LNA Prototype at 54 MHz to 88 MHz Using Discrete Components

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Abstract—This paper presents a design and prototyping of a Low-Noise Amplifier (LNA) for Wireless Regional Area Network (WRAN) operating in TV broadcast bands between 54 MHz – 88 MHz. The LNA design was then implemented by using discrete components. Components values was obtained by utilized DC analysis according to specifications which follows the Institute of Electrical and Electronics Engineering (IEEE) 802.22 standard on WRAN technical specifications. Simulation with 88 MHz produced S_{11} = -5.72 dB, S_{12} = -41.57 dB, S_{21} = 15.07 dB, S_{22} = -4.76 dB, Noise Figure (NF) = 3.9 dB, Input Third Order Intercept Point (IIP3) = 2.21 dBm, and power consumption of 45.39 mW. Experiments results on 88 MHz showed S_{11} = -6.13 dB and S_{21} = 0.74 dB.

Keywords—Low-Noise Amplifier, LNA, WRAN.

I. INTRODUCTION

In Indonesia's rural area, internet connectivity is severe [1]. Wireless Regional Area Networks (WRAN) is a one of a good choice to overcome that problem [2]. WRAN is an IEEE networking technology standard for Very High Frequency (VHF) and Ultra High Frequency (UHF) band [3]. VHF has a frequency range between 30 MHz - 300 MHz. In Indonesia, VHF is divided into two parts, VHF band I (47 MHz – 68 MHz) and VHF band III (174 MHz – 230 MHz). Each channel has a frequency width of 7 MHz. All of VHF channel are utilized by TVRI, an Indonesian state television service, but only VHF band III [4]. The unused channels of Band I can be referred to as TV White Spaces (TVWS). This TVWS reach is very suitable to overcome the internet gaps occurring in Indonesia.

However, in its use, not all devices can be used in TVWS which need suitable receivers. A Low Noise Amplifier (LNA) play a key role in a receiver. Performance of a receiver is depend on its LNA circuit [5]. This paper design and prototyping LNA which can be used in WRAN that operating in TVWS at frequency of 54 MHz – 88 MHz.

The standard technology developed for WRAN in TVWS is IEEE 802.22. LNA device specifications which close to IEEE 802.22 standard should have gain ≥ 14 dB, noise figure ≤ 5 dB, input matching ≤ -5 dB, output matching ≤ -5 dB, IIP3 ≥ -5 dBm, and power consumption ≤ 100 mW [6].

II. LNA PARAMETERS

A. Gain

Gain is the ratio between output signals and input signals, indicating the number of signals that can be amplified. Voltage

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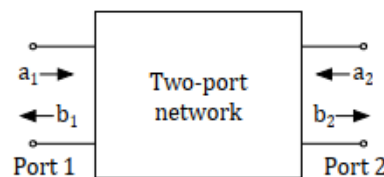
Fig. 1 S-parameters [7].

gain is the ratio between output voltage and input voltage whose equation is shown in (1) [7].

$$A_v = |20 \log \frac{Vo}{Vi} dB|. \tag{1}$$

Another gain is the power (power gain), which has a formula as in (2) [7].

$$A_p = |10 \log \frac{Po}{Pi} dB|. \tag{2}$$

B. Scattering-Parameters

Scattering-parameters is a parameter commonly used to describe two-port networks at high frequencies. These two network ports describe the reflected signals (reflection), both in input and output.

In Fig. 1, a_1 and a_2 are incident waves, while b_1 and b_2 are reflective signals. These reflective signals b_1 and b_2 contribute to scattering the signals on two-port networks, so they are called scattering parameters. The relationship between a_1, a_2, b_1, and b_2 is as follows [7].

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} x \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}. \tag{3}$$

From (3), the following equations can be obtained.

$$b_1 = S_{11}a_1 + S_{12}a_2 \tag{4}$$

$$b_2 = S_{21}a_1 + S_{22}a_2 \tag{5}$$

$$S_{11} = \frac{b_1}{a_1}, a_2 = 0 \tag{6}$$

$$S_{12} = \frac{b_1}{a_2}, a_1 = 0 \tag{7}$$

$$S_{21} = \frac{b_2}{a_1}, a_2 = 0 \tag{8}$$

$$S_{22} = \frac{b_2}{a_2}, a_1 = 0. \tag{9}$$

Each parameter in the S-parameters can be described as follows [8].

