

Numerical Analysis of High-Gain Printed Antennas for 40 GHz Millimeter-Wave Operation

Guilherme B. Dias, P. A. B. Leão, P. R. N. Marciano, G. F. Vicentine, J. A. Soares, Arismar Cerqueira S. Jr., C. E. Rothenberg, Evandro Conforti, and Dalton S. Arantes

Abstract—This paper presents a numerical study of four printed antennas for millimeter-wave operation around 40 GHz. Two single-element models are compared with two 10-element linear arrays designed to increase antenna gain. The antennas were evaluated through electromagnetic simulations in Ansys HFSS, considering the reflection coefficient and total-gain patterns in elevation and azimuth cuts. The results show S_{11} below -19 dB at 40 GHz for all models and gain up to 16.51 dBi in the elevation cut.

Keywords—Printed antennas, millimeter waves, 40 GHz, linear arrays, reflection coefficient, gain.

I. INTRODUCTION

Millimeter-wave communication systems have been investigated to expand the available bandwidth, increase data rates, and enable high-capacity links in mobile networks and point-to-point systems. The shorter wavelength facilitates the integration of compact antennas and multi-element arrays, but it also makes the link more sensitive to free-space path loss, blockage, fabrication tolerances, and angular misalignment [1], [2], [3], [4]. In this context, the frequency range around 40 GHz is particularly relevant for 5G and beyond-5G applications in higher-frequency bands. Recent reviews of mmWave MIMO and phased-array antennas also emphasize that bandwidth, feed-network loss, mutual coupling, efficiency, and sidelobe control must be considered jointly in FR2 antenna design [5].

High antenna gain is especially important at millimeter-wave frequencies because it improves the link budget and helps compensate for additional propagation losses. A common approach to obtaining higher directivity is to use antenna arrays, in which the fields radiated by individual elements are coherently combined. This strategy, widely discussed in antenna literature [6], increases gain and provides radiation-pattern control, although it also imposes constraints on element spacing, feeding, and sidelobe levels.

A. Related Work

Recent printed-antenna research near the operating range of this work shows two complementary design directions. At the element level, planar dual-band MIMO antennas around

27/39 GHz provide compact reference geometries for 5G mmWave operation [7], while multiresonant patch geometries and dedicated matching structures can extend the useful bandwidth while preserving wide angular coverage in the 34–39 GHz range [8]. Alternative feeding approaches, such as empty-substrate-integrated-waveguide excitation and aperture coupling, have also been investigated to improve gain and efficiency in 28 GHz mmWave patches [9]. At the array level, large effective aperture is used to increase gain, but the final response becomes strongly dependent on spacing, feed architecture, and angular behavior [10]; shaped-pattern microstrip arrays at X-band further illustrate how feedline topology and element interaction affect the main beam and sidelobes [11]. More recent FR2 array measurements reinforce this trade-off by comparing linear and planar arrays with over-the-air validation in the n257 band [12]. Together, these works position the present study between modified printed elements and higher-gain linear arrays for operation near 40 GHz.

This paper numerically evaluates four printed antennas for operation around 40 GHz. The first two models are single-element antennas with modified patch geometries. Using these elements as references, two 10-element linear arrays were proposed to increase gain in the main radiation direction. The simulations were performed in Ansys HFSS, and the reported results include the reflection coefficient S_{11} and two-dimensional total-gain cuts at 40 GHz. Section II describes the analyzed models. Section III presents the simulated results. Section IV summarizes the main conclusions.

II. METHODOLOGY

Fig. 1 presents the four investigated models. Antenna 1 is based on the 27/39 GHz planar MIMO antenna reported in [7] and is used here as the starting point for the remaining designs. It uses a partial ground plane, triangular side extensions, and a rectangular slot in the radiating patch. These changes modify the surface-current path and favor a multiresonant response. Antenna 2 extends this concept by parameterizing the patch and internal-slot geometries as polygons, allowing the effect of the radiating-element shape on resonance and impedance matching to be evaluated. This strategy is consistent with prior mmWave printed-antenna designs that exploit multiple resonances, parasitic features, and feed topology to improve bandwidth or angular coverage [8], [9].

