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Miniaturized Antenna on a Paper Substrate

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Abstract — This paper presents a miniaturized microstrip antenna on an air-filled paper substrate. The presence of air in the substrate accounts for low dielectric losses and a high dielectric thickness, resulting in a high radiation efficiency and a large bandwidth. In addition, the edge of the antenna is exploited to feed the antenna with a coplanar line that can be connected to a 50 Ω coaxial probe. This original feeding technique permits the reduction of the frequency of resonance as the air gap increases. The antenna is further miniaturized with the insertion of a slot in the ground plane. As a result, a high degree of miniaturization can be obtained along with a high efficiency. The influence of the air gap and of the slot on the antenna's performances is investigated. Two prototypes with dimensions of $0.29 \lambda_o \times 0.29 \lambda_o \times 0.065 \lambda_o$ radiating at 2.45 GHz are fabricated with copper tape and silver ink and the antennas' performances are experimentally validated: a gain of 4.5 dBi and a front-to-back ratio of 9.5 dB are measured, corresponding to a radiation efficiency of 70%.

Index Terms—Paper substrate, microstrip antenna, air gap, air-filled, miniaturization, light weight antenna, low cost.

I. INTRODUCTION

Cellulosic materials such as paper have recently gained a lot of attention for the design of printed electronics and antennas due to numerous benefits. The popularity of paper lies on its light-weight, flexible, eco-friendly and low-cost characteristics, which can serve the development of low-cost, low-impact, and low-power networks for the IoT ecosystem [1]-[3]. Nevertheless, for the design of antennas, the high dielectric losses of paper strongly limit the performances that can be obtained, and particularly for antennas with ground planes [4]. The radiation of directive planar antennas originates from the resonance of electromagnetic fields inside the substrate and is strongly degraded with highly lossy dielectrics. For microstrip antennas, a basic solution is to add an air gap between the ground plane and the patch [5], [6]. However, because of the low permittivity of air, the dimensions of the antenna can become very large.

In an effort of designing a compact and light-weight antenna on a paper substrate, this paper proposes a miniaturized microstrip antenna on an air-filled paper substrate fed by a coplanar line on its edge. While the presence of an air gap between the patch and the ground plane enhances the radiation efficiency, the expansion of the antenna size is limited thanks to the feed line, whose length is directly dependent on the thickness of the air gap. The size of the antenna is even further reduced with the insertion of a slot in the ground plane. The height of the air gap and the dimensions of

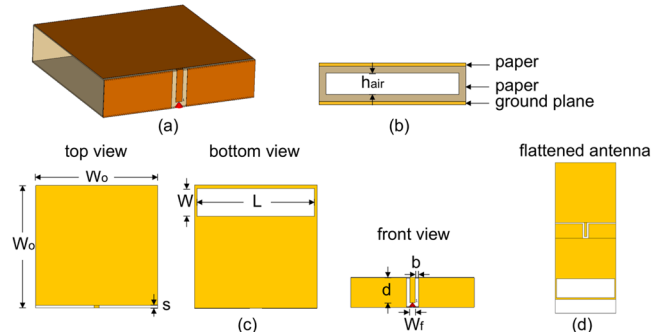


Fig 1. Geometry of (a) the proposed antenna with (b) the different layers, (c) the parameters of each layer and (d) the geometry of the antenna when flattened.

the slot are carefully chosen to reduce the dimensions of the antenna without degrading neither the directivity nor the antenna efficiency. As a result, a miniaturized antenna, radiating at 2.45 GHz, of dimensions $0.29 \lambda_o \times 0.29 \lambda_o \times 0.065 \lambda_o$, is fabricated and the performances of the antenna are experimentally validated.

In the section II of this paper, the description of the antenna is given and the influence of the air gap and of the slot on the antenna's performances is discussed. Finally, a prototype is fabricated, and section III shows the experimental results.

II. ANTENNA OVERVIEW

The proposed antenna, shown in Fig. 1 consists of a square microstrip antenna on a paper substrate, ensured by an air gap between the patch and the ground plane. Since the waves mostly travel in the air, with quasi-null losses, the antenna can reach a high radiation efficiency. Despite a low permittivity that tends to reduce the frequency bandwidth, the high thickness of the substrate enlarges the bandwidth. Furthermore, the antenna is fed by a coplanar line, positioned on the edge of the antenna. This feeding method cancels the enlargement of the antenna size imposed by the widening of the air gap, as it will be showed in next section. A 50 Ω SMA can be directly connected to the coplanar line. The microstrip technology is avoided to design the feed line since it would result in a bigger antenna but also a very wide line that would affect the radiation efficiency. The thin thickness of the paper also forbids to use of a microstrip line on the edge of the antenna since it would lead to a line with an extreme small width, difficult to fabricate. As shown in Fig. 1, the dimensions of the antenna's ground plane are similar to the

