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# Single Stage RF Amplifier with High Gain for 2.4GHz Receiver Front-Ends

**Achmad Munir, Biru Tutur Ranum**
Radio Telecommunication and Microwave Laboratory
School of Electrical Engineering and Informatics
Institut Teknologi Bandung
Jalan Ganesha 10 Bandung, 40132, Indonesia, Phone: +62-22-2501661
e-mail: munir@ieee.org

***Abstract***

*The paper deals with the numerical and experimental development of single stage radio frequency (RF) amplifier with high gain for 2.4GHz receiver front-ends. The work is motivated by the increasing demand of high-gain receiver amplifier in low-cost especially for wireless local area network (WLAN) application. Prior hardware realization and experimental characterization, the proposed amplifier which uses a single RF transistor of BFP420 type is numerically designed using ADS® software to satisfy the required specification. To obtain the impedance matching at ports of amplifier, microstrip lines are employed at the input and output ports. The prototype of amplifier is realized by use of a dielectric substrate of glass-reinforced epoxy lamination (FR4) board which has thickness of 0.762mm and relative permittivity of 4.3. The prototype is then experimentally characterized and demonstrates the gain of 13.35dB at frequency of 2.4GHz with the noise figure of 3.33dB, the input and output voltage standing wave ratio (VSWR) of 2.08 and 2.55, respectively.*

***Keywords****: BFP420, gain, noise figure, RF amplifier, single stage, VSWR*

## 1. Introduction

Along with the growth of communication technology in last 2 decades, the communication systems have significantly transformed from the wired-line to the wireless line. These can be perceived by appearance of many technologies for mobile and wireless communications such as GSM, CDMA, UMTS, WiFi, WiMAX and LTE [1]-[3]. Cellular phones, wireless local area networks (WLAN), and short-range data communication devices are the examples of wireless communication devices which apply those technologies. As the increasing demand for low-cost and multi-standard communication devices, the front-end device for RF receiver is playing an essential role in wireless communication system. Due to the expandable area of application, the front-end receiver should accomplish some requirements not only in technical specifications but also in some aspects such as compact size, low cost and light weight as well as long battery life. Hence, a lot of topologies and design method of RF receiver including RF-CMOS integrated circuit have been proposed in which some achievements of receiver front-ends accomplishing the specifications and aspects have been acquired [4]-[6].

In the design of RF receiver front-ends to support multi-purpose use, the stability of active components, e.g. transistor, is the most important thing that should be paid more attention. To attain the desired stability as well as the stability maintenance, there are few methods that could be implemented including resistive matching, network compensation, negative feedback, balanced circuits, and traveling wave [7]-[8]. However for some application, the method of resistive matching can potentially increase the noise figure and decrease the gain of RF receiver, while the method of negative feedback typically produces inferior return loss [9]-[10]. In addition, the method of traveling wave sometimes gives unimpressive performance on gain and noise figure [11].

In this paper, by eliminating the balance circuits due to the use of more than one transistor and by avoiding the traveling wave to achieve high gain performance, a single stage RF amplifier is proposed and developed by employing the method of network compensation. The amplifier that uses a single RF transistor of BFP420 type is intended to be applied for 2.4GHz WLAN receiver front-ends. The method of network compensation which aims to compensate impedance mismatch at the ports network is conducted by use of microstrip lines at

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the input and output ports. The dimension of microstrip lines are calculated and optimized to achieve the impedance matching and optimum performance of amplifier with some parameters design including gain, noise figure, and VSWR are used as performance indicators. After obtaining the optimum design, the prototype of amplifier is deployed on a dielectric substrate of glass-reinforced epoxy lamination (FR4) board for experimental characterization.

