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A Novel Solid State Power Amplifier for RF Cooking Applications

Uslu G[a*], Kızılbey O[b], Bayındır K. Ç[c]

[a]*Process Engineering Department, Udea Electronic Inc., Ankara, Turkey*
[b]*R&D Support and Information Systems TÜBİTAK National Metrology Institute, Kocaeli, Turkey*
[c]*Electrical and Electronic Engineering Department Ankara Yıldırım Beyazıt University, Ankara, Turkey*
[a]*Email: gorkem.uslu@udea.com.tr*
[b]*Email: oguzhan.kizilbey@tubitak.gov.tr*, [c]*Email: kcbayindir@ybu.edu.tr*

Abstract

In this paper, a single-stage solid-state power amplifier (SSPA) with 250W output power, high efficiency and 12 dB gain for use in 2.4-2.5 GHz RF cooking application is designed and simulation results are given. Gallium Nitride (GaN) high electron mobility transistor (HEMT) used as active device. Rogers RT5870 with dielectric constant of 2.33, dielectric thickness of 31 mil and a copper thickness of 35 µm is used as the substrate. According to the simulation results, 250 ± 5 W output power, 65 ± 1% power added efficiency and 12.1 ± 0.1 dB gain were obtained in the 2.4 - 2.5 GHz band. Because of the high output power of the amplifier, 2nd and other higher degree harmonic levels must be checked to prevent suppressing the communication of other electronic systems such as radars, base stations etc. 2nd harmonic is approximately 27 dB lower; 3rd harmonic is 20 dB lower; 4th harmonic is 36 dB lower and lastly 5th harmonic is 33 dB lower than fundamental over the band.

Keywords: GaN HEMT; Power amplifier; RF cooking.

1. Introduction

RF cooking term firstly appeared before World War II with invention of products which are using magnetron-based microwave devices. It is said that it was invented by chance by liquefying of a piece of candy in Percy Spencer's pocket during new war technology studies [1]. With the invention of magnetron which was planned to use as a radar system during war years, Spencer started doing experiments with radar waves and during these experiments he realized that the candy in his pocket was liquefying. By this result it was understood that microwave energy can warm up foods. Spencer continued food experiments with a pack of corn and obtained popcorn within seconds. After these experiments he applied for patent in 1945 and it was registered in 1950.

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* Corresponding author.

In his patent application he put a high-intensity electromagnetic field generator inside a metal box and then he put two magnetrons inside this controllable area to catch the microwaves emitting from the generator. In 1947 microwave ovens officially took place in the market but they were not found so feasible due to size and price issues. After making some optimizations on these issues microwave ovens started to become more feasible in 1967. Microwave ovens heat food using microwaves that form of electromagnetic radiation similar to radio waves, the atoms of the food are made to move [2]. A microwave oven is a small box like oven when compared to relatively conventional ovens that increase the temperature of food by exposing it to a high-frequency electromagnetic field [3]. Microwave oven mainly consist of transformer, capacitor, magnetron, cooling fan, antenna and turn table. Transformer; converts household electricity into electricity to power the magnetron. The voltage heats the filament at the center of the magnetron and activates the electrons [4]. Electrons are rotated by two ring magnets and microwaves are generated at the determined frequency. The antenna transmits the resulting microwaves to the oven cavity. Microwaves spread inside the cooking chamber and heat the food in the cavity. It has a rotating plate that rotates the food to heat it evenly.

In current studies within the scope of microwave oven, solid state power amplifier microwave oven is frequently encountered. Solid state power amplifier oven consists of oven cavity, power supply unit, small signal board and last but not least power amplifier. High power RF transistors that produced particularly ISM band applications play a critical role of developing and progressing of solid-state power amplifier microwave oven. Changeable load impedance which depends on load size, amount and density causes a changeable required power. Because of that changeable transferred power issue shows that solid state device technology is a logical alternative to magnetron systems [5].