S_{11} = a reflection coefficient input, the number of signals reflected on the input resulting in the main signal weakening.
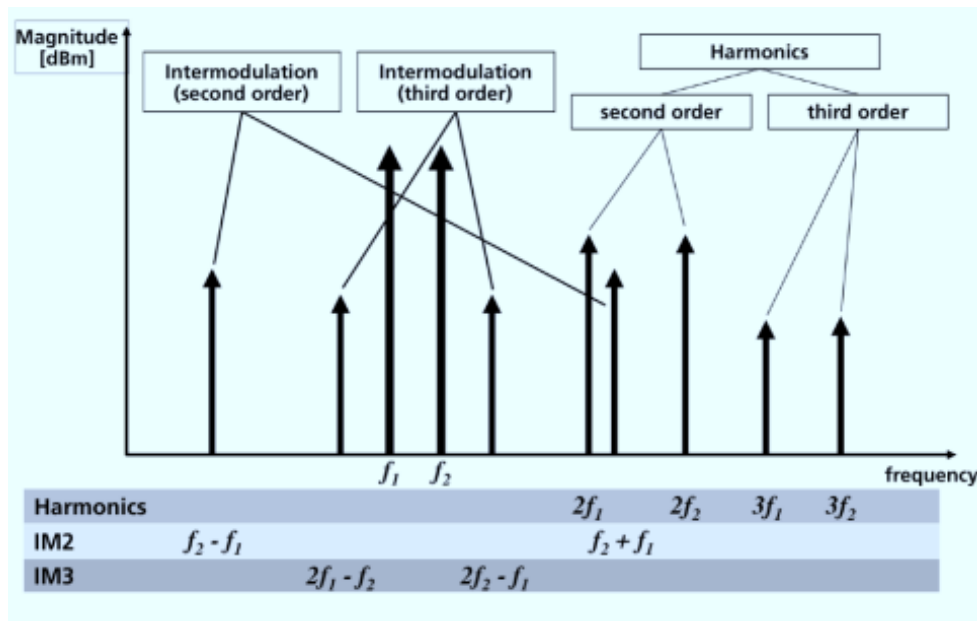
Fig. 2 Intermodulation product [6].

S_{12} = reverse voltage gain, the number of signals reflected and spread on both input and output ports.

S_{21} = forward voltage gain, the number of successfully amplified signals passing the input port to the output port.

S_{22} = the reflection coefficient output, the number of signals reflected in the output resulting in the weakening of the main signal.

C. Noise Figure and Noise Factor

Noise Factor (F) is a parameter on the LNA showing how much noise is added to the main signal. Those added noises are the ratio between Signal to Noise ratio on the input and output. SNR itself is the ratio between the main signal and the resulted noise. From noise factor calculations, it can be noted that the LNA design works to or not to suppress the noise. Noise figure, NF, is a noise factor in decibel (dB) [7].

$$F = \frac{SNR_{in}}{SNR_{out}} \qquad (10)$$

$$NF = 10\log(F). \qquad (11)$$

For other calculations, the obtained NF value is as in (12) [9].

$$NF = 10\log(Vn_{in}^2/4xkxRxT) \qquad (12)$$

with
Vn_{in} = noise on inputs that come with the main signal
k = Boltzman constant (1.38 x 10^{-23})
R = impedance on input (50 Ω)
T = maximum temperature on the system (300 K).

D. Linearity

A system that is not linear or low in its linearity will result in defective signals or distortions on the signals. The distortion occurring in these signals is caused by the use of active components such as transistors. IP3 is a parameter to find out the influence magnitude of the Third Order Intermodulation Product (IM3) against the main signal. The IM3 causes distortion on the main signal, so it should be avoided [3]. Intermodulation product is shown in Fig. 2.

Signals from the transmitters with different frequencies that have been amplified or received in the receiver produce the signals themselves and the signals distortions close to the main signals, which obstruct the main signals. These signals are complicated to eliminate, so the LNA design needs to pay attention to IP3 as the main parameter.

