APPLICATION **NOTE**

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AWR Software for the Design of a High-Efficiency Broadband GaN HEMT Doherty Amplifier for Cellular Transmitters

Next-generation 4G/5G telecommunication systems require power amplifiers (PAs) to operate with high efficiency over a wide frequency range to provide multi-band and multi-standard concurrent operation. In these systems with increased bandwidth and high data rates, the transmitting signal is characterized by high peak-to-average power ratio (PAPR) due to wide and rapid variations of the instantaneous transmitting power. Therefore, it is important to provide high efficiency at maximum output power and at lower power levels typically ranging from 6dB backoff and less over a wide frequency bandwidth.

Design Overview

This application note describes the design of an innovative Doherty amplifier architecture using 200W high-efficiency broadband 1.8-2.7GHz gallium arsenide (GaN) high-electron mobility transistor (HEMT) technology, which achieved average efficiencies of 50-60 percent for output powers up to 100W and significantly reduced the cost, size, and power consumption of the transmitters. The designers used Cadence® AWR® Microwave Office® circuit design software within the Cadence AWR Design Environment® platform for the development of this amplifier.

Previously published work in this area includes a conventional Doherty amplifier with a quarter-wave impedance transformer and a quarter-wave output combiner. The measured power-added efficiency (PAE) of 31 percent at backoff power levels of 6-7dB from the saturated output power of about 43dBm has been achieved across the frequency range of 1.5-2.14GHz.[1] To improve the broadband performance of a conventional Doherty amplifier, an output network can be composed of two quarter-wave impedance inverters with reduced impedance transformation ratios.[2] For broadband combining, an output quarter-wave transmission line with fixed-characteristic impedance can be replaced by a multi-section transmission line consisting of different characteristic impedances and electrical lengths in order to cover the frequency range from 2.2-2.96GHz.[3]

In this case, the broadband matching was realized by applying the simplified real-frequency technique with the desired frequency-dependent optimum impedances. However, nonlinear optimization of the entire Doherty amplifier system made the design more complicated in terms of circuit simulation and results in a sufficiently large size of the final board implementation.

Another example includes a PA design with high-peak power of 350W that was achieved across the lower frequency band of 760-960MHz using a modified combining scheme with two quarter-wave lines in the peaking path.[4] Using an asymmetric Doherty architecture, the saturated power of more than 270W and linear gain of more than 13dB with a drain efficiency of more than 45 percent at 8dB backoff points was achieved across the frequency range of 2.5-2.7GHz.[5]

Packaged Device

Multi-band Doherty amplifier capability can be achieved when all of its components are designed to provide their corresponding characteristics over the required bandwidth of operation. In this case, the carrier and peaking amplifiers should provide broadband high-efficiency performance when, for example, their input matching circuits are designed as broadband and the load network generally can represent a low-pass lumped or transmission-line structure with two or three matching sections. Therefore, it was very important for matching circuits to be partly implemented inside the device package to achieve an average output power of 40W and higher, especially for input matching circuit in view of very low device impedance across the required frequency bandwidth.

Figure 1 shows the equivalent circuit of the device inside the package with input matching elements and the small-signal S_{11} parameters at the input of the internal input matching circuit including package lead-frame. Here, the Sumitomo 50V device represents six basic 15W GaN HEMT cells connected in parallel and capable of providing more than 80W of saturated output power across the entire frequency bandwidth of 1.8-2.7GHz. The three-section microstrip transformer was implemented using a 0.16mm thick alumina substrate with high permittivity of 250 to achieve a compact structure.

