# High Efficiency Amplifier for use in portable Haemostatic Applications - Part A

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*Abstract*— This paper presents an integrated applicator structure achieving a sufficient power density to effectively coagulate bleeding sites which cannot easily be controlled under conventional haemostatic modalities. The portable haemostasis system operating at 5.8 GHz includes: a handheld applicator with a radiative tip and a 'power pack' housing high efficiency multistage amplifier capable of providing up to 17 W continuous wave (CW) output power with 61 % total efficiency. Initial device tests have shown effective energy delivery to porcine liver bench model over different intervals of time in a relatively small and controlled area.

Index terms— GaN HEMT, Electrosurgery, Microwave, Class F Amplfiier, Coagulation, haemorrhage.

## I. INTRODUCTION

Uncontrolled haemorrhage from major trauma is leading mechanisms of death on the battlefield. Studies have shown that this is the case in up to 80% of potentially survivable cases and that approximately 69% of these cases were either torso or junctional based and would be unsuitable for treatment with standard tourniquet methods. [1]

Presented herein is a portable microwave applicator capable of delivering microwave energy at 5.8 GHz to effectively coagulate bleeding sites which cannot easily be controlled under conventional haemostatic modalities. Using similar methods as used in operating theatres for the closure of bleeding vessels during surgery the device can coagulate both blood and specific vessels. This could be used an interim process to facilitate emergency evacuation to a suitable facility or, depending on severity, it can act as a longer-term solution if other facilities are not readily available.



Fig. 1. Rendered model of the complete device

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The device consists of a handheld applicator with a radiative tip shaped to allow the user to apply local tamponade to the site whilst delivering energy thus increasing the likelihood of haemostasis. Power pack provides sufficient power to the handheld applicator and houses microwave sources.

Less heating of the amplifier chip within the microwave sources can be achieved by using high efficiency amplifier modes like class B, class AB, class F, inverse class F, continuous class F and class J. [2] These amplifiers operate under reduced conduction angle with the device remaining 'switched off' during parts of its operation's cycle, thereby reducing power consumption or heat dissipation. [3] This limits the amount of dissipated heat and DC power consumption. Active cooling mechanisms within the device permit effective heat transfer for continuous use of the applicator whilst a removable battery provides sufficient DC power for each coagulation process and can easily be replaced if further energy delivery is required.

The multistage amplifier presented herein employs class AB and class F mode amplifiers in gain and power stages respectively to provide up to 17 W CW output power with 61 % total efficiency.

#### II. MICROWAVE DELIVERY

For the best chance of achieving haemostasis the applicator needs to apply as much energy as possible whilst maintaining a controllable and even delivery throughout the coagulation process. Microwave delivery has been shown to have these characteristics and its delivery has proved effective in a number of clinical applications [4]. Many of these applications however require the use of a large microwave generator which limits their usage to indoor facilities.

The main application envisioned for this device is field medicine either in remote areas or during military operations where access to electrosurgical haemostasis is limited and injuries are more likely to be fatal if treatment is not carried out as soon as possible.

Field haemostasis, as it shall be referred to in this paper, is usually achieved through the use of tourniquets and dressings. The most common of these dressings are usually impregnated with a haemostatic material. These dressings work in a number of ways including:

- *Factor Concentration* rapid absorption of water and thus concentrates the other components of blood which increases clotting ability
- *Mucoadhesive* material can create adhesions onto tissues and physically seal any wounds
- *Procoagulants* artificial supply of procoagulant factors which increase the amount of factors and coagulation ability

There are a number of issues with these dressings and an overview [5] discussed some of these. One main issue with the loose powder haemostatic agents was the difficulty in application in windy or poor weather conditions and more importantly the likelihood of burns or extraneous tissue damage caused by exothermic reactions caused by the powders. [6]

The ability for a medic in the field to accurately and safely coagulate bleeding vessels would save lives and provide interim treatment and extra time to enable the extrication of patients to further care facilities.

## III. DESIGN OF POWER AMPLIFIER

#### A. Two Stage Power Amplifier Design

The design of power amplifier has been carried out in Keysight's Advanced Design System (ADS) with the aim of achieving maximum output power by utilising commercially available Cree CGH55015 and CGH55030 devices that operate at 5.8 GHz. These devices have been arranged in gain and power stages, respectively.

