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Comparative analysis of sokal's equations versus load-pull implementation of class E low-pass network

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ABSTRACT

In this paper, Class E power amplifiers (PA) aimed at frequency bandwidth of 3.4 GHz to 3.6 GHz (LTE 42) and 3.6 GHz to 3.8 GHz (LTE 43) respectively are designed with objective of attaining high efficiency. The viability of Sokal's equations for present communication systems aimed at GHz are analyzed for high efficiency using HEMT (High-electron-mobility transistor) on Nitronex NPTB00004 as opposed to the Bipolar Junction Transistor used by Sokal in 1975. Load-pull configuration techniques aimed at the drain is implemented at the output matching network (OMN) and benchmarked against Sokal's equation. At the OMN, to suppress harmonics, band-pass filters are employed for the LTE 42 and 43 respectively. Sokal's equation shows that the drain must be conjugately matched before his equations are applied at the OMN. The efficiency at 3.4 GHz obtained for Sokal's circuit is at 67 % and gain of 9.3 dB. More than 65% efficiency is obtained from load-pull network at 3.4 GHz to 3.76 GHz before filter implementation while showing gain above 7.8 dB. After filter addition at OMN, the efficiency is above 65% and gain above 8 dB for dual - band having bandwidth of 3.4389 GHz - 3.542GHz and 3.6569GHz - 3.8GHz.

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1. INTRODUCTION

The present era has shown that highly efficient power amplifiers (PA) are a necessity for newly advanced wireless communication systems [1-3] in terms of achieving a low cost as well as reliable transmitters [4, 5]. A PA can be defined as an amplifier designed whereby the maximum power is transferred only for a selection of active devices such as transistors [6]. There are numerous advantages for circuits and systems involving RF and microwave sector in terms of power amplification methods which aims for high efficiency. In the RF and microwave engineering, it is a well-founded knowledge that high efficiency power amplifiers greatly improves the power consumption of a communication system as well as reduces the size and weight of radio transmitters. One of the main problems in techniques involving amplification, it is very difficult to use high efficiency power amplification techniques for operations involving high frequencies and high power level as the capacitance of devices used will cause hindrance in achieving desired result i.e. high efficiency and gain. Therefore the role of class of PA comes in the picture and designers use different classes of PA to solve different problems [7-9]. An example of power amplifier that enables high efficiency is Class E [5, 10-12] due to its ability of being unaffected to the transistor switching problems such as power losses in the transistor and capacitances of the transistor affecting the output [7, 13-16]. Theoretically Class E PAs can attain 100% effiency [1, 17].

In [18] the switching operation works the same as normal Class E amplifier would work and therefore attain the theoretical 100% efficiency. It employs two parallel resonators and a decoupling capacitor so as to reject the second harmonic (HD2) emission shown in while also providing a DC path for the supply current. The impedance-transformation technique in [19] for Class E PA to improve the reactance-compensation network whereby without adding any more components, the desired load resistance can be four times the original value, while the flat load angle is sustained. This means the output matching network at the drain can be significantly simplified. Therefore by implementing the exact number of components in the matching network, a greater operational bandwidth can be achieved and the extra network to match the output load is therefore made redundant. The method employed in [20] is such that the current fall time of switch is considerably reduced all while keeping the operating frequency to be quite large so that it will be possible to ignore the switching time of the transistor. The bi-harmonic operation (that is second harmonic) is considered as it is the largest harmonic and has to be eliminated. Trying to solve all multi-harmonic mode imposes considerable complications due to circuit complexity, while does not seem to offer any advantage as the power of the other harmonics are too low. The second harmonic frequency is tackled by harmonic injection method. The work [21] states that for the Class-E PA input and output matching networks design should aim to provide optimum impedances for both gate and drain connections of the active device in the required frequency. The broadband class-E power amplifier for 1.8 GHz–2.7 GHz LTE frequency range has to employ load/source –pull measurement for the range of frequencies to obtain accurate optimum load and source impedances of the active device. The use of Sokal's equation has been used to calculate the OMN matching network after which the lumped components have been converted to microstrip lines as the author claims that it is the impedance matching at the drain that will achieve Class E operation. The work was aimed at dual band operation and based on Sokal's equations would give two sets of lumped components. However by making use of transmission lines that satisfy the requirements of both lumped components the circuit can be transformed to microstrip lines [22]. In the work [23] Class E operation was performed only at simulation level using Sokal's equations however it does provide a useful insight on how the implementation of Sokal's formula at different transistors affect the power added efficiency (PAE). Although no fabrication was done, the Class E implementation on three different transistors has shown different efficiency and output power despite being matched by the same OMN that is based on Sokal's equations. Nevertheless the insight provided in this paper has allowed the research done within this paper to prove that the impedance at the drain need to be addressed first before implementing Sokal's formulas and that not all transistors will be able to achieve same efficiency at same frequency despite same OMN.