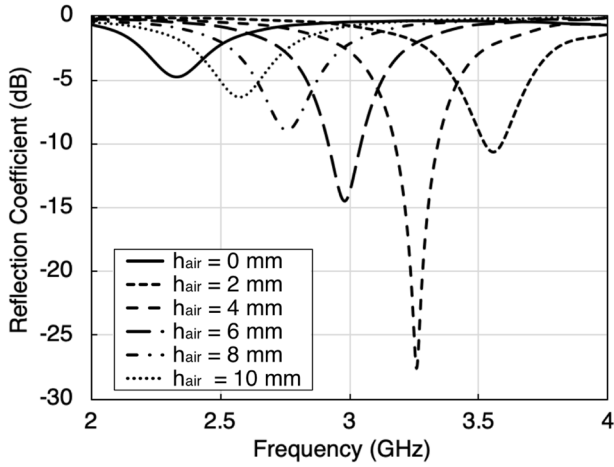


Fig. 2. Evolution of the reflection coefficient (dB) of the antenna with the air thickness. The dimensions of the antenna are: $W_o = 35.5$ mm, $s = 1.5$ mm, $W_f = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $L = W = 0$ mm.

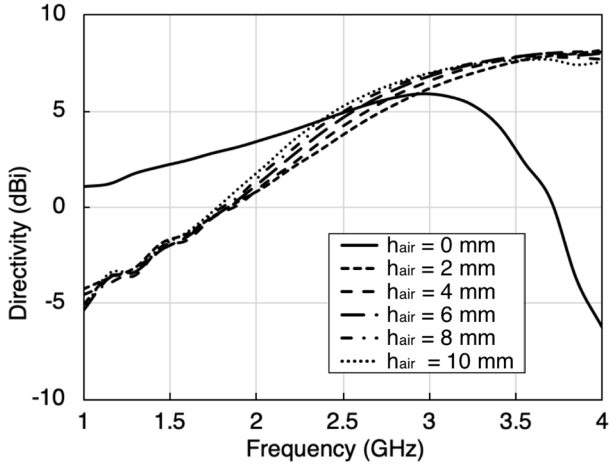


Fig. 3. Evolution of the directivity (dBi) of the antenna with the air thickness. The dimensions of the antenna are: $W_o = 35.5$ mm, $s = 1.5$ mm, $W_f = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $L = W = 0$ mm.

patch dimensions to limit the size of the antenna, at the expense of a limited directivity. The ground plane is separated from the patch by a distance s . Finally, a slot of dimensions $L \times W$ is inserted in the ground plane to miniaturize the antenna. Next section discusses the influence of the air gap and of the slot on the antenna's performances.

A. Influence of the Air Gap

The antenna is designed and simulated on the CST software with a paper of dielectric constant 3.36, loss tangent 0.125 and thickness 0.23 mm. The metallic parts are simulated with copper of thickness 35 μ m. The antenna is simulated with different values of air gap and the dimensions of the antenna are fixed to be: $W_o = 35.5$ mm, $W_f = 1.5$ mm, $s = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $L = W = 0$ mm. The air gap has an impact on the radiation efficiency of the antenna, but it also affects the resonance frequency. Indeed, a variation of the air gap modifies the effective permittivity of the substrate but also the length of the feed line, in the case of the proposed

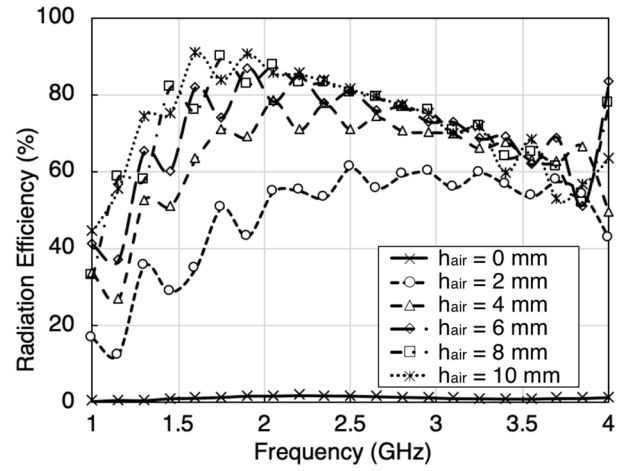


Fig. 4. Evolution of the radiation efficiency (%) of the antenna with the air thickness. The dimensions of the antenna are: $W_o = 35.5$ mm, $s = 1.5$ mm, $W_f = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $L = W = 0$ mm.