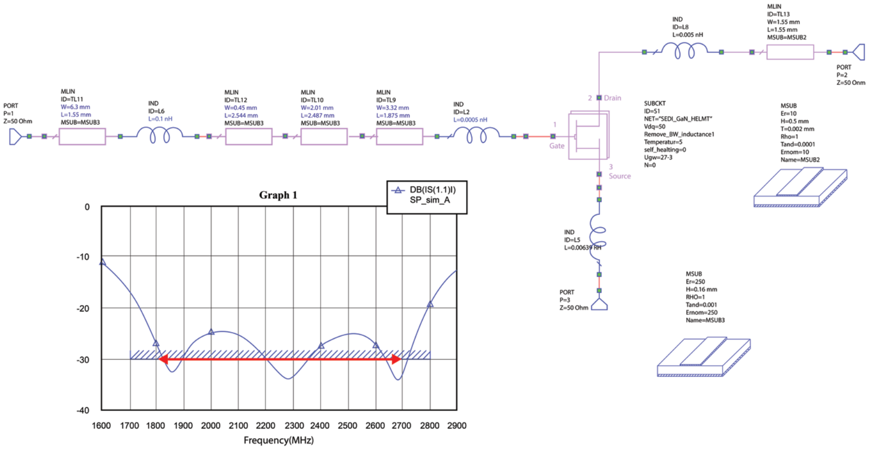


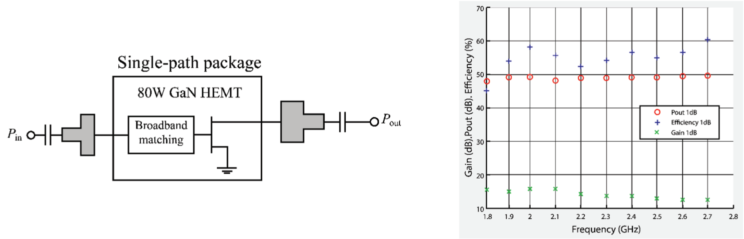
Figure 1: Equivalent circuit of packaged devices and its input return loss performance(dB(|S11|)

Through this structure, the impedance of the (bare transistor die) gate terminal was transformed to ~10ohm at the reference plane of the package input. When referenced to an environment with a 10ohm characteristic impedance, a return loss better than 25dB was achieved across the band of interests.

Broadband Performance

Generally, the multi-band impedance transformer required for broadband operation can represent a configuration with N (N ≥ 2) cascade-connected transmission lines with different characteristic impedances.[6] As an example, in order to match the output impedance of 25ohms with the load impedance of 50ohms, the broadband output transformer can be realized using a two-section microstrip line, where the characteristic impedance of the first quarter-wave section is equal to 30ohms and the characteristic impedance of the second quarter-wave section is set to 42ohms. In this case, the magnitude variations of ±0.5ohms and phase variations of ±1° of the input impedance was achieved across the frequency range from 2.0 to 2.8GHz covering simultaneously 2.1GHz (2.11-2.17GHz) and 2.6GHz (2.62-2.69GHz) wideband code-division multiple-access (WCDMA)/long-term evolution (LTE) bands.[7] At the same time, the magnitude variations of ±1.0ohms and phase variations of ±2 degrees were achieved with a 1GHz bandwidth from 1.9 to 2.9GHz, which meant that reducing the mid-band frequency to 2.3GHz resulted in a simultaneous tri-band operation with inclusion of an additional 1.8GHz (1805-1880MHz) digital cellular system (DCS)/WCDMA/LTE bandwidth.

Figure 2a shows the simplified circuit schematic of a single-ended 80W GaN HEMT power amplifier operating in a Class-AB mode with external input and output matching circuits to operate over a frequency bandwidth from 1.7-2.7GHz. Here, the input and output matching circuits implemented on RO4350 substrate (material from Rogers Corporation) represent the two-stepped microstrip-line transformer, each with different characteristic impedance ratio and different electrical lengths of the microstrip-line sections, providing the conjugate matching with the device input and equivalent output impedance at the fundamental frequency.As a result, an output power P1dB of more than 48dBm with a power gain of more than 12dB and drain efficiency of more than 52 percent was measured across the required frequency range from 1.8-2.7GHz, as shown in Figure 2b. Previously, drain efficiencies greater than 60 percent were achieved between 1.9-2.9GHz with a 45W GaN HEMT CGH40045F device using a simplified real-frequency technique to determine the optimum impedances and element values for highest efficiencies across the frequency range.[8]



a)

b)

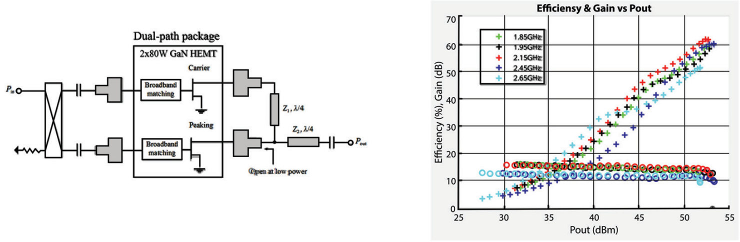
Figure 2: Single-ended Class-AB power amplifier with conjugate matching

