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Design of L-Band Power Amplifier by Using Microstrip-Based GaAs p-HEMT MMG15241H Transistor

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Abstract – The power amplifier which is designed by using BJT (Bipolar Junction Transistor) has a larger power consumption, hence in this research, the FET GaAs p-HEMT MMG15241H is used. The power amplifier designed in this research uses microstrip-based and works at the middle frequency of 1.27 GHz. This research yielded a power amplifier which works at the bandwidth with a range frequency of 1.265 – 1.275 GHz, a gain result of 20.02 dB, and input return loss result of -24.45 dB.

Keywords – Radio Frequency Communication (RF), L-Band, Power Amplifier, GaAs p-HEMT, BJT.

I. INTRODUCTION

Signal amplification is one of the most commonly used circuits in RF and microwave communication systems. Initially, RF power amplifiers use tubes such as klystron or solid-state reflection power amplifiers based on the negative resistance characteristics from varactor diode. Since the 1970s, the development and innovation of solid-state technology have been conducted. Nowadays, RF and microwave power amplifiers are designed by using transistor devices such as BJT, FET, GaAs HBT, Si MOSFET, GaAs MESFET, GaAs or GaN HEMT because their usage on active and passive components are easy to be integrated [1].

In its implementation to receive signals in the receiver, it requires high-signal transmit power. The Power amplifier is used to increase the signal power because during the transmission process, the signal transmitted by the transmitter pass through excessive obstacles and attenuations found on the transmission media as well as through the air medium.

A power amplifier using BJT need a larger power consumption than using GaAs p-HEMT[1], another advantage of GaAs p-HEMT is to have a higher gain compared to BJT, so in this research using GaAs p-HEMT.

The power amplifier is designed by using amateur radio frequency standard provided by ORARI (Organisasi Radio Amatir Indonesia), with a range of frequency between 1260-1300 MHz which is an L-Band frequency with 10 MHz bandwidth [2]. This range of frequency is widely used for radar applications, one of which is the SAR (Synthetic Aperture Radar) [3].

Research on RF power amplifier has been conducted on [4]-[7], one of the research on power amplifier was performed at the L-Band frequency by using the GaN HEMT transistor component yielding a power output of 45.50 dBm and a gain of 13.50 dB [4]. The design results in high output power but it requires high input power due to the small gain value.

A Research by Prayogo has used the BJT, the design was conducted on two levels and worked on 437.430 MHz frequency by using BJT component in the first level, i.e., BFR96S and BJT component in the second level, i.e., MRF555. The result of the measurements yielded a gain of 28.04 dB with an input power of 0 dBm [5].

Subsequently, the research [6] using FET transistors produced an output power of 43 dBm with a gain of 17 dB and in research [7] produced an output power of 40.70 dBm with a gain of 28.90 dB. Based on the results of the research [4]-[7], BJT has higher gain characteristics than FET but one of the developments from FET, i.e., GaAs pHEMT, has a higher gain than BJT with a small input voltage source and this can be used up to the frequency range of 100 GHz [1]. In its implementation, BJT is used on devices with high input voltage sources and FET is used on devices with small or high voltage sources [8].

Referring to the results of the research [4]-[7], in this research, the power amplifier is designed on one level by using the active component of GaAs (Gallium Arsenide) Pseudomorphic High Electron Mobility Transistor (p-HEMT) MMG15241H with high gain characteristics. The advantage of this transistor is the output power of 24 dBm at 1 dB compression and it has a maximum gain of 1.270 GHz at 20.57 dB.

II. SMALL SIGNAL POWER AMPLIFIER

A. *Power Amplifier*

A Power amplifier is one of the devices used to increase the input signal power in a predetermined range of frequency up to the desired output signal power. Power amplifier receives input power and is amplified to operate a device, therefore the power at the transmitter can be received by the receiver, the system block on the power amplifier can be seen in Fig.1.

The design of a power amplifier required high signal transmit power to receive signal by the receiver. Parameters on the power amplifier which should be concerned are gain, return loss, power amplifier stability factor and output power [9].