In this study we designed and implemented 2.4 – 2.5 GHz 250W 12dB gain power amplifier for RF cooking application. In order to design and analyze circuit AWR Microwave Office program was used. All simulations also demonstrate in same design program. For implementation side, Rogers RT5870 31mil thickness as a dielectric material and CREE CGH21240F GaN HEMT as a transistor will be used. In second section, heaters and vacuum tube technologies using solid-state power amplifiers were explained, compared and it was mentioned that why the solid-state power amplifiers are more advantageous. In third section, the 250-W power amplifier was designed and simulated. In forth section, simulation results were given and in fifth section, the results were evaluated.

2. Microwave Heaters

The High Electron Mobility Transistor is occurred by creating a special PN junction. This is also called a heterojunction. Hetero connection occurs when semiconductor materials with different bandwidths are used on both sides. GaN HEMT devices such as transistor have high bandwidth energy, high thermal conductivity, high melting temperature, high electron saturation, speed and high breaking stress by means of that superior material properties have attracted great attention by researchers. Some of the application areas of GaN-based materials are RF transistors, high frequency circuits, high temperature circuits, digital circuits, microwave circuits with low noise applications, pressure sensors, automotive applications, plasma display panels, mixed signal integration, high voltage electronics and military radar applications [6]. In order to examine the effects of materials on device performance in semiconductor device technology, Johnson, Keyes, Baliga, and Baliga HF value coefficients that are figures of merit are available. When Johnson and Baliga coefficient of value are examined, GaN-based materials are superior to other semiconductor materials. GaN HEMT transistors preferred by researchers because of their high-power features [7].

In LDMOS, which is also defined as a laterally diffused MOSFETs, the source is directly grounded, so they are suitable for operation at low microwave frequencies and high power. The difference of LDMOS devices, which are often preferred at low current and voltage values (less than about 200V), from MOS is that they contain a p (+) field under Source diffusion. Silicon LDMOS devices are preferred in many products in the RADAR system, thanks to their low cost and performance. In general terms, it is used in power amplifier applications up to about 2GHz and in power switching applications at frequencies lower than 2GHz.

According to the research, it has been observed that there are some differences between the GaN transistor and LDMOS, whose structures are given above. According to a study [7], it has been seen that the transistor is evaluated according to parameters such as output capacitor, breakdown voltage and current density in order to provide high efficiency, high output power conditions at high frequencies (microwave frequency). The output capacitor value should be low for a transistor operating in switched mode. When Si LDMOS and GaN transistor are compared, it is seen that GaN transistor has lower (low parasitic) parasitic output capacitance. Low output capacitance is important for wide bandgap. The breakdown voltage is directly related to the relationship between the voltage at the drain end and the voltage at the source end. In the power amplifier design, it is observed that the drain voltage is approximately 3 times the supply voltage. For this reason, there should be a difference of at least 4 times between the break-down voltage and the voltage at the supply end for a good operation. GaN transistor has 6 times higher breakdown voltage than Si LDMOS. When considering current density for transistors, it is an important factor in reducing the effects of unwanted signals such as noise. The current density of GaN-based transistors is about 600mA/mm and the current density of Si LDMOS is about 400mA/mm. In addition, some studies [9] show that in addition to high thermal conductivity and cut-off frequency, low turn on resistance can be given in addition to the above differences in GaN transistors.

It is necessary to analyze the transistors according to their usage areas. While designing the power amplifier, the power transistors decide what the structure will be like. For this reason, the choice of transistor comes to the fore in power amplifier. In order for the transistor to be preferred, it must exhibit a characteristic suitable for its intended use. The most suitable transistor to be used in RF cooking applications in our project is that it can operate at 2.45 GHz center frequency with high power and high efficiency [10]. When the parasitic output capacitance, breakdown voltage, current density, thermal conductivity, turn on resistance, and cut-off frequency are compared, it has been decided that the most suitable structure for the usage requirements is GaN HEMT.