Broadband Two-Stage Doherty Amplifier

In order to maximize operational bandwidth, it was important to minimize the loaded Q factor. (A loaded Q of unity has limitless bandwidth). However, in Doherty operations where a λ/4 transformer is necessary, the value of the loaded Q begins at a figure of 2. Therefore, it is possible to achieve wideband operation by balancing the amount of loaded Q necessary for Doherty operation and operational bandwidth. The classical two-stage Doherty amplifier has limited bandwidth capability in a low-power region since it is necessary to provide an impedance transformation from 25-100ohms when the peaking amplifier is turned off, thus resulting in a loaded quality factor $Q_L = \sqrt{100/25 - 1} = 1.73$ at 3dB output-power reduction level, which is sufficiently high for broadband operation. However, at high-power levels, due to broadband impedance output matching of the carrier and peaking amplifiers and using a broadband output quarter-wave transformer, it is possible to maximize the frequency bandwidth.

Figure 3a shows the circuit diagram of a conventional two-stage Doherty amplifier implemented on a 20mil RO4350 substrate and based on two 80W GaN HEMT power transistors with internal input matching in metal-ceramic flange packages. The input and output matching circuits are fully based on microstrip lines of different electrical lengths and characteristic impedances composing the two-stepped structures. An input splitter represents a broadband coupled-line coupler from Anaren, model X3C17A1-03WS, which provides maximum phase balance of ±5 degrees and amplitude balance of ±0.5dB across the frequency range of 690-2700MHz.

Figure 3b shows the measured power gain and drain efficiency of such a GaN HEMT Doherty amplifier across the entire frequency bandwidth for five in-band frequencies. In this case, a power gain of more than 9dB was achieved across the entire frequency range of 1.8-2.7GHz. At the same time, the drain efficiencies of about 60 percent at saturation power P_{3dB} (except high-bandwidth frequencies) and between 40 and 50 percent at 6dB backoff output powers were measured. In view of the bandwidth limitations of the conventional structure, the Doherty effect is not as strong across the bandwidth, with more effect at lower bandwidth frequencies.



a)

b)

Figure 3: Circuit diagram and performance of two-stage Doherty amplifier

Broadband Two-Stage Inverted Doherty Amplifier

Figure 4 shows the schematic diagram of an inverted broadband Doherty amplifier configuration with an impedance transformer based on a quarter-wave line connected to the output of the peaking amplifier. Such an architecture can be very helpful if, in a low-power region, it is easier to provide a short circuit rather than an open circuit at the output of the peaking amplifier, which depends on the characteristic of the transistor, specifically the C_{ds} of the transistor model, which is periphery (size) dependent.

The larger the transistor periphery, the more power it is capable of delivering and the higher the C_{ds} value. C_{ds} is also frequency dependent, which will impact the impedance matching criteria for broadband PAs.[9] In this case, a quarter-wave line is used to transform very low output impedance after the phase offset line to high impedance seen from the load junction. In particular, by taking the device package parasitic elements of the peaking amplifier into account, an optimized output matching circuit and a proper phase-offset line can be designed to maximize the output power from the peaking device in a high-power region and approximate a short-circuit termination in a low-power region.[10]

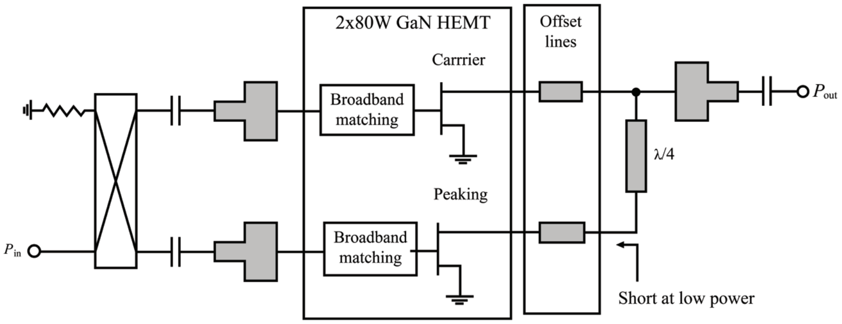


Figure 4: Block schematic of two-stage broadband inverted Doherty amplifier

To better understand the operation principle of an inverted Doherty amplifier, consider separately the load network shown in Figure 5a, where the peaking amplifier is turned off. In a low-power region, the phase adjustment of the offset line with electrical length θ causes the peaking amplifier to be short-circuited (ideally equal to 0ohms). The matching circuit in conjunction with phase offset line provides the required impedance transformation from 25ohms to the high output impedance Z_{out} seen by the carrier device output at the 6dB power backoff (ideally equal to 100ohms with the quarter-wave transformer), as shown in Figure 5b.

