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Design of a Triple-Band Power Amplifier Using a Genetic Algorithm and the Continuous Mode Method

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***Abstract*—Dual band power amplifiers use either large and lossy matching networks, or switches, which do not allow concurrent operation. In this work, a concurrent, triple-band power amplifier with a simple matching network is presented. The theory of continuous modes of operation has been used in the optimization of the input and output matching networks using a genetic algorithm. As proof of concept, a design at 0.8, 1.8, and 2.4 GHz has been fabricated and characterized in the laboratory. A maximum power added efficiency and output power of 70% and 41 dBm have been achieved using our novel design. The design described in this paper is based on a solid theoretical analysis and demonstrates a simplified biasing network. Such design is highly suitable for next generation wireless systems with aggregated carriers.**

***Index Terms*—Power amplifier, Multi-band, Triple-band, Genetic Algorithm, Continuous mode**

I. INTRODUCTION

THE evolution in wireless communications is ever increasing with more users and data-heavy applications being introduced. As a consequence, the future standards, such as advanced long-term evolution (LTE), are calling for considerably increased data rates. Obviously, the wireless systems currently used (below 6 GHz) will not be able to accommodate such rates. Moreover, future wireless systems are also featured by multiple services and applications which typically require multiple sub-systems. To optimally exploit the sub-6 GHz bands and reduce the number of sub-systems, multi-band wireless systems are thus required.

In the design of multi-band wireless systems the most challenging part is the RF front end. One of the most important components in the RF front end is the power amplifier (PA). To address the above-mentioned applications ultra-wideband PAs can be used. However, if the multiple bands are positioned wide apart, it becomes very challenging to maintain the performance (linearity and efficiency) of the wide-band amplifier; therefore, a multi-band design is preferable is such case.

The most critical part of the design of multi-band PAs is usually the matching networks (MN). An obvious solution is to design multiple defined MNs with switches [1]. This approach, however, does not provide concurrent operation and has increased insertion loss due to the use of switches. A conventional way to realize concurrent operation is to design multiple matching networks and introduce frequency selectivity using resonators in the form of lumped or distributed components [2]. These matching networks, however, become large as the number of bands is increased. They also impose restrictions on the frequency bands that can be accommodated, and they can provide the desired impedances at the fundamental frequencies only. Other designs utilize unified MNs designed to operate at multiple frequencies, which overcome the restrictions on the frequency bands and provide the desired impedances at both the fundamental as well as the second harmonic [3], [4]. Others are also designed for different classes of operation at different frequency bands [5], or utilizing the continuous modes [6]. These designs, however, use very complex methods to design the matching networks, which limits them to only two concurrent bands. They also require complex dual band biasing networks because the bias networks are not part of the main design [7]. For all of the above-mentioned designs, increasing the number of concurrent bands either increases the size, and hence losses, of the MN [2], or considerably increases the complexity of the MN [3], [4], [6].

In this work, a concurrent triple-band power amplifier is presented. A very simple and compact output MN is used, which is optimized by a robust genetic algorithm. The wide design space provided by the continuous modes has been used as the goal for the optimizer. Rather than starting from load pull simulations, this work starts from a theoretical base using the optimal output impedance at the current generator plane together with an accurate package model.

II. DESIGN METHODOLOGY

In a conventional class B PA the output current is half-wave rectified, and the output voltage is a full wave. To achieve these ideal waveforms the transistor must be biased with zero quiescent, and the output MN should provide the optimal impedance at the fundamental frequency and a short circuit at all the harmonics [8]. It has been shown in [9] that the linear and efficiency performance of the class B amplifier can be maintained over a wider impedance space, which is known as class B-J or continuous class BV. Such wide design space is very attractive for multi-band designs because the different bands do not necessarily need to have the same terminations, which provides flexibility for the optimization of the multi-band MN.

