Design of Two L-Band RF Amplifiers Combination Using Wilkinson Power Dividers

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***Abstract*—This paper presents the design and development of a combined L-band radio frequency (RF) amplifier which is implemented by combining two single-stage RF amplifiers in parallel. The applications such as radar systems, satellite systems, and wireless communications, require a high output power that is limited by a single-stage RF amplifier. The Class-A single-stage RF amplifier in this paper provides 95 W output power for the frequencies of 1.2 GHz to 1.3 GHz. The output power can be increased by the combined two single-stage RF amplifiers. The Wilkinson power dividers with a 90˚ phase shifter are used in this paper. The prototype power divider is realized by using low-cost FR4 PCBs. The constructed power dividers working at a center frequency of 1.25 GHz have lower than –10 dB reflected coefficients at all ports. The transmitted coefficients of S_{21} and S_{31} are –3.61 dB and –3.55 dB, respectively. A relative phase difference between the two output ports is 90˚±1˚. The combined amplifier achieves 175.4 W total output power, 14.74 dB gain, and efficiency 25% for a continuous wave (CW) input signal.**

***Index Terms*—L-band RF amplifier, Wilkinson power dividers, low-cost FR4 PCBs, two single-stage RF amplifiers combination**

I. Introduction

The L-band radio frequency (RF) power amplifiers are utilized in many applications such as satellite communications, GPS systems, and radar systems, etc. [1]. Conventional RF amplifiers are realized by using vacuum tubes to provide high output power. Vacuum tube RF amplifiers generate waste heat during operation which yields lower efficiency. Power amplifiers using a vacuum tube device has a usually higher cost than the same ratio a solid-state transistor device. Therefore, solid-state transistor devices are suitable to use in a single-stage RF amplifier of the L-band frequency [2]-[5]. A single-stage RF amplifier cannot provide high output power but can be realized by combining several single-stage RF amplifiers [6], [7].

Fig. 1 shows a diagram of a combination of two single-stage RF amplifiers in parallel. A power divider separates an input signal into two equal amplitude outputs. One output is 90˚ phase shifted and is injected to the first amplifier. Two amplifiers have the same configuration that provides equal output powers. The output of the second amplifier is 90˚ phase shifted. The total output power is a sum of two amplifiers.

In this paper we present the design of such a amplifier, i.e., combined L-band RF amplifier (combined amplifier for short hereinafter) which is implemented by combining two single-stage RF amplifiers in parallel. The combined amplifier works at 1.25 GHz±50 MHz. The GaN RF power transistors are used to realize solid-state amplifiers. The 90˚ phase shifter circuit is included in conventional Wilkinson power divider. The Wilkinson power divider using FR4 printed circuit broads (PCB) was investigated in [8]. The RF-4 PCBs is simple, low cost, small size, and easy to build. The prototype power divider is coated with gold to protect against oxidation.

The paper is organized as follows. In Section II, we describe the design, fabrication, and performance of the combined L-band RF amplifier. The Wilkinson power divider will be described in Section III. The measured results of the combined amplifier is presented in Sections IV, and the concussion is presented in Section V.

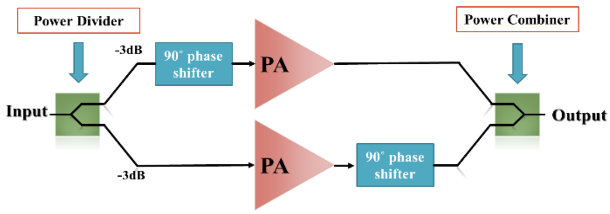

Fig. 1. Block diagram of combination of two single-stage RF amplifiers.

II. Single-Stage RF Amplifier Designs

A. Transistor Modules

The single-stage RF amplifier uses the GaN RF power transistors (T1G2028536-FL) operating from DC to 2 GHz with 18 dB linear gain [9]. It is a low-cost packaged transistor that is suitable to construct single-stage RF amplifiers. The specifications of the transistor module are presented in Table I.

