Broadband Class-E Power Amplifier Designed by Lumped-element Network Transforms and GaN FETs

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Abstract —It has been shown that broadband operation of class-E amplifiers is possible using the reactance compensation technique. In this paper, broadband lumped-element network transforms are used in order to design the loading network that provides broadband reactance compensation and broadband impedance matching simultaneously while keeping high efficiency and maintaining output power within wide bandwidth. The final output network topology is canonic and alternates series and shunt components which are more suitable for practical implementation and tuning. As proof of concept, a GaN FET prototype is presented achieving 80% efficiency over 43% fractional bandwidth at around 255-MHz and 60% efficiency over an octave bandwidth at around 245-MHz.

Index Terms — Amplifier, broadband, class-E, efficiency.

I. INTRODUCTION

The benefits of high efficiency power amplifiers (PAs) have been discussed in the literature and a class-E PA is attractive to serve this purpose. The optimum true-transient class-E PA operation is explained in [1] and its operating bandwidth is inherently narrowband since the active device acts as a true switch at a given fundamental-frequency (f_0). The basic schematic of an optimum class-E amplifier is shown in Fig. 1. Suboptimal class-E operation is possible at frequencies other than f_0. However, keeping high efficiency over wide bandwidth is not possible without changing one or more amplifier parameters [2] (i.e. B_S, X, V_{DD}, etc.), Fig. 1.

Other broadband class-E PAs techniques have been presented in the literature. I.e., a conventional broadband matching including device parasitics can be used [3]. Also, a balanced class-E amplifier can be implemented at the expense of using at least two amplifierswith transmission-line based matching networks [4]. These techniques are in general for high-frequency operation in the range of 800-MHz and above.

An alternative approach for broadband class-E amplification was first proposed in [5] taking advantage of a shunt reactive element and the L-C resonator frequency response to keep a constant reactance at the device drain for a wide frequency range, known as reactance compensation using a finite-inductance DC-feed inductor [6].

Nevertheless, the basic reactance compensation loading network carries several practical issues that limit high frequency performance of the PA. This network requires broadband impedance matching to 50-Ohms which is not generally easily achievable without introducing significant insertion loss which reduces the PA efficiency or limits the amplifier bandwidth.

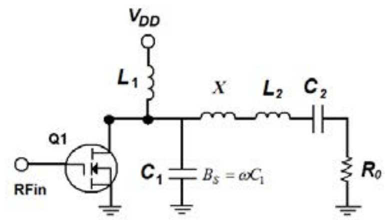

Fig.1. True-transient class-E PA with L_1 having infinite inductance.

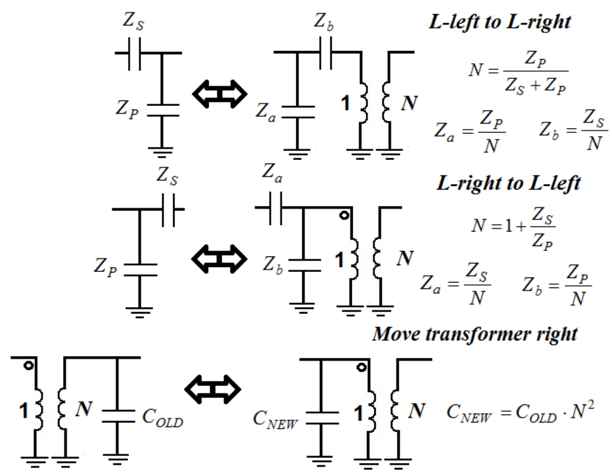

Fig.2. Exact equivalent network transforms (N=turns ratio).

Additionally, the series L-C resonator is sensitive to the parasitic straight capacitance to ground of the printed board (PWB) and in some cases designers will encounter impractical component values. In order to address the aforementioned practical issues of broadband class-E designs while maintaining high efficiency and flatter output power over a wide range of frequencies, a design technique based on lumped-element network transforms is described in the next sections. The final lumped-element loading network topology is then applied to a prototype and the experimental results show high efficiency over wide bandwidth.

II. LUMPED-ELEMENT NETWORK TRANSFORMS

A given reactive network has a dual network with exact reactance characteristics as a function of frequency. Meaning, a series-shunt network of capacitors (or inductors) can be represented by a shunt-series network of capacitors (or inductors), plus a transformer, Fig. 2. Likewise, a shunt-series network of capacitors (or inductors) can be represented by a

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series-shunt network of capacitors (or inductors), plus a transformer. These are called L-left to L-right and L-right to L-left transforms, respectively, with arbitrary transformer turn ratios, N. These types of network transforms are very popular in filter design [7].

