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A Wideband Curved Patch Antenna with Coplanar Microstrip Feeding

Giacomo Muntoni⁽¹⁾, Giovanni A. Casula⁽¹⁾, Enrico Mattana⁽¹⁾, and Giorgio Montisci⁽¹⁾

⁽¹⁾Department of Electrical and Electronic Engineering, University of Cagliari, 09123 Cagliari, Italy
(e-mail: giorgio.montisci@unica.it).

Abstract—We present a wideband curved patch antenna with direct coplanar microstrip feeding. The patch substrate is derived from a solid of revolution generated using a parabolic profile that rests on a planar substrate. The proposed antenna takes advantage of the local increase of substrate thickness in the patch region to improve the reflection coefficient bandwidth. This design reduces substrate losses in comparison with conventional patch antennas printed on a thick dielectric substrate (key for bandwidth improvement). Indeed, in our case, the thick (curved) substrate is limited to the patch region, whereas the surrounding substrate can be made as thin as necessary, depending on the operating frequency, dielectric permittivity, and loss tangent. The presented configuration exhibits a reflection coefficient bandwidth of 32%, increasing the bandwidth of state-of-the-art patch antennas fed by coplanar microstrip lines by over 50%. The achieved operating bandwidth is even comparable to that of several coaxial probe-fed configurations, which, although undesirable for integrated implementations, typically offer a larger bandwidth due to greater flexibility in accessing the optimal feeding point, as seen in stacked and suspended-substrate patch antennas. The proposed configuration represents a significant advancement for patch antennas suitable for integrated implementation and intended as elements in planar arrays with direct coplanar microstrip feeding.

Index Terms— Coplanar microstrip feeding, microstrip antennas, patch antennas, wide bandwidth.

I. INTRODUCTION

Microstrip patch antennas are widespread in several applications, including satellite communications, but also wireless scenarios, thanks to their reduced size, weight, and cost [1]. However, since they are resonant antennas, one of their major downsides is the narrow bandwidth [2], [3], [4]. Several solutions have been used to increase the operating bandwidth of conventional microstrip patch antennas. Excluding defected ground plane configurations [5] and monopole antennas [6] due to their high back radiation, most wideband microstrip antennas with solid ground plane can be classified as follows:

a1) patch antennas on thick substrates and low dielectric permittivity [1], [2], [7];

a2) stacked patch antennas and air gap and/or suspended substrate configurations [8], [9], [10], [11], [12].

The most popular and simple feeding techniques for the above configurations are: direct coplanar microstrip feeding and coaxial probe feeding. Aperture and slot coupling are also frequently used, requiring apertures in the ground plane and separate substrates for the feeding network and the radiating elements. This provides the undeniable advantage of high flexibility but comes at the expense of higher production costs, increased fabrication complexity, and greater back radiation.

A further classification distinguishes between patch antennas intended for use as a single element and those designed for use both as a single element and as part of an array.

Configurations intended for use as single-element antennas (see, e.g., [13], with a 44.6% reflection coefficient bandwidth) are likely to achieve a larger operating bandwidth than others as they are not constrained by antenna size requirements for array design. In fact, the array elements spacing D_s , which should be less than the free space wavelength λ_0 to avoid grating lobes [2], determines the maximum size of each array element. Since not suitable for the realization of arrays, single-element antennas with maximum size larger than λ_0 are not discussed in this work.

The type of application and the array feeding strategy also determines the design of the antenna single element [2], [7]. In this regard, coaxial probe feeding is undesirable in integrated implementations and it is well acknowledged that the most common and simple solution for the realization of beam forming networks of linear and planar arrays of patch antennas relies on coplanar microstrip feeding.

However, patch antennas belonging to category a1) usually employ coaxial probe feeding rather than direct microstrip feeding, since a thick substrate would increase the losses in a coplanar microstrip beam forming network.

Most of the broadband patch antennas configurations belonging to the category a2) also employs coaxial probe feeding, due to the impossibility to access the optimal antenna feeding point using a standard coplanar microstrip line. Specifically, to cite a few examples employing coaxial probe feeding, in [8], [9], and [10] stacked patch antenna configurations have been used, whereas in [11], a suspended

folded patch is proposed. In [8], [9], [10], and [11], the reflection coefficient percentage bandwidth ranges from 14% to 35%.

Considering the different configurations available in the literature, wideband patch antennas using coaxial probe feeding, such as those presented in [8], [9], [10], [11], cannot be easily adapted for direct coplanar microstrip feeding.

A successful strategy for converting coaxial probe feeding into direct microstrip feeding for suspended patches was proposed in [14], wherein a vertical metal feed strip connects the microstrip line to the suspended patch. Using this approach, the E-shaped suspended patch antenna in [14] exhibits a reflection coefficient bandwidth of 19.5%. To the best of the authors' knowledge, this is the highest reflection coefficient bandwidth achieved so far with direct coplanar microstrip feeding. However, the feeding conversion method proposed in [14] is specifically designed for the antenna presented in that paper and cannot be easily extended to other suspended or coaxial probe-fed antennas. Other, simpler configurations employing coplanar microstrip feeding are available in [15], [16] and [17], with a reflection coefficient bandwidth between 6.5% and 8.4%.

Recently, a curved patch antenna has been proposed [18], exploiting the local increase of the substrate thickness in the patch region to improve the reflection coefficient bandwidth (up to 9.3%) compared to a standard flat patch antenna. Although the radiating element described in [18] is fed using a coaxial probe, this antenna can be adapted for coplanar microstrip feeding, making it a promising candidate for the realization of planar arrays.

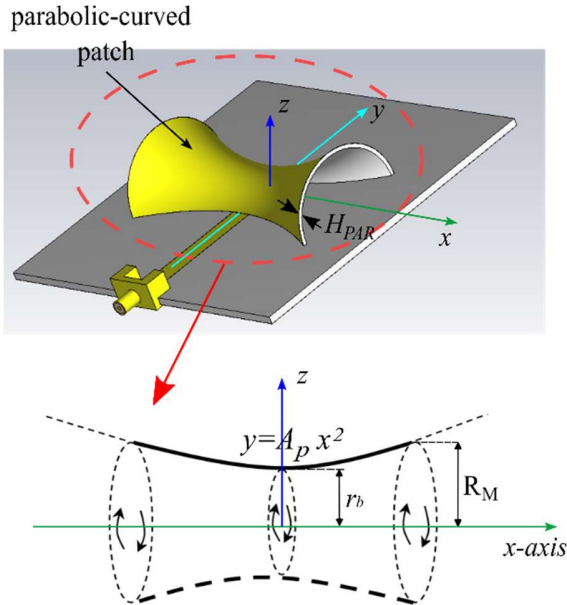


Fig. 1. Layout of the proposed antenna.