Table I. Specifications of Transistor Modules

Parameters	Specifications
Frequency	DC to 2 GHz
Maximum output power	230 W at 1.2 GHz
Linear gain	18 dB at 1.2 GHz
Drain voltage (V_D)	36 V
Drain quiescent current (I_{DQ})	576 mA
Maximum RF input power (CW)	47dBm

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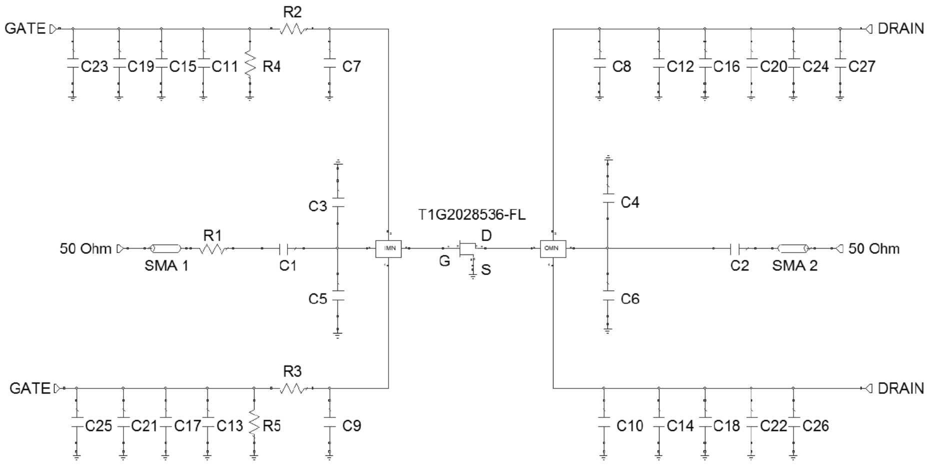

Fig. 2. Schematic circuit of a single-stage RF amplifier [9]. ($C1$=$C2$=27 pF, $C3$=$C5$=3.9 pF, $C4$=$C6$=4.7 pF, $R1$ = 12.1 Ω).

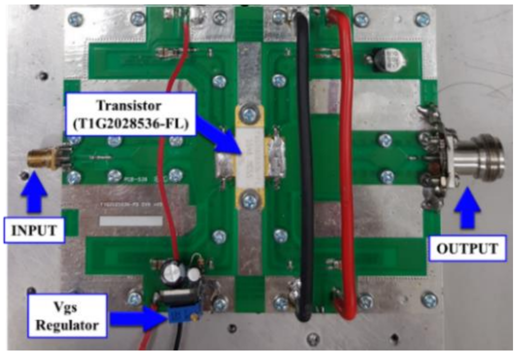

Fig. 3. Single-stage RF amplifier.

B. Single-Stage RF Amplifiers

The schematic of a single-stage RF amplifier is shown in Fig. 2. Resistors and capacitors are used to maintain the DC voltage of the drain and gate bias in a bias network. The impedance of input and output matching networks is 50 Ω. The designed matching networks are mixing lump elements and printed transmission lines. The capacitors of 3.9 pF and 4.7 pF are used to input matching network and output matching network, respectively. The capacitor for the input stage is 27 pF. The resistor and capacitor for the output stage is 12.1 Ω and 27 pF respectively. The single-stage RF amplifier uses Rogers RO4350 PCBs, 20mil substrate thickness, and 3.48 dielectric constant (ε_r). The final assembled amplifier is mounted onto an aluminum alloy heat sink, as shown in Fig. 3.

C. Performance of Single-Stage RF Amplifiers

A block diagram of a test bench configuration to measure the single-stage RF amplifier shown in Fig. 4. The equipment devices consist of a signal generator, a driver amplifier, a power supply, attenuator, and a spectrum analyzer. A signal generator creates a 1.25 GHz continuous wave (CW) signal. The driver amplifier provides 20 W maximum output power with gain 43 dB. The total attenuation of attenuators is 71.6 dB.

