Waveguide Multimode Directional Coupler for Harvesting Harmonic Power from the Output of Traveling-Wave Tube Amplifiers

Rainee N. Simons and Edwin G. Wintucky
NASA Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135, USA

***Abstract*—This paper presents the design, fabrication, and test results for a novel waveguide multimode directional coupler (MDC). The coupler fabricated from dissimilar frequency band waveguides, is capable of isolating power at the 2nd harmonic frequency from the fundamental power at the output port of traveling-wave tube amplifiers. Test results from proof-of-concept demonstrations are presented for Ku/Ka-band and Ka/E-band MDCs, which demonstrate sufficient power in the 2nd harmonic for a space borne beacon source for mm-wave atmospheric propagation studies.**

***Index Terms*—Directional coupler, harmonic frequency, 5G network, power amplifier, waveguide.**

I. Introduction

Because of increasing congestion in available spectrum at the currently used frequency bands (3-30 GHz) for space-to-ground data communications, coupled with the demand for higher data rates and wireless broadband services, there is now an interest by NASA, FCC, other U.S. Government Agencies, and the commercial satellite communications industry in developing the potential future use of the large bandwidth available at the mm-wave Q (37-42 GHz) and E (71-76 GHz) bands for this purpose. Prior to the use of these frequency bands for space communications, it is necessary to first rigorously characterize the many atmospheric effects, including rainfall, cloud coverage and gaseous absorption, on mm- wave propagation from space borne beacon sources. Additionally, for high data rate wide band communications, it will also be necessary to characterize the group delay effects [1].

In general, traveling-wave tube amplifiers (TWTAs) on board satellites for data transmission operate with constant envelope type waveform (for e.g. QPSK) and at saturation for peak efficiency. Consequently, they generate higher order harmonics that are unused and in that regard are considered "*wasted*," but potentially can be "*harvested*." There is sufficient power at harmonic frequencies that can be isolated, amplified, and diverted for useful space applications. The following example, which is a novel approach for the utilization of the normally unused RF power in the TWTA 2nd harmonic, supports the credibility and offers a good illustration of the concept. The magnitude of the space TWTA 2nd harmonic by design is less by a factor of 100X (–20 dBc) than the fundamental frequency power. Measured values range from as low as 0 dBm (1 mW) for some TWTAs (for example 125 W RF output power at Ka-band) to as high as 20 to 23 dBm (100 to 200 mW) for the 40 W K-band TWTA [2]. These levels of 2nd harmonic power can be isolated and amplified to the 1.5 to 2.0 W power levels that link budget calculations show is sufficient for CONUS mm-wave propagation studies [3].

In this paper, we present the design, fabrication, and test results for a novel waveguide multimode directional coupler (MDC) for harvesting the 2nd and potentially higher harmonics from a high power space TWTA. If the harmonic power is isolated from the fundamental using the MDC, it can potentially be amplified and used as a space borne beacon source for mm-wave propagation studies. For example, the Q-band and E-band propagation studies could be done using the 2nd harmonic from Ka-band and Q-band downlink TWTAs, respectively. The use of the 2nd harmonic has several technical advantages over conventional single frequency beacon sources. For one, it does not require an ultra-stable temperature compensated oscillator for frequency generation separate from that provided by the spacecraft transceiver. Second, tuning the input fundamental RF frequency to the TWTA allows measurements of group delay or dispersion at the 2nd harmonic frequency.

II. Waveguide MDC Design

A. Basic Concept and Design

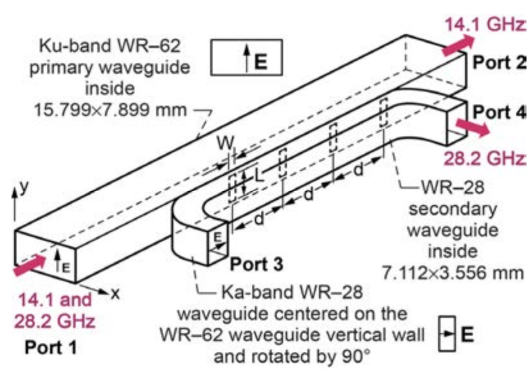

Fig. 1. Schematic of Ku-band/Ka-band waveguide MDC. Where **E** is TE_{10} mode electric field. W = 0.5 mm, L = 6.0 mm, and d = 3.527 mm.

