Keysight Technologies
1 WATT 17.7 GHz – 32 GHz Linear Power Amplifier

Technical Overview

1.0 Introduction

This application note provides application information and performance data on the use of TC915 linear amplifiers in multiple chip combined configurations to increase output power. Configurations of two (2x) and four (4x) MMICs were assembled and tested to demonstrate feasibility and measure performance.

2.0 Description

The TC915 (MMIC) is a 17.7 GHz to 32 GHz high performance linear power amplifier. Each MMIC provides greater than 1/4 watt output power at 1 dB gain compression (P_{-1}). The MMIC was designed as a linear power amplifier for use in microwave and millimeter wave transmitters. It is possible to power combine these amplifiers to increase the output power level. The results indicate > 1/2 watt for the 2x configuration, and > 1 watt for the 4x configuration. This is the P_{-1} power output into a 50 Ω load.

The demonstration circuits use high performance thin film microcircuit networks to power divide and equally drive the MMIC inputs. The same microcircuits are used to combine the output power of each MMIC. The circuits are a variation of the Wilkinson divider (Wilkinson, 1960; Mercer, 1996). When properly designed, these networks have remarkably low loss while maintaining a 50 Ω impedance at their input and output terminals.

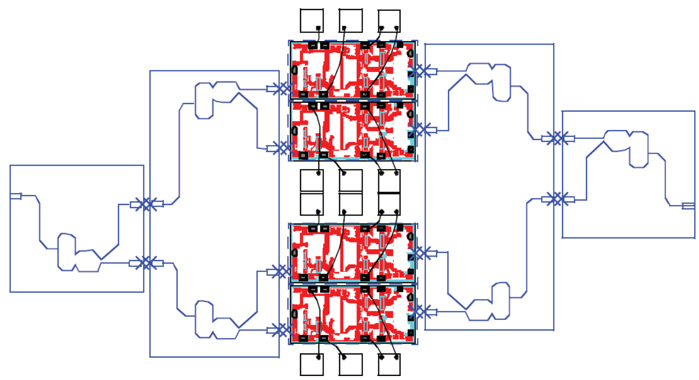

Figure 1. Assembly drawing of 4x amplifier

The networks used in the demonstration application were designed in a 5 mil sapphire thin film process usable to 50 GHz. Since the TC915 has integrated coupling capacitors and operates to 33 GHz, the combiner thin film circuits should perform adequately using a 5 mil alumina thin film process without the need for capacitors.[1]

Figure 1 illustrates the physical layout of the 4x amplifier configuration. Details of the 2x amplifier configuration are not illustrated. Biasing and bypassing of the combined amplifiers is covered in specific sections of this application note, as well as bonding and die attach.

The demonstration circuits were assembled in a specially designed, low loss, instrument grade microcircuit package. The RF connectors are 2.4 mm usable to 50 GHz. All measurements and performance data includes package and combiner losses.

3.0 Performance

Four 4x amplifiers were evaluated. All four amplifiers exhibited similar performance within a few tenths of one dB. Most measurements were performed on all four amplifiers. Typical performance is provided in this section. Only one 2x amplifier was evaluated.

A summary of the RF performance measurements on the
combined amplifiers is included in this section of the application note. The performance data includes: S–parameter sweeps, power and gain measurements at four temperatures, IMD measurements, and some load pull results.

3.1 S–Parameters

S–parameters were measured on the two–port amplifier assembly. Figure 2 gives test results for the packaged 4x amplifier assembly. Note the input and output return loss (S_{11} and S_{22}): both are similar because of the Wilkinson network on both input and output. S_{21} or the SS–gain is about 2 dB low which is attributed to connectors + connector launches + power divider + power combiner losses (see section 3.4 Load Pull).

3.2 Power

Figure 3 illustrates the P_{-1} performance of the 1x, 2x, and 4x amplifier configurations at four frequencies. The TC915 is designed to operate as a linear amplifier up to 1 dB of gain compression (P_{-1}). At P_{-1} the single amplifier provides better than 24 dBm (> 1/4 watt) output power; the 2x amplifier increases the output power level 3 dB to > 27 dBm (1/2 watt); and the 4x amplifier increases power by 6 dB to > 30 dBm (1 watt).

