X-band TR Module for Radar and Wireless Communication Systems

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Abstract: The paper presents the design and fabrication of an X-band transmit receive module operating in the frequency range of 9.25 to 10.75 GHz. The proposed TR module consists of a circulator, a power amplifier and a low-noise amplifier, which are fabricated using hybrid microwave integrated circuit technology. Amplifier design procedures are presented with focuses on stability improvement, wideband matching and noise matching techniques to improve amplifiers' performances. The designed power amplifier with good input and output matching exhibits 15-dB power gain and provides measured output power of 15.1 dBm and OP1dB of 22.5 dBm. The designed low noise amplifier has a very low measured noise figure of 2 dB and a high gain of 20 dB over the whole bandwidth, good input/output matching is also achieved with measured S11 and S22 smaller than -10 and -12 dB, respectively. Amplifiers are integrated with circulator to build a complete TR module which helps extend operating range of radar and wireless communication systems.

Keywords — Radar transceiver, TR module, MIC, wideband amplifier, power amplifier and low noise amplifier.

I. INTRODUCTION

The evolution of wireless communication systems in recent years has been taking place rapidly, making these systems become important in modern life. In addition, radar systems have been developed and commercialized to suit applications in many fields, such as: liquid level measurement, target detection… The development trends of these systems are high operating frequency, high speed data transfer, compact and integrated device and the ability to communicate as far as possible. However, most radar and wireless communication systems can only function correctly and efficiently within a limited range defined by their characteristics. Beyond that range, the connection is lost (in wireless communication systems) or target becomes undetectable (in radar systems). The decline in performance of these systems is due to the proportional increase in propagation loss and distance of the microwave signal [1]. As a result, transmitted signals are attenuated and become too small to be detected and processed accurately at receivers. Transmit-receive module (TR module) is normally used to compensate for the propagation loss and increase the sensitivity of wireless systems, hence improving system performance including range extension.

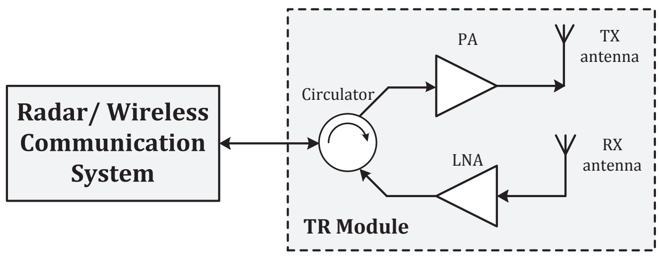


Fig. 1. Block diagram of TR module.

Researches on TR module focus on the development and implementation of new TR module topologies on various manufacturing technologies, including MMICs and hybrid MICs. Recently many designs using MMIC technologies have been reported, such as [2] – [5] in which the designs use GaAs, GaN or SiGe MMIC processes to obtain high quality and high level of integration. The drawbacks of MMIC technologies are manufacturing cost, complexities of circuits design and mismatches caused by fabrication process variations. In contrast, hybrid MIC circuits using discrete components occupy more area and dissipate more power. However, hybrid MIC technologies provide a shorter design time and capabilities of customization and fine tune of fabricated circuits. In [5], TR module uses TR switch to control the direction of signal flow. This topology provides the advantage of good isolation between transmitted and received signal thanks to the high isolation of TR switches but has the disadvantage of complexity in control circuit and the switching time of switches that limits the operating frequency of TR module. In this paper, a simpler and more cost-effective method to design a TR module, which extends the operating range of wireless systems, is proposed. The designed TR module using a ferrite circulator instead of TR switches relaxes the complexity of control circuits and switching time problems.

II. TR MODULE DESIGN

The block diagram of proposed TR module shown in Fig. 1 consists of a circulator, a power amplifier (PA) and a low-noise amplifier (LNA). The PA and LNA are connected together by a circulator, which splits input and output signals of transceiver into two directions. One drawback of this topology is RF leakage from output of transmitter to input of receiver, which is caused by low isolation of circulator and large disparity of RF signals. In addition, impedance mismatch between the ports of fabricated amplifiers and circulator produces internal reflected signals, which are then injected into transceiver. Despite being generated by reflection and coupling, RF leakages from transmitter are still larger than desired signal of receiver and may desensitize the whole transceiver system. To prevent the occurrence of these leakages, separate TX/RX antennas are used to improve the isolation between transmitted and received signals. Moreover, wideband amplifiers used in TR module should be well-matched with circulator's ports to meet the requirement of minimum internal reflected signals in designed module.

