Highly Linear & Efficient Power Spatium Combiner Amplifier with GaN HPA MMIC at Millimeter Wavelength Frequency

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***Abstract*—A 16-Way Spatium™ Combiner RF Amplifier (16W-SCRA) with GaN MMIC HEMT has been developed and tested over mm-wavelength frequency. Linear, and saturated output power of the 16W-SCRA over the frequency range between 27 and 31GHz were measured to be greater than 49dBm (79 Watt) and 50dBm (100 Watt), respectively. Power-Added Efficiency (PAE) of the 16W-SCRA was also measured to be > 17% at +71ºC. This 16W-SCRA has a compact form factor that can fit into ~40 in^3 space. In addition, this 16W-SCRA is relatively inexpensive compared to other high RF power amplifiers such as travelling wave tubes. Overall merit of this SCRA's high performance and low cost makes it a unique candidate as a next generation solid state RF amplifier replacing conventional more expensive and less reliable vacuum tube based RF amplifiers for communications and multi-function mm-wave frequency high power applications.**

***Keywords*—spatial power combiner, GaN MMIC, power amplifiers.**

I. Introduction

Demand for high performance, broadband, low cost and highly efficient RF power amplifiers in millimetre-wave (mm-wave) frequencies for modern communication and multi-function high power applications is higher than ever. For example, as commercial satellite telecommunications (Satcom) technologies are continuously evolving to meet growing demands for voice, video, high-rate data, and multimedia content distribution, where high power RF amplifier operation at mm-wave frequencies is one of the key pieces in the Satcom transponder. These RF power amplifiers are used to increase the power of an uplink signal (27 to 31GHz) to the satellite. Traditionally, traveling-wave tube amplifiers (TWTAs) have been the technology of choice due to the higher output power and high frequency operation [1]. However, use of today's Gallium Nitride (GaN) Monolithic Microwave Integrated Circuit (MMIC) HEMT for SSPAs provides technology advancement such as improving amplifier linearization and reliability, enabling miniaturization of amplifier, and low production cost. In addition, today's RF power amplifiers with GaN MMIC have also been demonstrated to produce similar RF output power performance to that of the TWTA. Therefore, GaN MMIC SSPAs can be an excellent choice as RF amplifiers for communication applications.

In recent years, spatial power-combining techniques have been demonstrated for high-power-combining capabilities at broadband operating frequencies with GaN MMIC SSPAs [2-4]. Qorvo, Inc. has developed and demonstrated spatial N-way power combiners, known as Spatium™, at decade (10:1) bandwidths in microwave frequencies (e.g., 2 to 20 GHz, 16-way Spatium power combiner amplifier) and at mm-wave frequencies (15 to 40 GHz, 16-way Spatium power combiner amplifier) and power levels exceeding >52dBm (CW 150 watts) by utilizing GaN MMICs [5-8]. The particular interest in this N-way Spatium power combiner amplifier with GaN MMICs has three major superiorities over other solid state power amplifiers: First, a Spatium™ power combiner has high combining efficiency over large bandwidths to provide a higher figure of merit in power-combining performances than any other current power combiner technique, such as SSPA radial waveguide power combiner, planar power combiner, etc., available today. Second, a Spatium power combiner amplifier with GaN MMICs can provide higher reliability than that of TWTAs. Third, a Spatium™ power combiner amplifier with GaN MMICs is compact, lightweight, and also low cost. Overall, this technology demonstrates clearly a practical, cost-effective Spatium power combiner amplifier that has advantages over current TWTA technologies for high-performance and broadband applications covering from microwave to over mm-wavelength.

In this paper, Qorvo's IDP division has leveraged internal GaN high power amplifier (HPA) technologies [9-10] to develop highly efficient 16-way Spatium™ combiner RF amplifier (16W-SCRA) that is proven to produce high linear & saturated output power in the mm-wavelength frequency, 27 to 31GHz, for high performance and reliable low cost Satcom systems. A performance of 16W-SCRA with GaN MMICs work is discussed next.