Conventional directional couplers are fabricated from two identical waveguides, which are either broadwall or narrow wall coupled [4]. In these couplers, the power in the dominant TE_{10} mode is coupled from the primary waveguide to the secondary waveguide. On the other hand, the MDC demonstrated in this paper consists of two dissimilar parallel waveguides, a larger primary waveguide for the fundamental frequency and a smaller secondary waveguide for the 2nd harmonic. Additionally, the secondary waveguide is rotated by 90° with respect to the primary waveguide and the two waveguides are joined together and share a common wall with apertures. A schematic of the Ku-band/Ka-band waveguide MDC is shown in Fig. 1. In the primary waveguide, the signal at the fundamental frequency propagates as the dominant TE_{10} mode. The power in the 2nd harmonic signal propagates as higher order modes [4]. If an aperture is cut in the shape of a narrow rectangular slot parallel to the y-axis along the primary waveguide narrow wall, the coupling to the TE_{10} mode will be negligibly small [5]. However, the slot aperture will couple strongly to the TM_{11} type higher order modes. Thus the power in the 2nd harmonic signal is selectively coupled from the primary waveguide to the secondary waveguide and can be amplified to a higher power level as needed.

B. Ku-Band/Ka-band MDC Design and Fabrication

For the proof-of-concept (POC) demonstration, the primary and the secondary waveguides were chosen as WR-62 and WR-28, respectively, as shown in the schematic in Fig. 1. The fundamental frequency is at Ku-band (13.25-18 GHz) and the 2nd harmonic is then at Ka-band (26.5-36 GHz). For simplicity, the coupling aperture pattern consisted of four apertures with the size and spacing of the slots designed for a fundamental frequency of 14.1 GHz and a corresponding 2nd harmonic frequency of 28.2 GHz [6], [7]. The shared common wall of the MDC is a section of the WR-62 waveguide in which, using conventional machining, coupling apertures are cut as shown in Fig. 2 (a). The corresponding wall section of the WR-28 waveguide is removed. Fig. 2 (b) shows the fabricated POC MDC used in the demonstration.

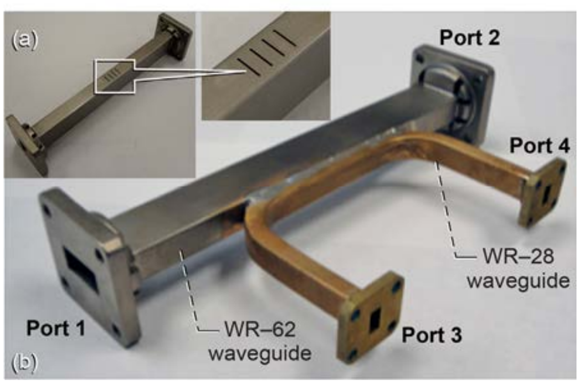

Fig. 2. (a) Coupling apertures in the Ku-band waveguide (WR-62) section. (b) Fabricated POC Ku-band/Ka-band waveguide MDC.

C. Ka-Band/E-Band MDC Design and Fabrication

The concept for the Ka-band/E-band MDC is similar to that for the Ku-band/Ka-band MDC and in this case has a primary Ka-band waveguide (WR-28, 26.5-40 GHz) for transmission of the fundamental frequency and a secondary E-band waveguide (WR-12, 60-90 GHz) for transmission of the coupled 2nd harmonic frequency. In this design a section of the WR-28 waveguide is machined to a thickness of 0.127 mm as the common wall. Five coupling apertures are laser machined in the common wall with the size and spacing of the slots designed for a fundamental frequency of 36 GHz and a corresponding 2nd harmonic frequency of 72 GHz. Fig. 3 shows the fully fabricated POC Ka-band/E-band MDC.

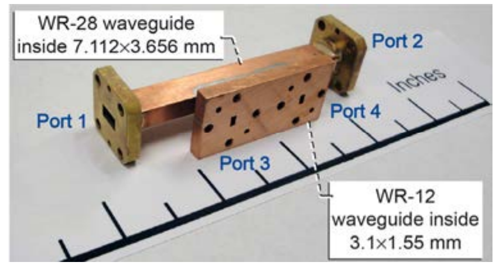

Fig. 3. Fabricated POC Ka-band/E-band waveguide MDC. W = 0.1 mm, L = 1.2 mm, and d = 1.36 mm are coupling aperture dimensions not shown.

