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Highly Efficient Balanced Power Amplifiers for Carrier Aggregation

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Abstract: This paper presents a highly linear balanced power amplifier with miniaturised quadrature hybrid coupler for carrier aggregation (CA). The miniaturised quadrature coupler is designed using a novel U-shaped transmission line (USTL) concept to achieve good size reduction. The novel branch-line coupler is used to design a wideband balanced PA. The performance of the balanced PA is compared to a single PA solution. The balanced PA shows better performance with improved matching properties and better electrical stability. There was an increase in saturated maximum output power (Pout) from 8 dBm for the individual PA to 13.41 dBm for the balanced with a power aided efficiency (PAE) of 43.92%. The highly linear balanced PA achieves a 14 dB ACPR reduction and also improves ACPR by 12 dB for non-contiguous and 9 dB for contiguous carrier aggregation.

Index Term— ACPR (Adjacent Channel Power Ratio); U-Shaped Transmission line (USTL); Quadrature Hybrid Couplers; Contiguous/Non-contiguous CA; Power Aided Efficiency (PAE).

I. INTRODUCTION

High speed data transmission is becoming more in demand for applications such as wireless personal area network and 4G network applications. Because of the shift towards higher power and more bandwidth applications, the flexibility of adapting to traffic and carrier aggregation (CA) is a dire need for next generation networks [1]. Because of such high data throughput rate, power and spectral efficiency over the whole bandwidth has to be improved to maintain good signal quality [2]. Important PA characteristics such as high power, high efficiency, linearity, gain flatness, and good input and output matching over the whole bandwidth has become more stringent to match the needs of such advanced networks.

Due to the ever growing demand for battery life extension, it is highly essential that the efficiency of the PA is significantly improved at both low output and peak power levels [3]. However, recent spectrum efficient modulation schemes such as OFDM and this day multiple access techniques result into signals with large peak-to-average power ratio (PAPR). Poor efficiency has been observed in conventional PAs operating with such signals, when operated at output power back-off (OPBO) region at saturation [4]. In such case other PA amplifier configurations such as Doherty and balanced PA could be used to improve efficiency.

In a balanced PA configuration, by taking advantage of the multi-mode operation of the coupler and the balanced topology, load-insensitivity characteristics could be accommodated thereby enhancing efficiency [5]. Similar balanced PA design techniques have been used in [3], [5] and [6] to increase the power aided efficiency (PAE) of the PA. However, the size of the balanced PA architecture could be very large when using conventional coupler designs that operate at frequencies below 4 GHz.

In this paper, a new balanced PA is presented using miniaturised quadrature hybrids. First of all, to achieve reduced size architecture, a compact quadrature hybrid coupler using a novel USTL concept has been designed and fabricated thereby achieving a 64% circuit size reduction in the balanced PA configuration. Small signal measurements show a good gain flatness match with an improvement of over 20 dB in input (S_{11}) and output (S_{22}) matching performance of the balanced PA as compared to the individual PA due to the absorption of the reflected power in the coupler terminations. Further analysis gives a better electrical stability for the balanced PA design.

More importantly, large signal measurements of the proposed design gave an increase in maximum saturated output power with good PAE when compared to the single PA to 68% with the balanced PA design thereby successfully enhancing efficiency and linearity at saturation. Furthermore, the balanced PA gave ACPR reduction of about 14 dB when implemented in a 4G system and was able to further achieve a 12 dB ACPR reduction for non-contiguous CA and a 10 dB ACPR reduction for contiguous CA involving two component carriers thereby improving the linear performance of the system. The proposed balanced PA is highly efficient, linear and will be very useful for next generation networks.

II. BALANCED POWER AMPLIFIERS DESIGN

The balanced power amplifier (PA) design makes use of two identical quadrature hybrid couplers which are mirrored at the input and output of the power amplifiers acting as splitters and combiners. The couplers provide equal amplitude with quadrature phase difference between the output ports.

A) Quadrature Hybrid Couplers

The quadrature hybrid couplers are usually designed using the characteristics impedance equations for four quarter wavelength ($\lambda_g/4$) transmission line segments each consisting two adjacent characteristics impedance Z_0 (50 Ω) and the other two with $Z_0/\sqrt{2}$ (35.33 Ω) as shown in Figure 1 below.

