Concurrent planar multiharmonic dual-band load coupling network for switching-mode power amplifiers

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Abstract—This paper presents a concept to design a compact planar multiharmonic load transformation network (MHLTN) for the realization of highly efficient dual-band power amplifiers (PAs). The proposed MHLTN consisting of only transmission-lines can precisely achieve impedance terminations at two distinct nonharmonic frequencies including up to three harmonics without switches or tuning elements. High impedance stubs are deliberately inserted at particular sections of the network for the harmonic frequency termination to be controlled. The topology was applied to implement a class-E PA using a GaN High Electron Mobility Transistor (HEMT) in a hybrid design for GSM1810 and LTE2655 operation. The measured impedances of the passive switchless MHLTN for a dual-band class-E load coupling network are in good agreement with simulation results. With a dual-band input matching network, the measurement results have shown 78.4 % and 61.3 % of peak power added efficiency (PAE) with an associated output power of 37.8 dBm and 36.9 dBm in the lower and upper band, respectively.

Index Terms—Class-E, GaN HEMT, dual-band, optimum impedances, output power, power added efficiency (PAE).

I. INTRODUCTION

Recent developments of modern wireless communication systems result in different communication standards and frequencies [1]. In order to increase the degree of integration of RF frontend integrated circuits (ICs), RF equipment is required to operate signals at different communication standards. Some of these standards need to be used concurrently. This demands multiband receivers and transmitters for multistandard communication protocols such that the total size, weight and power consumption of the terminal is reduced. However, the power amplifier (PA) residing in the transmitter unit presents a design challenge as it has high power levels and is, therefore, responsible for a substantial part of the total DC power consumption.

Several approaches have been investigated for multiband transmitter design namely broadband [2]-[3], unit selection [4]-[5] and reconfigurability [6]-[7]. Broadband techniques present a trade-off between bandwidth and efficiency while the unit selection and reconfigurable concepts require the usage of either power switches or electronic tunable elements, e.g. varactors or Micro-Electro-Mechanical Switches (MEMSs). These elements require additional control signals to modify the electrical properties of the reconfigurable elements and may introduce distortions.

A multiband approach [8]-[10] provides the capability to operate at different bands without the need of any switch, while the performance of the PA is optimised at the bands of interest. This is possible without any control signals and reduces the number of components in both the input matching and the load transformation network of the PA. Thus, a multiband design leads to flexible mobile communication equipment with a performance comparable to a single-band design. The major challenge in such an approach is to provide the optimum input and output impedances to the device at multiple bands and the corresponding harmonics.

In this paper, a novel architecture to implement a compact planar dual-band MHLTN for the design of a highly efficient PA is presented. The resulting switchless MHLTN is a concurrent dual-band load coupling network. The proposed approach is applied a class-E PA design with a dual-band input matching network. The MHLTN provides concurrently the required impedances at two distinct bands and their harmonics, while the amplifier achieves peak PAE of 78.4 % and 61.3 % with an output power of 37.8 dBm and 36.9 dBm, respectively.

II. MULTIHARMONIC LOAD NETWORK BASED ON TRANSMISSION-LINES

A. Single-band multiharmonic load network

The design of a highly efficient PA implies the optimization of the impedances to be presented to the active device’s input and output ports both at fundamental and harmonic frequencies [9]. For a real PA design, up to three harmonics are typically considered.

The class-E PA is a promising topology for high efficiency at high frequencies. The class-E operation principle is explained in detail in [11]. The load impedance at the fundamental frequency of a class-E operation is inductive, while all other harmonic load impedances are assumed to be infinite [12].