3. Power Amplifier Classes and Design

Power amplifiers have their own classification. These classifications are determined according to some topologies. The most common of these topologies are linear power amplifiers, non-linear power amplifiers, bias voltage dependent amplifiers, wave forming amplifiers. Linearity is the ratio between input power and output power. When the input power is expressed as a linear multiple of the output power, that power amplifier class is considered linear. In non-linear power amplifiers, the transistor used in the circuit is operated close to both the cut-off region and the saturation region due to high efficiency targeting. For this reason, spurious frequencies and intermodulation distortion can be observed in non-linear power amplifiers. Therefore, the linearity between input power and output power is broken. Each PA class has a conduction angle. This angle shows how long the transistor used during a period is in conduction. When making a distinction according to the polarization class, it is important to examine the transmission angle and the polarity point. In amplifiers based on wave shaping, the current or voltage on the drain is shaped using the design. Although it is difficult to design, complicated and complex compared to other methods, higher efficiency is obtained. Conduction angle term, on the other hand, constitutes the transmission angle of the signal at the output of the transistor [11].

3.1. Class A Power Amplifier

Class A power amplifiers form the basis of other amplifier classes. The transmission angle is 360 degrees. Examining the working style; The transistor is in the active region throughout the cycle. A continuous current flow through the transistor in the active region and the power consumption reaches very high levels. Since it is in the active zone during the entire cycle (thanks to), cross over distortion is not encountered. Efficiency in this class is quite low. However, a linear relationship is observed when the very small negligible harmonics between the input signal and the output signal are not taken into account [12].

3.2. Class B Power Amplifier

Class B power amplifier, the most important feature that distinguishes the A-Class from the amplifier is that the conduction angle is 180 degrees. The operating region of the transistor is in half a cycle of the input signal. They are linear power amplifiers designed to improve the efficiency problem of A class amplifiers. When the structure of Class B power amplifiers is examined, they consist of two transistors (PNP-NPN or NMOS-CMOS) operated as push-pull. This structure is set up for amplification throughout the entire cycle. Theoretical efficiency in Class B power amplifiers' is 78%.

3.3. Class AB Power Amplifier

Class AB power amplifier is designed to combine the advantages of Class A and Class B power amplifiers and to reduce the disadvantages of both. Class A has a similar operating style to the linearity property and efficiency of class B. In addition, it shows a current flowing performance almost between the conduction angle feature of Class A and Class B power amplifiers. There is a transmission angle of more than 180 degrees but less than 360 degrees. Since the operating point is above the cut-off region, the conduction angle is more than 180 degrees.

3.4. Class C Power Amplifier

Class C power amplifiers have a transmit angle of less than 180 degrees (around 90 degrees). The decrease of the conduction angle shows an increased efficiency in transmission. However, this decreasing conduction angle causes a decrease in RF output power. This brings the circuit closer to nonlinearity. Class C power amplifiers are not suitable for audio amplification as the smaller conduction angle will cause more distortion. It is more suitable to use for high frequency oscillators and RF frequency amplification. Class C power amplifiers operate at approximately 85% efficiency and thus offer a higher efficiency operating graph.

3.5. Class F Power Amplifier

Class F power amplifiers are at the forefront of studies developed to increase efficiency. Considering the F Class circuit topology, the transistor in the circuit is used as a switching element. There is an output load shown as RLoad. Class F power amplifier is formed by adding "harmonic tuning" to a class B power amplifier. It also acts as a current source in class F power amplifiers as well as class B power amplifiers.

There is an RF choke inductor at the input of the circuit. This element should be as high as possible so that it can only filter DC currents. As the frequency of the parallel capacitors in the circuit increases, the required capacitor value decreases, so the output capacitors have a higher value than they should be. A disadvantage of these capacitors used to prevent harmonics is this parallel output capacitance at high frequencies. To shape the output waveform like a square wave, the output filter (called as harmonic resonators) circuit is used at the output. In this way, both output power and efficiency are increased. It behaves like normally open on odd harmonics. It acts like a short circuit in even harmonics. More than 90% efficiency is obtained when infinite harmonic adjustment is made in class F amplifiers.

