Enabling Passive Components for High-Power Wideband Millimeter Wave Repeater Applications

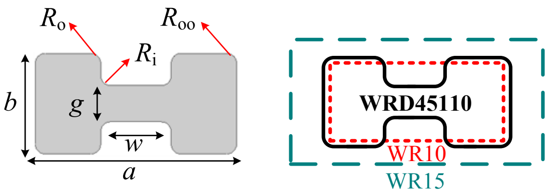
Sara Manafi, Mauricio Pinto, Muhannad Al-Tarifi, Gregor Lasser, Zoya Popovic, and Dejan S. Filipovic
Department of Electrical, Computer and Energy Engineering
University of Colorado Boulder
Boulder, CO, USA
[Sara.manafi,Dejan]@Colorado.edu

***Abstract*— A suit of enabling passive components covering entire V- and W- bands, i.e. 45-110 GHz, is built for the support of future RF repeater research and development efforts. Concerns such as loss, power handling, dispersion, and single-mode bandwidth are considered to design a custom double-ridge waveguide and components including antennas, bends, twists, dividers, hybrids, couplers, filters, and decoupling surfaces, just to name a few. Results show that the developed technology can pave the way for efficient, low-cost integrated wideband or multiband millimeter wave systems.**

***Keywords*— DMLS, Double-ridge waveguide cross section, Isolation improvement, Quad-ridge horn antenna, RF repeater**

I. INTRODUCTION

Emerging high power millimeter wave applications such as RF repeaters require transmission line technologies operating over a wide bandwidth with the ability to carry dozens of watts of continuous wave (CW) power [1]. To design these systems enabling components such as dual-polarized antennas, filters, couplers, bends and twists are needed. Active components are also needed, but they are not considered here. In this paper a high-power capable wideband 45-110 GHz double-ridge waveguide (WRD45110) with low loss and low dispersion is demonstrated first. Thereby, utilizing the engineered cross-section a suite of passive waveguide components required for a typical RF repeater system including transmission line, E- and H- plane bends, 90° twist, and termination load are developed. A quad-ridge horn antenna with constant broadside gain and stable E- and H- plane radiation patterns over the desired frequency band is also demonstrated. All components are carefully designed across different physics-based domains (RF, thermal, air-breakdown, etc) and fabricated with either a direct metal laser sintering (DMLS) 3-D printing or a conventional CNC machining with special care taken to allow for easy interconnecting. The cascade of fabricated transmission line, E- and H- plane bends, and 90° twist has insertion loss and VSWR better than 2 dB and 1.8, respectively over the entire 45-110 GHz range. To enhance isolation between the TX and RX antennas in an RF repeater, a reactive impedance surface (RIS) with mushroom structure is designed and built on a thin 0.79 mm TLY5 substrate. Simulations agree very well with measurements and isolation improvement of at least 8 dB in both V- and W- bands is demonstrated.



(a) (b)

Fig. 1. (a) Double-ridge waveguide cross-section with shown radius of curvatures for improved power handling, (b) the final cross-section of the custom double-ridge waveguide WRD45110 alongside the conventional WR10, and WR15 cross-sections.

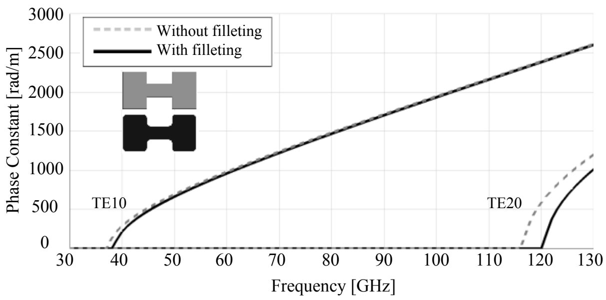


Fig. 2. Single-mode bandwidth of the double-ridge waveguide with and without filleting.

TABLE I. PARAMETERS OF THE WRD45110 DOUBLE-RIDGE WAVEGUIDE SHOWN IN FIG. 1.