The TR module boosts the maximum output power, $P_{t,max}$, of transmitter and enhances the overall system's NF, hence the sensitivity, $P_{r,min}$, of receiver. By increasing the ratio of maximum power transmitted to minimum power received $P_{t,max}/P_{r,min}$, the TR module allows transceiver to send and receive microwave signal at further distance. As a result, these systems are capable of communicating at a greater range. The operating range of communication systems is defined depending on Free-Space Path Loss formula:

$$
\begin{aligned}
FSPL &= \frac{P_t}{P_r} = \frac{(4\pi)^2 R^2}{G_t G_r \lambda^2} \\
\rightarrow R_{\max} &= \sqrt{\frac{G_t G_r \lambda^2}{(4\pi)^2} \frac{P_{t,\max}}{P_{r,\min}}}
\end{aligned}
\tag{1}
$$

where G_t, G_r are transmitted/received (TX/RX) antenna gains; $P_{t,max}$, $P_{r,min}$ are maximum transmitted, minimum received powers; R is operating range and λ is signal wavelength. With unchanged system's parameters such as G_t, G_r, λ…, maximum operating range R_{max} is proportional to square root of $P_{t,max}/P_{r,min}$ ratio. Thus, TR module extends the range of transceiver systems by maximizing this right factor. In order to extend the operating range of radar about 3.3 times, $P_{t,max}/P_{r,min}$, ratio must increase at least by 21 dB, resulting in requirement of a 15-dB-gain PA, that can provide 15 dBm output power, and a 20-dB-gain LNA with 2-dB NF to enhance the sensitivity of receiver up to 6 dB. The following parts of this paper present the designs of these MIC amplifiers.

III. Power Amplifier Design

PA is the last block in the transmitter to amplify and provide a large transmitted signal at transmitter's output. Thus, designed X-band PA must have wide operating frequency band and high gain while maintaining enough linearity to not distort RF signals. In addition, good input matching and low power consumption are also required. Fabricated PA uses two Eudyna's transistors FSX027WF for each stage to provide a 15-dBm output signal.

A. Bias & Stability Circuit design

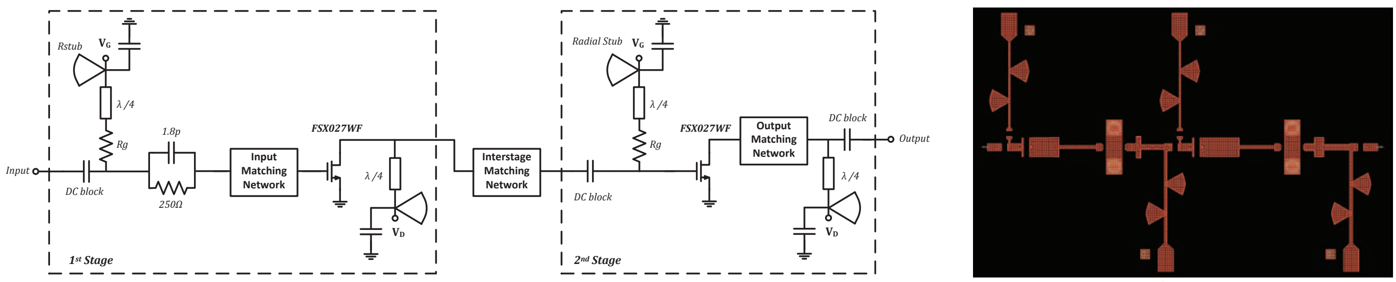
With the aim of achieving a high gain and stability amplifier, designed PA uses the common source topology where S terminal of transistor is connected to ground while input and output signals are injected and taken out at G and D terminals, respectively. The operating condition of transistor is determined where the PA design goals of high gain and linearity are ensured.