antenna. As a result, as shown in Fig. 2, the frequency of resonance is shifted from 2.34 GHz without air gap to 3.57 GHz with an air gap of 2 mm since the effective relative permittivity of the substrate get closer to 1 compared to 3.36 when there is only paper. On the contrary, the frequency of resonance decreases as the air gap becomes larger because the length of the feed line increases. The feeding method is highly efficient to limit the size of the antenna while the proportion of air increase. Note that, the variation of the distance d does not shift the resonance frequency. Fig. 3 shows that the directivity of the antenna is just slightly shifted towards the lower frequencies when the air thickness increases. The maximum directivity is indeed imposed by W_o and reaches here 7.7 dBi. We can still observe a slender increase in directivity for the higher air gaps [7]. Note that the directivity of the antenna without air gap does not have the same evolution with frequency due to the different effective relative permittivity. Fig. 4 depicts the variation of the radiation efficiency with the air gap, when the dimensions of the antenna are fixed. As expected, the larger, the amount of air is in the substrate, the higher the radiation efficiency is. While the efficiency does not exceed 1.6 % when no air gap is present, up to 90 % efficiency is obtained for the highest air gaps at 1.6 GHz, while the efficiency reaches 80 % at 2.45 GHz.

B. Influence of the Slot

In order to further reduce the dimensions of the antenna, a slot is introduced in the ground plane. The dimensions of the antenna are kept similar as previously, except for the air gap and the slot ($W_o = 35.5$ mm, $W_f = 1.5$ mm, $s = 1.5$ mm, $b = 1$ mm). The length L of the slot is fixed at 34 mm the air gap is 8 mm thick with $d = 7$ mm. Fig. 5 shows the variation of the reflection coefficient for different widths W of the slot. It can be observed that, as the width of the slot increases, the resonance frequency decreases. The same result is obtained when L is varied, and W is fixed. This technique of miniaturization is simple and shifts the resonance frequency at maximum from 2.8 GHz with no slot to 1.8 GHz with a 34mm

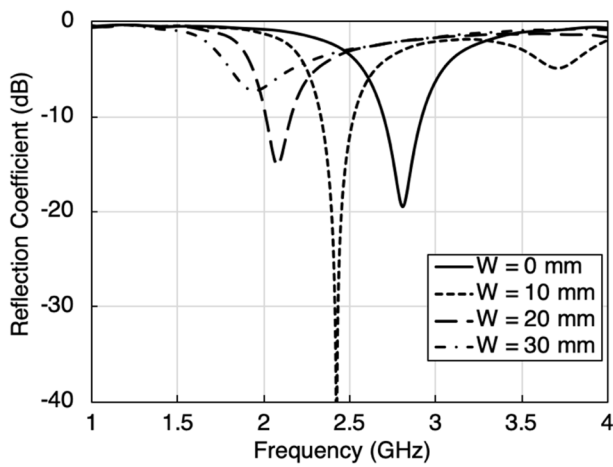


Fig 5. Evolution of the reflection coefficient (dB) of the antenna for with the width of the slot. The dimensions of the antenna are: $W_o = 35.5$ mm, $s = 1.5$ mm, $W_f = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $h_{air} = 8$ mm.

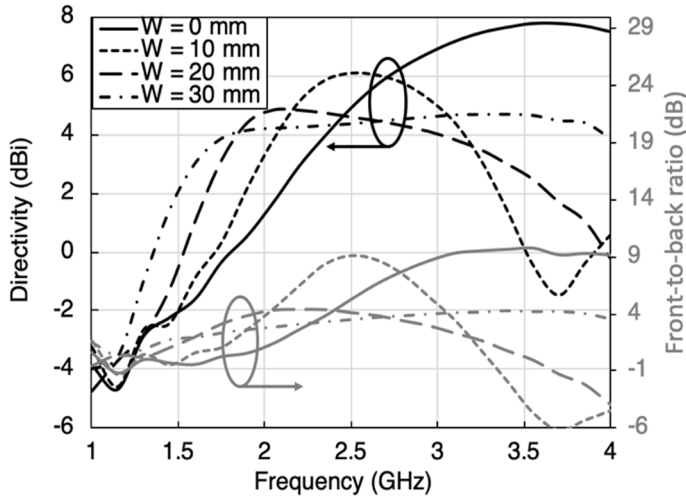


Fig 6. Evolution of the directivity (dBi) and front-to-back ratio (dB) of the antenna with the width of the slot. The dimensions of the antenna are: $W_o = 35.5$ mm, $s = 1.5$ mm, $W_f = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $h_{air} = 8$ mm.

