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***Abstract*— In this paper, a concurrent dual-band class-E power amplifier is proposed. A distributed matching network is designed without any switch to achieve dual-mode operation. The power amplifier works in the 777-787 MHz and 1710-1785 MHz bands for LTE system. The measured results show 22 and 27 dBm output power at first and second band, respectively. This power amplifier obtains efficiency of 60% in lower bandwidth and 84.5 % in higher bandwidth. A novel matching network is also presented to switch between two different optimum operations for class-E design to improve the efficiency in the lower band.**

Keywords—class-E; dual-band; high efficiency; power amplifier

I. INTRODUCTION

The significant increase in demand for wireless communication systems and the proliferation of communication standards has created interest in more efficient ways of sharing the spectrum in the last few years. Software Defined Radio (SDR) provides an adaptable technology with the potential to improve use of spectrum holes efficiently. The Power Amplifier (PA) is the most power consuming part in transmitters. Designing high efficiency multiband PAs is a critical research area.

Different multiband class-E PAs have been reported. Some of their features are summarized in table 1, [1]-[6]. Composite right/left-handed transmission lines (CRLH TLs) are used in [1] to provide dual-band amplification. In [2], MEMS are used to switch between two frequencies. A quad-band class-E PA is proposed in [3] which consists of four transistors and a single input/output matching network (MN). It works in one of the frequency bands at a time and is switched between bands by controlling the gate bias. Sub-optimum class-E operation is assumed in [4] with element values evaluated for a compromise between two bands. A multi-level switching resistance model is incorporated to switch between two frequencies in [5]. A dual-band class-E with finite DC-feed inductance is presented in [6]. A switch is applied to achieve optimum performance in the selected band, while the inductors are constant.

Class-E has highly frequency dependent characteristics. Therefore, designing a dual-band class-E PA is challenging

Table 1. Multiband class-E PAs

Reference	Frequency band (GHz)	Output power (dBm)	Efficiency (%)	PAE (%)
[1]	0.836 /1.95	27	N.A	42
[2]	0.9/1.8	20	38/26	N.A
[3]	1.9/2.3/ 2.6/3.5	24.2/23.8/ 23.4/20.5	48/44/40/35	N.A
[4]	L-/S-band	30/28	61/42	50/30
[5]	1.95/2.6	29/28	N.A	65/63
[6]	1.7/2.5	27	N.A	57
This work	0.782/1.748	22/27	60/84.5	55/72

because optimum output matching and harmonic elimination have to be achieved in both bands at the same time with a single output matching network (OMN) to satisfy the required efficiency and output power in both operating bands. In this paper, a dual-band class-E PA with high efficiency in both bands is presented. This PA is designed without switches to minimize the number of components and reduce the losses introduce by switches. The effect of the shunt capacitor across the transistor on efficiency is studied and a switched band MN is proposed to enable the OMN to switch between two optimum modes and improve efficiency further.

II. DUAL-BAND CLASS-E POWER AMPLIFIER

The class-E PA was invented by Nathan and Alan Sokal in the 1970s [7].The active device in class-E PA is operating as a switch; when the transistor is off, current flows through the shunt capacitance and in the on duration, current flows through the transistor. The OMN plays a crucial role in designing a highly efficient class-E PA. OMN includes a set of specific valued components at fundamental frequency to avoid any overlap between voltage and current waveforms; resulting in 100% efficiency, ideally. In practice some of the delivered power will appear in second and third harmonic frequencies. To maximize the efficiency, all harmonics should be open circuit. The transistor should be biassed at pinch off and driven into compression, so the transistor will be on for the forward cycle of sinusoidal input RF waveform and for all of the reverse cycle the transistor is switched off.

The first stage of designing a class-E PA is to calculate optimum parameters of OMN. Equations (3) to (6), taken from [7], are applied to provide values of components (i.e. load resistance R, shunt capacitance C, series capacitance and inductance, C_0 and L_0 respectively). These equations are derived from a time domain equation, according to required voltage and current assumption across the transistor, in OFF and On state, respectively, (1) and (2).

$$V_D(t)|_{t=T} = 0 \quad (1)$$

$$\frac{dV_D(t)}{dt}|_{t=T} = 0 \quad (2)$$

These components are calculated based on specific supply voltage V_D and required output power P_{out}. Loaded quality factor (Q_L) is a free choice variable and chosen by designers based on a tradeoff between operating bandwidth and rejection of harmonics. For having duty ratio of a usual choice, 50%, the minimum value of Q_L is 1.7879. The most desirable range to provide acceptable efficiency and linearity is between 5 and 10.