III. Experimental Results

A. Ku-Band/Ka-band MDC Test Results

Fig. 4 shows a schematic of the test circuit used for the measurement of power at the fundamental and the 2nd harmonic frequencies. Fig. 5 shows the MDC mounted at the output port of the Ku-band TWTA. Measurements were made over the fundamental frequency range of 13.5-15.0 GHz with the TWTA operating at a saturated power output of 41-42 dBm (12.6 to 15.9 W). The TWTA fundamental power measurements are shown in Fig. 6 (a) for both a power sweep and 50 MHz spaced spectral lines. Power measurements of the 2nd harmonic over the corresponding 3 GHz frequency range (27-30 GHz) is shown in Fig. 6 (b), for both power sweeps and individual 100 MHz spaced spectral lines. The test data indicates that there is a significant amount of power in the 2nd harmonic, with peak powers up to 5 dBm.

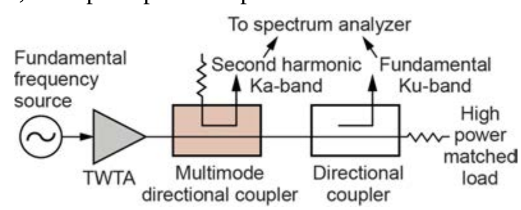

Fig. 4. Test circuit for measurement of power at the fundamental (Ku-band) and the 2nd harmonic (Ka-band) frequencies.

It is worth mentioning that the fundamental signal is below the cutoff frequency of the Ka-band secondary waveguide and hence propagates unperturbed in the Ku-band primary waveguide. The spectrogram, shown in Fig. 7 (a), for the fundamental Ku-band frequency of 14.1 GHz measured at the output port of the Ka-band waveguide confirms that no fundamental power is coupled to the secondary waveguide (Port 1 to Port 4). Additionally, Fig. 7 (b) shows that the measured insertion loss (Port 1 to Port 2) of the MDC Ku-band segment is negligibly small and on the order of 0.15 dB. In contrast, typical insertion loss of commercially available diplexers in WR-28 waveguide is on the order of 1.5 to 1.8 dB [8], [9].

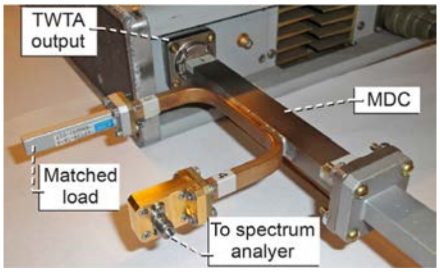

Fig. 5. MDC at the output port of a Ku-band TWTA.

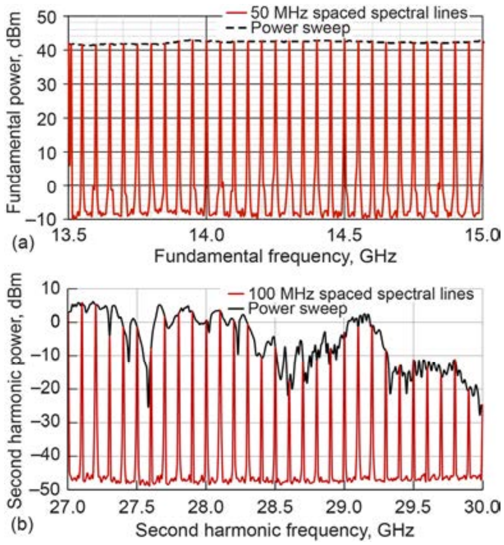

Fig. 6. (a) Measured TWTA fundamental power at port 2 of MDC. (b) Measured 2nd harmonic power at port 4 of MDC.

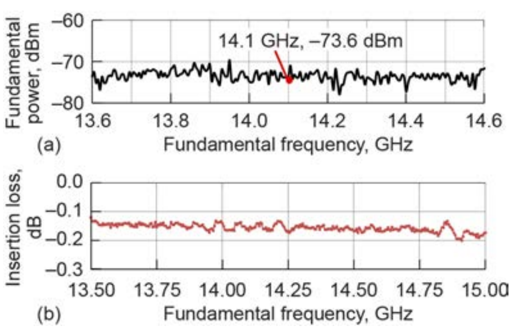

Fig. 7. (a) Measured fundamental power at the MDC Ka-band secondary waveguide port 4. (b) Measured insertion loss between port 1 and port 2 of MDC Ku-band primary waveguide.