Table 1. Comparison between wideband patch antennas suitable for planar array realization (size less than λ_0 in both planar directions). BW = percentage bandwidth, G_R = realized gain, S = radiating element size (planar)

Ref.	Center freq. (GHz)	Substrate Type	Feed	BW (%)	G_R (dBi)	S ($\lambda_0 \times \lambda_0$)
[8]	4	Stacked patch	Coax. probe	34.9	6.5	0.21×0.43
[9]	2.1	Stacked patch	Coax. probe	14	7	0.17×0.36
[10]	3	Stacked patch	Coax. probe	21	7.9	0.59×0.59
[11]	9.9	Susp. folded patch	Coax. probe	26	9.6	0.43×0.43
[14]	5.5	Susp. patch	Mstrip	19.5	6	0.41×0.61
[15]	6	Planar Patch	Mstrip	6.5	5.4	0.73×0.54
[16]	4.9	Planar patch	Mstrip	8.4	7.3	0.33×0.44
[17]	10	Planar patch	Mstrip	8	-	0.32×0.36
[18]	2.45	Curved patch	Coax. Probe (Mstrip)	9.3	6.3	0.18×0.38
This Work	2.5	Curved patch	Mstrip	32	7	0.27×0.5

In this paper, as in [18], we exploit the local increase in substrate thickness using a modified curved configuration fed by a coplanar microstrip line, aiming to improve the reflection coefficient bandwidth of the antennas presented in [14], [15], [16], [17], and [18]. Specifically, we propose a wideband curved patch antenna with a parabolic profile (see Fig. 1), which raises along the vertical direction. The radiating element geometry is derived from a solid of revolution obtained by a parabolic profile, halved, and placed on a planar substrate.

Table 1 highlights the performance of the proposed patch antenna, in comparison with state-of-the-art configurations suitable for planar array realization (i.e. with maximum planar size less than λ_0).

Our solution represents a significant advancement in patch antennas with direct microstrip feeding. Specifically, the local increase in substrate thickness beneath the patch, combined with the use of a curved patch with a parabolic profile, enables the following advantages, while maintaining stable gain across the operating bandwidth (ranging from 5.7 dBi to 7 dBi) and high radiation efficiency:

- The proposed design provides a higher impedance bandwidth than other coplanar microstrip-fed configurations reported in the literature (see Table 1, Refs. [14], [15], [16], [17], [18]). It achieves a reflection coefficient bandwidth of 32%, representing an increase of over 50% compared to the antenna in [14], and nearly a fourfold improvement over the antennas in [15], [16], [17], [18].
- The impedance bandwidth of the proposed antenna is comparable to or exceeds that of probe-fed configurations reported in the literature [8], [9], [10], [11], which typically achieve wider bandwidths due to increased flexibility in selecting the optimal feeding point.
- Increasing the substrate thickness in conventional

microstrip antennas typically enhances gain but also increases surface wave excitation. In the proposed configuration, however, the substrate thickness is locally increased only in the patch region, allowing the surrounding substrate to remain as thin as needed, depending on the operating frequency, dielectric permittivity, and loss tangent. This helps to reduce losses in the coplanar feeding network and limits surface wave excitation, thereby maintaining high radiation efficiency and, consequently, satisfactory realized gain.

The curved patch antenna proposed in this paper is conceived to exploit the 3D-printing manufacturing technology that enables a very simple and low-cost fabrication despite the unconventional shape.

The antenna design has been performed using the commercial software CST Studio Suite at the center operating frequency of 2.5 GHz. Then, a prototype of the designed antenna has been manufactured and measured, showing a good agreement with simulations.

Finally, to evaluate the potential of the proposed antenna, a 2×2 uniform planar array was designed. Simulations indicate a -10 dB return loss bandwidth of 28% and a maximum realized gain of 11.6 dBi.

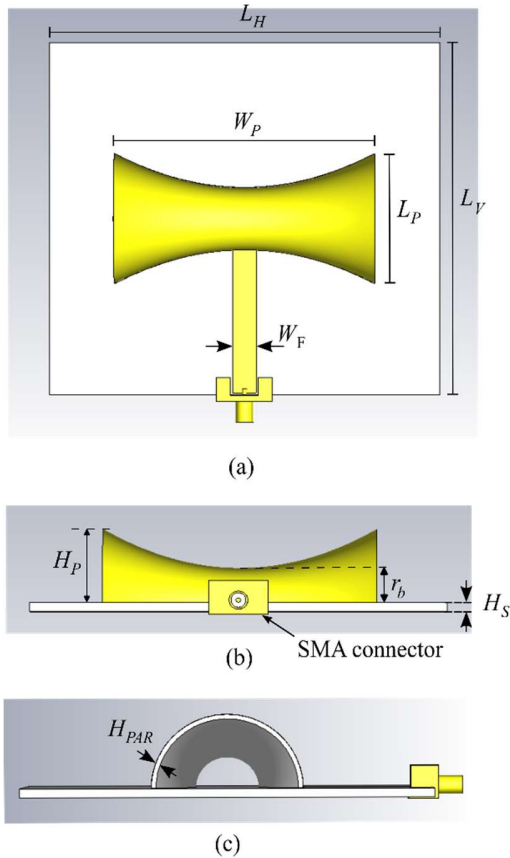


Fig. 2. Layout of the proposed antenna: (a) top view; (b) side view (xz plane); (c) side view (yz plane).

II. ANTENNA GEOMETRY AND DESIGN

The layout of the antenna, along with its key design parameters, is depicted in Figs. 1 and 2. The proposed design is realized by generating a solid of revolution of thickness H_{PAR} obtained by a parabolic profile. This solid of revolution is then halved and placed on a planar substrate of thickness H_S and size $L_H \times L_V$. The parabolic profile in the xy -plane is mathematically defined by the equation $y = A_p x^2$, wherein A_p is the curvature parameter that determines the steepness of the parabolic shape, x is the horizontal coordinate on the axis of revolution, and y is the corresponding height (see Fig. 1). The maximum and minimum radii of the solid of revolution are denoted by R_M and r_b , respectively (Fig. 1).