$$R = 0.5768\left(\frac{V_D^2}{P_{out}}\right)\left(1 - \frac{0.451759}{Q_L} - \frac{0.402444}{Q_L^2}\right) \quad (3)$$

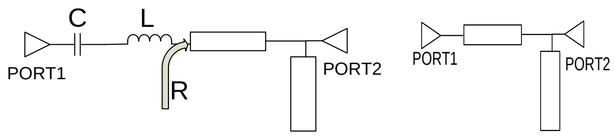
$$C = \frac{1}{5.44668\omega R}\left(1 + \frac{0.91424}{Q_L} - \frac{1.03175}{Q_L^2}\right) + \frac{0.6}{\omega^2 L_D} \quad (4)$$

$$C_0 = \frac{1}{\omega R}\left(\frac{1}{Q_L - 0.104823}\right)\left(1 + \frac{1.101468}{Q_L - 1.7879}\right) - \frac{0.2}{\omega^2 L_D} \quad (5)$$

$$L_0 = \frac{Q_L R}{\omega} \quad (6)$$

The dual-band class-E PA presented in this work is designed with a transmission line OMN based on two lumped element networks. Each lumped element network is designed to operate in one of the desired frequencies. As it is understandable from equations, the value of components will be different for each band of frequency, hence a simple lumped element matching network would require a switch. For that reason, a distributed OMN which works simultaneously in two different frequencies without switches has been proposed here to avoid losses of switch. Generally, transmission line MNs are preferred over using lumped elements as their practical implementation is more convenient and they have more reliable performances as well as less insertion loss. To fulfill the requirements of the two lumped element network using a single transmission line and stub, a required reflection coefficient has to be obtained from the two lumped element MN in the two operation frequency bands. A single transmission line and a single stub, tuned by width and length, have been used in the OMN to provide the same reflection coefficient as the lumped element networks at desired frequencies, Fig.1. Having only a single transmission line and a stub will enable working simultaneously in two frequencies and make the design more compact than substituting each component with their equivalent transmission line.

It has been shown that second harmonic termination is sufficient to have class-E performance to a reasonable approximation [8]. The second harmonic termination (HT) is designed to behave as open circuit at drain of the transistor at both frequencies. The basic idea to terminate the harmonic frequencies is using a transmission line and



(a) (b)

Fig. 1. OMN (a) basic OMN for class-E (b) distributed OMN

an open stub both with electrical length of λ/4, Fig. 2. Thus this block is composed of a transmission line and a stub which is λ/4 at the second harmonic of the higher frequency. To terminate the second harmonic of the lower frequency, a second λ/4 stub is required. Then another λ/4 transmission line is required to convert the short circuit to open circuit at port 1. This requirement is satisfied by the aid of the first transmission line, the first stub and an added transmission line (TL). By adjusting the length of TL, the cascaded line-stub-line combination can be made equivalent to an impedance inverter at that specific frequency. This harmonic termination circuit concept could be extended for terminating *n* harmonics with *n* transmission lines and stubs. The OMN and HT circuits are implemented together to provide the required performances for class-E operation.

The dual-band input matching network (IMN) is designed to have promising return loss in both desired bands.

III. SIMULATION AND MEASUREMENT

This dual-band PA is designed for the LTE system to cover two bands, 777-787 MHz and 1710-1785 MHz and output power of 23 dBm in both bands.

A. Simulation

Components are calculated for both bands, based on desired output power and voltage supply (Q_L set as 10). The calculated values are illustrated in table 2. A transmission line and stub are used to transform the 50**Ω** impedance of the transmitting antenna to the calculated load impedance, 62.45**Ω**. Then calculated capacitance and inductance for both bands are simulated to find out their reflection coefficient at the required frequencies to be used in designing the equivalent distributed version, Fig. 3.

In order to design this OMN practically, termination of the second harmonic frequencies is considered. Thus, the introduced HT circuit aims to provide open circuit at second harmonic frequencies of operating frequencies, 782 and 1748 MHz. The designed HT circuit is implemented with OMN. IMN is modeled to provide reasonable match at both frequency bands, by the aid of a transmission line and two stubs.