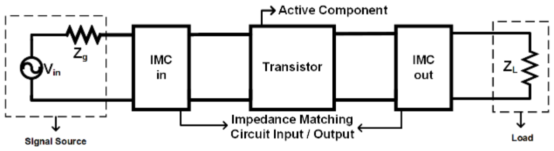

Fig.1. Power Amplifier System Block [9]

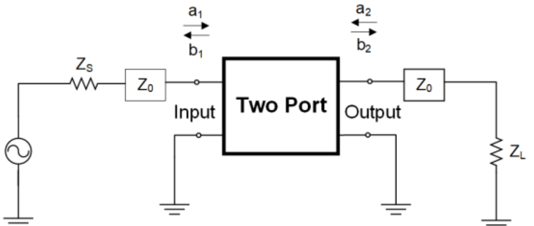

Fig.2. Two-Port of Scattering Parameter [10]

B. *S-Parameter (Scattering)*

Scattering parameter is one of the most commonly used parameters in radio frequency (RF) and microwave circuits. In the design of power amplifiers at high frequencies, scattering parameter is used to obtain the characteristics of transistor performance based on the two-port network. Power amplifier is included in a two-port network device with two poles which are input and output as shown in Fig.2 [10].

C. *Stability Factor*

In designing a power amplifier, stability is required which shows the performance of the transistors in the circuit. The stability of the power amplifier can be determined by calculating the stability factor based on the S parameter obtained from the transistor datasheet used. If the transistor used is unstable, oscillation will occur. In a two-port network, oscillation will occur if the magnitude of the reflected coefficient at the input and the output is greater than $|\Gamma_{IN}| > 1$ or $|\Gamma_{OUT}| > 1$. In the power amplifier stability factor, several frequent definitions of constants used are as follows [9],

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \tag{1}$$

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

From the factors above, we can determine the type and condition of the stability of the power amplifier, which are [9],

a) Unstable condition is a condition when K > 1 and $|\Delta| < 1$. Power amplifier is always stable for a random selection of Γ_S and Γ_L on the Smith chart. In addition, the requirement for an unstable condition is $|\Gamma_{in}| < 1$ or $|\Gamma_{out}| < 1$.
b) Stable condition is a condition when K < 1 and $|\Delta| < 1$. Power amplifier can be stable for certain regions only. Therefore the determination of Γ_S and Γ_L should not be arbitrary. The selection Γ_S and Γ_L are merely in the stable region of the Smith chart.

D. *Power Amplifier Equations*

Power gain on the power amplifier has the following definitions [9],

a) Transducer power gain (G_T) is the ratio of the power absorbed by the load (P_L) towards the available power of the signal source (P_{AVS}).
b) Operating power gain (G_P) is the ratio of the power absorbed by the load (P_L) towards the power which inserts the network or transistor (P_{IN}).
c) Available power gain (G_A) is the ratio of the existing power from the network or transistor (P_{AVN}) towards the power available from the signal source (P_{AVS}).

In absolute stable conditions on the bilateral case where $S_{12} \neq 0$, the transducer power gain will be maximum and the third gain becomes equal $G_{T,MAX} = G_{A,MAX} = G_{P,MAX} = G_{MAX}$ [9],

$$G_{MAX} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right) \tag{3}$$

The gain will be maximized when $\Gamma_S = \Gamma^*_{IN}$ and $\Gamma_L = \Gamma^*_{OUT}$, the source reflection coefficient and the load coefficient are obtained from the following equation [9],

$$\Gamma_S = \Gamma^*_{IN} = \frac{B_1 \pm \sqrt{{B_1}^2 - 4|C_1|^2}}{2C_1} \tag{4}$$

$$\Gamma_L = \Gamma^*_{OUT} = \frac{B_2 \pm \sqrt{{B_2}^2 - 4|C_2|^2}}{2C_2} \tag{5}$$

Where [9],

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 \tag{6}$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 \tag{7}$$

$$C_1 = S_{11} - \Delta {S_{22}}^* \tag{8}$$

$$C_2 = S_{22} - \Delta {S_{11}}^* \tag{9}$$

E. *Microstrip Line*

Microstrip line is a popular type of line used in the design of microwave power amplifiers [11]. The advantages of microstrip line are easy to be miniaturized and easy to be fabricated by using the circuit printing technique [1]. The dimension calculation of microstrip line can be obtained by using the following equation [1],

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12(h/w)}}\right] \tag{10}$$

$$(\lambda_m) = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}} \tag{11}$$

For the ratio of w/h < 2, can be determined using the following equation [1],

$$\frac{w}{h} = \frac{8e^A}{e^{2A} - 2} \tag{12}$$

For the ratio w/h > 2, can be determined using the the following equation [1],

$$\frac{w}{h} = \frac{2}{\pi}\left\{\begin{matrix} B - 1 - \ln(2B - 1) \\ + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B - 1) + 0{,}39 - \frac{0{,}61}{\varepsilon_r}\right] \end{matrix}\right\} \tag{13}$$