Figure 4 illustrates the gain and power saturation characteristics of the 4x amplifier at four frequencies. The gain of the power–combined amplifier is the gain of the single MMIC less the resistive losses of the package, power divider, and power combiner.

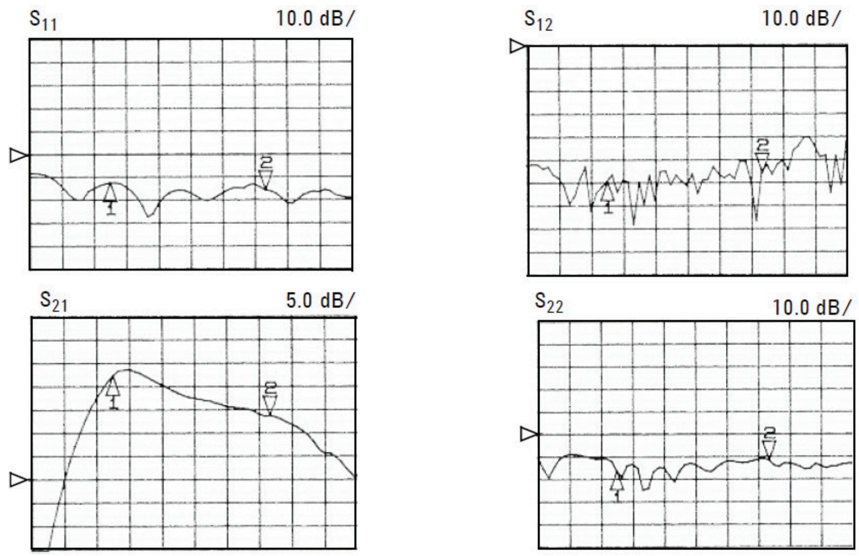

Figure 2. 10 – 40 GHz S parameters of 4x marker 1 = 17.7 GHz, marker 2 = 32 GHz

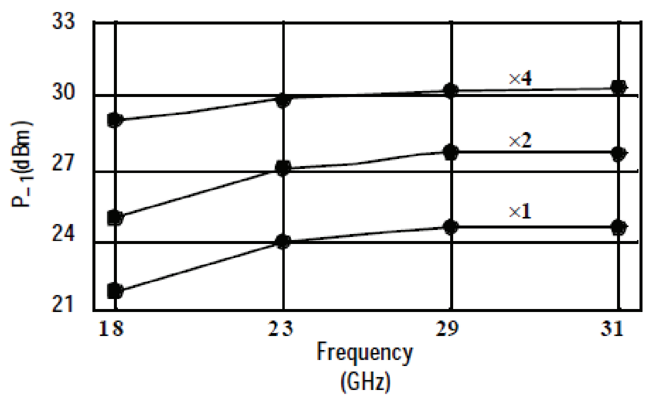

Figure 3. P_{-1} Performance for 1x, 2x, 4x amplifiers

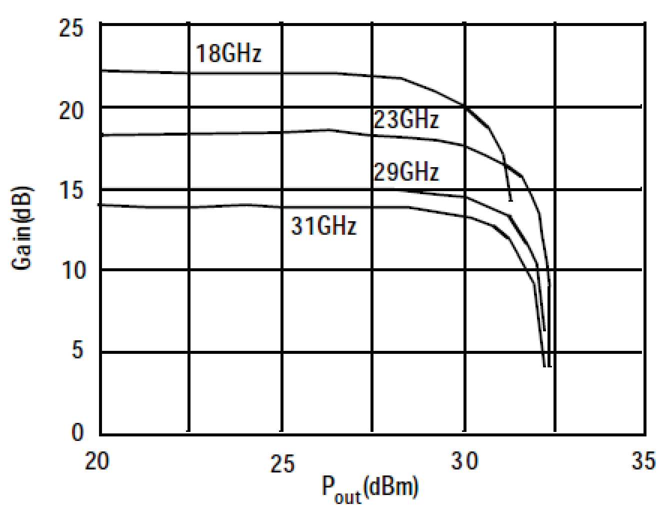

Figure 4. 4x amplifier gain and saturation characteristics at four frequencies

3.3 Power vs. temperature

Gain and power performance of the 4x amplifier were measured at –25 °C, 0 °C, 25 °C and 75 °C. Figure 5 illustrates the amplifier performance at these four temperatures. Thermal coefficients of gain and P_{-1} were calculated for temperature 25 °C to 75 °C. The temperature coefficient of gain is –0.05 to –0.06 dB/°C and the coefficient of P_{-1} is –0.01 dB/°C.

3.4 Load Pull

