Millimeter Wave Antenna on Eco-friendly Substrate for Radar Applications

M. E. de Cos Gómez[1], H. Fernández Álvarez[1], F. Las-Heras Andrés[1]
[1] TSC, Electrical Engineering Department. Universidad de Oviedo. Gijón, Spain, medecos@uniovi.es

***Abstract*—A compact low-cost series end-fed 1 x 10 array antenna on polypropylene (PP) for imaging applications in the 24.04 - 24.25GHz band is presented. The envisioned use is in a wearable radar system for collision avoidance to aid visually impaired people. The eco-friendly PP substrate is electromagnetically characterized at 24.15GHz for the first time. A modified Dolph-Chebyshev (D-C) distribution is optimized in simulation to achieve an improved performance in terms of beam width, Side-lobe level (SLL) and Gain. A prototype of the PP based array antenna is fabricated and tested. The overall size of the antenna is 98.68 x 14.4 x 0.52 mm^3. Consistent agreement is achieved between simulation and measurement results. Comparison with literature shows that the proposed array antenna overcomes the state of the art on 24GHz antennas for wearable radar applications.**

***Index Terms*—antennas, mm-wave antenna, collision avoidance radar, array antenna, radar antenna, eco-friendly, wearable antenna.**

I. Introduction

Radars are frequently used for detection, situating, movement identification and imaging, in security, industrial and medical applications. Collision avoidance is a profitable radar application both in terms of security and economical incomes, for example in automotive industry. However, it could be also very promising to help blind or visually impaired people.

Mm-waves are particularly suitable for radar applications since they enable high resolution (the smaller the wavelength, the smaller the objects the radar is able to detect). In addition, compared to cameras, laser and infrared sensors, millimeter-wave radar is strongly effective to penetrate fog, smoke, and dust.

Automotive radar working at 24GHz is typically devoted to short range applications as impact evasion and vulnerable side recognition, whereas the one operating at 77GHz is intended to long range uses, such as cruise control [1].

The antenna has a great impact on the radar system performance. Radar antennas at high mm-wave frequencies often suffer from fabrication accuracy impairments due to limited technological conditions, even using common substrates [1]. Thus, the 24GHz band is more advantageous to explore the use of eco-friendly substrates for mm-wave prototypes fabrication.

The European Telecommunications Standards Institute (ETSI) has a standard [3] for Short Range Radar (SRR) operating in the frequency band from 24.05GHz to 24.25GHz, which in addition, is the 24.125GHz Industrial Scientific and Medical (ISM) license free band.

High antenna directivity is desirable for object detection at long distance, whereas a wide beam width is preferable for detection when illuminating the whole scene at a time at a shorter distance. A trade off solution between range and coverage area has to be adopted, depending on the requirements that would be imposed for the envisioned application. In addition, the directivity of the antenna also influences the angle determination of the target. Since by measuring the direction in which the antenna is pointing when the echo is received, the angles (azimuth and elevation) from the radar to the target can be figured out. For the envisioned application of collision avoidance in aid to visually impaired people, at a medium-long distance, an antenna with narrow beam and low side-lobe level (SLL) is required.

The paper is organized as follows: first the design of the antenna based on an eco-friendly substrate is presented, including the electromagnetic characterization of the selected material at 24GHz. Then the fabrication of a prototype of the optimized antenna is shown, along with a detailed description of the measurement results, which matching with the ones obtained in simulation is analyzed. Next, comparison with the state of the art on radar antennas operating at 24GHz is shown. At the end, some conclusions are drawn.

II. Design of The Eco-friendly Array Antenna

For the envisioned application, the antenna, in addition to exhibit proper impedance matching and radiation properties, has to be light, compact and easy to wear and connect to the radar. Hence, a plastic substrate with a relative dielectric permittivity in the 2-3 range, very similar to commonly used commercial substrates, is a good candidate since, in addition, is flexible. Furthermore, to be aligned with the green technology principles and circular economy objectives, a recyclable substrate is particularly suitable.

The Polypropylene (PP) which is a thermoplastic polymer with wide use in medical, food packaging and automotive applications, among others, is chosen due to its environmental benefits, lightness and flexibility.

However, on the one hand, PP it is not a material usually utilized for the manufacture of antennas and in previous work its use has only been explored for frequencies in the lower range of microwaves, such as 2.45GHz [4], which is ten times lower than the one in question. On the other hand, PP has never been used in millimeter frequencies, so its electromagnetic behavior and its limitations in terms of manufacturing with conventional machining techniques are unknown in the 24GHz band, which is much more demanding.

