Design and fabrication of S-band power amplifier for wireless sensor networks

Tran Van Hoi, Ngo Thi Lanh, Bach Gia Duong
Faculty of Electrical and Electronic Engineering, Thuyloi University, Hanoi, Vietnam

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ABSTRACT

This paper discusses the process of designing and manufacturing a wideband power amplifier operating in the S-band. To amplify a low power and broadband radio frequency signals from 2.1 GHz to 2.5 GHz, the proposed power amplifier uses a diagram of a two-stages amplification with peak offset amplification frequency 2.3 GHz. The power amplifier is designed with a center frequency difference of 2.2 GHz and 2.4 GHz respectively to achieve a bandwidth of 400 MHz. The proposed power amplifier (PA) uses RF transistor SHF-0589 using gallium arsenide heterostructure field-effect transistor (GaAs HFET) technology for high gain and low power consumption. The complete amplifier achieves power gain 21.1 dB inband 2.1-2.5 GHz and achieve maximum power gain of 22.5 dB at the frequency of 2.4 GHz; the output power rise up to 33 dBm; input reflection coefficient (S_{11}) reaches -19.2 dB and output reflection coefficient reaches -17.2 dB. The designed amplifier circuit can be used for wireless sensor networks operating at S-band.

Corresponding Author:

Tran Van Hoi
Faculty of Electrical and Electronic Engineering, Thuyloi University
175 Tay Son, Dong Da, Hanoi, Vietnam
Email: hoitv@tlu.edu.vn

1. INTRODUCTION

A wireless sensor network (WSN) is a network consisting of network nodes that are independent devices in space. These devices collect necessary information and transmit it to a monitoring center. In the WSN system, there are also base stations and control centers. The base station acts as a gateway between the network node and the control center, receiving information from the network nodes and transferring it to the control center in many different ways. Network nodes transmit messages in a multi-hop way, from one node to another and transfer to the base station. From the base station can send information to the control center in many ways such as directly through the computer system, via the Internet, and via satellite, so that the supervisor can receive information trust wherever you are.

In wireless sensor network, the NRF2401 standard module operates at 2.4 GHz frequency with an output power of about 50-100 mW, that can only connect outdoors about 100 m and indoors about 30 m. To expand the communication distance between the base station and the network nodes, solutions can be used such as: The first solution is to use many sensor nodes connected in a tree or mesh structure, but this solution increases the complexity of the WSN. The second solution is to improve the sensitivity of the receiver and the gain of the receiving antenna. The third solution is to increase the transmit power for the base station and network nodes. In this paper, the authors choose a design solution to increase the transmit power for the transmitter module of the base station.

In the transmitter, the power amplifier (PA) circuit amplifies the radio frequency (RF) signal to a power level high enough to provide the antenna with the lowest possible distortion. Depending on the specific application, research will solve different problems of power amplifiers [1]-[25]. Some research addresses the issue of increasing the gain and efficiency of amplifier circuits [1]-[9]. Some research addresses the issue of increasing bandwidth and reducing intermodulation distortion [10]-[20].

To design power amplifiers with high-power and wide-bandwidth, there are a number of solutions proposed such as designing parallel power amplifiers with power dividers/adders [10], [13], [14], [19]-[24]. This solution is often used for high-power and high reliability requirements. One of the most used methods is the use of multistage power amplifier circuits [2], [6], [17].

Therefore, the article proposes a solution to design a PA using two-stages connected in series. The block diagram of the proposed 2-stage PA is shown in Figure 1. In order to widen the passband, increase the dynamic range, ensure linear amplification, the paper proposes a solution to design the center frequencies of the 1st and 2nd stages that are different from each other, with frequencies of 2.2 GHz and 2.4 GHz respectively. The first stage is the driver stage using the power transistor SHF-0589, which requires the gain >12 dB. The driver stage amplifies the small input signal from a few tens of mW up to a few hundred mW to provide the power amplifier stage. The second stage is a 2 W power amplifier using the power transistor SHF0589 with the manufacturing technology of gallium arsenide heterostructure field-effect transistor (GaAs HFET), requiring the gain of this stage to be >12 dB. With an input power level of less than 20 dBm, the amplifier circuit has a maximum output of 33 dBm. In addition, the input/output impedance matching networks are designed to transmit the maximum power from the source to the load to ensure the standing wave coefficient.