To calculate the output-IP3 (OIP3), (13) is employed [10].

$$OIP3 = 10\log(Vce(V)x\ Ic_{Total}(mA)x\ 5). \qquad (13)$$

Or it can also use the (14) [5].

$$OIP3 = Av_s + 0{,}5\ x(\ Pout - IP3) \qquad (14)$$

with

$$P_s = 20\ log\left(\frac{Vp_{in}\ (rms)}{224\ mV}\right) \qquad (15)$$

and the relationship between OIP3 and IIP3 is

$$IIP3 = OIP3 - Gain. \qquad (16)$$

III. LNA TOPOLOGY

A. Common-Source (CS) and Common-Emitter (CE)

Common-Source (CS) and Common-Emitter (CE) are topologies commonly used on LNA. CS and CE topology is shown in Fig. 3. This topology is often used as an input stage on LNA. It has a high gain value and low noise [11]. If in this topology, an inductor is added in the source or emitter, this inductor will take effect on the gain and noise values. Generally, this topology is combined with cascode topology and negative feedback. In Fig. 4 and Fig. 5, the small-signal analysis for CE and CS is presented. The weakness of this topology is that it
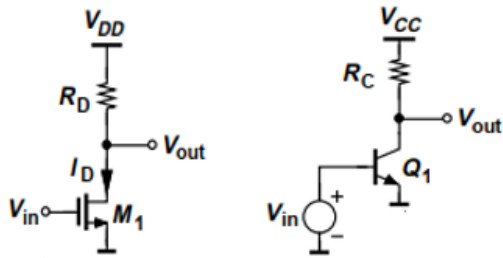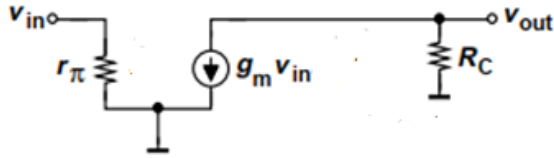
Fig. 3 CS and CE stage [12].
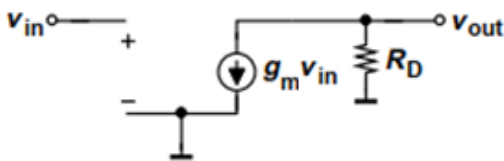

Fig. 4 Small signal analysis on CE stage [12].

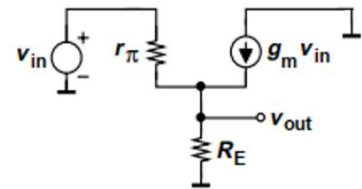
Fig. 5 Small signal analysis on CS stage [12].

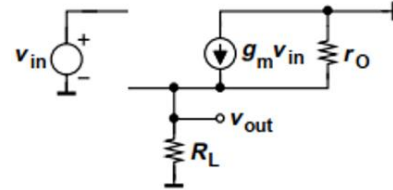Fig. 6 Small signal analysis on CD stage [12].

Fig. 7 Small signal analysis on CC stage [12].
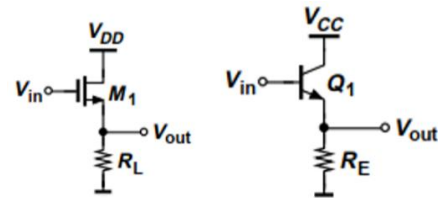
Fig. 8 CD and CC stage [12].

TABLE I
LNA SPECIFICATION BASED ON IEEE 802.22 [2]

Parameters	Values
Gain (S_{21})	≥ 14 dB
Input Matching (S_{11})	≤ -3 dB
Output Matching (S_{22})	≤ -3 dB
Isolation (S_{12})	≤ 0 dB
Noise Figure	≤ 5 dB
Input Third Order Intercept Point (IIP3)	≥ -5 dBm
Power Consumption	≤ 100 mW
V_{CC}	3 V
Bandwidth	34 MHz

requires additional components to obtain suitable input matching values [11].

For BJT:

$$V_{in} = V_{\pi} \qquad (17)$$

so that

$$A_v = \frac{V_{out}}{V_{in}} = -g_m R_C = -\frac{I_C}{V_T} R_C \text{ (ac analysis)} \qquad (18)$$

$$A_v = \frac{R_{out}}{R_{in}} = -\frac{R_{in}}{Z_{in}} \text{ (dc analysis).} \qquad (19)$$

For FET:

$$-\frac{2I_D}{V_{ov}} R_D A_v = \frac{V_{out}}{V_{in}} = -g_m R_D \text{ (ac analysis)} \qquad (20)$$

$$A_v = \frac{R_{out}}{R_{in}} = -\frac{R_D}{Z_{in}} \text{ (dc analysis).} \qquad (21)$$

