

Interaction of The Human Body on The Performance of Class E PAs in Body Area Networks

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Abstract—This paper describes a class E power amplifier (PA) for use in biomedical and healthcare Body Area Networks (BAN). A combination of lumped component and transmission line matching networks results in a compact form factor at 2.5GHz. Optimum simulated Power Added Efficiency (PAE) was 76.7% at 11.5dBm output power (P_{OUT}) and 66.1% at 12.7dBm into a 50Ω load when measured. When combined with a BAN antenna 60.8% PAE was achieved in free space and 64.4% when in close proximity to a human arm. P_{OUT} in free space was 13.2dBm and 12.3dBm near the arm. These results indicate that PA performance is not greatly affected when in the presence of a human body.

Index Terms; Antenna, body area networks, class E amplifier, healthcare, biomedical.

I. INTRODUCTION

Body Area Networks (BANs) will in the future be used in many biomedical and healthcare applications [1]. To facilitate this they must be unobtrusive; therefore physically small and of long battery life. It is likely that the power amplifier (PA) will be responsible for a large proportion of the overall power consumption during the transmit phase. A high efficiency PA is therefore necessary.

The FCC have defined a band between 2.36GHz and 2.4GHz for medical BANs [2]. Although lower frequency bands exist [3] they require large obtrusive antennas. Due to the short path length between BAN nodes a high path loss is tolerable. Although the IEEE 802.15.4 “Zigbee” standard has been proposed [4], more power efficient standards using constant envelope modulation like frequency shift keying (FSK) may be better suited [5], allowing non-linear switching PAs to be used.

Class E is the most applicable switching PA architecture since it can be realized with lumped components [6]. High efficiency is achieved by manipulating the fundamental and harmonic zone impedances presented to the transistor. This does however mean that any change in load impedance can detune a class E PA away from its optimum operating point. Antennas are rarely a pure real 50Ω impedance. Presenting the antenna’s non-ideal impedance to a PA often leads to sub-optimal PA operation [7].

For this work an operating frequency of 2.5GHz was chosen which is compatible with a short circuited square patch antenna specifically designed for BANs [8].

II. CLASS E AMPLIFIERS

The class E amplifier is designed so that its current and voltage waveforms do not overlap as shown in Fig. 1. It is generally assumed that a high Q band-pass filter composed of L_F and C_F presents the transistor with a large impedance at the harmonic zones. Practically a low Q L-type matching network is often used [6]. The shunt capacitance (C_S) is usually fulfilled by the transistor’s stray drain capacitance, which cannot be controlled and largely dictates the PA’s operating characteristics. C_S and L_S depend on load impedance (R_L), Q and the operating frequency [9]. R_L is a function of the supply voltage (V_{DD}), the output power (P_{OUT}) and Q [9].

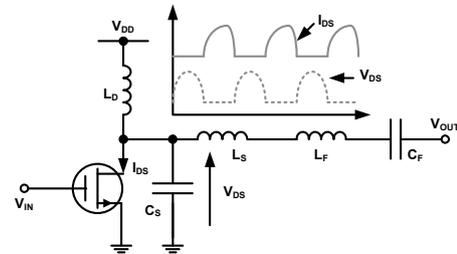


Fig. 1. Class E amplifier with simplified voltage and current waveforms.

A. Limit of C_S

The BAN compatible PA envisaged here is powered by a single 1.4V mercury button cell as used in watches and hearing aids. The target P_{OUT} is 10mW [10]. An Avago Tech ATF-54143 transistor was used, which has a 1dB compression point (P_{1dB}) of 20.4dBm at 2GHz with a V_{DD} of 3V. According to the datasheet, C_S of the ATF-54143 is estimated at 0.7pF; based on package strays, drain source capacitance (C_{DS}) and gate drain capacitance (C_{GD}) [11]. The optimum values of R_L and C_S are determined by Fig. 2. given these operating conditions.

Operation is constrained to a region of Fig. 2 where R_L is positive and C_S greater or equal to 0.7pF. The maximum output network Q is therefore 1.02, with a corresponding R_L of 15.5Ω. A low Q increases PA tolerance to variations in R_L .

B. Simulated Results

Generally, the transistor in a class E amplifier is biased at its threshold voltage (V_T) so that 50% duty cycle is achieved. The ATF-54143 has a typical V_T of 0.38V. A bias of 0.32V was used, resulting in a quiescent current consumption of 640μA. Transmission lines with a characteristics impedance of 76Ω – equivalent to a width of 1.27mm on a 1.6mm height FR4 substrate – were used to reduce overall size. A simplified schematic of the PA is shown in Fig. 3.

