NASA/TM—2010-216253

High Efficiency Ka-Band Solid State Power Amplifier Waveguide Power Combiner

Edwin G. Wintucky and Rainee N. Simons
Glenn Research Center, Cleveland, Ohio

Christine T. Chevalier
QinetiQ North America Corporation, Cleveland, Ohio

Jon C. Freeman
Glenn Research Center, Cleveland, Ohio

March 2010

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2010-216253

High Efficiency Ka-Band Solid State Power Amplifier Waveguide Power Combiner

Edwin G. Wintucky and Rainee N. Simons
Glenn Research Center, Cleveland, Ohio

Christine T. Chevalier
QinetiQ North America Corporation, Cleveland, Ohio

Jon C. Freeman
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

March 2010

Acknowledgments

The authors acknowledge the precision fabrication of the waveguide combiner by
Astro Manufacturing & Design, Eastlake, Ohio

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://gltrs.grc.nasa.gov

High Efficiency Ka-Band Solid State Power Amplifier Waveguide Power Combiner

Edwin G. Wintucky and Rainee N. Simons
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Christine T. Chevalier
QinetiQ North America Corporation
Cleveland, Ohio 44135

Jon C. Freeman
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

A novel Ka-band high efficiency asymmetric waveguide four-port combiner for coherent combining of two Monolithic Microwave Integrated Circuit (MMIC) Solid State Power Amplifiers (SSPAs) having unequal outputs has been successfully designed, fabricated and characterized over the NASA deep space frequency band from 31.8 to 32.3 GHz. The measured combiner efficiency is greater than 90 percent, the return loss greater than 18 dB and input port isolation greater than 22 dB. The manufactured combiner was designed for an input power ratio of 2:1 but can be custom designed for any arbitrary power ratio. Applications considered are NASA's space communications systems needing 6 to 10 W of radio frequency (RF) power. This Technical Memorandum (TM) is an expanded version of the article recently published in Institute of Engineering and Technology (IET) Electronics Letters (Ref. 1).

Introduction

Ka-band communications links for a number of NASA Science and Exploration Missions will need amplifiers with 6 to 10 W of RF output power to satisfy the data rate requirements. For example, relevant Lunar exploration links include those between the Crew Exploration Vehicle (*Orion*) and the International Space Station (ISS) and the Tracking and Data Relay Satellite System (TDRSS) and between the Lunar Lander (Altair) and the Lunar Relay Satellite. The highest power Ka-band (31.8 to 32.3 GHz) Solid State Power Amplifier (SSPA) to have flown in space had an output power of 2.6 W and an overall efficiency of 14.3 percent. This SSPA was built around discrete GaAs pHEMT devices and flew aboard the Deep Space One spacecraft (Ref. 2). A second example is a 2.5 W SSPA, which will fly on the Juno spacecraft in the NASA New Frontiers Mission to Jupiter scheduled for launch in August, 2011 (Ref. 3). This SSPA will not be used for data communications to Earth but as part of a gravity science experiment.

The maximum power output at Ka-band frequencies of state-of-the-art GaAs monolithic microwave integrated circuit (MMIC) pHEMT based power amplifiers (PAs) ranges from about 3 W with a power added efficiency of 32 percent to about 6 W with a power added efficiency of 26 percent (Ref. 4). Hence power combining of two or more PAs is needed to achieve the required higher power levels.

Conventional binary waveguide power combiners, such as the short slot and magic-T, require MMIC PAs with equal amplitudes and phases for high combining efficiency. However, due to manufacturing process variations, the output powers of MMIC PAs tend to be unequal. Rectangular waveguide unequal power combiners investigated in the past are based on a hybrid ring (Ref. 5), shunt/series coupling slots (Ref. 6), E-plane septums (Ref. 7) or H-plane T-junctions (Ref. 8), all of which were designed to operate at frequencies at or below X-Band (12.4 GHz). The only waveguide unequal power combiner for operation at Ka-band is the 2-way branch-line combiner reported by the authors of this TM (Ref. 9).

This paper presents the design and characterization of a Ka-band high efficiency waveguide asymmetric unequal power combiner and also the results using two MMIC PAs with output powers of 1.0 and 0.5 W. Although the combiner input power ratio was 2:1 in this case, it can be custom designed for an arbitrary power ratio. One other constraint is that the two input signals should be in phase for maximum combining efficiency. The combiner design is based on the 4-port L-band (508.6 MHz) asymmetric high power divider reported by Takahashi et al. (Ref. 10), but scaled and dimensions optimized for operation as a combiner over NASA's deep space network (DSN) frequency range of 32.05±0.25 GHz. This combiner has additional advantages: (1) it enables the combining of different types of PAs, e.g., a lower power GaAs with a higher power GaN MMIC PA; (2) it enables high efficiency power combining of three PAs using either two asymmetric power combiners or an asymmetric power combiner with a conventional magic-T; and (3) it is potentially applicable for use with very high power amplifiers, as was shown in the high efficiency power combining of two Ka-band traveling wave tubes (TWTs) with a magic-T as the power combining element (Refs. 11 and 12).

