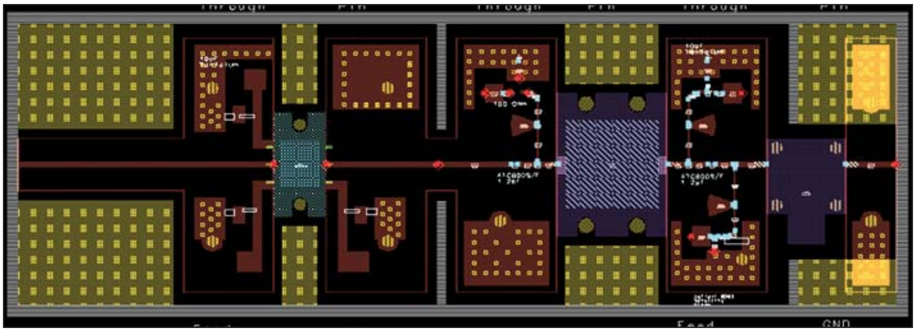

Figure 5 · PCB layout of HPA module.

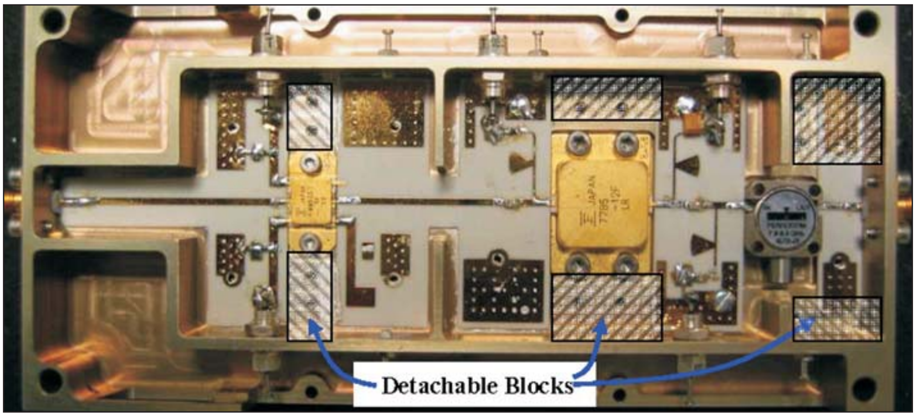

Figure 6 · Inner view of HPA module developed.

Figure 5 shows the layout of the HPA module designed in the ADS layout. With operating frequency going higher into the microwave and millimeter-wave band, the cavity resonance effects become a common problem when the standing wave resonance (SWR) peaks at certain points. In the design, more isolation walls and blocks are added to avoid cavity resonance. The walls in the grey colour are fixed while blocks shaded in yellow are detachable blocks. If the cavity resonance happens, the detachable blocks can be installed into the module to solve the problem. The completed module is shown in Figure 6.

When the SSPA was first powered up, a resonant frequency of 7.55 GHz is observed on the VSA even without feeding test signal at the input. However, if the cover was removed, nothing was observed on the VSA. It has been identified that the cavity resonant is introduced by the HPA1 because resonant frequency is detected only when the HPA1 compartment is enclosed. Furthermore, the resonant frequency can be observed on the VSA even only HPA1 is powered up.

The effect of cavity resonance is mainly due to the module height and the housing structure. The standing wave has the characteristic such that the E and H fields are 90° out of phase with each other. The impedance will therefore fluctuate wildly across the cavity causing unknown effects on circuitry including the introduction of instability to active devices [7]. It is