The solid of revolution generated from the parabolic profile can be seen as a raised region within the planar substrate, serving as a support for a shaped metallic patch fed by a 50Ω coplanar microstrip line with a width of W_F .

The planar substrate ($L_V = L_H = 90$ mm, thickness $H_S = 2$ mm) and the parabolic protrusion (with thickness H_{PAR} set to 1 mm) are both made of polylactic acid (PLA), which has a dielectric permittivity of 2.55 and loss tangent of 0.008 at 2.50 GHz. Accordingly, the width W_F of the 50Ω feeding microstrip line is equal to 5.5 mm. Both the substrate and the parabolic support for the patch are fabricated using a 3D printing additive manufacturing process.

The metallic patch and the feeding microstrip line are made of aluminum tape of thickness $50 \mu\text{m}$, L_P is the projected planar resonant size of the patch in the xy -plane, and W_P is the projected planar radiating size.

The width of the patch W_P is set to 60 mm and the height H_P of the parabolic solid of revolution over the flat substrate is set to R_M . Therefore, exactly half of it protrudes above the flat substrate (see Fig. 1) and $L_P = 2R_M$. We have observed that increasing H_P can result in a larger bandwidth. However, this configuration causes an undesired current distribution in the metallic patch, degrading the radiation performance. Conversely, reducing the value of H_P narrows the operating frequency band.

The antenna design has been performed using CST Studio Suite and the main design steps are described in detail in the following subsections A and B. In subsection C, the influence of the curved parabolic profile in the improvement of the antenna performance is discussed.

A. Design Step 1

The goal of the first design step is to achieve the largest reflection coefficient bandwidth for the patch antenna, in the pre-established frequency range 2 - 3 GHz, by varying the following design parameters: the minimum radius of the parabolic protrusion r_b and the curvature parameter A_p . These two parameters are paramount, as they directly control the patch shape and the extent of its curvature. Consequently, they determine the maximum projected resonant length of the patch, which can be defined as $L_P = 2r_b + 2A_p W_P^2/4$ (Fig. 2).

A two-variable optimization procedure has been performed using CST Studio Suite leading to the optimal values $r_b = 7.95$ mm and $A_p = 0.0096$, which correspond to a percentage bandwidth of 20%, with reflection coefficient less than -10 dB between 2.25 GHz and 2.75 GHz. The optimization was

carried out through extensive parametric sweeps. For each combination of r_b and A_p , the reflection coefficient was meticulously simulated and analyzed. By thoroughly exploring the design space defined by r_b and A_p through this systematic simulation-based approach, we were able to precisely determine the values that provided the widest bandwidth.

In Fig. 3, we report the parametric variation of the reflection coefficient for different values of r_b with A_p fixed to 0.0096 and, in Fig. 4, the parametric variation of the reflection coefficient for different values of A_p with r_b fixed to 7.95 mm, is depicted.

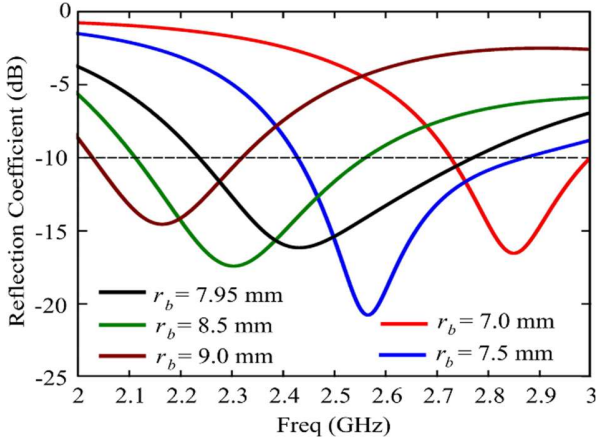


Fig. 3. Reflection coefficient of the patch antenna for different values of r_b , with $A_p = 0.0096$.

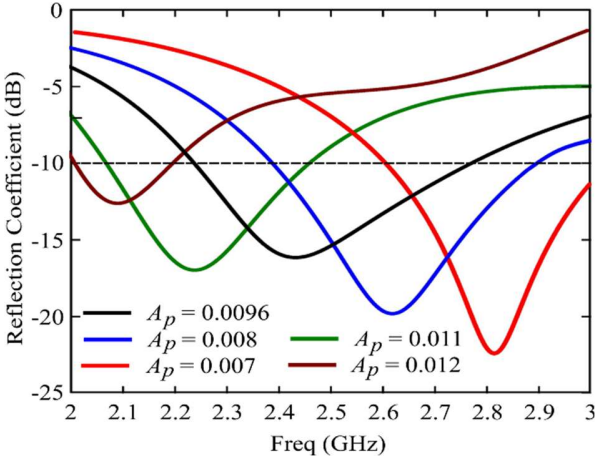


Fig. 4. Reflection coefficient of the patch antenna for different values of A_p , with $r_b = 7.95$ mm.

The reflection coefficient related to the optimal parameters $r_b = 7.95$ mm and $A_p = 0.0096$ is represented by the black curve in Figs. 3 and 4. Finally, in Fig. 5, the corresponding input impedance is also reported, with stable real part and low-slope imaginary part, highlighting the impedance matching over the operating bandwidth 2.25 GHz - 2.75 GHz.

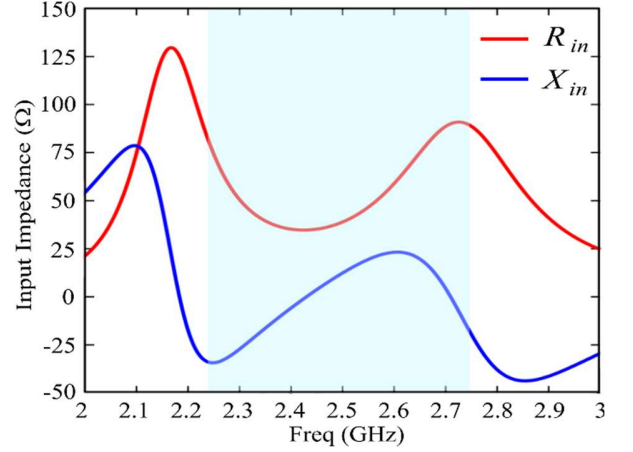


Fig. 5. Input impedance of the optimized patch antenna for $r_b = 7.95$ mm and $A_p = 0.0096$.