Table 2. Calculated components for both bands

	R	C	C_0	L_0
First band	62.45 **Ω**	0.6 pF	0.4 pF	127 nH
Second band	62.45 **Ω**	0.3 pF	0.2 pF	56 nH

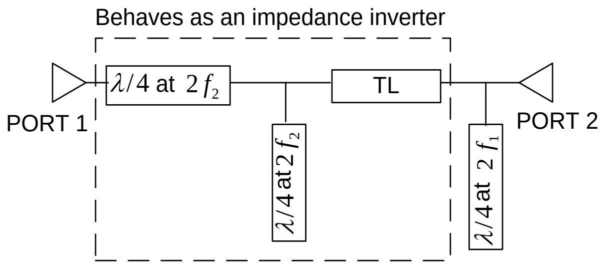
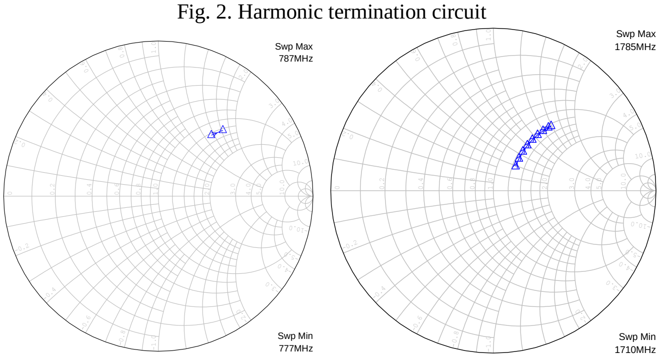


Fig. 2. Harmonic termination circuit



(a) (b)

Fig. 3. Load reflection coefficient data for OMN in (a) first band and (b) second band

B. Measurement

To verify this method, the PA is fabricated on a microstrip substrate with thickness of 0.76 mm and relative dielectric constant of 3.5 using a HFET from TriQuint as a power device. Fig. 4 shows the image of the manufactured PA. In class-E operation, the transistor should be biased close to pinch off and driven into compression. To find the desired gate voltage and RF input power, to make the transistor switch, a few measurements are required. The pinch off value was obtained from the device datasheet which is -2.1v. Then, the PA was driven with different input RF power to find the required input power to make the performance of the PA independent of gate voltage. Input power more than 10 dBm is appropriate for both bands.

The PA performance using the obtained parameters from the above measurements is presented in table 3 in terms of output power and efficiency. Fig. 5 shows efficiency and output power of the PA with varying input power in both bands. In the higher band, efficiency of 94% at 18 dBm input power is obtained. In the case of operating the PA as a concurrent dual-band PA, both bands should be driven with the same input power. In table 3, the power and efficiency figures given are for 16 dBm input power. The obtained efficiency is the highest reported efficiency for dual-band class-E with such a big difference of frequency bands.

Table 3. PA performance

	Output Power	Drain Efficiency	PAE
First band	22 dBm	60 %	55 %
Second band	27 dBm	84.5 %	72.6 %

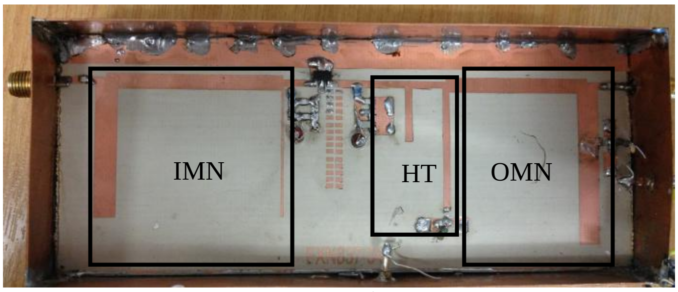


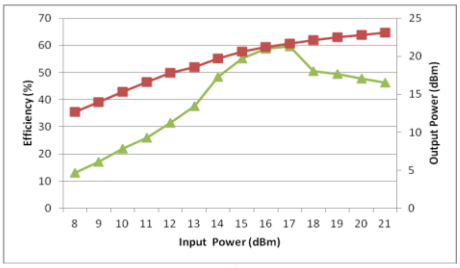
Fig. 4. Fabricated prototype of dual-band class-E PA

C. Discussion

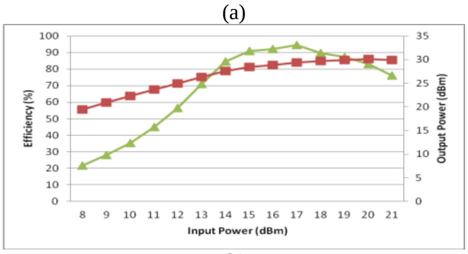
This design has demonstrated that having a concurrent dual-band class-E PA in two different and widely separated bands is feasible at the cost of having a lower efficiency in one of the band.The measurements show higher efficiency at the higher band of frequency and more output power. Although the efficiency of the lower working frequency is good among reported efficiencies, the big gap introduced between efficiencies of two working frequency bands is due to the required shunt capacitor across the transistor. The value of shunt capacitor across the transistor is an important component to produce desired efficiency and output power and its ideal value is different for different frequencies. In the higher band, the required shunt capacitance is calculated to be 0.3 pF and internal capacitance of transistor is close to 0.3 pF which fulfills the required capacitance. To have the same performance in lower band, a shunt capacitance of 0.6 pF is required. Setting the value of capacitance close to one of the operation frequencies using a shunt capacitor will yield a high performance in that particular frequency and relatively lower performance in the other frequency. One option could be using a capacitance in between which would degrade the performance of both bands from their ideal result. Therefore, to have high efficiency in both bands, it is required to have different shunt capacitance which could be done using a switch. This option is explored further in the next section.