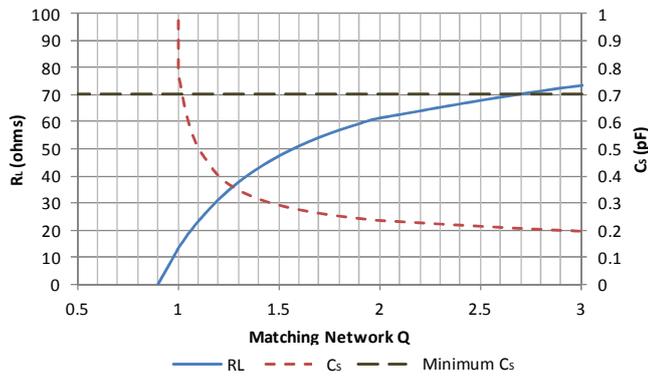


Fig. 2. Optimum R_L and C_S , where minimum C_S is determined by the transistor.

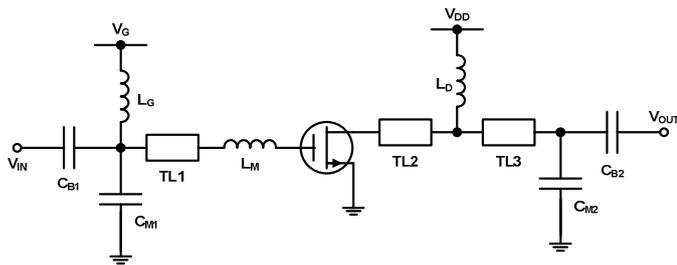


Fig. 3. Schematic of the class E PA.

Optimum P_{OUT} at 2.5GHz was 11.5dBm with an efficiency of 82.5%; a PAE of 76.7% and a gain of 11.5dB. A power sweep at 2.5GHz is shown in Fig. 4. Optimum performance across the band is shown in Fig. 5.

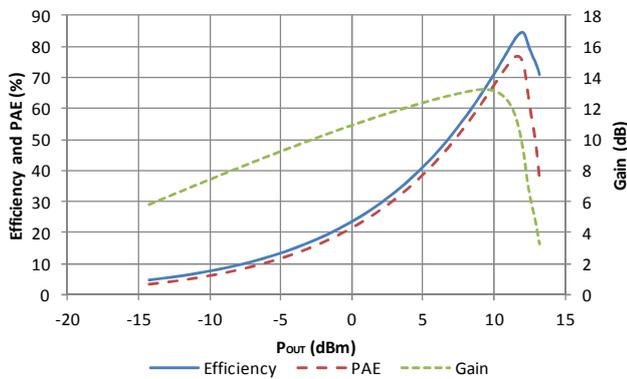


Fig. 4. Simulated power sweep at 2.5GHz.

C. Measured Results

A practical PA measured 30mm by 10mm excluding the input and output SMA connectors was built on an FR4 substrate. A photograph of the PA is shown in Fig. 6. with a ruler for comparison. The measured power sweep at 2.5GHz is shown in Fig. 7.

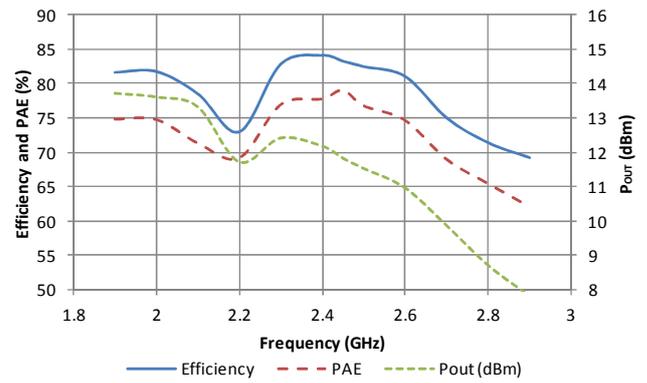


Fig. 5. Simulated frequency sweep at optimum operating point.

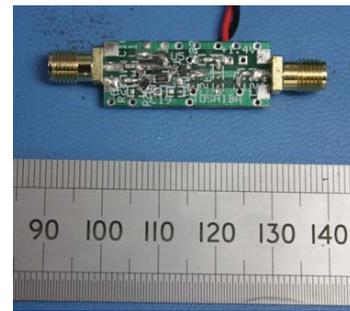


Fig. 6. Photograph of the PA.