Where [1],

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0{,}23 + \frac{0{,}11}{\varepsilon_r}\right) \tag{14}$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \tag{15}$$

F. *Impedance Matching*

Impedance matching is the matching on the transmission line therefore the power will not be reflected, where the transfer of power becomes maximum. A line is said to be matching if the input impedance is equal to the load impedance ($Z_0 = Z_L$). The ideal matching circuit is lossless to avoid unwanted power losses and is designed until the impedance seen in the matching circuit is Z_0 [1]. Fig.3 indicated the concept of an impedance matching circuit.

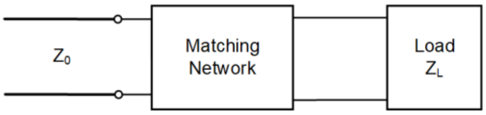

Fig.3. Impedance Matching Circuit [1]

In this design, the impedance matching used is a single stub parallel open circuit because it is simple. The parameters which affect the impedance matching are the length of the stub position of the load impedance (L), the length of the input stub (L_{in}) and the length of the output stub (L_{out}) [1]. Fig.4 indicated an impedance matching circuit using a single stub parallel open circuit.

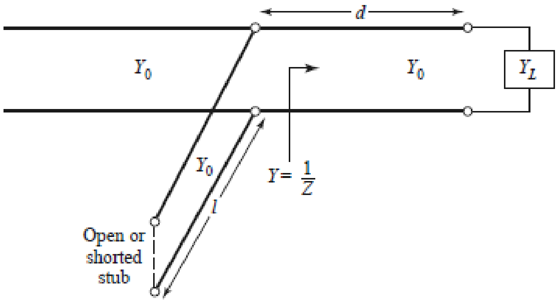

Fig.4. Impedance Matching with Stub Parallel Open Circuit [1]

G. *Power Amplifier and DC Bias Circuit*

An important factor in designing a power amplifier in order to work optimally is to provide a DC bias circuit to the transistor [9]. The transistor is an active component that is applied to work in the active region. The power supply used is DC power supply. Fig.5 indicated the power amplifier circuit scheme and DC bias circuit used in the design of the power amplifier in this research.

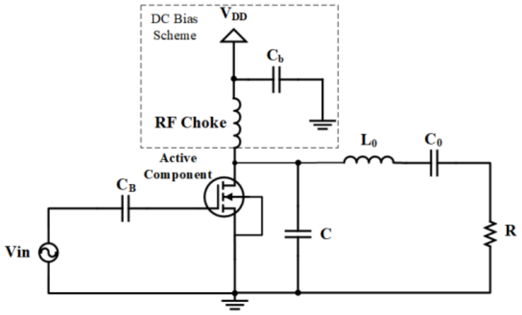

Fig.5. Power Amplifier and DC Bias Circuit [15]

In the power amplifier circuit, value of the capacitor (C) can be determined using the following equation [12],

$$C = \frac{0.685}{\omega R} \quad (16)$$

Where [12],

$$R = 1.365 \frac{V_{dd}{}^2}{P_{out}} \quad (17)$$

L_0 and C_0 series components are obtained by using the equivalence of microstrip line circuit with 50 Ω impedance to the L_0 and C_0 series components. The equivalent circuit of the L_0 and C_0 series components can be seen in Fig.6 [12].

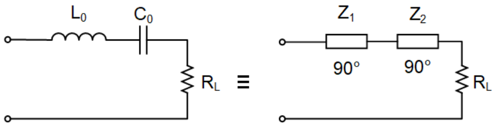

Fig.6. Lumped Element and Microstrip Line Equivalent Circuit [12]

The DC block (C_B) placement at the input section is used to prevent the DC from going out of the bias DC circuit. To prevent the interference of AC signals in bias DC circuits is by using RF choke as shown in Fig.7 [13], while bypass capacitor (C_b) is used to determine the stability point of the power amplifier. The DC block value is obtained by using the following equation [10],

$$C_B = \frac{1}{2\pi f X_c}, \text{ where } X_c \leq \frac{Z_0}{10} \quad (18)$$