## 2. Overview of RF Amplifier Design

In general, as shown in Figure 1, a circuit design of single stage RF amplifier is constructed of microstrip lines at the input and output ports as matching impedance circuits and an RF transistor of BFP420 type as the heart of amplifier. As the transistor has a wide transition frequency, therefore it is suitable to be employed as RF amplifier for 2.4GHz receiver front-ends. Actually, a similar circuit design of RF amplifier based on BFP420 transistor has been implemented for low noise amplifier at 2.4GHz [12]. Unfortunately, the circuit has a complicated dc biasing using a double-transistor to provide a temperature stable current source. In addition, the circuit needs an emitter inductance as negative feedback to increase the stability but, in other hand, affecting to the overall gain. Therefore, in the current design, the complicated dc biasing and negative feedback are avoided to prune the complexity of design. Based on scattering parameter data of transistor which are provided in the data sheet [13], the input and output impedances of transistor are then calculated to determine the dimension of microstrip lines. Two pairs of microstrip lines at the input port ($M_1$ and $M_2$) and the output port ($M_3$ and $M_4$) are employed as impedance matching networks. The junction capacitors are connected at the input and output ports of transistor to interconnect the microstrip lines as well as to block dc current. In this case, it is beneficial to first build up the circuit design with lossless microstrip lines and ideal lumped components, just to verify that input and output impedances indeed produce the required performance.

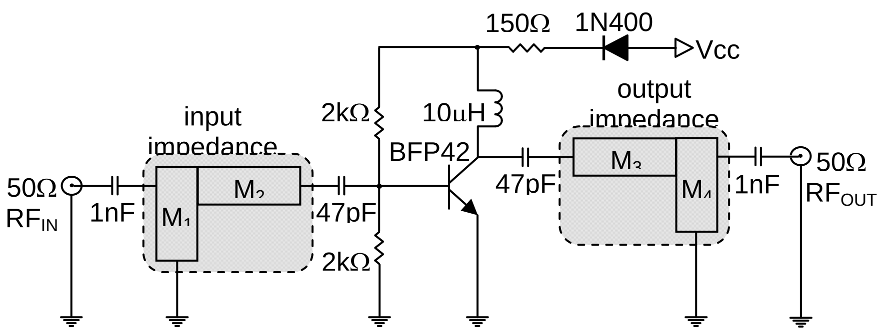


Figure 1. Circuit design of single stage RF amplifier

The dimension of each microstrip lines can be determined from Smith chart by mapping the reflection values of transistor ($\Gamma_S$ and $\Gamma_L$). Since the goal of design is to acquire the maximum power gain of amplifier, regarding to stability factor of transistor and according to design method based on simultaneous-conjugate-match technique, the reflection value at source ($\Gamma_S$) should be equal to the optimum reflection value ($\Gamma_{OPT}$). If the condition can be achieved, the input impedance of amplifier will match and equals 50Ω. This procedure is also applied for the output port of transistor. Here, the input impedance ($RF_{IN}$) and the output impedance ($RF_{OUT}$) are set to be 50Ω in which this is also an impedance of microstrip lines. Whilst the reflection value at load ($\Gamma_L$) can be obtained using the following equation [8].

$$\Gamma_L^* = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1 - S_{11}\Gamma_S} \quad (1)$$

By utilizing the scattering parameter of transistor at frequency of 2.4GHz, the reflection values of transistor are ($0.25\angle-164.19^o$) and ($0.31\angle-52.04^o$) for $\Gamma_S$ and $\Gamma_L$, respectively. After mapping both values of reflection into Smith chart, then the electrical length of each microstrip line can be calculated by putting the input and output impedances of amplifier to be 50Ω. While to determine the physical length, the electrical length of each microstrip line should be de-normalized using the wavelength on the dielectric substrate for 2.4GHz. As the physical length is numerically calculated for the circuit design with assuming lossless microstrip lines, thence for the simulation design which is run on ADS® software the actual physical length has to be optimized by taking into account all parameters of involved materials including microstrip line, lumped component and dielectric substrate. Basically, parameters of materials should cover the thickness and conductivity of microstrip line, the frequency range of lumped component, and the dielectric loss and thickness of dielectric substrate. This is required to obtain the actual design of amplifier to be satisfied with the desired performance and suitable for realization. Moreover, the optimization is also useful to compensate impedance mismatch at the ports network, hence the amplifier characteristics can be improved. Table 1 summarizes the electrical length of each microstrip line obtained from Smith chart, and the physical length before and after optimization. It should be noted that the width of each microstrip line is 3mm which corresponds to the impedance line of 50Ω.

