10W GaN PA for 5G NR n78 Band Utilizing RFT Parametric Approach

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***Abstract*—The focus of this paper is to design the input and output matching networks of a power amplifier to achieve the broadband and high efficiency performance which is mandatory for 5G NR operations. The Real Frequency Technique - RFT has been utilized in the design for the synthesis of broadband matching networks which is a good for broadband matching. A 10-Watt, 3.2-3.9GHz power amplifier is designed that covers the 5G NR n78 (C-Band, 3.3-3.8GHz) spectrum. The input matching network and output matching network are extracted using the RFT parametric approach employing lumped components. Then, the lumped elements are converted into distributed elements using microstrip line inductance and capacitance equivalences. Once the networks are designed, power amplifier (PA) stage is completed with the inclusion of bias feeds and performance is validated. Finally, the PA layout has been obtained for fabrication.**

Keywords—power amplifier, broadband matching, real frequency techniques

I. Introduction

Power amplifier is the last component in any transmitter line-up and the most important one as well in terms of operating bandwidth and energy conversion efficiency. As the telecommunication standards are advancing from 2G to 3G and 4G to 5G, uplink and downlink transmission bandwidths are also getting wider, to accommodate higher data rates. This means that broadband amplifiers are ever so important; however, efficiency is equally important as well to reduce the carbon foot print of the transmitter and to reduce the day to day running cost of the base station. Nonetheless, these amplifiers are not readily available in the market for 5G NR since the 5G technology itself is Novel and new.

In this paper we are presenting an amplifier design that has been designed utilizing Real Frequency Techniques (RFTs). The design covers 5G NR sub 6GHz n78 band frequencies 3.3GHz to 3.8GHz and has efficiency more than 60%. Real frequency technique has been introduced in the Section III, for the synthesis of broadband matching networks.

For our amplifier design, Wolfspeed’s 10-Watt GaN HEMT CGH40010F is used. Gallium nitride (GaN) transistor technology has been chosen because of its high break down voltage, good thermal performance, and more importantly friendly broadband impedance characteristics.

To initiate the design, first current vs voltage curves (IV-curves) are plotted to define the power amplifier class of operation and to find the bias point, for our design we have selected Class AB; since this class gives good compromise between efficiency and linearity. Once the class of operation has been defined; source and load pull is performed to extract the optimum input and out impedances of the device respectively for the best power, gain and efficiency performance. Then the input matching network (IMN) and output matching network (OMN) are extracted using the RFT Matlab programs [1-2]. However, Matlab program provides matching network elements in the lumped element form, which are converted into distributed elements, using microstrip line inductance and capacitance formulas given in; later filter performance is optimized using MWO. Once the networks are designed, power amplifier (PA) stage is completed with the inclusion of bias feeds and performance is validated. Finally, the PA layout has been designed for fabrication.

II. Bias Point Selection and Load-Source Pull

To establish the operating class of operation, first IV-Curve data is extract from the non-linear model of the device (CGH40010F); ***Fig. 1*** shows the MWO IV-Curve circuit schematic and ***Fig. 2*** shows the IV-Curves.