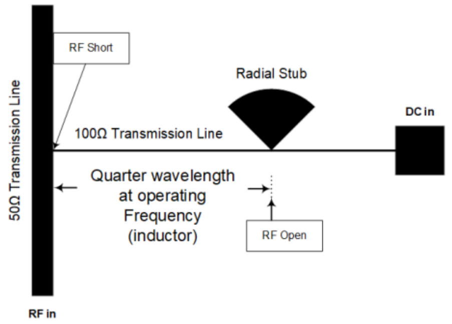

Fig.7. RF Choke Model [13]

III. DESIGN OF POWER AMPLIFIER

A. *Power Amplifier Specifications*

The design of this power amplifier uses the FR4 epoxy substrate with substrate thickness characteristics of 1.6 mm, the conductor thickness of 0.035 mm and dielectric constant of 4.3.

The power amplifier specifications designed as follows [3],

a) Operation Frequency : 1.265 – 1.275 GHz
b) Central Frequency : 1.270 GHz
c) Input Power : 0 dBm
d) Output Power : 20 dBm
e) Gain : 20 dB
f) Impedance : 50 Ω
g) Return Loss : ≤ -10 dB

B. *Transistor Selection*

Power amplifier is designed by using the active components of GaAs p-HEMT MMG15241H. The transistor is capable of operation in the frequency range of 0.5 to 2.8 GHz, with output power characteristics of 24 dBm at 1 dB compression at a frequency of 0.9 GHz and a small signal gain of 20.50 dB at 0.9 GHz, whereas at 1.270 GHz frequency the maximum gain is 20.57 dB [14].

C. *S-Parameter and Stability Factor*

S-parameter values are obtained from the simulation results by using ADS because the datasheet does not mention the S-parameter value for the frequency of 1.270 GHz. The result of simulation on S-parameter at the operation frequency of 1.270 GHz can be seen in Fig.8.

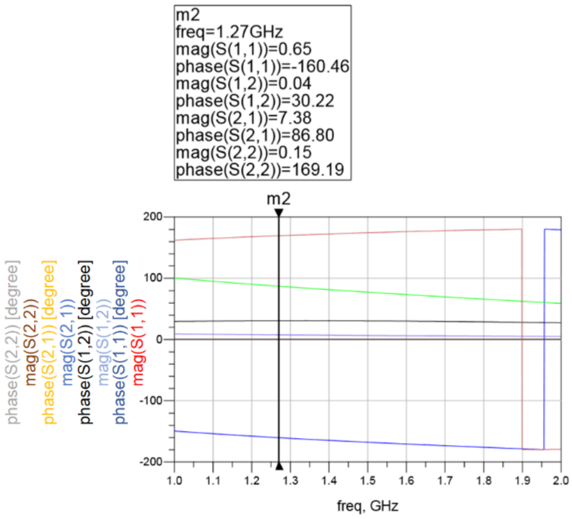

Fig.8. S-Parameter Simulation Result

At the frequency of 1.270 GHz, the S parameter value obtained are as follows,

$S_{11} = 0.65 \angle 160.46^{\circ}$
$S_{12} = 0.04 \angle 30.22^{\circ}$
$S_{21} = 7.38 \angle 86.80^{\circ}$
$S_{22} = 0.15 \angle 169.19^{\circ}$

By using (1) and (2) then the stability of the power amplifier can be obtained with the value of $|\Delta| = 0.38$ and K = 1.19, while the simulation result of stability factor by using ADS is shown in Fig.9 and obtained the value of K = 1.08 so that the active component is unstable condition and all the regions within the circle of smitch chart are stable region.

D. *Power Gain Calculation*

The design of the power amplifier under the unstable condition, $K > 1$ and $|\Delta| < 1$ wherein bilateral case of $S_{12} \neq 0$, therefore G_{MAX} is obtained according to (3) of 20.02 dB. Besides using (3), the G_{MAX} value can be determined by using simulations in ADS as shown in Fig.9, therefore simulation results obtained the G_{MAX} values of 20.56 dB.