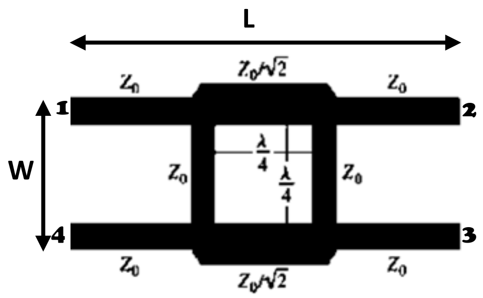

Figure 1 Conventional BLC with four quarter wavelength TL

The quadrature hybrid coupler shown in Fig. 1 was designed using electromagnetic software (*em* sonnet) giving a large size (LxW) of 108.9 x 40.4 mm^2 at centre frequency of 1.725 GHz. Due to this, a compact coupler has to be designed whilst maintaining/improving performance.

The principle used for the proposed USTL coupler design is similar to the CRLH transmission line (TL). The unit cell of the CRLH TL is shown in Fig. 2.

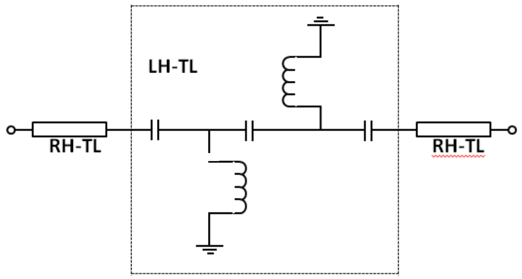

Figure 2 CRLH-TL with two unit cells

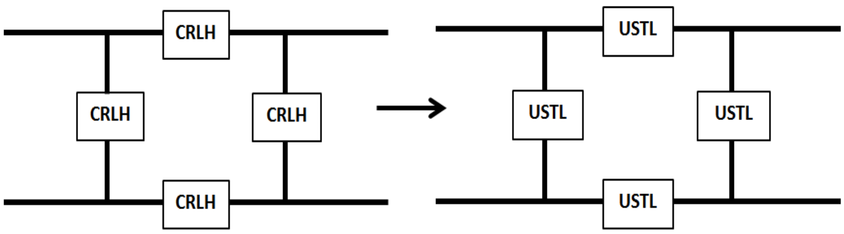

Figure 3 Proposed Transmission line Model

The inductance and capacitance of a U-shaped defect can be modified by altering the structure until it matches the CRLH values. Once this is determined, the conventional ($\lambda_g/4$) transmission section is then substituted for a discontinuous U-shaped transmission line (USTL) as shown in Figure 3. The proposed USTL shape and its dimensions are shown in Figure 4 and TABLE I respectively.

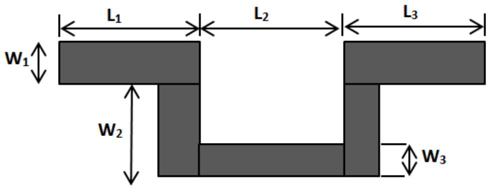

Figure 4 The USTL Structure

TABLE I.

USTL DESIGN PARAMETERS

Characteristic impedance (Ω)	**W_1 (mm)**	**W_2 (mm)**	**W_3 (mm)**	**L_1 (mm)**	**L_2 (mm)**	**L_3 (mm)**
50 (Z0)	2.4	9.1	2.4	11	5	11
35.35(Z0/√2)	3.9	6.2	3.9	6.5	8	6.5

B) Power Amplifiers

The unit amplifiers are identical PAs. The individual PA model chosen is the ZFL-500 Mini-circuits PA. The unit PA in conjunction with the USTL coupler is used for the balanced PA configuration. The design of the power amplifier is based on load-pull simulations at 1.6 GHz covering a band from 1.6 GHz to 1.9 GHz. It was optimized through the band to obtain improved PAE. Figure 5 shows the schematic of the designed balanced power amplifier configuration. The input signal is split into two signals out of phase by 90^0 and then passed through both PAs for amplification after which the signals are combined again.

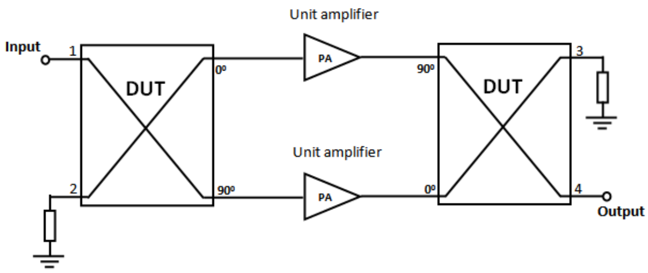

Figure 5 Schematic of the balanced power amplifier

The balanced power amplifier has been designed using the USTL coupler and PA in section II A and B into Figure 5. Measured results are presented for the balanced PA in section III and compared with single/individual ZFL-500 Mini-Circuits PA.