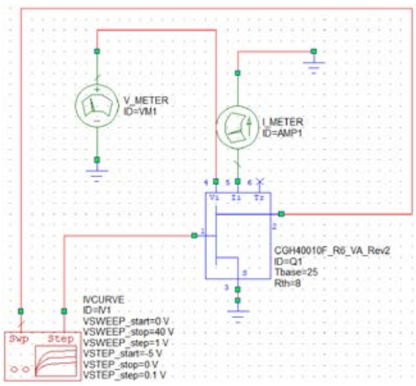

Fig. 1. IV-Curve Circuit Schematic in MWO

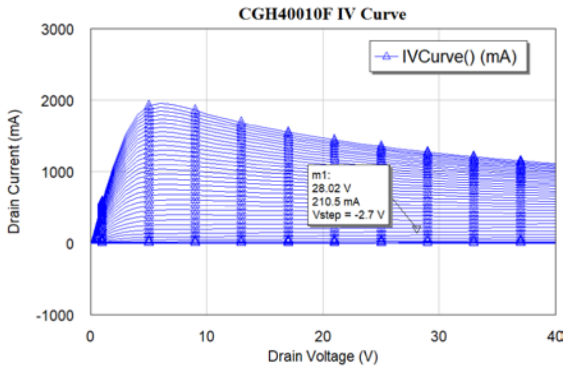

Fig. 2. IV-Curve data for CGH4010F GaN HEMT in MWO

From the IV-Curves we have selected the bias point at -2.7V gate voltage to provide 210mA drain current, which satisfies the Class-AB operating point. Since the peak current is 2A; therefore, setting the bias point at half of the peak value defines the Class-A and half of the Class-A operating point defines the Class-AB region (approximately) and finally half of the Class-AB value defines the Class-B operating point. The bias point selection criteria presented here is based on first author's personal experience of designing power amplifiers as a rule of thumb.

Once the power amplifier class of operation is defined, next we performed the source and load pull measurements to extract the optimum input and output impedances for maximum Power Added Efficiency (PAE) and output power over 3.2 to 3.9 GHz (5G NR n78 band). There are two methods that can be used to obtain the optimum source and load impedances utilizing the device's non-linear model in MWO and mentioned below.

1. Load pull template (provided in MWO) is used to extract the gamma (reflection coefficient) points on the smith chart and then optimum impedance is extracted by drawing the data contours through extracted gamma points. For this case, frequency is swept along the gamma points during the data extraction, while keeping the input power constant.
2. Source and load pull values at certain frequency points are extracted through load pull tuner optimization in the MWO.

For this work, second method has been used since it provides more control in terms of setting up the output performance goals (gain, power and efficiency) for the extracted impedance values. Impedance values extracted using this method are presented in the **Table I** and utilized to synthesis the matching networks. Whereas ***Fig. 3*** shows the MWO circuit schematic for the extraction setup.

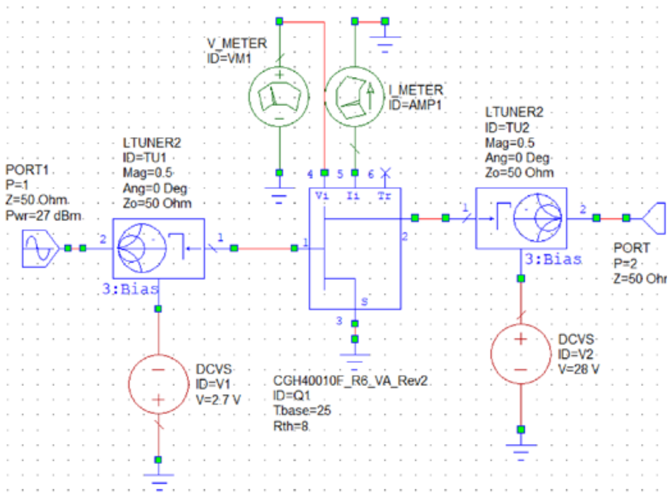

Fig. 3. Impedance extraction setup in MWO

TABLE I. SOURCE AND LOAD PULL IMPEDANCE DATA

No.	freq (GHz)	RS (Ω)	XS (Ω)	RL (Ω)	XL (Ω)	PAE (%)	Gain (dB)
1	3.2	1.417	-9.677	14.495	4.895	71.03	15.20
2	3.3	1.418	-9.993	14.016	4.148	71.01	15.20
3	3.4	1.426	-11.313	13.502	3.325	70.90	15.20
4	3.5	1.450	-12.159	13.086	2.625	70.80	15.20
5	3.6	1.453	-12.997	12.672	2.098	70.80	15.15
6	3.7	1.470	-13.844	12.438	1.141	70.23	15.15
7	3.8	1.493	-14.261	12.238	0.336	69.84	15.12
8	3.9	1.560	-15.583	12.088	-0.479	69.20	15.09

Now that we know the source and load impedances, next we can start designing the IMN and OMN for our power amplifier.

