Miniature Patch and Slot Microstrip Arrays for IoT and ISM Band Applications

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ABSTRACT In this paper we present the design and fabrication of a two-antenna array to resonate at 5.8 GHz, a frequency that satisfies a host of applications, especially those associated with the ISM band, but including IoT applications. The design incorporates several techniques to improve figures of merit and reduce its size. The array presents a measured bandwidth of 617 MHz (from 5.503 to 6.120 GHz, or 10.63% about the central frequency) when built on a thin substrate, and of 455 MHz (from 5.517 to 5.972 GHz; 7.84%) when fabricated using a thicker one. The simulated gains were of 6.89 dBi and 7.63 dBi, whereas the measured ones were 6.7 dBi and 7.2 dBi, respectively. Size reduction is better than 30% and the simulated efficiencies are higher than 90%.

INDEX TERMS Antenna arrays, DGS, IoT, ISM, wide bandwidth.

I. INTRODUCTION

In recent times the world has experienced the proliferation of Internet of Things (IoT) or Internet of Everything (IoE) applications, which are designed to suit everyday more needs in our connected way-of-life. These are tailored for the industrial, commercial, banking, entertainment and communications sectors, to mention a few [1]–[4]. But regardless of the use, all share common grounds in terms of technological requirements: the devices for these applications have to be of reduced size, consume very low power, meld with the environment, and be robust, trustworthy and reliable. Furthermore, wireless connectivity meeting all these requirements has to be guaranteed, which has been the aim of many research groups worldwide for several decades now, as the proliferation of journals dedicated to the field attests. The fundamental element in connectivity is the antenna, or antennas, that are incorporated in the devices. Of these, the ones that have garnered most of the attention are microstrip antennas or arrays, since the fabrication processes are mature, the cost is reasonable, and the design techniques are well established.

Applications for IoE cover a wide bandwidth of the spectrum, however, and antennas have to be designed for specific needs at specific frequencies and with determined bandwidths. A frequency range that has received much attention recently is that based on the license-free ISM (Industrial, Scientific and Medical) band, centered at 5.8 GHz. This band is relatively unencumbered at present, and wider bandwidths can be achieved, and hence, many research groups have worked towards improving microstrip antenna response about this frequency [5]–[19]. For instance, the design reported in [11] optimizes geometry to obtain a higher gain and reduced size. The work in [2] shows that the frequency of operation can be doubled by etching slots on the patch. And of course, as reported in [13]–[15], arrays can provide higher gain without affecting other important figures of merit. Moreover, Defected Ground Structures (DGS) are used to improve gain, ease matching, tailor the radiation pattern and reduce the number and magnitude of side-lobes [17]–[19].

Furthermore, standards such as IEEE 802.11 require band channeling, specially about the 5 GHz ISM band. In general, their bandwidths can vary from 20, 40, 80 and 160 MHz based on the number of channels required. Thus, it is evident that the wider the BW the antenna can handle, the more channels are available, and thus the more versatile the antenna is.
Herein we present a two-antenna array, designed using a combination of some of the different techniques so far reported, to achieve a reduced size with acceptable gain and a wide bandwidth, which represents an important contribution to the field by judiciously combining the advantages offered by each technique.

The basic design procedure is presented in Section II, followed by simulation and experimental results in Section III, which demonstrate the attained characteristics. The results are further discussed in Section IV, and the principal conclusions of this work are then presented in Section V.

II. DESIGN PROCEDURE

An initial design of a two-antenna array was determined using conventional microstrip theory, and its characteristics were subsequently improved using a modified distribution and size of the I-Beam etched slots reported in [14], to be further tailored by etching slots on the ground plane using the DGS technique. The selected substrate was of permittivity, \( \varepsilon_r = 2.2 \), and three different thicknesses were used, to wit, 0.508mm, 0.787mm and 1.575mm. The copper metallization was either one ounce or half an ounce per square foot.

The array was extensively simulated using a full-wave simulator [20], into which all known parameters were defined; surface roughness of 1.7\( \mu \)m (dielectric side) and 0.4\( \mu \)m (top side), and loss factor tan \( \delta = 0.0009 \).

To determine the array dimensions, an independent patch antenna was initially designed using traditional microstrip theory, and then an in depth analysis of the effects of etching I-Beam cavities on the top surface of the antenna was conducted, as [14] does not provide sufficient information on size, number and distribution of these cavities. As a consequence of these analyses, we determined the optimal size to alter the current distribution so that the slots present a resonance frequency above 200 GHz, which let us reduce the size of the antenna overall. We concluded that 15 cavities for each antenna was the better alternative, with the dimensions and separations indicated in Fig. 1.