B. Design Step 2

The parabolic solid of revolution supporting the patch is a 1mm-thick (H_{PAR}) curved sheet of PLA (see Figs. 1 and 2c). The air zone beneath this curved PLA slab contributes to enhance the return loss bandwidth of the proposed configuration. However, this region can also be effectively utilized to further improve input impedance matching. This is achieved by implementing a matching network printed on the planar PLA substrate beneath the curved PLA slab. The matching elements can be connected to the 50 Ω microstrip feeding line at the patch feeding point (see Fig. 6), thereby realizing a parallel connection.

Therefore, starting from the optimal configuration obtained in the first design step, we add an open-ended microstrip line (open stub) to the feeding line, which extends beneath the patch (Fig. 6), acting as a capacitive load in parallel with the patch. The length of this stub is L_{STB} , and its width is W_{STB} .

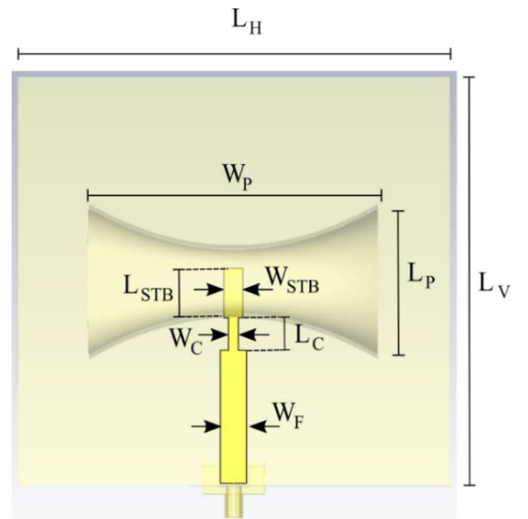


Fig. 6. Antenna layout including the matching network composed of an open-ended microstrip stub and a short microstrip line.

A two-variable (L_{STB} , W_{STB}) optimization procedure was performed using CST Studio Suite, aiming to improve the input impedance bandwidth by generating a second minimum in the reflection coefficient within the target operating bandwidth. This leads to the optimal values $L_{STB} = 10.8$ mm and $W_{STB} = 4.1$ mm.

The parametric variation of the reflection coefficient for different values of L_{STB} with $W_{STB} = 4.1$ mm, and for different values of W_{STB} with $L_{STB} = 10.8$ mm, is shown in Figs. 7 and 8, respectively. In these figures, the optimal configuration is represented by the black curve, which clearly shows the two desired minima of the reflection coefficient.

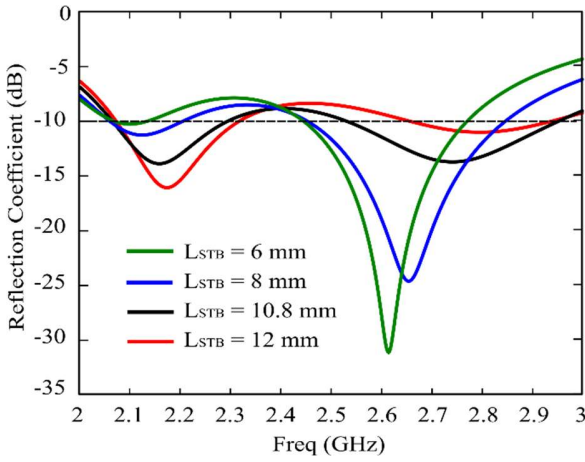


Fig. 7. Reflection coefficient of the patch antenna for different values of L_{STB} , with $W_{STB} = 4.1$ mm ($r_b = 7.95$ mm and $A_P = 0.0096$).

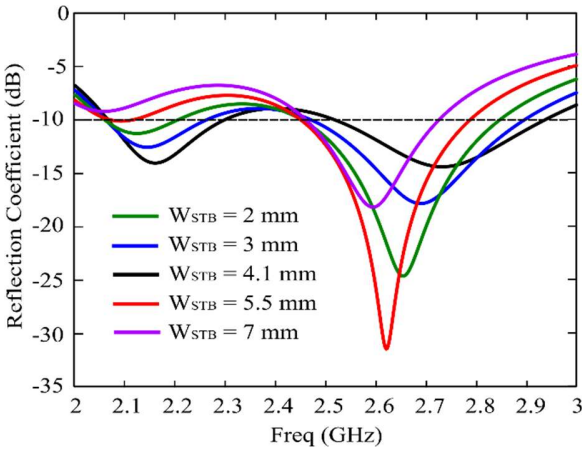


Fig. 8. Reflection coefficient of the patch antenna for different values of W_{STB} , with $L_{STB} = 10.8$ mm ($r_b = 7.95$ mm and $A_P = 0.0096$).

In Fig. 9, the reflection coefficient and input impedance of the designed antenna are shown, highlighting the effect of the added stub. It is apparent that the inclusion of the stub smooths impedance variations and that the second minimum

in the reflection coefficient can be used to improve the bandwidth. However, further modification is required, as the maximum reflection coefficient within the operating bandwidth (see Fig. 9) is -8.8 dB and should be reduced below -10 dB. This can be achieved by adding a short microstrip line (length L_C) with relatively high characteristic impedance (width W_C) between the feedline and the patch (Fig. 6), acting approximately as a series inductor [19].

The width W_C has been selected equal to 2 mm and the L_C has been optimized to maximize the -10 dB reflection coefficient bandwidth. As reported in Fig. 10, the optimal value of L_C is 2.2 mm, which ensures a -10 dB reflection coefficient bandwidth of 32% (2.07 – 2.87 GHz).