The L-band RF amplifier is biased in a Class-A amplifier. A drain voltage (V_D) of the amplifier is 36 V dc. First tested for stable bias point that applies a gate voltage (V_G) of –2.9 V dc, it obtains a drain current (I_{DQ}) is approximately 500 mA. Then the stable bias point is achieved, 1.25 GHz CW signal from a driver amplifier is applied to the L-band RF amplifier. The measured results of the L-band RF amplifier are shown in Fig. 5 and Fig. 6. The amplifier achieves 95.5 W output power and approximate 25% efficiency when the input power is 5.5 W.

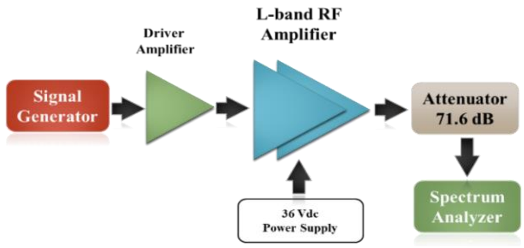

Fig. 4. Block diagram of test bench configuration.

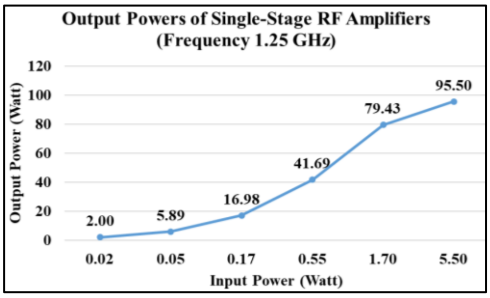

Fig. 5. Output powers of a single-stage RF amplifier with V_{CC} = 36 V, V_G = -2.9 V, I_{DQ} = 500 mA and efficiency 25%.

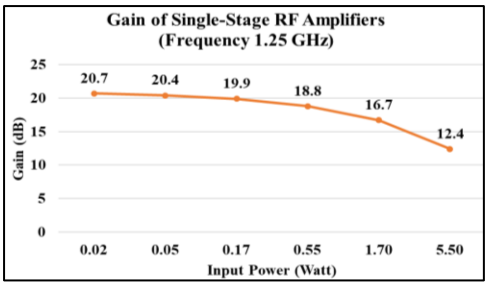

Fig. 6. Gain of a single-stage RF amplifier with V_{CC} = 36V, V_G = -2.9V, I_{DQ} = 500 mA and efficiency 25%.

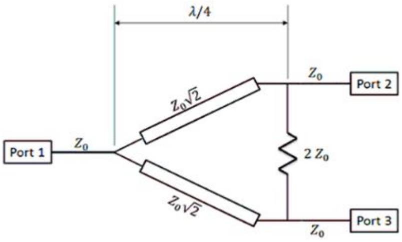

Fig. 7. Basic schematic of a Wilkinson power divider.

III. Design of Power Dividers

A. Wilkinson Power Dividers

The Wilkinson power divider device, as shown in Fig. 7, has two functions, power divider and power combiner [9], [10]. The power divider splits the power of an input signal (port 1) into two equal output signals (–3dB), injected to port 2 and port 3, respectively. On the contrary, the power combiner combines the signals from port 2 and port 3 into port 1.

B. Power Dividers Design

The configuration in Fig. 7 is used to design 2-way power dividers. The characteristic impedance (Z_0) is 50 Ω that is used to calculate an impedance of quarter wave-length transmission line ($Z_0\sqrt{2}$). The power divider is realized by using microstrip lines, as shown in Fig. 8. A conductor and a ground plane are separated by a 1.6 mm substrate thickness (h). The dielectric constant (ε_r) of FR4 PCBs is 4.6. The width (W) and length (L) of the microstrip line can be calculated by the method in [10].