II. 16-Way Spatium Combiner RF Amplifier (16W-SCRA)

The developed 16W-SCRA has a 16 channel Spatium™ splitter at the input, with 16 GaN HEMT HPA MMICs one loaded on each channel, and a 16 channel Spatium™ combiner at output. The input RF signal (from 2.92mm coax connector) is split into 16 channels and amplified by the GaN HPA MMICs. After the 16 GaN HPA, the amplified RF signals are combined using a 16 channel Spatium™ combiner into a single output WR-28 waveguide. Fig. 1 illustrates the block diagram of the developed 16W-SCRA. As shown in the block diagram, the 16W-SCRA is comprised of passive splitter & combiner parts and a MMIC-based active amplifier part. The next section describes (a) the 16W-SCRA passive (16-way Spatium™)

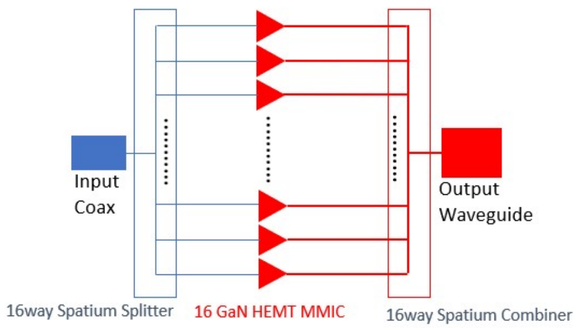


Fig. 1. 16-waySpatium™ combiner RF amplifier(16W-SCRA) block diagram.

part, (b) the 16W-SCRA active (with GaN HPA MMICs) part, and (c) 16W-SCRA saturated & linear output power measurements.

A. Passive 16-way Spatium™

The Spatium™ is designed to operate over decade bandwidths by employing antipodal finline antenna on low loss PCB material. This antipodal finline antenna in the Spatium™ acts as a probe for mode transition between a coaxial waveguide and a microstrip line, where a TEM wave propagation in a coaxial waveguide can be transitioned to a TEM propagation in a microstrip line.

Each antipodal finline antenna is attached to a wedge-shape metal blade carrier fixture (1/16th of 16-way structure), and the assembly of all 16 antennas on the blade carrier fixtures form the coaxial waveguide structure. This coaxial waveguide structure formed by the 16-blade assembly is assembled to a 50-Ω input and the output coaxial cones at the input and output sides of the 16-way Spatium™ splitter and combiner structure, respectively. Each antenna then transitions to a 50-Ω microstrip line in the center of the Spatium™ structure that allows further transitions to the active components (GaN HPA MMICs). The cone shaped coaxial structure between the 50-Ω coaxial input and the large diameter of the coaxial waveguide structure acts as an impedance transformer.

Before building the 16W-SCRA active hardware, a passive 16-way Spatium™ combiner having back-to-back antipodal antennas with microstrip thru lines (will be replaced by GaN MMICs for the active version i.e. 16W-SCRA) was designed and built to demonstrate RF responses for validating the modelled performance. This passive 16-way Spatium was assembled with 2.92mm coax connectors on both input and output sides for checking broadband passive response, but custom designed WR28 waveguide was used at output side of the 16W-SCRA, as depicted in Fig. 1 system block diagram, to handle high output power.

Fig. 2 shows overlay plots of predicted and measured passive responses for the HFSS 16-way passive Spatium model and the passive Spatium hardware. Dashed and solid line of the RF responses in the Fig. 2-(a) and (b)corresponds to HFSS prediction and hardware measurement, respectively.

Profiles in Fig. 2 exhibit broadband RF response which covers the 20 to 35 GHz, but effective operable bandwidth for the antipodal antenna in the 16-way Spatium™ was designed to