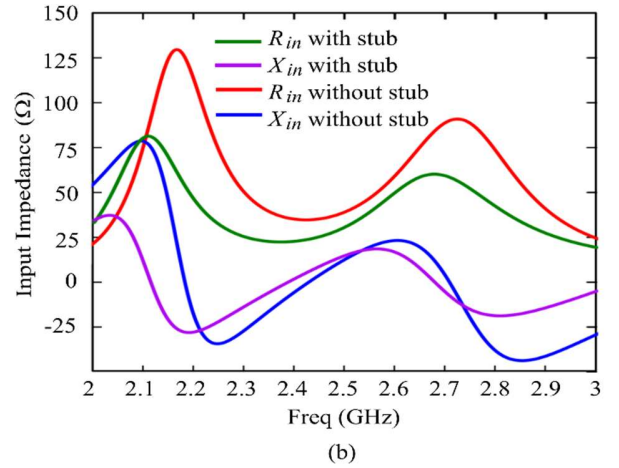
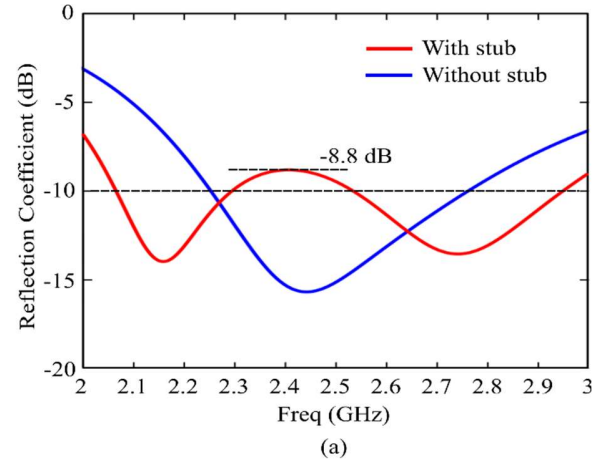


Fig. 9. Reflection coefficient (a) and input impedance (b) of the patch antenna with and without the open ended stub ($L_{STB} = 10.8$ mm, $W_{STB} = 4.1$ mm, $r_b = 7.95$ mm, and $A_P = 0.0096$).

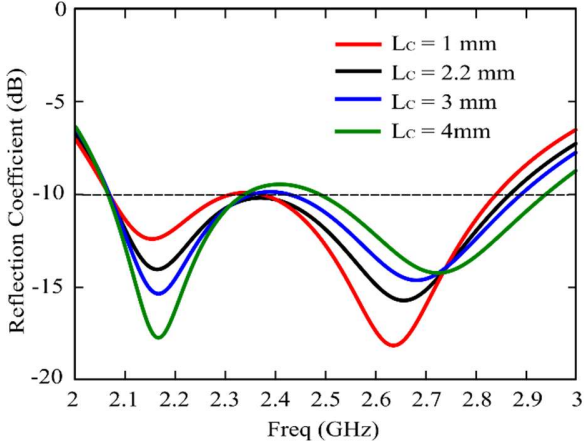


Fig. 10. Reflection coefficient of the patch antenna for different values of L_C , $W_C = 2$ mm ($L_{STB} = 10.8$ mm, $W_{STB} = 4.1$ mm, $r_b = 7.95$ mm, and $A_P = 0.0096$).

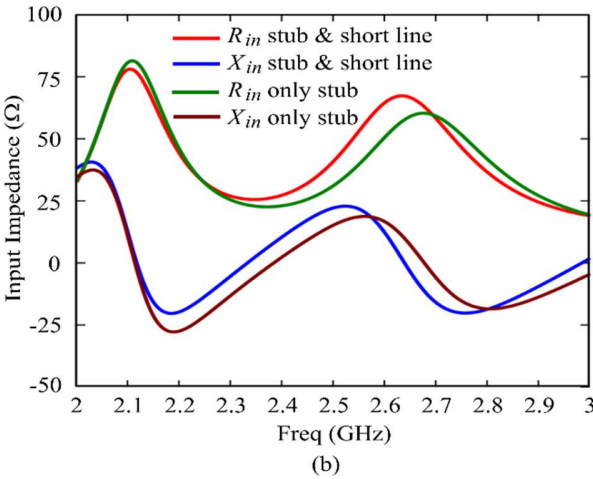
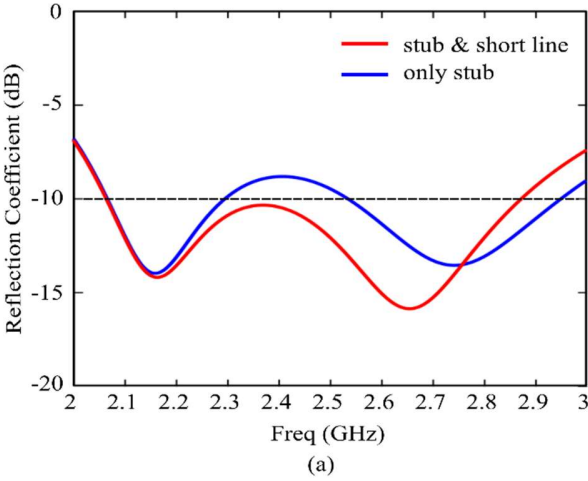


Fig. 11. Reflection coefficient (a) and input impedance (b) of the patch antenna with and without the short microstrip line ($L_C = 2.2$ mm, $W_C = 2$ mm, $L_{STB} = 10.8$ mm, $W_{STB} = 4.1$ mm, $r_b = 7.95$ mm, and $A_P = 0.0096$).

The improvements attributed to the introduction of the short microstrip line are shown in Fig. 11, wherein the reflection coefficient and input impedance of the last two configurations (patch fed by the $50\ \Omega$ microstrip line with the open-ended stub and the final configuration incorporating the short microstrip line) are compared.

Summarizing, at the end of the design procedure, the geometric parameters of the optimized configuration are reported in Table 2.

Table 2. Geometrical parameters of the optimized configuration.

