



A Novel Ku-Band/Ka-Band and Ka-Band/E-Band Multimode Waveguide Couplers for Power Measurement of Traveling-Wave Tube Amplifier Harmonic Frequencies

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Abstract

This paper presents the design, fabrication and test results for a novel waveguide multimode directional coupler (MDC). The coupler, fabricated from two dissimilar frequency band waveguides, is capable of isolating power at the second harmonic frequency from the fundamental power at the output port of a traveling-wave tube (TWT) amplifier. Test results from proof-of-concept demonstrations are presented for a Ku-band/Ka-band MDC and a Ka-band/E-band MDC. In addition to power measurements at harmonic frequencies, a potential application of the MDC is in the design of a satellite borne beacon source for atmospheric propagation studies at millimeter-wave (mm-wave) frequencies (Ka-band and E-band).

1.0 Introduction

Because of increasing congestion in available spectrum at the currently used frequency band (3 to 30 GHz) for space-to-ground data communications, coupled with the demand for higher data rates and broadband services, there is now an interest by NASA, other government agencies and the commercial broadband satellite communications industry in developing the potential future use of the large bandwidth available at the mm-wave Q (37 to 42 GHz) and E (71 to 76 GHz) frequency 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 adsorption, on RF signal propagation from a space-based beacon source. For high data rate wide band communications, it will also be necessary to characterize the group delay effects. The design of any operational system will depend on the results of the propagation studies. Although solutions to provide the high frequency beacon sources are being solicited and proposed, they do not presently exist. The potential emerging applications at these frequencies include space communications for exploration missions, communications for unmanned aerial vehicles (UAV), and terrestrial broadband communications.

NASA has an expressed interest in the propagation studies and is currently supporting ground-based radiometer studies (E-band) in collaboration with DoD (AFRL), which has an intended use for this band. The commercial satellite communications industry is planning to use Q-band for broadband services and needs the propagation studies for implementation of Adaptive Coding and Modulation for

mitigation of atmospheric data transmission losses. A high power, high efficiency Q-band TWT is currently under development at L-3 Communications Electron Technologies, Inc., under a contract from NASA GRC.

In general, the TWT higher order harmonics and modulation frequency products are unused and in that regard can be considered “wasted”, but potentially can be “harvested”. There is sufficient power at these unused 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 TWT 2nd harmonic, supports the credibility and offers a good illustration of the concept. The specific application is a mm-wave beacon source for in-depth RF propagation studies (Ref. 1) for either atmospheric science or high data rate communications. The magnitude of the space TWT 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 TWTs (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 Lunar Reconnaissance Orbiter (LRO) TWT. 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 propagation studies (Ref. 1).

The beacon source for the propagation studies could be provided by a number of spacecraft in GEO orbit. For example, the Q-band and E-band propagation studies could be done using the 2nd harmonic from Ka-band and Q-band downlink TWTs, respectively. The use of the 2nd harmonic has several technical advantages over conventional single frequency beacon sources. For one, it does not require a temperature-stabilized oscillator for frequency generation separate from that provided by the spacecraft transceiver. Second, varying the input fundamental RF frequency to the TWT allows measurements of group delay or dispersion at the 2nd harmonic frequency. This is a critical issue that need to be thoroughly understood before design of any operational system can commence (Ref. 2).

In this paper, we present the design, fabrication, and test results of two different waveguide multimode directional couplers (MDC) for the measurement of the second and potentially higher harmonics from a high power space traveling-wave tube amplifier (TWTA) (Refs. 3 and 4). These measurements are necessary at a production facility to qualify and control the amount of interference power that a TWTA would generate. The knowledge of the amount of interference power can be factored into the interpretation and correction of

the measurements from radio science observation systems. In addition, the knowledge of the amount of interference power can be considered in improving accuracy of navigation systems. Furthermore, if the harmonic power is isolated from the fundamental using the MDC, it can potentially be amplified and used as a beacon source for mm-wave atmospheric propagation studies as discussed above. Such a study is required for the design of robust space-to-ground satellite communication links (Refs. 1 and 2).

2.0 Waveguide MDC Design and Experimental Results

2.1 Basic Concept and Design

The waveguide MDC used in the proof-of-concept (POC) demonstrations consists of two dissimilar parallel waveguides, a larger primary waveguide for the fundamental frequency and a smaller secondary waveguide for the second harmonic. 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. A schematic of the Ku-band/Ka-band waveguide MDC is shown in Figure 1. In the primary waveguide, the signal at the fundamental frequency propagates as the dominant TE_{10} mode. The power in the second harmonic signal propagates as higher order modes. 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. However, the slot aperture will couple strongly to the TM_{11} type higher order mode. Thus the power in the second harmonic signal is selectively coupled to the secondary waveguide and can be amplified to a higher power level as needed.

2.2 Ku-Band/Ka-Band MDC Design and Fabrication

For the initial POC demonstration, the primary and the secondary waveguides were chosen as WR-62 and WR-28,

respectively, as shown in the schematic in Figure 1. The fundamental frequency is at Ku-band (13.25 to 18 GHz) and the second harmonic is then at Ka-band (26.5 to 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. The shared common wall of the MDC was a section of the WR-62 waveguide, in which the coupling apertures, shown in Figure 2, were cut by conventional machining, with the corresponding wall section of the WR-28 waveguide removed.

Figure 3 shows the fabricated POC MDC used in the demonstrations. Two MDCs with identical design (serial # 1 (SN1) and serial # 2 (SN2)) were fabricated to enable the measurement of the coupling coefficient at the second harmonic frequencies.

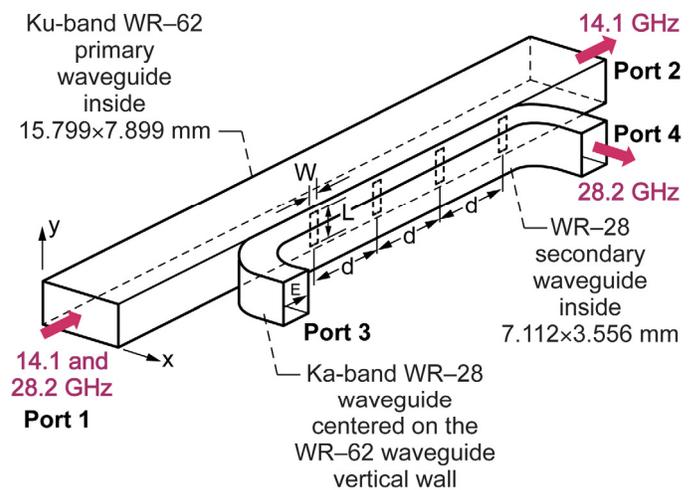


Figure 1.—Schematic of Ku-band/Ka-band waveguide multimode directional coupler (MDC). E is TE_{10} mode electric field.

