A Compact 90W Broadband Doherty Amplifier

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***Abstract*—Traditional power amplifiers use transmission lines (TL) as a means of matching the transistor to the system. This results in large matching networks and thus large amplifiers. To reduce circuit size, as well as maintain the power handling, we have developed a method to construct a lumped-element/TL hybrid matching network. To demonstrate this method, we have applied it to a broadband 700-1000MHz 90W Doherty amplifier with minimal degradation in the performance of the amplifier and a 45% reduction in size. Measured results are also given.**

***Index Terms*—Integrated Circuit Modeling, Electromagnetic Modeling, Lumped-Element Equivalent Circuit Modeling, Parasitics.**

I. Introduction

The increasing demand for better service has led to rapid advancement in technology. The next generation protocol focuses on better utilization of the wireless spectrum. This results in a higher peak-to-average power ratio, which is problematic. RF power amplifiers' efficiency drops significantly at the back off power. Doherty amplifier has a simple and low cost design; it also provides better efficiency at back off power than other power amplifiers. Most medium to high power Doherty amplifiers use transmission lines (TL) as matching networks and phase shifters[1][2][3][4][5][6]. The lower power Doherty amplifiers designs can be made using lumped elements making them compact and inexpensive[7][8]. Lumped elements are usually not implemented at higher power because of their current limitations.

In this paper, a hybrid lumped element/TL transformation technique was used to construct a compact 90W Doherty broadband amplifier while maintaining performance. This method will allow for a more compact construction of both medium and high power Doherty amplifiers. Measured results are given. A photo of the constructed amplifier is shown in Fig. 1.

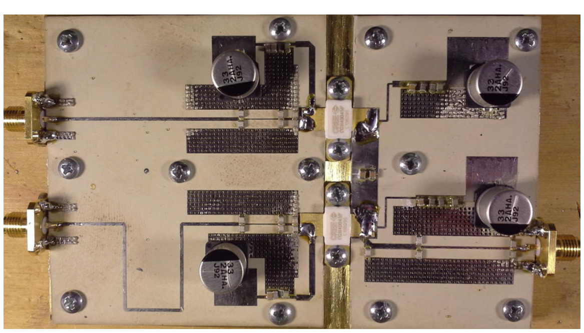

Fig. 1. Photograph of the Fabricated Compact 90-W Broadband Doherty Power Amplifier.

II. Theory

The method used is an extention of the work we did converting distributed microve components to lumped elements[9]. This in turn came from the understanding of parasitics of lumped components which allows for rapid development of microwave and RF circuits[10].

The hybrid lumped element/TL transformation technique was developed to reduce $\lambda/4$ matching TL size, at the same time maintaining the power handling capabilities. The size reduction greatly depends on the power handling of the printed circuit board. The transformation is divided into three steps: 1) converting the TL to the lumped element model, 2) replacing the modelled inductance with a thin TL (that can handle the power through put), and 3) adjusting hybrid lumped element/TL impedance/velocity to be the same as the original TLs impedance/velocity. Fig. 2 shows the conversion from TL to its lumped equivalent[9], where for the TL we have the characteristic impedance, Z_o , the signal velocity, v, inductance per unit length, L', and the capacitance per unit length, C'.

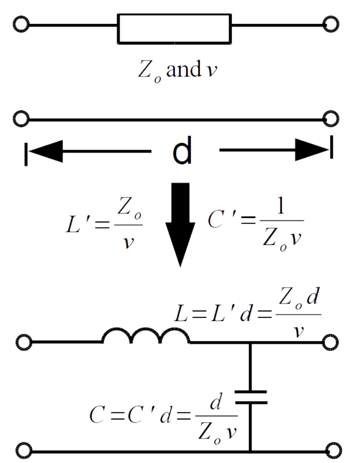

Fig. 2. Equivalent Transmission Line Circuit with Lumped Element Model.

