

Ultra-wideband GaN HEMT power amplifier with practical mixed lumped approach employing real-frequency technique

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Abstract: An ultra-wideband power amplifier (PA) design employing Real Frequency Technique (RFT) with Gallium Nitride high-electron-mobility-transistor (GaN HEMT) technology is presented. The practical implementation was done with combination of distributed and lumped elements (mixed lumped elements combination) for the need of industrial requirements for the small form factor and low cost. This is an attractive approach for Software Defined Radio (SDR) products to meet wide bandwidth range of 80–2200 MHz. The measured results of the prototype reported good performance over the bandwidth of the interest (i.e. power of 34 dBm to 43 dBm, efficiency about 39% to 69% and gain in the range of 11 dB to 18 dB), and reasonable agreement with the simulated data. According to author's knowledge, these results are significant for single-ended GaN HEMT device for the wideband operation starting from low frequency 80–2200 MHz.

Keywords: power amplifier, wideband, real frequency technique, mixed-lumped elements

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Software defined radio (SDR) demand is increasing particularly for the two-way radio communications system to cater emergency situation [1]. One of the key challenges to the development is PA design whereby the requirements such as bandwidth, power level, efficiency, gain are design trade-off. Power amplifier designed by Peng Chen *et al.* using Bayesian optimization strategy provides results of average efficiency around 45%–53%. [2] The work carried out by F. A. Mughal *et al.*, power amplifier designed using GaN able to achieve maximum efficiency of 67% and output power of 37 dBm in the frequency range of 150–550 MHz. [3] The work presented by Alireza proposed design method with Butterworth/Chebyshev low pass filter topology to obtain a microstrip-based matching network achieved a satisfactory results of efficiency of 63.6% and output power of 43 dBm in the desired frequency range of 1.2–1.4 GHz. [4] A PA designed by [5] proposed a new technique by vectorially combined the output current sources when the transistors are loaded by their distributed output networks. The performances of this design

is excellent (output power above 43 dBm, gain of 37 dB and maximum efficiency of 57%).

In this paper, a design method of ultra-wideband PA employing RFT as a guideline to obtain input matching and output matching network (IMN and OMN), respectively from the actual source and load pull measured results. The topology interest of this work is required to cover from low frequency such as 80 MHz up to 2200 MHz. Furthermore, in terms of realization on the printed circuit board (PCB) level, a technique with mixed-lumped elements is implemented for smaller form factor. The performance of the prototype showed the approach is quite acceptable to the SDR applications over the entire bandwidth operation.

2 Design methodology

For wideband requirements, the main focus will be the development of IMN and OMN of the PA. The source and load impedance are extracted with measurement under optimum biasing condition i.e. class AB (to meet power performance over the bandwidth). In this case, a technique called RFT is employed to obtain the matching networks. Brief theory of RFT is discussed in this section for better understanding. In principle, RFT is a lossless equalizer explained in terms of its unit normalized scattering parameter. [6, 7] Scattering parameter is the method used in computational for the blocks to be matched, results in numerically well behaved gain optimization of the system. Therefore, RFT is a favourite method to design microwave wideband amplifiers due to its simplicity and faster compared to other existing algorithm. [8] Fig. 1 shows the lossless matching circuits in terms of Darlington's driving point impedance. The minimum reactance impedance function can be represented in mathematical form, as shown below:

$$Z_M(j\omega) = R_M(\omega) + jX_M(\omega). \quad (1)$$

The term $R_M(\omega)$ is a non-negative even function in angular frequency ω . When it is terminated in a resistance, it represents the lossless lumped element network. The general form of $R_M(\omega)$ is shown as follows:

$$R_M(\omega^2) = \frac{A_1\omega^{2n} + A_2\omega^{2(n-1)} + \dots + A_n\omega^2 + A_{n+1}}{B_1\omega^{2n} + B_2\omega^{2(n-1)} + \dots + B_n\omega^2 + 1} \geq 0; \forall \omega. \quad (2)$$

The above equation represents a highly complicated circuit topology and the parameter $A_i; i = 1, 2, \dots, (n+1)$, the numerator of the coefficient is the important factor that influenced of circuit structure. The simpler form of the equation is obtained for producing a LC low-pass ladder circuit topology with “ n ” elements terminated at $Z_M(0) = R_M(0) = R_L$ as desired. The equation is shown below:

$$R_M(\omega^2) = \frac{R_L}{B_1\omega^{2n} + B_2\omega^{2(n-1)} + \dots + B_n\omega^2 + 1} \geq 0; \forall \omega. \quad (3)$$