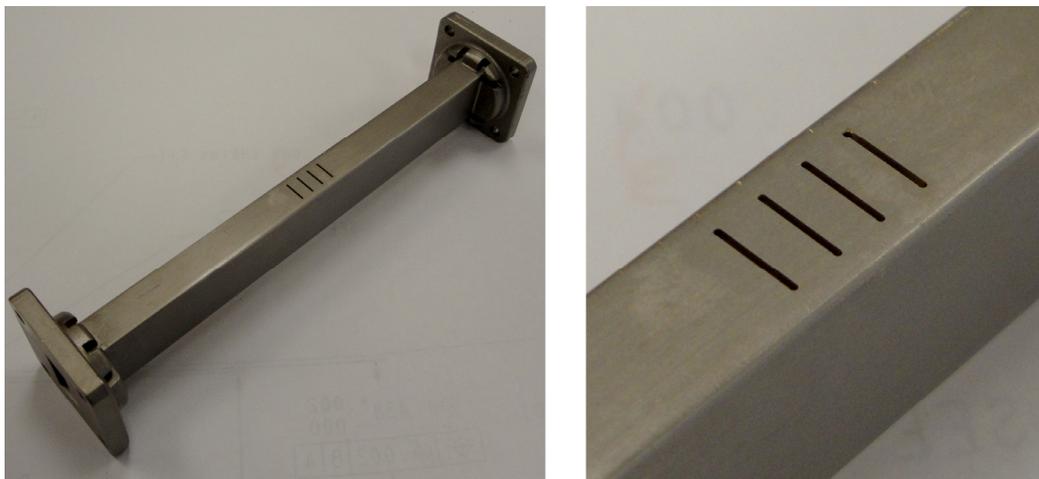


Figure 2.—Coupling apertures in the Ku-band waveguide section.

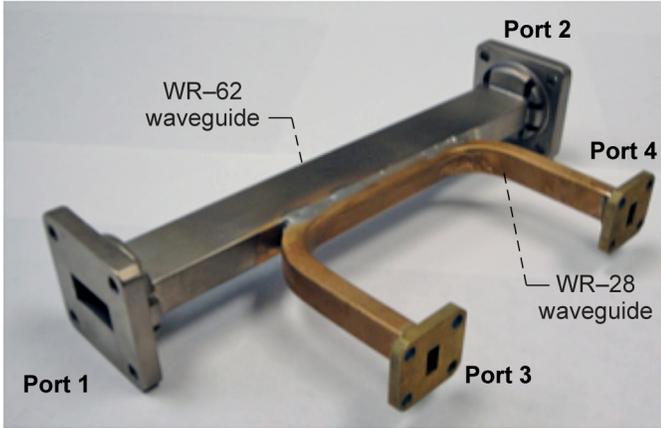


Figure 3.—Fabricated proof-of-concept Ku-band/Ka-band waveguide multimode directional coupler (MDC).

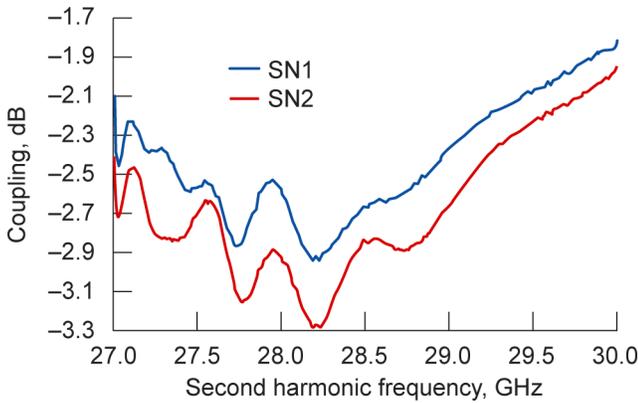


Figure 4.—Measured coupling coefficients for the two MDCs.

Figure 4 compares the coupling coefficients measured over a 3 GHz span. The small difference in coupling between SN1 and SN2 MDCs is on the order of 0.25 dB.

2.3 Ku-Band/Ka-Band MDC Test Data

Figure 5 shows a schematic of the test circuit used for the measurement of power at the fundamental and the 2nd harmonic frequencies. Figure 6 shows the experimental test setup and Figure 7 shows the MDC mounted at the output port of the Ku-band TWT. Measurements were made over a 1.5 GHz fundamental frequency range centered at 14.25 GHz with the TWT operating at a saturated power output of 41 to 42 dBm (12.6 to 15.9 W). The TWT fundamental power measurements, frequency band 13.5 to 15.0 GHz, are shown in Figure 8 for both a power sweep and 50 MHz spaced spectral lines.

Power measurements of the 2nd harmonic for the two MDCs (SN1 and SN2) over the corresponding 3 GHz frequency range (27 to 30 GHz) are shown in Figures 9 and 10, for both power sweeps and individual 100 MHz spaced spectral lines. The

results for the two Ku-band/Ka-band MDCs are nearly identical with a large variation in amplitudes, up to about 30 dB, unlike the fundamental power which was relatively uniform over the frequency band. The test data indicates that there is a significant amount of power in the second harmonic, with peak powers up to 5 dBm.

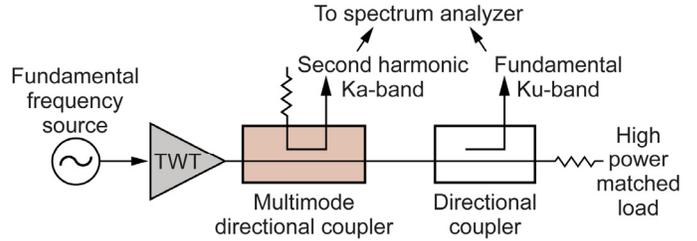


Figure 5.—Test circuit for measurement of power at the fundamental (Ku-band) and the second harmonic (Ka-band) frequencies.