B. Common-Drain (CD) and Common-Collector (CC)

This topology has two functions, as buffer and adder. Buffer is used to amplify the current without any voltage gain so that the voltage at the output is equal to the voltage at the input (unity gain). Whereas adder adds two different signals, namely, signals on the input and signals on the drain or collector [7]. This topology function as an adder is often used in the noise cancellation technique. One of the advantages of using this topology is the output impedance value that will not decrease if there is a load; therefore, it is more stable. This topology is generally used at the output stage. The form of a small signal analysis is shown in Fig. 6 and Fig. 7. This CD and CC topology can use FET or BJT transistors, as shown in Fig. 8.

For BJT:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{1}{1 + \frac{r_\pi}{\beta + 1} \times \frac{1}{R_E}} = \frac{R_E}{R_E + 1/g_m} \text{ (ac and dc analysis)} \qquad (22)$$

$$\frac{1}{g_m} = \frac{I_C}{V_T} = re \qquad (23)$$

assuming $I_C \cong I_E$.

For FET:

$$V_{out} = g_m V_{in} (ro || R_L) \qquad (24)$$

$$V_{in} = V_{GS} + V_{out} \qquad (25)$$

so that

$$A_v = \frac{V_{out}}{V_{in}} = \frac{g_m (r_0 || R_L)}{1 + g_m (r_0 || R_L)} = \frac{r_0 || R_L}{1/g_m + r_0 || R_L}. \qquad (26)$$

IV. METHODOLOGY

The LNA design was carried out by dc analysis to determine the value of the utilized components. The employed method was reverse engineering. The value determination of the series
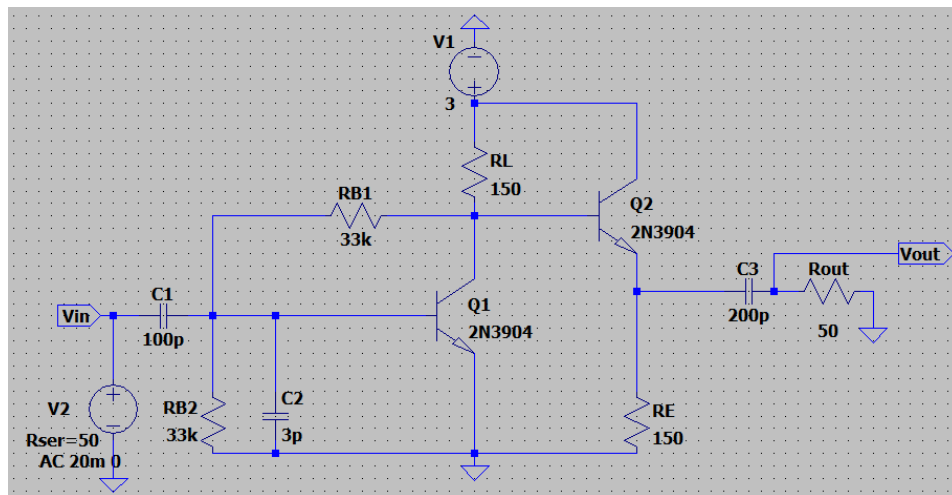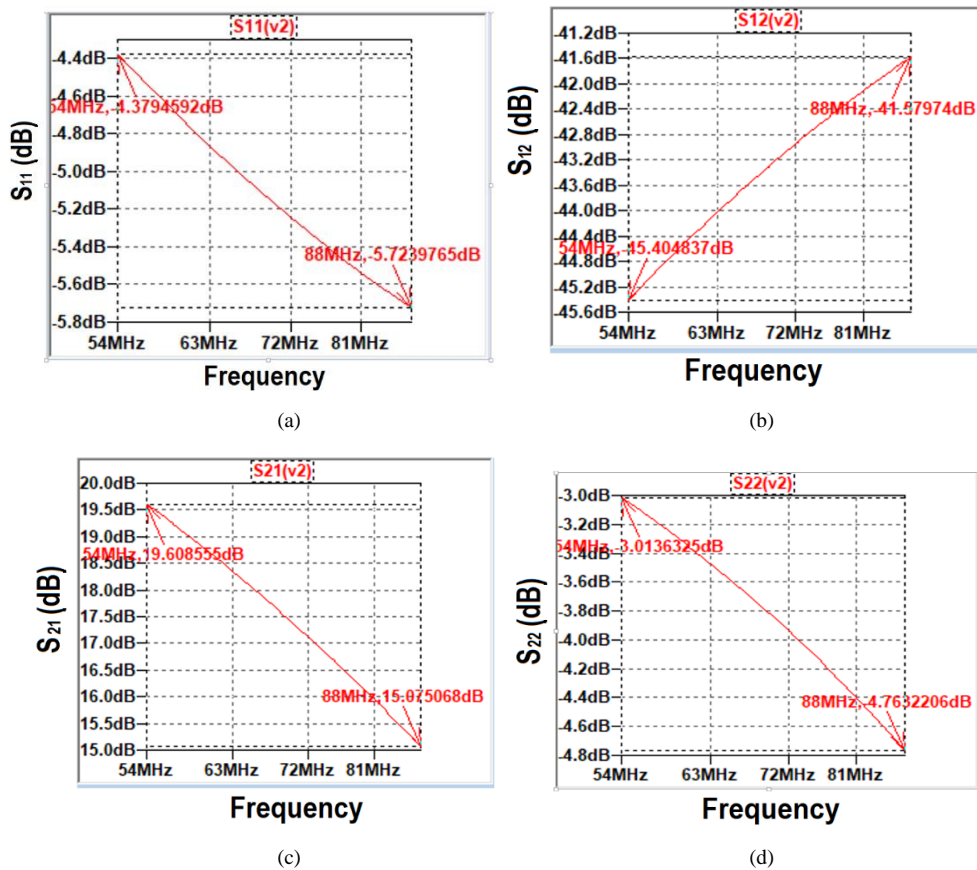
Fig. 9 LNA Circuit.

