GaN based 2-stage Wide Band Doherty PA for 3.4-3.8 GHz Using Hybrid Integration with IPDs on HPSI SiC Substrate

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Abstract

Compact 2-stage Doherty PAs (Power Amplifiers) have been designed and fabricated with GaN HEMT discrete devices and IPDs (Integrated Passive Devices) on HPSI (High Purity Semi Insulating) SiC substrates. The Doherty PAs are composed of input, inter and output stage matching circuits which are IPDs and 5 GaN HEMT devices. The output matching circuit also serves as a 90° phase shifter between main (carrier) and auxiliary (peak) branch of the PA. 2 of 2-finger device and 10 finger devices are used for main branch and a 6-finger device and a 20-finger device are used for auxiliary branch of the PA. The gate width of each finger is 350 ums, and the gate length is 0.3 um which are designed for sub-6 GHz 5G telecom base stations. The components were integrated on 10x10 mm^2 area QFN packages. 22.8 dB small signal gain, 47 dBm peak output power, -24 dBc ACLR (Adjacent Channel Leak Rate) without DPD (Digital Pre-Distortion) and 37.2% PAE (Power Added Efficiency) were measured for 3.4 ~ 3.8 GHz frequency band.

INTRODUCTION

The market adoption of GaN HEMT (high electron mobility transistor) devices has been rapidly increasing in 5G base stations, high power radar systems, electronic warfare systems. This is due to the superior performance of the technology such as high output power density, high breakdown voltage, high thermal conductivity, high frequency operations etc. [1] Especially in the commercial market, GaN HEMT becomes the major choice of technology for 5G telecom infra-structure application in many countries. 3.4 – 3.8 GHz frequency band has been designated for FR1 frequency of 5G NR (new radio) in Korea in 2018. To support the requirements of telecom base station applications, the HPAs need to have high output power, high efficiency, high linearity, and small form factor with lower manufacturing cost. [2]

The quasi-MMICs fabricated by hybrid integration of low cost IPDs and high-power transistors are one of the most promising technologies for the next generation telecommunication systems. [3] The other solutions such as hybrid HPAs on a printed circuit board (PCB) or monolithic microwave integrated circuits (MMICs) are either too bulky or too costly.

Small footprint IPDs have been developed on high resistivity silicon (HRS), high purity semi-insulating (HPSI) SiC, glass, semi-insulating GaAs substrates or as a form of low temperature co-fired ceramic (LTCC). [4] For high power applications, HPSI SiC is a more feasible candidate because of the superior thermal conductivity of SiC wafers. [5]

Also, to further reduce the footprint of HPAs, it is essential to have a TSV process to connect the circuit components on the front side of the substrate to the back-side metal. [6]

In this work, IPDs on HPSI SiC substrates with TSV process have been demonstrated. The compact wideband 2-stage Doherty PAs have been designed and assembled using the IPDs and GaN HEMT devices on a QFN packages with 10 x 10 mm^2 area.

DESIGN AND FABRICATION OF POWER AMPLIFIERS

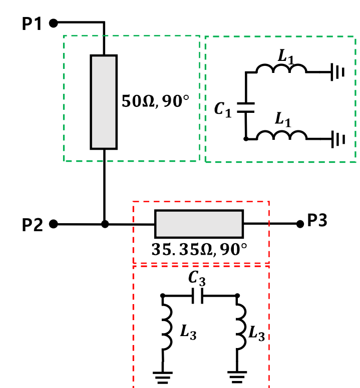


Fig. 1. Schematic diagram of conventional Doherty Combiner

1) Doherty combiner design – Doherty PA is composed of main and auxiliary branches combined with 90° phase difference. In this reason, the band width of Doherty PA is very narrow if you use transmission lines to make this phase difference. However, by adding resonators, the band width of 90° phase difference can be expanded. Figure 1 and 2 shows

the schematic of the conventional and the proposed combiner circuit design, respectively. The proposed design has series and parallel LC resonators.