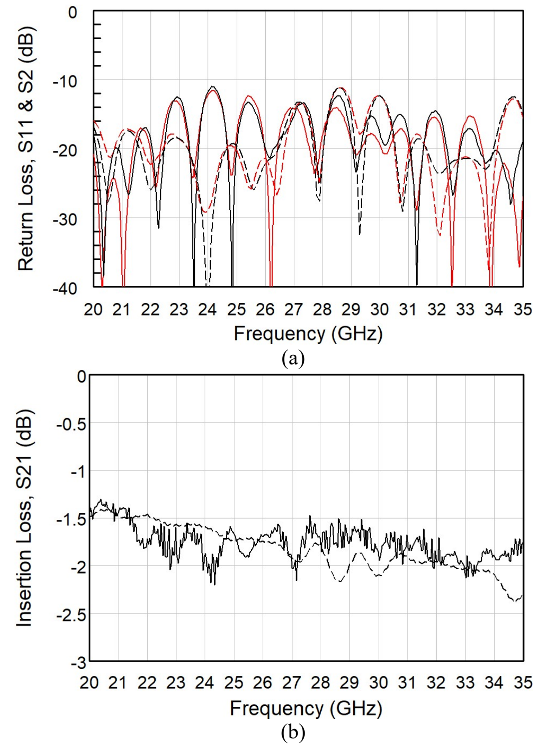


Fig. 2. Passive 16-way Spatium™ back to back RF responses HFSS simulated (dashed lines) vs. measured (solid lines): (a) Input (black) & output (red) return loss response; (b) Insertion loss response

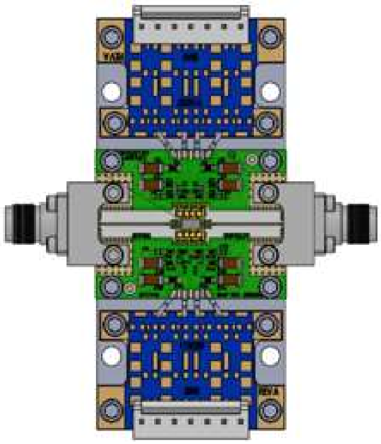
cover 15 to 42GHz. Return loss and insertion loss in the 16-way Spatium™ are measured to be > 10dB and <2.5dB, respectively. Fig. 2 shows a small deviation of the RF responses between prediction and hardware which can be due to the assembly tolerance in the Spatium hardware. However, the trend of RF responses between the HFSS prediction and the hardware measurement is exhibiting good correlation.

B. Active 16-way Spatium with GaN MMICs (16W-SCRA)

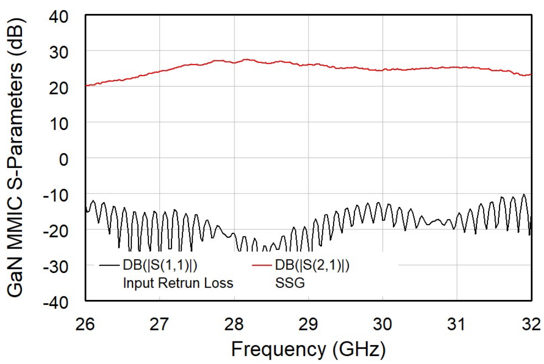
An active Spatium™ 16W-SCRA, integrated with 16 GaN MMIC HPAs in the passive Spatium™, was built after the passive 16-way Spatium development. The passive components influence mainly the RF matching and loss in the 16W-SCRA whereas the GaN HPA MMIC influences the 16W-SCRA's output power density, output power linearity, and power-added efficiency (PAE).

In recent years, Qorvo Inc. IDP has developed various GaN MMIC HPAs for mm-wave frequency applications. Output power levels of the Qorvo's mm-wave GaN MMIC HPAs are from 5W to ~40W [7-8]. In this paper, Qorvo GaN (QPA2211D) MMIC (max 14W with 25% PAE at 25°C) operating at Ka-band frequency (especially at 27 to 31GHz) is selected and utilized in building a 16W-SCRA for Satcom uplink applications.

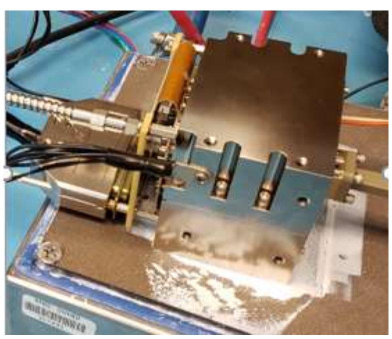
Prior to building the 16W-SCRA with the QPA2211D GaN MMIC. The QPA2211D was RF tested and evaluating. Typical test fixture for the GaN MMIC HPA evaluation is shown in Fig. 3-(a). The QPA2211D die is soldered to a CuMo carrier plate and the screwed down to a Cu heat sink base. Fig. 1-(b) shows scattering parameters, small signal gain (SSG) and input return loss responses, of the QPA2211D die as shown in Fig. 3-(a).