Antennas 3 and 4 are 10-element linear arrays based, respectively, on the geometries of Antennas 1 and 2. The main objective of these arrays is to increase gain at 40 GHz

Guilherme B. Dias, P. A. B. Leão, G. F. Vicentine, J. A. Soares, Christian Esteve Rothenberg, Evandro Conforti, and Dalton S. Arantes are with the Department of Communications, University of Campinas (Unicamp), Campinas-SP, Brazil, e-mail: g247041@dac.unicamp.br; P. R. N. Marciano is with the Department of Electrical Engineering, Federal University of Espírito Santo, Vitória-ES, Brazil; Arismar Cerqueira S. Jr. is with the WOCA Laboratory, National Institute of Telecommunications, Santa Rita do Sapucaí-MG, Brazil.

while preserving an operating region with $S_{11} < -10$ dB. The motivation for this array step follows recent results showing that FR2 linear and planar arrays can reach substantially higher gain than isolated elements when feed networks and array geometry are co-designed [10], [12], [5]. Rogers RT/duroid 5880 was used as the substrate in all models, with a thickness of 0.51 mm and relative permittivity $\epsilon_r = 2.2$. The main dimensions used in the simulations are summarized in Tables I and II.

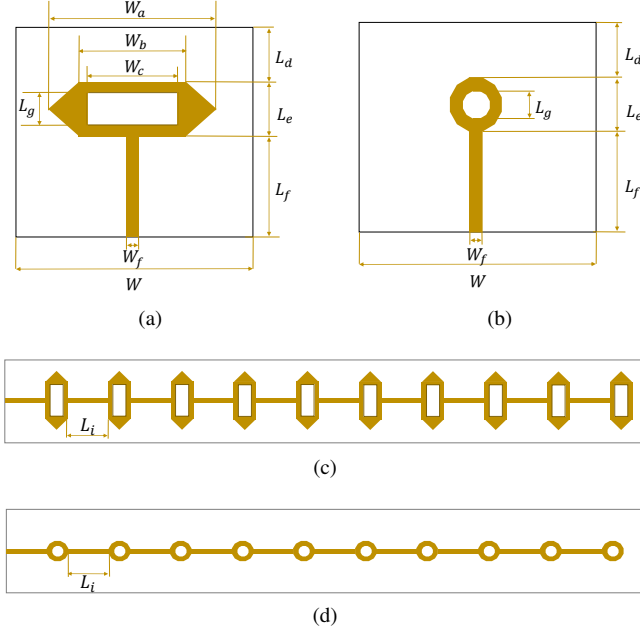


Fig. 1. Proposed models: (a) Antenna 1; (b) Antenna 2; (c) Antenna 3; (d) Antenna 4.

TABLE I
PARAMETERS OF ANTENNA 1 AND ANTENNA 3.

Parameter	Antenna 1	Antenna 3
W_a (mm)	8.35	7.92
W_b (mm)	5	5
W_c (mm)	2.34	2.34
W_f (mm)	0.55	0.3
W (mm)	16	16
L_d (mm)	5.08	-
L_e (mm)	2.92	3.65
L_f (mm)	8	8
L_g (mm)	3.8	3.8
L_i (mm)	-	8

III. RESULTS

Fig. 2 shows the simulated reflection coefficient of the four antennas. All models exhibit a band with $S_{11} < -10$ dB that includes 40 GHz, as summarized in Table III. At 40 GHz, the simulated S_{11} values range from -19.19 dB to -24.44 dB, indicating good impedance matching for the four models. Antenna 1 provides the widest bandwidth in the region of interest, with 5.977 GHz between 35.158 GHz and 41.135 GHz. The linear arrays reduce this bandwidth to 2.551 GHz for

TABLE II
PARAMETERS OF ANTENNA 2 AND ANTENNA 4.

Parameter	Antenna 2	Antenna 4
W_f (mm)	0.55	2
W (mm)	11	11
L_d (mm)	2.52	-
L_e (mm)	1.6	2.5
L_f (mm)	6.88	6.88
L_g (mm)	0.86	0
L_i (mm)	-	6.6

Antenna 3 and 2.442 GHz for Antenna 4, while still retaining 40 GHz inside the operating band.