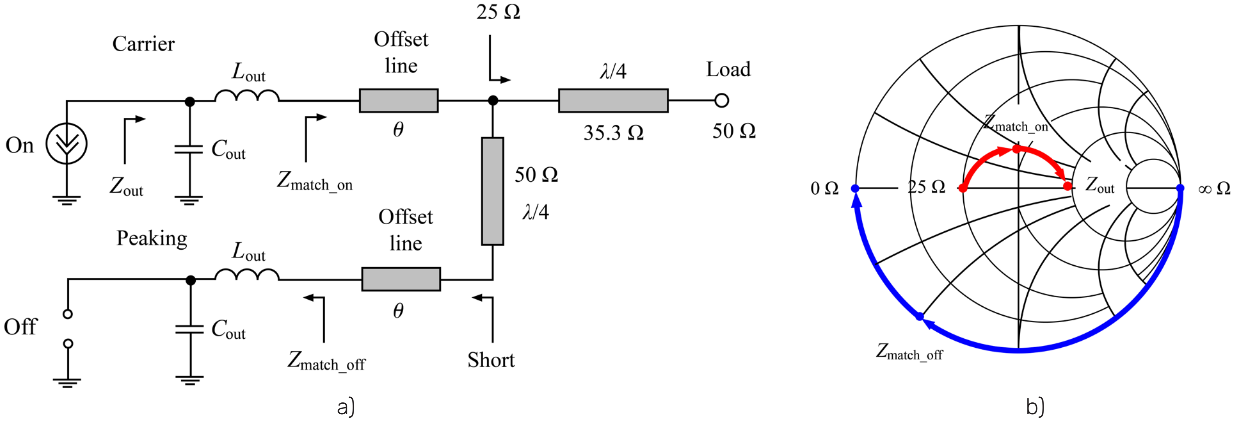
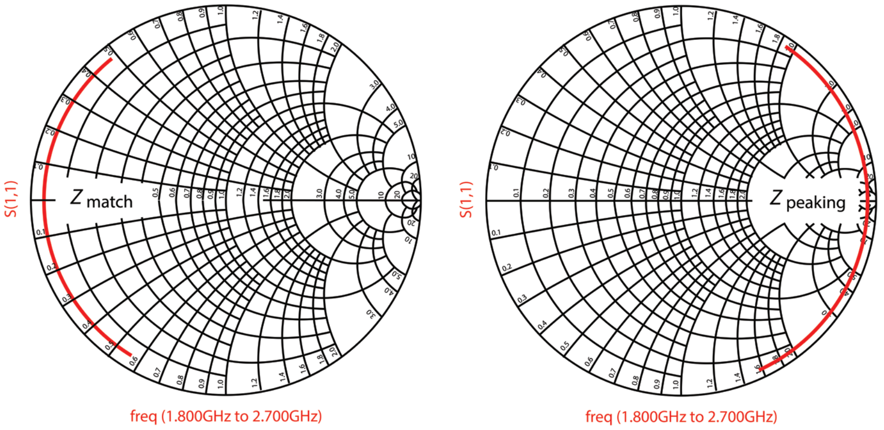


Figure 5: Load-network schematic and impedances

In this case, the short circuit at the end of the quarter-wave line transforms to the open circuit at its input so that it prevents power leakage to the peaking path when the peaking transistor is turned off. In a high-power region, both carrier and peaking amplifiers are operated in a 50ohm environment in parallel, and the output quarter-wave line with the characteristic impedance of 35.3ohms transforms the resulting 25ohms to the required 50ohm load. Based on this configuration, the broadband inverted GaN HEMT Doherty amplifier was designed with average drain efficiency of 47 percent, average output power of 38dBm, and saturated power of 44dBm with a power gain of more than 11dB operating across the frequency range of 1.8–2.7GHz using two 10W Cree GaN HEMT power transistors CGH40010P.[7, 11] Note: in a symmetrical Doherty amplifier, the dynamic range for maximum efficiency is 6dB. Therefore, maximum efficiency begins at 6dB from saturated power (in this case, at 38dBm).

