1-6 GHz 35W Balanced GaN-HEMT Power Amplifier with Innovative Quadrature Couplers

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***Abstract* — This paper presents a 1 – 6 GHz, 35 W high efficiency GaN-HEMT balanced power amplifier utilizing an innovative topology ultra-wideband 3-dB quadrature couplers. Load-pull analyses through simulations as well as simple-model output matching design are applied to driver and output stages design. New topology of small-size quadrature thin-film 3-dB couplers are realized to form the balanced configuration. The amplifier delivers 45.5 – 46.5 dBm continuous wave output power with an average power-added efficiency (PAE) of 24 – 35% across the 1 – 6 GHz band. The amplifier has a flat linear gain (61 ± 1.5 dB), very good input and output matching (VSWR lower than 1.5) and need a single +27 V supply with a 4.5 – 6.5 A current at maximum output power.**

***Keywords* — ultra-wideband, GaN-HEMT, balanced amplifier, quadrature coupler.**

I. Introduction

Development of telecommunication networks supporting various data transmission ranges and standards instigate developers to search and find engineering solutions for construction of efficient transistor power amplifiers overlapping the maximum possible continuous frequency band. Broadening of the frequency band complicates matching 50-Ohm transistors significantly. In order to achieve the required parameters in a broad frequency band, developers use various well-known [1] amplifier circuit design methods, such as reactive matching (RM), reactive lossy matching (LM), negative feedback (FB), and travelling-wave amplifier (TWA). The RM and LM circuits allow to realize the high input power and PAE of an amplifier, but at the same time it is often too hard to ensure good input and (or) output matching. The FB and TWA circuits, vice versa, provide an optimized match but limit the maximum attainable power-added efficiency of an amplifier.

However, it is possible to ensure both good amplifier input and output matching and high efficiency, when has been used balanced connection of amplifier chains with 3-dB quadrature directional couplers. At the same time, the frequency band of conventional circuits of such couplers (Lange coupler [2], branch-line coupler, tandem coupler) is limited to 40-100%, and thus developers need novel solutions to design balanced amplifiers with broader frequency bands.

Results of development of a high-efficiency hybrid integrated amplifier with high output power, based on an innovative design of a space-saving 3dB quadrature coupler are described below.

This paper is structured as follows: Section II provides the amplifier architecture, design and parameters of the developed quadrature couplers. Section III discusses methods of matching circuit design, modeling results, design, and results of experimental study of balanced amplifier stages prototypes. Section IV provides detailed information about the design and measurement results for the developed amplifier.

II. Amplifier Structural Arrangement and Design of the Quadrature Couplers

In order to achieve output power higher than 35W and 1 – 6 GHz ultra-broad band with low input and output SWR, was opted the architecture based on a balanced combiner circuit (Amp3) with two balanced amplifiers (Amp2) in it as provided in Figure 1.

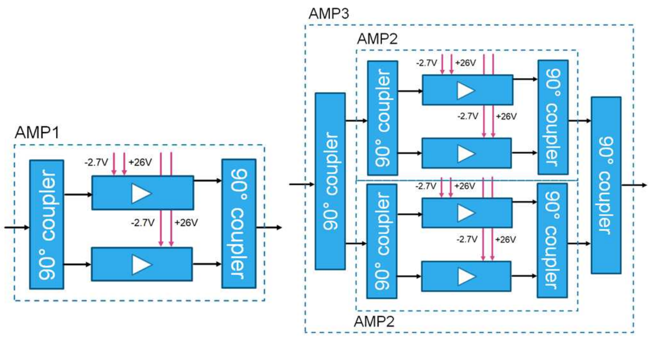


Fig.1 Structural arrangement of pre-stage and output cascades

A balanced driver stage (Amp1) featuring the half-power transistors as the ones detailed above were used as also provided in Figure 1.

For power combining with frequency overlap more than 2.5:1, it is required to use combiners with cascade connection of several groups of coupled lines with different coupling [3].

In order to combining the output power of two amplifiers Amp2, this principle was used to develop a quadrature coupler with 25x9 mm^2. It has area with a tightly coupled central section shaped as a 6-strip inter-digital structure arranged on a suspended Al_2O_3 substrate 0.5 mm thick with a 0.5 mm air gap (see Fig. 2).

