Design and Realization of H-plane Stepped Horn Antenna for E-Band mm-Wave Link

Siniša Jovanović, *Member, IEEE* and Nebojša Pupavac

***Abstract*—This paper presents the design, implementation, and measured results of a horn antenna that covers a broad frequency range spanning from 60 GHz to 90 GHz. The antenna is created as an input/output component for the RF front-end of an E-Band mm-Wave Link which operates in the 71-76 GHz and 81-86 GHz sub-bands. E-Band links provide a large bandwidth, which is essential for supporting the high data rates required by 5G applications. The antenna's design is adapted to the available mechanical technology and tolerances. The H-plane antenna profile is designed and implemented with stepped segments that gradually increase in dimensions, optimized for achieving maximum gain and good matching across the entire frequency range. Two test setups were used to measure the antenna characteristics, and the obtained results show good agreement with the characteristics predicted by EM simulation. Overall, the results demonstrate that the proposed antenna exhibits comparable performance to commercial counterparts but with a significantly lower cost and faster turnaround time.**

***Index Terms*—Horn antenna; RF front end; E-Band mm-wave link; 5G applications.**

I. Introduction

E-band became a very popular mobile backhaul (MBH) solution, thanks to the wide spectrum and channels that give very high capacities up to 5.5 Gbps or even 10 Gbps when both polarizations are used. Light licensing regime and/or low spectrum fees makes the E Band links very attractive for 5G deployment. In more than 80 percent of countries with a known regulatory status, it is open for deployment or considered to be open for deployment Fig.1 [1]

Fig. 1. E-Band worldwide deployment [1].

A very wide frequency band is divided in the lower sub-band from 71 to 76 GHz and the upper sub-band from 81 to 86 GHz providing 19, 9 and 6 channels having bandwidths of 250, 500 and 750 MHz respectively. E Band links sub-bends exhibits relatively low free space attenuation, not affected by interaction with atmospheric O_2 and H_2O as shown in Fig. 2. Typical hop lengths of E Band links are in km range, which is quite suitable for dense urban environment.

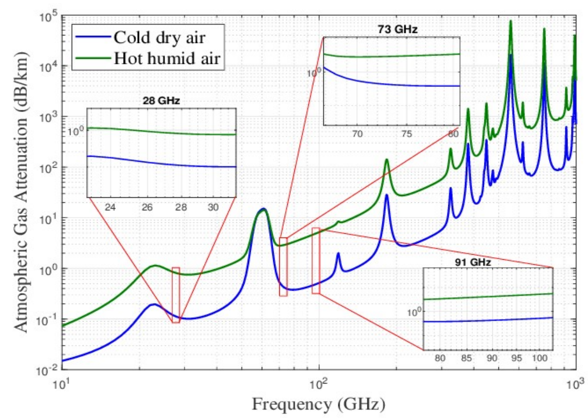

Fig. 2. Attenuation of the mm-Wave signals [2].

There are several chip suppliers providing highly integrated MMIC based upconverters with power amplifiers (PA) and down converters with low noise amplifiers (LNA) having integrated (WR12 compatible) waveguide port. These MMICs have frequency multipliers for local oscillator (LO) signals which helps RF frontend design. Analog Devices (AD) manufactures ADMV7310, ADMV7410, ADMV7320, ADMV7420 components that are a fully integrated system in package (SiP), in phase/quadrature (I/Q) up converters and down converters that operate between an intermediate frequency (IF) input range of DC to 2 GHz and RF output ranges from 71 to 76 GHz and from 81 to 86 GHz. The characteristics of these SiP are detailed in [3-6]. All these components share the same footprint with RF input/output realized as a waveguide WR-12 port at the bottom of their package as shown in Fig. 3.