Fig. 10 S-parameters, (a) $S11$, (b) $S12$, (c) $S21$, (d) $S22$.

was based on the LNA specification made with IEEE 802.22 standard. Table I shows the values of the designed LNA parameters. Proposed LNA circuit is shown in Fig. 9 [13].

V. Discussions and Analysis

This section discusses and displays the simulation results based on the methods described earlier. The simulation was carried out with LTSpice XVII and the ELVIS II+ NI tool, as well as the TINY MiniVNA.

A. S-Parameters Simulation Results

The results of the S-Parameters simulation are shown in Fig. 10. The simulation results for $S11$ is -5.72 dB. It indicates that the signals reflecting from the LNA inputs to the antenna are very insignificant. The lower the $S11$ value, the signal reflected from the input to the antenna is getting smaller, and this is called input matching. The better the input matching, the more signal is transmitted, because of the low reflecting signals. This
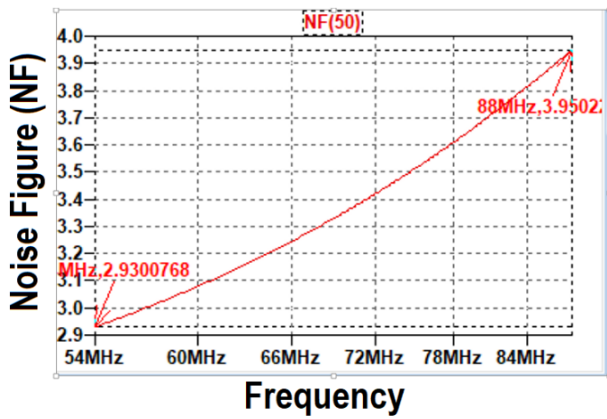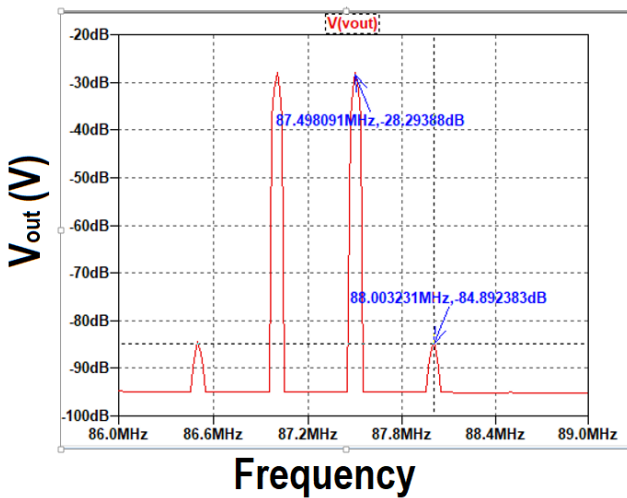
Fig. 11 Noise figure simulation results.