It will eventually come out with the schematic of the matching network and also a graph of transducer power gain (TPG) against the desired bandwidth. The unknown coefficient of the matching network in (3) are determined by the optimization of TPG. [7] In terms of theory, the TPG of the circuit can be expressed in mathematical form as shown below:

$$T(\omega) = \frac{4R_MR_L}{(R_M + R_L)^2 + (X_M + X_F + X_L)^2} \quad (4)$$

The TPG graph provides an indication to the user on how well the performance of the matching network. It is the best that to achieve TPG as low as possible and within the range of 0 and -1 dB. [9] For instance, for GaN HEMT device (CGH40010F), source and load pull measurement are performed to identify the optimum impedances over the entire bandwidth operation, which are represented by the term Z_{in} and Z_{out} in Fig. 1. Thus, the initial values of the matching elements presented through this method is optimized where necessary in order to obtain a better performance, refer to Fig. 1 to see the IMN circuit. The series DC capacitor is included to block the DC from mixing with RF signal.

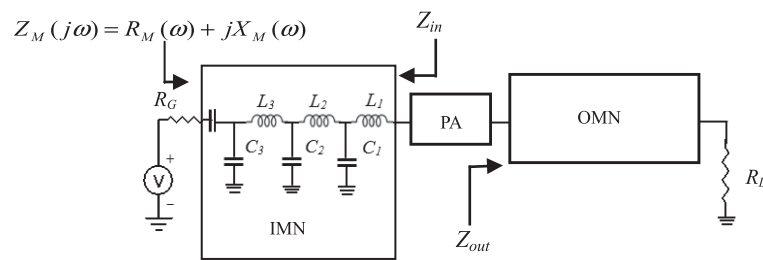


Fig. 1. Lossless matching network in terms of Darlington's driving point impedance.

As for next step, the conversion process of the series lumped element to coplanar waveguide with grounded (CPWG) is carried out and typically began with S-parameter conversion of two-port to single port. [7] This is due to make good optimization or tuning of the overall matching networks (with mixed lumped elements) from effective individual series inductor that converted. From practical implementation point of view, it is an optimum that series configuration component (inductor as shown in Fig. 2 left) is represented by CPWG and shunt configuration is represented by high-Q capacitor on PCB.

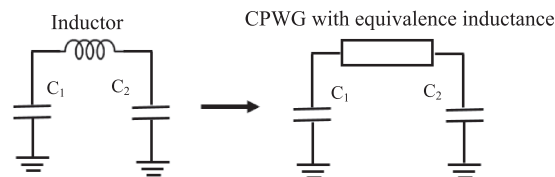


Fig. 2. Conversion of inductor to active transmission line CPWG with equivalence inductance.

The physical parameters of CPWG, which are length (l) and width (w) needed to be synthesized [10] and overall TPG of the matching networks has to be fulfilled over the frequency range. The significance of this conversion method is to identify and verify the exact amount of coplanar from the equivalent inductance, provided the value of l and w that synthesised earlier. The conversion of two-port to single-port is based on the formula as follow:

$$S_{11}(1p) = S_{11}(2p) - S_{12}(2p) * \frac{S_{21}(2p)}{(1 + S_{22}(2p))}, \quad (5)$$

where (1p) and (2p) are referring to single and two-port configurations, respectively. As the results, the effective impedance of the element from two-port can be determined from the as shown in following equation:

$$\text{Impedance} (1p) = \frac{50 * (1 + S_{11}(1p))}{(1 - S_{11}(1p))}, \quad (6)$$

and the impedance which leads towards the equation of inductor for single-port.

$$L(1p) = \text{imag} \frac{\text{Impedance}(1p)}{2\pi f}. \quad (7)$$

3 Measurement results

The prototype is fabricated and validated with measured data. The board size is measured 119 mm × 120 mm, using Roger 4350B with dielectric constant ϵ_r of 4.3 as the material of manufacture. Heat sink is mount under the PCB to ensure maximized heat dissipation. The board consists of IMN, OMN, RF input and output ports and 2 voltage supply feeds. ATC 100A series of capacitor is used in this work as well as air wound type of RF choke. The air wound RF choke is used in DC feed line to provide high impedance so that the RF signal would not mix with the DC signal. Besides, the capacitors (100 pF, 33 nF, 10 uF) are used in both voltage supplies feed lines in order to bypass the DC gate biasing to the ground. The thickness of the DC routing should be designed carefully so that appropriate amount of DC current is able to flow into the transistor. The actual prototype of wideband PA design board is shown in Fig. 3.