The impedance conditions at different points of the load network of the peaking amplifier when it is turned off are shown in Figure 6, where Z_{match} shown in Figure 6a indicates low reactance at the output of the load network over the required frequency range from 1.8-2.7GHz, having near-zero reactance at the mid-band frequency with some inductive and capacitive reactances when the operating frequency approaches the bandwidth edges. At the same time, by using a series transmission line one quarter-wavelength long at high-band frequency, an open-circuit condition is provided at higher band frequencies with sufficiently high inductive and capacitive reactances across the frequency bandwidth, indicated by $Z_{peaking}$ shown in Figure 6b. Hence, the broadband performance of such an inverted Doherty structure can potentially be achieved in a practical realization.

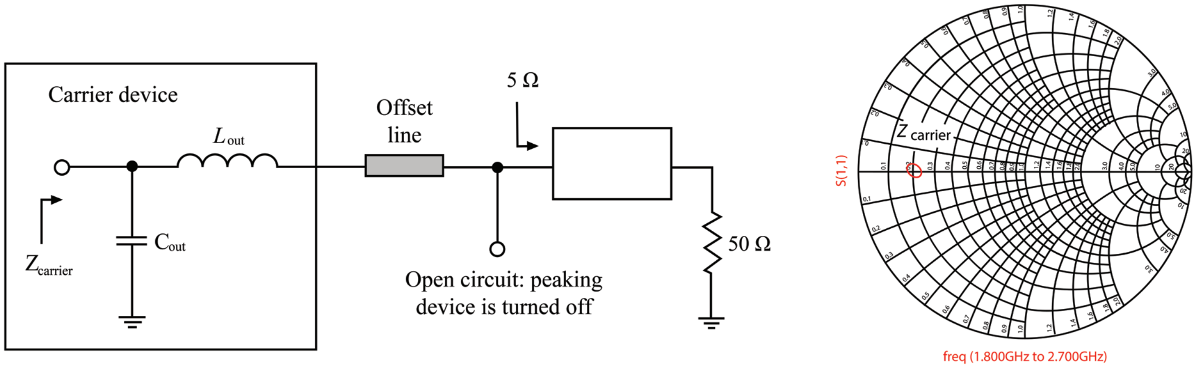


a)

b)

Figure 6: Impedances for peaking amplifier

Figure 7a shows the load-network equivalent circuit for a carrier amplifier with a frequency behavior of the impedance $Z_{carrier}$ seen by the carrier device, whose real component slightly varies around 10ohms, shown in Figure 7b. This means that, taking into account the device output shunt capacitance C_{out} of about 5pF and series output inductance L_{out} provided by the overall bond wire and package leadframe inductances, the impedance seen by the device multi-harmonic current source at the fundamental frequency across the entire frequency bandwidth of 1.8-2.7GHz has been increased by two times from the initial 5ohms at the input of the broadband output impedance transformer. This is a high enough impedance to achieve high efficiency at backoff output power levels.



a)

b)

Figure 7: Matching network and load impedance for carrier amplifier

In this case, the device output capacitance and bondwire inductor constitute a low-pass L-type matching section to increase the load impedance at higher harmonics (second and above) seen internally by the device at the current source. Figure 8 shows the simulation results for the small-signal S_{11} and S_{21} parameters versus frequency, demonstrating the bandwidth capability of a modified inverted transmission-line GaN HEMT Doherty amplifier covering a frequency range of 1.6-3.0GHz with a power gain over 11dB.