To determine the optimal conditions for this substrate, three different thicknesses were initially used; 0.508, 0.787, and 1.575 mm. The three arrays were simulated incorporating all the pertinent and available data, and also taking into account the possible geometry variations due to the etching process. The results of some of these are shown in Fig. 2, which indicates the return losses as well as the predicted gain. The bandwidths obtained are 70, 100 and 150 MHz, while the gains are 6.51 dBi, 7.07 dBi and 7.13 dBi, respectively.

As a result of these extensive simulations, the 0.508 mm substrate was discarded, as with this thickness the simulated bandwidth and gain were considered very poor. For the others, the dimensions and geometry arrived at are shown in Fig. 3, a top view of the array on the PCB. An important step in the design of the arrays was the feeding network, which was designed to obtain minimal reflections and high gain. It consists of two quarter-wavelength transformers (to match the input impedance of each patch), followed by a T-junction and another quarter-wavelength transformer for the 50 \( \Omega \) feed line.

Knowing that by using the DGS technique the bandwidth can be increased, simulations were performed to study the effect of the geometry of slots on the back plane of the arrays. In these simulations, the size and position relative to the edges of the patch antennas on the top plane were systematically varied and the effects analyzed.

These ground-plane slots behave both as open-circuit and resonant stubs, altering the overall array response, since they are excited by the fields produced by the feed lines to the antennas. In fact, these are slot-antennas, with a resonant frequency determined by the slot size and their interaction with the patch antenna, which is a function of the relative position of the slot with respect to the patch; it can be optimized to attain larger bandwidths. This statement is based on, and validated by, the analysis presented in the following paragraphs.
The wavelength of the slot-line ($\lambda_s$) was calculated as in [21] (Equ. 5.44), and the resonance length was then determined from [9]:

$$L_r = \frac{\lambda_s}{2} - \Delta L_s$$  \hspace{1cm} (1)

where $\Delta L_s$ is the termination effect of the microstrip line.

Fig. 4 shows the simulation results while varying the length of the slots, $L_s$. A short length displaces the second resonance towards higher frequencies, while longer lengths have no appreciable effect on the resonance frequency. The analyses of the different simulations led us to determine the final values as $L_s = 21.5$ mm and width $W_s (\ll \lambda_0) = 0.5$ mm for the thin substrate and $L_s = 19$ mm and width $W_s (\ll \lambda_0) = 1$ mm for the thick one.

The optimal position of these slots was determined from further simulations, which consisted of varying the distance of the slots (on the ground plane) from the bottom edge of the antennas (on the top plane), here labeled “DisX”, as well as the position of the slot in reference to the center of the array, here denoted by “Off-center”. These parameters are shown in Fig. 5, while the results of some simulations are presented in Fig. 6. The final design including dimensions is that shown in Fig. 3; the corresponding parameters are listed in Table 1.

Once the appropriate dimensions and placing for the slots on the ground plane were determined to optimize the design, simulations were carried out to study the resulting electric and magnetic fields of the array. These are shown in Fig. 7. Fig. 7 a) shows the fields due to the slot on the ground plane, whereas 7 b) depicts the total electric field, considering both the array on the top plane and the slot on the ground plane. These figures show that there is a strong interaction between the patch antennas and the slots, which cannot be treated independently. On the one hand, the patches behave as open-circuit resonant stubs (Fig. 5a), which alter the resonant frequency of the slots (i.e., $\Delta L_s$ in Equ. (1)); on the other hand, the ground plane slots modify the resonant frequency of the patches by changing the electric and magnetic field distribution (Fig. 7a) of the patches, and hence the input
impedance. Therefore, both antennas have to be designed in conjunction to obtain the desired response.

Once all dimensions were determined, simulations were performed to determine several of the most important figures of merit for the arrays. The simulated peak gain as a function of frequency is presented in Fig. 8 for both types of substrates; and cross-polarization vs. frequency in Fig. 9 (relative to co-polarization). The simulated radiation patterns

FIGURE 7. Simulated E and H fields of the complete structure, incorporating the effects of the ground-plane slots. a) Electric and magnetic fields due to the ground-plane slot. b) Resulting electric field for the array and the ground-plane slot antenna.