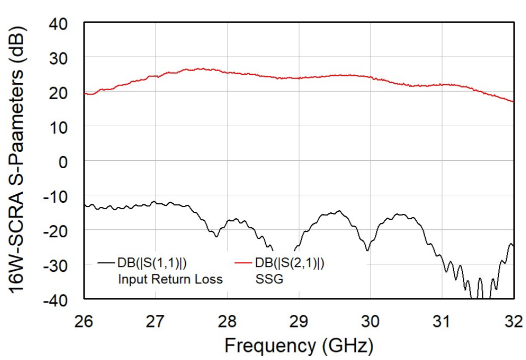
(a)



(b)



(c)



(d)

Fig. 3. (a) GaN MMIC die on measurement carrier fixture, (b) S-parameter of GaN MMIC die (c) Assembled 16W-SCRA on test plate, (d) S-parameter of 16W-SCRA

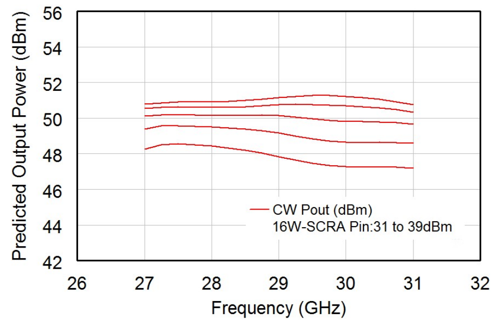


Fig. 4 Predicted CW output power simulated from 16W-SCRA non-linear circuit model

The bias point of the SSG measurement was 22V and ~300mA at 25^{o}C backside of the carrier plate, and measured SSG was >23dB at 27 to 31GHz.

Fig. 3-(c) shows the16W-SCRA hardware. As shown in Fig. 3-(c), the 16W-SCRA is assembled within a rectangular clamp that provides heat sinking and mounting. A WR28 waveguide, instead of using coaxial connector, is used at the output section. Use of WR28 waveguide on the output of the 16W-SCRA allows power handling >100W across the 27 to 31GHz operating band. However, a 2.92mm coax connector is still used at input side of the 16W-SCRA. Dimensions of the 16W-SCRA alone is 4 × 3 × 3.25 inches. Typical scattering parameter of the 16W-SCRA is shown in Fig. 3-(d). Bias point of the measurement in Fig. 3-(d) was 22V/ ~5A (~300mA × 16) at a 16W-SCRA clamp plate temperature of 25^{o}C. The 16W-SCRA has a peak small signal gain of 26dB at 27.5GHz and return loss of > 10dB measured at the frequencies between 27 and 31GHz. This scattering parameter measurement (shown in Fig. 3-(d)) plot is comparable to the plot of SSG from the QPA2211D die on the measurement carrier fixture (shown in Fig. 3-(b)) which indicates that the module RF loss and gain of the 16W-SCRA between 27 to 31GHz are similar to the carrier fixture measurements of the QPA2211D.

C. 16W-SCRA output power prediction and measured results

Fig. 4 show plot of the predicted CW saturated output power which was simulated from the 16W-SCRA non-linear circuit model. The non-linear circuit model was created by using HFSS generated scattering parameters of the 16-way Spatium^{TM} passive input splitter and output combiner 3D models and included the QPA2211D non-linear GaN MMIC circuit model. Boundary temperature of +85^{o}C on the surface of the 16W-SCRA clamp was used in the simulation to predict CW saturated output power of the 16W-SCRA at the worst environmental condition. The 16W-SCRA non-linear model was simulated with input driving power from 31dBm to 39dBm in 2dB steps. The maximum driving input power was estimated to be 39dBm based on the QPA2211D evaluation test data which included ideal insertion loss (~12dB) of the 16-way power splitter. In Fig. 4, saturated CW output power with input driven power of >37dBm is predicted to be >50dBm (>100W) over the frequency between 27 and 31GHz, where output powers of 50.8dBm (120W), 51.2 dBm (131W), and 50.8dBm (120W) at the corresponding frequency points of 27GHz, 29GHz, and 31GHz are predicted. The predicted output power