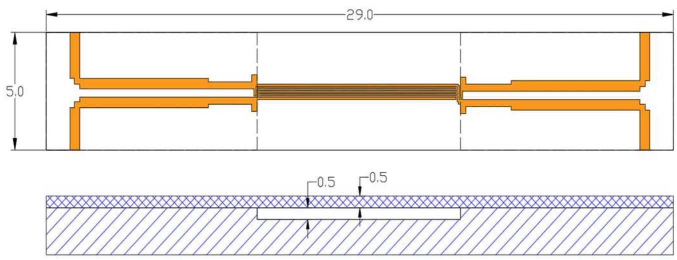


Fig.2 Design of a three-section coupler with a suspended-line central section

Use of the suspended-line section allowed to make the coupled strips wider, and to increase the clearances between them. The outside microstrip-line coupled sections compensate for tight coupling of the central section and make the total coupling characteristics flatter. The simulated and measured coupler characteristics are provided in Fig. 3.

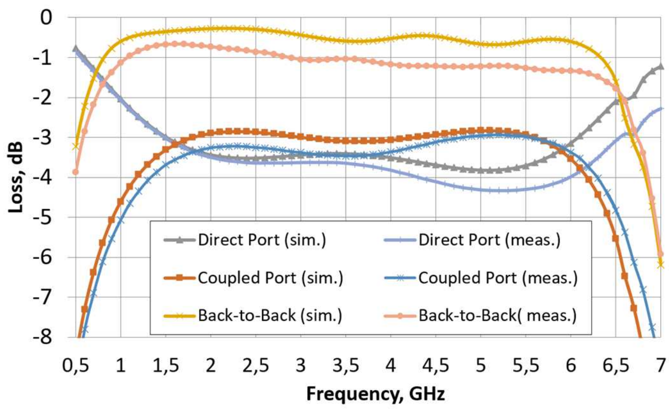


Fig.3 Simulated and measured characteristics of the 1-6 GHz three-section quadrature coupler

Couplers of this type are longer and are optimal for adding two output balanced stages in the circuit Amp3. For the application in the balanced circuits Amp1 and Amp2, a more space-saving coupler should be used; otherwise, the ready-to-use amplifier will be much wider than desired. Thus, an innovative solution of the quadrature coupler was developed in the form of a multi-cascade tandem with tight coupling inserts [4]. The developed microstrip-line coupler has a low 14x8 mm^2 area arranged on an Al_2O_3 substrate and showed in Fig. 4. The loosely coupled output sections have openings acting as a slow-wave system and making the sections shorter [5].

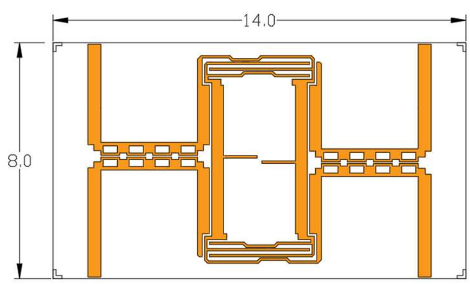


Fig.4 Topology of the new multi-cascade tandem quadrature coupler

The simulated and measured characteristics of the new coupler are provided in Fig. 5. For the EM-simulation of couplers was used self-developed software.

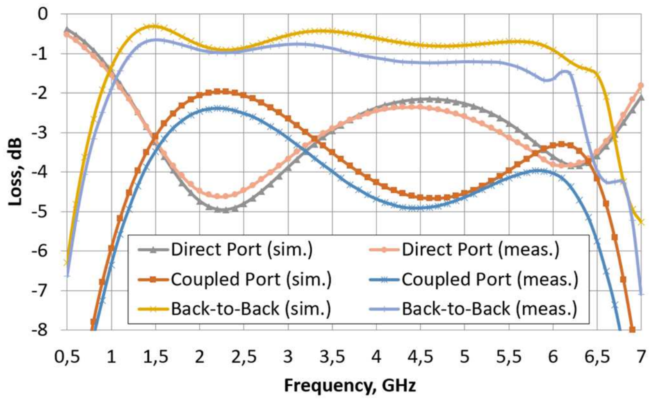


Fig.5 Simulated and measured characteristics of the new tandem coupler

Fig. 6 provides images of the developed quadrature couplers for comparison of their dimensions.