A_P	r_b [mm]	W_P [mm]	L_P [mm]	H_P [mm]	L_{STB} [mm]	W_{STB} [mm]	L_C [mm]	W_C [mm]
0.0096	7.95	60	33.2	16.6	10.8	4.1	2.2	2

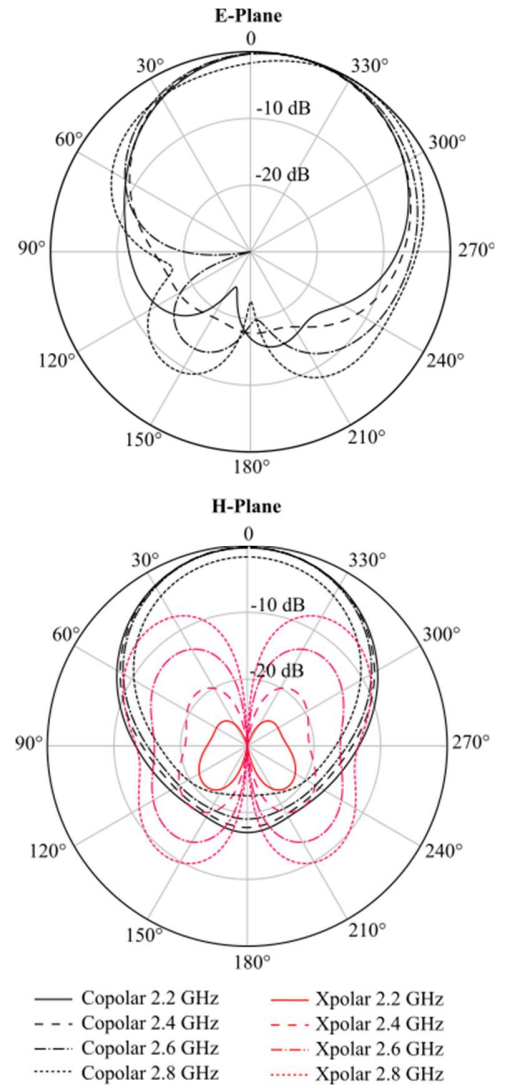


Fig. 12. Simulated far field pattern of the proposed antenna. The simulated cross-polar component in the E-Plane is not shown since lower than -60 dB.

Finally, in Fig. 12, we present the simulated radiation pattern in the principal planes of the designed antenna at selected frequencies. An asymmetrical radiation pattern is observed in the E-Plane with the radiation maximum ranging from -11° to -32° in the operating bandwidth. The realized gain is stable (between 5.7 dBi and 7 dBi) (see Fig. 17) and the simulated radiation efficiency ranges from 92.2% to 93.6%, which is an excellent performance for a patch antenna, consistent with the other curved configurations proposed so far [18], [20].

C. Influence of the Curved Parabolic Profile on Antenna Performance

In this subsection, building on the results of the previous subsections, we summarize how the curved parabolic profile of the patch influences the antenna performance - specifically its impedance bandwidth, gain, and impedance matching:

Bandwidth Enhancement: The impedance bandwidth of printed antennas is inversely proportional to the radiation quality factor Q_{rad} , which is, in turn, inversely proportional to the substrate thickness [2]. In a planar microstrip patch antenna, the bandwidth is often limited by the thin dielectric substrate. By curving the patch upwards, the distance between the metallic patch and the ground plane increases. The increase of the average substrate thickness in the patch region leads to a reduction of the radiation quality factor Q_{rad} and, consequently, increases the impedance bandwidth. In addition, the curved parabolic profile allows for multiple current paths along the resonant direction, which favor the enhancement of the impedance bandwidth. Figures 3 and 4 illustrate the effect of the curvature parameters (r_b and A_p) on the reflection coefficient, showing how the resonant frequency shifts and the bandwidth broadens, indicating the influence of curvature on impedance bandwidth.

Gain: Increasing the substrate thickness of conventional microstrip antennas increases their gain but it also enhances the surface wave excitation [2]. However, in the proposed configuration, the local increase of the substrate thickness in the patch region allows the surrounding substrate to be made as thin as necessary. This helps to mitigate both the losses in the coplanar feeding network and the surface wave losses, thus contributing to maintain a high radiation efficiency and, consequently, a satisfactory realized gain, as outlined at the end of the previous subsection.

Impedance matching: The hollowed-out region beneath the curved patch plays a key role in achieving impedance matching. It forms an air-filled zone that, in combination with the optimized coplanar microstrip matching network—comprising an open-ended stub and a short microstrip line—enables precise control of the input impedance. The stub and short line introduce additional reactive components that compensate for the reactive part of the patch impedance over a wide bandwidth, while matching the real part to approximately 50Ω . Figures 5, 9, and 11 demonstrate the evolution of the input impedance (real and imaginary parts) as the matching network elements are added. This clearly shows how the curvature, combined with the matching network, enables the

wideband impedance match by smoothing impedance variations.

III. ANTENNA FABRICATION AND EXPERIMENTAL VERIFICATION

A prototype of the designed antenna has been fabricated using the commercial 3D-printer PRUSA MK3S+ and a PLA thermoplastic filament (see Fig. 13). The metallization of patch, feeding microstrip, matching network, and ground plane have been realized using 50 μm -thick adhesive aluminum tape.

The frequency response, realized gain, and radiation pattern of the manufactured prototype have been measured in an anechoic environment (Fig. 14) by using the Anritsu MS46322B two-port vector network analyzer and a test calibrated antenna (model HyperLOG 7060 by AARONIA AG) [21]. The test antenna has been connected to a broadband Low Noise Amplifier (LNA) (model ZX60 83LN-S+ by Minicircuits) to improve the sensitivity of the measurement.



Fig. 13. Prototype of the designed antenna.

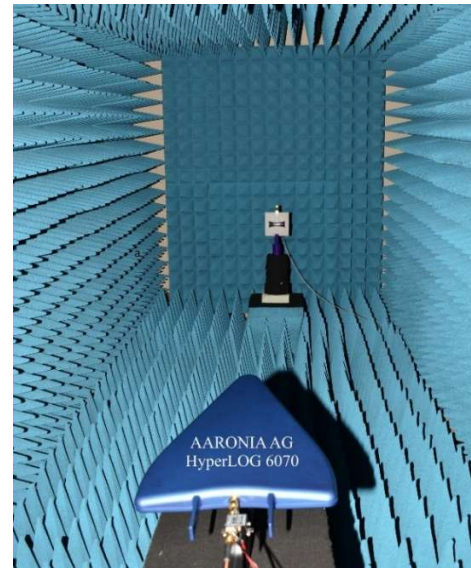


Fig. 14. Experimental setup for the measurement of fabricated antenna.