One 4x amplifier was tested at 29 GHz on a load–pull system. This system adjusts the output match or impedance while monitoring output power. The results indicate that the output impedance of the amplifier package is somewhat capacitive, probably due to imperfect connector transitions. This capacitive loss (3/4 dB) could be reduced by milling out a small air cavity under the connector launch–to–substrate area. The load–pull system cannot adequately check the MMIC output to the combiner match directly.

3.5 Intermodulation Distortion (IMD)

Two–tone measurements were performed at 23, 29 and 31 GHz. Two tones were combined and calibrated as an input signal to the 4x amplifiers. The input tones were of equal amplitude and stepped in two dB increments from –15 dBm to +15 dBm. Output power and third order intermodulation products were measured. The third order intercept (TOI) was calculated. The results indicate similar performance at all three test frequencies. The calculated intercept varied from 36 dBm to 40 dBm, depending on input level. Figure 6 illustrates typical third order products at 29 GHz, with 1, 10 and 200 MHz input signal spacing.

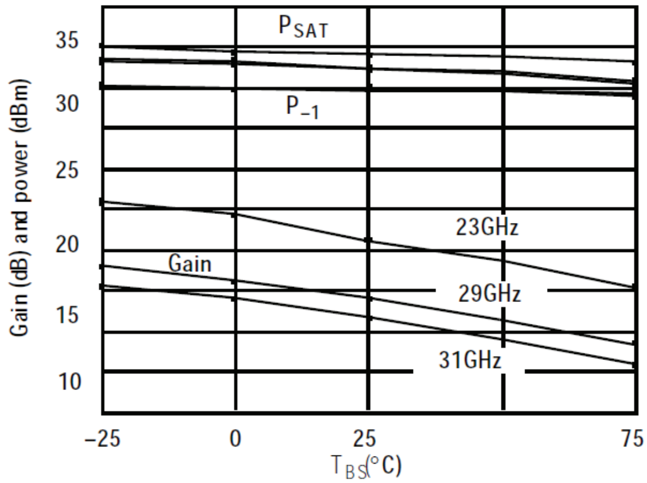

Figure 5. Temperature performance of 4x amplifier gain, P_{-1}, PSAT at three frequencies