Table 1. Electrical and physical lengths of microstrip lines

| Microstrip line | Electrical length (m) | Physical length (mm) | |
|---|---|---|---|
| | | before optimization | after optimization |
| M1 | 0.174 | 12 | 10 |
| M2 | 0.418 | 29 | 27 |
| M3 | 0.077 | 5 | 3 |
| M4 | 0.159 | 11 | 12 |

Figure 2 plots the simulated results of amplifier gain and noise figure before and after optimization. It is shown that the dimension of microstrip lines after optimization affects the improvement of amplifier gain for frequency range higher than 2.25GHz. It seems that optimization has shifted the curve of overall gain to higher frequency range which produces the increase of gain especially at frequency of 2.4GHz. However there is no significant effect appears for the noise figure of amplifier, on the contrary the noise figure becomes to be worse for frequency range lower than 2.25GHz.

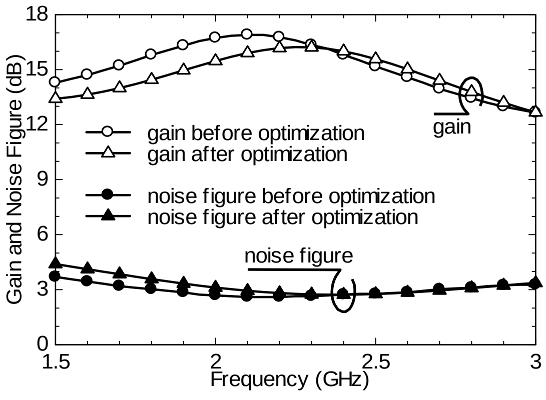


Figure 2. Simulated results of gain and noise figure before and after optimization

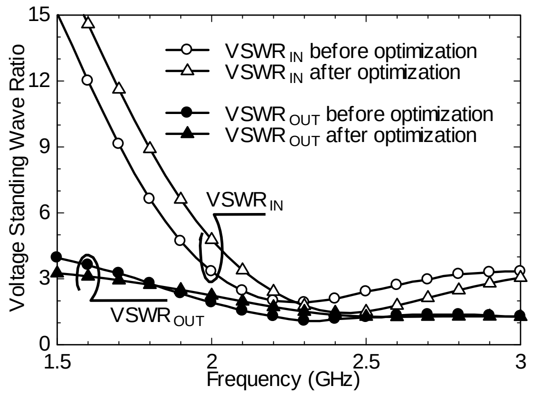


Figure 3. Simulated results of $VSWR_{IN}$ and $VSWR_{OUT}$ before and after optimization

This can be figured out that the dimension variation of microstrip lines influences the reactance value of impedance matching networks. Hence, it is noticeable that the reactance value of impedance matching networks is sensitive with the change of microstrip lines dimension. As a result, the impedance value of impedance matching networks at the input and output ports will vary consecutively minimizing the overall impedance mismatch of amplifier although it has to be paid by sacrificing the noise figure. Even so, this is usefulness of using microstrip lines as impedance matching networks in RF amplifier design to compensate the impedance mismatch in uncomplicated manner which occurs due to the characteristic variation of transistor or other materials, i.e. lumped components or dielectric substrate, used in the design.

The optimization also enhances the values of VSWR at the input and output ports around the frequency of 2.4GHz as depicted in Figure 3. It can be noticed that the output port of amplifier after optimization has better impedance matching than the input port. The result demonstrates that the value of VSWR at the input port ($VSWR_{IN}$) is 1.46 at frequency of 2.4GHz, whilst at the output port ($VSWR_{OUT}$) is 1.36. This can be understood that the value of VSWR especially at the input port is strongly influenced by the gain, or vice versa. More improvement in impedance matching will not always increase the gain of amplifier as the transistor will be loaded more affecting to the overall gain. Therefore, there is a compromise value or trade-off between the gain and VSWR of amplifier. Nevertheless, from the simulated result, it is shown that the final design of RF amplifier has exhibited the gain up to 16dB and the noise figure of 2.73dB at frequency of 2.4GHz. This achievement is sufficient for WLAN application and has satisfied the desired performance which requires at least 13dB gain and 3dB noise figure.