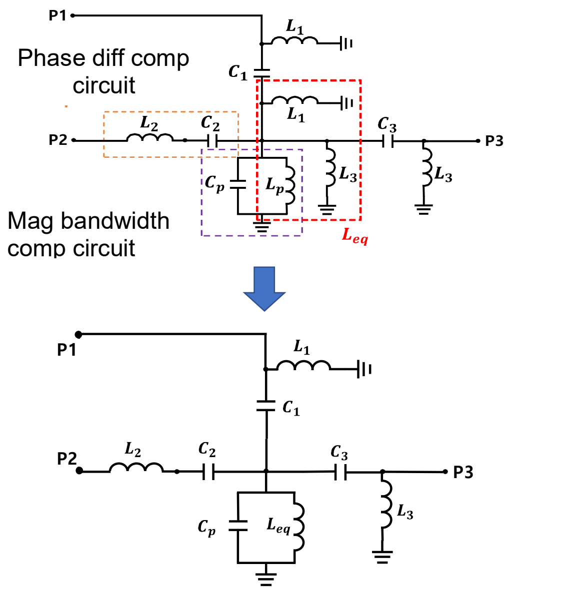


Fig. 2. Schematic diagram of proposed Doherty combiner circuits

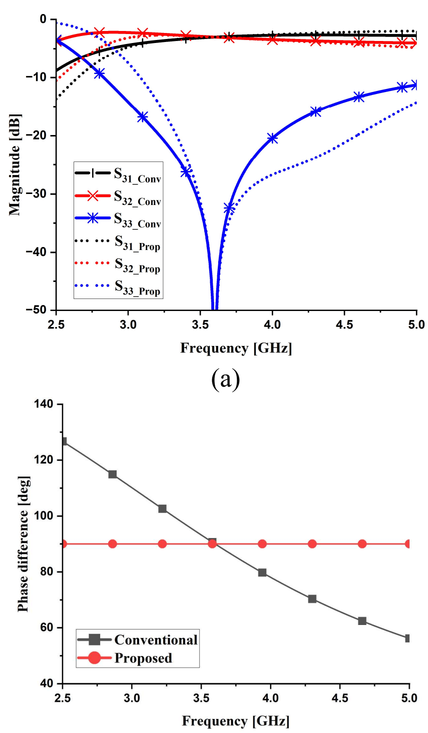


Fig. 3. Comparison of simulation data from conventional and proposed Doherty combiner circuits. (a) S-parameter and (b) phase difference

Figure 3 shows the simulation data from the conventional and proposed combiner for (a) s-parameters and (b) phase difference. Both combiners show -3.01 dB of S31 and S32 and very low reflection loss of S33. However, the phase difference is quite different. While the conventional combiner shows 90 ° phase difference only at 3.6 GHz as expected, the proposed one shows 90° for more than 500 MHz band width. The magnitude and phase difference from conventional and proposed combiner at 3.4 and 3.8 GHz are summarized in Table 1.

Table 1. summary of simulation data of conventional and proposed Doherty combiner circuits at 3.4 and 3.8 GHz.

Type	parameter	f_{LOW} ($3.4\ GHz$)	f_{HIGH} ($3.8\ GHz$)
Conventional	Magnitude (dB)	−26.21	−26.37
	Phase difference (deg)	96.53	83.83
Proposed	Magnitude (dB)	−23.54	−30.10
	Phase diff Difference (deg)	90	90

2) PA design - Figure 4 shows the schematic diagram of the 2-stage Doherty PA. It has 5 GaN HEMT devices which are 2 of 2-finger devices for the driver amplifier and 10-finger devices for the 2nd stage amplifier for the main branch.

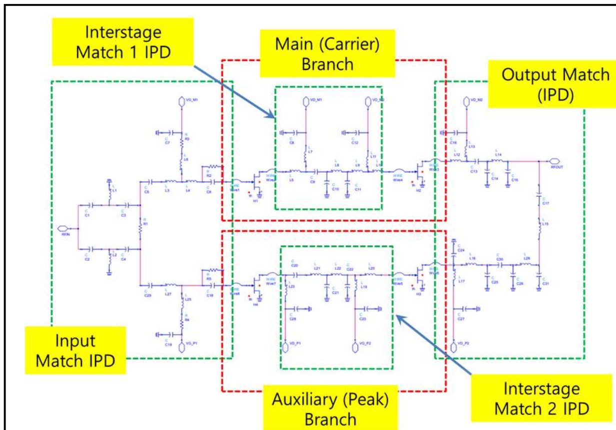
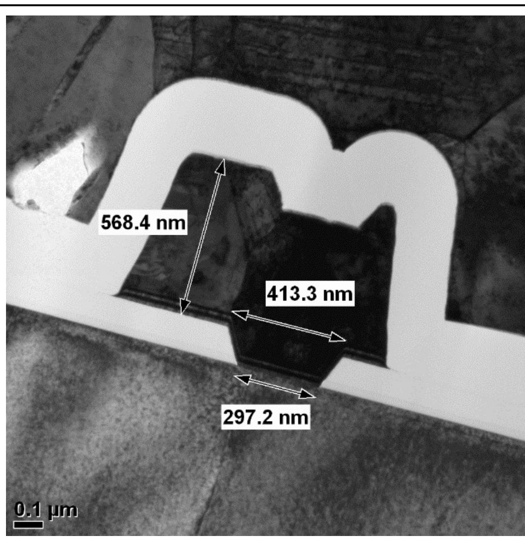


Fig. 4. 2-stage Doherty PA design with 5 GaN HEMT devices and 4 pieces of IPDs designed in ADS environment

The auxiliary branch of the PA uses a 6-finger device and a 20-finger device for driver and 2nd stage amplifier respectively. The IPD circuits include an input and output match, and 2 of inter-stage matches. The device models of GaN HEMT transistors and passive devices are available for Keysight ADS and Cadence Microwave Office circuit design software.