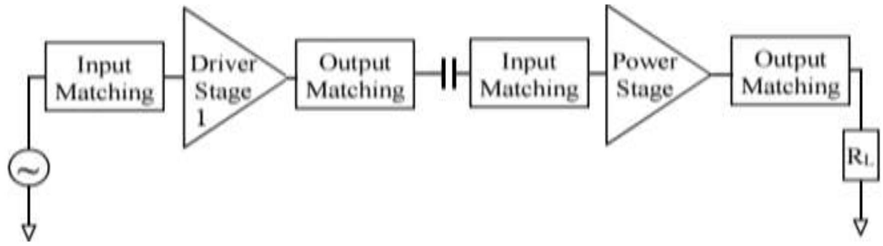

Figure 1. Block diagram of the proposed 2-stage PA

Among impedance matching circuit design methods, the impedance matching method using lumped elements; microtrip line such as single stub or double stub is often used for narrowband impedance matching circuits. For wideband impedance matching circuits, quarter wavelength transformer matching and multisection transformers are often used. In the design, the authors used a quarter wavelength transformer matching.

2. DESIGN AND SIMULATION

Figure 2 shows the principal diagram of a single-stage power amplifier. In a single-stage amplifier using transistors, the input impedance matching circuit performs matching of the source impedance Zs with the input impedance of the transistor; the output impedance matching circuit performs matching of the output impedance of the transistor with the load impedance Z_L. The gain of the whole circuit depends on the gain of the input impedance matching (G_S)/output impedance matching (G_L) and the gain of the transistor (G_0) [22].

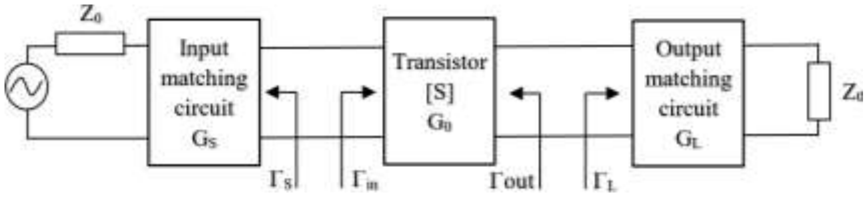

Figure 2. The typical diagram of amplifier circuit

The gain of the whole circuit $G_T = G_S.G_0.G_L$, where,

$$G_S = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2} \quad (1)$$

$$G_0 = |S_{21}|^2 \quad (2)$$

$$G_L = \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \quad (3)$$

In designing a power amplifier, the stability condition of the amplifier circuit is very important and must be ensured. If the amplifier circuit is unstable then any oscillations can occur and damage the amplifier. Therefore, first we need to check the stability of the transistor based on S-parameter, the microwave amplifier will be unconditionally stable if the $|\Gamma_{in}|$ and $|\Gamma_{out}|$ is less than 1.

$$|\Gamma_{in}| = \left|S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1-S_{22}\Gamma_L}\right| < 1 \quad (4)$$

$$|\Gamma_{out}| = \left|S_{22} + \frac{S_{21}S_{12}\Gamma_S}{1-S_{11}\Gamma_S}\right| < 1 \quad (5)$$

One of the other methods used to determine the stability of PA is K-Δ test. The stability factor (K) and stability measure (Δ) using equations (6) and (7). The microwave amplifier will be unconditionally stable if the k-factor is greater than 1 (K>1) and the Δ-factor is less than 1 (Δ<1) [23].

$$K = \frac{1-|S_{11}|^2-|S_{22}|^2+|S_{11}S_{22}-S_{12}S_{21}|^2}{2|S_{12}S_{21}|} \quad (6)$$

Along with the auxiliary condition that:

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (7)$$

Secondly, from the S parameter of the transistor, we can calculate the input impedance and output impedance of the transistor, from which we can design a circuit to coordinate the source impedance with the input impedance of the transistor and the output impedance of transistor with load impedance. There are many different impedance matching design methods, depending on the requirements of the circuit as well as through experiments, the authors chose the impedance matching method for this designed circuit by using a quarter wavelength transformer matching (λ/4). Because this impedance matching method has wide-band and is easy to implement both in theoretical calculations and in practical circuit fabrication. This method can only be used to match the purely resistive impedance with the transmission line, while the input and output impedance have complex components, so we must transform this complex resistance point to the purely resistive impedance value by use a 50 Ω transmission line and a phase rotating capacitor between the load and the λ/4 line.