The bias conditions shown in Table 1 have been chosen to attain a half rectified current waveform. This would generate the fundamental and even order current harmonics by clipping of the waveform when high enough input signal level swings across the knee region. [3]

The requirement for load line analysis on device's IV curves is important for linear amplifiers like class A that have a linear load line. However, for non-linear amplifiers like class F amplifiers, the load line is generally elliptical. Suitably terminated power stage in class F configuration could utilize

these nonlinearities due to device's operation under deep saturation conditions to provide high efficiencies along-with high output power.

TABLE 1: BIAS CONDITIONS OF CLASS AB (GAIN) AND CLASS F (POWER)

Stage	Condition 1		Condition 2	
	$V_{DS}(V)$	I <sub>DQ</sub> (mA)	$V_{DS}(V)$	I <sub>DQ</sub> (mA)
Gain	28	120	25	140
Power	28	260	25	290

The design procedure involved the evaluation of small signal S-parameters and stability analysis under the selected bias conditions.

The transistor devices showed unconditional stability in large impedance regions of the smith chart (towards the right) and tends to become unstable when the device is terminated with low impedance values or a short circuit. Poor stability at lower frequencies that may cause oscillations within the amplifier circuit were also observed.

Stability of the device can be improved by using various techniques like the addition of a series or shunt resistor to the device's gate terminal. Analysis between the two cases indicate that higher stability is observed when a small series resistor is added to the device's gate terminal, however, this comes at the cost of reduced device gain and output power. Shunt stabilisation resistor shows around 3 dB better gain while series stabilisation technique provides wider space to design load termination on the smith chart.

In the design of class AB and class F amplifiers discussed here, a shunt resistor of 22  $\Omega$  has been added to high impedance gate bias lines to provide stability to the device. Stability of the amplifier has also been improved through the design of appropriate decoupling networks in the bias lines. Multi-tone stability analysis has also been performed to ensure device stability for two closely located input tones. Fig. 2 shows the amplifier block diagram.



Fig. 2. Two stage GaN power amplifier block diagram.

Classical class A amplifiers are biased in the middle of cut off and saturation regions on the load line. Thus, linear amplifiers can be terminated in conjugately matched networks. However, as the signal passes through the limits of a transistor's operation; non-linearities are presented by the device and conjugately matched networks no longer remain effective in deriving the desired properties. After small signal s-parameter and stability analysis, load pull data provided by Wolfspeed has been simulated in ADS to optimize high efficiency performance.

For class F amplifiers, load pull is conducted simultaneously alongside source pull where load and sources impedances are both identified for optimum performance of the device in terms of output power and PAE. The process is cyclic where the optimum load impedance is found by varying the source impedance and vice versa. This continues until both the source and load impedances have been optimised. Table 2 shows comparison between simulated load and source pull impedances and the suggested impedances for optimized device performance in the datasheet. Input, interstage and output matching networks have been designed according to the simulated load and source pull data.

TABLE 2: SIMULATED AND DATASHEET LOAD AND SOURCE PULL IMPEDANCES AT 5.8 GHZ

Stage	Source Pull		Load Pull	
	Simulated	Datasheet	Simulated	Datasheet
Gain	9.1 - j6.8	12.3 - j24.3	11.7 - j31.7	26.5 - j7.5
Power	15.9 - j22.6	8.4 - j14.0	5.8 - j9.9	15.4 - j11.0

The input matching network consists of shunt resonant stubs, DC block capacitor and transmission lines that feed into gate of the gain stage transistor. Interstage matching network transforms output impedance of the gain stage to optimum source impedance of the power stage, DC block capacitor has also been incorporated within the interstage matching network. The output network of the amplifier is composed of harmonic trapping network and the fundamental matching network.

The harmonic trapping network provides short circuit impedance to the second harmonic component while open circuit impedances to the fundamental and the third harmonic components for class F operation. EM simulated results of the harmonic trapping network have been shown in Fig. 3.

Low impedances for short circuit conditions over a wider range of frequencies makes the circuit less susceptible to any variations in transmission line length. Radial stubs have been used in this design to provide low impedance values over a broader frequency range due to large fringing effects at their ends. Fundamental matching network provides optimum load impedance to the power stage transistor and includes output resonant stubs, DC block capacitor and transmission lines.



Fig. 3. EM simulated results of harmonic trapping network.

The amplifier has been processed on Rogers RO4350B board because of its suitability for high power RF designs and the ability to support high bias line currents through narrow high impedance lines. The amplifier PCB has been bonded to an aluminum block using CircuitWorks CW2400 silver based conductive epoxy.

Slots have been routed for the two transistors to sit directly on the aluminum block while multiple ground vias covering maximum area on the PCB have been placed in the amplifier PCB to provide same ground reference to the decoupling capacitors in the bias network as the transistor. The assembly has been finally bolted to a heatsink. Fig. 4 shows final assembly of the power amplifier.