3.6. Class E Power Amplifier

Undoubtedly, E class power amplifier class is one of the most frequently used switch mode power amplifiers. Thanks to its ease of application and simple structure, it is suitable for use in many areas. Class E power amplifiers are nonlinear amplifiers and are used as switches. In Class E power amplifiers, the conduction angle between cut-off and saturation is 180 degrees [13]. Efficiency is 100% when calculated theoretically. But the actual efficiency of the circuit is not like this. Considering the actual efficiency of the circuit, the device power dissipation, which is also shown in the figure, is time-effective among the reasons why the efficiency is less than 100%. In addition, the intermingling of current and voltage waveforms is one of the factors that cause the efficiency to be less than 100%.

An example Class E power amplifier topology is shown in the Figure-1 below. Considering other power amplifiers, since their transistors are used as current source, the output matching circuit is designed in accordance with the consumption here. But in Class E power amplifiers, this consumption is negligible. In Class E power amplifiers, there is a trade-off between efficiency and output harmonic content [14].

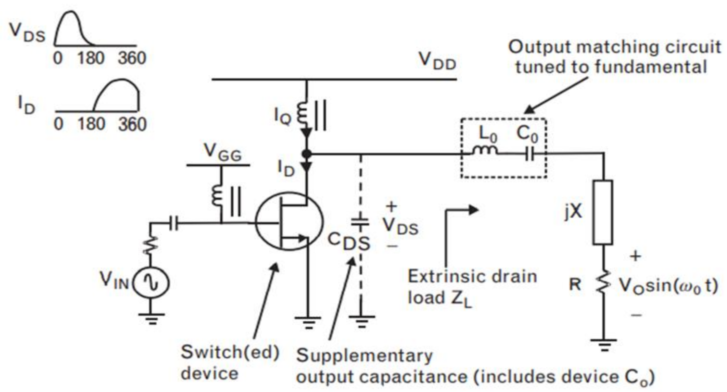

Figure 1: General Topology of Class E Power Amplifier**.**

The circuit consists of a transistor working as a switch and the supplementary grounded CDS capacitance connected in parallel, series network C_0 and series L_0 RF supply inductance, adjustable L_0-C_0 circuit. In addition, it consists of a load resistor R_L. The C_0 capacitance also includes the total output parasitic capacitance of the transistor. The calculation of the capacitor C0 depends on the frequency. Therefore, the current in the circuit is an effective element in voltage waveforms. The L_0-C_0 circuit operates in resonance at the same frequency as the fundamental component of the input signal and transfers a sinusoidal current to the R_L load. The task of the reactance jX is to regulate the flowing current and the voltage across the capacitance C_1.

Capacitor C_1 is also called shunt capacitor. In addition to supporting the transistor, which acts as a switch in the circuit, during switching, it also helps to absorb the parasitic capacitance of the transistor. In this way, Class E power amplifiers can also operate at high GHz frequencies. As Sokal mentioned in his article [15], the following 3 conditions must be met in order to achieve high efficiency;

First, when the transistor is in the ON position, current flows through it. When the transistor is in the OFF position, the current prefers the way the capacitor is and continues to flow through the capacitor C1. If the voltage rises rapidly on the capacitor C1 while the current is flowing through the capacitor: there is a possibility that the current and voltage waves will overlap. This is undesirable. The voltage rise across the capacitor must be delayed. It should not coincide with the instantaneous rise time of the voltage before switching to the off position.

Second, when the transistor is in the OFF position, no current flows through it. In this case, the current flows through the capacitor and creates a voltage across the capacitor. When voltage is present on the capacitor, the transistor turns ON. This voltage will be discharged through the transistor on the circuit. To avoid this, the voltage across the capacitor must be set to zero before the transistor turns ON.

Third, to ensure the situation described in the second item, the slope of the voltage should be zero on the capacitor.