Asymmetric Combiner Design and Fabrication

The design incorporates a horizontal rod (0.8 mm diameter), vertical inductive post (0.5 mm diameter and 5.0 mm height) and capacitive iris (0.65 by 0.08 mm) sized and internally positioned to achieve the desired asymmetric power transmission, phase equality and high port isolation. Figure 1(a) shows the port configuration and relative sizes and positions of the rod, post and iris. Figure 1(b) is a cross-section drawing showing the dimensions of the combiner junction in a plane parallel to coplanar ports 1, 2, and 3. For combiner operation, power input is at ports 2 and 3 and the combined power output is at port 1. Port 4 is the isolated port. The circuit was initially modelled and simulated as a power divider, with the input signal at port 1, using the transient solver package of the CST Microwave Studio software (Ref. 13). The design goals were (1) a 2:1 power ratio ($|S_{31}|^2 = 2\times|S_{21}|^2$) with equal phases at ports 2 and 3 for maximum power combining efficiency, (2) a high return loss (S_{11}) at port 1, and (3) high isolation between ports 1 and 4 (S_{41}) and ports 2 and 3 (S_{23}). The design procedure included adjustments to the horizontal position of port 4 for a 2:1 power split, the distances of ports 2 and 3 from the junction with port 1 to achieve phase balance and the iris width and post height to increase isolation (S_{41}) and decrease reflection (S_{11}), respectively. Thus, in the fabricated combiner the location of port 4 with respect to ports 2 and 3 is offset by 0.74 mm closer to port 2 while the location of port 1 with respect to ports 2 and 3 is offset by 0.84 mm closer to port 3. To simultaneously optimize the combiner for low insertion loss, high isolation, and good impedance match over 32.05±0.25 GHz, the model required non-standard internal dimensions for the waveguide (3.0 by 6.1 mm). A linear taper of length 1 mm was added at each port to transition to standard WR-28 waveguide (3.556 by 7.112 mm) for Ka-band operation and ease of network analyzer testing. The fabricated combiner shown in Figure 1(c) was precision machined from aluminium and measures 40 by 39 by 39 mm.