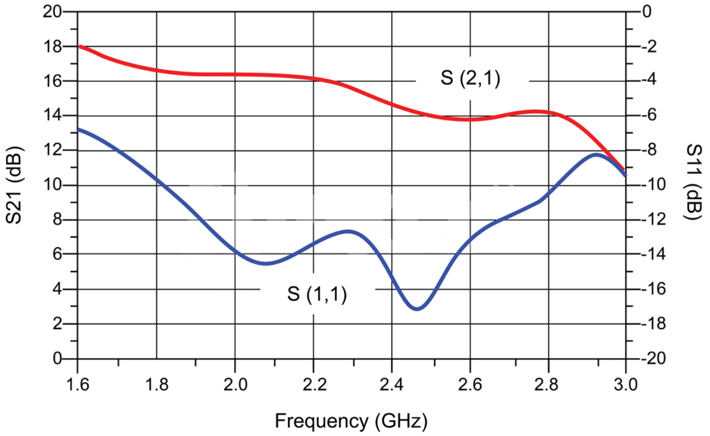


Figure 8: Simulated small-signal S-parameters versus frequency

Figure 9 shows the simulated large-signal power gain and drain efficiency of a transmission-line GaN HEMT tri-band inverted Doherty amplifier based on a 20mil RO4350 substrate, with the carrier gate bias V_{gc} = −2.5V, peaking gate bias V_{gp} = −5.5V, and dc supply voltage V_{dd} = 50V. An output power of more than 53dBm and a linear power gain of more than 10dB were achieved across the entire frequency range of 1.8-2.7GHz. At the same time, the drain efficiencies of more than 50 percent at saturation and 7dB backoff output powers were simulated at frequencies of 1.85GHz, 2.15GHz, and 2.65GHz, respectively, with maximum drain efficiency of more than 70 percent at peak power of 52.5dBm and lower band frequency. The drain efficiency levels were above 50 percent over the entire frequency range when this power level was reduced to ~46dBm (the maximum back-off output powers of around 6dB).

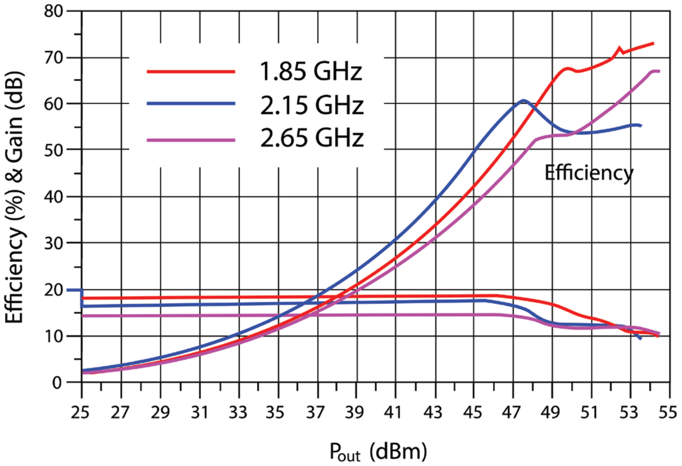


Figure 9: Simulated power gain and drain efficiency of broadband two-stage inverted Doherty amplifier

The test board of a 1.8-2.7GHz inverted Doherty amplifier based on two 80W GaN HEMT power transistors with internal input matching in metal-ceramic flange packages was fabricated on a 20mil RO4350 substrate to cover three key frequencies in the mobile/cellular bands. A broadband 90-degree hybrid coupler from Anaren model X3C17A1-03WS provides the input power split with a maximum phase balance of ±5 degrees and amplitude balance of ±0.5dB across the frequency range of 690-2700MHz. The input matching circuit, output load network, and gate and drain bias circuits (having bypass capacitors on their ends) are fully based on microstrip lines of different electrical lengths and characteristic impedances.

Figure 10 shows the measured power gain and drain efficiency of a transmission-line GaN HEMT inverted Doherty amplifier across the entire frequency bandwidth for five frequencies. In this case, a power gain of more than 9dB was achieved in a frequency range of 1.8-2.7GHz. At the same time, the drain efficiencies of more than 55 percent at saturation power P_{3dB} and around 50 percent at 7dB backoff output powers were measured across the entire frequency bandwidth, with maximum drain efficiency of more than 70 percent at lower bandwidth frequencies below 1.95GHz and peak efficiency points at maximum backoff output powers of around 6dB over the entire frequency range. The test conditions for concurrent transmission of 4-carrier global system for mobile communications (GSM) signal and a 10MHz LTE signal with a PAR of 8dB are shown Table 1.