III. RESULTS

The simulated and measured response of the designed balanced PA and the individual ZFL-500 mini-circuits PA are presented and compared in this section. Small and Large signal measurements were made.

Figure 6 shows the simulated and measured gain S_{21} and the input and output reflection S_{11} and S_{22} measurement results are presented in Figure 7 and Figure 8 respectively. The simulated gain of the balance PA shows flat gain show behaviour in the frequency band from 1.6 GHz to 1.9 GHz of about 32 dB. The measured gain of the individual PA actually increase steadily from 32 towards 34 dB throughout the whole bandwidth whilst the measured balanced PA also increases from 31 dB towards 33 dB after which it starts to drop again more notably than the simulated gain. The bandwidth of the balanced PA is slightly narrower due to the characteristics of the USTL which acts as both the splitter and the combiner. The slight deviation from the simulation results could be caused by tolerances in the components and the milling of the PCBs.

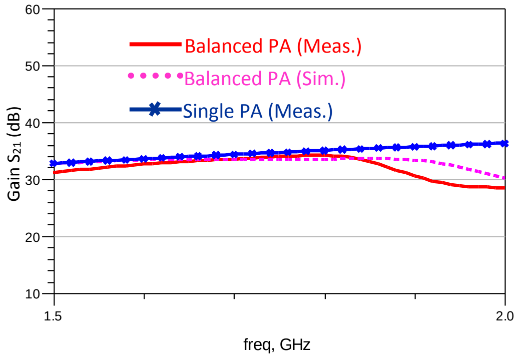

Figure 6 Measured and simulated S-paramter (S_{21}) responses.

The designed balanced configuration was able to significantly improve the input and output return loss performance due to its improved matching abilities. From Figure 7, the poor S_{11} results for the individual PA around -5 dB is significantly improved whilst the measured and simulated S_{11} results at the required frequencies are lower than -25 dB giving a very good matching improvement.

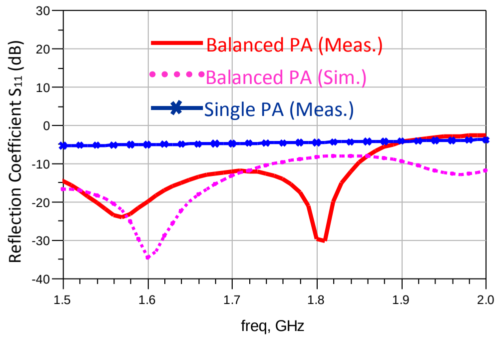

Figure 7 Measured and simulated S-paramter (S_{11}) responses.

Similarly, the measured and simulated S_{22} results of the balanced PA design was able to show even better improvement than the individual PA under test. The S_{22} results are lower than -35 dB at the required operating frequencies for the balanced PA in comparison to about -12 dB for the individual PA as shown in Figure 8.

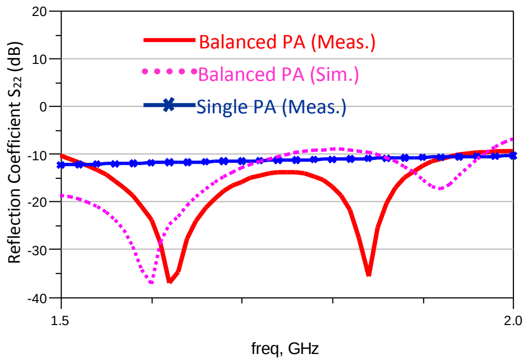

Figure 8 Measured and simulated S-paramter (S_{22}) responses.

The large-signal measurements were obtained by power sweeps at several frequency points and the PA in the balanced topology uniquely uses the isolation port of the quadrature USTL hybrid coupler as its signal path. Figure 9 shows the measured saturated output power (P_{out}) and its corresponding power aided efficiency (PAE) against the wideband frequency of operation of the balanced PA. The balanced PA improves the maximum saturated P_{out} of the single PA from 8 dBm to 13.41 dBm with a peak PAE of 43.92%.