The bias network with DC feed and DC block is designed and realized. DC feed provides DC voltage for transistor while isolating RF signal. A λ/4 transmission line terminated by an AC short component has the characteristics of infinity input impedance with AC signal at designed frequency and zero input impedance with DC supply [6]; this topology can be used to realize DC feed. AC short component in this case is a 60-degree radial stub which serves as an open circuit at DC and a short circuit at designed frequency. The use of transmission line reduces the size of bias network and eliminates passive components which are expensive and lossy at high frequency. On the other hand, DC block prevents DC bias voltages from being changed when the amplifier is connected with other circuits; it is realized by a large capacitor.

To improve the stability, a parallel resistor-capacitor block is added at the amplifier's input to filter out the low frequency signal that may produce oscillation. A resistor R_G is also added between the gate terminal and DC feed to compensate for the input negative resistor of transistor, which causes oscillation at low frequency. The values of resistors and capacitors are carefully tuned to optimize the gain while maintaining sufficient stability of amplifier. The RC filter, R_G resistor used to improve the stability of designed PA as well as transistors' bias circuits are shown in the schematic in Fig. 2(a).

B. Conjugate Matching for Wideband Amplifier

PA designed based on load-pull technique provides the largest output power [7]. However, two main drawbacks of this method are the requirements of precise measurement equipment and large computation to determine optimum impedances. A less-exact but more-effective method is



(a) (b)

Fig. 2. Schematic (a) and Layout (b) of designed PA.

designing the matching networks based on conjugate matching technique [8]. This method, which ensures the maximum power gain of designed amplifier, is not only suitable in designing the 1st stage of PA working with small signals but also provides an acceptable error in designing the 2nd stage of PA working with medium output signal of 15 dBm. Proposed PA uses conjugate matching method to design input/output matching networks for the first and second stage of amplifier.

The wide operating frequency band requirement of PA underlines the need for designing matching networks that translates optimum impedances into source/load impedances, which are 50 Ohm, in the whole frequency band from 9.25 to 10.75 GHz. This requirement is met by using the stepped transmission line where multiple quarter-wave dielectric transmission lines with tunable characteristic impedances are placed serially. The frequency response of matching networks can be controlled by changing the width, thus the characteristic impedance, and the length of each stepped line.

Designed PA with bias circuit and matching network is laid-out as in Fig. 2(b) and design-rule checked. Electromagnetic (EM) simulation and post-layout simulation are performed to verify the parameters of PA before being fabricated. The simulated and measured results are shown in part V.

IV. Low Noise Amplifier Design

LNA is the first block in the receiver to amplify weak received signals and minimize noise added by the amplifier itself, thus improving receiver's sensitivity. To meet the TR module's performance, the designed X-band LNA must provide a gain over 20 dB with a NF of 2 dB. The design of broadband LNA focuses on wideband input matching, low NF and sufficient gain. Fabricated LNA uses two CEL's transistors NE3210S01, which have super low noise performance, high gain providing capacity and small input impedance, to provide the desired performance.

A. Bias & Stability Circuit design

Because of FET's high gain characteristic, especially at low frequency that may cause oscillation, the designed LNA uses common source topology. Besides, transistor's operating point is chosen to achieve the stable operation and minimum thermal noise. Two $\lambda/4$ transmission lines terminated by radial stubs are reused to provide DC supply.

Stability of amplifier at low frequency is ensured thanks to inductive degeneration technique where an additional inductor is placed between S terminal and ground. This technique also decreases the difference in real part of NE3210S01's input impedance and noise impedance, making noise impedance approach input impedance. Thus, simultaneous input impedance and noise matching can be achieved through optimizing the value of degenerative inductor.

Although inductor degeneration increases the stability of LNA at low frequencies, it is less effective at high frequencies. Another technique must be used to improve stability at all frequencies from 0 to 15 GHz. Because of low noise requirement of LNA, RC filter is no longer suitable. The solution using large shunt resistor connected at the output of transistor is more suitable due to its less-affective characteristic to noise performance. A demonstration of stability improvement techniques applied in LNA is shown in Fig. 3(a).