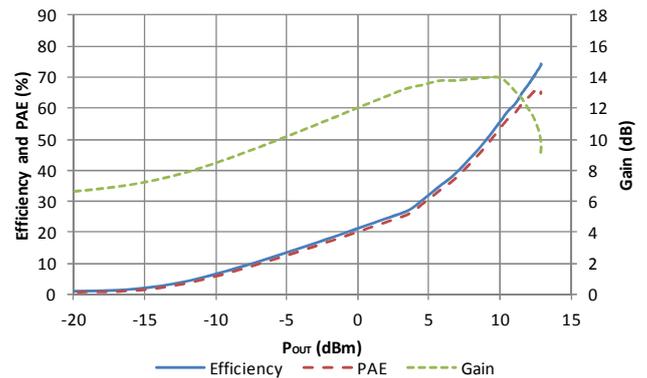


Fig. 7. Measured power sweep at 2.5GHz with 50Ω load.

Fig. 7 shows that an optimum P_{OUT} of 12.7dBm was achieved at 66.1% PAE, higher than the intended 10dBm P_{OUT} . This indicates that C_S is larger than the estimated 0.7pF which is probably due to stray parasitic capacitance of the PCB layout. An optimum frequency sweep across the operating band is shown in Fig. 8. .

The good broadband response is due to the low Q output matching network. The lower efficiency and PAE are likely due to discrepancies between the simulated and measured PAs. Although FR4 PCB material does incur a loss, it is only 0.012dB per millimeter at 2.5GHz [12]. The 13mm transmission line between the transistor drain and the output connector will only reduce the efficiency by 1%.

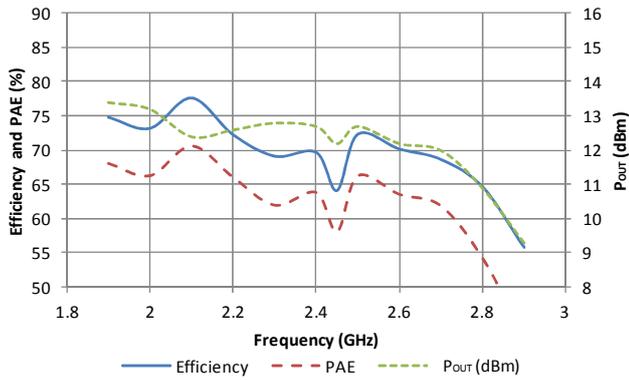


Fig. 8. Measured frequency sweep at optimum operating point with a 50Ω load.

III. BAN ANTENNA

A BAN antenna [8] was developed for use on the human body based on a vertically polarized short circuited square patch antenna as shown in Fig. 9. Fig. 9 also shows that it has a omnidirectional radiation pattern in horizontal plane. It is a conformal antenna and less sensitive to near field effects of the body.

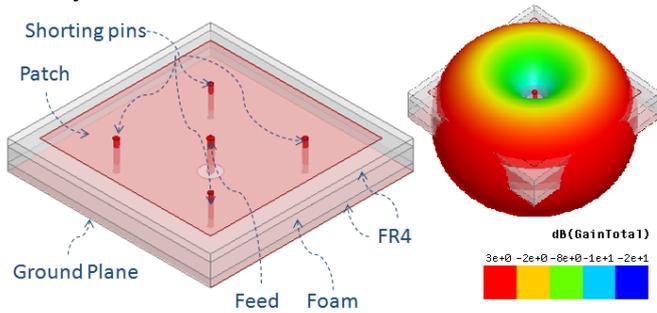


Fig. 9. Antenna model and the 3D radiation pattern.

For ease of fabrication, the patch and the ground plane of the antenna are fabricated on two pieces of FR4 with a 3.2mm thick polyethylene foam [13] sandwiched between them. The antenna is 0.375λ by 0.375λ . The simulated radiation efficiency in HFSS [14] is 94%.

IV. PA AND ANTENNA RESULTS

A Narda 29820 directional coupler with a through loss of 0.14dB and a coupling of 16.3dB at 2.5GHz was used to measure the incident power flowing between PA and antenna. Any incident power reflected back from the antenna was measured by reversing the connections to the directional coupler and repeating the measurement. The PAE equation is modified to account for the reflected power as shown in (1).

$$PAE = \frac{P_{FRW} - P_{REV} - P_{IN}}{P_{DC}} \quad (1)$$

P_{FRW} is the forward incident power flowing from PA to antenna, P_{REV} is the reflected power, P_{DC} the DC power and P_{IN} the RF input power to the PA.

A. Free Space Measurements

With the antenna connected the optimum operating point is shown in Fig. 10. RL' is the antenna return loss found by subtracting P_{FRW} from P_{REV} .