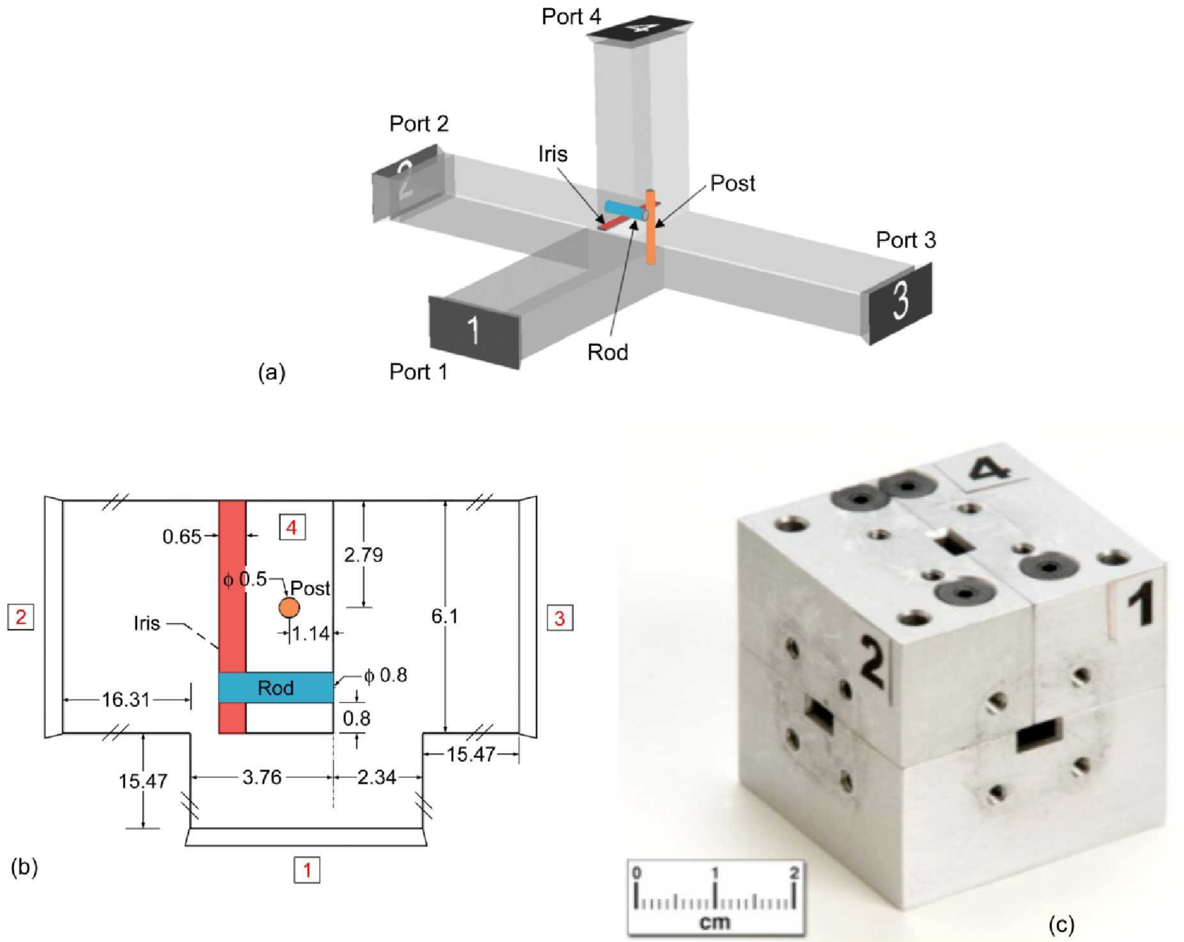

Figure 1.—(a) Transparent view of asymmetric coupler showing port configuration and relative orientation of rod, post and iris. (b) Cross-section of asymmetric coupler junction showing dimensions (units: mm) in plane parallel to coplanar ports 1, 2, and 3. (c) Photograph of asymmetric coupler used in combiner tests.

Simulated and Measured Power Divider Results

The circuit was first characterized as a power divider (signal input at port 1) with both a computer simulation (Microwave Studio) and network analyzer measurements over a 6 GHz span (29 to 35 GHz). Figure 2 shows the measured and simulated return loss (S_{11}) at the divider input port 1 as a function of frequency. The measured data shows that the best return loss occurs at a frequency higher than the simulated frequency. The reason for the shift in frequency is because of the challenge in precisely manufacturing the rod, post and iris in accordance with the design dimensions. Nevertheless, the measured return loss over the desired 32.05±0.25 GHz is greater than 18 dB, which is adequate for a proof of concept demonstration. The measured isolation between ports 2 and 3 (S_{23}) and between ports 1 and 4 (S_{41}) over the above frequency band, shown in Figure 3, were greater than 18 and 22 dB, respectively. These results also vary slightly from the simulated data due to manufacturing tolerances, but are adequate for a proof of concept demonstration. Figures 4 and 5 show the measured and simulated ports 2 and 3 (combiner input ports) power division over 6 GHz and 500 MHz, respectively. These results show that the measured and simulated data are in good agreement over the 32.05±0.25 GHz frequency band. Figure 6 shows the measured and simulated power ratio and the phase difference between ports 2 and 3. The measured power ratio, ($|S_{31}|^2 / |S_{21}|^2$), was within 1 percent of 2 and the measured phase balance was within 2.6°, resulting in near perfect agreement with the design goals. Based on the above S_{21} and S_{31} network analyzer measurements, the efficiency ($|S_{21}|^2 + |S_{31}|^2$) over the above frequency band is in the range of 95 to 97 percent.

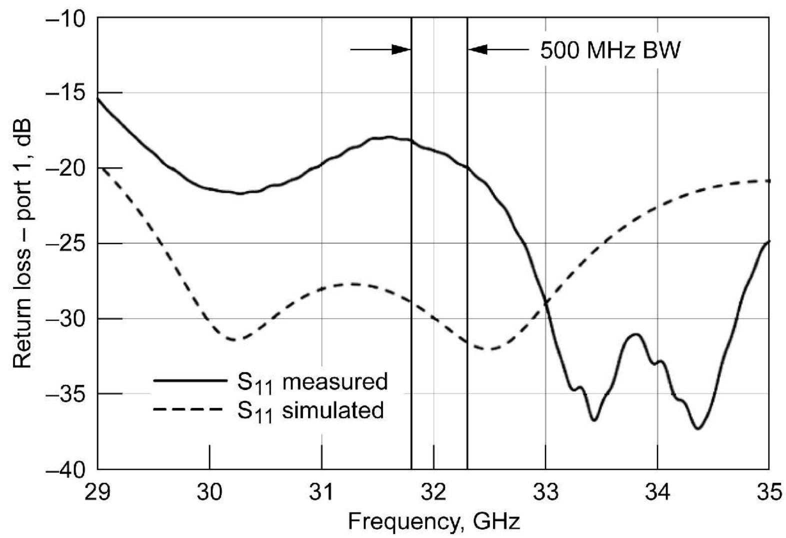

Figure 2.—Measured and simulated return loss (S_{11}) at output port 1 over a 6 GHz band centered at 32.05 GHz.