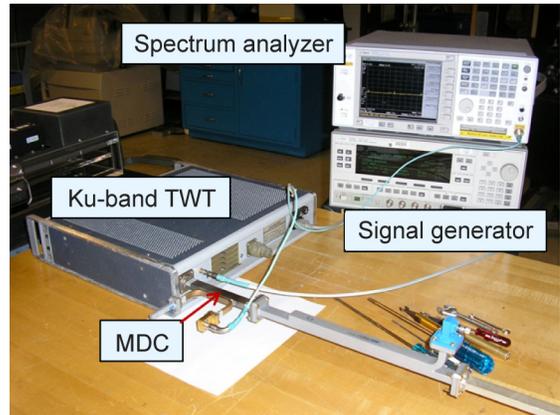


Figure 6.—Experimental setup for Ku-band/Ka-band MDC tests.

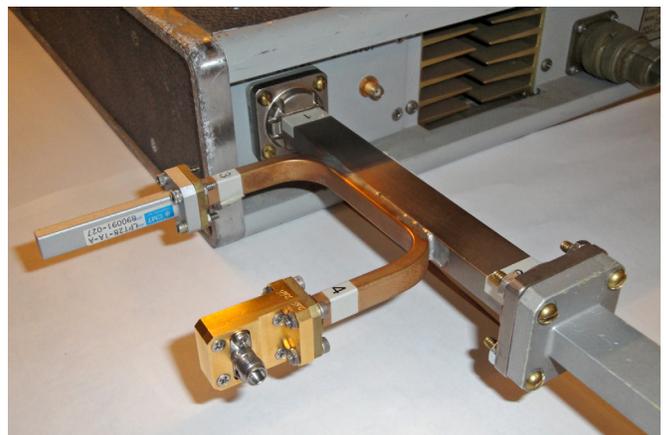


Figure 7.—MDC at output port of Ku-band traveling-wave tube (TWT).

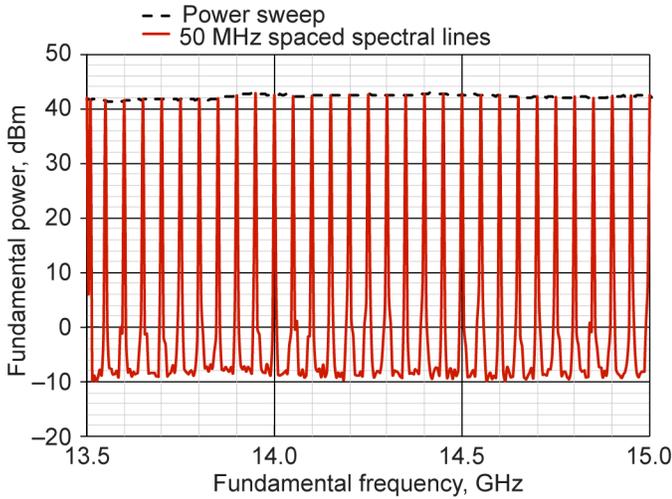


Figure 8.—Measured TWT fundamental power, 13.5 to 15.0 GHz.

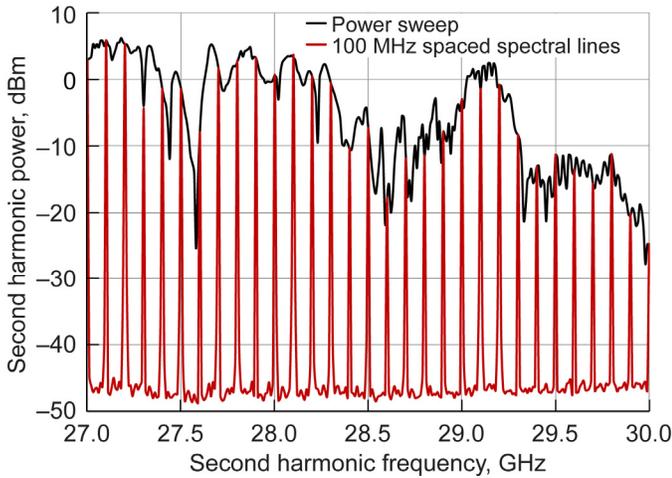


Figure 9.—Measured second harmonic power at port 4 of SN1 MDC.

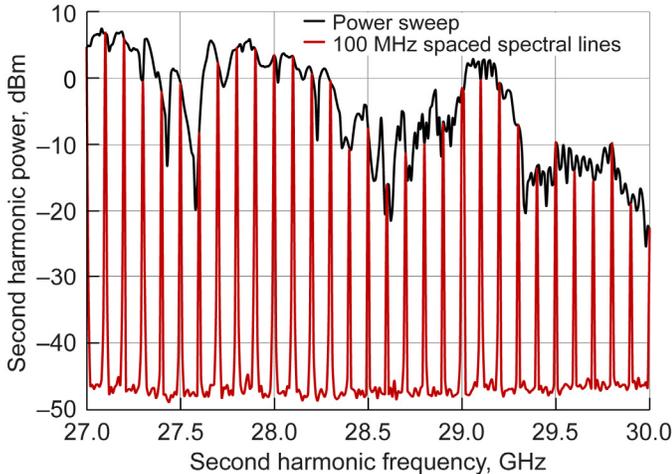


Figure 10.—Measured second harmonic power at port 4 of SN2 MDC.

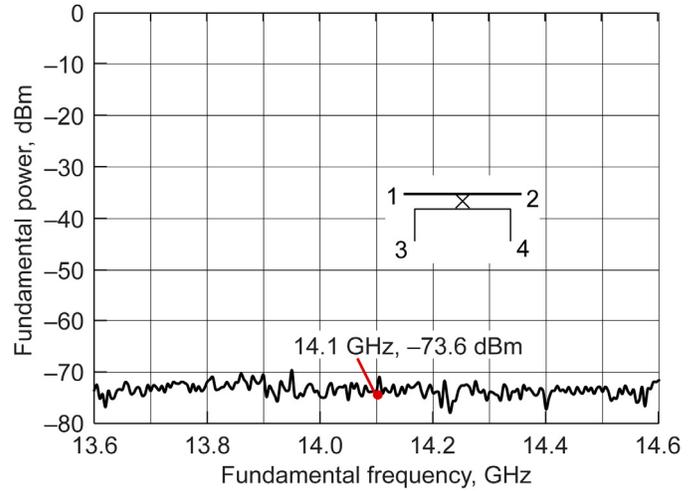


Figure 11.—Measured fundamental power at the MDC Ka-band secondary waveguide port 4.