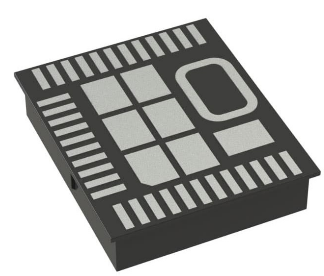

Fig. 3. Bottom view of AD's SiP up/down converters [3-6]

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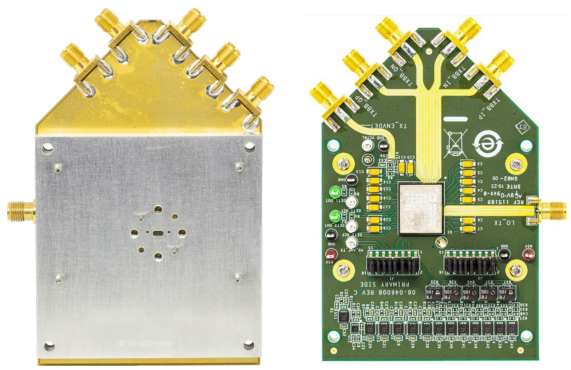

Fig. 4. Bottom and top view of evaluation board for AD's up/down converters

Fig. 4 displays both top and bottom views of an evaluation board designed for AD's up/down converters, featuring a standard UG-387/U flange that can easily be connected to a variety of commercially available horn antennas, such as the one described in [7]. This setup effectively creates an almost complete RF frontend for an E Band link.

Due to their high price, commercially available horn antennas are not a convenient option for both development and mass production of E-band mm-wave link RF front ends. A more practical and cost-effective solution would be to use a custom-designed antenna that has been tailored to meet the specific electrical and mechanical requirements during the design and development process of the E-band mm-wave link.

In this paper a design of an antenna which can be connected directly to the WR-12 input port of AD's SiP up and down converters to produce transmitting and receiving RF front-ends. The aim of the design was to cover both sub-bands (71-86 GHz) and to allow easy production and to achieve the overall antenna gain of more than 20 dBi within the entire working frequency range.

II. Horn Antenna Design and Simulation Results

An important objective during the antenna design process was to enable the antenna realization with existing/available mechanical technology and tolerances. This meant that the horn antenna would be composed of two halves mutually symmetrical with respect to the central E plane, whose inner cavity is formed by digging with milling cutters on a programmable CNC (Computer Numerical Control) milling machine. For achieving simple processing and low cost, the antenna was chosen to be made of an aluminum alloy which is typically used to make most mechanical housings for electronic devices prototyping. The H-plane antenna profile is designed with stepped segments that gradually increase in dimensions with rounded corners in accordance with the diameter of the milling cutters. The number of segments, the scale factor between the segments and all significant dimensions of the horn antenna are optimized for achieving maximum gain and good matching across the entire frequency range, as well as the maximum side lobe suppression in H plane. Fig. 5 shows the final shape of the antenna with all important dimensions that are listed in Table I.

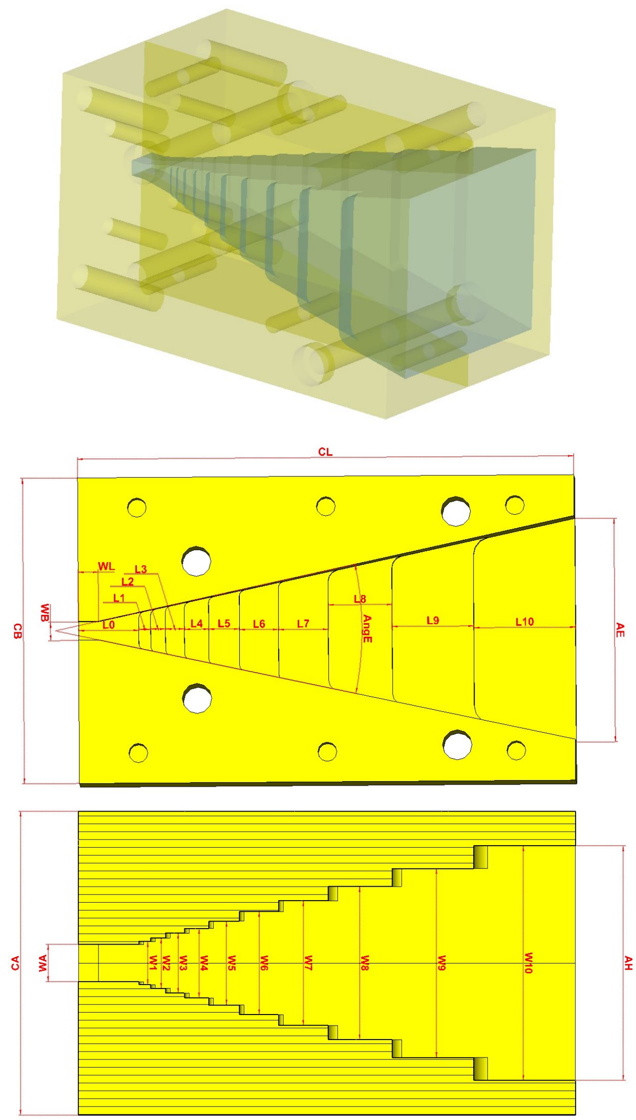

Fig. 5 Shape and important dimensions of the H-plane-stepped horn antenna: (a) 3D view (top); (b) E-plane view (middle); (c) H-plane view (bottom)
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TABLE I: Values of All Important Dimensions [mm] of the Proposed Horn Antenna After Optimization