FIGURE 8. Simulated peak gain vs. frequency for both substrates.

FIGURE 9. Simulated cross-polarization vs. frequency for both substrates.

FIGURE 10. 2-D Representation of radiation patterns of the proposed arrays for $h = 0.787\text{mm}$ (left) and $h = 1.575 \text{ mm}$ (right), for both the H-Plane and the E-Plane. a) 5.5 GHz, b) 5.6 GHz, c) 5.8 GHz, d) 6.0 GHz, e) 6.1 GHz. The radial axis in dBi.
are shown in Fig. 10, including magnetic and electric planes; for h = 0.787 mm (left) and h = 1.575 mm (right). HPBW is illustrated in Fig. 11.

The simulated gain across the bandwidth is above 4.5 dBi, presenting peak values of 6.89 dBi for the thin substrate and 7.63 for the thick one, as shown in Fig. 8. The corresponding directivities are of 7.1 dBi and 7.8 dBi; with gain and directivity we can calculate the efficiencies as 97.04% for h = 0.787 mm and 97.82% for h = 1.575 mm.

The axial ratio calculated by the simulator is of 61 dB for the thin substrate and 48.58 dB for the thicker one. The polarization is right-handed elliptical, and the cross component is lower than 40 dB at the central frequency, as can be observed from Fig. 9, meaning the dominant component is the right-hand one.

### III. EXPERIMENT

To validate simulation results, the arrays were fabricated and measured. The substrate used was DiClad 880, an anisotropic dielectric substrate [22], [23]. Moreover, the substrate was characterized with the sensor of [23] in our laboratory. Photographs of two arrays, showing both front and back sides, are presented as Fig. 12, whereas the experimental setup is shown in Fig. 13. The measurement range was from 4.5 GHz

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**TABLE 1.** Dimensions of the proposed arrays.

| Parameter | h=0.787 mm | h=1.575 mm |
|-----------|------------|------------|
| L_x       | 14.5       | 14.6       |
| W_x       | 16.6       | 16.5       |
| d_x       | 2.7        | 2.7        |
| d_w       | 0.42       | 0.42       |
| L_{e1}    | 9.9        | 9.9        |
| W_{e1}    | 0.5        | 1.0        |
| L_{e2}    | 4.0        | 4.0        |
| W_{e2}    | 2.4        | 4.9        |
| L_{t1}    | 9.3        | 9.3        |
| W_{t1}    | 3.9        | 8.0        |
| d         | 17.44      | 17.44      |
| L_e       | 21.5       | 20.0       |
| W_e       | 0.5        | 1.0        |
| DistX     | 1.0        | 1.0        |
| Off-center| 3.3        | 3.3        |

**TABLE 2.** Figures of merit of the proposed arrays.

| Figure of Merit | Simulation | Measurement |
|-----------------|------------|-------------|
|                  | h=0.787 mm | h=1.575 mm | h=0.787 mm | h=1.575 mm |
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to 7.5 GHz, and the system was previously calibrated using a coaxial calibration kit and the SOLT routine.

Fig. 14 shows the measured $|S_{11}|$ response, compared to the simulation prediction, of two arrays with different substrate thicknesses. The important figures of merit deduced from these experimental data are listed in Table 2.

The gain patterns of the two proposed arrays were measured in an anechoic chamber, as shown in Fig. 15. To determine the gains, the method proposed in [24] was followed. The results of the measured gain, compared to simulation, are shown in Fig. 16.

Experimental and simulation results show very good concordance, principally due to the fact that simulations included as many parameters as possible, such as copper resistivity, metal surface roughness, losses, and dielectric anisotropy, among others. The still apparent differences are attributed to the fabrication process, as chemical etching was used, with which features cannot be perfectly defined.

In any case, the fabrication results show that wide bandwidths can be achieved with the combination of techniques used for these arrays, attaining over 600 MHz for the 0.787 mm thick substrate. Moreover, a size reduction of 31.52% for the 0.787mm substrate, and of 30.12% for the 1.575mm one, when compared to an ordinary array, can be achieved with this combination of techniques. Other figures of merit, listed in Table 2, are very close to the expected values. We note here that the experimental efficiency was not measured directly, but calculated from the experimental gain and the simulated directivity.