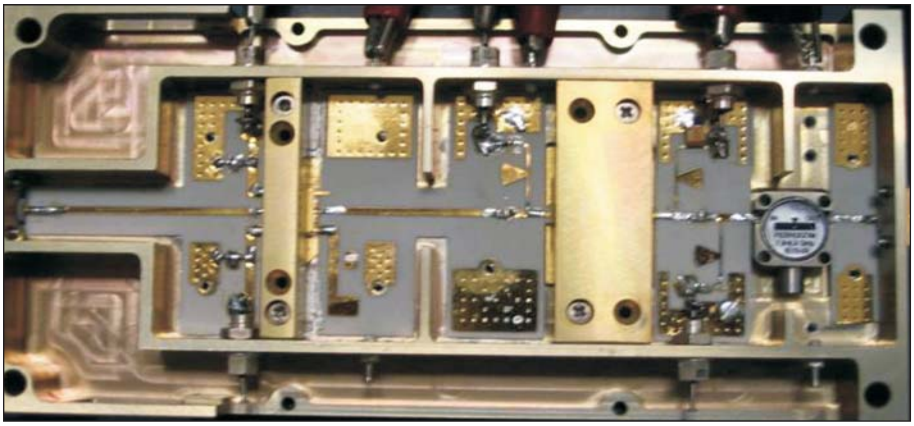

Figure 7 · Removing cavity resonance using aluminium blocks that extend over the HPA devices.

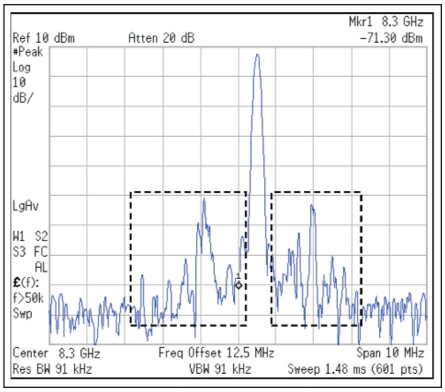

Figure 8 · Spectrum plot showing the output carrier with spurious caused by RF in the DC supply.

hard to simulate the impact of cavity because not all the component properties can be accurately defined, especially the active components. A more practical approach is to examine and identify the cavity resonance on the actual hardware. Relocating a particular circuit element to a different position in the cavity can often fix the problem but it involves an investment in engineering redesign time and possible manufacturing delays. Hence a few simpler approaches are demonstrated to solve this problem.

Microwave Absorber

Pasting microwave absorber on the module cover is the quickest and easiest solution to get rid of cavity resonance. The absorber placement is determined based on the cut-and-try trial and error method. This solution might incur additional cost to purchase space grade absorber or to conduct qualifying tests for the absorber and adhesive material. In addition, the output power is a few dB lower due to the wave absorption.

Detachable Isolation Block

The concept of using isolation block is to disrupt the standing wave via intelligent positioning of the blocks. It is difficult to determine *a priori* where the optimum blocks placement would be because the isolation blocks act to damp the resonance sometimes, other times they act to shift the SWR peaks to a less detrimental location. As a result, this approach might require more time to determine the optimum placement of the blocks.

Since most cavities are somewhat rectangular in shape [7], two isolation blocks extending over the HPA devices were manufactured to reduce the cavity size of each compartment, as shown in Figure 7. This method effectively damps the resonance but unfortunately another problem arises. When CW was fed into the SSPA input, the output carrier was coupled with spurious, as shown in Figure 8. This resulted in extremely high EVM and PE of the modulated signal. The cause was identified as interference from the input RF on the DC supplied to HPA1. To filter out the spurious, the optimal arrangement is to detach the first isolation block and add another two tantalum capacitors to the bias network of HPA1.

Performance of the SSPA Module

The optimized SSPA module was enclosed with screws as shown in Figure 9. The amplifier was tested with 25 Msps QPSK signal at 8.3 GHz.

To examine the Relative Constellation Error (RCE) of the modulated signal introduced by the these HPAs, the 25 Msps QPSK test signal was generated from the Agilent PSG E8267D Vector Signal Generator (VSG) instead of Continuous Wave (CW) and analyzed by using the Agilent PSA E4440A Vector Signal Analyzer (VSA). The performance of the engineering model is shown in Figure 10. Figure 10 (c) shows that the DC voltage measured at the output of the detector. Each RF power level is corresponding to a DC level. At the output power of 38.5 dBm, Figure 10(d) shows that the 2nd and 3rd harmonics are at least 60 dBc below the desired frequency.