2. RESEARCH METHOD

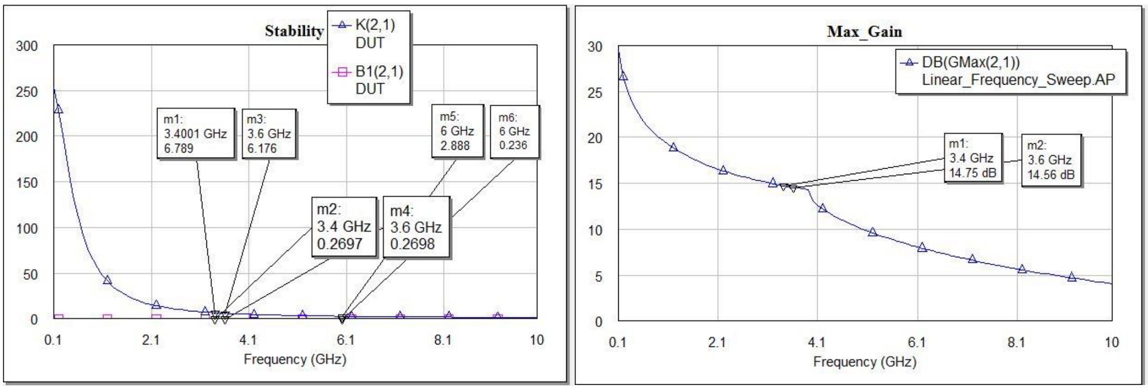
2.1. Stability of transistor

The stability of a transistor is a primordi1al factor that has to be taken into consideration when designing a power amplifier. Usually the design of an amplifier involves the use of stability circles whereby if the $|S_{11}|$ of the transistor is less than 1 then the stable region should be located outside the stability circles while if the opposite is true then the stable region is found inside [24]. However, such a concept cannot be applied here as the stability region would always change when the frequency of operation is changed. Hence if we are designing an amplifier for a wide range of frequencies such as multiband concept then it may happen that for some frequencies it will be stable while for others it will not work as amplifier. Therefore, we would need to choose a transistor that can be implemented over a wide range of frequencies where it is unconditionally stable. This is usually tested by employing the Rollet's condition as shown in (1) and (2) [3, 24-27].

$$K = \frac{1+|\Delta|^2-|S_{11}|^2-|S_{22}|^2}{2|S_{12}S_{21}|} > 1 \tag{1}$$

$$|\Delta| = S_{11}\,S_{22} - S_{12}\,S_{22} < 1 \tag{2}$$

It is shown in Figure 1(a) that the transistor is unconditionally stable for a wide range of frequencies from DC up till 6 GHz. Although it is able to operate beyond that but for efficiency reasons, we choose not to implement it above this range. The next step is to test whether the transistor is able to work as an amplifier or not which is shown in Figure 1(b) that the transistor can work as amplifier. It is to be noted thought that there is indeed a correlation between the gain and stability of the amplifier as from Figure 1(a) that the transistor is very stable at lower frequencies and also in Figure 1(b) the transistor shows higher gain at lower frequencies.



(a) (b)

Figure 1. (a) Stability of NPTB0004 transistor showing unconditionally stable condition at both LTE bands of 42 and 43 (b) Maximum gain that the transistor can give at the particular frequency

2.2. Class E PA using sokal's equations

It is already known that Class E works as a switching mode amplifier and was invented in 1970s by Nathan Sokal and Alan Sokal [28]. The basic topology of the Class-E PA is shown in Figure 2.