Other network transforms are available and can be used to change a given network topology with an exact equivalent network at all frequencies [7].

The number of transforms and type of transform used in a given network design depends upon the desired final topology that satisfies the designer's need. The first applied transforms are vital in determining the final topology. Therefore, being aware of which transforms are available for a given component or components and knowing where to apply them is greatly advised before starting to transform a circuit.In the next section, a design example includes the network transforms from Fig. 2 which are described accordingly.

III. Broadband Class-E PA Design

In order to exemplify the use of network transforms we begin the design with a reactance compensation loading network using the equations given in [6].

The design parameters of the loading network are computed based on the Polyfet GP2001 GaN FET device with a low parasitic drain-to-source capacitance, C_{DS}=4 pF. Using equations from [6]; the target output power is 18.0 W, with a supply voltage V_{DD}= 18.2 V the required load impedance is R_0=25-Ω, as shown in Fig. 3. The component values computed at 200-MHz are: C_1=17.8 pF (a total of 21.8 pF minus C_{DS}) and L_1=14.56 nH. For broadband operation the series resonator L_2 =20.4 nH and C_2=31.02 pF. Notice the finite-inductance choke, L_1. Also notice that the PA load impedance is 25-Ω, hence requiring matching, Fig. 3. The impedance at device drain is Z_{VD}=17.3+j11.8 Ω. Network transforms are then applied to this basic network.

The first transform is impedance matching from 25 up to 30-Ohms where the impedance transformation ratio is only 1.2 (Q=0.4) maintaining broadband performance. For this purpose, a typical L-C matching network can be used as shown in Fig. 4a.

In the next transform, the inductors L_2 and L_3 from Fig. 4a merge to form inductor L_4, Fig. 4b. Also capacitor C_2 from Fig. 4a splits into capacitor C_4 and C_5.

It is important to mention that capacitors C_4 and C_5values are computed taking into account the next two transforms. Since C_5 and C_3 form an inverted L-shaped network, as from Fig. 2, the applied transform is an "L-left to L-right" with a specified transformer T1 turns ratio of 0.74, Fig 4c. Likewise, C_4 and C_1 are transformed using the "L-right to L-left" transform from Fig. 2, with a specified transformer T2 turns ratio of 1.046, Fig 4d. The transformation ratio values of T1 and T2 can be chosen specifically so that they will vanish with a third transformer T3 in the final step as shown in Fig. 5b. Therefore, the transform sequence from Fig. 4 is as follows:

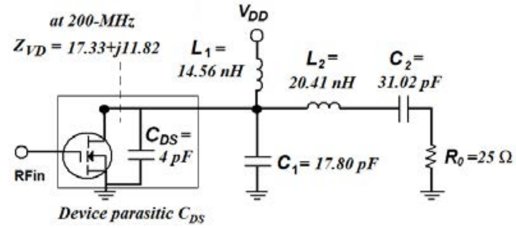

Fig.3. Original broadband class-E PA. Notice the 25-Ω load.

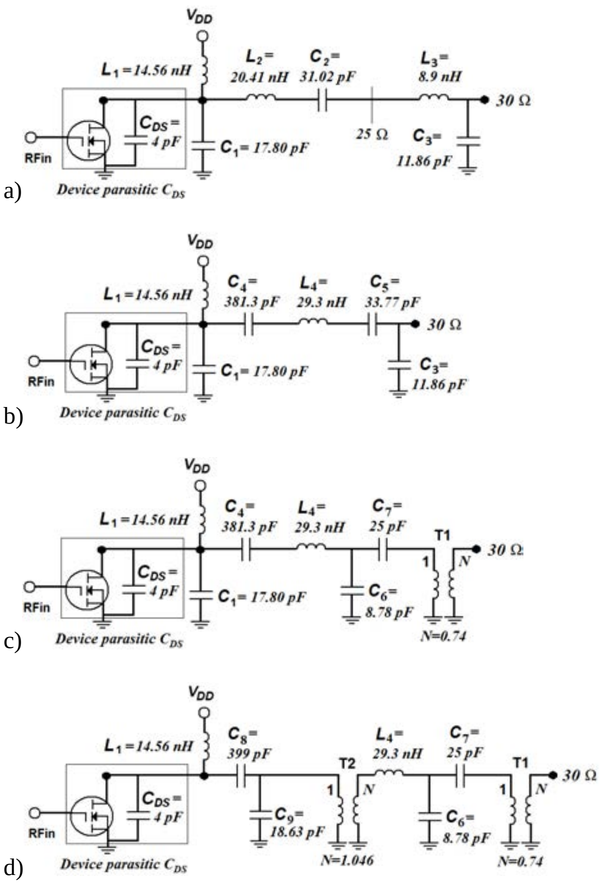

Fig.4. Transforms sequence with 30-Ω load impedance.