1) Effective dielectric constant

The effective dielectric constant (ε_{eff}) can be calculated from (1) and (2) [10]:

$$\varepsilon_{eff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12h/W}}\right], \text{ for } W/h\geq 1 \quad (1)$$

$$\varepsilon_{eff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\times \left[\frac{1}{\sqrt{1+12h/W}}+0.04\left(1+\frac{W}{h}\right)^2\right], \text{ for } W/h<1 \quad (2)$$

2) The length of the microstrip line

The length of microstrip lines (L) can be calculated from a quarter wavelength value ($\lambda/4$) with an effective dielectric constant (ε_{eff}). It is given by

$$L=\frac{\lambda}{4}, \quad \lambda=\frac{c}{f\sqrt{\varepsilon_{eff}}} \quad (3)$$

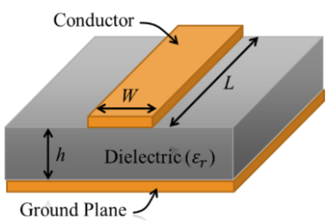

Fig. 8. Microstrip transmission lines.

where f is an operating frequency and c is a speed of light, 3×10^8 m/s.

3) The microstrip line width

The effective dielectric constant (ε_{eff}) from (1) and (2) and characteristic impedance (Z_0=50 Ω) are used to calculate a microstrip line width (W) by using (4) and (5):

$$Z_0=\frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{W}{h}+1.393+\frac{2}{3}\ln\left(\frac{W}{h}+1.444\right)\right]}, \text{ for } W/h\geq 1 \quad (4)$$

$$Z_0=\frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(\frac{8h}{W}+\frac{W}{4h}\right) (\Omega), \text{ for } W/h<1 \quad (5)$$

Also, the microstrip line width of quarter wavelength transmission lines can be calculated from (4) and (5), using an impedance is 70.7 Ω ($Z_0\sqrt{2}$). The power dividers in this paper operating at center frequency are 1.25 GHz. Using (1)-(5), suppose the length (L) of a microstrip line is 32.3 mm, then the width (W) of the microstrip line of impedance 50 Ω is 2.9 mm while the width (W) of the microstrip line of impedance 70.7 Ω is 1.5 mm. Wilkinson power dividers are usually integrated with a load resistor as 100 Ω ($2Z_0$) to achieve better isolation between two output ports. These parameters are simulated with the CST software to verify a power divider circuit designed.

C. Implementations

The constructed power divider is shown in Fig. 9. The overall physical dimension is 52 mm ×127 mm. A quarter wavelength transmission line is included in port 2 that leads to a 90˚ phase difference between two output ports. The prototype power divider is coated with gold to protect against oxidation. The experimental results of Wilkinson power divider working at 1.25 GHz center frequency are shown in Table II.

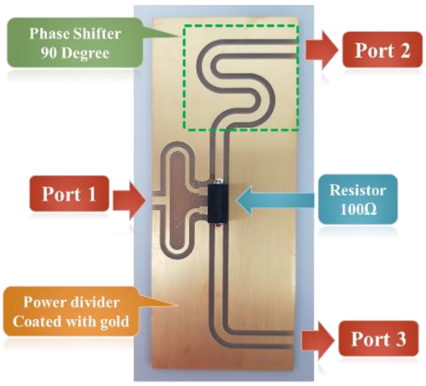

Fig. 9. A photograph of a prototype Wilkinson power divider.

TABLE II. Measured Results of Constructed Power Divider Working at 1.25 GHz Center Frequency

Reflected coefficients (dB)		Transmitted coefficients (dB)		Isolation (dB)		Phase (Degree)	
S_{11}	-31.35	-	-	-	-	S_{21}	20.10
S_{22}	-12.15	S_{21}	-3.61	-	-	S_{31}	109.64
S_{33}	-12.52	S_{31}	-3.55	S_{32}	-15.14	Δ	90.92

The reflected coefficients of all ports are lower than −10 dB. The transmitted coefficient between port 1 and port 2 (S_{21}) is −3.61 dB and the transmitted coefficient between port 1 and port 3 (S_{31}) is −3.55 dB. The insertion losses of two output ports are approximately 0.6 dB. The isolation value between port 2 and port 3 (S_{32}) is lower than −15 dB. The relative phase difference between two output ports is 90.92˚.