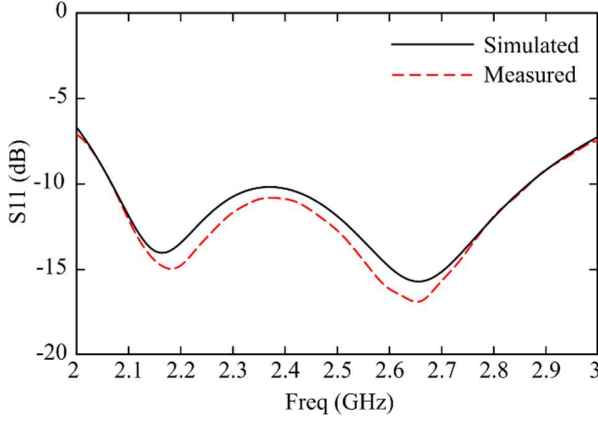


Fig. 15. Comparison between simulated and measured reflection coefficient of the manufactured prototype.

In Fig. 15, the reflection coefficient of the manufactured prototype is reported, showing a good agreement between simulation and measurement with a measured percentage -10 dB bandwidth of 32% (between 2.07 GHz and 2.87 GHz). In Fig. 16, the realized gain is shown, ranging from 5.7 to 7 dBi in the operating bandwidth. Finally, in Fig. 17 the comparison between measured and simulated far-field pattern at 2.4 GHz and 2.6 GHz is depicted.

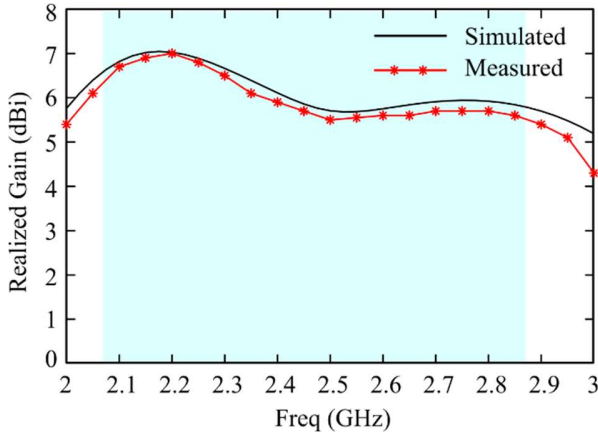


Fig. 16. Comparison between simulated and measured realized gain of the manufactured prototype.

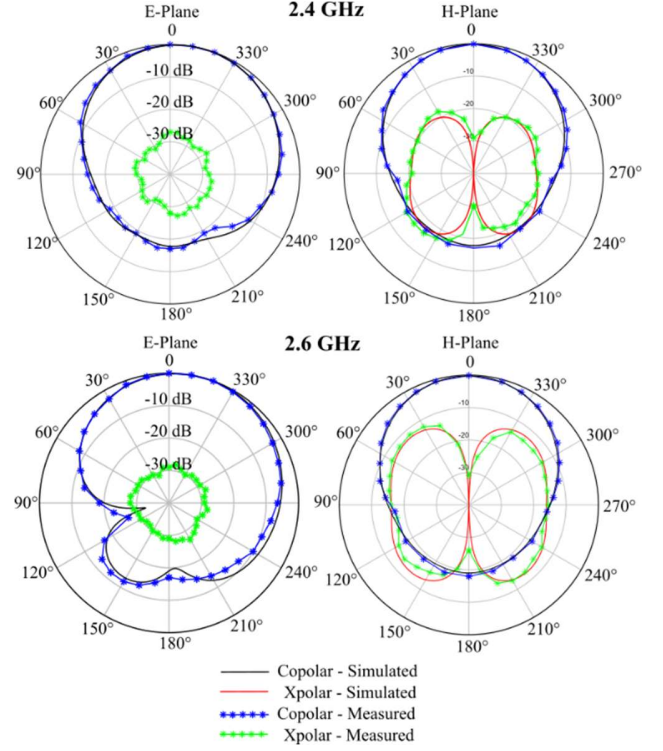


Fig 17. Comparison between simulated and measured far field pattern at 2.4 GHz and 2.6 GHz. The simulated cross-polar component in the E-Plane is not shown since lower than -60 dB.

IV. 2×2 PLANAR ARRAY DESIGN

A simple two-by-two uniform planar array has been designed and characterized using CST Studio Suite to assess the performance of the proposed antenna configuration. The four antennas in the array are identical, and a parallel coplanar feeding network has been implemented using quarter-wave transformers. The beamforming network is shown in Fig. 18, where the dimensions of the lines are indicated. The geometry of the antennas is the same as designed in Section II, except for the matching network, which requires further optimization due to mutual coupling between the array elements. The new optimized values are $L_{STB} = 13$ mm, $W_{STB} = 4.7$ mm, $L_C = 2$ mm, and $W_C = 2$ mm. The size of the array PLA planar substrate is 155 mm $\times$ 180 mm.

In Fig. 19, the simulated reflection coefficient of the designed array is reported, showing a -10 dB percentage bandwidth of about 28% (between 2.04 and 2.70 GHz). The simulated array realized gain within the operating bandwidth ranges from 8.4 to 11.6 dBi, and the simulated radiation efficiency is between 80% and 87% (see Fig. 20). Finally, in Fig. 21, the simulated far-field pattern at selected frequency points is shown.

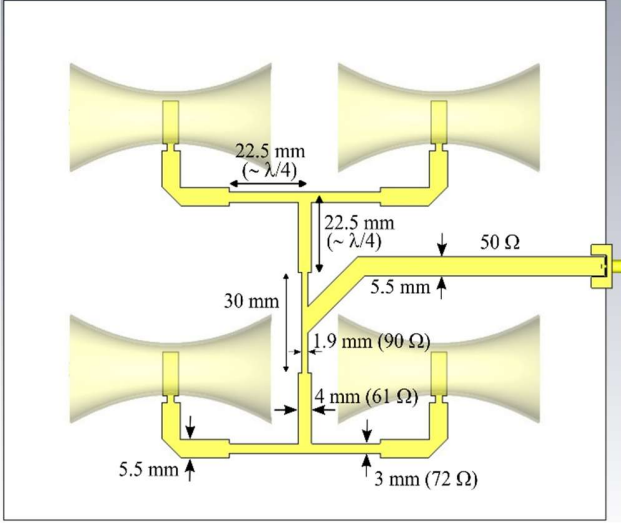


Fig. 18. Geometry of the 2 x 2 uniform planar array.