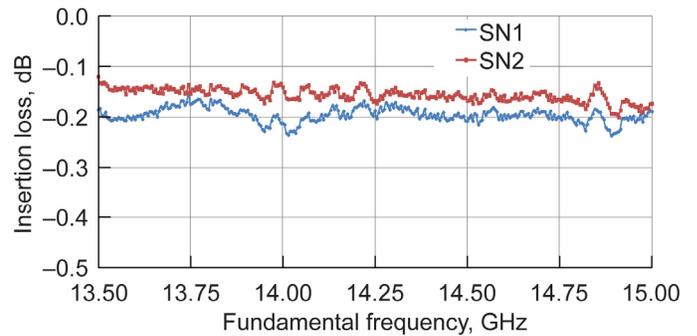


Figure 12.—Measured insertion loss between port 1 and port 2 of MDC Ku-band primary waveguides.

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, which is a major advantage over traditional harmonic filters and conventional diplexers. The spectrogram, shown in Figure 11, 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). Figure 12 shows that the network analyzer measured insertion loss (S_{21}) from Port #1 to Port #2 of the MDC Ku-band segment for the two MDCs. The insertion loss is small and hence would cause only very small corresponding losses in the fundamental RF power needed for space communications.

2.4 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 to 40 GHz) for transmission of the fundamental frequency and a secondary E-band

waveguide (WR-12, 60 to 90 GHz) for transmission of the coupled 2nd harmonic frequency. However, the much smaller dimensions of the coupling apertures necessitated taking a different approach to the design and fabrication of the MDC. Two important considerations were the waveguide wall thickness and the limited in-house availability of resources for fabrication. Instead of the two standard waveguides configured as shown in Figure 1, it was decided to custom design the E-band segment and use a section of the WR-28 waveguide segment machined to a thickness of 0.005 in. as the common wall. The E-band waveguide design featured mitered corners and was formed using Electrical Discharge Machining (EDM). The coupling aperture pattern in this case consisted of five apertures with the size and spacing of the apertures designed for a fundamental frequency of about 36 GHz and a corresponding 2nd harmonic frequency of 72 GHz. Figures 13(a) and (b) show the laser-cut coupling apertures in the Ka-band WR-28 waveguide section. Figure 14 shows the fully fabricated Ka-band/E-band MDC.

2.5 Ka-Band/E-Band MDC Test Results

In addition to being a second proof-of-concept MDC demonstration at higher frequencies, the Ka-band/E-band was chosen because of the availability of a Ka-band space TWT for the fundamental frequencies and also to investigate the potential for generating the 2nd harmonic mm-wave frequencies in the 71 to 76 GHz range of interest for atmospheric propagation studies. The Ka-band space TWT used for this demonstration was the L-3 Communications Electron Technologies Inc. Model 999HA, Serial No. 203, which was also the same TWT used for the 20 Gbps data transmission demonstration performed in collaboration with L-3 Communications West (Ref. 5). This TWT was developed under a contract from NASA GRC. A plot of the RF output power, gain, and efficiency performance of the 999HA over a 9 GHz bandwidth (Ref. 6) is presented in Figure 15.

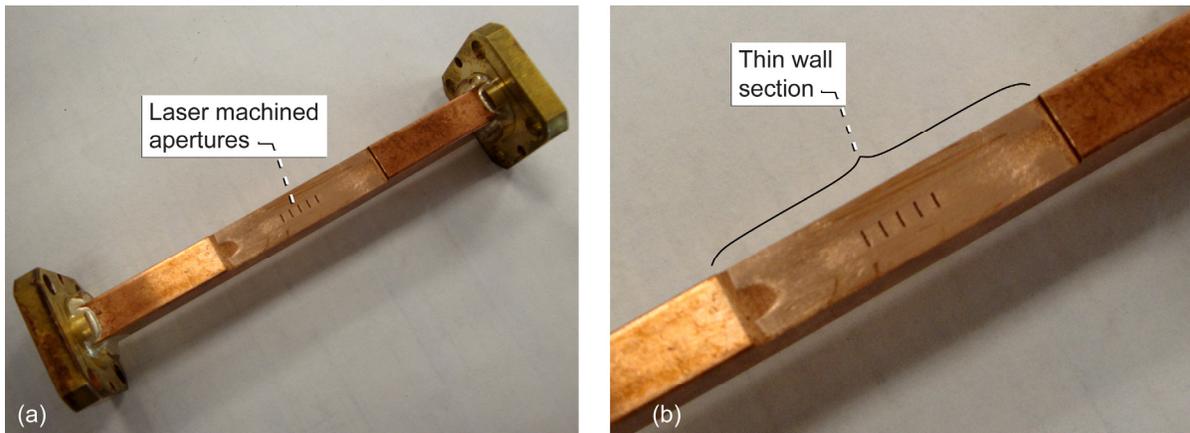


Figure 13.—(a) Ka-band WR-28 waveguide with thinned wall section and laser machined apertures. (b) Enlarged view of coupling apertures.

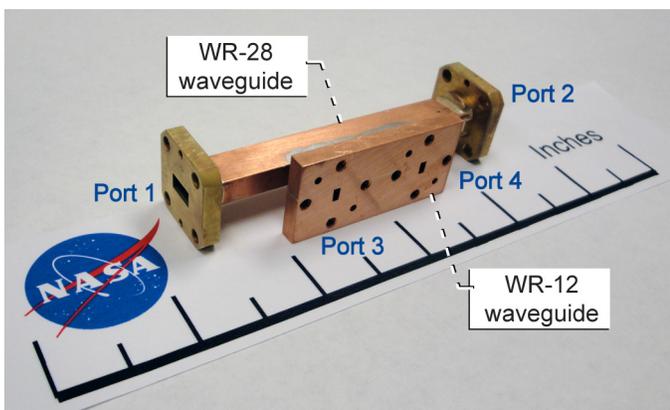


Figure 14.—Fabricated Ka-band/E-band waveguide MDC.