Parameter	Value [mm]	Parameter	Value [mm]	Parameter	Value [mm]
L1	1	W1	3.6	L0	5.1
L2	1.25	W2	4.2	CA	25.4
L3	1.6	W3	5	CB	25.4
L4	2.05	W4	5.8	CL	42
L5	2.6	W5	7	WA	3.1
L6	3.3	W6	8.6	WB	1.55
L7	4.2	W7	10.2	WL	1.7
L8	5.4	W8	12.8	AH	19.6
L9	6.9	W9	15.8	AE	18.6
L10	8.6	W10	19.6	AngE	24°

The antenna is designed and optimized with EM simulation tools CST Microwave Studio and WIPL-D [8, 9].

The initial design models included only inner cavity of horn antenna bordered with infinitely thin perfect conductor. Such a simplified model was convenient for reducing computation time which allowed optimization of the antenna parameters. Final antenna models included all mechanical parts that were required for antenna assembling and replacing the perfect conductors with aluminum alloy that have realistic metal losses.

Fig. 6 shows Return Loss simulation results in very wide frequency range from 55 to 95 GHz for antenna model shown in Fig. 5, having dimensions shown in Table I, while Fig.7 shows maximum gain.

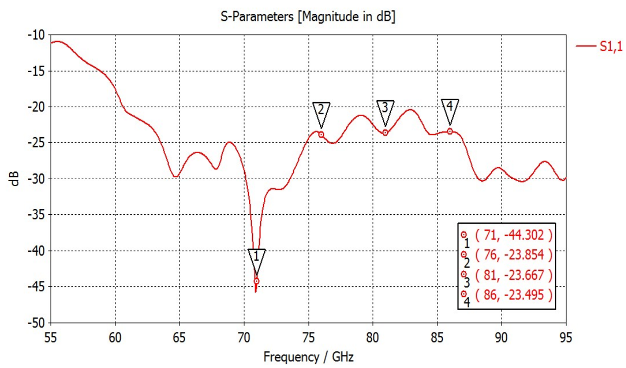

Fig. 6. Return Loss (RL) simulation results of horn antenna after parameter optimization

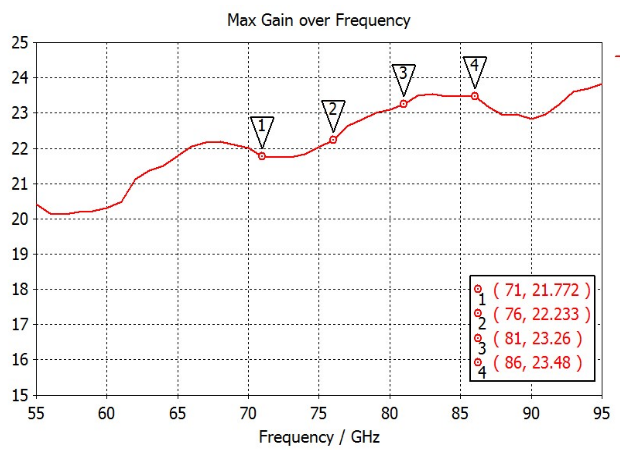

Fig. 7. Maximum Gain vs. frequency of the designed antenna (EM simulation results)

Fig. 8 displays 3D radiation pattern for the same antenna model at four bordering frequencies of E-band link sub-bands, showing maximum gain between 21.8 dBi @71 GHz and 23.5 dBi @86 GHz.

Fig. 9 and 10 shows radiation patterns cross sections in E and H plane, respectively, while Table II outlines the overview of the main electrical characteristics of the antenna model from Fig. 5 obtained by EM simulation.