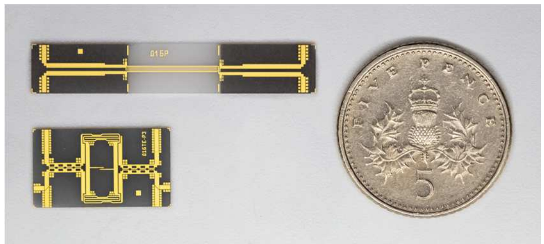


Fig.6 images of the developed quadrature couplers

III. Modeling and Investigation of the Balanced Amplifying Stages

In order to prototype balanced amplifiers Amp1 and Amp2, we used GaN/SiC HEMT transistors CGH60008D and CGH60015D in die-form manufactured by *Wolfspeed*. These transistors can be successfully used up to C-band with breakdown voltage of 120 V.

The output and driver stages were designed using AWR Microwave Office with both linear and non-linear analysis. The input matching circuit (IMC) of Amp1 and Amp2 are of the same structure, which is provided in Fig. 7.

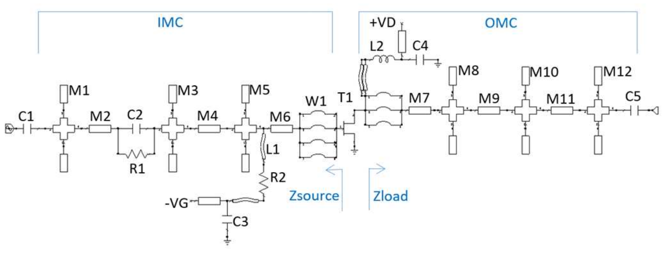


Fig.7 Structural arrangement of input and output matching circuits

IMC designing does not solve the problems of matching; instead, it is aimed to align the amplitude-frequency characteristics of the amplifier in the wide frequency band. As already mentioned, two transistor cells are connected with the two quadrature couplers in order to provide for good matching with a 50-Ohm transmission line. In addition to distributed matching elements and connecting wires, the IMC comprises two RC-circuits acting as stabilization networks.

The output matching circuit is synthesized on the basis of the condition of achieving the maximum saturated output power within the operating frequency range.

By investigating non-linear models of the transistors provided by the manufacturer, was determined parasitic transistor parameters and performed Load-Pull analysis to establish requirements to the output matching circuit impedance.

The following approach was used to simplify the output circuit synthesis process: The transistor was designed as an equivalent parallel RC-circuit shown in Fig. 8.

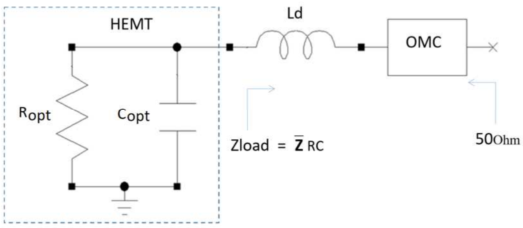


Fig.8 Equivalent RC-Circuit

Parameters R_{opt} and C_{opt} were choosen so as to bring the complex conjugate impedance of this circuit as close as possible to the optimal curve plotted as a result of Load-Pull analysis through simulation. Table 1 provides the optimal values.

In this case, the problem of output circuit design is broadband matching the equivalent RC-circuit with a 50-Ohm transmission line. In order to reach a compromise between the physical dimensions, loss and matching quality, was opted an LPF-type six-element line-stub circuit. The synthesized impedances of the realized matching circuits are provided in Fig. 9 (for Amp1) and Fig. 10 (for Amp2) in comparison to the results of Load-Pull analysis through simulation and to complex conjugates of the equivalent RC-circuit.