A widely used distributed-element topology for class-E PA is shown in Fig. 1. This network provides the optimum fundamental impedance and correct impedance terminations up to the third harmonic frequency. Because, it is the starting
Fig. 1. Schematic of the transmission-line based single-band multiharmonic load transformation network suitable for class-E operation.

point for the proposed dual-band MHLTN, the principle of operation is briefly outlined here. The length of line $TL_2$ is one quarter wavelength ($\lambda/4$) at $3f_0$, where $f_0$ is the fundamental frequency. It provides a short circuit at its connection point with $TL_1$ at node $A$. Therefore, the circuit to the right of this connection point is ineffective at this frequency. By making $TL_1 \lambda/4$-long at $3f_0$, the low input impedance of $TL_2$ will be transformed into a high reactive impedance at the transistor’s output terminal. Similarly, the impedance at the second harmonic frequency is controlled. $TL_4$ is made exactly $\lambda/2$-long at $2f_0$ and short-circuited to ground by a large capacitor on one end to provide a low input impedance at node $B$. The total length of $TL_1$, $TL_3$ and the capacitive loading of $TL_2$ at this frequency are designed to provide a high impedance at $2f_0$ at the output of the transistor. Taking into account the length of $TL_1$, which is $\lambda/12$, and neglecting the capacitance at this frequency at node $A$ due to $TL_2$, the electrical length of $TL_3$ should be approximately $\lambda/24$ at the fundamental frequency $f_0$. Finally, the required fundamental impedance transformation is obtained by tuning the characteristic impedances of $TL_1$, $TL_2$ and $TL_3$. The capacitor $C_1$ is used for DC-blocking only and has no effect on the RF performance.

B. Dual-band multiharmonic load network

The proposed dual-band MHLTN uses the concept to insert high impedance stubs of $\lambda/4$ length at specific locations of the network to get a short-circuit for the frequencies to be controlled. The characteristic impedance $Z_0$ of an open transmission-line and its shunt capacitance are related by:

$$C = \frac{\tan(\beta l)}{\omega Z_0},$$

(1)

where $\beta$ is the propagation constant, $l$ is the length of the line and $\omega$ is the angular frequency. According to (1), the high impedance stub has low shunt capacitance which means less capacitive loading and, thus, a marginal influence at the fundamental frequencies. The dual-band MHLTN is designed for class-E conditions, where the lower and upper band frequencies are denoted by $f_1$ and $f_2$, respectively.

The concept is implemented by partitioning $TL_1$ in Fig. 1 into two lines comprising $TL_1$ and $TL_3$ as shown in Fig. 2.

Fig. 2. General schematic for the proposed multiharmonic dual-band load transformation network appropriate for class-E operation.

The high impedance line $TL_2$ of $\lambda/4$ length at $3f_2$ is used to control the third harmonic of the upper band. It is connected at node $A$ so that $TL_1$ is $\lambda/4$ at $3f_2$, which provides the required impedance termination at $3f_2$. Similarly, to control the third harmonic of the lower band $3f_1$, the high characteristic impedance line $TL_4$ of $\lambda/4$ length at $3f_1$ is connected at node $B$. The length of $TL_3$ can be tuned according to the capacitive loading of $TL_2$ and the length of $TL_1$ in order to obtain the desired impedance termination at this harmonic frequency.

Transmission-line $TL_5$ of length $\lambda/2$ at $2f_2$ is connected at node $C$ to control the second harmonic of the upper band, $2f_2$. Considering the circuit from the output of the device till node $B$, $TL_5$ is tuned to transform the low impedance at node $C$ to the targeted high reactive impedance at the device output at this frequency, while it also provides the required DC-biasing at the drain. To control the second harmonic of the lower band, i.e. $2f_1$, $TL_8$ of $\lambda/4$ length at $2f_1$ is connected at node $D$. Taking into account the network from $TL_1$ to node $C$, $TL_7$ is adopted to transform the short-circuit at node $D$ to high reactive impedance at the device output.

Finally, the optimum fundamental impedances at the bands of interest are adjusted. For this purpose, transmission-lines $TL_9$ and $TL_{10}$ along with the characteristic impedances of $TL_1$, $TL_3$, $TL_7$ and $TL_8$ are tuned to obtain optimum load impedances at $f_1$ and $f_2$.