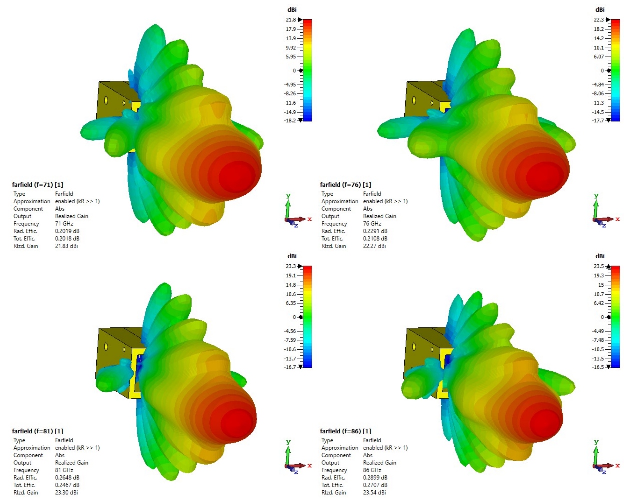

Fig. 8. 3D radiation pattern of the antenna at frequencies: 71 GHz (top left), 76 GHz (top right), 81 GHz (bottom left), and 86 GHz (bottom right)

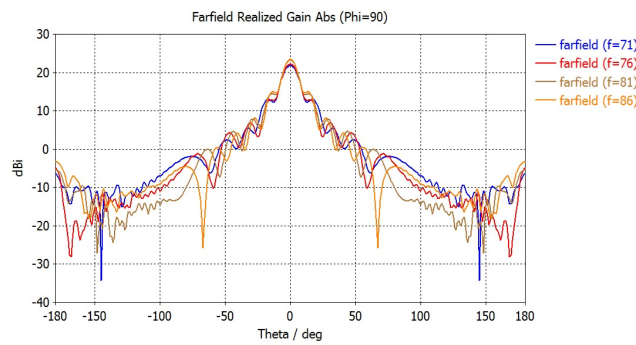

Fig. 9. E-Plane radiation patterns at 71, 76, 81, and 86 GHz

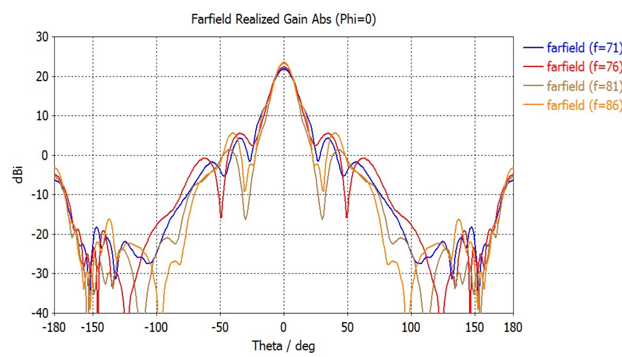

Fig. 10. H-Plane radiation patterns at 71, 76, 81, and 86 GHz

TABLE II
OVERVIEW OF ANTENNA'S MAIN ELECTRICAL CHARACTERISTICS
EM SIMULATION RESULTS

Frequency [GHz]	71	76	81	86
Gain [dBi]	21.8	22.3	23.3	23.5
3dB Beamwidth, E-plane [°]	12.2	11.5	10.7	10.1
3dB Beamwidth, H-plane [°]	14.6	14.8	12.7	11.6
Side Lobe Suppression, E-plane [dB]	8.8	9.4	8.8	8.6
Side Lobe Suppression, H-plane [dB]	17.5	16.8	21.9	17.9
VSWR	1.01	1.14	1.14	1.14

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III. Horn Antenna Realization

To ensure the best possible symmetry of the parts that form the antenna, both halves are fabricated simultaneously from a common piece of aluminum alloy as shown in Fig. 11.

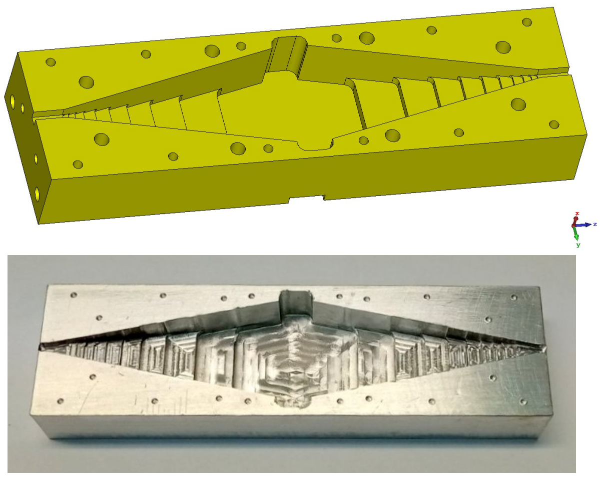

Fig. 11. Both halves of the antenna joined in one piece for simultaneous fabrication