**IV. DISCUSSION**

Experimental results are very close to the predictions obtained from simulation, especially considering that there are many manufacturing factors that cannot be reliably

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**TABLE 3. Comparison with other works (s = simulation; m = measurement).**

| Parameter              | [14]            | [11]            | [15]            | [25]            | [26]            | [27]            | This work (h=0.787mm) | This work (h=1.575mm) |
|------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------------|----------------------|
| Substrate              | $\varepsilon_r = 3.36$ h=0.508mm | $\varepsilon_r = 4.4$ h=1.5mm | $\varepsilon_r = 10.2$ h=1.28mm | $\varepsilon_r = 3.2$ h=3.064 mm | $\varepsilon_r = 2.2$ h=1.57 mm | $\varepsilon_r = 4.4$ h=1.6 mm | $\varepsilon_r = 2.2$ h=0.787 mm | $\varepsilon_r = 2.2$ h=1.575 mm |
| L x W (mm²) (total)    | 33 x 26         | 105 x 165.5     | 27 x 36 (only patches) | 21.6 x 21.6     | 40 x 40         | 64 x 48         | 50 x 54               | 50 x 54               |
| $|S_{11}|$ @ 5.8 GHz (dB) | -24 (s)         | -31.42 (s)      | -14 (s)         | -22 dB (s)      | NA              | NA              | -24.11 (s)            | -34.41 (s)            |
| Gain @ 5.8 GHz (dBi)   | 6.40 (s)        | 6.51 (s)        | 6.20 (s)        | 6.60 (s)        | 4.97 (s)        | 4.63 (s)        | 6.89 (s)             | 7.63 (s)              |
| Bandwidth (MHz)        | 78.30 (s)       | 380 (s)         | 260 (s)         | 140 (m)         | 3,300 (m)       | 480 (s)         | 458 (s)              | 455 (s)               |
| Directivity            | NA              | NA              | NA              | NA              | NA              | NA              | 7.1 dBi (s)           | 7.80 dBi (s)          |
| Radiation efficiency   | NA              | NA              | NA              | 1.0 (s)         | 0.7 (s)         | NA              | 0.97 (s)             | 0.97 (s)              |
| VSWR @ 5.8 GHz         | 1.134 (s)       | 1.055 (s)       | 1.498 (s)       | 1.259 (m)       | NA              | NA              | 1.132 (s)            | 1.038 (s)             |

**FIGURE 12.** Fabricated antenna arrays on DiClad 880 with thickness (h) of (a) 0.787 mm, and (b) 1.575 mm.
FIGURE 13. Laboratory setup showing the VNA (Vector Network Analyzer), the coaxial calibration kit, and the measured arrays.

FIGURE 14. Simulated and experimental return losses for the two proposed arrays. (a) $h = 1.575$ mm, and (b) $h = 0.787$ mm.

FIGURE 15. Setup in anechoic chamber to measure the gains of the proposed arrays.

included in simulation, such as dimension variations due to the transfer and etching process, slight changes in permittivity and geometry with temperature, metal thickness, and many more.

FIGURE 16. Comparison of the simulated and measured gains for the arrays on the E-Plane and at $f = 5.8$ GHz. a) $h = 0.787$ mm, b) $h = 1.575$ mm. The gain scale is in dBi.

Notwithstanding, the figures of merit shown in Table 2 for these arrays indicate that they are feasible, and can meet a host of applications designed to operate about the 5.8 GHz ISM band. The measured bandwidth for the arrays built on the $h = 0.787$ mm substrate is 617 MHz (from 5.503 to 6.12 GHz, or 10.63%), whereas that of the $h = 1.575$ mm substrate is 455 MHz (5.517 GHz to 5.972 GHz, or 7.84%). Both present adequate gains; furthermore, their size is smaller than when compared to a traditional microstrip array for the same central frequency, as illustrated in Fig. 17.

Due to the importance of this frequency range, many works have been published in the last few years. To place this work in context, Table 3 presents a comparison of ours with some others, all designed to operate at the frequency of interest. The arrays presented in this work achieve higher gain...
and bandwidth than most (with the notable exception of the one reported in [27]), and still maintain a relatively small footprint.

V. CONCLUSION

Herein we have shown that with a judicious combination of several reported techniques, the performance of antenna arrays on microstrip can be greatly enhanced. The use of cavities on the top plane, as well as resonant slots on the back one (DGS) led to arrays operating at 5.8 GHz with wide bandwidths, acceptable gains and simulated efficiencies higher than 90%, while at the same time obtaining a size reduction better than 30%. These arrays can cover connectivity needs about the 5.8 GHz range, such as ISM, Wi-Fi, and future IoT applications.

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