TABLE 1 Calculated Parameters of the Equivalent RC-Circuit

Transistor type	**C_{opt}, pF**	**R_{opt}, Oh**
CGH60008D	0.6	40
CGH60015D	1.25	20

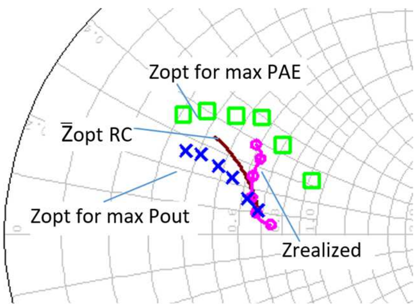


Fig.9. Realized impedance of output matching circuit Amp1

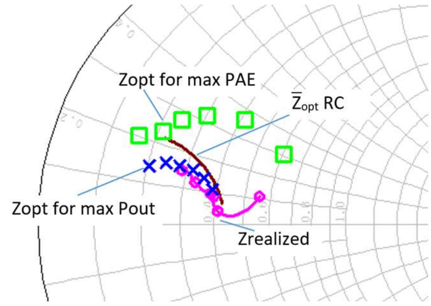
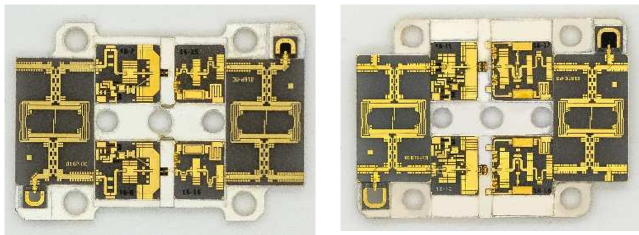


Fig.10. Realized impedance of output matching circuit Amp2

Input voltage supply to the transistor drain was realized through an SMD inductor; and bias input voltage to the gate was realized through the wire inductor. The power supply and bias circuits were connected closely to transistor’s gate and drain pads, which ensured the best decoupling.

Fig. 11 provides images of the developed balanced amplifiers. The microstrip matching circuits made on Al_2O_3 ceramics 0.25 mm thick, and those of the quadrature couplers are soldered on Cu-Mo bases; and the transistors are mounted one the epoxy adhesive with high heat conductivity.



Amp1 Amp2

Fig.11 Images of the developed balanced amplifiers

The simulated and experimentally measured output power and power-added efficiency characteristics of the developed balanced amplifiers Amp1 and Amp2 are provided in Fig. 12 and Fig. 13.

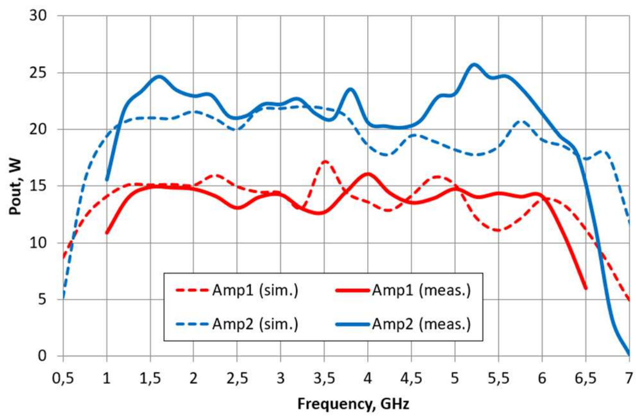


Fig.12 Simulated and measured output power of Amp1 and Amp2

As it shown on the plots, the characteristics have a good match. The gate width of the CGH60008D transistor is 2100um, and the CGH60015D is 3500um, which is 1.67 times larger. Since the output power is proportional to the gate width

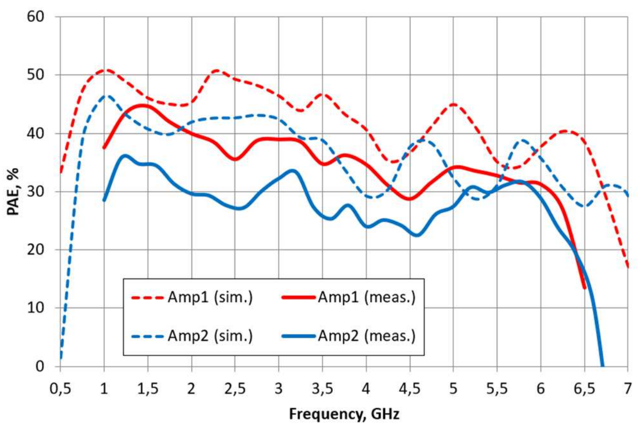


Fig.13 Simulated and measured PAE of Amp1 and Amp2

of the transistor, the expected output power of the Amp2 amplifier should be 1.67 times greater than the Amp1 power. From the measurement results (Fig.12), it follows that average output power of Amp1 is 14 W, and the output power of Amp2 is 22.5 W, which is 1.6 times more and corresponds to the expected with an accuracy of 0.2 dB. A slight decrease of measured output power of Amp2 possibly related to the implementation of drain supply circuits in OMC board and could be improved by placing the drain power supply circuits outside of ceramic OMC board closer to the transistors.