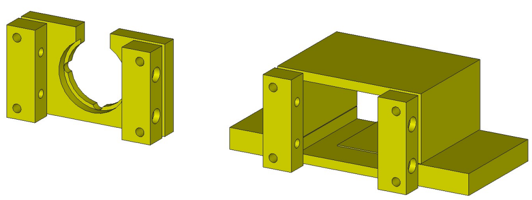

Fig. 12. Additional mechanical parts for the antenna.

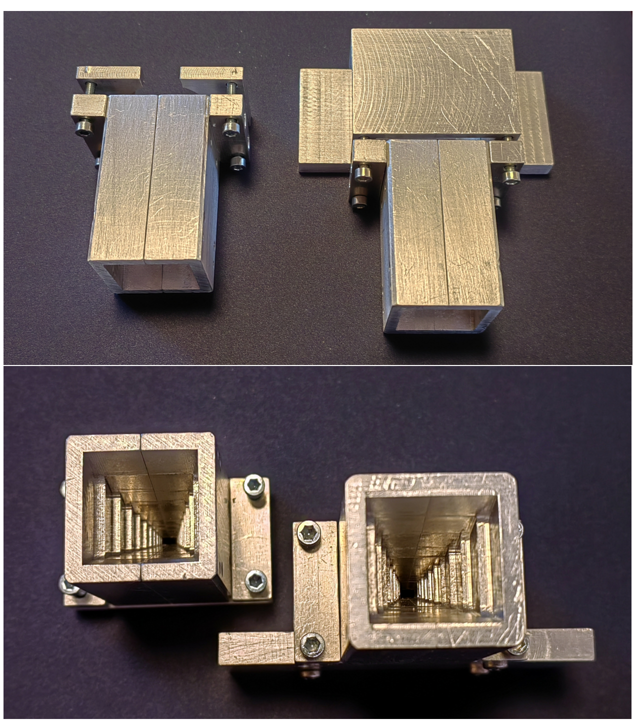

Fig. 13. Fabricated pair of horn antennas with additional mechanical connecting parts: top view (top) and front view (bottom).

Additional mechanical parts shown in Fig. 12 were fabricated to ensure a tight connection of the antennas to the waveguide ports of the measuring instruments. A pair of identical antennas was manufactured to enable their gain determination based on free space measurement. Fig. 13 shows top and front view of a pair of assembled antennas together with additional mechanical parts from Fig. 12. Two identical horn antennas were manufactured.

IV. Test Methods and Measured Results

The gain of the manufactured antenna is determined from free space loss measurement for specified distances between two identical antennas. Two different test setups were used; one with signal generator and spectrum analyzer that is shown in Fig. 14 and 15, and the other with network analyzer that is shown in Fig. 16.

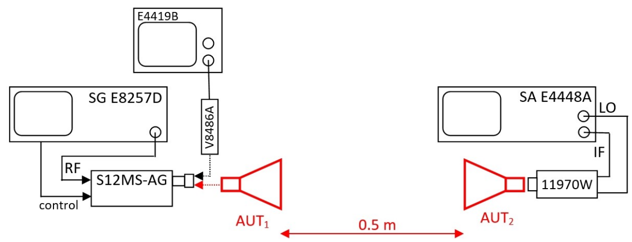

Fig. 14. Schematic of the test setup No.1 for antenna gain determination based on free space loss measurement.

Fig. 15. Photo of the test setup No.1 for antenna gain determination based on free space loss measurement.

The test setup No1 contains the following instruments:

1) E8257D PSG (Programmable Signal Generator) Analog Signal Generator, that generates initial RF signal in frequency range from 11.666 GHz to 15 GHz;

2) S12MS-AG mm-wave Source Modules, that 6× multiply the initial RF signal into the frequency range from 70 GHz to 90 GHz with constant output level of + 4 dBm;

3) V8486A Power Sensor with E4419B Power Meter for verifying the output level of +4 dBm.