III. DESIGN AND SYNTHESIS OF INPUT - OUTPUT MATCHING NETWORKS USING REAL FREQUENCY TECHNIQUES

Let $Z_{in}(j\omega) = R_{in}(\omega) + jX_{in}(\omega)$ be the optimum termination (or immittance) for the input port of a power transistor [Tr] over the measured frequencies. Let $Z_C(j\omega) = R_C(\omega) + jX_C(\omega)$ (computed immittance) be a realizable model for the optimum immittance Z_{in} (Fig. 4 & Fig 5). Based on the above description, an immittance function "Z" either refers to an impedance or an admittance.

A realizable model $Z_C(p) = \frac{a(p)}{b(p)}$ may be determined using Parametric immittance modelling technique introduced in [1-2].

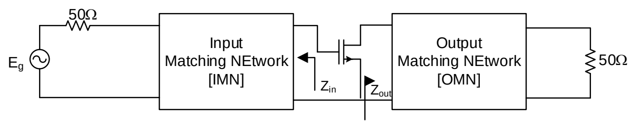

Fig. 4. A Typical Power Amplifier with [IMN] and [OMN]

In this regard, input immittance Z_{Tr-in} of the transistor under consideration is described as the complex conjugate of the termination immittance Z_{in}. In other words,

$$Z_{Tr-in} = Z_{in}^{*}(j\omega) = R_{in}(\omega) - jX_{in}(\omega) \tag{1}$$

Referring to ***Fig. 5***, quality of immittance model may be measured by means of the transducer power gain over the frequency band of interest. Obviously, perfect immittance model $Z_{C-imn}(j\omega) = R_C(\omega) + jX_C(\omega)$ for Z_{in} yields unity transducer power gain over the band of interest.

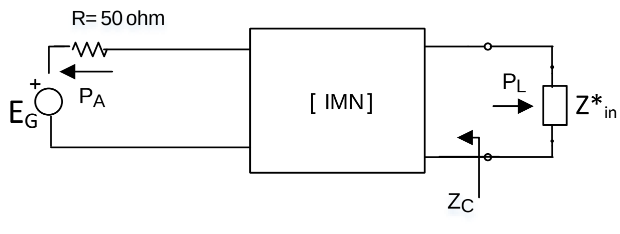

Fig. 5. Quality of Impedance Modelling of $Z_{in} \cong Z_C$ via TPG

Transducer power gain (TPG) of ***Fig. 5*** is expressed in equation (2) and detailed derivation is given in [1-2].

$$TPG_{(IMN)} = \frac{P_L}{P_A} = \frac{4R_C R_{in}}{(R_C + R_{in})^2 + (X_C - X_{in})^2} \qquad (2)$$

Quality of IMN is measured by means of TPG of (2) as shown in Fig.6 and synthesized Z_C is depicted in Fig.7.