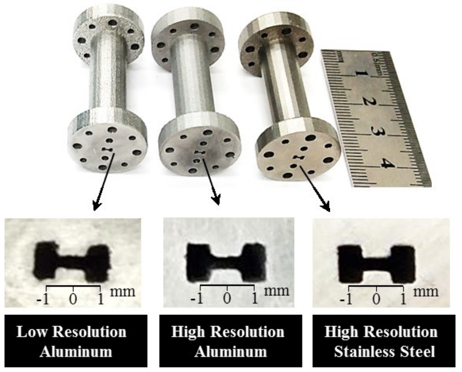
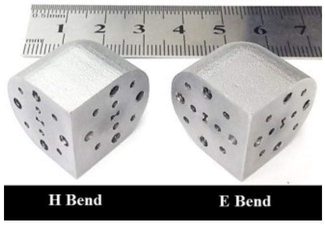
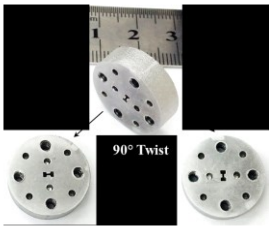
WRD45110 45-110 GHz	a (mm)	b (mm)	w (mm)	g (mm)	R_i (µm)	R_o (µm)	R_{oo} (µm)
	2.60	1.30	0.91	0.47	127	127	127
WR15 45-75 GHz				**WR10 75–110 GHz**			
a (mm)		b(mm)		a (mm)		b(mm)	
3.76		1.88		2.54		1.27	

II. CUSTOM DOUBLE-RIDGE CROSS-SECTION WAVEGUIDE

To the best of our knowledge outside the initial work by the authors [2]-[4], no double-ridge waveguides are reported with octave or more bandwidth above 40 GHz. Whereas printed transmission lines and micro-machined recta-coax lines [5] can readily cover this range, they are not considered here due to the low power handling capability of the former and high cost of the latter. Therefore, a custom double-ridge waveguide with

978-1-5386-4584-0/18/$31.00 ©2018 IEEE

TABLE II. 45-110 GHZ DOUBLE-RIDGE WAVEGUIDE COMPONENTS

<table>
<tr><th colspan="2">Components and the pictures</th></tr>
<tr><td colspan="2"> </td></tr>
<tr><td> </td><td> </td></tr>
<tr><td> </td><td> </td></tr>
</table>

operational bandwidth from 45 to 110 GHz was developed [2]. A comprehensive experimental validation of various lines and components based on the developed cross section is then carried out to further the research hypothesis.

Fig. 1 shows the designed WRD45110 double-ridge waveguide cross-section. To visually comprehend the differences with the conventional lines, the WR10 and WR15 rectangular waveguide cross sections are also outlined. The ridge gap *g* and ridge width *w* are set to provide the required single-mode bandwidth, minimum attenuation, and minimum dispersion. To maximize the peak power handling filleting is applied to the edges of the ridge cross-section. Fig. 2 shows the single-mode bandwidth of the WRD45110 cross-section and the filleting effect on the fundamental and higher order mode. Table I lists the values of the corresponding parameters. The single-mode bandwidth is 38-120 GHz, and the in-band (45-110 GHz) attenuation and group delay for smooth aluminum walls are below 0.06 dB/cm, and 0.06 ns/cm, respectively. A carefully executed simulations with HFSS and CST show that this cross-section can handle up to 400 W peak-power (with safety factor of 4) under normal conditions in air.