A. Electromagnetic Characterization of the PP at 24 GHz

Most commercial dielectrics are characterized at 1GHz or 10GHz at most. Accordingly, the available electromagnetic characterization devices work at such frequencies. Therefore, conducting the electromagnetic characterization of the PP around 24 GHz is a challenge itself.

In this work, with the aim of achieving an accurate characterization, a combination of two methods is used to determine the relative dielectric permittivity (ε_r) and the loss tangent (tan δ). On the one hand, the results are obtained from a higher order mode close to 24GHz, of a 10 GHz resonant cavity (Agilent Technologies 85072A 10 GHz split-cylinder resonator). On the other hand, a microstrip line and an open-circuit resonant stub at the target frequency are used. This is particularly useful to account for the fabrication tolerances regarding microstrip technology, which are not considered in the former method and are crucial to get measurement results that match the simulation ones.

For a PP sheet with a thickness of h=0.52 mm the values ε_r=2.2 and tan δ=0.002 were obtained.

B. Design of the MM-wave Array Antenna

The advantages of array antennas in terms of gain and directivity compared to single patch antennas are well-known. Series or corporate (parallel) feeding can be chosen for the array antenna. Series feed is chosen because is advantageous in terms of lower losses, structure simplicity, smaller space occupation and providing higher radiation efficiency than parallel feeding when the number of array elements increases [5]. In series feeding the amplitude of the excitation is controlled through the variation of the width of the microstrip patches and/or feeders, whereas the phase control is achieved by adjusting the patches spacing.

It is also well-known that optimal compromise between side lobe level (SLL) and main lobe width can be provided by Dolph-Chebyshev (D-C) distribution [6]-[9]. However, in this work a modified D-C current distribution will be used instead, aiming at achieve optimized performance not only in terms of (SLL) and beam width but also regarding impedance matching bandwidth.

As a starting point, the length (P_L) and width (P_W) dimensions of a simple patch element operating at the center frequency (24.15GHz) of the band are obtained. Those are the initial dimensions of the two central patch array elements.

The number of patch elements in the array is 10. The last element of the patch array is terminated with a half-wavelength open-ended stub, pursuing an optimized power use. The length of the patches (P_L) is uniform and approximately equal to half the guided wavelength at the central frequency (24.15GHz) of the operating band. The width of the patches (P_W) is tapered, following a ratio from the initially optimized central patches, to acquire a non-uniform excitation. The spacing between two adjacent patch antenna elements (A_G) is identical and is also about half the guided wavelength at 24.15GHz.

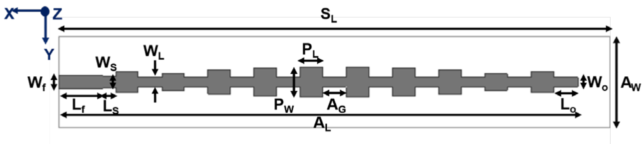

Fig. 1. Top view of the geometry of the series feed 1 x 10 patch array with detailed parameterized dimensions.

For optimization purposes of the overall array performance (not only in terms of the radiation characteristics, but also in terms of the impedance matching level and bandwidth) the lengths and widths of each array element and the connecting transmission lines were defined with variables in the simulation set-up.

The resulting optimized dimensions are indicated in TABLE I. The patch width ratio is 1: 0.92 : 0.8 : 0.55 : 0.7 from the center patch to edge as shown in TABLE II. As previously mentioned it does not follow a conventional Dolph-Chebyshev (D-C) distribution. The total length of the array is A_L, whereas the overall PCB length and width are respectively S_L and A_W.

TABLE I. DIMENSIONS OF THE OPTIMIZED ARRAY ANTENNA DESIGN

Dimensions (mm)						
S_L	A_W	*h*	A_L	W_t	L_f	L_S
98.68	14.4	0.52	83	1.61	6.6	3
W_S	W_L	P_W	P_L	A_G	L_O	W_O
1.0	1.3	4.8	4.15	4.22	4.2	1.3

TABLE II. POWER RATIO FROM THE CENTER PATCH TO EDGE

P1	*P2*	*P3*	*P4*	*P5*
1	0.92	0.8	0.55	0.7

C. Impedance Matching of the MM-wave Array Antenna

From the S11(dB) results obtained in simulation for the optimized array antenna design (see Fig. 2), it can be observed the very good matching achieved in the target 24.05GHz - 24.25GHz band. Furthermore, as indicated in TABLE III. , the antenna is properly matched in 23.99GHz – 24.27GHz.