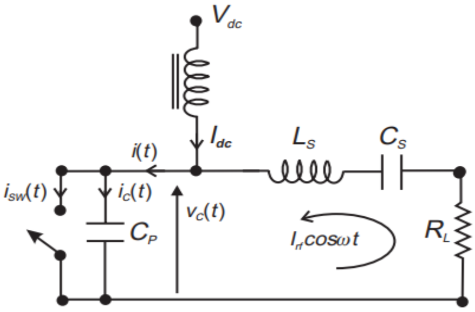


Figure 2. Basic Class E amplifier schematic [6]

Using Sokal's equations presented in [29] as shown in (3) – (6) below. These components are calculated based on specific supply voltage V_{DC} and required output power P_{OUT}. The Loaded quality factor (Q_L) is a free choice variable where the most suitable range for an efficiency and linearity that is applicable for design is usually chosen between 5 and 10. The Q_L values are chosen by designers with the knowledge that there will be a trade-off between frequency of operation and elimination of harmonics. The equations provided by Sokal's are derived with the duty ratio set at the usual choice that is 50% as stated in [29] and the minimum value of Q_L is 1.7879 [28].

$$R_{LOAD} = 0.5786\left(\frac{V_{DD}}{P_{out}}\right)\left(1-\frac{0.451759}{Q_L}-\frac{0.402444}{Q_L^{\ 2}}\right) \tag{3}$$

$$C_S = \frac{1}{\omega R_L}\left(\frac{1}{Q_L-0.104823}\right)\left(1+\frac{1.101468}{Q_L-1.7879}\right)\frac{0.2}{\omega^2 L_S} \tag{4}$$

$$C_P = \frac{1}{5.44668\omega R_L}\left(1+\frac{0.91424}{Q_L}-\frac{1.03175}{Q_L^{\ 2}}\right)+\frac{0.6}{\omega^2 L_S} \tag{5}$$

$$L_S = \frac{Q_L R_L}{\omega} \tag{6}$$

These equations give the values of the passive components for the output matching network (OMN) design which will enable a non-overlapping current voltage waveform which is primordial for achieving a very high efficiency. The loaded quality factor Q_L plays a vital role in the design of the amplifier as the output will change depending on the value that has been assigned to Q_L. The Table 1 display the values obtained from the (3) to (6) in order to calculate the output matching network parameters. It is important to know that Vgs is constantly maintained at a DC bias of -2.0 V at pinch-off condition while Vds = 10 V. The circuit of the Class E PA based on Sokal's equation is shown in Figure 3. The load-pull will give us the maximum gain and efficiency that can be achieved by the transistor at 3.4 GHz. From that reflection coefficient obtained we can thus build our required circuit. The load-pull output shown in Figure 4 shows at which point we can obtain the best results for both power added efficiency and output power.

Table 1. Values for the passive component in Class E OMN

Passive Component (OMN)	Values (Q_L =10, F = 3.4GHz)
R_L	50Ω
C_P	0.242pF
C_S	0.089pF
L_s	23.41nH

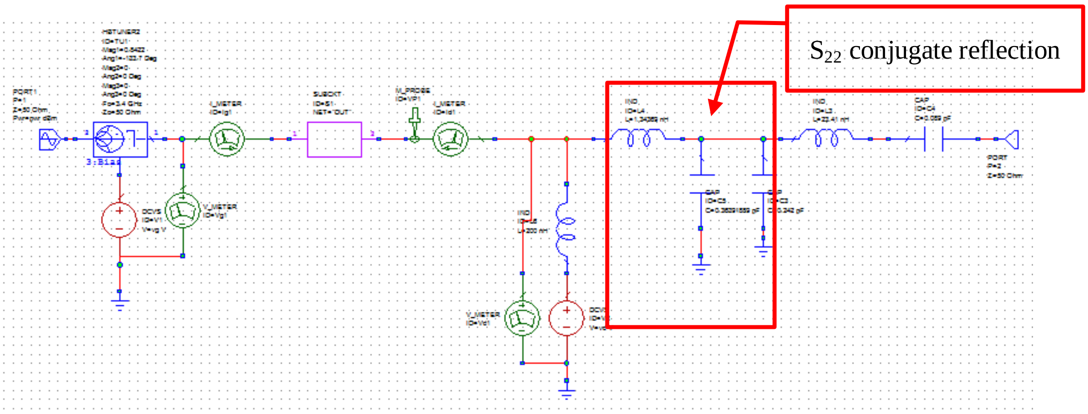


Figure 3. Sokal's Class E circuit implemented with S22 matching of the transistor