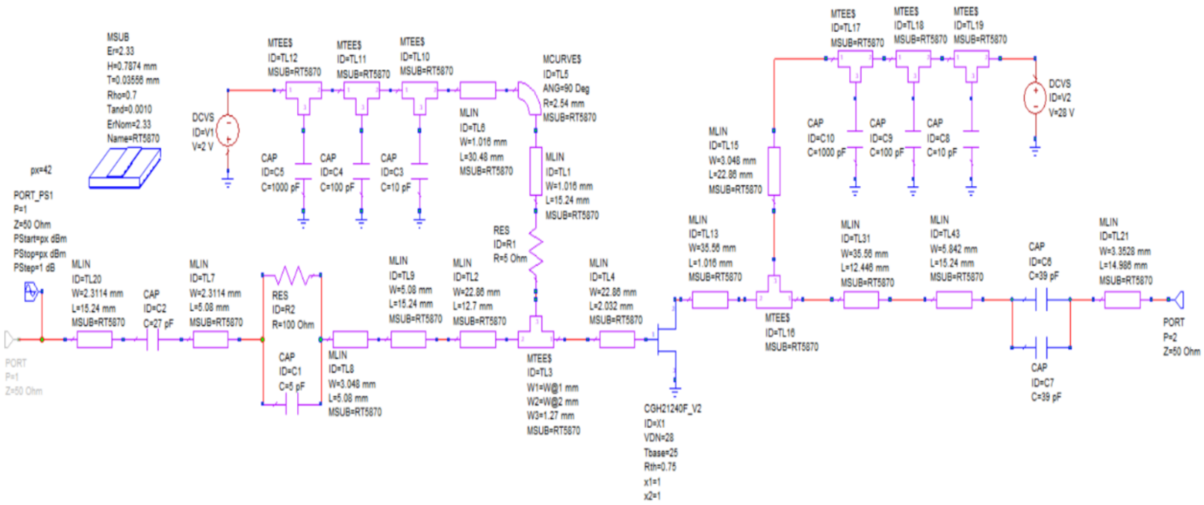

Figure 2: Full Schematics of Power Amplifier.

For power amplifier design, Cree CGH21240F transistor was chosen. This transistor is the fundamental part of the amplifier with Rogers RT5870 dielectric substrate which has a 31 mil of thickness and other lumped circuit components. Because of that the design has approximately 5% band width, input and output impedance matching were made for 2.45 GHz center frequency. By the help of this method, keeping efficiency and output power values at optimum level was provided. Input matching circuit designed with microstrip lines and lumped circuit components are shown in Figure-2. 42 dBm power was applied as input signal. To isolate input signal from direct current components a 27pF ATC branded high frequency capacitor was used. Also, to prevent oscillation a parallel RC circuit (100 Ohm and 5 pF) was added. Impedance matching process was maintained with the microstrip lines up to the transistor input. To supply gate of the transistor -2V was applied through a 5 Ohm resistor by a narrow microstrip line which shows a RF choke characteristic. 10 pF, 100 pF and 1000 pF bypass capacitors were added from supply line to the ground end. By this method incoming noises from supply line and leaking noises to supply line were prevented. Output matching circuit designed with microstrip lines and lumped circuit components are shown in Figure 2. To supply drain of the transistor 28V was applied through a narrow microstrip line which shows a RF choke characteristic with the width of 120 mil and length of 900 mil. Because of the wide gate and drain ends of the transistor, these lines must be fitted to a 50 Ohm impedance value in a multi-staged way. For this purpose, a microstrip line structure was added to the design to match impedance. Because of the high output power (250-Watt) 2 pieces of ATC branded parallel 39pF capacitors which has high power rating were added to the end of the circuit as decoupling capacitor. 10 pF, 100 pF and 1000 pF bypass capacitors were added supply line to the ground end. By this method incoming noises from supply line and leaking noises to supply line were prevented. Sub miniature-A connector was chosen for input side. Type-N connector was chosen for output side because of high level output.