3) Fabrication Process – The device fabrication process is composed of GaN HEMT transistor and IPD device fabrication. The fabrication process of GaN HEMT MMIC of Wavice comprises implanted and recess-etched ohmic, stepper-defined 0.3 um gates, electro-plated source-connected field plates (SCFPs), electro-plated 5 um thick metal layers, TaN thin film resistors, through-SiC via, 85 ums SiC substrate after thinning, 7 um thick back side metal. [7] Figure 5 shows a SEM cross-section of the gate area of the devices in use.

The IPD process consists of TaN resistors with 25 Ω/□ sheet resistivity, SiNx based MIM capacitors with 7.7 pF/mm^2 capacitance density, 2 layers of 5 um thick interconnect metals, spiral inductors with dielectric cross over. An identical IPD process on HRS substrates in Wavice was reported elsewhere. [8] The passive device process is based on 4” HPSI SiC wafers. MMICs are processed on GaN epi on SiC wafers while for IPDs the process was done on bare HPSI SiC wafers without GaN epi. For both cases, the substrates were thinned to 85 um thickness and electro-plated 7 um thick metal is coated on the backside of the wafer after TSV etch.



(b)

Fig. 5. SEM cross section of gate area showing 0.3 um at the foot of the gate

3) Assembly process – The GaN HEMT devices and IPDs were bonded on a 10 x 10 mm^2 QFN packages using Ag epoxy. After the wafer bonding, Au wires were ball-bonded to electrically connect the devices. Figure 6 shows the 2 stage Doherty PA after assembly is completed.

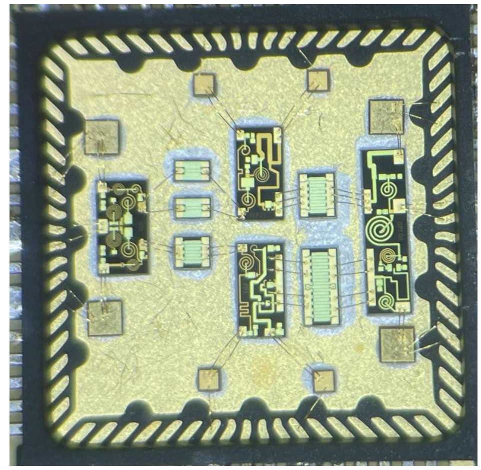
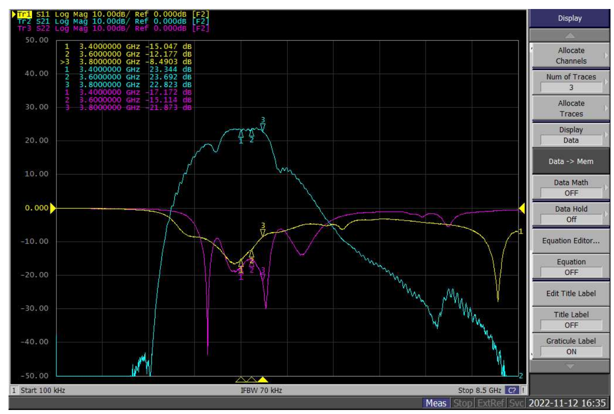


Fig. 6. Optical microscope picture of a 2-stage Doherty PA assembled on a 10 x 10 mm^2 QFN package.

RESULTS AND DISCUSSIONS



(a)

(b)

Fig. 7. (a) S parameter data and (b) spectrum data of 2-stage Doherty PA.

Figure 7 shows the RF performance of the 2-stage Doherty PAs. The measurement was done at room temperature without active cooling. Figure 7 (a) shows higher than 22.3 dB gain for 3.4-3.8 GHz. Figure 7 (b) shows spectrum data of Doherty PA with 100 MHz bandwidth LTE signal at 3.6 GHz with 9 dB back off. The PA shows -24 dBc ACLR without DPD correction and 37.2 % PAE for the 3.4 ~ 3.8 GHz frequency range.

CONCLUSIONS

A compact hybrid packaged wide band 2-stage Doherty PAs with GaN HEMT devices and IPDs have been demonstrated. The PA was assembled on a 10 x 10 mm^2 QFN packages with 5 GaN HEMTs with 0.3 um gate length and 4 pieces of IPD circuits. Over 50 W peak output power was measured. With 100 MHz band LTE signal, 22.3 dB gain, over 37.2% PAE and lower than -24 dBc ACLR were measured at the 3.4~3.8 GHz band with 50 V drain bias and 9 dB output power back off.

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ACRONYMS

HEMT: High Electron Mobility Transistor
HPSI: High Purity Semi Insulating
IPD: Integrated Passive Device
LTCC: Low Temperature Cofired Ceramic
HRS: High Resistive Silicon
TSV: Through Substrate Via
MIM: Metal Insulator Metal
MMIC: Monolithic Microwave Integrated Circuit
ADS: Advanced Design System
PCB: Printed Circuit Board
PAE: Power Added Efficiency
RF: Radio Frequency
PA: Power Amplifier
HPA: High-Power Amplifier