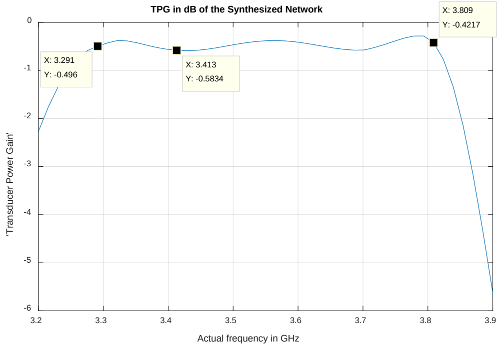

Fig. 6. Quality of immittance modelling by TPG in dB of IMN using Matlab

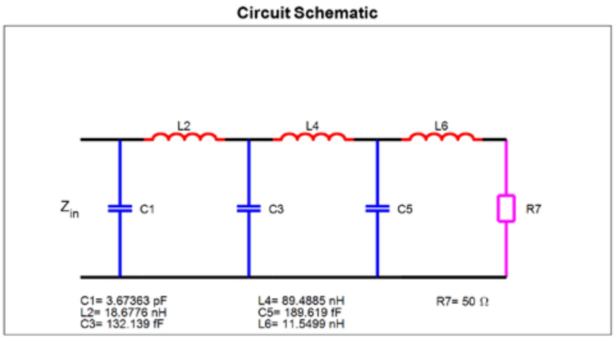

Fig. 7. Synhesized IMN with actual element values

Computed minimum susceptance parameters for the synthesized IMN are given in the ***Table II***.

Table II. Computed minimum susceptance Z_{C-imn} for IMN

$Z_{C-imn}(p) = \frac{a(p)}{b(p)}$	
$a(p) = a_1p^n + a_2p^{n-1} + \cdots + a_np + a_{n+1}$	$b(p) = b_1p^n + b_2p^{n-1} + \cdots + b_np + b_{n+1}$
0	1.0000
0.2280	0.1813
0.0413	1.7890
0.4021	0.1791
0.0398	0.7885
0.1737	0.0145
0.0030	0.0030

Just to recapitulate, in the above, it is assumed that optimum input impedance of the transistor is the complex conjugate of the transistor's optimum termination Z_{in}. In this case, input matching network is driven by a voltage source with $R = 50\,\Omega$ internal resistance. On the other hand, $Z_C(j\omega) = R_C(\omega) + jX_C(\omega)$ is the output impedance of [IMN] which is terminated in $Z_C^* = Z_{in}$.

In the optimization scheme, the real part $R_C(\omega)$ or equivalently the even part $R_C(p^2)$ is selected to yield a lowpass ladder structure. In this form R_C is given as

$$R_C(p^2) = \frac{a_0^2}{[c(p)^2 + c(-p)^2]} \qquad (3)$$

Where,

$$c(p) = c_1p^n + c_2p^{n-1} + c_3p^{n-2} + \cdots + c_np + c_{n+1} \qquad (4)$$

As a result of optimization $c(p)$ is found as in the following table

Table III. Computed auxiliary polynomial $c(p)$ for IMN

For T_0=1; ndc=0, ntr=0
$c(p) = c_1p^n + c_2p^{n-1} + c_3p^{n-2} + \cdots + c_np + c_{n+1}$
$c_n = [-329.1979 \quad -47.9241 \quad 587.0143 \quad 38.0094 \quad -257.8459 \quad 4.3931]$

Where,

T_0 is the idealized flat transducer power gain level in the passband;

ndc is the total number of transmission zero at DC

ntr is a program flag such that if the network includes a transformer, it is selected as ntr = 1; otherwise it is set to ntr=0. For the case under consideration, we have selected ntr=0.

In ***Fig. 4***, immittance-modelling set-up is shown. In this figure, we assume that output port of the transistor [Tr] is complex conjugate of the termination impedance Z_{out}. In other words, if the optimum output impedance of the transistor is designated by $Z_{Tr-out} = R_{Tr-out} + jX_{Tr-out}$, then, it is given by

$$\begin{aligned} Z_{Tr-out} = R_{Tr-out} + jX_{Tr-out} = Z_{out}^* \quad &= R_{out} - jX_{out}c(p) \\ = c_1p^n + c_2p^{n-1} + c_3p^{n-2} + \cdots + c_np + c_{n+1} & \end{aligned} \qquad (5)$$

Hence, the power transfer between the optimum output immittance $Z_{Tr-out} = R_{Tr-out} + jX_{Tr-out}$ of the transistor and the computed termination immittance $Z_C = R_C + jX_C$ is specified as in the generic form of the transducer power gain formula

$$TPG_{(OMN)} = \frac{P_L}{P_A} = \frac{4R_{out}R_C}{(R_{out} + R_C)^2 + (X_C - X_{out})^2} \qquad (6)$$

Maximization of (6) results in good immittance matching which in turn yields the optimum immittance model [1-3].