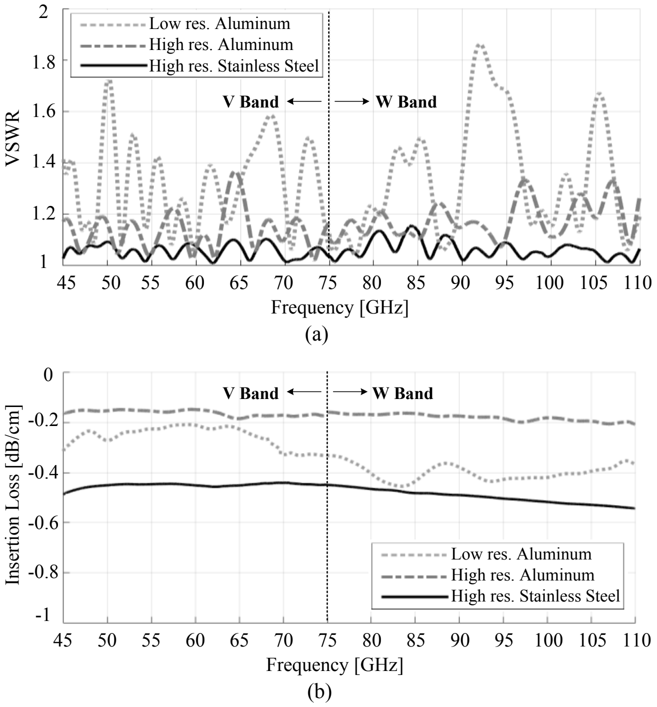


Fig. 3. Illustration of measured (a) VSWR, and (b) insertion loss of 4-cm lines in aluminum and stainless steel with different resolutions.

III. CASCADING THE COMPONENTS AND ISOLATION IMPROVEMENT FOR RF REPEATER

RF repeaters often require high-power capable passive components which are also mechanically sturdy to survive harsh deployment scenarios. Easy integration with active components such as low-noise and high-power amplifiers as well as antennas is also desired. Repeater antennas need to have stable radiation patterns with constant gain over the entire bandwidth. Sometimes, the pattern of the TX and RX antennas can be tailored to the RF system gain to project the required effective radiated power over the field of view.

The double-ridge waveguide components (see Table II for a selected few) are developed to aid the design of such a repeater in the desired bandwidth. Fig. 3 illustrates the measured VSWR and insertion loss of the DMLS fabricated 4-cm transmission lines in low-resolution aluminum, high-resolution aluminum, and high-resolution stainless steel (see Table II for the close-up images of the cross-sections). As seen, in DMLS fabrication process the high resolution aluminum and high resolution stainless steel provide the lowest insertion loss and highest integrity, respectively [6]. As expected the insertion loss in metal 3-D printing is a function of metal type and manufacturing resolution. Note that the high loss in low-resolution aluminum line is not only because of the larger roughness, but also due to the lower integrity of the cross-section and the associated mismatch.

Fig. 4 shows the measured VSWR of the connected transmission line, bends, twist and open termination load as depicted in the inset. As seen, the measured VSWR is better

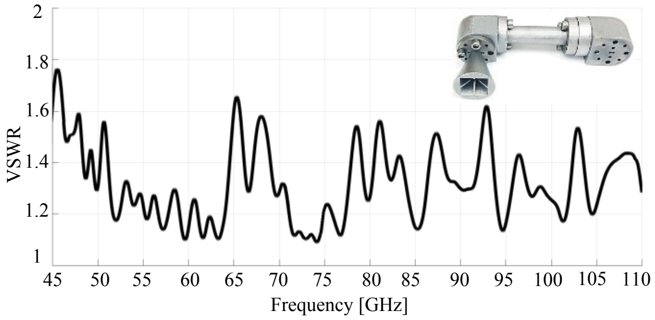


Fig. 4. Measured VSWR of cascaded WRD45110 line, twist, bends, and

than 1.8 over the entire 45-110 GHz range, which indicates the good performance of the fabricated components and their connections.