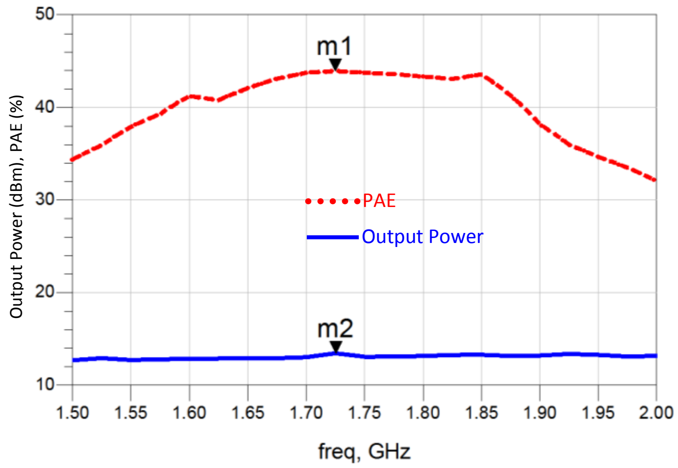

Figure 9 PAE and saturated output power against frequency

The balanced PA gives good measurement results that would be important in design of wireless transmitters for next generation networks. The S-parameter results of the balanced PA show a great improvement in matching and stability. The unconditional stability achieved helps to reduce attenuation in the input network and makes the network more electrically stable resulting in a more efficient PA. The Large signal improvements enable the PA to operate more efficiently at saturation which could help extend the battery life of mobile phones. Due to the encouraging measurement results performance of the balanced PA at saturation, the spectral efficiency of balanced PA design will be evaluated in a 4G wireless transmitter to observe for linearity improvements.

IV. BALANCED PA IMPLEMENTATION IN WIRELESS TRANSMITTERS FOR 4G

Figure 10 shows the balanced PA measurement setup in wireless transmitters for 4G. In this setup, a 3 MHz 4G signal is generated in the signal generator.

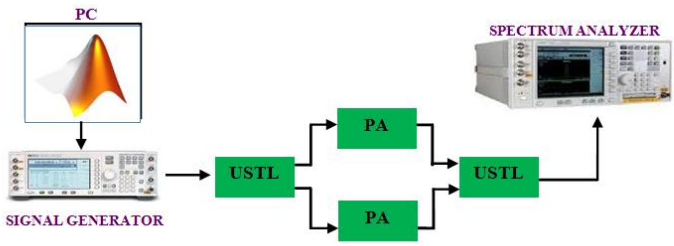

Figure 10 Balanced PA measurement setup.

The signal is modelled and measured results used in Agilent Keysight Signal Studio Kit. The USTL quadrature coupler (Device under Test (DUT)) designed and fabricated in section II was fed by 4G signal at the center frequency of 1.725 GHz. The signal passes through the

USTL coupler which splits the signal to both Mini-circuits unit PAs before combining the signal again. The output power spectral density results with the individual PA and the designed balanced PA is shown in Figure 11.

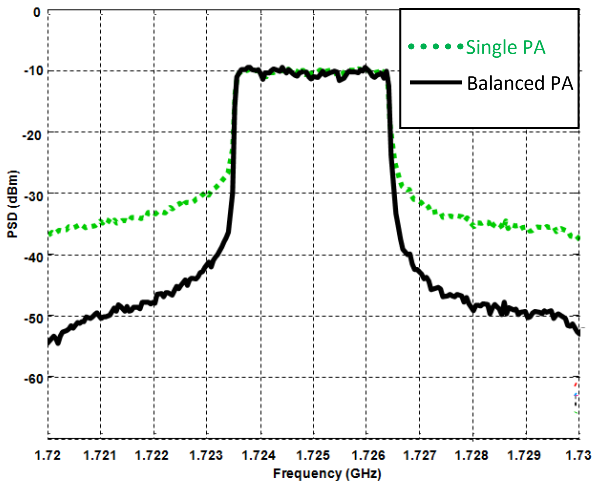

Figure 11 Ouput power spectra of balanced PA

The ACPR of the individual PA test is around -31 dBm and the ACPR of the balanced PA is around -45 dBm showing an improvement of about 14 dB with the balanced PA. The output of the balanced PA design gives better overall output performance with increasing sensitivity, better linearity and better spectra efficiency.

Furthermore, the proposed balanced PA can be very useful in next generation wireless systems such as 4G and 5G communication systems as these networks need a highly efficient and linear output performance at saturation. A carrier aggregation is becoming very prominent as the quest for higher data speeds increase. By aggregating carriers, higher data speeds could be achieved but it leads to increasing nonlinear performance at saturation. The ability of the balanced PA to improve performance at saturation for intra-band contiguous and inter-band non-contiguous carrier aggregation will be evaluated.