## 3. Prototyping and Experimental Characterization

Based on the design explained in the previous section, the prototype of proposed single stage RF amplifier is then realized to be characterized experimentally as indicated in Figure 4. Whilst Figure 5 shows a picture of final board of RF amplifier deployed on a dielectric substrate of glass-reinforced epoxy lamination (FR4) board in which the thickness and the relative permittivity are 0.762mm and 4.3, respectively. The dimension of final board of RF amplifier is 40mm (length) by 30mm (width). The experimental characterization results for gain and noise figure of amplifier, and the value of VSWR are depicted in Figures 6 and 7, respectively. It should be noted that the measured noise figure shown in Figure 6 is obtained from the correlation of measured gain instead of direct measurement due to the unavailability of instrument for noise figure characterization. In addition, simulated results of gain, noise figure and VSWR are also plotted together in each respected figure as comparison.

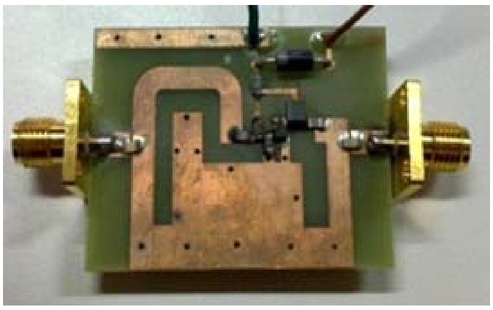

Figure 4. Picture of RF amplifier prototype

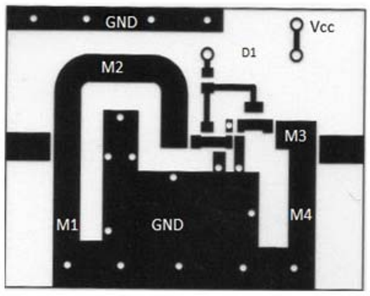


Figure 5. Picture of RF amplifier final board

As shown in Figure 6 the measured gain has coincided with the simulated one up to frequency of 1.9GHz, whereas in the rest frequency the measured gain is lower than the simulated result and tends to decrease for higher frequency range. The similar case also happens for the measured noise figure but in the opposite manner. From the results, the gain and noise figure of RF amplifier prototype at frequency of 2.4GHz are 13.35dB and 3.33dB, respectively, in which these are worse than the simulated one at the same frequency with the gain of 16dB and noise figure of 2.73dB. There are some possibilities which evokes these discrepancies. One of the most possibilities is caused by the parameters of dielectric substrate of glass-reinforced epoxy lamination (FR4) board, i.e. dielectric loss and relative permittivity, used for realizing the prototype. It should be noted that in the design the dielectric loss and the relative permittivity are set to be 4.3 and 0.02, respectively, in which both parameters are assumed to be flat for all frequency ranges. Whilst in actual condition, the dielectric loss and the relative permittivity are almost frequency-dependent. In the case of measured results which are different with the simulated ones, it is probably caused by the dielectric loss which has the actual value slightly higher than in the design. Since the actual dielectric loss is higher than in the design especially for high frequency region, thus some amount of energy from the input port that should be actually transmitted to the output port is absorbed by the dielectric substrate affecting to the decrease of measured gain. As the escalation of energy absorbed by the dielectric substrate, the total noise of amplifier grows up consecutively resulting the increase of noise figure in total.