Fig. 12 Simulation results of IIP3.

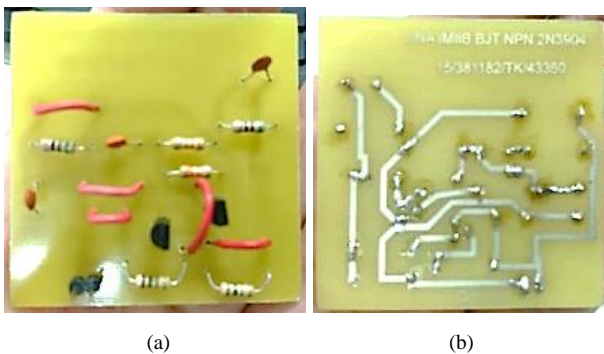

Fig. 13 Simulation results of DC Opt.

Fig. 14 Prototype 1 without SMA connector, (a) top view, (b) bottom view.

$S11$ result corresponds to the specification, which is $\leq$ -3 dB. From the simulation to $S12$, obtained a result of -41.57 dB. It shows low isolation between the output and input. In other words, the signal passing or returning to the input from the output is minimal so that the scattered signal from the output to
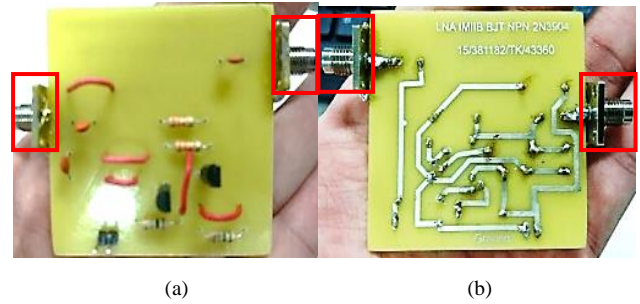

Fig. 15 Prototype 12 with SMA connector, (a) top view, (b) bottom view.
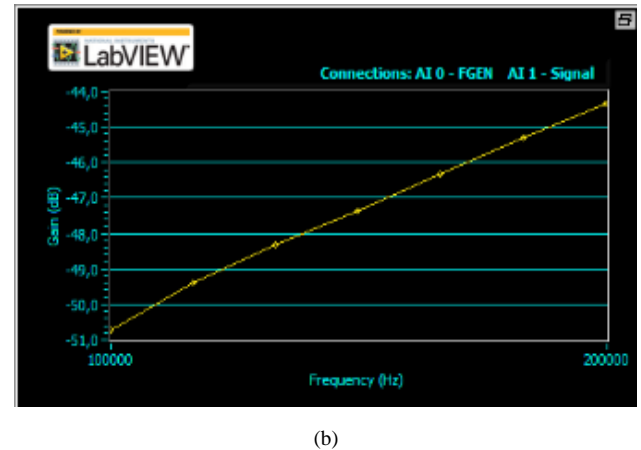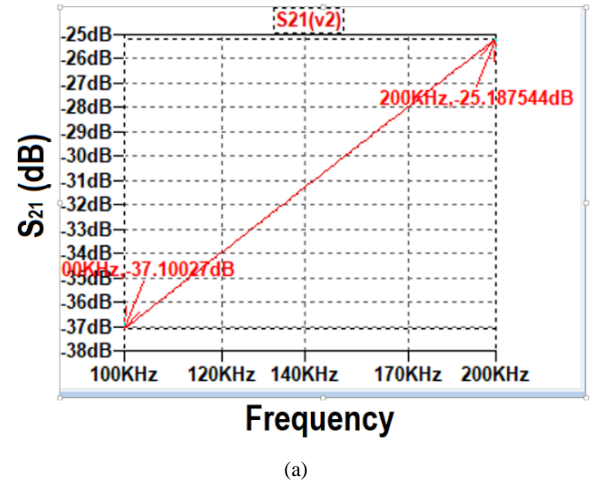

(a)

(b)

Fig. 16 The test results, (a) using LTSpice XVII, (b) using NI ELVIS II+.

the input is not significant. This $S12$ result corresponds with the specifications, which is $\leq$ 0 dB. The simulation result of $S21$ is 15.07 dB. It indicates that reinforcement occurs more than 5 times. The result is relevant because the value is greater than 14 dB, so it meets the specifications. The obtained result from the $S22$ simulation is -4.76 dB. This indicates that signal reflected in the output has a low value so that the signal is generated maximally. It is called output matching. This $S22$ result corresponds with the specifications, which are $\leq$ -3 dB.