4) E4448A PSA Spectrum Analyzer (SA) with 11970W Series Harmonic Mixers, for receiving, converting and displaying the RF signal received by the second antenna under test.

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Table III displays all electrical values measured by test setup No.1, as well as the resulting average antenna gain of the antennas under test with the assumption that both antennas are mutually identical. Column B contains the readings of the measured signal level as displayed on E4448A SA. The values of the Column B are increased for the insertion losses of the 11970W mixer (outlined in Column C) to obtain the levels of the received signal (Column D). The values in column H, which is equal to the sum of gains of both test antennas are obtained as H=D-E-G, where Column E contains signal levels at the input of the transmitting antenna and (Column G) contains the free space loss values calculated for the distance between the test antennas (0.5 m). Under assumption that the both test antennas are identical, Column I shows the gain of each antennas tested in accordance to setup No. 1.

TABLE III
MEASURED VALUES FOR ANTENNA GAIN MEASUREMENT WITH TEST SETUP 1

A	B	C	D=B+C	E	F=D-E	G	H=F-G	I=H/2
Freq	Rx(m)	Mixcc	Rx(c1)	Pout	Rx(c2)	FSL(@0.5m)	$G_{Rx}+G_{Tx}$	G_{avg}
[GHz]	[dB]	[dB]	[dB]	[dBm]	[dB]	[dB]	[dB]	[dB]
70	-53.5	37.7	-15.8	4	-19.8	-63.3	43.5	**21.8**
71	-53.5	37.7	-15.8	4	-19.8	-63.4	43.7	**21.8**
72	-53.4	37.7	-15.7	4	-19.7	-63.6	43.9	**21.9**
74	-55.5	37.7	-17.8	4	-21.8	-63.8	42.0	**21.0**
75	-54.6	37.7	-16.9	4	-20.9	-63.9	43.0	**21.5**
76	-53.8	38.6	-15.2	4	-19.2	-64.0	44.8	**22.4**
78	-55.2	38.0	-17.2	4	-21.2	-64.3	43.1	**21.5**
80	-54.5	38.3	-16.2	4	-20.2	-64.5	44.3	**22.1**
81	-55.6	38.3	-17.2	4	-21.2	-64.6	43.4	**21.7**
82	-56.6	38.4	-18.2	4	-22.2	-64.7	42.5	**21.3**
84	-57.2	38.9	-18.3	4	-22.3	-64.9	42.6	**21.3**
86	-55.1	39.0	-16.1	4	-20.1	-65.1	45.0	**22.5**
88	-55.4	39.3	-16.1	4	-20.1	-65.3	45.2	**22.6**
90	-55.7	39.6	-16.1	4	-20.1	-65.5	45.4	**22.7**

Test setup No.2 is performed with N5253E1 PXI 20 GHz network analyzer with E-Band (60 GHz to 90 GHz) VDI Extenders shown in Fig. 16.

Fig. 16. Photo of the test setup No.2 for antenna gain determination based on free space loss measurement.

Test setup No.2 is used to measure S-parameters of 2-port networks consisting of two test antennas facing each other and separated for 0.35 m, which is maximum achievable distance for the available connecting cables within the test setup.

S_{11} and S_{22} values obtained by this measurement represents RL at corresponding test antennas port, while S_{21} represents the sum of the antenna gains and the free space loss at the distance of 0.35 m. The measured S-parameters are shown in Fig. 17.

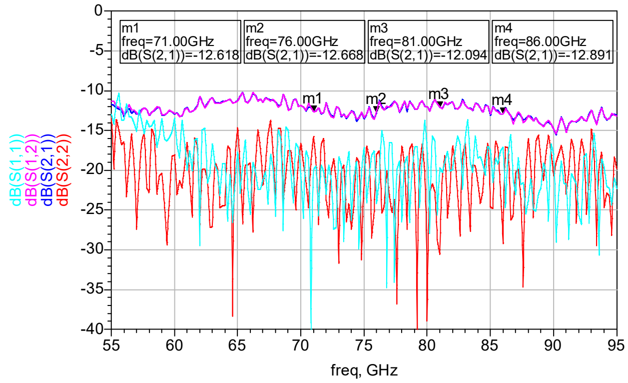

Fig. 17. Measured S-parameter results for the pair of test antennas separated by 0.35 m