The power amplifier circuit, first stage uses transistor SHF-0589 operating in the frequency range of 50 MHz to 3 GHz, the circuit operates effectively at a frequency of 1.96 GHz when polarized and operates in AB mode with a power supply of 7 V/345 mA and achieves a gain of 12 dB; output power P1dB=33.4 dBm with compression point of +1 dB; output power OIP3=46.5 dBm. The first stage is designed at the center frequency of 2.2 GHz, the input impedance of transistor $Zin = 3 + j * 3.4\,\Omega$, using the λ/4 impedance matching circuit design method we can determine, d=0.489 λ, Z(d)=2.986 Ω, and $Z_{\lambda/4}$ =12.219 Ω. Similar to $Zout = 14.8 + j * 2.7\,\Omega$, we can also determine, d=0.49 λ, Z(d)=14.753 Ω, and $Z_{\lambda/4}$=27.159 Ω.

The second stage is designed at the center frequency of 2.4 GHz, the input impedance of transistor $Zin = 3.2 + j * 5.3\,\Omega$, using the λ/4 impedance matching circuit design method we can determine, d=0.483 λ, Z(d)=3.164 Ω, and $Z_{\lambda/4}$=12.5784 Ω. Similar to $Zout = 14.6 + j * 3.5\,\Omega$, we can also determine, d=0.4878 λ, Z(d) 14.52 Ω, and $Z_{\lambda/4}$=26.95 Ω. Using the strip circuit calculation tool in ADS, the results of the SHF0589 power amplifier circuit are shown in Figure 3. Simulation results of the K parameter of transistor SHF0589 are shown in Figure 4. From Figure 4, it shows that the K factor is >1 in the design frequency range which makes the unconditional stability for the power stage.