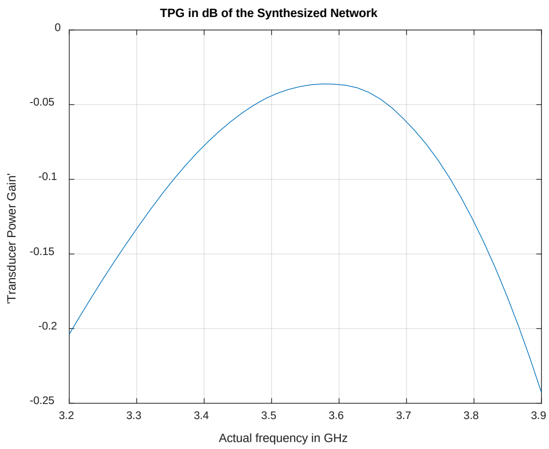

Fig. 8. Quality of immittance modelling by TPG in dB of OMN using Matlab.

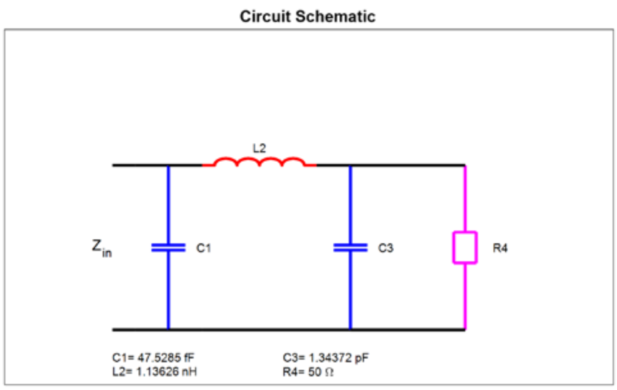

Fig. 9. OMN with actual element values

Table IV. Computed minimum susceptance Z_C for OMN

$Z_{C-omn}(p) = \dfrac{a(p)}{b(p)}$	
$a(p) = a_1p^n + a_2p^{n-1} + \cdots + a_np + a_{n+1}$	$b(p) = b_1p^n + b_2p^{n-1} + \cdots + b_np + b_{n+1}$

0	1.0000
17.6243	0.6234
10.9868	33.6309
20.2488	20.2488

Quality of immittance modelling of the OMN can be measured by means of the transducer power gain as represented in ***Fig. 5***. In this case, TPG is given as in (6)

In this concept, it is assumed that optimum output impedance of the transistor is the complex conjugate of the transistor's optimum termination Z_{out}. In this case, output matching network is terminated into a load with $R = 50\ \Omega$ internal resistance. On the other hand, $Z_{C-omn} = R_C + jX_C$ is the input impedance of [OMN] which is terminated in $Z_C^* = Z_{out}$.

Computed auxiliary polynomial $c(p)$ for T_0=1; ndc=0, ntr=0 for the designed OMN is given as in the ***Table V***.

Table V. Computed auxiliary polynomial c(p) for OMN

For T_0=1; ndc=0, ntr=0
$c(p) = c_1p^n + c_2p^{n-1} + c_3p^{n-2} + \cdots + c_np + c_{n+1}$
$c_n = [0.0494 \quad -0.0287 \quad -1.6596]$

IV. Performance Results

After synthized lumped IMN and OMN, next we convert lumped elements to distributed elements using formulas given in [4] and [5]. For the distributed design, dielectric constant $\epsilon_r = 3.66$; substrate tickness $H = 0.508mm$; metal tickness $t = 35\mu m$; dielectric loss $tand = 0.0037$ is selected.Finally distributed element IMN **Fig. 10** and OMN **Fig. 11** is placed in the power amplifier schematic of MWO and optimization is performed to attain the desired results. **Fig. 12** shows the amplifier circuit schematic in MWO and **Fig. 13** shows the amplifier performance; last but not least, **Fig. 14** shows the power amplifier layout that is ready to be fabricated.