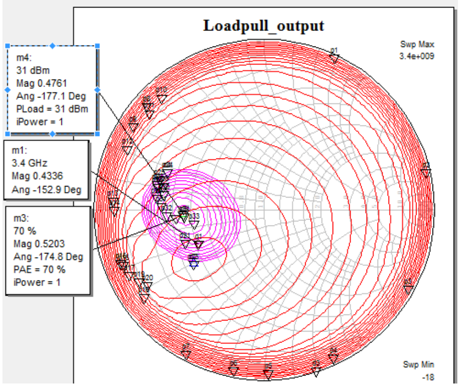


Figure 4. Load –Pull contour lines showing results for 3.4 GHz

2.3. Dual-band class E PA

The lumped elements were transformed from the impedances obtained from the load pull and the conjugate matching. The main concept in converting the reflection coefficient here to lumped components is by taking the load-pull reflection coefficient as a conjugate value and then matching it to create the same reflection coefficient at the drain. The same technique is applied for the reflection coefficient of S_{11} at the gate. The circuit is shown in Figure 5 which display the NPTB0004 transistor connected with the translated reflection coefficient to lumped components at both input and output.

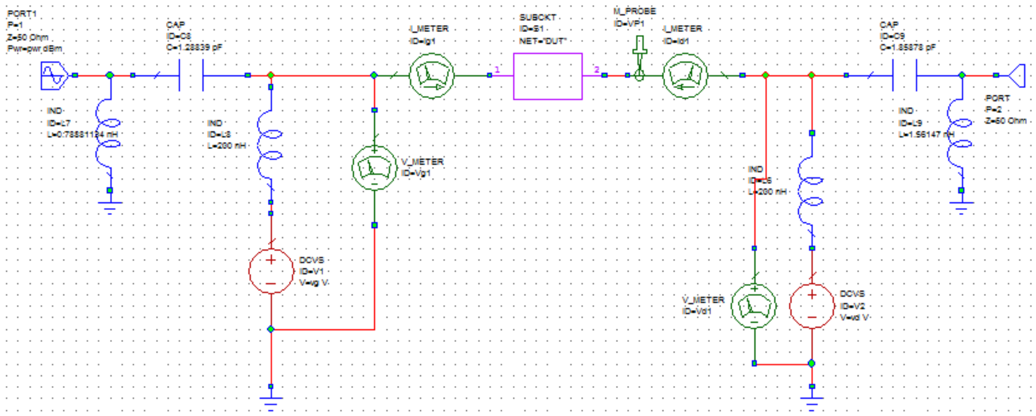


Figure 5. Implementation of Class E power amplifier based on lumped components

Usually harmonics in Class E is terminated by using open circuit stubs aimed at each harmonics frequencies [6]. But since in this project the aim is for the Class E operation at dual band then matching each specific harmonics is not a viable option which is why band pass filter is implemented and designed by using the (7) to (13) from Pozar [24]. Since LTE band 42 and 43 is the main bandwidth frequency therefore it is preferred to implement a bandpass filter to have cut-off frequencies of 3.35GHz to 3.85 GHz. The center frequency can be calculated by the (7) stated below which is obtained at 3.59 GHz.