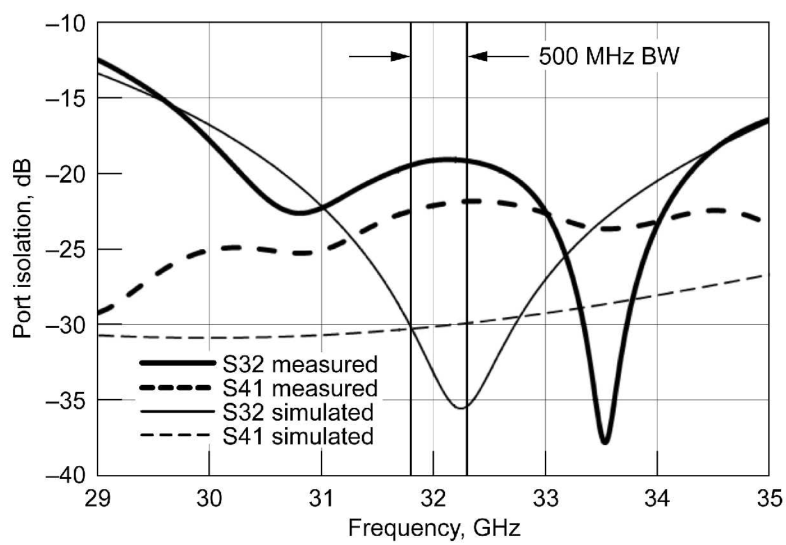

Figure 3.—Measured and simulated input and output port isolation over a 6 GHz band centered at 32.05 GHz.

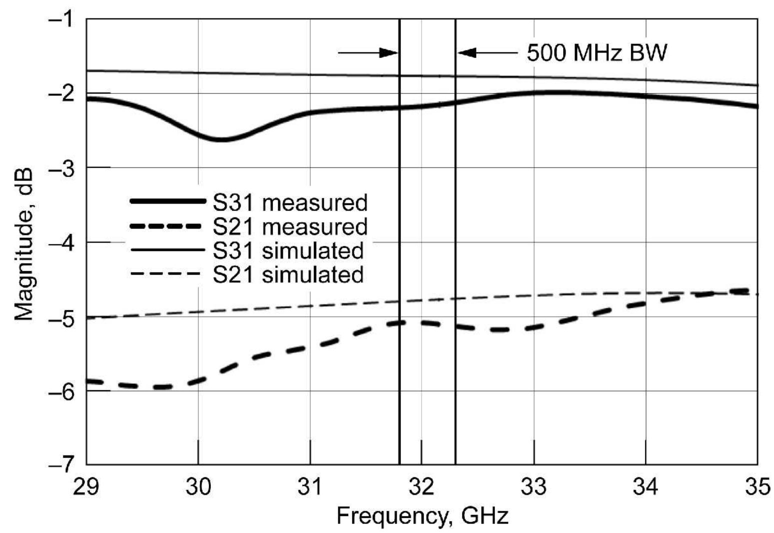

Figure 4.—Measured and simulated input port power division over a 6 GHz band centered at 32.05 GHz.

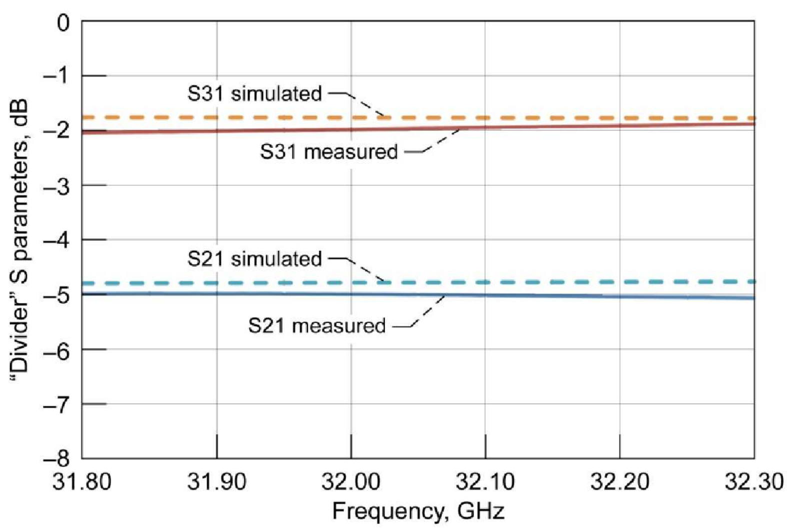

Figure 5.—Measured and simulated input port power division over a 500 MHz band centered at 32.05 GHz.