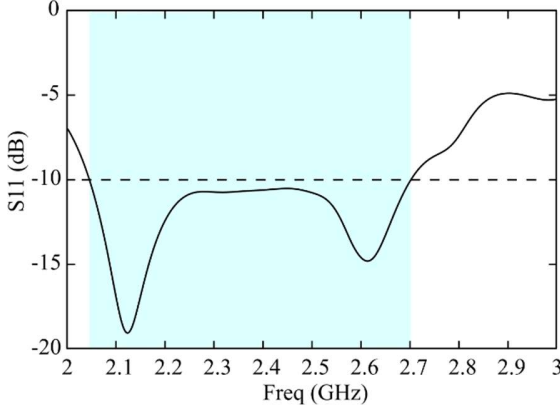


Fig. 19. Simulated reflection coefficient of the designed 2 x 2 uniform planar array depicted in Fig. 18.

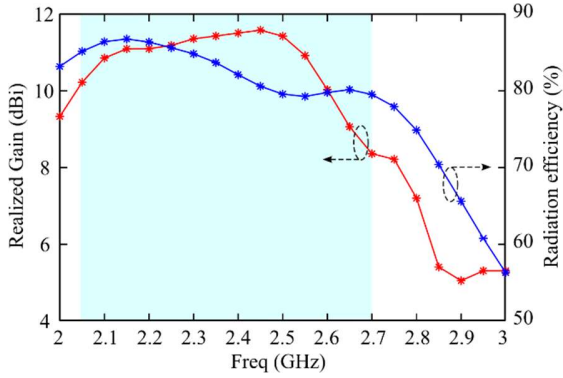


Fig. 20. Simulated realized gain and radiation efficiency of the 2 x 2 planar array depicted in Fig. 18.

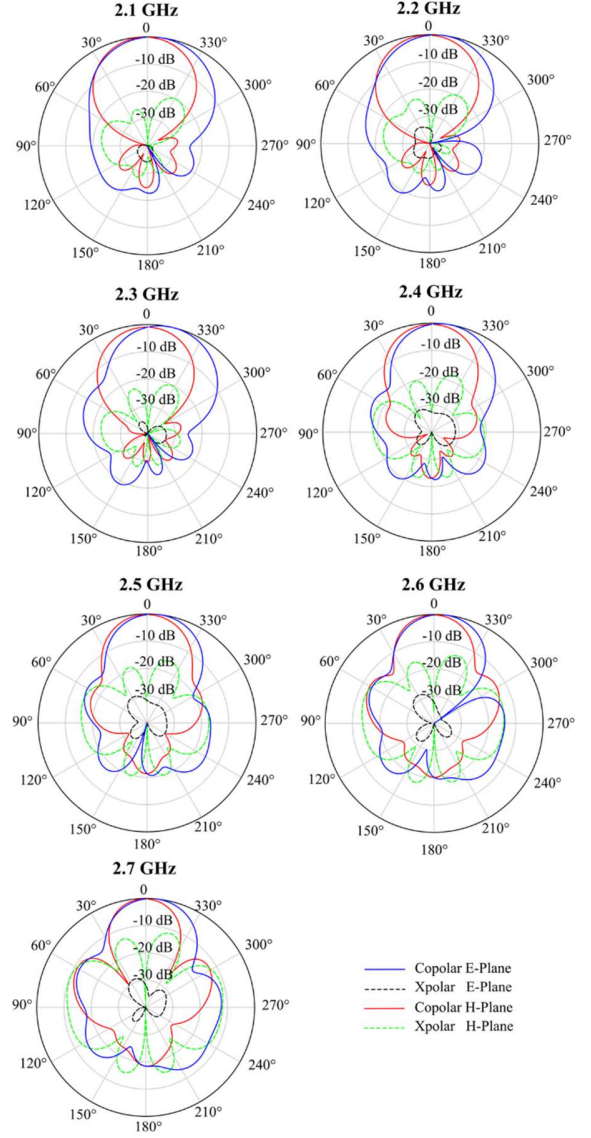


Fig. 21. Simulated far field pattern of the 2 x 2 planar array depicted in Fig. 18.

V. CONCLUSION

Designing broadband patch antennas with conventional coplanar microstrip feeding poses significant challenges, as achieving wide bandwidth typically requires complex substrate configurations (e.g., stacked or suspended designs) that commonly rely on coaxial probe feeding, thereby hindering fully integrated implementations.

This work presents a novel and effective solution, consisting of a parabolic-curved patch antenna implemented on a planar substrate. The proposed geometry employs a localized increase in substrate thickness beneath the metallic patch to enhance the reflection coefficient bandwidth, while allowing the surrounding substrate to remain as thin as needed to minimize losses in the coplanar feeding network.

Building upon previous curved antenna concepts [18], our enhanced configuration significantly advances the state-of-the-

art through the following key innovations:

- The use of a parabolic solid of revolution for the curved patch optimizes current paths and substantially increases the operational bandwidth compared to the simpler curved geometry [18].
- Hollowing out the area beneath the curved patch, allowing it to be supported by a thin curved sheet, minimizes unwanted dielectric losses and enables efficient integration of the stub-based matching network in the planar substrate beneath the metallic patch.

The proposed antenna boasts easy and cost-effective fabrication via 3D printing additive manufacturing, enabling the precise realization of its complex curved shape. The parabolic-curved configuration achieves an impressive reflection coefficient bandwidth of 32% (2.07 - 2.87 GHz), demonstrating a substantial improvement over previous coplanar-fed design. Furthermore, it maintains high radiation efficiency (around 90%) over the operating bandwidth and exhibits stable realized gain (between 5.7 and 7 dBi).

Thanks to direct coplanar microstrip feeding, the presented patch antenna can be used both as a single-element antenna in planar integrated RF circuits and as an element in planar arrays with direct microstrip feeding. To demonstrate the potential of the proposed configuration, a 2×2 planar array with a parallel coplanar feeding network has been designed and simulated, confirming the wideband behavior observed in the single element. The array exhibits a reflection coefficient bandwidth of 28%, high radiation efficiency exceeding 80% despite the coplanar feeding network, and a realized gain between 8.4 dBi and 11.5 dBi within the operating bandwidth.

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