The hybrid lumped element/TL in Fig. 3, should maintain the same amount of total inductance and capacitance as the original TL, in Fig. 2 so that the impedance and velocity is to remain the same. The width, w_n of the hybrid TL should be as narrow as possible. The minimum width is primarily limited to current density and heat dissipation of the PCB. Once the new width is obtained, the new TL impedance, Z_{on} can be calculated. The length of the hybrid TL can be calculated using

$$L = L_n = L'd = L'_n d_n \tag{1}$$

or

$$d_n = \frac{L'}{L'_n} d \tag{2}$$

It should be noted that L'_n is greater then L'; thus d_n will be less then d. Capacitor, C_a is added to the hybrid TL to adjust the impedance to be equal to that of the original TL. Therefore write

$$C = C_n = C'_n d_n + C_a \tag{3}$$

The adjust capacitor, C_a, needed to make $C = C_n$ is given by

$$C_a = C - C'_n d_n \tag{4}$$

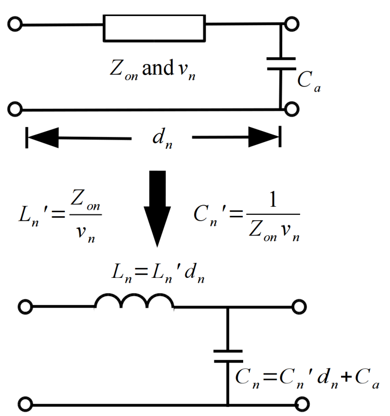

Fig. 3. Equivalent Hybrid Lumped Element/Transmission Line with Lumped Element Model.

III. Implementation

The fundamental design of the Doherty amplifier itself is identical to that used in [1] but we only reduce the size of the broadband impedance transformer. This is done by first replacing the Klopfenstein impedance transformers[1] by a binomial impedance transformer[11]. Both Klopfenstein and Binomial impedance transformers are broadband. The binomial impedance transformer is a cascade of fixed impedance λ/4 TL sections. The conversion of the individual λ/4 TL sections to a hybrid lumped element/TL sections were made to have equivalent performance. It was found that two section binomial transformer provides enough bandwidth, 35% bandwidth [1], for this application, and minimizes footprint compared to using more sections.

Our design used two PCB substrates: one for the input and the other for the output of the amplifier. Rogers Duroid RO-3006-25mil 2oz copper was used for both input and output matching network for this report to simplify the overall design process. The three Klopfenstein impedance transformers in the broadband Doherty amplifier[1], two on the input side and one on the output side, were replaced by three binomial impedence transformers. According to [1], the input impedance of the transistors are both 4Ω and the output impedance is 8Ω, and are all matched to 50Ω for external connection. The line impedances of the binomial transformer were calculated according to the method described in [11] for the frequency range of 700 to 1000 MHz, and shown in Table I. The required dimensions of the TLs in the binomial transformer were found using ADS linecalc.

TABLE I
N=2 Binomial Impedance Transformer

	$Z_1[\Omega]$	$Z_2[\Omega]$
Input	26.6	7.5
Output	13.6	32.4

The two TLs that make up the binomial transformer were treated separately and merged back together at the end of the TL to hybrid transformation.

The input matching networks will be the first to be converted in this paper to demonstrate the procedure and all other networks followed a similar procedure.

The input matching networks were converted, firstly the model of the TL, L and C, were obtained through equations of Fig. 2.

Secondly, we determine the width of the hybrid TL for the lumped element/TL matching network. Since the application is a 90W power amplifier, the concerning factor for the width is the current density and power handling of the PCB. The width was designed to withstand twice the maximum power. With a known TL resistance, the current flow can be calculated using (5), at the corresponding power level. The maximum input current was 2A and maximum output current was 4.8A calculated.

$$I = \sqrt{\frac{2P}{R}} \tag{5}$$

Given the current and copper thickness, one can determine the TL width for the printed inductor by using an on-line tool [4]. The minimum width of the input printed hybrid TL was found to be 0.221mm. With this new width, the input hybrid TL impedance can be calculated using linecalc in ADS. Since the hybrid TL and original TL have the same inductance, (1), we could then use (2) to determine the length of the hybrid TL.

Finally, the C_a required to adjust the capacitance was calculated through (4), and found to be 9pF. In order to maintain symmetrical designs for better broadband characteristic and power handling, C_a was split into four capacitors, $C_a/4$, and were used and placed at the four corners of the hybrid TL as shown in Fig. 4.

Following the same procedures, the second half of the binomial transformer was also converted. The two hybrid TL were combined, and the middle four capacitors were reduced to two capacitors in order to simplify the design. This can be seen in the schematic shown on Fig. 5. Capacitors C_1 are adjusting capacitors from the first section of the binomial transformer with capacitance of 2.25pF each; C_2 are from the

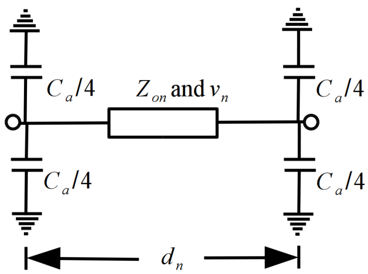

Fig. 4. Equivalent Hybrid Transmission Line Circuit.

second section with capacitance of 10pF each. The middle capacitors C_M is equal to the sum of C_1 and C_2, 12.25pF.