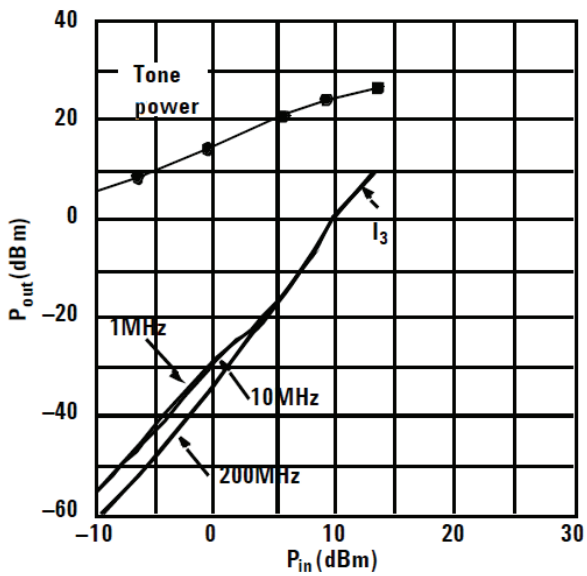

Figure 6. 29 GHz third order intermodulation products at three tone spacing

4.0 Driving the Power Amplifier

Driving the 4x amplifier to P_{-1} (30 dBm) requires about 17 dBm input drive power. TheTC906 provides 18 to 19 dBm at P_{-1} and is the “designated driver” for the TC915. The gain of the TC915 is 24 dB typical at 29 GHz. If the TC915 is used to drive the 4x amplifier, then the input drive power would be about –6 dBm. In cases where there may be excessive losses between the driver and the power amplifier, such as a filter network, the TC916 may be selected. The TC916 provides 22 dBm at P_{-1}. This selection provides 5 dB more drive power in the linear range than the TC906. The TC916 provides 7 dB of gain which means that the driver input power would be 10 to 11 dBm.

5.0 Thermal Considerations

Thermal performance is an important design consideration for any power amplifier. Reliability considerations dictate that the maximum channel temperature of the output power FETs be maintained below the specified 170 °C for a MTTF greater than one million hours. Eight to ten degree rise above this maximum results in a 50% reduction in MTTF.

High performance linear amplifiers, by design, have low power added efficiency (PAE). As PAE goes up, the signals are swinging closer to current saturation and toward pinchoff, resulting in more nonlinearity than if the signal swing, relative to the drain current saturation and pinchoff margin, was lower. Low PAE translates to more power dissipation and higher temperatures, but improved linear performance. Thermally, the multichip combined amplifier distributes the heat over a larger area improving the thermal dissipation possibilities. This translates to lower channel temperatures of active devices improving reliability and performance.

Analysis of the 4x amplifier’s thermal performance made use of on chip temperature diodes, backside temperature measurement devices (RTDs), and correlations to determine channel temperatures of the four MMIC chips in close proximity.

During the design of the TC915 MMIC thermal profiling was performed using an IR system. The system resolves temperatures with 5 μm^2 resolution. Also, liquid crystal measurements were used to determine the thermal resistance of 37 °C/W for the output stage of the MMIC amplifier as specified in the data sheet. Liquid crystal measurements were in close agreement with the IR profiling. From this work a correlation was developed between the on–chip temperature diodes and the output FETs channel temperature.

The results of the measurements and thermal study of the 4x demonstration amplifier indicate that the thermal reliability requirements provided in the TC915 data sheet can be met using conventional thermal design techniques.

6.0 Die Attach

The MMICs, combining substrates, and bypass capacitors were epoxy die attached using Ablebond 84–1. Epoxy die attach is the preferred production die attach method because it is faster, done at lower temperatures, and allows more precise placement of components. When properly used, thermal and electrical results are comparable to eutectic die attach.

It is important to control the thickness of the epoxy attachment layer. The nominal epoxy thickness is 0.5 mils. Thick epoxy layers increase MMIC temperatures and can affect RF performance and DC grounding. Die attach epoxies are thermally and electrically conductive when applied at the specified thickness. When properly used, thermal gradients are low and adequate grounding results

7.0 Bypassing

Selection of bypass capacitors, their location, bond wire diameter and length, are important criteria in the implementation of the power combined amplifier assembly.

RF grounding and bypassing of each bias port is important to obtain full performance and prevention of bias oscillations in the combined amplifiers. The demonstration amplifiers use four stages of RF bypassing. The first stage of bypassing actually provides the RF ground for the amplifiers passband frequencies; 100 pF microwave bypass capacitors are located near each bias pad (see Figure 1). A short bond wire (low inductance) to the 100 pF capacitor completes the RF ground for the passband frequencies. The second stage starts with a longer bond wire from the 100 pF caps to 800 pF microwave chip capacitors to provide bypassing or suppression for microwave frequencies below the passband. The inductance of the bond wire provides decoupling from the first stage network. The final bond wire from the 800 pF caps goes to the package feedthrough. A 1500 pF feedthrough suppresses RF frequencies to 1 MHz. Outside the microcircuit package, a 3 to 6 µF tantalum capacitor provides the final bypass network for frequencies below 1 MHz. This bypass scheme provides good RF grounding and good oscillation suppression for the MMICs from the passband frequencies to DC.