IV. Realization and Measurements

Fig. 14 shows layout of the realized power amplifier comprising six hybrid stages, which include input low-noise amplifier, a digital attenuator, thermal-compensating circuit, medium-power TWA, driver (Amp1) and output balanced amplifier (Amp3). A directional power detector is installed at the output of the amplifier.

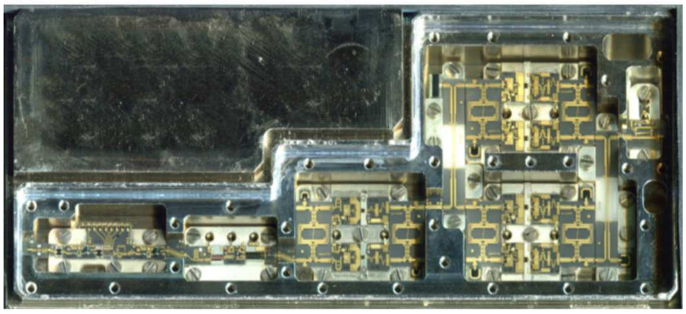


Fig.14 Layout of the amplifier

Measured characteristics of the device are provided in Fig. 15 and 16. All measurements were performed at 28 V single-voltage power supply. The frequency flatness of the output power and the small-signal gain of the amplifier have the same behavior and amount not more than 1.2 dB (except for the lower edge of the operating range 1-1.5 GHz).

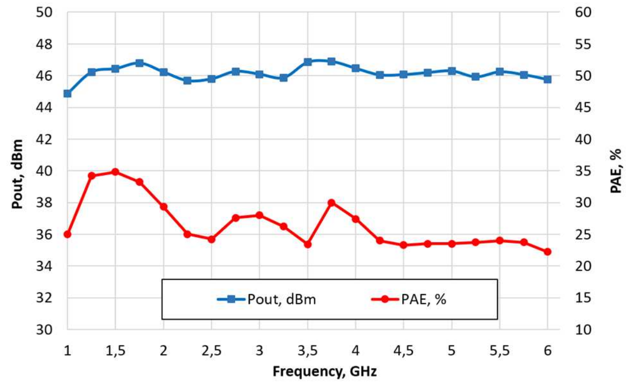


Fig.15 Measured output power and PAE at P_{in} = 2 mW

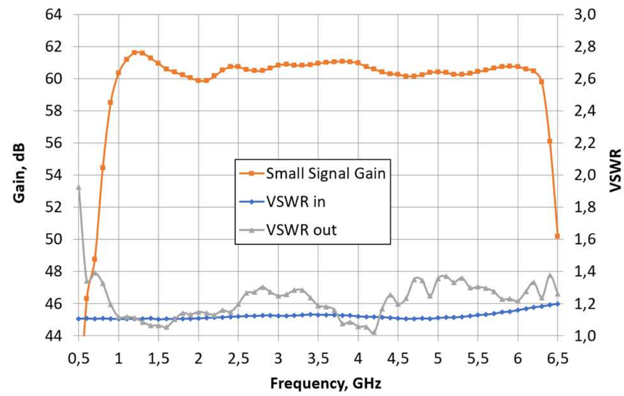


Fig.16 Measured small-signal gain and input/output VSWR

V. Conclusion

In this paper the use of balanced circuit for the development of the power amplifier based on innovative quadrature couplers with operating range from 1 to 6 GHz has been presented. It allows to realize a low-cost and space-saving amplifier with good matching and low gain ripple. Under CW operation it demonstrates the output power 36W to 50 W, and PAE 24% to 36%. The application of GaN discrete transistors could significantly reduce the final cost of amplifier compared to other solutions based on MMIC circuits.

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