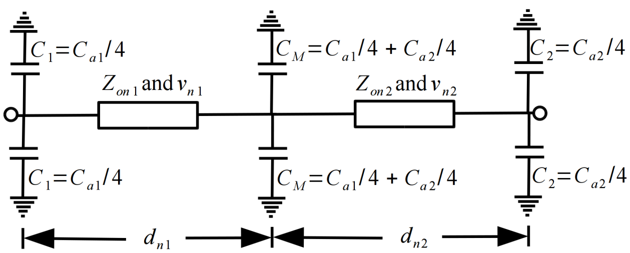

Fig. 5. Binomial Impedance Transformer N=2 using Two Hybrid Transmission Line Circuit.

Once the new hybrid lumped element/TL parameters are known, then the circuit is modeled in Keysight ADS through a momentum and circuit simulation. The layout is shown in Fig. 6. Capacitors C_1, C_2 and C_M were optimized using ADS.

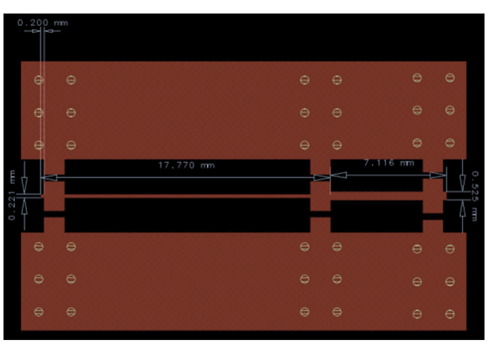

Fig. 6. Binomial Impedance Transformer N=2 using Two Hybrid Transmission Line Circuit Layout.

The total length of the original binomial transformer N=2 is 75.874mm, while the hybrid lumped/TL version has a total length of 24.886mm. The length of the TL is reduced by 67%.

The output matching was designed following the same procedure as the input matching. The optimized values of the adjusting capacitors are given in Table II.

The design used two commercially available 45-W CGH40045F packaged GaN transistors from Cree Inc. The main device was biased in deep class AB with a quiescent current of 400 mA and a drain voltage of 28 V. The auxiliary device was biased in class C with a gate voltage of 5.3 V and a drain voltage of 53.2 V. This is the same bias used in [1].

TABLE II
CAPACITORS VALUES AFTER OPTIMIZATION

	$C_1[pF]$	$C_2[pF]$	$C_3[pF]$
Input Binomial Transformer	2.7	9.0	9.0
Output Binomial Transformer	4.0	1.2	4.0

IV. MEASURED RESULTS

The measurement setup for the Doherty amplifier consists of an Anritzu ML2437A power meter with a MA2423D thermal sensor, Minicircuits BW-40N100W 100W 40dB power attenuator, 2w 26dB gain driver amplifier and an Anritzu MG3694A frequency source. A photo of the measurement setup is shown in Fig. 7.

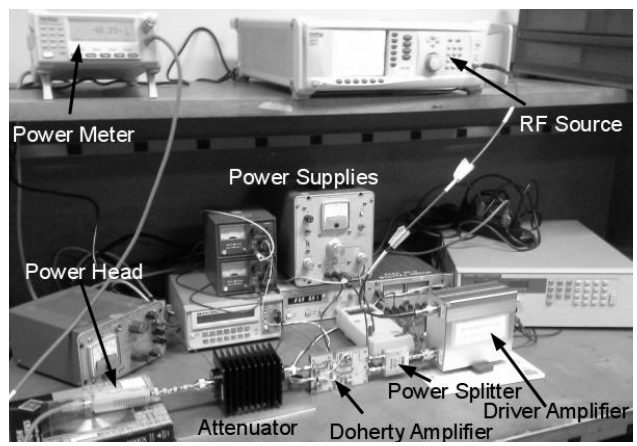

Fig. 7. Photo of measurement setup with Doherty amplifier under test.

The input matching network consisted of an external 3-dB Wilkinson power divider that operated from 500 to 1000 MHz, a 90 degree delay line, and two hybrid lumped element/TL transformers, which feed the main and auxiliary devices. A photo of the constructed amplifier is shown in Fig. 1.