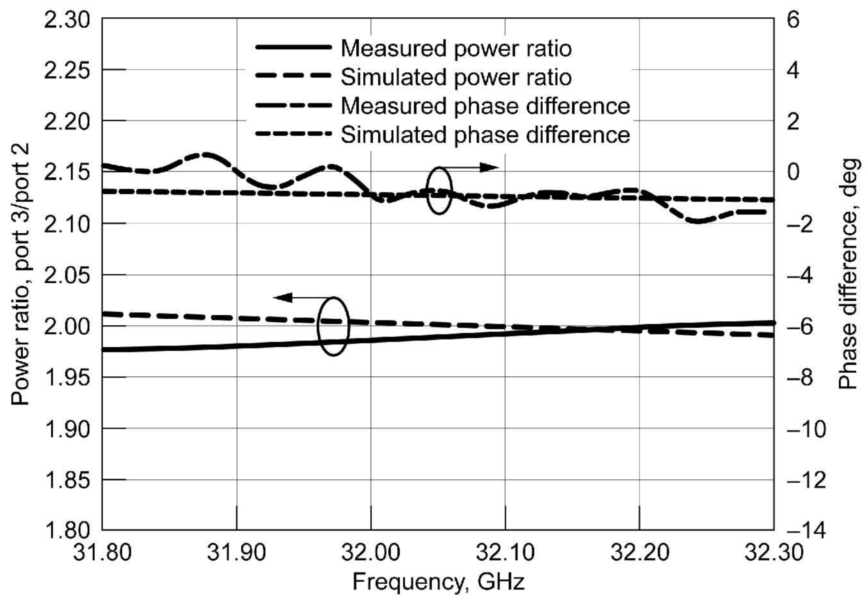

Figure 6.—Measured and simulated power ratio and phase difference between ports 2 and 3 for signal input at port 1.

Experimental Power Combining Results

Figure 7 shows a schematic of the complete power combiner test circuit and Figure 8 is a photograph showing the benchtop layout. Figure 9 is another schematic of the power combiner test circuit showing specifically the two GaAs pHEMT MMIC PAs, XP1026 and XP1027, manufactured by Mimix Broadband (Ref. 14). Figures 10 and 11 are close up views of the test circuit showing the asymmetric power combiner and the two MMIC power amplifiers.

The microwave powers were measured at five frequencies across the 32.05±0.25 GHz frequency range with input powers for each frequency at 0.5 W (XP1026) at port 2 and 1.0 W (XP1027) at port 3 for a total input power of 1.5 W. The phase was adjusted at each frequency for maximum power output at port 1. Figure 12 shows the measured combined powers, which ranged between 1.35 and 1.37 W. The corresponding combining efficiency is about 91 percent. A measure of the sensitivity to variation in input phase of combined power output and efficiency is shown in Figure 13. The combining efficiency was observed to be at or above 90 percent for a phase imbalance of ±6° in the two input powers.

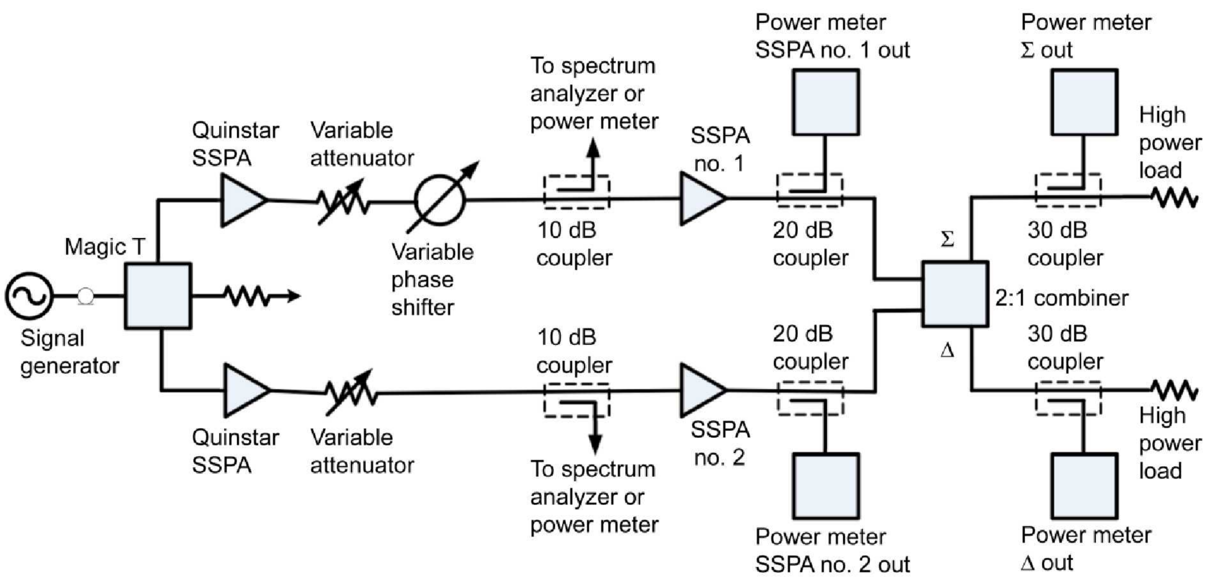

Figure 7.—Schematic of 2-way power combining circuit.

Figure 8.—Laboratory bench top 2-way MMIC power combining test circuit.