$$\omega_C = \sqrt{F_1 \times F_2} \tag{7}$$

$$\Delta = \frac{F_2 - F_1}{\sqrt{F_1 F_2}} \tag{8}$$

$$\frac{\omega}{\omega_C} = \frac{1}{\Delta} \cdot \left(\frac{\omega}{\omega_C} - \frac{\omega_C}{\omega} \right) \tag{9}$$

$$L'_1, L'_3 = \frac{g_K R_0}{\omega_0 \Delta} \tag{10}$$

$$C'_1, C'_3 = \frac{\Delta}{\omega_0 g_K R_0} \tag{11}$$

$$L'_2 = \frac{\Delta R_0}{\omega_0 g_K} \tag{12}$$

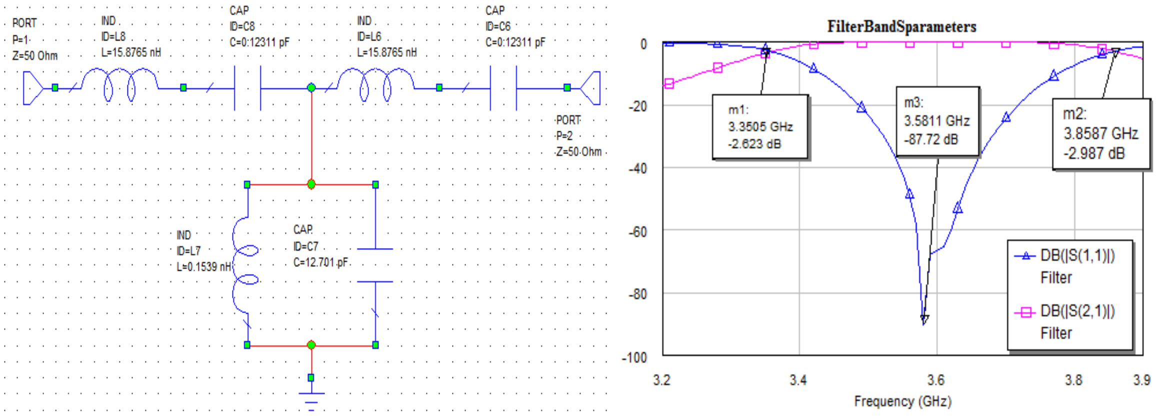
$$C'_2 = \frac{g_K}{\omega_0 \Delta R_0} \tag{13}$$

The order of the filter is very important as it tell us how many components are going to be incorporated and secondly how steep the response is going to be. Based on the attenuation versus normalized frequency and element values for maximally low pass filter values taken from [24]. Then based on the order, the element values from Table 2 can be obtained which will be used to calculate the capacitors and inductors for the band–pass filter.

Finally, the design bandpass filter is shown in Figure 6(a) by using the calculated values of capacitors and inductors. To prove that the filter is indeed working a simple frequency response curve of S_{11} and S_{21} against frequency in Figure 6(b) clearly shows that the filter works as it filters out all frequencies before 3.35 GHz and after 3.85 GHz thereby allowing the main frequencies of LTE 42 and 43 to pass through. The filter is then added to the main Class E power amplifier shown in Figure 5 where then the newly formed power amplifier incorporated with harmonic filter is shown in Figure 7.

Table 2. Band-pass filter Parameters for (g_1 , g_2 = 1.0 , g_3 =2.0, $\omega_0 = 2\pi \times 3.59$ GHz, $\Delta = 0.139$, $R_0 = 50\ \Omega$.)

Element	Values
L'_1, L'_3	15.8765 nH
C'_1, C'_3	0.12311 pF
L'_2	0.1538 nH
C'_2	12.701 pF



(a) (b)

Figure 6. (a) Band pass filter for elimination of harmonics (b) S_{11} and S_{21} parameters of the band-pass filter.