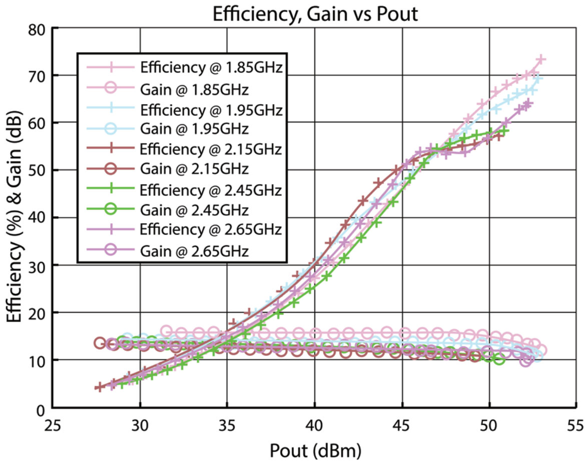
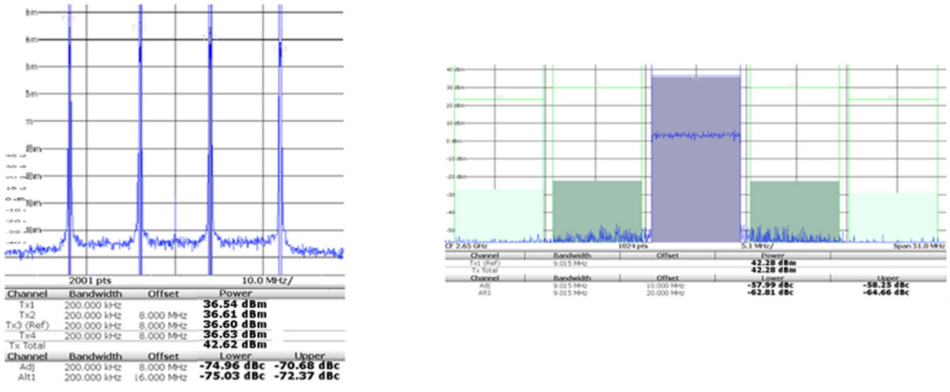


Figure 10: Test performance of broadband two-stage inverted Doherty amplifier

Test Conditions	
DUT	1.8-2.7GHz 2 x 80W GaN HEMT
Signals Tested:	1850 4C GSM + 2650 10MHz LTE
GSM 4xCarrier Power	42.62dBm (18.2W)
LTE 10MHz 1 Carrier Power 8dB PAR	42.3dBM (17W)
Composite Signal PAR	7.1dB
Total RF Power	35.2W (45.5dBm)
Drain Efficiency	51%

Table 1: Test conditions for concurrent signal transmission.

As a result, the drain efficiency of 51 percent with an average total output power of 45.5dBm (18.2W for the GSM signal and 17W for the LTE signal) was achieved using an in-house digital predistortion (DPD) linearization scheme. Figure 11 shows the spectral performance after dual-band DPD linearization of the broadband two-stage inverted Doherty amplifier: for the four-carrier GSM signal with an out-of-band intermodulation level lower than –70dBc, as shown in Figure 11a, and for the 10MHz LTE signal with adjacent channel leakage ratio (ACLR) lower than –57dBc, as shown in Figure 11b.



Channel	Bandwidth	Offset	Power	
Tx1	200.000 kHz		36.54 dBm	
Tx2	200.000 kHz	8.000 MHz	36.61 dBm	
Tx3 (Ref)	200.000 kHz	8.000 MHz	36.60 dBm	
Tx4	200.000 kHz	8.000 MHz	36.63 dBm	
Tx Total			42.62 dBm	
Channel	**Bandwidth**	**Offset**	**Lower**	**Upper**
Adj	200.000 kHz	8.000 MHz	-74.96 dBc	-70.68 dBc
Alt1	200.000 kHz	16.000 MHz	-75.03 dBc	-72.37 dBc

a)

Channel	Bandwidth	Offset	Power	
Tx1 (Ref)	9.015 MHz		42.28 dBm	
Tx Total			42.28 dBm	
Channel	**Bandwidth**	**Offset**	**Lower**	**Upper**
Adj	9.015 MHz	10.000 MHz	-57.99 dBc	-58.25 dBc
Alt1	9.015 MHz	20.000 MHz	-62.81 dBc	-64.66 dBc

b)

Figure 11: Dual-band DPD linearization of broadband two-stage inverted Doherty amplifier: a) four-carrier GSM signal and b) 10MHz LTE signal

Conclusion

Next-generation 4G/5G telecommunication systems require new power amplifier architectures that can operate with high efficiency over a wide frequency range to provide multiband and multi-standard concurrent operation. This application note has presented an innovative Doherty amplifier design using AWR Microwave Office circuit design software that leveraged 200W high-efficiency broadband 1.8-2.7GHz GaN HEMT technology to achieve average efficiencies of 50-60 percent for output powers up to 100W that significantly reduced the cost, size, and power consumption of the transmitters.

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Acknowledgment

Special thanks to James Wong, Andrei Grebennikov, Naoki Watanabe, and Eiji Mochida of Sumitomo Electric for their technical article “200-W High-Efficiency Broadband 1.8-2.7GHz GaN HEMT Doherty Amplifiers for New Generation Cellular Transmitters,” which inspired the creation of this application note.