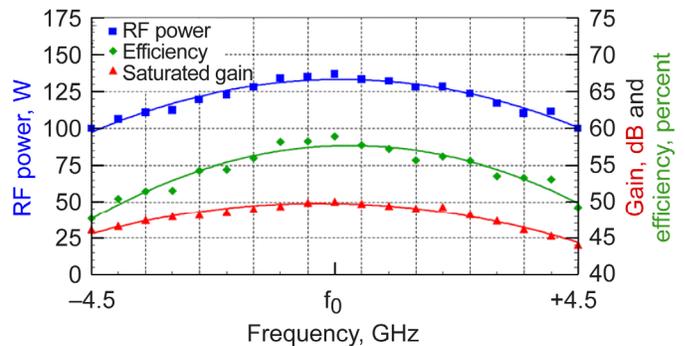


Figure 15.—9 GHz bandwidth performance of Ka-band TWT (L-3 Model 999HA).

The 999HA TWT design and performance, including the permanent magnetic focusing of the electron beam, was optimized for high electrical efficiency (60 percent) operation at saturated output power over the 500 MHz frequency band of 31.8 to 32.3 GHz allocated for deep space communications. Consequently, operation of the TWT, without defocusing the beam and risk of damage, was limited to the predetermined design voltages with RF input power at a given frequency being the only variable allowed for control of the RF output power. The MDC power measurements were performed over two Ka-band fundamental frequency ranges of 31 to 35 GHz and 35 to 38 GHz with corresponding respective E-band 2nd harmonic frequency ranges of 62 to 70 GHz and 70 to 76 GHz, the latter of which included the 71 to 75 E-band frequency band of interest for atmospheric propagation studies and potential space communications. Because of the wide 9 GHz bandwidth capability of the 999HA, as shown in Figure 15, the TWT was operable in both frequency ranges.

The 2nd harmonic E-band power measurements were made by means of two different methods, both with and without a Low Noise Amplifier (LNA) in the circuit. One method used an E-band power sensor/power meter, in which all of the

measurements were made with the TWT operation at saturated power output. The second method utilized a spectrum analyzer and a harmonic mixer (frequency extension module) (Refs. 7 and 8). In this case not all the measurements were made with the TWT in saturation and depending on the magnitude of the input power, compression effects limited the accuracy of the measured amplitudes, particularly with the LNA. The second measurement method was thereby more focused on a proof-of-concept demonstration that the MDC had the capability to detect the TWT 2nd harmonic with the potential for extraction and amplification. In both methods, the TWT input and output powers were measured with Ka-band power sensor/power meters.

2.6 E-Band Power Sensor/Power Meter Measurement Test Results

A schematic of the test circuit used for measurements of the fundamental (Ka-band) and the second harmonic (E-band) powers using the E-band power sensor/power meter is shown in Figure 16. Figure 17 shows photographs of the experimental test setup for the Ka-band/E-band MDC power measurements.

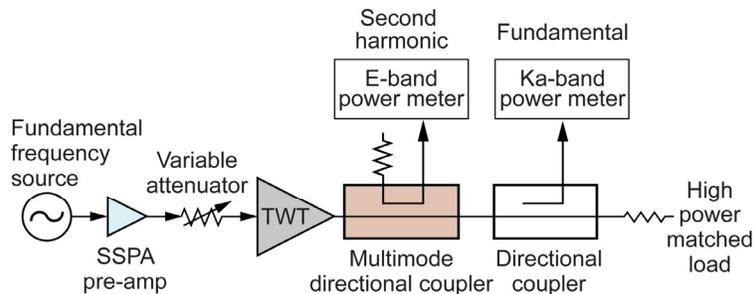


Figure 16.—Test circuit schematic for measurements of the fundamental (Ka-band) and the second harmonic (E-band) powers using the E-band power meter.

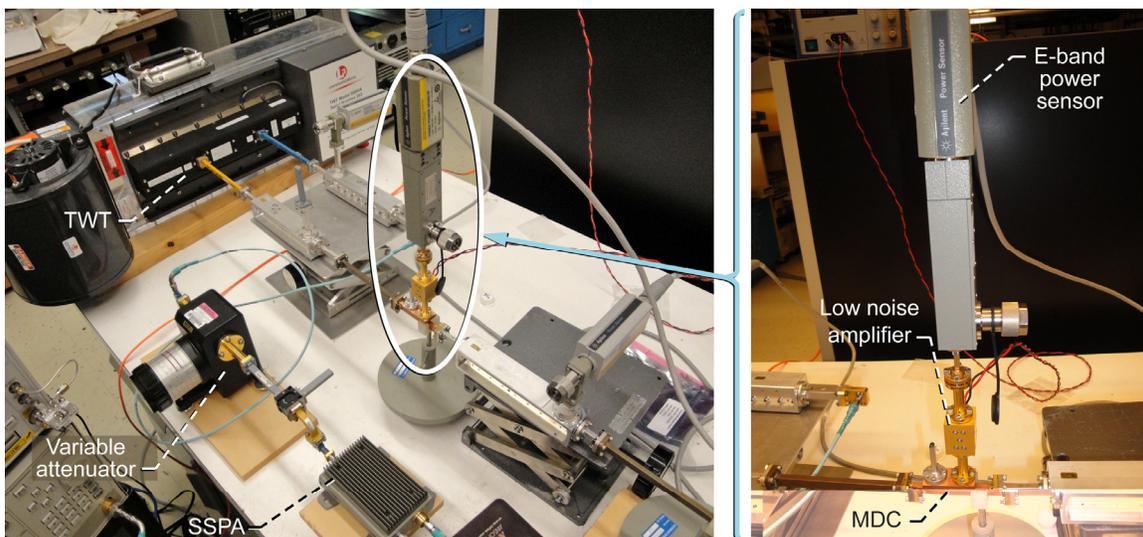


Figure 17.—Experimental setup for Ka-band/E-band MDC tests using the E-band power sensor/power meter for measurements.