Conclusion

When testing the RF subcircuits in a microwave transmitter, the modulated signal should be used instead of CW. The evaluation of bias network is recommended to ensure minimum RF leakage at the frequency band of interest. By modifying the DC bias network, the insertion loss of the described X-band divider is significantly lower than a conventional coupler, if broadband coupling response is not required.

Figure 9 · Outer view of the optimized HPA module.

It is common to encounter cavity resonance when RF circuits are placed in an enclosure. Without much redesign and rework effort, microwave absorber or a detachable isolation block can be used to eliminate the cavity resonance. Depending on the system requirement, the trade-off between the tolerable impairment and desired output power can be determined.

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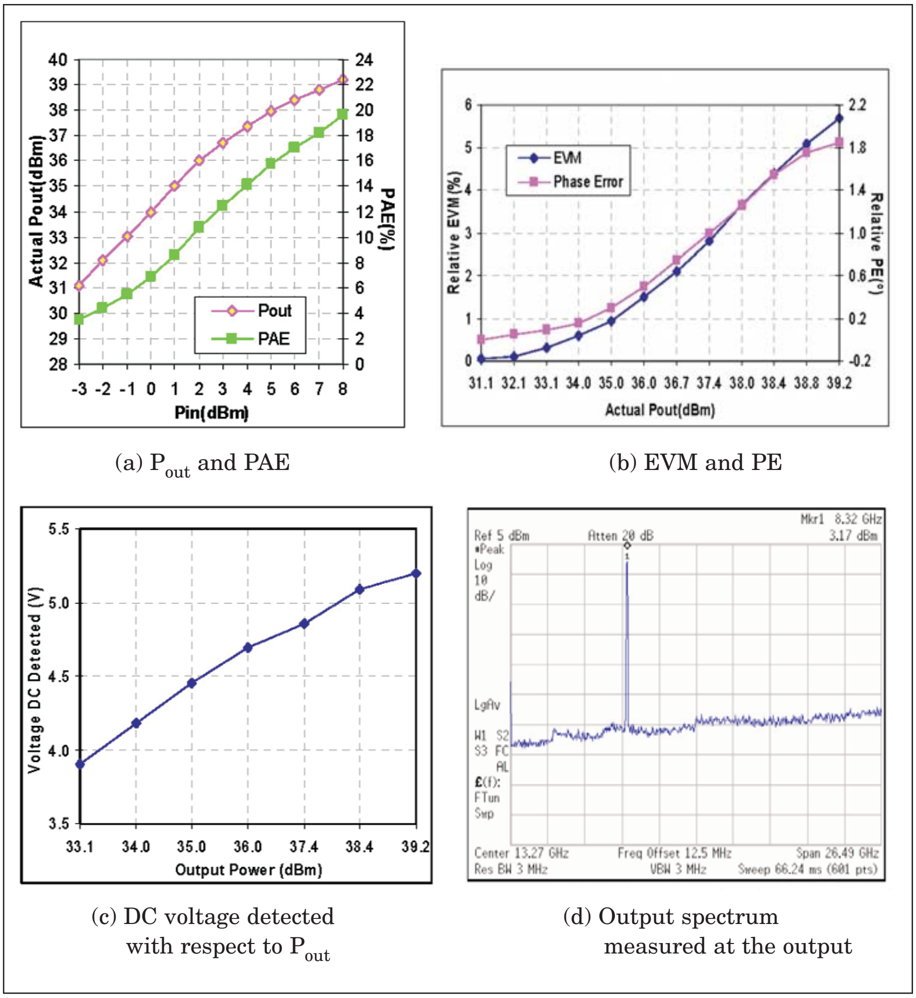

(a) P_{out} and PAE

(b) EVM and PE

(c) DC voltage detected with respect to P_{out}

(d) Output spectrum measured at the output

Figure 10 · Performance of the optimized HPA module.

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