1) Raise the load impedance from 25 to 30 Ω, Fig. 4a.

2) Split capacitor C_2 from Fig. 4a into C_4 and C_5, Fig. 4b.

3) Apply L-left to L-right to capacitors C_5 and C_3, and create C_7, C_6 and T1, Fig. 4c. Merge inductor L_2 and L_3 into L_4.

4) Apply L-right to L-left to capacitors C_4 and C_1, and create C_8, C_9 and T2, Fig 4d.

This transformation sequence changes the network topology so that the first element from drain to load is the series capacitor C_8. Notice that the network now has components to ground at all nodes. The next two steps are to eliminate transformers T1 and T2 using the "move transformer right" transform from Fig. 2 and match to 50- Ω using a transformer T3 with turns ratio N=1.29. The transform sequence follows:

*5)*Step-up the load impedance from 30 to 50- Ω by adding transformer T3 with N=1.29. This is broadband matching since an ideal transformer is used with more turns in the primary than in the secondary, Fig. 5a.

*6)*Shift the transformer T2 to the right, Fig. 5b, in order to reach transformer T1 and T3 using the transform in Fig. 2. The final network is shown in Fig. 5c and has no transformers.

Although the network transforms from Fig. 2 are exactly equivalent at all frequencies the frequency response of the original network from Fig. 3 is not exactly equal to the frequency response of the final network from Fig. 5c because the 30 to 25-Ω impedance matching is only equivalent at one frequency. Nonetheless, Fig. 6 shows similar simulated impedance magnitude $|Z_{VD}|$ and phase angle presented at the intrinsic drain across frequency for both networks.

Notice that the final network, Fig. 5c, does not include a transformer and that all nodes have shunt capacitors to ground. Also notice that T3 turns ratio, N=1.291, matches 30 to 50-Ω and this value was anticipated when applying the previous transforms as the inverse value of the product of T1 and T2 turns ratios, hence, the equivalent transformer turns ratio in Fig. 5b equals to unity and vanishes (1.046 x 0.74 x 1.291=1).

Other transformation sequences are available [7] and yield to different topologies but only the applied transforms used in this paper are described in Fig. 2. Nevertheless, the final network topology for this design is found to be very convenient for implementation and tuning in a frequency range of 150 to 350-MHz. It is worth mentioning that the same transform sequence previously described can be applied to a true-transient class-E amplifier, however, the benefits of broadband operation will not be noticed.

IV. Broadband Class-E PA Prototype

The schematic from Fig. 5c is implemented in a prototype shown in Fig. 7, where trimmer capacitors as well as ceramic chip capacitors are used for C_9 and C_{11}. For C_{10}, two parallel-connected high-Q capacitors were used.

The inductor L_4 is a wire-wound solenoid with self-resonant frequency beyond 900-MHz assuring flat inductance value from 100 to 350-MHz. Capacitor C_8 value is rather large but it can be implemented using an array of four high-Q ceramic capacitors and they can be of values in between 91 to 100-pF depending of tuning. The finite-inductance DC-feed inductor $L_1$is also implemented using a wire-wound solenoid with high self-resonant frequency, Fig. 7.

The input matching network is of special interest since it has to provide broadband input match. Since a 10-Ohms resistor is added at the gate mainly for stability, the input impedance is more favorable for a three section match in order to achieve broadband matching, Fig. 8.

The amplifier performance is depicted in Fig. 9 and it is measured from 150 to 350-MHz in 5 MHz steps for a fixed input power of 28 dBm.