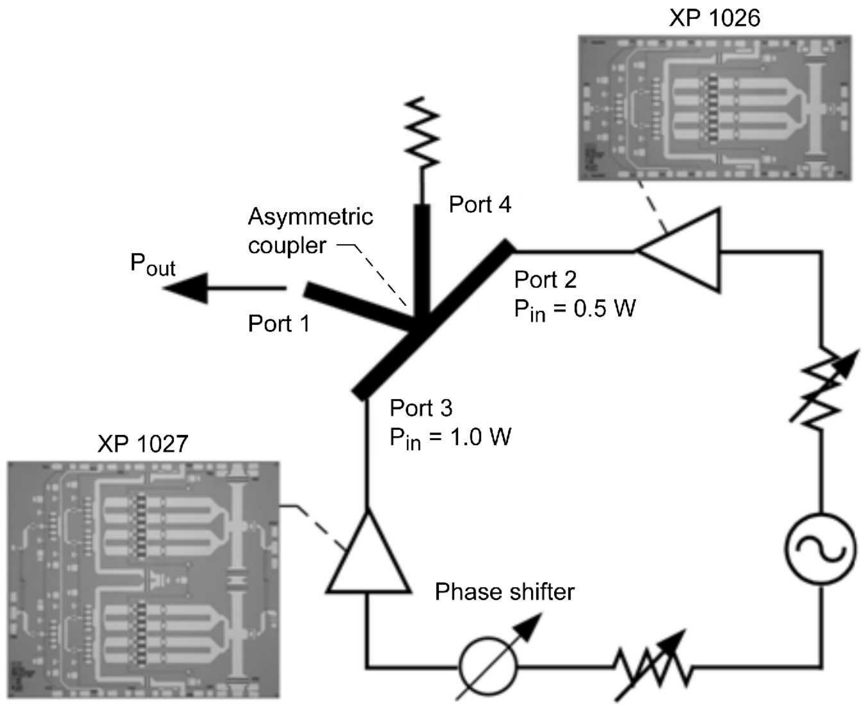

Figure 9.—Schematic of power combiner test circuit using the asymmetric combiner for the demonstration of power combining of two GaAs pHEMT MMIC PAs with unequal power outputs.

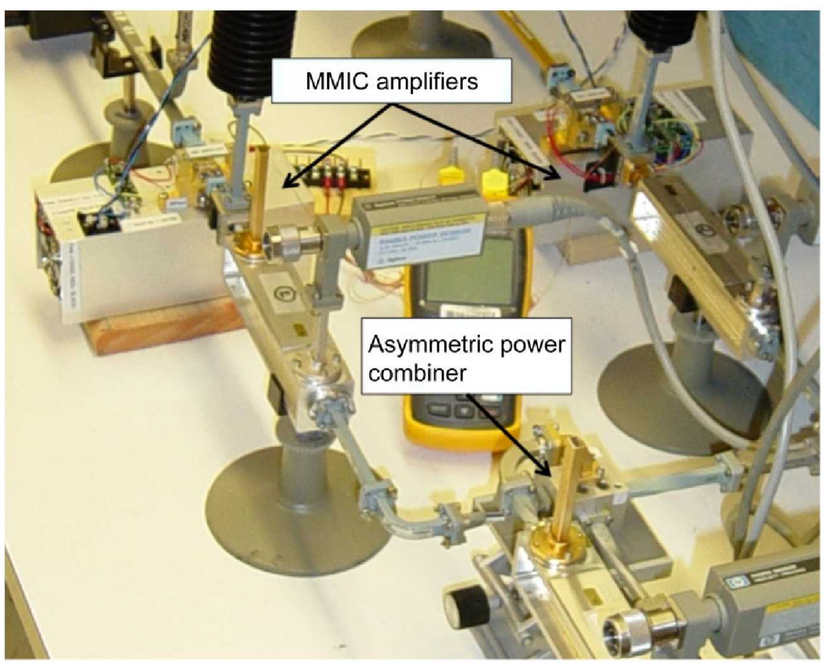

Figure 10.—Close-up view of test circuit showing the asymmetric power combiner and the two MMIC power amplifiers.