B. Noise Impedance Matching for Wideband Amplifier

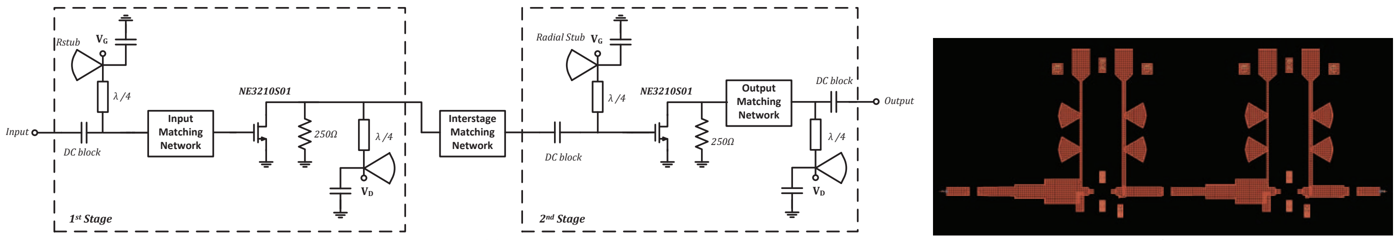
Attaining both minimum NF and good input matching is the most important goal in LNA design. Thanks to the characteristic of decreasing difference between the two input impedances of inductor degeneration technique, noise matching and input matching can be achieved simultaneously [8]. In addition, due to the small magnitude of transistor's input reflection coefficient Γ_{in} and high isolation of the chosen topology, wideband input matching as well as noise matching can be achieved easily by using stepped transmission line to transform input and noise impedance to source/load impedance in the whole frequency from 9.25 to 10.75 GHz.

Designed LNA is laid-out as in Fig. 3(b). EM simulation and post-layout simulation are also performed to verify the LNA's performances before being fabricated. The results are shown in the next part.

V. Measured Results & Complete TR Module

A. Measured Results

PA and LNA are fabricated using Isola's substrate. All passive components and SMA connectors used in the circuits are low-loss, high-quality, and high-frequency devices, which are precisely mounted on the circuits. Discrete transistors are placed carefully on the substrate to ensure good connection to the signal path and to the ground plane. All the circuits are enclosed by an aluminum box that functions as a strong ground and thermal radiator for the circuits.



(a) (b)

Fig. 3. Schematic (a) and Layout (b) of designed LNA.

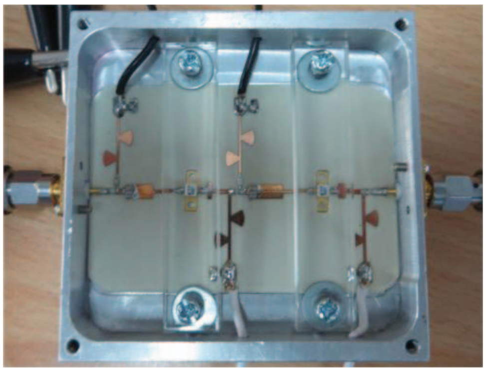


Fig. 4. Photograph of fabricated PA.

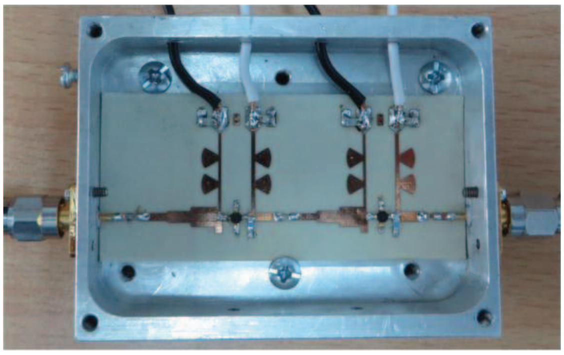


Fig. 7. Photograph of fabricated LNA.