The current distribution on the array antenna at the center frequency of operation (24.15GHz) and at a non-operating frequency, is shown in Fig. 3. As it could be expected, for the operating frequency, each and every one of the array patches exhibits a similar distribution, with high current level at the center and decreasing to the edges in the X (feeding) direction, since all of them are contributing to the antenna operation. Conversely, the distribution for the non-operating frequency does not match a mode of the patches, is different from the patches closer to the feeding line to the ones at the end of the array and the current levels are lower.

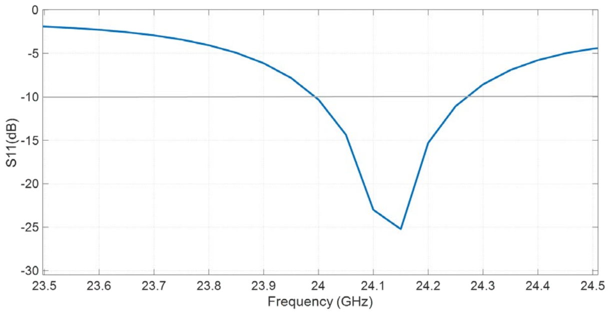

Fig. 2. Simulation results of the reflection coefficient, S11(dB), for the array antenna on PP.

TABLE III. FREQUENCY BAND AND BANDWIDTH OF THE ANTENNA IN SIMULATION

Frequency band			
Freq (GHz)		***Bandwidth***	
f_{LOW}	***f_{UP}***	***Total (MHz)***	***(%)***
23.99	24.27	280	1.16

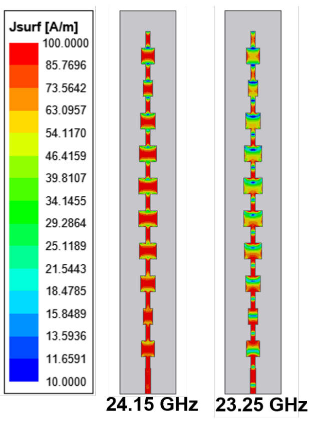

Fig. 3. Surface current distribution on the array antenna at the center frequency of the operating band (24.15GHz) and at a non-operating frequecy (23.25GHz).

D. Radiation Characteristics of the MM-wave Array Antenna

The radiation characteristics of the antenna obtained in simulation in terms of: peak realized gain (G), peak directivity (D), radiation efficiency (η) and front to back ration (FTBR), are indicated in TABLE IV. for the center and ends frequencies of the target band.

In addition to the high G (>16dBi) and D (>17dB) levels achieved in the whole band, which are suitable for radar, it is noteworthy the levels of both the high radiation efficiency (>80%) and the FTBR (>24 dB), which are critical in a wearable application.

From the radiation pattern cuts for Phi=0º and Phi=90º at the center frequency of the band (24.15GHz) shown in Fig. 4, the Side-lobe level (SLL) and the Half-power beam width (HPBW) are obtained: SLL_{Phi0^o}=-18dB; $HPBW_{Phi0^o}$=9.2º; SLL_{Phi90^o}=-25dB; $HPBW_{Phi90^o}$=64º; These results are suitable for the envisioned collision avoidance application. Therefore, the use of the modified D-C distribution, probes to be a good trade-off solution to achieve the intended radiation properties and the target operating band.

TABLE IV. RADIATION PROPERTIES RESULTS OBTAINED IN SIMULATION

Freq (GHz)	G (dBi)	D (dB)	η (%)	FTBR (dB)
24.05	16.6	17.1	89	26.4
24.15	16.8	17.2	91	25.7
24.25	16.4	17.1	85	24.5

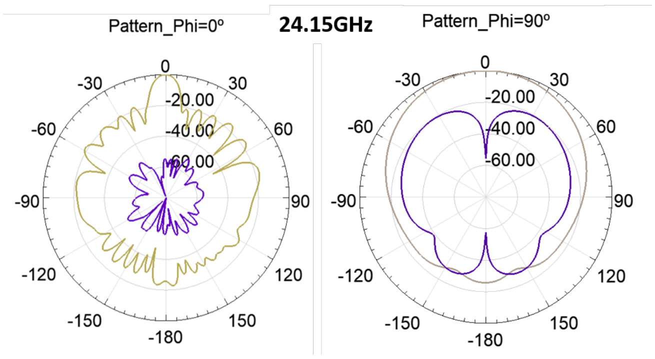

Fig. 4. Radiation pattern results at 24.15 GHz: cuts for Phi=0º and Phi=90º. The khaki traces are for copolarization (CP) and the violet ones for crosspolarization (XP)

III. FABRICATED ANTENNA ON PP

A 35 µm thick tin-copper (Sn/Cu) alloy foil is used for the conductive parts of the array antenna. It incorporates and adhesive backing so that it can be fixed to the 0.52mm thick PP sheet. Then, conventional laser micromachining, with LPKF protolaser machine, is used to fabricate the antenna, and a SMA connector operating up-to 26GHz is soldered by hand to feed it (see Fig. 5 which includes the resulting prototype).