Fig. 4. Two stage GaN power amplifier.

#### B. Large Signal Measurements:

The processed amplifier assembly was switched on and measured for any oscillations at 5.8 GHz and out of band low frequencies that were observed in stability analysis of the transistors during the design phase. Small signal measurements of the amplifier were performed to analyse comparison between EM simulated and measured results. Large signal measurement setup of the amplifier has been shown in Fig. 5.

Due to limitations of the VCO available at the measurement facilities, gain amplifier was used in the measurement setup to provide sufficient input power to the amplifier under test for operation in the saturation region. Fig. 6 shows large signal measurement results of the two stage amplifier.



Fig. 5. Large signal measurement Setup.



Fig. 6. Large signal measurements results.

The amplifier shows 3 dB saturated power of 42.3 dBm at 5.8 GHz CW operation with 61 % total efficiency. Heat dissipation from the devices take place through the heat sink that can be air cooled within the 'power pack'.

#### IV. RADIATIVE TIP

The radiative tip was designed to allow optimum energy delivery into tissue whilst initially allowing for a smaller, more accurate area of coagulation. A 50  $\Omega$  coaxial cable was used with a modified radiative tip comprised of Macor, machineable ceramic, was used. This tip was designed to match the cable to the tissue and was further optimised in CST Microwave Studio. Macor was chosen due to its higher dielectric constant and its ability to be machined and processed much easier than other ceramic materials. Due to the portable requirements of this device it was vital that the tip be matched as well as possible to allow the optimal delivery of energy and minimise losses.



Fig. 7. Model of the radiative tip in CST Microwave Studio

As can be seen in fig 7 the tip was simulated pressing against a block of liver which is often used to test microwave coagulation ability during bench testing. The S parameters for this design can be seen in fig 8 and show good match and therefore optimal energy delivery at 5.8 GHz.





The results from the initial design were then simulated both in terms of power loss within the tissue and also thermally to ascertain what level of energy delivery was occurring.

# A. Thermal Testing

The thermal solver requires the loss results from a power loss density in the electromagnetic solver. The results of this loss density monitor can be seen in fig 9 and it can be seen that the energy dispersion is quite small and concentrated. For accurate haemostasis this result is positive as it means that there will only be energy delivery where it is required and will therefore minimise damage to surrounding healthy tissue.

The electromagnetic simulation in CST studio uses a 0.5W input power which means that the power loss needs to be scaled in order to approximate the output from an expected input. For this simulation a scale factor of 20 was used which equates to an input power of approximately 10W.



Fig. 9. Simulated Power Loss Density monitor



Fig. 10. Simulated thermal profile of the radiative tip

It can be seen in fig 10 that at the tip a temperature of almost 360 degrees is reached. The thermal simulation provided by CST studio has a number of issues and it is unlikely that this high a temperature will be achieved due to perfusion, steam generation as tissue is heated and also the bodies' ability to thermoregulate. What this simulation does show is that the energy is being delivered effectively to the area where it is required.

# V. INITIAL TESTS

For an initial test a hollow coaxial cable and haemostatic probe, as discussed in [7] was used. This initial test was to ascertain the ability of the amplifiers to deliver enough energy and to assess the effects of the energy delivery. Figure 11 shows the results of a number of energy delivery sites into a porcine liver bench model.



Fig. 11. Energy delivery sites on porcine liver model

The top row of delivery sites are 10s, 20s and 30s and the bottom row is the same but with a more optimal setup for the amplifiers. It can be seen that the energy is being delivered in a relatively small and controlled area. The strength and effect of this energy can be seen in the colour change of the tissue. The white areas are the coagulated tissue, the darker areas are where the tissue has been heated above that required for coagulation and the tissue has started to be vaporised and carbonised.

# VI. DISCUSSION

Future iterations of the amplifier board will include an on board VCO capable of driving a single stage class F amplifier up to 6 dB compression level to achieve improved efficiency. In terms of the microwave delivery section; the radiative tip structure will be optimised to ensure optimal energy delivery, manufacture a prototype tip and test microwave delivery with a more optimal amplifier. Investigation into the most common injuries and treatment requirements will also inform a variety of tips which can be interchanged depending upon clinical need.

As can be seen from the timings used during the bench tissue testing it appears that the tip used is not optimally matched to the tissue and requires a longer delivery time to achieve temperature increase. The simulated tip should offer much better performance and therefore show similar results for much less delivery time.

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