Also shown in Figure 17 is a Low Noise Amplifier (LNA) at MDC output port 4 for amplification of the 2nd harmonic signals. All of the power measurements using this set-up were made with the TWT operated at saturated output power. The TWT input and output powers were measured with Ka-band power sensor/power meters. The solid-state power amplifier (SSPA) pre-amplifier and variable attenuator shown in the TWT RF input segment of the test circuit were used in cases when the output power of the fundamental frequency source (signal generator) was insufficient to drive the TWT to saturation.

Power measurement results over the fundamental frequency range of 31 to 35 GHz and the 2nd harmonic frequency range of 62 to 70 GHz are shown in Figures 18 and 19, respectively. In addition to the TWT fundamental saturated power output, Figure 18 also shows the TWT RF input power required to achieve saturation. Figure 19 compares the MDC 2nd harmonic

amplitudes with and without the LNA in the circuit and shows that the TWT 2nd harmonics from the MDC can be amplified to potentially useful power levels.

Power measurement results over the fundamental frequency range of 35 to 38 GHz and the 2nd harmonic frequency range of 70 to 76 GHz are shown in Figures 20 and 21, respectively. In addition to the TWT fundamental saturated power output, Figure 20 also shows the TWT RF input power required to achieve saturation. Figure 21 compares the MDC 2nd harmonic amplitudes with and without the LNA in the circuit and shows that the TWT 2nd harmonics from the MDC can be amplified to potentially useful power levels, in particular the beacon source levels needed for atmospheric propagation studies.

Overall, there is significant variation in the amplitudes of the 2nd harmonic, as was observed in the results for the Ku-band/Ka-band MDC.

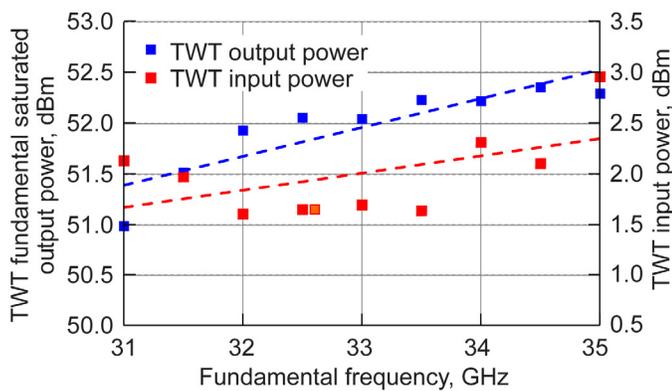


Figure 18.—TWT input power and TWT saturated output power measured over the fundamental frequency range of 31 to 35 GHz.

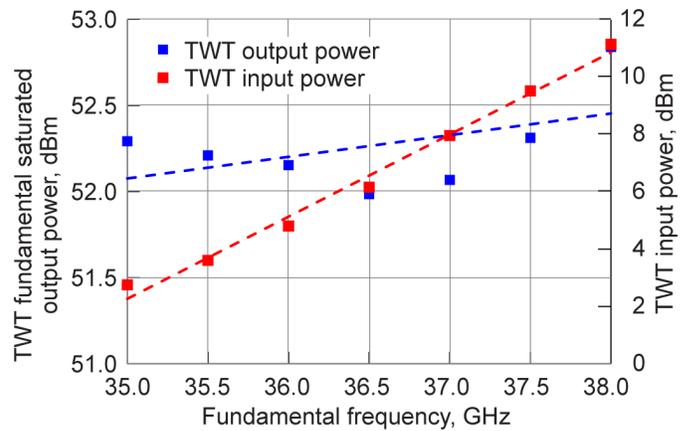


Figure 20.—TWT input power and TWT saturated output power measured over the fundamental frequency range of 35 to 38 GHz.

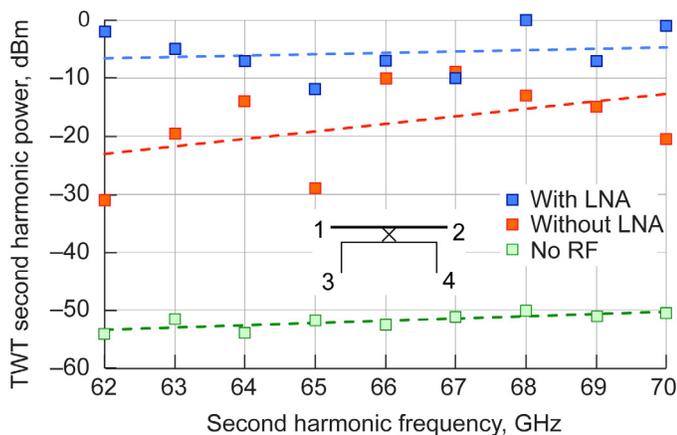


Figure 19.—TWT second harmonic power, with and without the Low Noise amplifier (LNA), measured over the frequency range of 62 to 70 GHz.

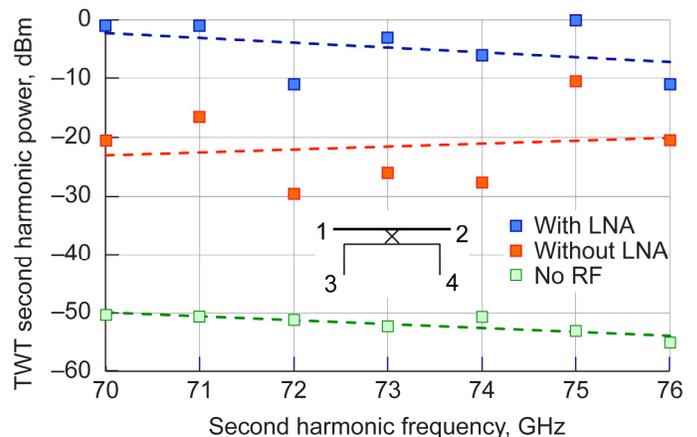


Figure 21.—TWT second harmonic power, with and without the LNA, measured over the frequency range of 70 to 76 GHz.