A. Impedance matching

The measured reflection coefficient for the fabricated antenna on PP is depicted in Fig. 5 along with the simulated one for comparison. It can be observed that simulation and measurement are in good agreement. It has to be taken into account that the connector was not included in simulation and it is soldered by hand, so that it causes a slight disturbance in terms of widening the frequency band. Nonetheless, the prototype exhibit proper matching in the target ISM radar frequency band from 24.05GHz to 24.5GHz.

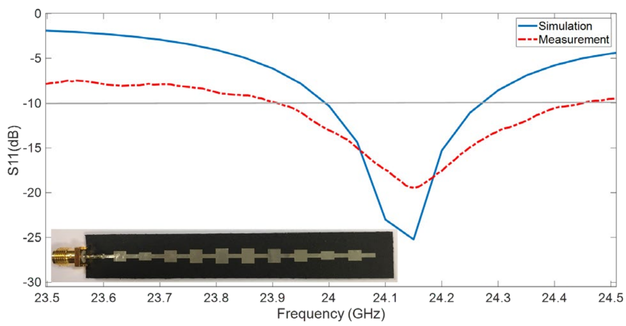

Fig. 5. Measurement results of the reflection coefficient, S11(dB), for the fabricated array antenna on copper plated PP versus the simulation results.

B. *Radiation properties*

The fabricated prototype of the array antenna was measured in an anechoic chamber (see Fig. 6).

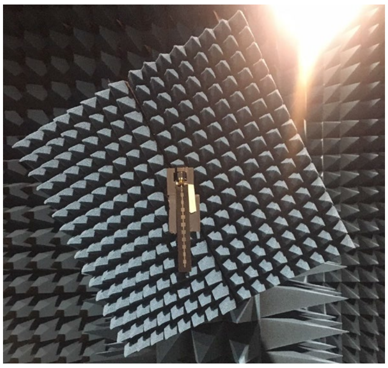

Fig. 6. Measurement set-up in anechoic chamber. Antenna under test (AUT) arrangement.

The radiation pattern cuts for Phi=0º and Phi=90º at the center frequency of the band (24.15GHz) were measured and the results, along with the simulation ones, are depicted in Fig. 7 for both co-polar (CP) and cross-polar (XP) components, for a fair comparison.

Fairly good agreement is achieved between simulation and measurement results, especially for the CP components. The resulting HPBW level is almost identical to the one obtained in simulation for both Phi=0º and Phi=90º cuts, whereas the SLL slightly worsens in measurement for Phi=0º. Nevertheless, it should be noted that the connector was not considered in simulation and, in addition, it was soldered by hand. Both the cable and the connector can severely perturb the current distribution on the small antenna, and be responsible for the observed XP levels in measurement. Furthermore, the 3D printed polylactic Acid (PLA) based piece used to fix the antenna for the measurement, can cause reflections.

Measurements of the peak realized gain were conducted using the gain transfer method, which involves inter-comparison of the array antenna prototype (antenna under test, AUT), with a Flann Microwave Standard horn 20240-25 (Probe antenna of known characteristics). G=13 dBi was obtained at 24.15GHz, which is lower than the simulation result. It has to be taken into account that, in addition to the aforementioned effects of the cable and the connector, the gain measurement can be disturbed by other effects [10]: multipath and reflections due to the fixing PLA structure and other set-up elements, misalignment of AUT-probe and impedance mismatch of antennas.

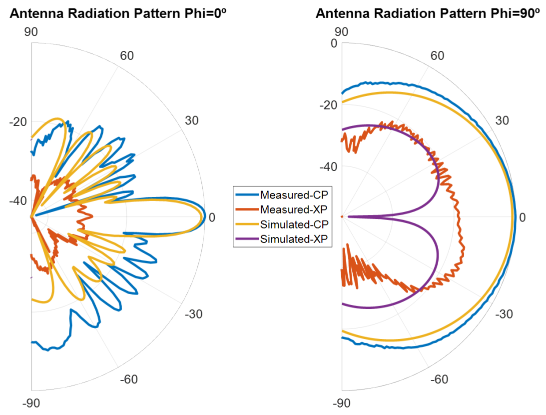

Fig. 7. Simulated and measured co-polar (CP) and cross-polar (XP) radiation pattern components of the array antenna for Phi=0º and Phi=90º cuts at 24.15 GHz.