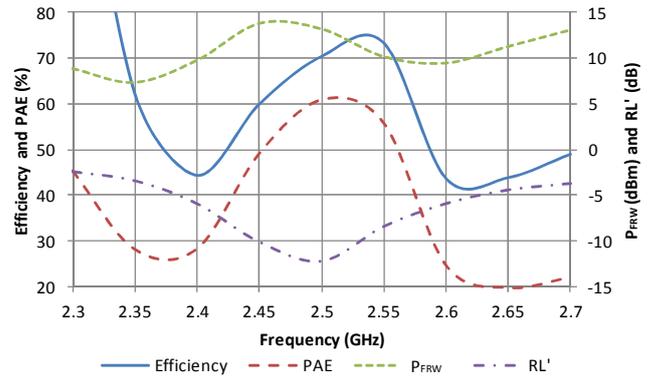


Fig. 10. Measured optimum frequency sweep of amplifier with antenna in free space.

As shown in Fig. 10, P_{FRW} varies between 8dBm and 14dBm due to the antenna's input impedance interacting with the PA. At 2.3GHz, a high efficiency is reported, but since the antenna is far from resonant (RL' is only -2.4dB) most of the incident power is reflected back into the PA. In the regions of poor RL' the PA experienced some instability.

Optimum performance was achieved at 2.5GHz, at the antenna's resonance as indicated by RL' . The P_{FRW} was 13.2dBm with 11.2dB gain. With an RL' of -12.2dB about 1dBm of power was reflected back into the amplifier, approximately 5% of P_{FRW} . Under these conditions the optimum efficiency was 70.4% and PAE 60.8%.

B. In the Presence of a Human Arm

BAN antennas like that described in Section III are generally in close proximity to the human body. Its performance with the PA is measured by holding the directional coupler (with antenna and PA connected) in the crook of a tightly bent human arm as shown in Fig. 11. The antenna was separate from the arm by approximately 10mm [8] using a corrugated cardboard spacer. This setup will introduce some small errors since it is difficult to ensure the antenna is in exactly the same position between measurements. However, only a 10% variation in current consumption was observed between P_{FRW} and P_{REV} measurements, indicating a negligible effect. Alternatively a phantom [15] could be used if available. The frequency sweep is shown in Fig. 12.



Fig. 11. Photograph of antenna in situ.

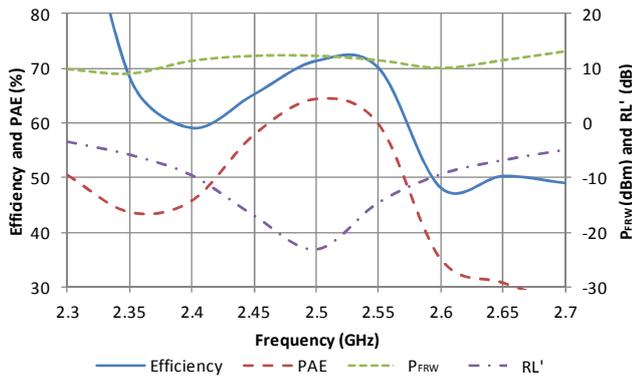


Fig. 12. Measured optimum frequency sweep of amplifier with antenna in the presence of a human arm.

As expected RL' was improved with respect to Fig. 10. since the antenna was optimized for BAN applications. Efficiency and PAE are also slightly higher, although gain was reduced. P_{FRW} was also slightly lower. Although the antenna is better matched in the presence of a human arm, when in free space it may provided a better P_{OUT} match.

These results indicate that Class E PAs are well suited for BAN use with a correctly designed antenna. The results recorded at 2.5GHz in each of the four described scenarios are listed in TABLE I.

TABLE I. PA COMPARISON AT 2.5GHZ

Scenario	P_{OUT} or P_{FRW}	Gain	Efficiency	PAE
Simulation	11.5dBm	11.5dB	82.5%	76.7%
50Ω load	12.7dBm	10.7dB	72.3%	66.1%
Antenna in free space	13.2dBm	11.2dB	70.4%	60.8%
Antenna in presence of human arm	12.3dBm	10.3dB	71.4%	64.4%

V. CONCLUSION

In this paper a miniature high efficiency class E PA intended for healthcare and biomedical BANs at 2.5GHz is described. When simulated a PAE of 76.7% was achieved at 11.5dBm P_{OUT} . Practically, 66.1% PAE at 12.7dBm P_{OUT} could be achieved when driving an ideal 50Ω load. When coupled to a BAN antenna in free space a PAE of 60.8% was achieved at 11.2dBm P_{OUT} . The PAE equation was modified to include the power reflected back into the PA due to antenna mismatch. In the presence of a human arm the PAE was increased to 64.4% PAE at 12.3dBm P_{OUT} . The difference in the performance of the PA when driving a BAN antenna compared to the 50Ω load is not significant, validating the use of class E PAs for BANs.

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