2.7 E-Band Harmonic Mixer/Spectrum Analyzer Measurement Test Results

A schematic of the test circuit used for measurement of RF power at the fundamental (Ka-band) and the second harmonic (E-band) frequencies is shown in Figure 22. Figure 23 shows photographs of the experimental setup for the Ka-band/E-band MDC tests using the harmonic mixer/spectrum analyzer. The spectrum analyzer, Agilent Model E4446A was equipped (external mixing option AYZ) for use with an external frequency extension module (OML diplexer model DPL26 and OML WR-12, 60 to 90 GHz, harmonic mixer model M12HWD, shown in Fig. 23) that enabled the E-band RF power measurements. The harmonic mixer, using the 12th harmonic, was factory calibrated for the conversion losses (an average of about 42 dBm across the E-band) associated with the necessary frequency down-conversion required by the spectrum analyzer. The conversion loss calibration was performed at an input power of -30 dBm. Measurements made at input powers greater than -20 dBm could result in loss of accuracy from signal compression.

The test data for the 31 to 35 GHz Ka-band fundamental frequency range, which includes the optimized 500 MHz space

communication band, is shown in Figures 24 and 25. Operation of the TWT was set for a saturated output power at 33 GHz with the same RF input power from the signal generator used for the full frequency range of 31 to 35 GHz. Although the fundamental power was observed to fall below saturation at the low end (31 to 31.5 GHz) for this set of measurements, an increase in RF input power could correct this if needed. Figure 25 shows the measured power of the 2nd harmonic frequencies, 62 to 70 GHz, at the MDC E-band output port with and without the LNA and also for no RF power input. Overall, there is significant variation in the amplitudes of the 2nd harmonic, as was observed in the results for the Ku-band/Ka-band MDC. The measurements with the LNA, where 2nd harmonic amplitudes ranged mostly between 0 and -20 dBm, provide additional validation of the MDC concept, in particular the capability to isolate 2nd harmonic frequencies with significant amounts of power available for further amplification. It is noted that a minimum in the 2nd harmonic power occurred around a fundamental frequency of 32.5 GHz, which is most likely by design, since this is close to the optimized 500 MHz frequency band. It was also observed that raising the RF fundamental input power a few dBm past saturation also increased the 2nd harmonic amplitude.

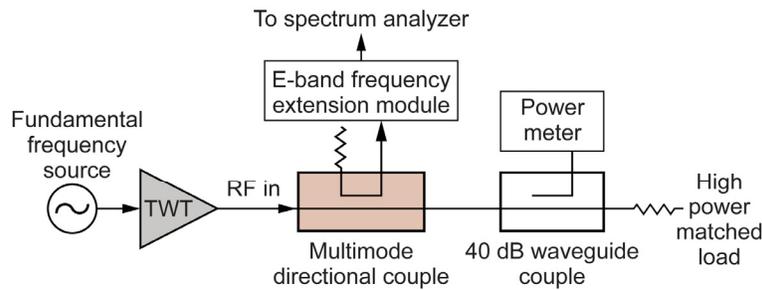


Figure 22.—Test circuit schematic for measurements of the fundamental (Ka-band) and the second harmonic (E-band) powers.

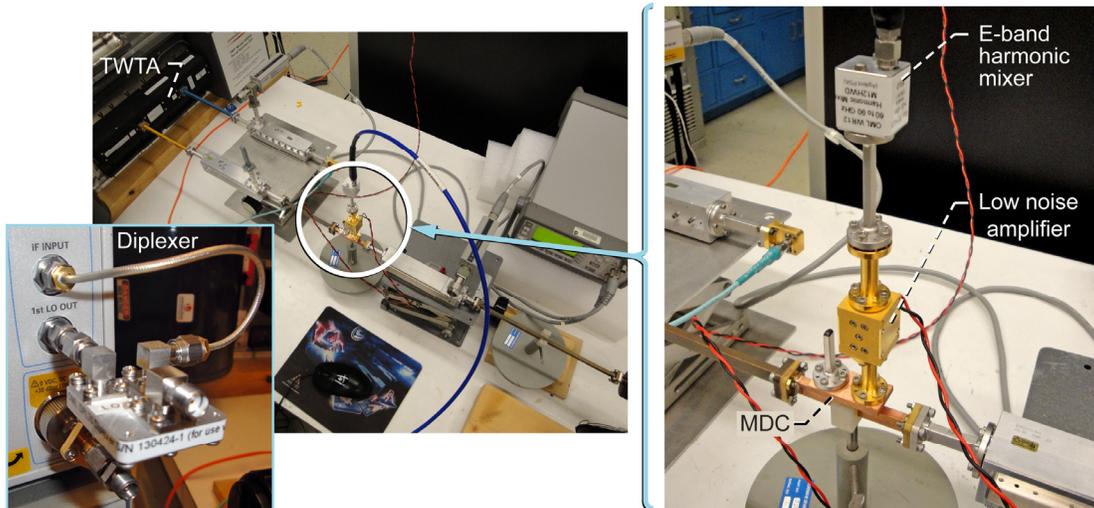


Figure 23.—Experimental setup for Ka-band/E-band MDC tests using the harmonic mixer and spectrum analyzer for E-band measurements.

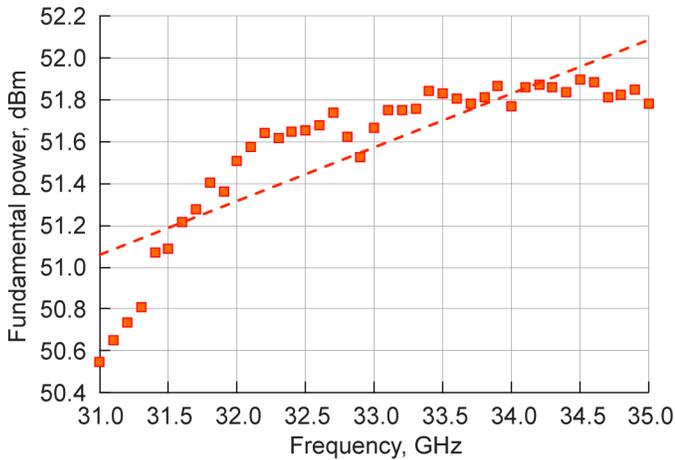


Figure 24.—TWT output power measured over the fundamental frequency range of 31 to 35 GHz.