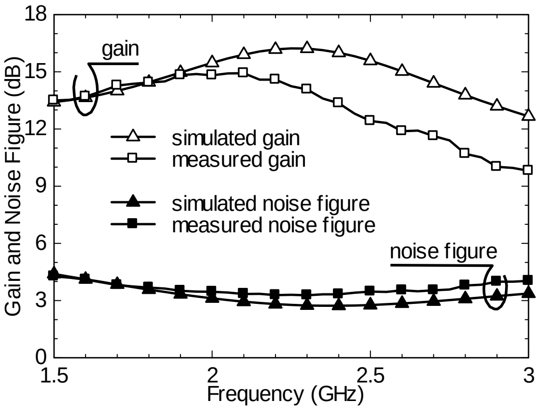


Figure 6. Measured and simulated results of gain and noise figure of amplifier

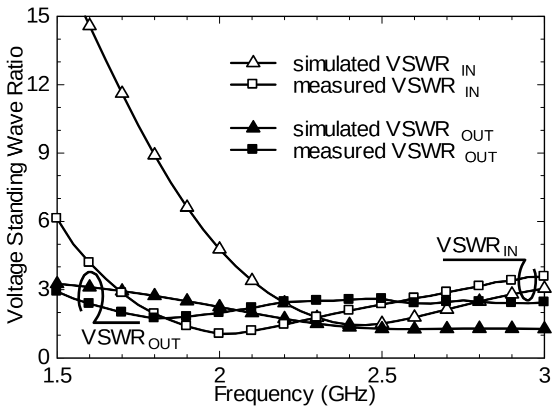


Figure 7. Measured and simulated results of $VSWR_{IN}$ and $VSWR_{OUT}$

The different results of experimental characterization are also found for the value of VSWR at the input and output ports, as plotted in Figure 7. It shows that the measured $VSWR_{IN}$ has better value than the simulated one for frequency range up to 2.3GHz and be contrary for the rest frequency. The similar tendency also occurs for the $VSWR_{OUT}$ with the frequency range lower than 2.05GHz. From the results, the prototype of RF amplifier has $VSWR_{IN}$ of 2.08 and $VSWR_{OUT}$ of 2.55 at frequency of 2.4GHz. Similar to the measured gain and noise figure, these results are worse than the simulated ones with $VSWR_{IN}$ of 1.46 and $VSWR_{OUT}$ of 1.36 at the same frequency. The discrepancy in the measured results of VSWR is probably evoked by the different value of relative permittivity of dielectric substrate used in the realization and the design. For the results shown in Figure 7, the actual value of relative permittivity of dielectric substrate seems to be slightly higher than in the design. If the actual relative permittivity is higher, thus the impedance value of impedance matching networks, i.e. microstrip lines, reacts to move to be smaller resulting the decrease of VSWR and it is seen being happened at the lower frequency range. As the increase of frequency, the actual relative permittivity which is usually frequency-dependent and tends to be lower for higher frequency region, the impedance value of impedance matching networks gradually moves to be higher affecting to the increase of VSWR. Moreover, another possibility which causes the discrepancies in the measured result of gain, noise figure and VSWR is the inaccuracy effect in hardware realization. However, to our knowledge, the effect of inaccuracy gives no significantly influence compared to the effect of material parameter variation. Nevertheless, from the measured results depicted in Figure 6 and 7, in despite of some measured values need to be improved, it can be concluded that the prototype of single stage RF amplifier built of BFP420 type transistor has demonstrated acceptable performance for desired application.

## 4. Conclusion

The development of single stage RF amplifier with high gain for 2.4GHz receiver front-ends has been investigated numerically and experimentally. The prototype of amplifier with a single RF transistor of BFP420 type as a core component has also been realized for experimental characterization by deploying it on a dielectric substrate of glass-reinforced epoxy lamination (FR4) board. From characterization results, it has been demonstrated that the prototype exhibits the gain of 13.35dB at frequency of 2.4GHz with the noise figure of 3.33dB, $VSWR_{IN}$ of 2.08, and $VSWR_{OUT}$ of 2.55. Although the measured results are slightly worse than the simulated ones and need to be enhanced, the prototype of single stage amplifier has shown acceptable performance for WLAN application. It should be noted that parameters of involved materials in the design process should be taken into account to avoid the discrepancies which may occur in the realization. In addition, a further investigation on the enhancement of RF amplifier gain and noise figure by implementing some design method using non simultaneous-conjugate-mach technique is still in progress where the results will be reported later.

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