The theoretical impedance space for continuous class B is defined at the current generator plane (Z_{gen} in Fig. 1) and can be conveniently expressed as:

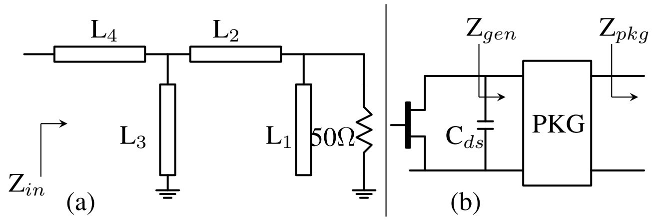

Fig. 1. (a): Schematic of the simple matching network used for both the input and the output. (b): Block diagram of the transistor with the package and current generator impedances.

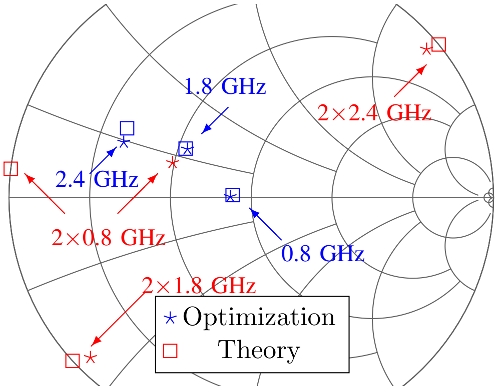

Fig. 2. Theoretical and optimized complex impedances (at the package plane) at the fundamental frequencies as well as the second harmonics.

$$Z_{f_0} = R_{opt}\left(1 - j\delta\right), \tag{1a}$$

$$Z_{2f_0} = j\delta\frac{3\pi}{8}R_{opt}, \tag{1b}$$

and

$$R_{opt} = 2V_{DS}/I_{max}, \tag{1c}$$

where Z_{f_0} and Z_{2f_0} are the fundamental and second harmonic impedances, respectively. R_{opt} is the optimal resistance, which allows peak voltage swing at maximum output current. V_{DS} is the peak drain voltage and I_{max} is the maximum drain current. δ is the design space parameter, which can take any real number between -1 and 1. A lumped model for the package [10] can be used to transform the impedances to the package plane (Z_{pkg} in Fig. 1).

After the theoretical target impedances are defined, the next step is to select a suitable matching network that can transform the 50 Ω of the antenna to the appropriate impedance termination at each band. In this work, a simple two L-sections have been used as shown in Fig. 1. For biasing purposes, the stub closer to the transistor is terminated with a short. This way, no complex, multi-band network is needed for biasing. This matching circuit has four lines; therefore, eight optimization parameters (characteristic impedance and length of each line).

A. Optimization using Genetic Algorithm

The final step in the design is to optimize the MNs. Three frequency bands have been selected: 0.8, 1.8 and 2.4 GHz. These frequencies have been chosen as proof of concept and due to the many applications using them, but other sets of frequencies can be targeted using this method. Two types of parameters are used in the optimization process: the eight parameters of the lines, which are constant across the different frequencies, and δ, which can change between the three frequencies providing great flexibility to the optimizer.

Since both the input impedance of the matching network and the target impedance can be expressed in closed forms, mathematical optimizers can be used to design the matching network. In this work, a genetic algorithm has been used due to its speed and suitability for such problems. The goal of the optimization is to minimize the difference between the synthesized and the theoretical input impedances. For each optimization run, the goals are calculated for all the values of the variable δ and for all the frequencies (the three frequencies and their second harmonics). The value of δ that gives the minimum total goal for the three frequencies and their second harmonics is selected. This process is repeated until the algorithm converges giving the characteristic impedances and lengths of the optimized transmission lines. In Fig. 2, the optimized complex impedances of the output MN are plotted with the theoretical values. It can be seen that the genetic algorithm has provided very close values at the three fundamental frequencies and their second harmonics. It is worth mentioning that for the case of the input MN, the same algorithm is used, but for conjugate matching and at the fundamental frequencies only.

B. Simulation

The genetic algorithm described in the previous section generates values for ideal transmission lines. The next step is to provide physical dimensions for the matching network. First, approximate, microstrip dimensions have been obtained from empirical formulas. Next, a full wave simulation has been performed to optimize the MN design. This process has been performed for both the input and output matching networks; however, only the fundamental is considered for the case of the input MN. After the MNs have been optimized, the complete amplifier design is simulated using the transistor model and the S-parameters of the MNs from the full wave simulator.