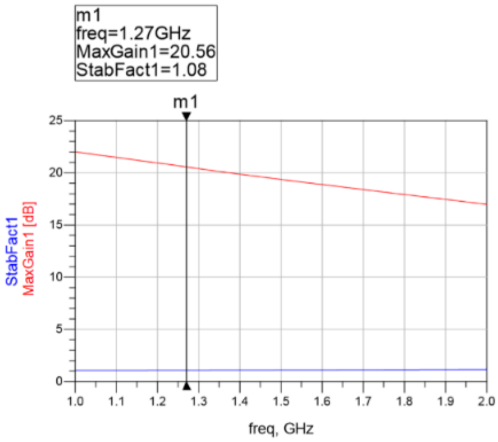

Fig.9. Maximum Gain and Stability Factor Simulation

E. *Microstrip Line Calculation*

By using (12) and (14) the width value (W_1) of the microstrip line obtained a value of 3.11 mm. In addition to (12), the width (W_1) and length (L_2) of the microstrip line can be determined by using Line Calculation ADS, therefore the value of width (W_1) and length (L_2) of microstrip line are 3.07 mm and 2.62 mm.

Results obtained from the Line Calculation ADS have a higher level of accuracy by considering the parameters based on the substrate specifications and theoretical parameters on microstrip line dimension calculations, therefore the value used in the design is the value obtained from the Line Calculation ADS.

F. *Impedance Matching Calculation*

In determining the impedance matching, the value of input matching impedance (Z_S) and output matching impedance (Z_L) must be calculated first. Using (4) and (5) in stable conditions on the bilateral case obtained the values of $\Gamma_S = 0.97 \angle 146.28°$ and $\Gamma_L = 0.21 \angle -169.81°$.

By inserting Γ_S and Γ_L into the following equation [1],

$$Z_S = Z_0 \frac{1+\Gamma_S}{1-\Gamma_S} \tag{19}$$

$$Z_L = Z_0 \frac{1+\Gamma_L}{1-\Gamma_L} \tag{20}$$

From the calculation, the values obtained are Z_S = 0.97 + j 15.15 and Z_L = 32.61 – j 2.57 so the length of input microstrip line (L_1), the length of input stub (L_{in}), the length of output line (L_6), and the length of output stub (L_{out}) can be determined with the value of (L_1) = 0.03λ, (L_{in}) = 0.27λ, (L_6) = 0.12λ and (L_{out}) = 0.06λ and the results are needed to prevent the reflection and to obtain the desired return loss value.

Based on (10) and (11), the value of the microstrip line wavelength is 130.71 mm, the length of input line (L_1) = 3.67 mm and the length of input stub (L_{in}) = 35.20 mm, then the length of output line (L_6) = 15.68 mm and the length of output stub (L_{out}) = 8.29 mm.

G. *Power Amplifier and DC Bias Circuit Calculation*

In the power amplifier circuit, the value of C is determined by using (16) and (17), the C value of 0.5 pF was obtained. Whereas, the equivalence of the microstrip line towards the L_0 and C_0 series components is determined using Line Calculation ADS, so that the width (W_1) and length (L_4) of the microstrip line for L_0 component are W_1 = 3.07 mm and L_4 = 32.73 mm, then width (W_1) and length (L_5) of microstrip line for C_0 component are W_1 = 3.07 mm and L_5 = 32.73 mm.

In DC bias circuit, DC block (C_B) value is determined by using (18), so the DC block (C_B) value obtained 27 pF, and RF choke value can be determined by using Line Calculation ADS, then RF choke obtained with the value of W_2 = 0.73 mm and L_9 = 2.74 mm, then the value of microstrip line with the impedance of 100 Ω in RF choke obtained W_2 = 0.73 mm and L_7 = 32.73 mm. At the datasheet, the bypass capacitor value (C_b) and V_{DD} value have been obtained, therefore the DC bias circuit used the V_{DD} value of 5 Volt and bypass capacitor value (C_b) of 56 pF.

After checking the power amplifier stability, microstrip line dimension, DC bias circuit, and impedance matching, the power amplifier design is then performed in the simulation phase of the initial design on the circuit using ADS software. The simulation results of circuit shown in Fig.10.

IV. RESULT

Based on the simulation result of calculation dimension in Fig.11, the stability factor of the power amplifier is 1.40, it shows that the active component is in an unstable condition (K > 1), and in Fig.11 the gain value obtained at 1.27 GHz frequency is equal to 7.94 dB.

Considering the simulation results of the power amplifier circuit shown in Fig.12 and 13, input return loss (S_{11}) and output return loss (S_{22}) parameters at 1.27 GHz frequencies obtained with the value of S_{11} = -0.61 dB and S_{22} = -3.94 dB, these results are not in accordance with the desired specifications so that the optimization of the simulation circuit and obtained a comparison of the dimensions of the calculation results and optimization result dimensions as shown in Table 1.