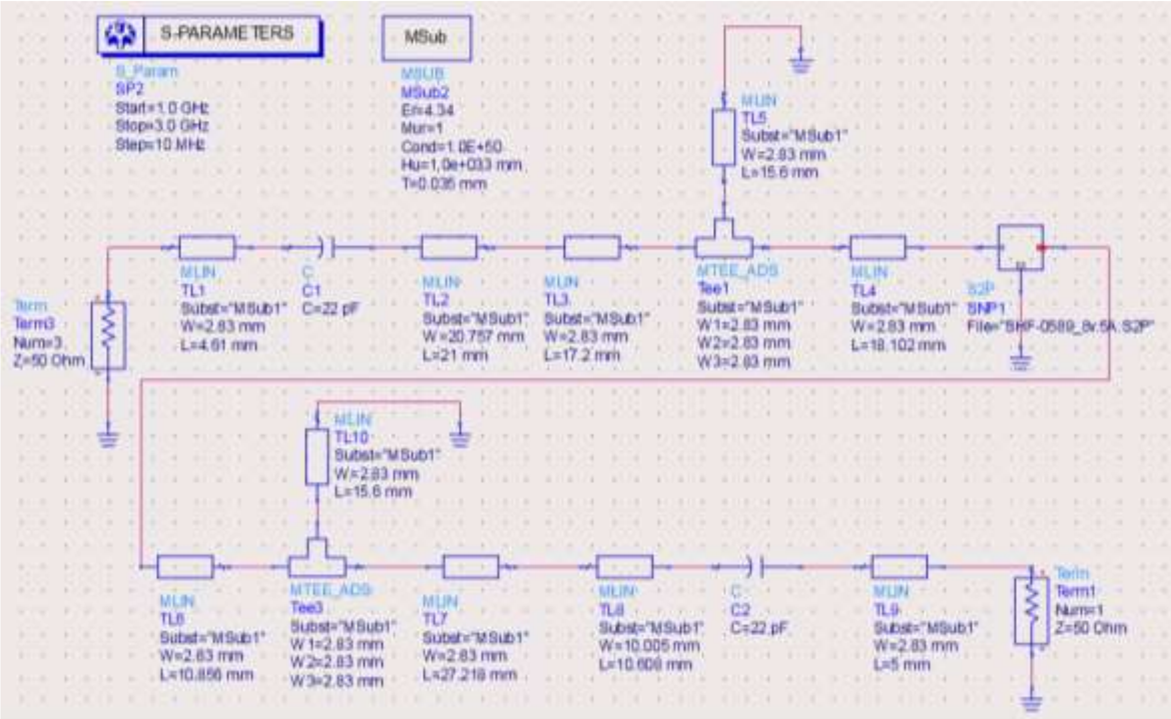

Figure 3. Schematic diagram of PA

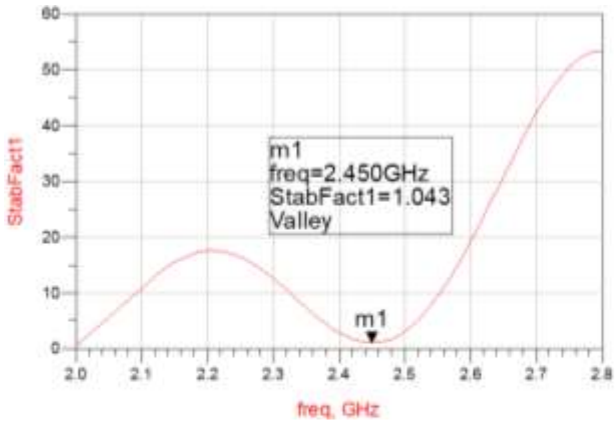

Figure 4. Simulation results of K factor

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The two-stage PA's printed circuit board (PCB) is designed using the substrate FR4 with parameters: dielectric substrate of 4.34; 1.5 mm height; and thickness 0.035 mm. The layout of the PA was designed, simulated, and optimized using ADS software and machined using an LPKF C40 milling machine. To power the amplifier circuit, we use $\lambda/4$ segments to form ultra-high frequency blocking coils. The final PA's PCB is presented in Figure 5.

The two-stage PA circuit is DC powered to operate in mode A. The small-signals of the PA circuit are tested and measured using vector network analyzer 37369D-Anritsu technology up to 40 GHz. The forward gain of the PA circuit is shown in Figure 6. From Figure 6, it can be seen that the forward gain is greater than 21.1 dB in the working band 2.1 GHz to 2.5 GHz, and the maximum gain reaches 22.5 dB at 2.4 GHz, the measured results are smaller than the simulation results, but the measured results are relatively consistent with the simulation results.

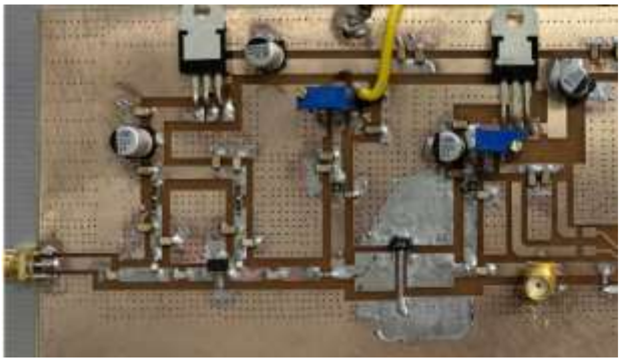

Figure 5. PCB of PA

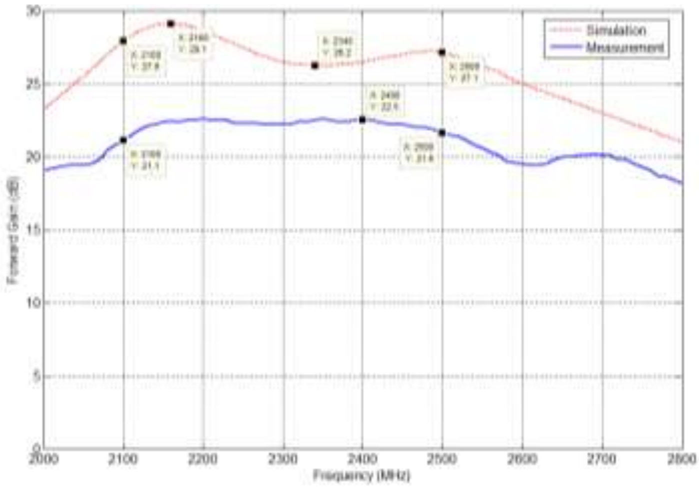

Figure 6. The forward transmission of PA

Figure 7 shows the both curves of measurement's input return loss (S_{11}) and simulation's one. The value of the input return loss (S_{11}) achieves -19.26 dB at 2.36 GHz also agrees with simulation of -22.8 dB at 2.3 GHz. Although the simulation results are smaller, the measurement results give a wider frequency range.