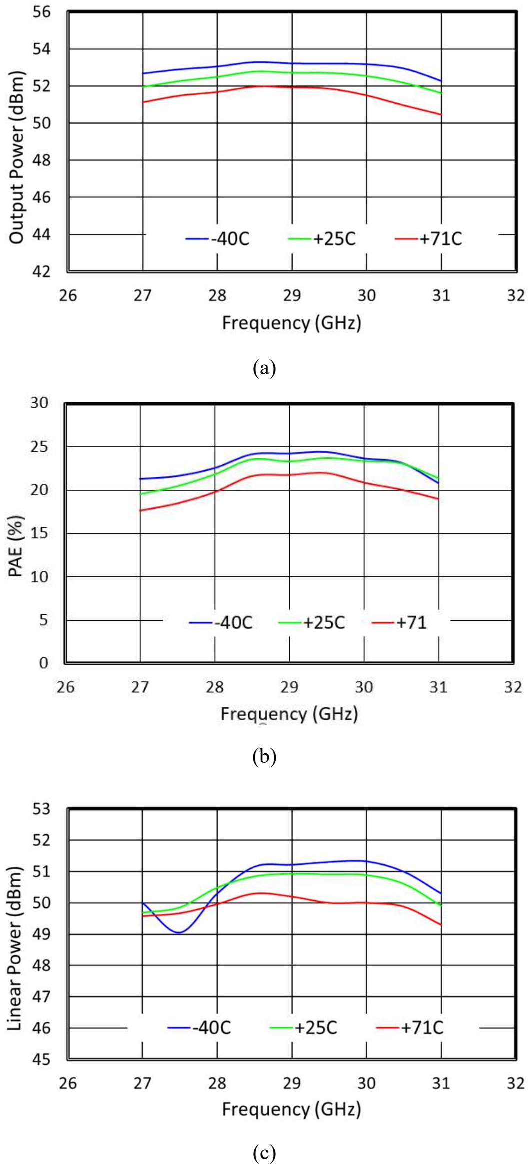


Fig. 5 Measured CW power and PAE vs. frequency 16W-SCRA at 22V/~5A: (a) saturated power (c) PAE (d) linear power

trend as shown in Fig. 4 also exhibits that the output power has reached saturation with input drive power of 39dBm.

Fig. 5 shows plots of the measured CW saturated output power, PAE, and CW linear output power of the 16W-SCRA hardware at various temperatures as measured on the surface of the 16W-SCRA clamp. Bias point of the measurements in Fig. 5 was 22V and ~5A. The 16W-SCRA produced >50dBm (>100W) CW output power at +71ºC clamp temperature over the 27 to 31GHz (Fig. 5-(a)) with greater than 17% PAE (Fig. 5-(b)) with input drive power of 39dBm. This measured CW output power data shows good agreement to the predicted CW output power plot as shown in Fig. 4 with +85ºC clamp temperature. On the other hand, linear output power of the 16W-SCRA was measured using an OQPSK modulation signal with a 30dBc signal at 1MHz based on MIL-STD-188-164b. Based on the OQPSK measurement, 16W-SCRA produced >49dBm of linear power over the 27 to 31GHz band as shown in Fig. 5-(c). Overall, performance of the 16W-SCRA from 27 to 31 GHz is as follows: (1) high CW output power >50dBm (>100W) at +71ºC (2) high linear power >49dBm (79W) at +71ºC, and (3) highly efficiency >17% at +71ºC. This demonstration indicates that the16W-SCRA is an excellent RF power amplifier candidate for Satcom transponder applications.

III. CONCLUSION

High linear and saturated output power with a highly efficient 16-Way Spatium™ Combiner RF Amplifier (16W-SCRA) has been developed and tested over the 27 to 31 GHz frequency range. The low cost, compact size, and high output power with high efficiency of this 16W-SCRA makes it an excellent solid-state RF amplifier candidate to replace conventional expensive and less reliable tube RF amplifiers for next generation communications and multi-function mm-wave frequency high power applications.

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