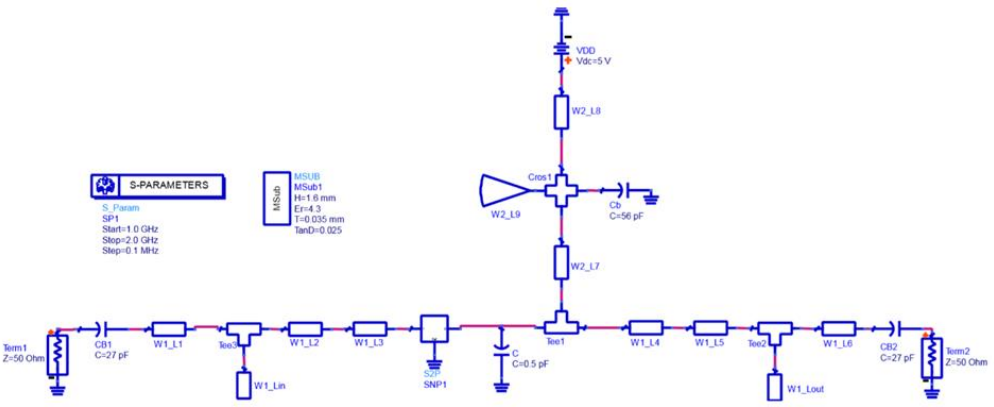

Fig.10. Power Amplifier Simulation Circuit

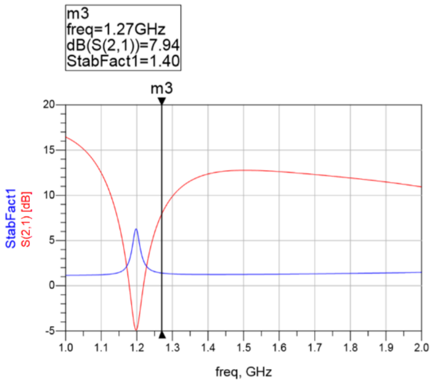

Fig.11. Gain and Stability Factor Simulation Result

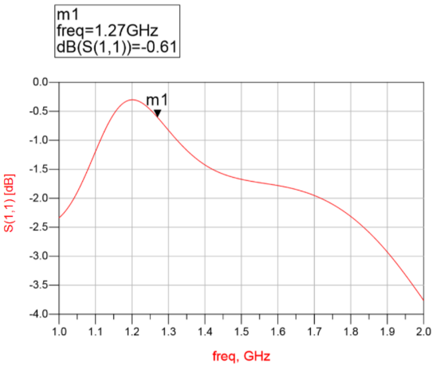

Fig.12. Input Return Loss Simulation Result

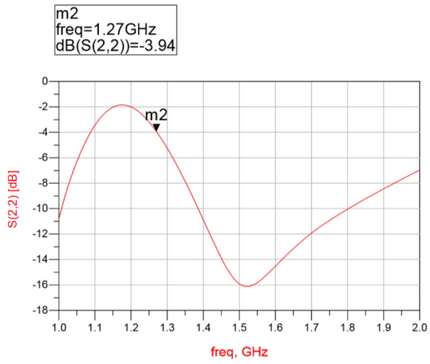

Fig.83. Output Return Loss Simulation Result

Table 1. Calculation and Optimization Dimensions

Parameter	Symbol	Calculation Result Dimension (mm)	Optimization Result Dimension (mm)
Microstrip Line Width of 50 Ω	W1	3.07	4.37
Microstrip Line Width of 100 Ω	W2	0.73	1.78
Input Microstrip Line Length	L1	56.60	0.51
Microstrip Line Length of 50 Ω	L2	2.62	10.42
Microstrip Line Length of 50 Ω	L3	2.62	2.10
Microstrip Line Length of L_0	L4	32.73	1.43
Microstrip Line Length of C_0	L5	32.73	0.74
Output Microstrip Line Length	L6	15.40	0.75
Microstrip Line Length of 100 Ω	L7	32.73	9.38
Microstrip Line Length of 100 Ω	L8	32.73	9.64
Microstrip Line Length of Radial Stub	L9	2.74	6.79
Input Stub Length	Lin	35.20	22.41
Output Stub Length	Lout	8.29	3.80

Based on the results of the optimization conducted at 1.27 GHz, obtain the value of input return loss shown in Fig.14 with the value of S_{11} = -24.45 dB and the output return loss shown in Fig.15 with the value of S_{22} = -23.32 dB.