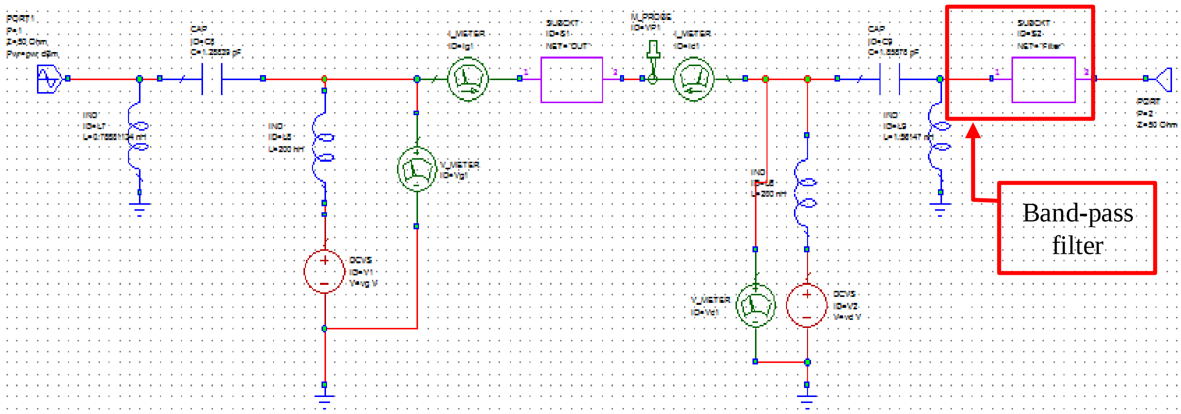


Figure 7. Class E power amplifier with bandpass filter for harmonics terminations.

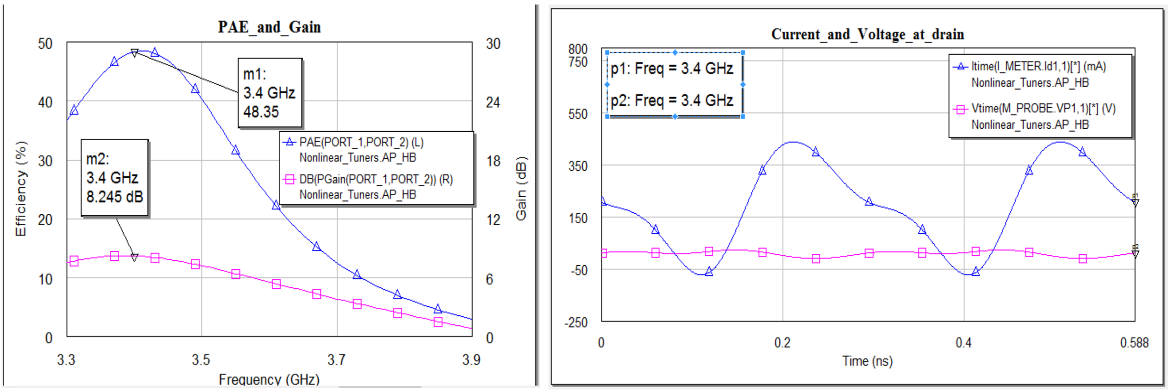
3. RESULTS AND DISCUSSION

In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Results can be presented in figures, graphs, tables and others that make the reader understand easily [2, 5]. The discussion can be made in several sub-chapters.

3.1. Sokal’s class E results

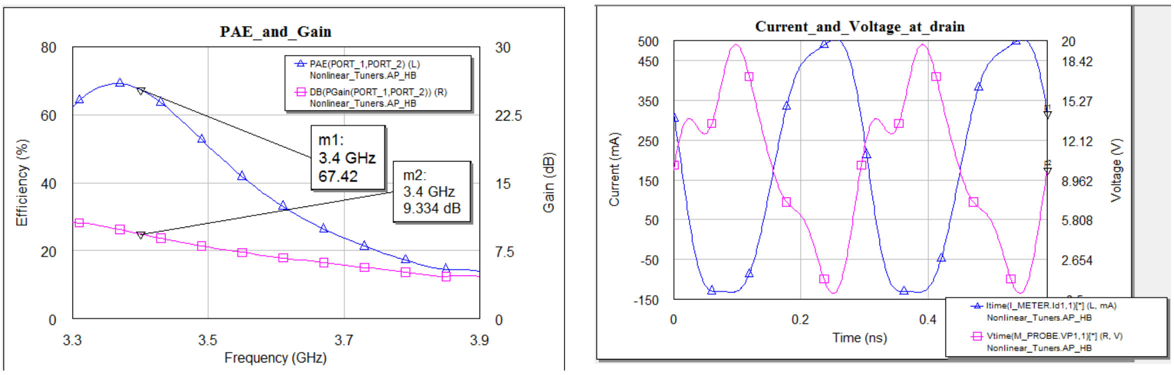
The use of Sokal’s formula to the design of Class E amplifier was a bit tricky. Sokal’s equations were derived more than 3 decades ago and technology at that time were not as advanced as todays. The results shown in Figure 8 displays very poor efficiency and relatively narrow bandwidth. Hence if we wanted to prove the operation ability of Sokal’s equation and why in this case it is now working, a new design has to be added to this present output matching network.