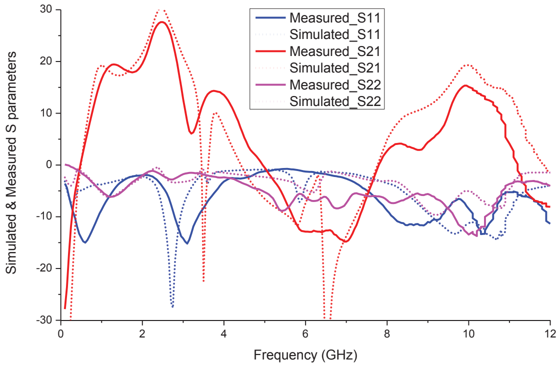


Fig. 5. Measured and Simulated S-parameters of designed PA.

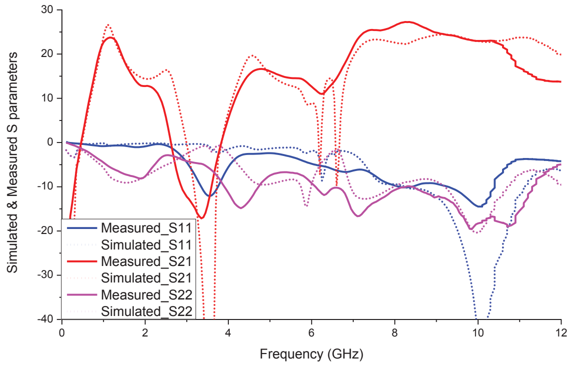


Fig. 8. Measured and Simulated S-parameters of designed LNA.

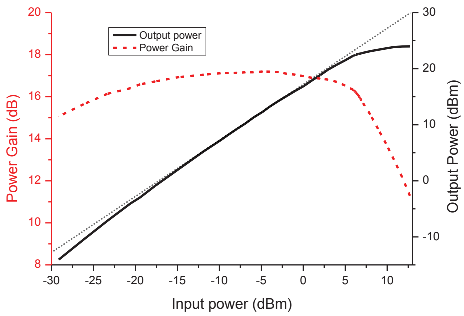


Fig. 6. Measured Output Power and Output P1dB of designed PA.

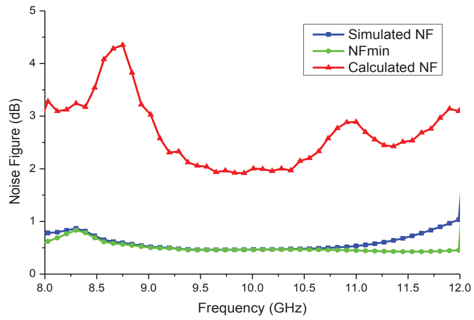


Fig. 9. Measured Noise Figure of designed LNA.

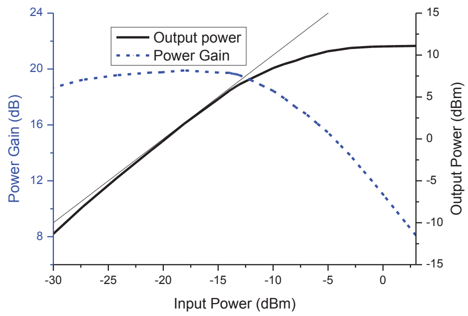


Fig. 10. Measured Output Power and Input P1dB of designed LNA.

1) Power Amplifier

Designed PA is measured using Agilent 20GHz Vector Network Analyzer E5071C. Fig. 4 is the photograph of designed two-stage PA enclosed by an aluminum box. The measured and simulated S parameters of this PA in the frequency range of 0 to 12 GHz are shown in Fig. 5.

As shown in Fig. 5, simulated and measured S parameters, including input/output return loss (S11/S22) and power gain (S21), are well agreed. At low frequency, the difference between simulated and measured input return loss is rather small but at high frequency, the input measured return loss is frequency-shifted down. The measured S11 varies from -6.5 dB to -13 dB in the frequency range from 9.25 to 10.75 GHz. Measured and simulated S22 have the same response. The measured gain has the same shape as the simulated one but a little bit lower at high frequencies. This may be caused by the lossy substrate and the effect of inaccurate fabricating process. The measured S21 varies from 6.1 to 15.1 dB and maximizes at the center of operating frequency band.