8.0 Bonding

Bias power distribution is important when power combining MMICs. Each MMIC should be biased equally. When high currents are flowing, voltage drops in bond wires become important. Table 1 gives the resistance per inch for three common bond wires. V_{d2} of the TC915 nominally requires 0.46 amps, and increases to over 1/2 amp at P_{-1}. At 1/2 amp, the voltage drop per inch for the three wires is 1.15 V, 0.65 V, and 0.25 V, respectively. Also important is the bond wire fusing current. Gold wire melts at 1067 °C.

Table 1. Bond wire resistance

Measured resistance	
Diameter (inch)	**Ohms/inch**
0.0007	2.3
0.0010	1.3
0.0015	0.5

Figure 7 shows the melting point for the three bond wires vs. length and current. Note that at 1/2 amp a 0.7 mil bond wire melts if it is longer than 100 mils. Since 0.7 mil bond wire is preferred for connection to the MMIC pads at high currents, the bond wires must be short.

Ideally, separate and equal length bond wires to each of the MMIC's bias ports would insure that the voltage drops in each bond wire would be equal.

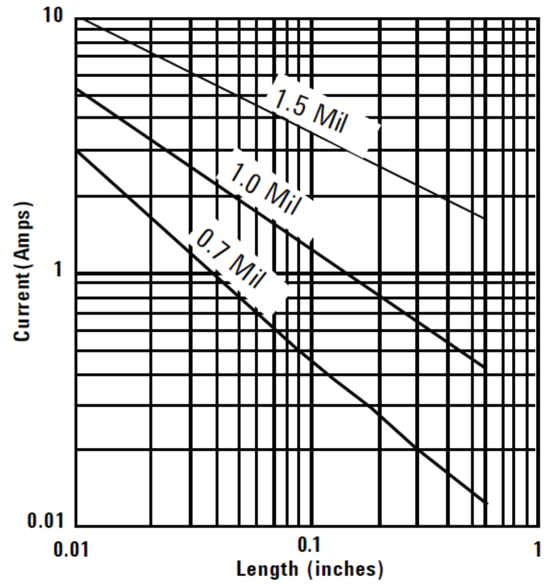

Figure 7. Bond wire fusing current vs. length for three wire diameters

9.0 Biasing

To bias the 4x amplifier, three sources are needed: one adjustable negative supply (–2.0 to 0.0 V) and two positive supplies (V_{d1} = 3.5 V with 1.5 amp capacity, V_{d2} = 5.0 V with 2.5 amp capacity).

With no RF applied, apply –2.0 V to V_{gg}; then apply V_{d1} and V_{d2}. With –2.0 V on the gate the amplifier is pinched off so that I_{d1} and I_{d2} should be only a few mA. Adjust V_{gg} toward 0 V until I_{d2} = 1.84 amperes. I_{d1} should self bias to approximately 1.0 amperes. RF may now be applied. As RF power input level is increased, I_{d1} and I_{d2} will increase. When P_{out} reaches P_{-1} power level, I_{d1} will increase only slightly, and I_{d2} will increase to about 2.2 amps.

10.0 Conclusion

Power combining MMIC amplifiers provide a practical method to efficiently increase available RF power levels. Power dividing and power combining networks such as the Wilkinson design on 5 mil substrates have excellent performance at millimeter frequencies; are small, have low loss, and result in a cost effective method to increase RF power.

The demonstration circuit illustrated in this application note provides linear performance and output power to satisfy many of today's point–to–point and point–to–multipoint transmitter design requirements.

11.0 References

1. Wilkinson, E.J., *An N–Way hybrid power divider,* IRE Trans. On microwave Theory and Techniques, Vol.8, No. 1, January 1960, pp. 116–118.

2. Mercer, S.R., *Linear Simulators Offer Successful Microstrip Modeling for Wilkinson Power–Splitters,* RF Design, September 1996, pp. 38–48.

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