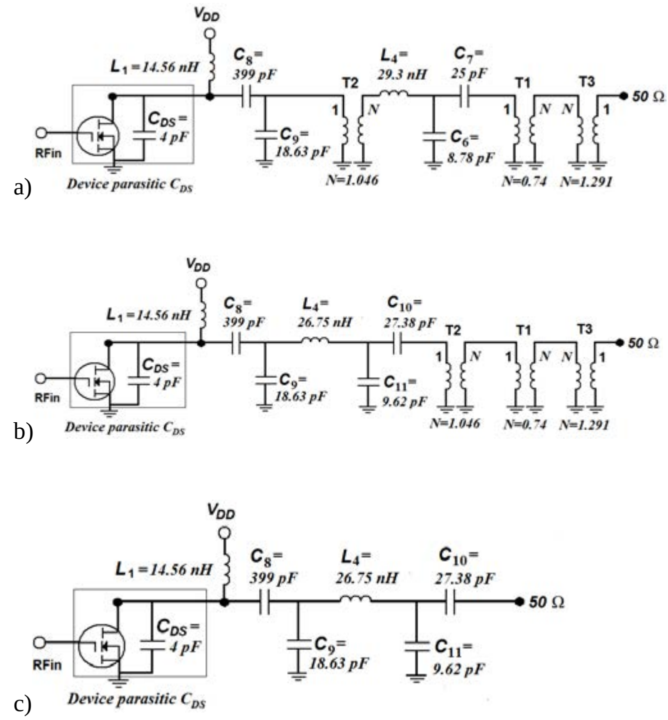

Fig.5. Transforms sequence for impedance matching to 50-Ω.

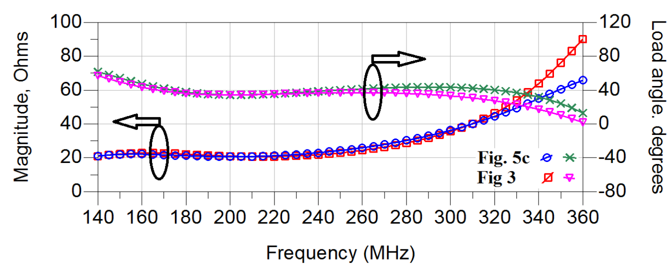

Fig.6. Simulated impedance seen at the device intrinsic drain.

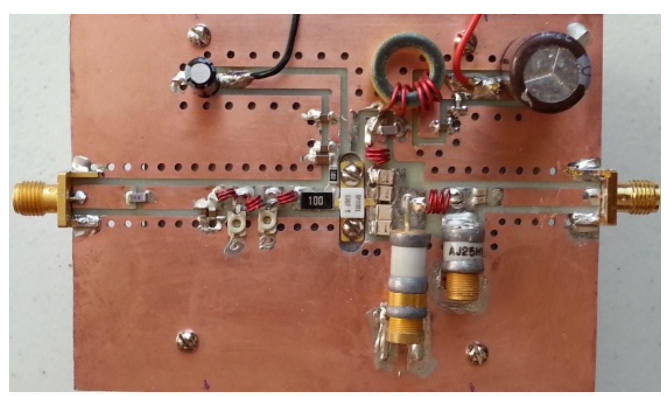

Fig.7. Broadband Class-E amplifier prototype.

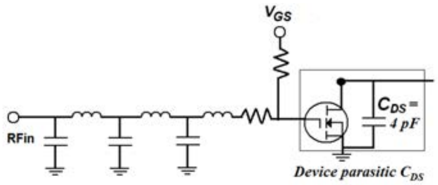

Fig.8. Input matching network schematic.

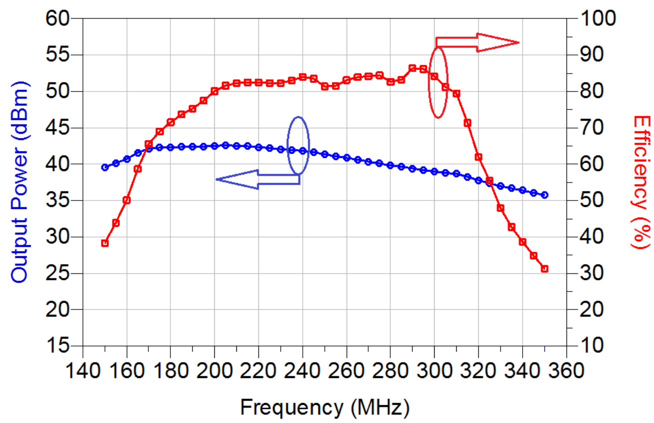

Fig.9. Measured output power and efficiency.

It is shown that the 60% efficiency bandwidth is an octave with an output power variation within 4 dB (42.54 to 37.55 dBm). The 80% efficiency bandwidth is 110-MHz (43% fractional bandwidth) with an output power variation of 3.82 dB (42.54 to 38.71 dBm). Nevertheless, the efficiency at the designed frequency of 200-MHz is 79.8% with a measured output power of 42.5 dBm (17.8 W) so the gain is 14.5 dB. It is observed, that the broadband performance is kept beyond the design frequency and high efficiency is maintained only for a few MHz below the design frequency. The highest efficiency is 85.8% and it is achieved at 290 –MHz.

V. Conclusions

Network transforms is a powerful way to design PA loading networks as well as broadband matching circuits. Choosing the right transform sequence is very important for a given topology so that broadband efficiency and output power can be achieved for a class-E amplifier with a more suitable network for practical implementation.

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