III. IMPLEMENTATION AND MEASUREMENTS

The prototype of the triple-band PA has been fabricated on an RT/Duroid® 5880 with a thickness of 0.79 mm. A GaN FET from Cree has been used (CREE CGH40010F) with standard lumped components for the DC and RF blocks as shown in Fig. 4.

A single tone, continuous wave (CW) signal has been used in the measurement of the amplifier with a constant input power of 27 dBm. The measured and simulated efficiencies, output powers and gains are plotted in Fig. 3 for the three frequency bands. A good agreement between the simulation

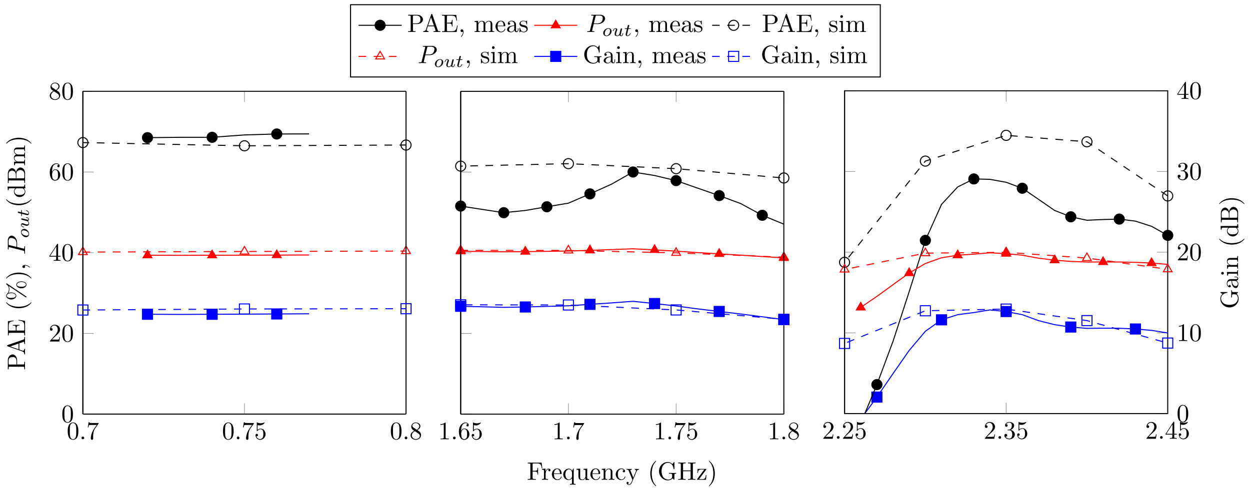

Fig. 3. Simulated and measured PAE, power gain, and output power across the three frequency bands for constant input power of 27 dBm.

and the measurement can be clearly observed with the measured results shifted downwards slightly (50 MHz). For the lower band, the PA provides a maximum PAE of 70 % and an output power of 40 dBm with a flat gain of about 12 dB. For the middle and high bands, the maximum PAE is 60% and 58%, respectively. The output powers for these bands are 41 dBm and 40 dBm, respectively, and the gains are about 12 dB and 11 dB, respectively. It can also be seen that the gain is very stable especially for the first two bands. These results verify the capabilities of the design methodology to provide good performances at three different frequencies with such a simple matching network topologies.

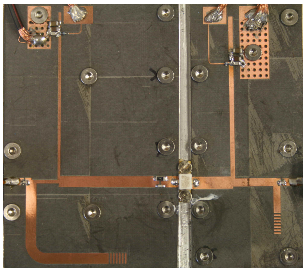

Fig. 4. Photograph of the fabricated power amplifier.

IV. CONCLUSION

In this work, a new design methodology based on the continuous modes is presented. This design approach eliminates the need for complex and multiple matching networks typically used for the design of multi-band PAs. To demonstrate the impact of the new approach, a triple-band amplifier has been reported. This amplifier uses a matching network much simpler than the ones used for most of the reported dual-band designs with comparable PAEs. This triple-band amplifier is suitable for future wireless applications, which require multi-carrier operations.

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