B. Ka-Band/E-band MDC Test Results

The test circuit used for measurements of the fundamental (Ka-band) and the 2nd harmonic (E-band) powers is similar to Fig. 4. The only exception is the replacement of the spectrum analyzer by Ka-band and E-band power sensors/meters. All of the power measurements were made with the TWTA operated at saturated output power. Power measurement results over the fundamental frequency range of 35-38 GHz and the 2nd harmonic frequency range of 70-76 GHz are shown in Figs. 8 (a) and (b), respectively.

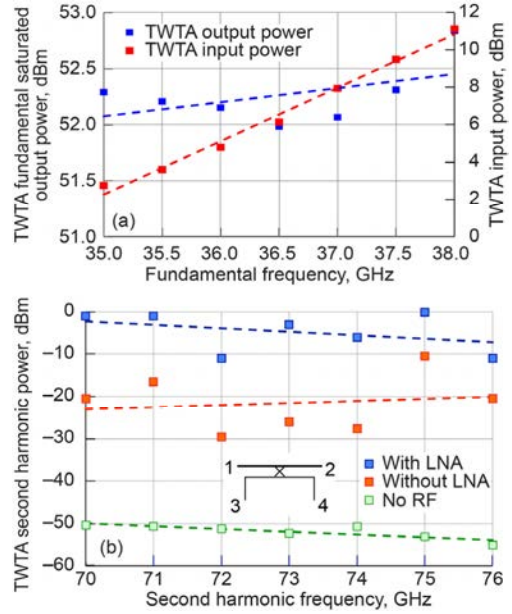

Fig. 8. (a) TWTA input power and TWTA saturated output power measured over the fundamental frequency range of 35-38 GHz. (b) TWTA second harmonic power, with and without the low noise amplifier (LNA), measured at port 4 of MDC over the frequency range of 70-76 GHz.

IV. Conclusion

The design, fabrication, and test results are presented for a novel mm-wave MDC, the application of which is harvesting of the 2nd harmonic frequencies from a space TWTA. Traditional harmonic filters and diplexers suffer from high insertion loss and have poor efficiency. The advantage of the MDC is that it very compact and can be connected directly to the RF output port of a TWTA with negligible loss of fundamental power and therefore highly efficient. The test results demonstrate sufficient power in the 2nd harmonic for potential application of the MDC in a TWTA based space borne beacon source for mm-wave atmospheric propagation studies.

Acknowledgment

The work reported in this paper was supported by the 2012/2013 NASA GRC Center Innovation Fund (CIF).

References

[1] R.J. Acosta, J.A. Nessel, R.N. Simons, M.J. Zemba, J.R. Morse, and J. Budinger, "W/V-band RF propagation experiment design," *Proc. 18th Ka and Broadband Communications Navigation and Earth Observation Conf.*, pp. 355-362, Sept. 24-27, 2012, Ottawa, Canada.

[2] R.N. Simons D.A. Force, and T.J. Kacpura, "High efficiency traveling-wave tube power amplifier for Ka-band software defined radio on International Space Station - A platform for communications technology development," *2013 IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 1-4, June 2-7, 2013, Seattle, WA.

[3] R.N. Simons and E.G. Wintucky, "Q-Band (37-41 GHz) satellite beacon architecture for RF propagation experiments," *2012 IEEE Antennas and Propagation Int. Symp. Dig.*, July 8-14, 2012, Chicago, IL.

[4] D.M. Pozar, *Microwave Engineering*, 3rd ed, New Jersey: John Wiley & Sons, 2005, Section 3.3, pp. 106-115.
[5] H.Y. Yee and R.C. Voges, Slot-Antenna Arrays, in R.C. Johnson, Ed., *Antenna Engineering Handbook*, 3rd ed, New York: McGraw-Hill, 1993, Chap. 9, pp. 9-1 to 9-39.
[6] R. Levy, Directional Couplers, in L. Young, Ed., *Advances in Microwaves*, vol. 1, New York: Academic Press, 1966, pp. 115-211.
[7] R.E. Collin, Foundations For Microwave Engineering, 2nd ed, New York: McGraw-Hill, 1992, Section 4.13, pp. 284-294, and Section 6.4, pp. 413-427.
[8] http://www.ducommun.com/pdf/passive-components-pdc.pdf
[9] http://www.cernex.com/PRODUCTS_NEW/Filter-diplexer-PDF/diplexers_waveguide_coaxial.pdf