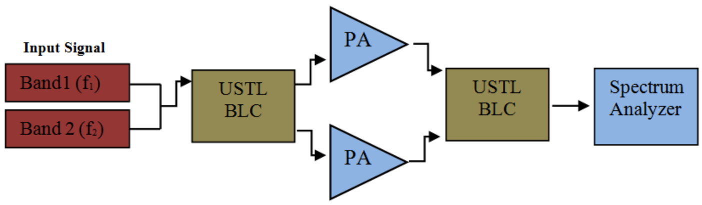

Figure 12 Two-component carrier aggregation test setup

The balanced PA test set up in Figure 12 will be used for both non-contiguous (inter-band) and contiguous (intra-band) carrier aggregation. First of all, in this test setup, two 3 MHz 4G inter-band signals (f_1 and f_2) at 1.725 GHz and 1.84 GHz are fed through the presented USTL coupler and split to each ZFL-500 Mini-circuits PA before being recombined at the output of each PA. The output spectra for the concurrent dual band CA components at both frequencies are presented in Figure 13.

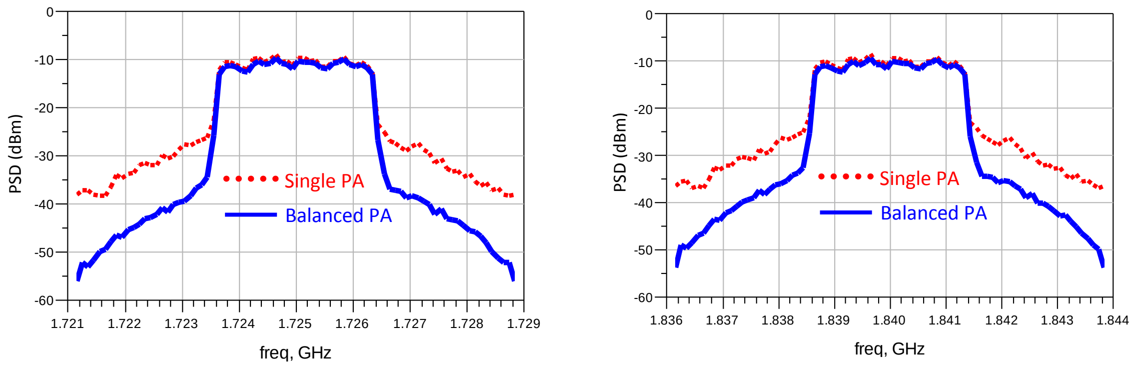

Figure 13 Ouput Spectra at 1st and 2nd non-contiguous CA band.

The ACPR result for both inter-band CA components gives an improvement of 12 dB and 11 dB at bands 1.725 GHz and 1.84 GHz respective ely. The test set up in Figure 12 is also adopted for contiguous CA. In this case, the two 3 MHz LTE signals are now intra-band at 1.72 GHz and 1.725 GHz. The ACPR of the output spectra for the contiguous CA components at both intra-band frequencies are presented in Figure 14 and show an ACPR improvement of over 9 dB for both bands.

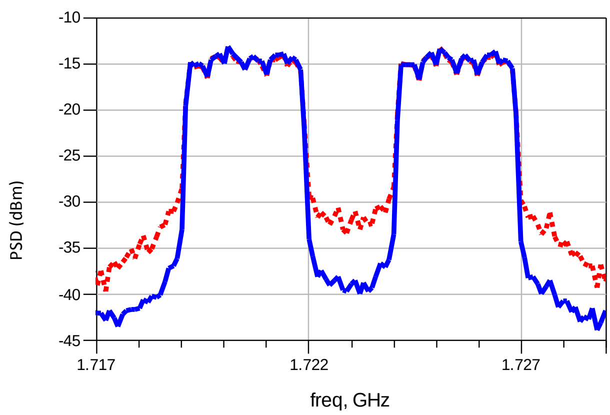

Figure 14 Ouput power spectra at contiguous intra-band frequencies

V. CONCLUSION

A wideband highly linear and efficient balanced PA using a miniaturised coupler for carrier aggregation has been successfully presented in this paper. The novel USTL based quadrature hybrid coupler achieved a considerable size reduction (64%) when compared to its conventional equivalent. The Balanced PA was able to achieve similar gain and bandwidth when compared to the single PA case whilst improving the matching significantly at both the input and output. The input and output reflection coefficient (S_{11} and S_{22}) measured results are about -25 dB and -35 dB respectively showing an improved matching performance for the balanced PA configuration when compared to the single PA case with -5 dB and -12 dB respectively. The proposed balanced PA also improves the maximum saturated power from 8 dBm to 13.41 dBm with PAE of 43.92% thereby enhancing the efficiency of the individual PA (ZFL-500) at saturation. The proposed balanced PA configuration is also highly linear achieving ACPR reduction of 14 dB without CA with reduction of 12 dB for non-contiguous and 9 dB for contiguous CA obtained during measurements in a 4G wireless system. The proposed balanced PA will be very useful for 4G and B4G wireless communication systems.

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