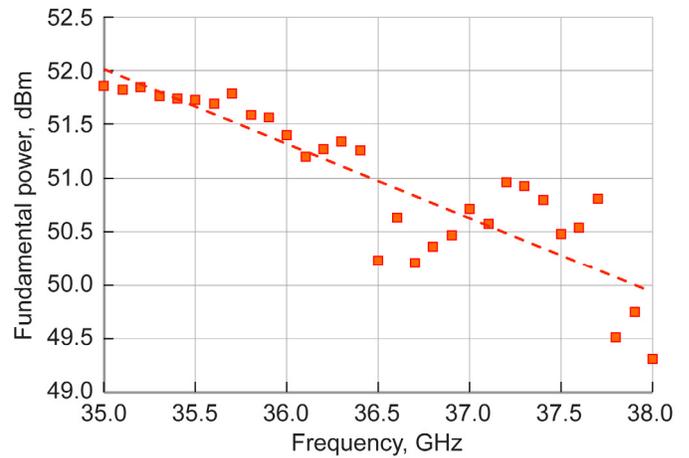


Figure 26.—TWT output power measured over the fundamental frequency range of 35 to 38 GHz.

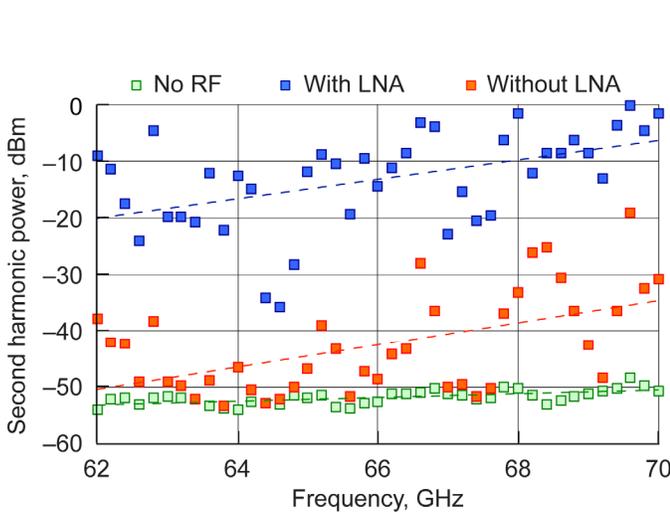


Figure 25.—TWT second harmonic power, with LNA, without LNA, and no RF input, measured over the frequency range of 62 to 70 GHz.

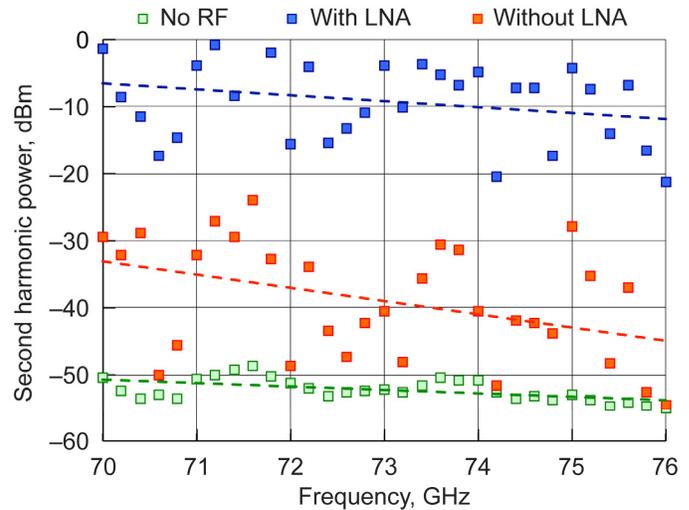


Figure 27.—TWT second harmonic power, with LNA, without LNA, and no RF input, measured over the frequency range of 70 to 76 GHz.

The test data for the 35 to 38 GHz Ka-band fundamental frequency range is shown in Figure 26 and 27. The operation of the TWT in this frequency range was limited by the available RF input power from the signal generator. Up to 36 GHz, the TWT was operated at saturated power output. Above 36 GHz, the TWT was operated at the maximum available RF input power from the signal generator where the RF output power was observed to be in the transition region between fully linear and saturation. Figure 27 shows the measured power of the 2nd harmonic frequencies, 70 to 76 GHz, at the MDC E-band output port with and without the LNA and also for no RF power input. The results with the LNA in the circuit demonstrate that significant 2nd harmonic power levels, ranging between 0 and -20 dBm, are achievable even when the TWT is operated below saturation and outside the frequencies used for space communications.

It is noted in Figures 25 and 27 that the 2nd harmonic E-band power measurements without the LNA were at -20 dBm or below and hence within the range of accuracy of the harmonic mixer/spectrum analyzer, although not so with the LNA. This suggests the feasibility of doing all the measurements with the TWT operating at saturation.

These results add credence to the possible use of the TWT 2nd harmonic as a potential beacon source for the 70 to 76 GHz E-band frequencies of interest for atmospheric propagation studies. It is important to recognize that the Ka-band/E-band MDC tests were primarily for proof-of-concept demonstration purposes. The design and fabrication of the MDC were not optimized for maximum coupling of the 2nd harmonic and efficient operation. Because of time and resource limitations, only one Ka-band/E-band MDC was fabricated and the coupling coefficient for the 2nd harmonic E-band frequencies was not measured.

3.0 Conclusions

The design, fabrication and successful proof-of-concept demonstration results are presented for a Ku-band/Ka-band MDC and a Ka-band/E-band MDC, the application of which is measurement and potential utilization of the 2nd harmonic frequencies from a TWTA. The MDC can be connected directly to the RF output port of the TWT with no loss of fundamental power, which is an advantage over traditional harmonic filters and conventional diplexers. Although the two MDCs reported here were designed and fabricated only for proof-of concept purposes, the efficiency and performance of the MDC can be optimized using appropriate computer modeling software for coupling aperture design and currently available high precision fabrication techniques for minimization of RF losses. The test results demonstrated sufficient power in the 2nd harmonic for potential application of the MDC in a TWT based space borne beacon source for atmospheric propagation studies at mm-wave frequencies (Ref. 1).

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