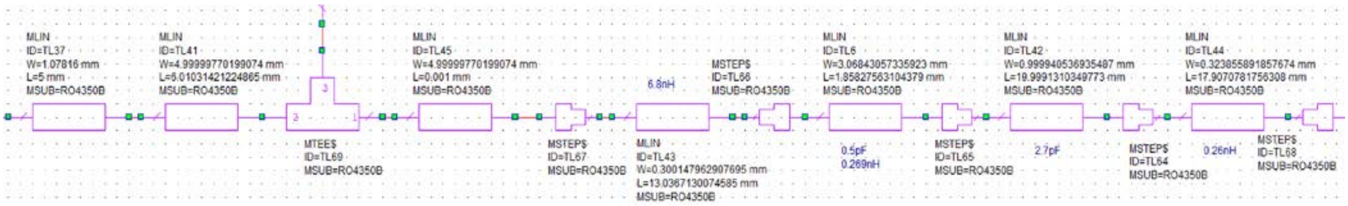

Fig. 10. IMN schematic after optimization and parasitic inclusion

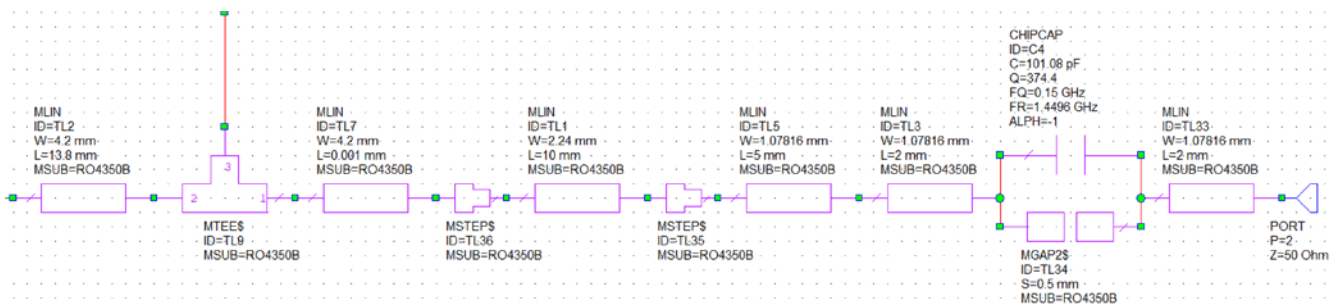

Fig. 11. OMN schematic after optimization and parasitic inclusion

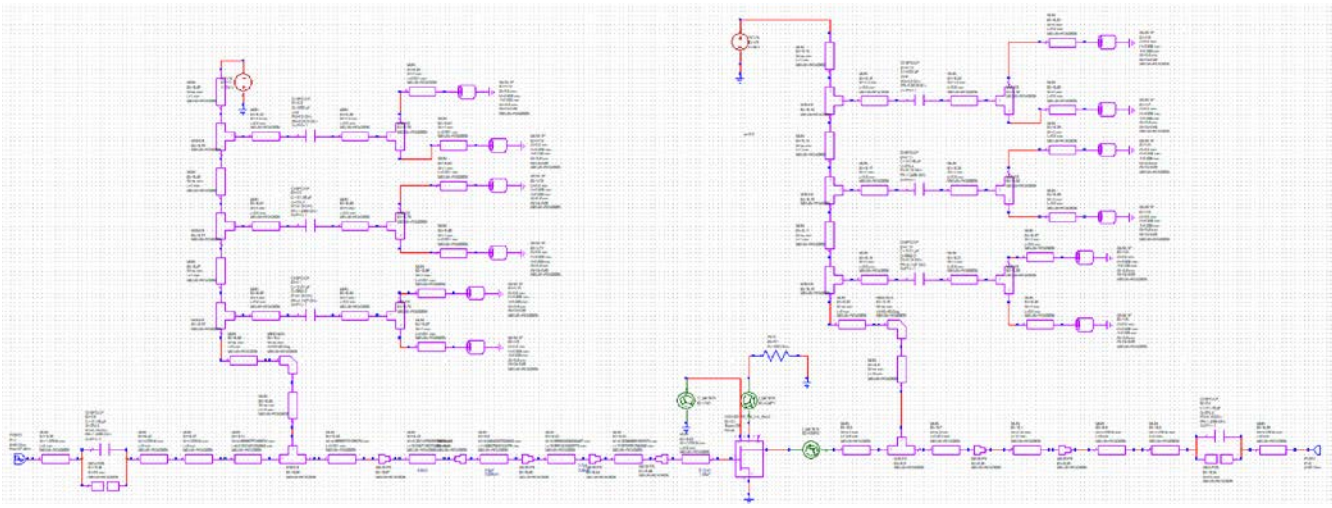

Fig. 12. Circuit schematic of PA in MWO

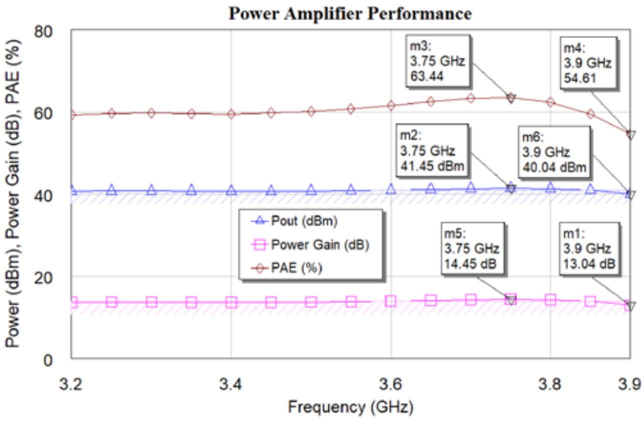

Fig. 13. Power amplifier performance with realized IMN and OMN in MWO

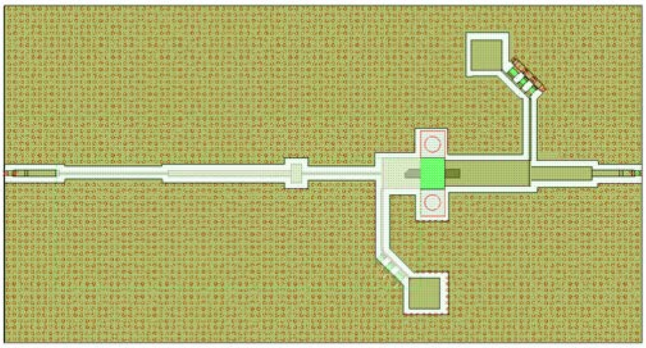

Fig. 14. Power amplifier layout for fabrication in MWO

V. CONCLUSION

From the design exercise it has been proven that the real frequency technique (RFT) along with the microstrip theory can produce wideband distributed element matching networks that translate into wideband, high efficiency power amplifier design. Therefore, RFT can be explored further for the design of broadband Doherty amplifier and Envelope Tracking amplifier designs for 5G NR and broadband medical applications. Simulated performance of the design presented in this study is quite impressive, since it covers the entire n78 spectrum of the 5G NR with very flat power gain and greater than 60% of power added efficiency (PAE) within the band of interest. In order to realize the calculated lumped element network values into microstrip structures, microstrip inductance and capacitance formulas are used but in future work Richards' transformation and Kuroda's Identities [6] will be explored for lumped element to distributed element transformations to compare the transformation accuracy.

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