B. Noise Figure Simulation Results

Results of the noise figure simulation are presented in Fig. 11. From the chart above, it can be seen that the frequency value
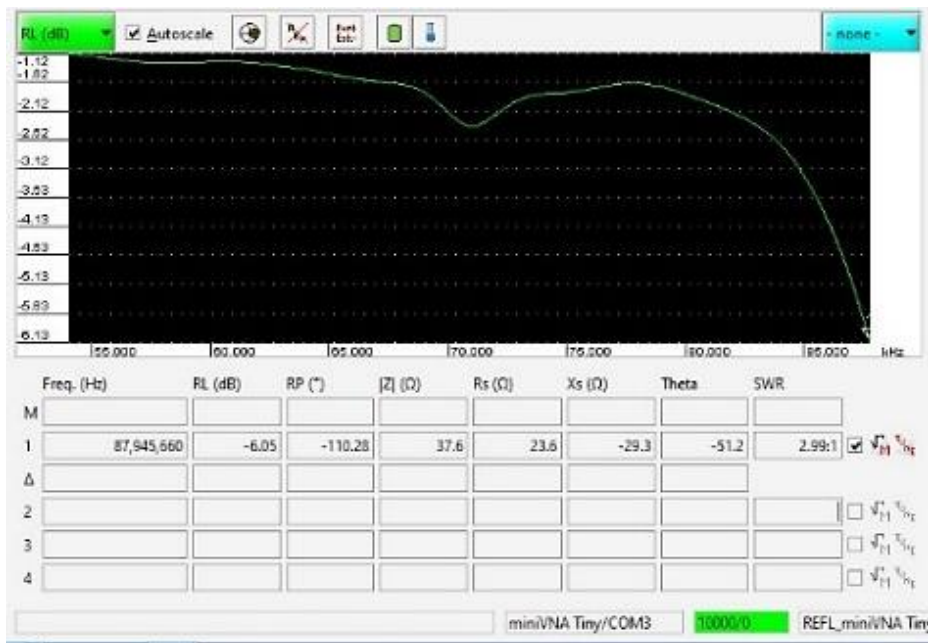
(a)
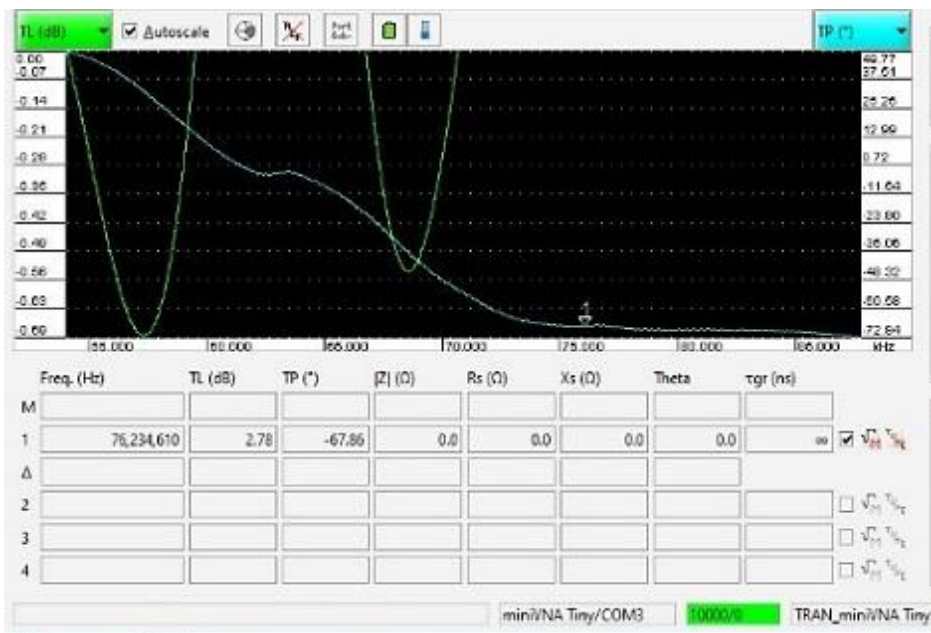
(b)

Fig. 17 Test results using MiniVNA TINY, (a) $S11$, (b) $S21$.

is proportional to the high noise value. A value of 2.9 dB is obtained at a frequency of 54 MHz, and a value of 3.9 dB is obtained at 88 MHz frequency. The result on the frequency of 54 MHz – 88 MHz corresponds to the specification, which is a maximum of 5 dB. The noise figure indicates the noise magnitude present in the main signal, so this value should be as small as possible.