The measurement of P1dB is also performed and the result is shown in Fig. 6. The PA's measured OP1dB equals to 22.5 dBm, which is 7.5 dB larger than desired operating signal of 15

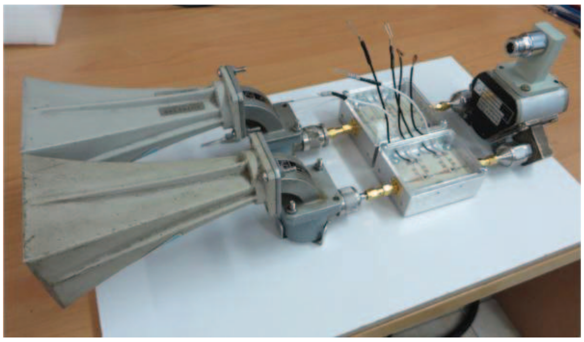


Fig. 11. Designed TR module.

dBm at output of transceiver, assuring that the transmitted signal is not distorted by the non-linearity of amplifier. Besides, measured maximum output power of PA is 24 dBm, which is large enough to make the designed PA attractive in many applications.

2) Low Noise Amplifier

Designed LNA is fabricated and enclosed in an aluminum box to prevent noises and interferers injecting to the circuit (Fig. 7). The measured and simulated S parameters of this LNA in the frequency range of 0 to 12 GHz are shown in Fig. 8. In Fig. 8, simulated and measured S parameters, including input/output return loss (S11 and S22) and power gain (S21), are plotted. The simulated and measured return loss, S11 and S22, show small differences at low frequencies. At high frequencies, the measured ones are a little worse than simulated ones. The measured S11 is always lower than -10 dB in the frequency range of 9.25 to 10.4 GHz. From 10.5 GHz and above, S11 decreases and equals to -4.1 dB at 10.75 GHz. The measured S22 is always lower than -12 dB. The decrease in quality of real circuit is explained as the effect of lossy substrate and the inaccuracy of fabricating process. Moreover, the measured gain, S21, is well agreed with the simulated one, which means that the amplifier provides a high and flat gain which is higher than 20 dB in the whole designed bandwidth. The maximum gain that LNA achieves is 24.4 dB at 9.25 GHz.

The measurement of NF is carried out and results are shown in Fig. 9. The minimum NF is 1.97 dB at 9.9 GHz and the maximum one is only 2.5 dB on the whole bandwidth from 9.25 to 10.75 GHz. The low NF and the high gain of LNA provide the sensitivity enhancement for systems. The P1dB measurement is also conducted and the results are shown in Fig. 10. Measured IP1dB of LNA equals to -11 dBm, which is large enough to prevent distortions.

B. Complete TR Module

TR module is integrated from fabricated amplifiers and waveguide circulator as shown in Fig. 11. Due to the applied stability improvement techniques and the isolation of metal box, oscillation caused by mutual influence between PA and LNA is under control. The designed TR module uses two separate horn antennas to transmit and receive RF signals. Integrated TR module is supplied by a designed DC power supply and carefully measured to verify its performance before being connected with an X-band transceiver.

The measured results show that the designed TR module has input return loss of 20 dB in frequency range of 9.25 to 10.75 GHz. The designed TR module is then connected with an X-band radar transceiver to verify its performance and demonstrate its range extension capability. Experimental results show that proposed module can operate stably in many conditions and helps extend the detection range over 200 meters, which is 3.5 times further than original transceiver.

VI. CONCLUSION

The paper presents the design of TR module, which consists of PA and LNA, to extend the operating range of a radar system. The measured results of fabricated two-stage PA satisfy the requirements of large output power of 15.1 dBm, high linearity and good input matching. At the same time, the fabricated two-stage LNA provides a very low NF of 2 dB, high gain with S21 larger than 20 dB while maintaining good input/output matching. The whole TR module are assembled and integrated with a radar system to demonstrate its range extension effect. Performance of TR module is verified through experimental results of radar system connected with designed TR module. The promising results enable proposed TR module to be further developed to suit in many applications in long range radar and wireless communication systems.

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