wide slot. As depicted in Fig. 6, for fixed antenna dimensions, the directivity of the antenna is reduced when the slot is enlarged due to the diminution of the resonance frequency. However, the reduction of directivity of the antenna in the broadside direction, as W increases, is also due to a lower quality factor at high values of W . This results in a low front-to-back ratio and degrades the directivity [8]. Indeed, for very large values of W , the antenna radiates more like a slot antenna. Still, for these dimensions of the antenna, this effect does not seem to degrade the radiation of the antenna for values of W lower than 10 mm. Fig. 7 shows the variation of the gain of the antenna in the broadside direction, without mismatch losses, that is the results of the radiation efficiency and of the directivity affected by a low front-to-back ratio at high W . It can be observed that at the frequency of interest (2.45 GHz), the highest gain, for these dimensions of antenna, is obtained when $W = 10$ mm. As shown in Fig. 8,

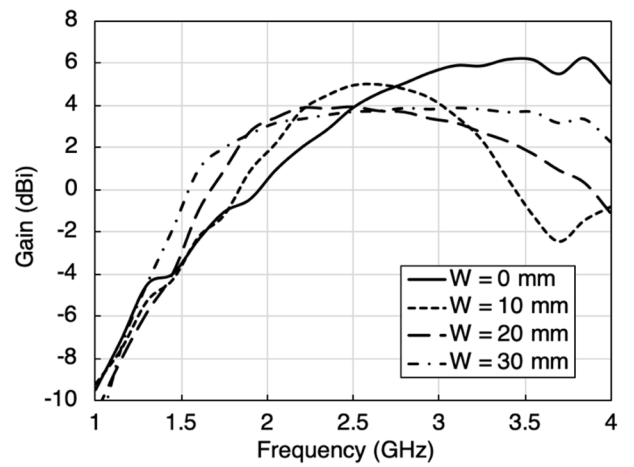


Fig 7. Evolution of the gain (dBi) (without the mismatch losses) of the antenna with the width of the slot. The dimensions of the antenna are: $W_o = 35.5$ mm, $W_f = 1.5$ mm, $s = 1.5$ mm, $b = 1$ mm, $d = 7$ mm, $h_{air} = 8$ mm.

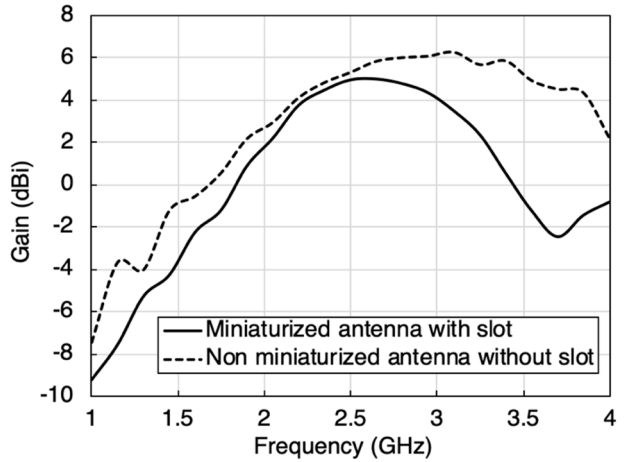


Fig 8. Gain (dBi) (without the mismatch losses) of the miniaturized antenna ($W_o = 35.5$ and $W = 10$ mm) compared to the gain of the non-miniaturized antenna ($W_o = 42$ mm and $W = 0$ mm).

the resulting gain is compared to the gain of an antenna without slot in the ground plane and dimensions optimized for 2.45 GHz: $W_o = 42$ mm, $W_f = 1.5$ mm, $s = 1.5$ mm, $b = 1$ mm, $d = 3$ mm, $h_{air} = 8$ mm. The size of the miniaturized antenna is reduced of 15% compared to the size of the antenna without the slot. The gain in the broadside direction is only reduced by 0.4 dB at 2.45 GHz after the miniaturization, passing from 5.2 dBi to 4.8 dBi, which corresponds to an efficiency of 73 %.