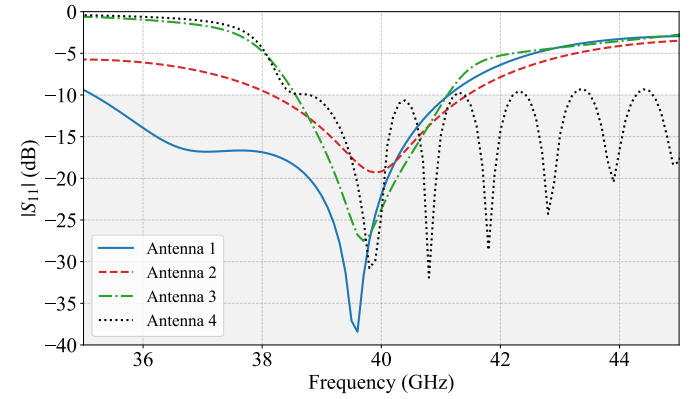


Fig. 2. S_{11} of the four antennas.

The total-gain patterns at 40 GHz are shown in Fig. 3. In the elevation cuts, the arrays provide a substantial gain increase compared with their corresponding single elements. Antenna 3 reaches 13.99 dBi, whereas Antenna 1 reaches 3.18 dBi in the same cut, yielding an increase of approximately 10.81 dB. Similarly, Antenna 4 reaches 16.51 dBi, compared with 1.35 dBi for Antenna 2, corresponding to an increase of approximately 15.16 dB.

The azimuth cuts show that the gain enhancement is not uniform across all analyzed planes. This behavior indicates that, in addition to impedance matching, the array feed and element spacing must be jointly optimized to control sidelobes and direct the radiated energy according to the target application. This interpretation is consistent with array theory and with recent array studies, in which larger aperture tends to increase directivity but the realized response depends strongly on excitation, coupling, and the base-element geometry [6], [10], [11], [5]. Even so, the elevation-cut gains in Table III confirm that the linear arrays are the most promising configurations for higher-gain operation around 40 GHz, especially Antenna 4.

IV. CONCLUSIONS

This paper presented a numerical study of four printed antennas for millimeter-wave operation around 40 GHz. The simulated results show that all models have a band with $S_{11} < -10$ dB that includes 40 GHz and S_{11} values below -19 dB at this frequency. The gain-cut comparison indicates that

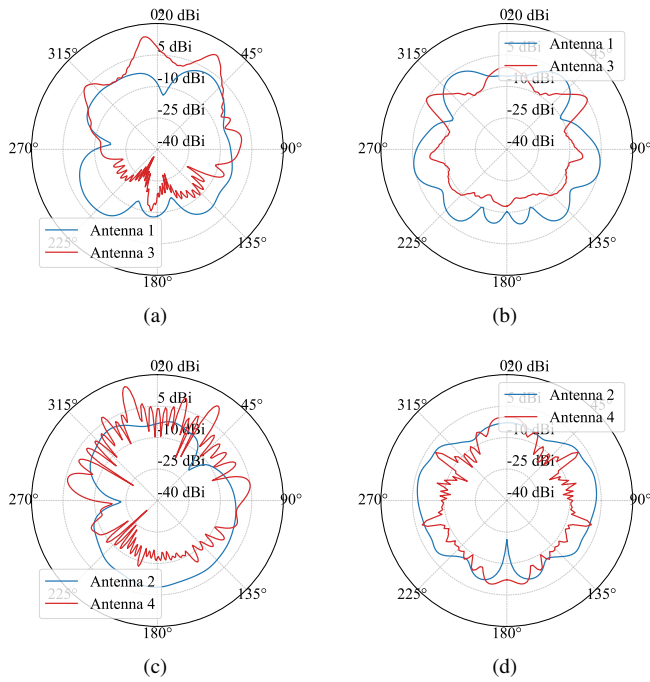


Fig. 3. Simulated gains: (a) elevation cut of Antennas 1 and 3; (b) azimuth cut of Antennas 1 and 3; (c) elevation cut of Antennas 2 and 4; (d) azimuth cut of Antennas 2 and 4.

TABLE III

BANDWIDTH BELOW -10 dB AROUND 40 GHz AND MAXIMUM ELEVATION-CUT GAIN FOR THE INVESTIGATED ANTENNAS.

Antenna	f_i (GHz)	f_f (GHz)	BW (GHz)	Max. gain (dBi)
Antenna 1	35,158	41,135	5,977	3.18
Antenna 2	38,158	41,448	3,290	1.35
Antenna 3	38,560	41,111	2,551	13.99
Antenna 4	38,800	41,242	2,442	16.51

the linear arrays substantially increase the elevation-plane gain, reaching 13.99 dBi for Antenna 3 and 16.51 dBi for Antenna 4. Future work should include experimental measurements of S_{11} and radiation patterns, as well as optimization of the element spacing and feeding network to reduce sidelobes.

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