Fig. 8 shows the measured drain efficiency at the peak and 6-dB back-off power levels from 700 to 1000 MHz under a continuous-wave (CW) stimulus. Within the design frequency band from 700 to 1000 MHz, the average values of the peak efficiency and the 6-dB back-off efficiency were 59% and 59%, respectively.

Fig. 9 contains the measured peak output power and the associated gain versus frequency under a CW stimulus. From 700 to 1000 MHz, the average values of the peak output power and the associated gain were 51 dBm and 17 dB, respectively. To assess the efficiency enhancement at the back-off power levels, we measured the drain efficiency versus output power at 850 MHz. Figs. 10 to 11 show measured drain efficiency and gain versus output power at 850. At 1 GHz, though the 6-dB back-off efficiency is still about 60%, the efficiency enhancement is reduced.

It should be noted that a further reduction of the input side of the amplifier in Fig. 1 can be made by replacing the 90^o phase shifter at the input of the auxiliary amplifier with a lumped element/TL hybrid. The compact broadband 90 W Doherty amplifier was 45% smaller in area than the amplifier in [1].

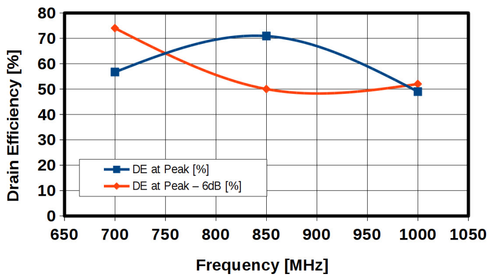

Fig. 8. Measured Drain Efficiency of the Compact Broadband Doherty Amplifier at the Peak Power and 6-dB Back-Off Power from 700 to 1000 MHz.

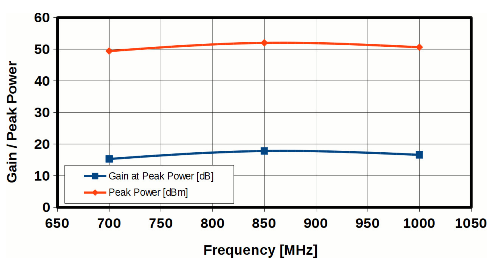

Fig. 9. Measured Peak Output Power and Gain of the Compact Broadband Doherty Amplifier from 700 to 1000 MHz.

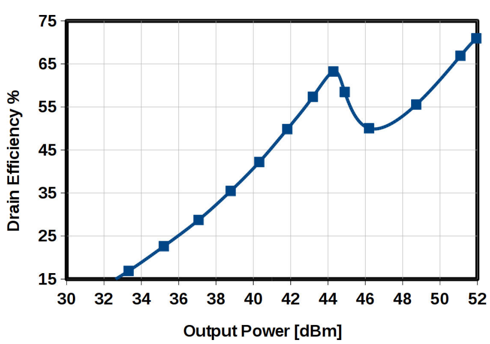

Fig. 10. Measured Drain Efficiency versus Output Power of the Compact Broadband Doherty Amplifier at 850 MHz.

V. Conclusion

Hybrid lumped element/TL transformation technique was successfully applied to a modified Doherty amplifier for size reduction. The hybrid lumped element/TL binomial matching was used instead of the original Klopfenstein taper. Hybrid lumped element/TL technique was able to achieve over 60% length reduction from original binomial transformer while maintaining good performance. The average peak output power of 51 dBm, an average gain of 17 dB, and average peak

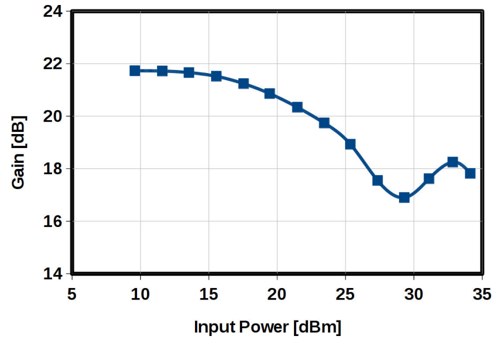

Fig. 11. Measured Gain versus Input Power of the Compact Broadband Doherty Amplifier at 850 MHz.

and 6-dB back-off efficiencies of 59% and 59%, respectively, were obtained across the design frequency band of 700 to 1000MHz or 35% bandwidth. The compact broadband 90 W Doherty amplifier was 45% smaller in area than the original amplifier.

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