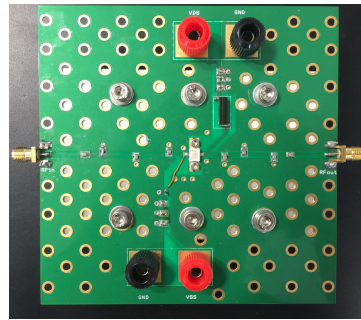


Fig. 3. The actual prototype wideband PA design board with mixed-lumped elements.

The measurement performances with the proposed topology are shown in Fig. 4 and Fig. 5 respectively. The measurement results are compared with the simulation results. The simulated and measured result of power added efficiency (PAE) and gain are shown in Fig. 4. From the graph, the measured PAE of the designed PA achieved around 46%–69% along the frequency range of 80 MHz to 1800 MHz. However, the PAE of the PA started to decrease after 1800 MHz (39% to 43%), which is still acceptable for the wide bandwidth application. The gain of

the designed PA measured at the range of 11 dB to 18 dB, which is considered a stable and satisfactory performance for the wideband PA. It is worth to note that the simulation of the designed PA is carried out under an ideal situation, therefore the performances of the measurement are slightly deviated with the simulation results.

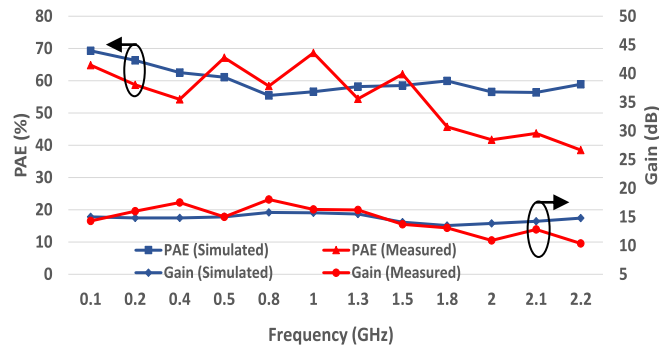


Fig. 4. Simulated and measurement results of the power added efficiency and gain over desired frequency range.

In Fig. 5, the simulated and measurement results of output power and also the DC current in the frequency range of 80 MHz to 2200 MHz are shown. The output power achieved more than 34 dBm and it is able to achieve maximum output power of 43 dBm in the desired frequency bandwidth. The performances of recent work in the context of GaN wideband PA are summarized in Table I. This work showed high gain within the bandwidth of interest for SDR applications while other performance such as power and efficiency are within the requirement. Note that stability performance are checked with 8:1 VSWR and no issue is reported in experimental level.

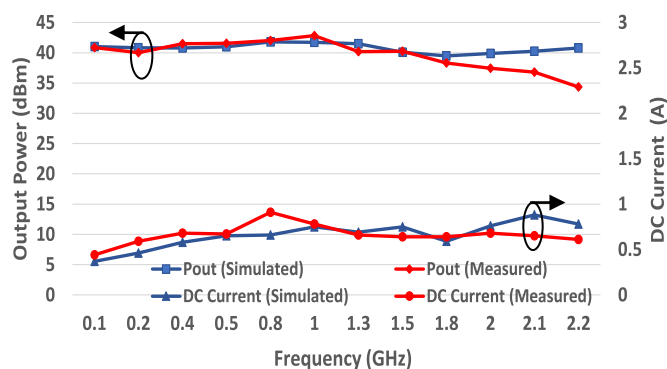


Fig. 5. Simulated and measurement results of the output power and DC current over desired frequency range.

Table I. Comparison of performances of wideband power amplifier in different works

Work	Device	Bandwidth (GHz)	Efficiency (%)	Output Power (dBm)	Gain (dB)
[11]	GaN HEMT	0.5–1.5	44–75	45	10
[12]	GaN HEMT	1.4–2.7	68	41	9
[13]	GaN HEMT	2–6	18–22	41–43	22
This work	GaN HEMT	0.08–2.2	39–69	34–43	11–18

4 Conclusion

The proposed PA design with GaN HEMT presents a satisfactory achievement in terms of PAE, gain and output power in the frequency range of 80 MHz to 2200 MHz. The maximum PAE of the PA achieved 69% (in the range of 39% to 69%) and the gain is around 11 dB to 18 dB, which is considered a good gain achievement. The output power of the PA achieved 34 dBm to 43 dBm in the desired frequency range. The PA designed for wideband operation across low frequency (80 MHz) to higher frequency (2200 MHz) achieved state-of-the-art performances according to author's knowledge. Therefore, the proposed methodology in this paper is practical with the solution for low cost implementation and particularly beneficial in SDR applications.