4. Simulation Results

The simulation results are given in this section. Figure-3, indicates the power added efficiency, gain and output power values respect to frequency. Between 2.4 - 2.5 GHz band, the output power is approximately 54 dBm (250 Watt). Power added efficiency is at 65%±1. Gain is shown as approximately 12dB. Because of the high output power of the amplifier, 2nd and other higher degree harmonic levels must be checked to prevent suppressing the communication of other electronic systems such as radars, base stations etc. This amplifier was designed to work between 2.4 – 2.5 GHz frequencies and the amplitudes of the harmonics up to 5th degree are shown in Figure-4. 2nd harmonic is approximately 27 dB lower; 3rd harmonic is 20 dB lower; 4th harmonic is 36 dB lower and lastly 5th harmonic is 33 dB lower than fundamental over the band. In Figure-5, drain current and voltage waveforms of the CGH21240F are given. The current and voltage waveforms are not overlapping so much and this brings the amplifier high-efficiency nature. It can also be said that transistor works as a kind of switch.

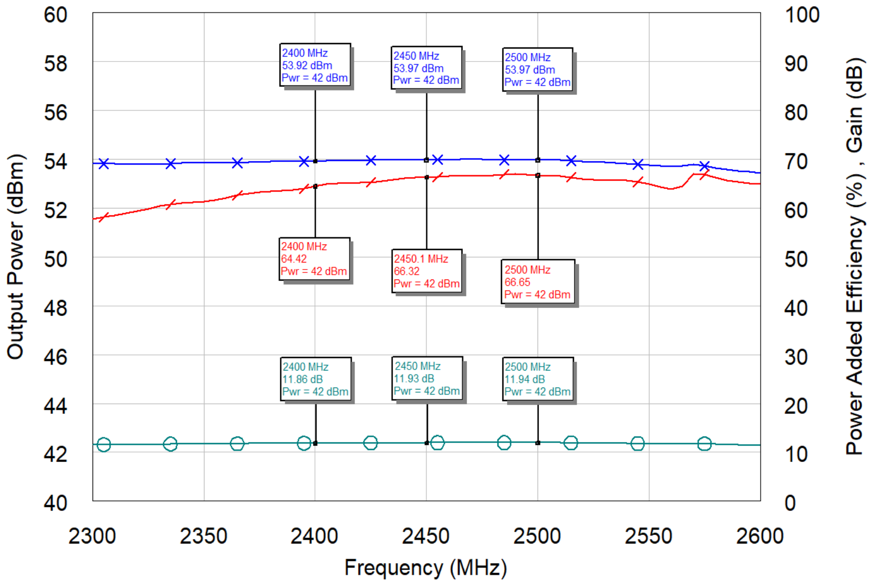

Figure 3: Output Power, Power Added Efficiency and Gain Results.

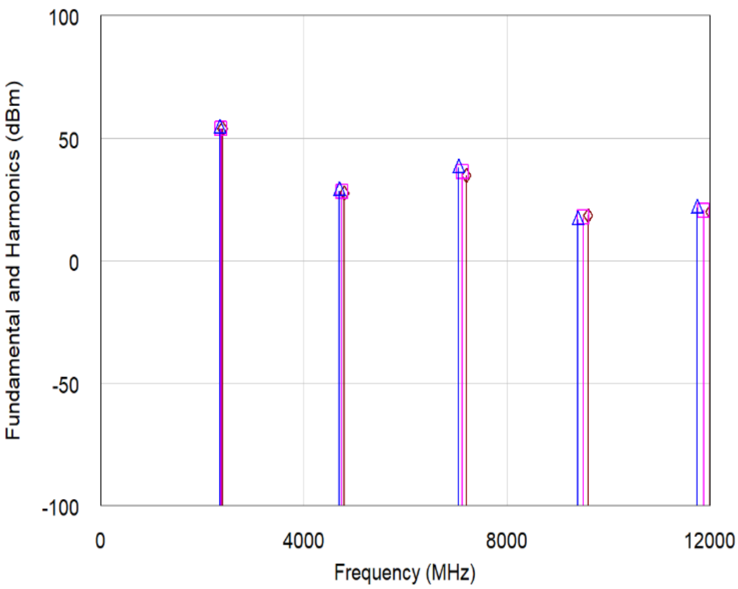

Figure 4: Amplitude of Fundamental and Harmonics Over 2.4-2.5 GHz.