III. EXPERIMENTAL VALIDATION

The antenna was fabricated on the paper substrate with two different conductors: copper tape and silver ink, as shown in Fig. 9. Fig. 10 shows the measured reflection coefficient. A good agreement between measurement and simulation can be observed for both antennas. As demonstrated by Fig. 10, the probe seems to slightly lower the reflection coefficient. The realized gain of the antenna has been measured in an anechoic chamber in the E-plane and in the H-plane of the antenna. As shown in Fig. 11, the experimental results agree well with the

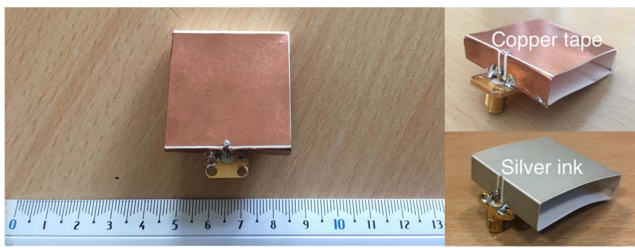


Fig 9. Photographs of the fabricated antenna prototypes.

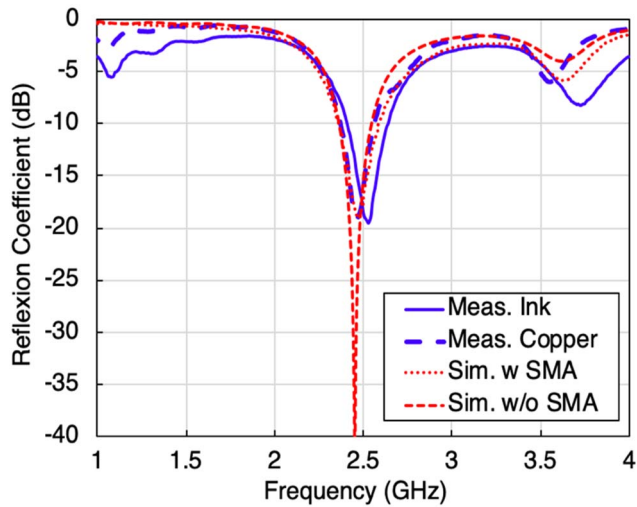


Fig 10. Reflection coefficient (dB) of the antenna prototypes.

simulation with a measured gain of 4.5 dBi in the broadside direction and a measured front-to-back ratio (FBR) of 9.5 dB for the antenna fabricated with copper tape. The difference in gain with the simulation (0.3 dB) is due to the uncertainty of the measurement setup and the fabrication tolerance. As suggested in simulation, the radiation efficiency of the antenna is 70 %. The antenna gain and FBR with the silver ink are 4.1 dBi and 8.6 dB, a little bit less than with the copper tape. This can be explained by the thin layer of the conductive ink that makes the antenna rapidly subject to small defects affecting its conductivity.

IV. CONCLUSION

In this paper, a miniaturized microstrip antenna on paper substrate with an air gap was proposed. The thickness of the antenna was exploited to place a coplanar line for feeding the antenna. It was observed that the expansion of the air gap helps in achieving a higher radiation efficiency and in reducing the resonance frequency. A slot was inserted in the ground plane for further reduction of the antenna size. Finally, a prototype with dimensions of $0.29 \lambda_0 \times 0.29 \lambda_0 \times 0.065 \lambda_0$, radiating at 2.45 GHz was fabricated with copper and silver ink. The performances of the antenna were experimentally validated with measured gain and front-to-back ratio of 4.5 dBi and 9.5 dB respectively, corresponding to a radiation efficiency of 70 %.

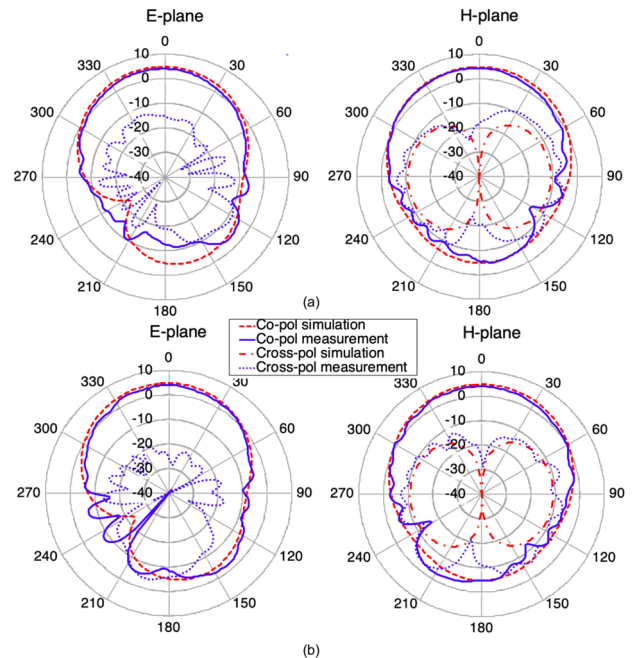


Fig 11. Simulated and measured realized gain pattern (dBi) of the antennas in the E-plane and H-plane (a) with copper tape and with (b) silver ink.

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