Sokal’s equation did not account for the reflection coefficient needed at the drain of the transistor to satisfy the efficient way of transferring power. Hence at this point, S_{22} conjugate matching has been employed and the relevant impedance obtained from the S_{22} conjugate reflection coefficient has been converted to lumped components and added before the circuit network of Sokal at the drain of the transistor as shown in Figure 3 while Figure 9(a) below which at 3.4 GHz shows a higher gain at 9.3 dB and much higher efficiency at 67 %. Figure 9(b) shows the non-overlapping current and voltage waveform thus showing switching operation.



(a) (b)

Figure 8. (a) PAE and gain for Sokal's equation. (b) Current and voltage at drain with Sokal's equations

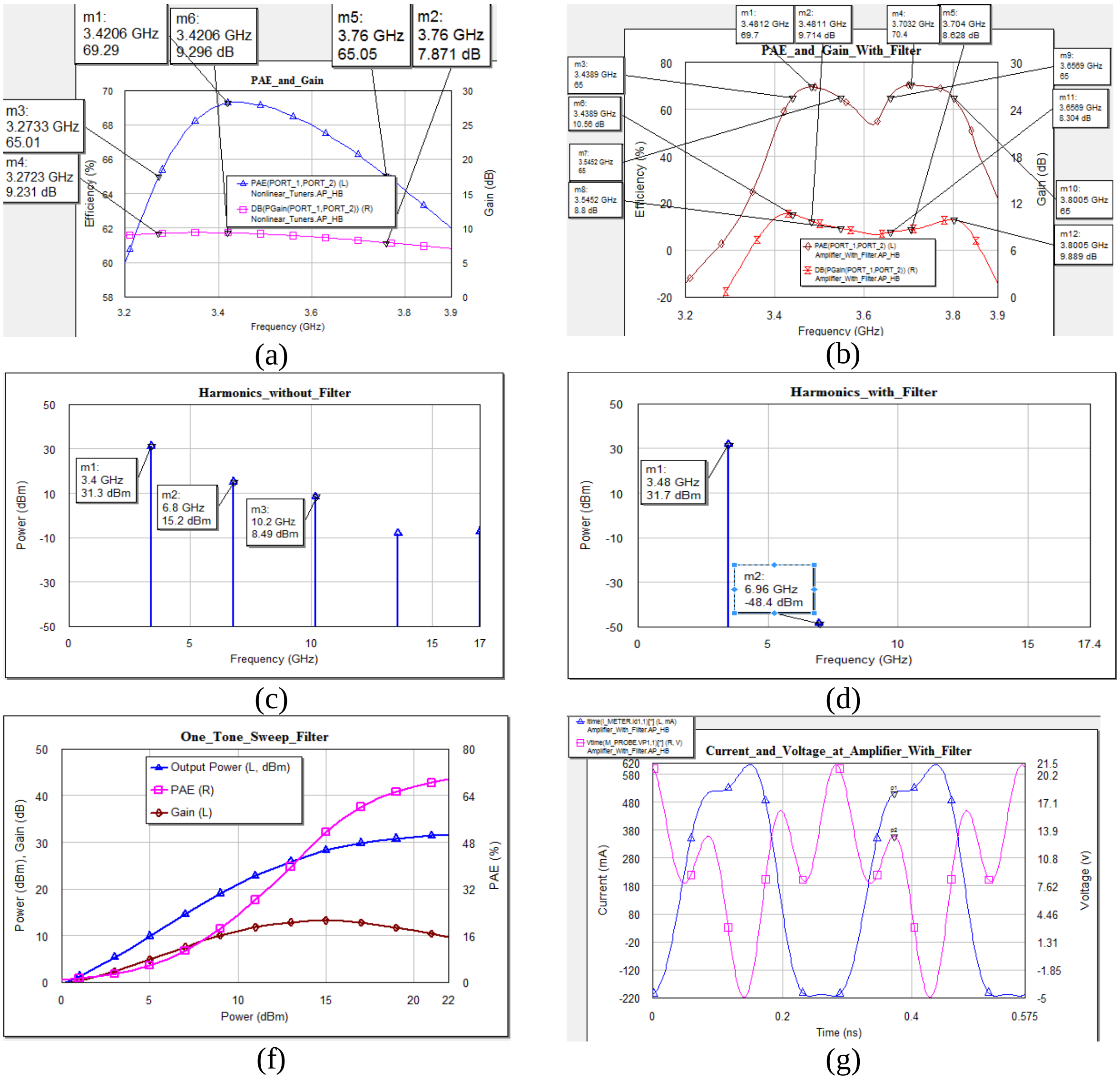


(a) (b)

Figure 9. (a) PAE and Gain by applying S22 conjugate with Sokal's lumped components (b) New current and voltage waveform for Sokal's equation

3.2. Dual-Band class E PA

The result in Figure 10(b) obtained from Figure 7 the gain and efficiency is higher compared with the result in Figure 10(a) from design shown in Figure 5. Although there is a frequency shifting but nevertheless the designed amplifier is still working at Class E in both dual-band but with a narrower bandwidth of 3.43 GHz – 3.54 GHz and 3.65 GHz to 3.8 GHz achieving an above 65 % efficiency and above 8.6 dB gain. This proves the correlation of a higher efficiency and gain for the Class E by implementing the addition of the filter to remove the harmonics. The Figure 10(c) versus Figure 10(d) shows the harmonics spectrum before and after filter has been added at the OMN of the transistor respectively where it can be seen that the harmonics except the fundamental one has all been suppressed. A 1dB compression test is performed and the results is shown in Figure 10(e). This result indicates that the high input power of 22 dBm achieves the maximum efficiency but the output power is beyond 1 dB compression point. Hence going beyond the 15 dBm is going to compress the output signal in such a way that the circuit will no longer linearly amplify. But this has been shown not to be much of a problem as stated in [4] where and it showed high efficiency if the supplying voltage was large enough thus proving that such type of PA is optimum for envelope elimination and restoration (EER) transmitters (burst mode transmitters). High PAE and gain does not guarantee Class E operation. So in order to validate the Class E power amplifier we would need to view the current and voltage at the drain of the transistor whose result is shown in Figure 10(f) shows non-overlapping current-voltage waveform.