The directivity calculated through the Krauss approximation [11] considering the HPBW levels from the radiation pattern cuts for Phi=0º and Phi=90º, is D=18.4dB, and D=17.4dB using the Elliot correction [12], which agrees very well with the one obtained in simulation.

IV. COMPARISON WITH OTHER MM-WAVE RADAR ANTENNAS

TABLE V. and TABLE VI. provide data for performance comparison of the presented array antenna with other radar antennas at 24GHz, in terms of size, bandwidth and radiation properties, to assess the relevance of this contribution.

Compared to the antennas on substrates with higher relative dielectric permittivity (most of them Teflon based and therefore not eco-friendly), the presented antenna on PP provides higher gain than [14], [16] and [19], being smaller in terms of area than [14] and overcoming [19] in terms of HPBW for Phi=0º. It is also smaller than [13], [15], [17],and [18] while providing the same bandwidth than [13] and [18], covering the target 24.05GHz -24.25GHz band. It is noteworthy that the presented antenna provides almost identical performance in bandwidth and radiation properties than [18], which is a commercial one, much larger, thicker, expensive, heavy and not suitable for wearable applications.

With regards to antennas on substrates with relative dielectric permittivity values closer to the one of the PP, the proposed antenna is much smaller than [20] and [21] for similar bandwidth. It outperforms [21] in terms of HPBW for Phi=90º while providing very similar values for G, and SLL. It overcomes [20] (which yields higher G and similar SLL and HPBW) in radiation efficiency, which is key parameter for the envisioned wearable application and its value is not provided in general. Finally, [22] presents a paper based eco-friendly design, but less robust and technologically advantageous (due to multilayered design), with less than half gain, worst HPBW for Phi=0º and similar for Phi=90º, and one-third in radiation efficiency compared to the proposed in this contribution.

TABLE V. SIZE, BANDWIDTH AND IMPEDANCE MATCHING

Ref.	Elements	Size (mm^3)	ε_r	Band (GHz)	BW (%)	S11 (dB)
[13]	6 x 8	50 x59x 0.254	3.66	0.25	1.0	-
[14]	1 x 4	60 x 30 x 1.6	4.4	2.9	12	-23
[15]	12x1x 8	135x58.7x0.254	3.6	0.65	2.7	-20
[16]	1 x 6	67x16.5x0.254	3.48	0.40	1.5	-12
[17]	8 x 8	50x50 x 0.754	3.66	1.5	6.3	-27
[18]	2 x 8	74.9x74.9 x 3.3	-	0.2	1.0	-8
[19]	2 x 2	29 x 21x0.254	3.48	0.51	2.1	-35
[20]	2 x 24	230 x 31x 0.254	2.17	0.39	1.6	-20
[21]	1 x 10	160 x 43.2 x 0.5	2.3	0.32	1.3	-20
[22]	2 x 2	20 x 20x 0.68	2.9	2.0	8.3	-35
This work	1 x 10	98.7x 14.4x0.52	2.2	0.28	1.2	-25

TABLE VI. RADIATION PROPERTIES

Ref.	G (dBi)	η (%)	SLL (dB) φ=0º	HPBW (º) φ=0º	SLL (dB) φ=90º	HPBW(º) φ=90º
[13]	20.6	-	-18	19.2	-19	12.2
[14]	9.7	-	-	-	-	-
[15]	24.2	-	-23	12.5	-23	5.6
[16]	13	-	-26	17.5	-	-
[17]	20.9	-	-21	15	-22	28
[18]	17	-	-20	12	-20	50
[19]	10.4	-	-	58.5	-	47.5
[20]	21.7	60	-21	3.6	-21	46
[21]	17	-	-18	8.2	-18	80
[22]	7.4	35	-	54	-25	48
This work	16.8	91	-18	9.2	-25	64

V. CONCLUSIONS

In this contribution a 1 x 10 series-fed PP based compact and low-cost array antenna operative in the 24.04GHz – 24.25GHz band is presented. It provides suitable Gain, SLL and HPBW for collision avoidance radar while being low-cost and easy to manufacture with conventional techniques.

The resulting outline dimensions along with the flexibility properties of the PP, the high radiation efficiency and the reduced FTBR make the antenna suitable for wearable applications. Furthermore, the eco-friendly properties of the PP substrate, pave the way to reduce the environmental footprint of electronic devices.

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