The obtained VSWR, gain and HPBW variations over the 45-110 GHz bandwidth of the designed antenna [3] are below 1.7:1, 1.7 dB, and 9°, respectively. Fig. 5 shows the VSWR and directivity of the DMLS printed antenna. As seen, the agreement between simulation and measurement is noticeable which confirms the maturity of the current DMLS printing technology. These apertures, when used as transmit and receive antennas of a repeater system, need to be well isolated to avoid undesired oscillations. Techniques for enhancing isolation such as corrugations, and mushroom structures are investigated. In Fig. 6 the isolation improvement over the entire bandwidth is depicted with the mushroom RIS [4].

IV. CONCLUSION

We report research and development of a complete suite of enabling waveguide components for the future RF repeaters operating over V- and W-band frequencies. For this purpose a custom waveguide cross-section was developed first followed by several critical components. Conventional CNC and fast maturing DMLS 3-D printing have shown the capability of realization of the developed components. The future work is to fully integrate all the functional subsystems into a repeater and demonstrate its operation in discussed frequency range.

ACKNOWLEDGMENT

This work is supported by the Office of Naval Research (ONR) grant # N00014-15-1-2111.

REFERENCES

[1] W. J. Kerins "Analysis of Towed Decoys," IEEE Trans. of Aero. And Elec. Sys., Vol. 29, No. 4, pp. 1222 – 1227, 1993.

[2] M. Al-Tarifi, S. Manafi, D. S. Filipovic, "Design of Wideband Dual-Polarized Horn Antennas for Space Constrained V-through W-Band Decoy Repeaters," in Proc. Antenna Appl. Symp., Monticello, IL, USA, 2015, pp. 474-491.

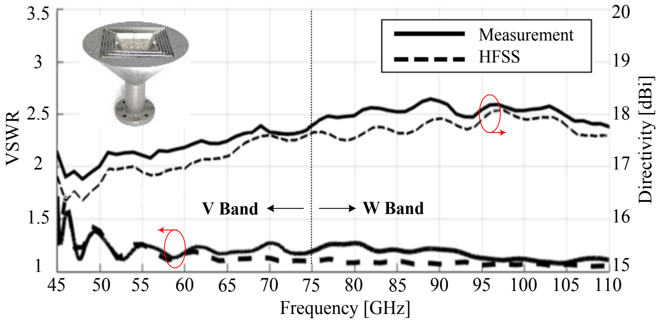


Fig. 5. Obtained VSWR and directivity of the DMLS printed antenna with custom made TRL calibration.

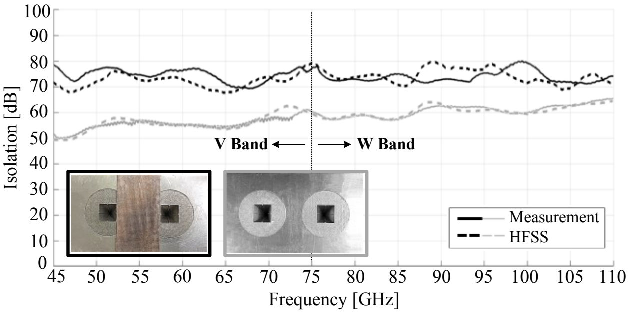


Fig. 6. Obtained isolation level between TX and RX antennas over V- and W- bands with and without RIS in between.

[3] S. Manafi, M. Al-Tarifi, , D. S. Filipovic, " 45-110 GHz Quad-Ridge Horn with Stable Gain and Symmetric Beam," IEEE Transactions on Antennas and Propagation, vol. 65, no. 10, pp. 4858-4863, Sep. 2017.

[4] S. Manafi, M. Al-Tarifi, D. Filipovic, "Isolation Improvement Techniques for Wideband Millimeter Wave Repeaters," IEEE Antennas and Wireless Propagation Letters, vol. 17, no. 2, pp. 355-358, Feb. 2018.

[5] D. S. Filipovic, et.al., "Modeling, Design, Fabrication and Perfromance of Rectangular micro-Coaxial Lines and Components," Proc. 2006 IEEE IMS, San Francisco, June, 2006.

[6] Proto Labs, Inc. [Online]. Available: http://www.protolabs.com