(a) (b) (c) (d) (f) (g)

Figure 10. (a) PAE and gain for realized Class E circuit using lumped components before addition of filter (b) PAE and gain for realized Class E circuit using lumped components after addition of filter (c) Harmonics before added filter (d) Harmonics spectrum after filter is implemented (e) 1dB compression point for the Dual Band Class E amplifier (f) Current and Voltage waveform at drain after addition of filter network

4. CONCLUSION

The Class E design implemented in this work is aimed at Dual-Band operations specifically in the bandwidth range of LTE 42 and LTE 43 having frequency of 3.4 GHz to 3.8 GHz combined. As it has been mentioned before it is unrealistic to realize a Class E PA using Sokal's equation for wideband or broadband operations. Although the equation derived by Sokal's do only work on modern transistor only if the drain has been already conjugate matched.

The Class E designed within this work before filter implementation shows that it achieves an above 65% efficiency even below the 3.4 GHz and it does indeed cover up to the end of the LTE 43 at 3.8 GHz. The major trade-off here is the harmonics present within the output waveform. It has already been known that implementing an open-circuit stub for each harmonic frequencies which is usually employed for Class E PAs is not viable option for wideband or broadband frequency of operations. Hence it was decided to go for the band-pass filter. The results are promising as all the harmonics have been filtered out with the integration of a band-pass filter. The newly measure PAE and gain looks promising as the range are well within the LTE 42 and LTE 43 bands at 3.4389 GHz - 3.542GHz and 3.6569GHz - 3.8GHz with an efficiency above 65% and gain above 8 dB. But there is a trade-off here which is that the newly designed bandpass filter adds a new reflection coefficient at the drain. This will smoothen the current waveform and make it look square like as it should be for an ideal Class E PA but the voltage waveform are no longer smooth as before. But this undesirable effect does not affect out targeted efficiency, gain or frequency since the applications of Class E are mostly for non-linear based operations.

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