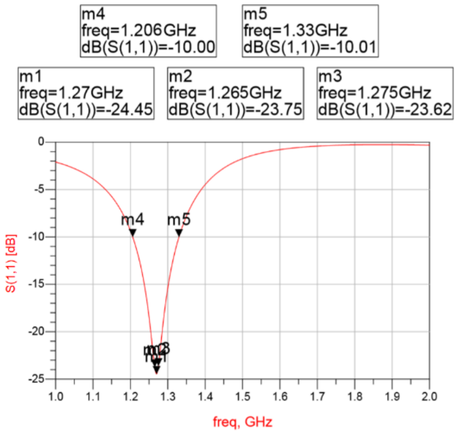

Fig.94. Input Return Loss Optimization Result

The result on the parameter of gain and stability factor of the power amplifier is shown in Fig.16, the gain parameter value is 20.02 dB with a stability factor of 1.14.

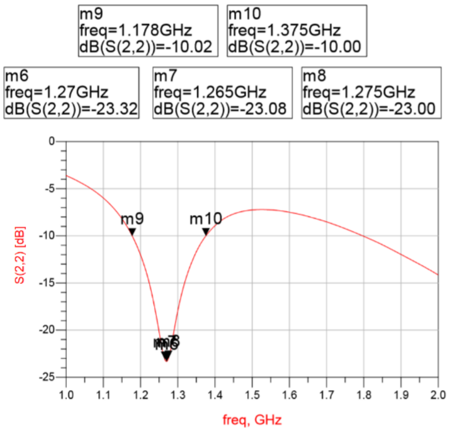

Fig.105. Output Return Loss Optimization Result

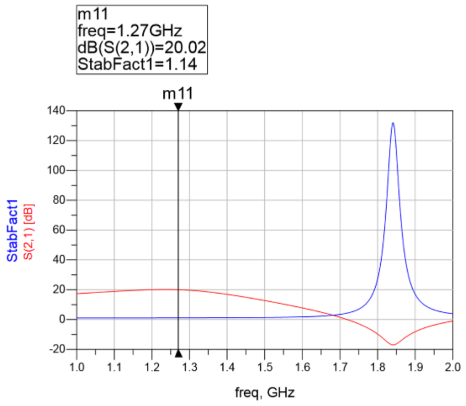

Fig.116. Gain and Stability Factor Optimization Results

V. DISCUSSION

Considering the simulation results of the power amplifier circuit, these results show that the best performance of the power amplifier at 1 GHz. The result of gain at 1 GHz is better than frequency operation at 1.27 GHz with the value of gain at 1 GHz is about 16 dB.

Then, the results of the optimization shown in Fig.14 and 15 indicate that the minimum reflected power value attributed to the port 1 as input and the maximum power value at port 2 as output. The results of the optimization show that the best performance of the power amplifier at 1.27 GHz.

Based on the result of gain parameter shown in Fig.16, so that the gain has reached the optimum result by giving a gain of 20.02 times greater than ac power input, and then with a power input of 0 dBm, power output obtained 20.02 dBm

The bandwidth is shown based on the S_{11} parameter at the frequency of 1.265 GHz with the value of $S_{11} = -23.75$ dB and at the frequency of 1.275 GHz with the value of $S_{22} = -23.62$ dB, if the results of S_{11} parameter less than -10 dB then the frequency is in the range of 1.206 GHz – 1.33 GHz so the bandwidth obtained at 124 MHz. The optimization results are in accordance with the desired specifications for designing a power amplifier.

VI. CONCLUSION

Based on the results of this power amplifier design, it can be concluded that L-Band power amplifier can be designed by using GaAs p-HEMT MMG15241H transistors in an unstable condition ($|\Delta| < 1$ and $K > 1$). Power amplifier can work in the frequency range of 1.265 – 1.275 GHz with the central frequency of 1.270 GHz, therefore the value of input return loss (S_{11}) of -24.45 dB, output return loss (S_{22}) of -23.32 dB, gain of 20.02 dB and output power of 20.02 dBm were obtained. The bandwidths in the frequency range of 1.265-1.275 GHz obtained the S_{11} values of -23.75 dB and -23.62 dB respectively.

In this research, load-pull simulation was not used to determine the load that used before the matching condition. Therefore, as a continuation of this research, load-pull simulation should be used to determine the appropriate load. Then, for the transistor model, use the transistor model that have a library on the software.

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