In Figure-6 output power and power added efficiency graph respect to input power is given. When 42 dBm power is applied to the input, transistor enters into saturation region. In this region the efficiency value that could be obtained from the transistor is maximum. When the circuit is operated under this condition, the efficiency value is acquired over 60% and the output power is obtained approximately at 54 dBm.

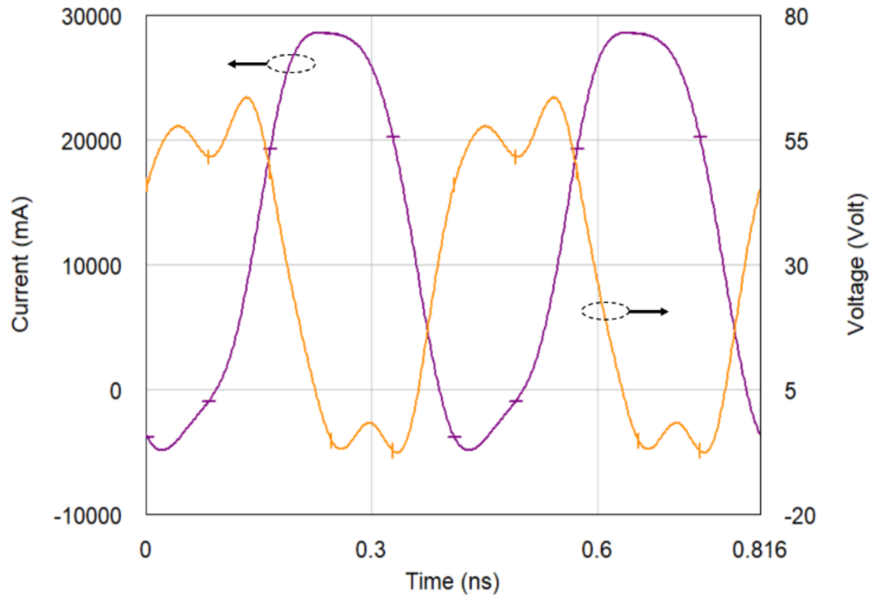

Figure 5: Current and Voltage Waveforms at Drain of GaN HEMT.