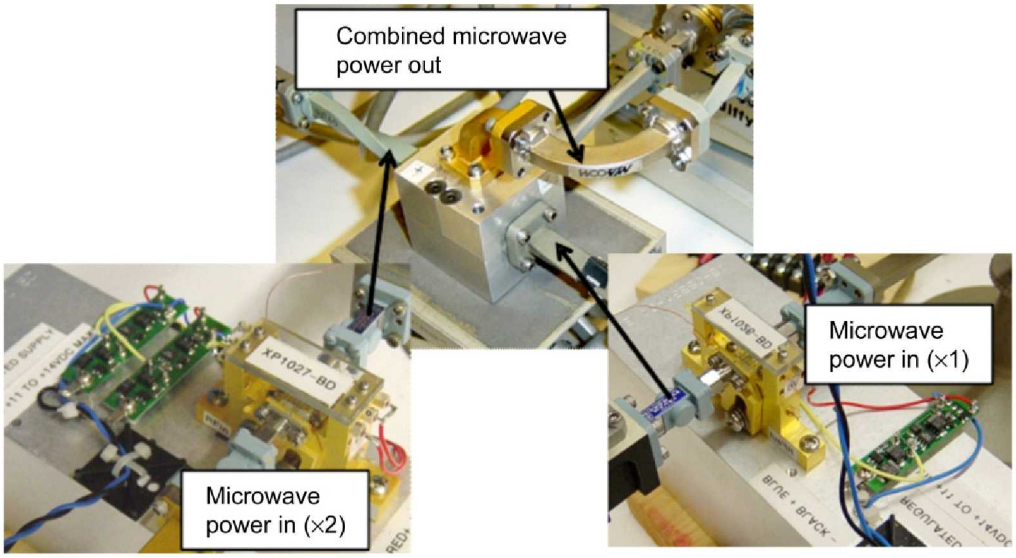

Figure 11.—Close-up view of asymmetric power combiner and the MMIC power amplifiers showing input/output power arrangement.

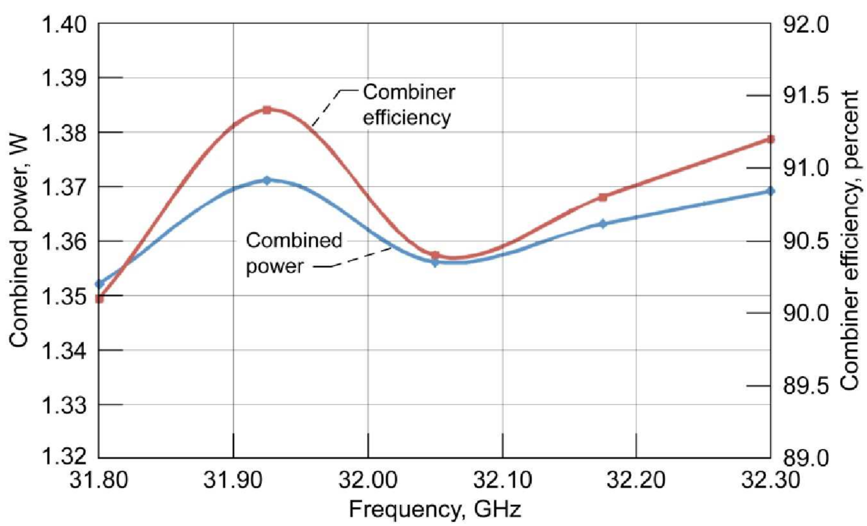

Figure 12.—Combined power and corresponding combiner efficiency measured across NASA's DSN frequency band.

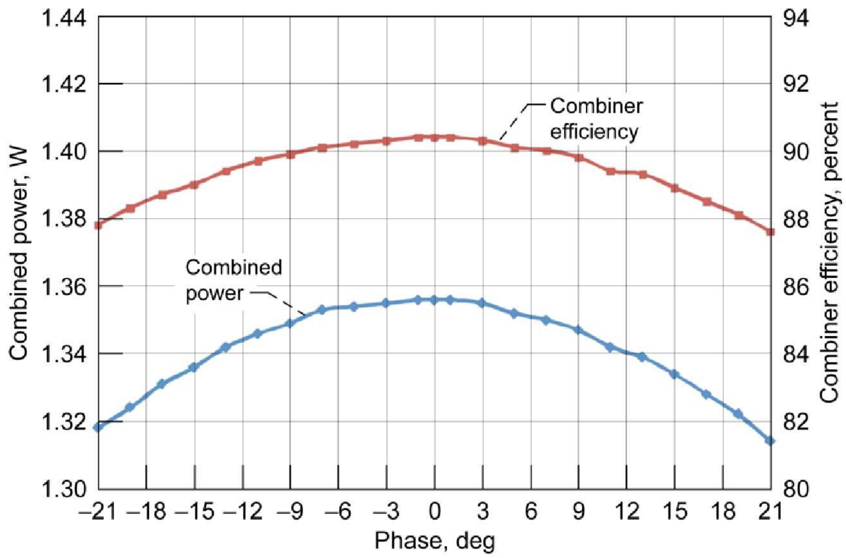

Figure 13.—Measured combined power and corresponding combiner efficiency versus imbalance in input power phase.

Conclusions

A novel high efficiency Ka-band two-way asymmetric power combiner has been successfully designed, fabricated and characterized for operation over the 32.05±0.25 GHz frequency range. Although designed for a 2:1 input power ratio, it can be easily designed for an arbitrary power ratio. The measured power ratio when tested as a power divider was very close to 2 and the phase balance was within 2.6° resulting in near ideal performance. When tested as a combiner, an efficiency greater than 90 percent was demonstrated over the above frequency range using two MMIC PAs with 2:1 power output ratio. In addition, the combining efficiency was observed to be at or above 90 percent for a phase imbalance of ±6° in the two input powers. These results show the combiner reported here to be a good candidate for high efficiency power combining of two or more PAs needed to achieve the 6 to 10 W of microwave power required by space communications systems of future NASA missions.