C. IIP3 Simulation Results

The simulation results for IIP3 used a 20 mV input signal with a 500 kHz bandwidth. The simulation results are shown in

Fig. 12. In order to determine the IP3 value, the simulation had to be converted into a Fast Fourier Transform (FFT) form. In this simulation, the sample point value of 131077 with a 0–20 μs period was used. After the results appear, it was necessary to set the frequency range between 86 MHz to 89 MHz (x-axis) and the range of dB values (y-axis) between -30 dB to -130 dB. It needed to be carried out to obtain the desired result, which was the main signal (*Pout*) and IP3 product which results can be seen in Fig. 12. In the main signal simulation, the value of -28.1 dB was obtained at frequencies of 87 MHz and 87.5 MHz. Whereas for the IP3 product, the -84.6 dB was obtained at

Parameters	IEEE 802.22	LTSpice	Prototype 1 (200 kHz)	Prototype 2 (88 MHz)
Gain (S_{21})	≥ 14 dB	-25.26 dB (200 kHz), 15.07 dB (88 MHz)	-44.4 dB	0.78 dB
Input Matching (S_{11})	≤ -3 dB	-5.72 dB	Was not conducted	-6.13 dB
Output Matching (S_{22})	≤ -3 dB	-4.76 dB	Was not conducted	Was not conducted
Isolation (S_{12})	≤ 0 dB	-41.57	Was not conducted	Was not conducted
Noise Figure	≤ 5 dB	3.9 dB	Was not conducted	Was not conducted
Input Third Order Intercept Point (IIP3)	≥ -5 dBm	2.21 dBm	Was not conducted	Was not conducted
Power Consumption	≤ 100 mW	45.39 mW	Was not conducted	Was not conducted
V_{CC}	3 V	3 V	3 V	3 V
Bandwidth	34 MHz	34 MHz	100 kHz	34 MHz

*was not done due to the limited measurement instruments.

frequencies of 86.5 MHz, and 88 MHz. The calculation of the IIP3 value of the simulation results was carried out using (14) to (16), resulting in the value IIP3 = 2.21 dBm.

The IIP3 value from that calculation corresponds to the desired specification, which is ≥ -5 dBm. The IIP3 is a parameter that pays attention to linearity. The higher the value, the more linear and closer to the ideal value.

D. Power Consumption Calculation

From Fig. 13, the *Ic* values in transistors 1 and 2 can be obtained.

$$V_{dc} = 3V, I_{c_{total}} = I_{c1} + I_{c2} = 6.08 + 9.05 = 15.13 \ mA$$

$$P_{dc} = V_{dc}I_{c_{total}} = 3 \ x \ 15.13 \ = 45.39 \ mW$$

These calculation results correspond with the specifications, namely, power consumption ≤ 100 mW.

E. Discrete Component Simulation Results

Prototype 1 uses an ELVIS II+ NI tool (Fig. 14) and prototype 2 using the TINY MiniVNA tool (Fig. 15). The test results using NI ELVIS II+ are shown in Fig. 16, compared with the LTSPICE results, and the test results using MiniVNA

TINY are shown in Fig. 17. The results of measurement and comparison to the IEEE 802.22 standard are presented in Table II.

VI. CONCLUSION

LNA prototype has been made using 2N3904 transistors to be tested on two devices, namely, NI ELVIS II+ with a frequency range of 100 kHz - 200 kHz and MiniVNA TINY with a frequency range of 54 MHz - 88 MHz. The constructed prototype has the following characteristics. Prototype 1 has a frequency range of 100 kHz - 200 kHz and can amplify as much as 56.89%. Prototype 2 has a frequency range of 54 MHz - 88 MHz and can amplify as much as 5.57%. It also can suppress the noise by 204.33%. It can be concluded that the constructed prototype has been able to function as LNA, even though it has not met the IEEE standard and needs to be improved.

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