III. CONCURRENT PLANAR DUAL-BAND MULTIHARMONIC LOAD TRANSFORMATION NETWORK DESIGN

In this paper, the design has been focused on GSM1810 and LTE2655 bands, i.e. 1.81 GHz and 2.65 GHz, respectively.
According to the operating frequencies, $2f_2 = 5.30$ GHz and $3f_1 = 5.43$ GHz. Due to the small frequency spacing between $2f_2$ and $3f_1$, it is difficult to tune them to the desired values. Since, the second harmonics has higher impact on amplifier efficiency, the impedance at $3f_1$ is compromised to achieve the desired impedance at $2f_2$. The high impedance transmission-line $TL_4$ (illustrated in Fig. 2) is hence removed, while $TL_5$ can be combined with $TL_3$ to optimise impedance termination for $2f_2$. The schematic of the proposed concurrent dual-band MHLTN for class-E load conditions is reported in Fig. 3.

IV. Dual-band multiharmonic load transformation network implementation

Based on the single-band multiharmonic load network for class-E PA as discussed in Sec. II, two class-E PAs have been designed at 1.81 GHz and 2.65 GHz, using a large-signal model provided by the manufacturer. A 10 W GaN HEMT from CREE is used for this application. The transistor was biased with a drain supply voltage $V_{DD} = 28$ V and the gate-to-source bias voltage $V_{GS} = -2.6$ V. The simulated output impedances along with output power ($P_{out}$), power added efficiency (PAE) and large-signal gain ($G_{LS}$) at these two frequencies are summarized in Table I. The concurrent dual-band MHLTN was implemented using the schematic shown in Fig. 3 for the desired impedances. The layout of the design has been analysed and optimised through electromagnetic (EM) simulation using Momentum in Agilent ADS. The dual-band MHLTN was designed and fabricated on Roger RT5870 substrate ($\varepsilon_r = 2.33$ and thickness $h = 508 \mu$m) whose photo is reported in Fig. 4. The part highlighted by the dotted box controls the harmonic impedances while the remaining part completes the load transformation to the optimum fundamental impedances at the two bands of interest.

The measured output impedances at the fundamental frequencies $f_1$ and $f_2$ and the corresponding harmonics are reported in Fig. 5. The fundamental impedances and all higher harmonic impedance terminations are in good agreement with the required impedances (summarised in Table I), except at $3f_1$, which was intentionally compromised for $2f_2$, as discussed in Sec. III.

V. Amplifier Design

The input matching network (IMN) was realised by fulfilling the power matching conditions at the two fundamental frequencies through a dual-band matching network.

Simulated $P_{out}$, drain efficiency ($\eta$) and PAE for an input power of 31 dBm are plotted in Fig. 6, for the frequency range from 1.7 GHz to 2.7 GHz. The simulation of the amplifier results in 75.5 % and 68.0 % PAE with 40.7 dBm and 41.1 dBm output power at 1.81 GHz and 2.65 GHz, respectively. The dual-band performance can be clearly observed at the frequencies of interest with attenuation in between. The dual-band IMN is then prototyped and the photo of the realised PA is shown in Fig. 7. The total size of the PA module is 5.5 cm x 8.6 cm.

<table>
<thead>
<tr>
<th>$f_0$ (GHz)</th>
<th>$Z_{opt.1f}$ ($\Omega$)</th>
<th>$Z_{opt.2f}$ ($\Omega$)</th>
<th>$Z_{opt.3f}$ ($\Omega$)</th>
<th>$P_{out}$ (dBm)</th>
<th>PAE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.81</td>
<td>13.7 + j23.7</td>
<td>∞</td>
<td>∞</td>
<td>39.7</td>
<td>75.6</td>
</tr>
<tr>
<td>2.65</td>
<td>12.5 + j13.2</td>
<td>∞</td>
<td>∞</td>
<td>40.8</td>
<td>70.1</td>
</tr>
</tbody>
</table>
low shunt capacitance. This makes the switchless MHLTN easy to design and compact for dual-band applications. The desired and the measured impedances of the passive switchless MHLTN show that the required dual-band impedances for the class-E operation can be precisely synthesised with the proposed approach. The experimental results of the proposed MHLTN was validated through the fabrication and prototyping of a PA module for 1.81 GHz and 2.65 GHz applications. Measured peak PAE at 1.75 GHz and 2.54 GHz is, respectively, 78.4 % with \( P_{\text{out}} = 37.8 \text{ dBm} \) and 61.3 % with 36.9 dBm of output power.

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**REFERENCES**