References

1. Wintucky, E.G.; Simons, R.N.; Chevalier, C.T.; Freeman, J.C.; “Ka-Band High Efficiency SSPA Asymmetric Power Combiner for Space Communications,” *IET Electronics Letters*, Vol. 46, No. 1, pp. 91–93, Jan 2010.
2. Karnacewicz, M.K.; Taft, W.J.; Valenti, S.; Renna, T.; Hirokawa, M.; Conway, S.; Newman, L.; “2.6 Watt Ka-Band Solid State Power Amplifier for Deep Space Communications,” *1999 Government Microcircuit Applications Conference (GOMAC 1999) Digest of papers*, Vol. XXIV, pp. 247–250, Monterey, CA, March 8–11, 1999.
3. http://juno.wisc.edu/index.html
4. Smith, P.M.; “PHEMT and MHEMT Devices for Millimeter-Wave Power Amplifiers,” Workshop (WMD) on Millimeter-Wave Power Amplifier Technology: Power, Linearity and Efficiency, *IEEE MTT-S Int. Microw. Symp.*, *Workshop Notes*, Atlanta, GA, June 16, 2008.
5. Pon, C.Y.; “Hybrid-Ring Directional Coupler for Arbitrary Power Divisions,” IRE Trans Microwave Theory Techniques, Vol. 9, No. 6, pp. 529–535, November 1961.
6. Park, P.K.; Slaterbeck, M.E.; Bradshaw, S.E.; “Shunt/Series Coupling Slot in Rectangular Waveguides,” *1984 IEEE Antennas & Propagation Society Int. Symp.*, pp. 62–65, Boston, MA, June 25–28, 1984.

7. Christopher, S.; Abid Hussain, V.A.; Easwaran, M.S.; Dabade V.N.; “Design Aspects of Compact High Power Multiport Unequal Power Dividers,” *IEEE Int. Symp. Phased Array Systems & Technology*, pp. 63–67, Boston, MA, October 15–18, 1996.
8. Yang, S.; Fahey, A.E.; “Synthesis of a Compound T-Junction for a Two-Way Splitter with Arbitrary Power Ratio,” *IEEE MTT-S Int. Microw. Symp. Dig.,* pp. 985–988, Long Beach, CA, June 12–17, 2005.
9. Simons, R.N.; Chevalier, C.T.; Wintucky, E.G.; Freeman, J.C.; “Ka-Band Waveguide Hybrid Combiner for MMIC Amplifiers With Unequal and Arbitrary Power Output Ratio,” *IEEE MTT-S Int. Microw. Symp. Dig.,* pp. 1541–1544, Boston, MA, June 7–12, 2009.
10. Takahashi, T.; Sakanaka, S.; Izawa M.; “Development of an Asymmetric Power Divider for a High-Power RF Distribution System,” *IEEE Trans. Nucl. Sci.*, Vol. 48, No. 4, Part 3, pp. 1592–1597, August 2001.
11. Wintucky, E.G.; Simons, R.N.; Vaden, K.R.; Lesny, G.G.; Glass, J.L.; “High Power Combining of Ka-Band TWTs for Deep Space Communications,” *IEEE Int. Vacuum Electronics Conf.*, pp. 63–64, Monterey, CA, April 25–27, 2006.
12. Simons, R.N.; Wintucky, E.G.; Wilson, J.D.; Force, D.A.; “Ultra-High Power and Efficiency Space Traveling Wave Tube Amplifier Power Combiner with Reduced Size and Mass for NASA Missions,” *IEEE Trans. Microw. Theory Tech.*, Vol. 57, No. 3, pp. 582–588, March 2009.
13. http://www.cst-america.com
14. http://www.mimixbroadband.com

REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-03-2010	Technical Memorandum	

4. TITLE AND SUBTITLE High Efficiency Ka-Band Solid State Power Amplifier Waveguide Power Combiner	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Wintucky, Edwin, G.; Simons, Rainee, N.; Chevalier, Christine, T.; Freeman, Jon, C.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER WBS 806866.02.03.0645.01
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E-17239
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2010-216253

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 17
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A novel Ka-band high efficiency asymmetric waveguide four-port combiner for coherent combining of two Monolithic Microwave Integrated Circuit (MMIC) Solid State Power Amplifiers (SSPAs) having unequal outputs has been successfully designed, fabricated and characterized over the NASA deep space frequency band from 31.8 to 32.3 GHz. The measured combiner efficiency is greater than 90 percent, the return loss greater than 18 dB and input port isolation greater than 22 dB. The manufactured combiner was designed for an input power ratio of 2:1 but can be custom designed for any arbitrary power ratio. Applications considered are NASA's space communications systems needing 6 to 10 W of radio frequency (RF) power. This Technical Memorandum (TM) is an expanded version of the article recently published in Institute of Engineering and Technology (IET) Electronics Letters.

15. SUBJECT TERMS
Telecommunications; Transmitters; Deep space network; Space communication; Satellite communications; Microwave transmission; Microwave amplifiers; Power amplifiers; Power efficiency

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	18	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802