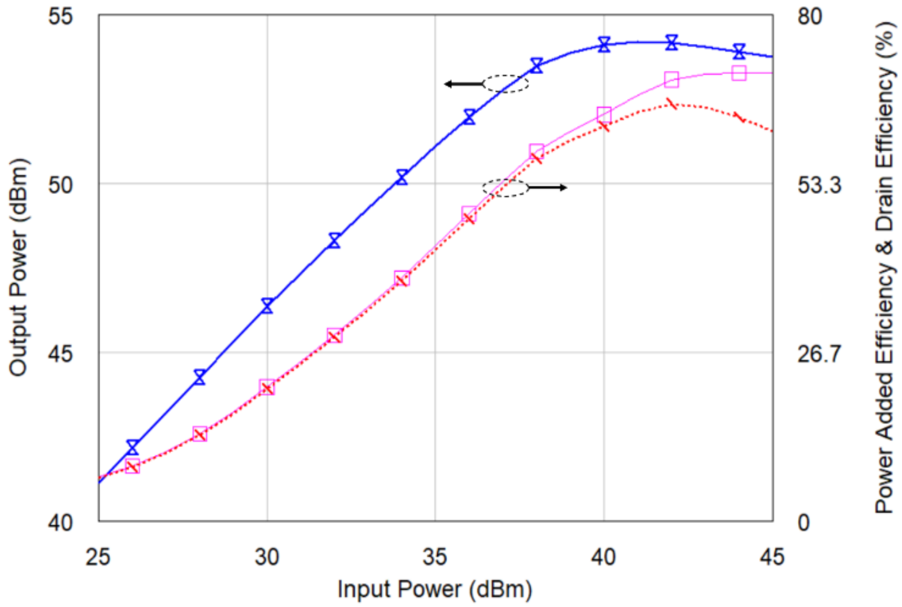

Figure 6: Output Power, Power Added Efficiency and Drain Efficiency.

After the simulation of the circuit, the layout required for production was prepared. The layout of the circuit is given in Figure-7. As seen in the figure, -2V and 28V are applied at the gate and drain terminals of the transistor.

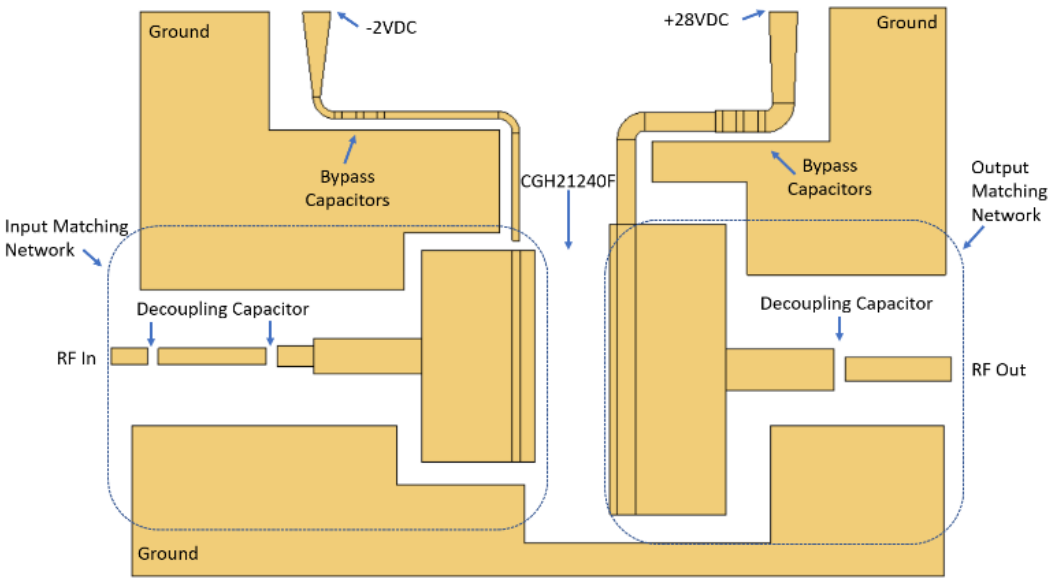

Figure 7: Layout of power amplifier.

Bypass and decoupling capacitors have been added to the supply lines and RF input and output parts. The CGH21240F transistor is placed in the middle. Other parts within the area were left as copper. The dimensions of the circuit are measured as 113x80 mm.

5. Results

This amplifier was prepared to propose an alternative to the currently used magnetron-based systems for use in radio frequency cooking applications. 250W output power was obtained by using Gallium Nitride HEMT instead of magnetron which is a vacuum electronics product. 2.4-2.5 GHz was chosen as the operating frequency. The simulations were made with the AWR Microwave Office program. According to the simulation results, 65±1% power added efficiency, 67±1% drain efficiency, 12 dB gain and 250W+-1 output power were obtained in the 2400-2500 MHz range. Because of the high output power of the amplifier, 2nd and other higher degree harmonic levels must be checked to prevent suppressing the communication of other electronic systems such as radars, base stations etc. 2nd harmonic is approximately 27 dB lower; 3rd harmonic is 20 dB lower; 4th harmonic is 36 dB lower and lastly 5th harmonic is 33 dB lower than fundamental over the band.

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