IV. Switched-Band Matching Network

A switched-band OMN is proposed to design a switched-band class-E PA with high efficiency in both bands. In dual-band OMN case, a transmission line and a stub are used to provide desired performance at both bands. Performance will be improved by applying a switch to have more accurate result. The OMN is proposed in this work called Stub to Short switching (STS), which is composed of one transmission line and one stub and utilizes a switch somewhere in the middle of the stub to connect it to the ground, Fig.6. Placing the switch between stub and ground to open or short the stubs can provide different impedances in different operating frequencies and help to minimize losses which are introduced by the switch. When the switch is ON, the stub is shorter and is grounded. The longer and open stub is provided in the OFF state of the switch. Typically, the higher frequency needs a shorter stub than the lower frequency; therefore ON state of the switch is applied at higher frequency. As a result, there is a better match between lumped element and distributed OMN. Simulation and measurement results are plotted in the Smith chart in Fig. 7 in lower and higher band of operation.



(a)



(b)

Fig. 5. Measured efficiency and output power vs input power for concurrent design.(a) first band (b) second band

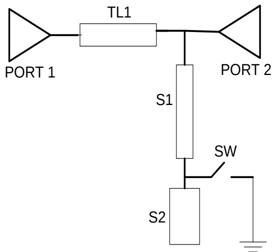
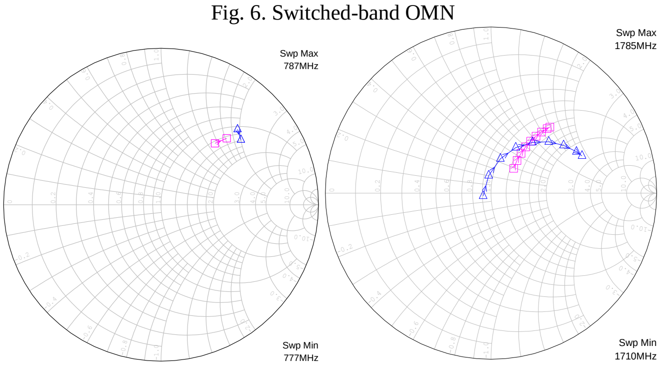


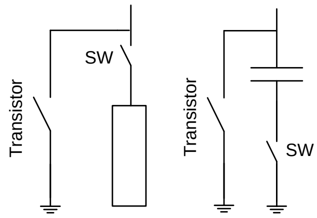
Fig. 6. Switched-band OMN



(a) (b)

Fig. 7. Simulation and measurement result of switched-band OMN (a) lower band (b) higher band of operation

The PA design shows that to achieve a high efficiency in both bands, the shunt capacitor across the transistor also has to be variable. To make this possible, two switching capacitance methods are presented here. In most cases the internal capacitance of the transistor is high enough. In this case for lower band, another 0.3 pF needs to be connected to the transistor. Fig. 8 (a) illustrates the first method. When the switch is ON, a stub is introduced to the circuit and provides shunt capacitance of 0.3 pF. Appropriate length and width are chosen for the stub to provide the required capacitance. In



(a) (b)

Fig. 8. Proposed method for shunt capacitance (a) with a stub (b) with a capacitor

higher frequency, the switch is OFF but it leaves a small residual capacitance of about 0.007 pF, resulting from the series combination of the switch in its OFF state and the stub. Method 2 uses a capacitor with a switch to ground, Fig. 8 (b).

V. Conclusion

A concurrent dual-band class-E PA is presented in this paper to operate in up-link band of LTE system. Dual-band transmission line OMN is applied to achieve amplification in both bands without any switches, with high drain efficiency of 60% and 84.5% and output power of 22 and 27 dBm at 777-787 and 1718-1785 MHz, respectively. The proposed OMN is based on tuning of the characteristic impedance and electrical length of transmission line and stub. The high efficiency of this PA encourages further study on the effect of shunt capacitance on the efficiency of class-E operation. The novel switched-band OMN is presented and fabricated to improve the efficiency. In future work, a switched-band class-E PA based on the proposed OMN will be designed.

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