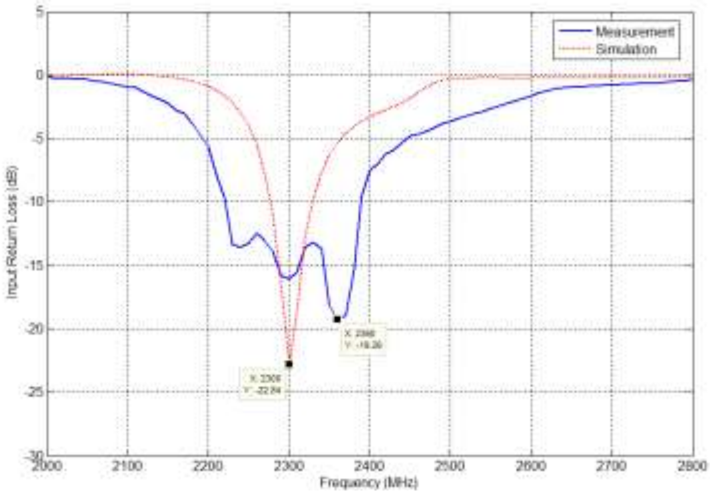

Figure 7. Simulation results and measurement results of input return loss S_{11}

Likewise, Figure 8 shows the simulation results and the measurement results of output return loss (S_{22}). The measured output return loss reaches -17.19 dB at 2.33 GHz and is less than -10 dB in the working band. Although the measured value is larger than the simulated value, the measured result is wide in the operating frequency range.

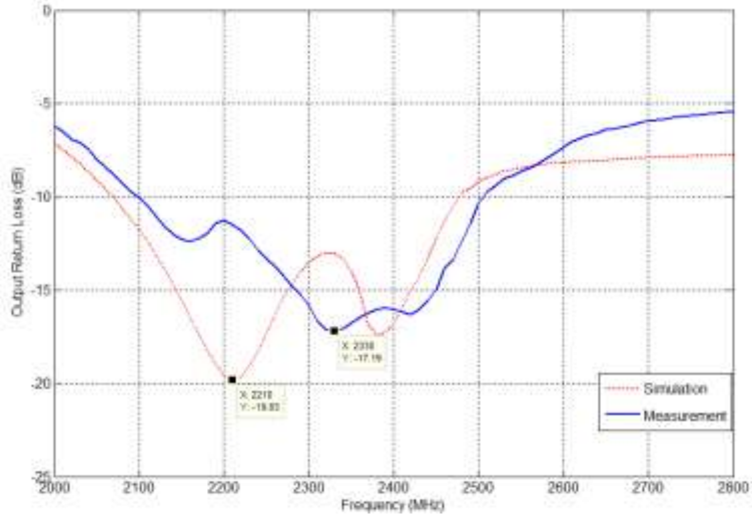

Figure 8. The measurement result of output return loss S_{22}

Perform large signal measurements of the PA circuit using the spectrum analyzer ESP13 Rohde & Schwarz and the signal generator agilent 8648C. The output power measurement results of the PA circuit are shown in Figure 9. The measured output power reached 32.9 dBm with an input power of 11 dBm, compared to the simulation result of 33.3 dBm.