IV. Measured Results of the Combined Amplifier

The measured results of the combined amplifier are presented in this section. The combined amplifier is composed of two single-stage RF amplifiers in parallel, as shown in Fig. 10. The combined amplifier achieves a total output of 175.4 W with gain 14.74 dB, as shown in Fig. 11. Both amplifiers use a 15 A average drain current and a 36 V power supply leading to the efficiency of approximate 31.4%. The total output power has been dropped off 15.6 watts, calculated from 2×95.5W output power of single-stage RF Amplifiers, due to the insertion loss of the power combiner at the output stage. The measured results of the combined amplifier are given in Table III. The results show the equal output powers of three frequencies.

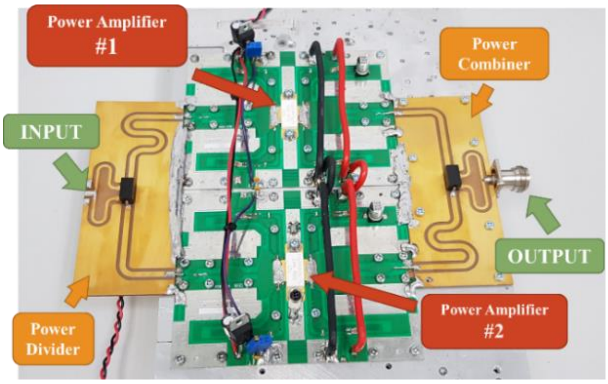

Fig. 10. Photographs of the combined L-band RF amplifier.

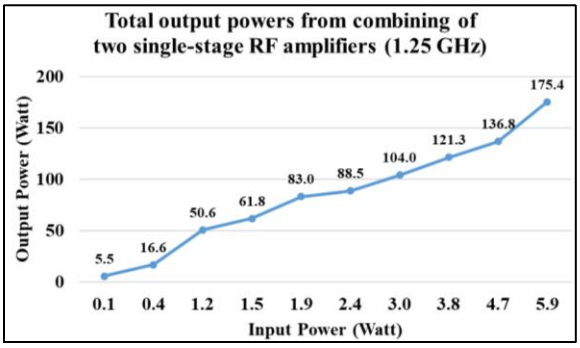

Fig. 11. The total output power of the combined L-band RF amplifier.

Table III Summary Measured Results of L-band RF Amplifiers

Frequency (GHz)	Output power (dBm)	Output power (Watt)	Gain (dB)
1.2	52.47	176.60	14.77
1.25	52.44	175.39	14.74
1.3	52.39	173.38	14.69

V. Conclusion

This paper proposes a combined L-band RF amplifier with developed Wilkinson power dividers. The L-band RF amplifier based on a Class-A amplifier uses GaN RF power transistors to construct a prototype. A single-stage RF amplifier provides 95.5 W with gain 12.4 dB for a 1.25 GHz continuous wave (CW) input signal. The FR4 PCBs are used to make the developed Wilkinson power divider, which is simple, low cost, small size, and easy to construct. A 90˚ phase shifter is integrated into a power divider circuit. The prototype power divider is coated with gold to protect against oxidation.

The reflected coefficients of prototype power divider for all ports are lower than −10 dB. The transmitted coefficient of S_{21} and S_{31} are −3.61 dB and −3.55 dB respectively. The relative phase difference between the two output ports is 90.92˚. The combined amplifier achieves the total output power of 175.4 W (52.44 dBm), efficiency 31.4% and 14.74 dB gain at the frequency of 1.25 GHz in CW mode. The output power has been slight dropped due to the insertion losses of the power combiner at the output stage. The experimental results from Table III support the L-band RF amplifier in this paper to operate at a center frequency of 1.25 GHz ±50 MHz.

Acknowledgment

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