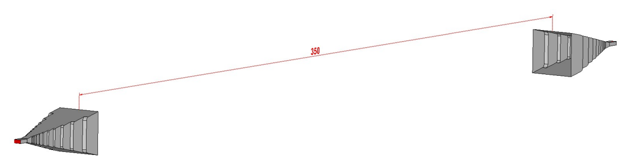

Fig. 18. Simulation model for test setup No. 2

Fig. 18 displays a simulation model designed to replicate the testing conditions of test setup No.2. Its purpose is to compute the S parameters of 2-port networks composed of two test antennas placed 0.35 m apart and facing each other. In order to reduce the number of unknowns and shorten the calculation time, the model is simplified to the greatest degree by eliminating all non-essential mechanical components and keeping only inner cavity of horn antenna bordered with infinitely thin perfect conductor.

The EM simulation results obtained for model from Fig. 18 is shown in Fig. 19.

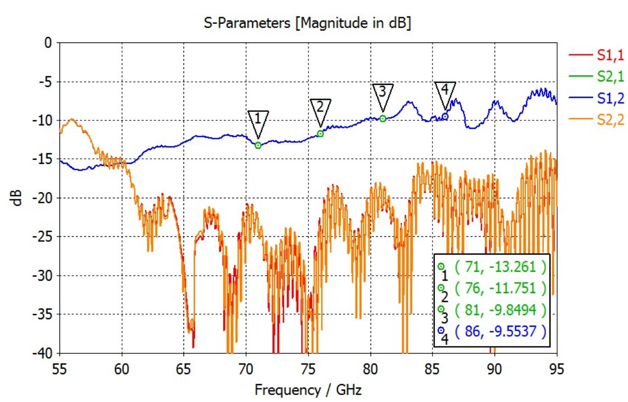

Fig. 19. Simulated S-parameter results for the pair of test antennas separated by 0.35 m

Based on the results of S_{21}, at frequencies 71, 76, 81 and 86 GHz from Fig. 19 and Fig. 17 (indicated by markers 1 to 4 and presented in column B and C in Table IV) as well as the calculated free space loss for the distance of 0.35 m (column D in Table IV), the corresponding antennas' gains are calculated and presented in Table IV for both simulated results (G_{SM2} – column E) and measured results (G_{MM2} – column F) obtained from test setup No.2. These results are within Table IV compared to the simulated and measured antenna gain results obtained by initial antenna model simulation (G_{SM1}) and the measured results obtained from test setup No.1 (G_{MM1}).

Rippled S-parameter results that could be seen on both Fig. 17 and Fig. 19 indicates non-negligible reflection between the measured antennas, that cannot be avoided due to mechanical constrains (connecting cable lengths) of the test setup No.2.

Table IV shows the antenna gain difference of about 2 dB between the results obtained with test setup No.2 and No.1 for both simulated and measured values, which could be partially explained by limited (not sufficient) distance in the case of test setup No.2.

TABLE IV
COMPARISON BETWEEN SIMULATED AND MEASURED VALUES OBTAINED BY TEST SETUP NO. 2 AND TEST SETUP NO.1

A	B	C	D	E=(B-D)/2	F=(C-D)/2	G	H
Freq	$S_{21(s)}$	$S_{21(m)}$	FSL(@0.35m)	G_{SM2}	G_{MM2}	G_{SM1}	G_{MM1}
[GHz]	[dB]	[dB]	[dB]	[dBi]	[dBi]	[dBi]	[dBi]
71	-13.26	-12.6	-60.3	**23.5**	**23.9**	21.8	21.8
76	-11.75	-12.7	-60.9	**24.6**	**24.1**	22.3	22.4
81	-9.85	-12.1	-61.5	**25.8**	**24.7**	23.3	21.7
86	-9.55	-12.9	-62.0	**26.2**	**24.6**	23.5	22.5

V. CONCLUSION

In this paper, the design, realization, and measured results of a horn antenna that covers a broad frequency range of 60 GHz to 90 GHz is presented. The antenna has been developed as an input/output component for the RF front-end of an E-Band mm-Wave Link. Our proposed antenna design is adapted to the available mechanical technology and tolerances. The obtained results show good agreement with the characteristics predicted by EM simulation, and demonstrate comparable performance to commercial counterparts at a significantly lower cost and faster turnaround time.

Overall, this study presents a promising solution for the development of cost-effective and high-performance antennas for use in 5G applications.

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