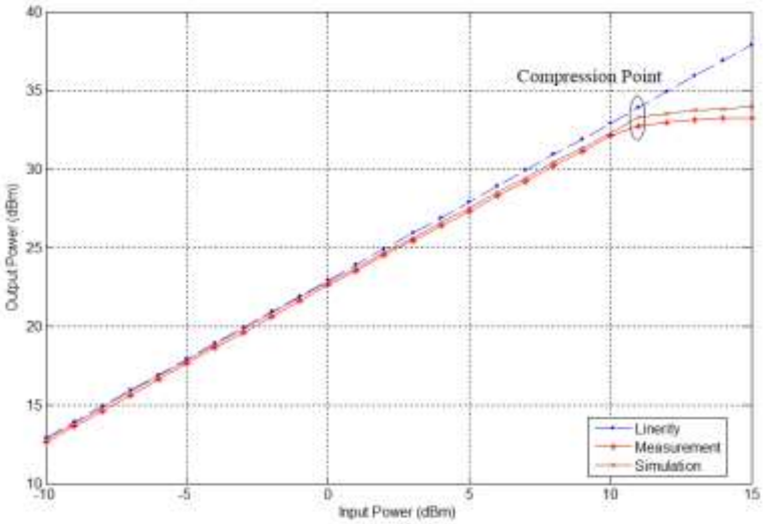

Figure 9. Output power of two stage PA' circuit

Comparing the parameters of the proposed amplifier circuit with some existing works in the literature on the gain of the PA circuit, bandwidth and reflection coefficient, the comparison results are presented in Table 1. From Table 1, we can see that reference 2 uses a 2-stage amplifier circuit connected in series with a center frequency of 3.5 GHz. Although the maximum gain of the circuit is larger than this work, but the ripple throughout the range is lower than this work.

Table 1. Comparison with published works

Reference	Frequency (GHz)	Pout (dBm)	S_{21} (dB)	S_{11} (dB)	S_{22} (dB)
[2]	3.2-3.8	19	20-28	-30	-29
[6]	2.7-3.1	27	19-31.9	-20.3	-16.7
[17]	1.5-2.6	35	18.2-20.4		
This work	2.1-2.5	33	21.1-22.5	-19.2	-17.2

Similarly, reference 6 also uses a 2-stage amplifier circuit with a center frequency of 2.9 GHz. Although the maximum gain of the circuit is also larger than this work, but the ripple throughout the range is lower than this work. Reference 17 uses a 2-stage amplifier circuit using a wilkinson power divider. Although the frequency range is wider, but the gain of the circuit is lower than this work. From the above analysis we can see that the proposed design has relatively good performance compared to the reported works.

4. CONCLUSION

In conclusion, the article presents the process of research, design, simulation and manufacturing experimental measurements of a 2 W power amplifier working in the S band. The article also proposes a design plan for a cascaded amplifier circuit to increase gain of PA and frequency range expansion. The PA circuit has been successfully designed and manufactured with the following characteristics: the highest gain is 22.5 dB at the frequency of 2.4 GHz and greater than 21.1 dB in the frequency from 2.1 GHz to 2.5 GHz. The circuit is applied in the wireless sensor network operating in the 2.4 GHz ISM band; with a wideband frequency from 2.1 GHz to 2.5 GHz, the PA circuit can be applied in the 4 and 5G mobile communication systems in Viet Nam operating in the 2.1-2.4 GHz band.

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BIOGRAPHIES OF AUTHORS

Dr. Tran Van Hoi obtained the B.S. degree in telecommunication techniques from University of Transport and communications in 2001. He received M.S degree in electronic wireless and communication from Le Quy Don Technical University in 2004. He has been a lecturer in Broadcasting College 1, Radio the Voice of Viet Nam from 2001 to 2017. He received Ph.D. degree in Electronics and Communication Technology in University of Engineering and Technology, Vietnam National University in 2018. Since 2018, He has been working in Faculty of Electrical and Electronic Engineering, Thuyloi University. His research interests involve wireless communication, internet of things (IoT), RF design, and RF chip design. He can be contacted at email: hoitv@tlu.edu.vn.

M.S. Ngo Thi Lanh obtained the B.S degree in Electronics and Telecommunications from University of Engineering and Technology, Vietnam National University in 2001. She received M.S degree in electronic wireless and communication from Le Quy Don Technical University in 2004. She was a lecturer in Broadcasting College 1, Radio the Voice of Viet Nam from 2001 to 2018. She was a lecturer at the University of Transport Technology from 2019 to 2023. Since 2023, He has been working in Faculty of Electrical and Electronic Engineering, Thuyloi University. Her research interests involve RF design, wireless communication, and IoT. She can be contacted at email: lanhnt@tlu.edu.vn.

Prof. Bach Gia Duong received the B.S degree in radio physics in 1972 and the Ph.D. degree in wireless physics from Vietnam National University, in 1988. He was a research assistant in Leningrad University, Russia, from 1988 to 1990. He was a researcher at the Academy of air force from 1991 to 2005. He was a lecturer and Head of electronics and telecommunication center, University of Engineering and Technology, Vietnam National University From 2006 to 2022. Since 2023, He has been working in Faculty of Electrical and Electronic Engineering, Thuyloi University. His research focuses on automatic control, radar engineering and technology, analog signal processing, RF design, and RF chip design. He can be contacted at email: duongbg@tlu.edu.vn.