Conformal antenna array for communications in millimeter waves

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Abstract—Planar and conformal antennas are described and analyzed. Transmission line model is explained as well as the properties of the substrate, and possible types of feeding methods. Regarding the deformable antennas, the cylindrical aggregated patterns were addressed.

A conformal microstrip array is designed and tested, operating in the ISM band, with the frequency of 58.8 GHz. This array was made up of a grid of four rows consisting of four elements each, being series fed in a center line feed structure. Two substrates were chosen, Taconic (TLY-5) and Kapton, to be analyzed and compared in relation to the project efficiency. In order to do this, the S parameters, the radiation pattern and efficiency were analyzed. After choosing what suits best to the desired settings the cylindrical array was then tested, first in a free space environment and then with the presence of an insulating material in order to prove the feasibility of the initially proposed work.

Keywords: Antenna arrays, Conformal antennas, Cylindrical array, ISM Band 58.8 GHz

I. INTRODUCTION

A conformal antenna is an antenna that can be adapted to something, either a structure or a certain desired shape. Since we can replicate the shape of an object it is then possible to integrate these antennas on a plane, in a high-speed train or other vehicle without the latter being affected. Another application can also be to make the antenna not visible to the naked eye, for military applications, for example.

The field of antenna arrays was a very active research area since World War II until about 1975. During this period, developed a great amount of work regarding conformal antennas was produced. However, it was not possible to find widespread use for them until it was possible to feed and monitor.

Integrated circuit technology (IC), including Monolithic Microwave Integrated Circuits (MMIC) came to fill the gap, providing reliable technical solutions with a low cost potential, even in aggregates very complex antennas. An important factor was also the development of digital processors that they could deal with the huge increase in the rate of information provided by the phased array systems. Thus, digital processing techniques to become profitable antennas aggregated systems.

In the last 10 to 20 years, numerical techniques, electromagnetic methods of analysis and understanding of antennas on curved surfaces have improved greatly. Important advances have been made in high-frequency techniques, including surface wave diffraction analysis and modeling of radiation sources on curved surfaces.

II. ANTENNA ARRAYS

A. Definition of array

An antenna array is a set of N individual antenna elements. This value of N ranges from 2 to several thousand. The main reason for using this setting is the ability to analyze not only the frequency band, but also the coverage area without compromising the overall size of the system. Based on different spatial distributions of elements and applying the added signal processing units, the latter can offer superior performance in terms of bandwidth and directivity when compared to a single antenna.

There are three major possible configurations: linear, for only one dimension; planar if the antenna take up two axes; or conformal, which is three dimensional and will be the major focus of this work.

Irradiated fields from linear array is a superposition of radiated fields for each element in the presence of others. Each element has an excitation parameter stream for serving a dipole and a slot for the voltage. The excitement of each element is a complex number, with amplitude and phase. This discrete distribution is called a distribution aperture, wherein the matrix is aperture.

B. Microstrip antennas

The microstrip structures are made of a thin sheet of low loss insulation material called dielectric substrate. The ground plane is composed of metal and covers the entire side of the structure while antenna circuit, called patch, will partly cover the opposite side, where it is printed.

The patch has a metal tape thickness of \( t \ll \lambda_0 \), which is spaced from the ground plane by a distance \( h \), usually in the range of \( 0.003\lambda_0 < h < 0.05\lambda_0 \). For rectangular antennas, usually the length \( L \) lies in the range of \( \lambda_0/3 < L < \lambda_0/2 \). As mentioned, the dielectric substrate makes the separation between the patch and the ground plane, and has a permittivity \( \varepsilon_r \) and thickness \( h \). These characteristics can be seen in Figure 1.
The most popular forms of patches are rectangular and circular because of the simplicity in the analysis and manufacturing, as well as its features and efficient radiation. These antennas have a wide range of advantages, such as its easy adaptation to planar and non-planar structures, its simple execution, lightness and low manufacturing cost. Thanks to these advantages the microstrip antennas have found various applications, particularly in mobile communication stations, satellite communications systems and even mobile phones.

### C. Transmission line model in a rectangular patch

There are several analysis methods for microstrip antennas, the most popular being the line transmission method, cavity and also the full wave method. The transmission line method is the simplest method and therefore was chosen to describe and analyze the patch. The patch used in the simulations will be rectangular as it is, as mentioned above, one of the most used settings and is easy analysis using transmission line method.

Since the dimensions of the patch are finite in length and width, the fields in the corners of the patch will suffer from the fringing fields, i.e., the opposition from the magnetic surfaces. This effect reflects on the patch dimensions and the substrate height. For the main plane (XY plane) the fringing effect is a function of the effective dielectric constant and the width to height ratio $(W/h)$. A practical way to demonstrate the value of the normalized length is

$$\frac{\Delta L}{h} = 0.412 \left( \varepsilon_{\text{eff}} + 0.3 \right) \left( \frac{W}{h} + 0.264 \right) $$

(2)

Since the patch size was extended on each side, the effective length of the patch is given by

$$L_{\text{eff}} = L + 2\Delta L$$

(3)

For the dominant $TM_{010}$ mode, the resonant frequency is given by

$$f_{r0} = \frac{1}{2L \sqrt{\varepsilon_{\text{eff}} \mu_{0} \varepsilon_{0}}} = \frac{c}{2L \sqrt{\varepsilon_{r}}}$$

(4)

Since this expression does not take into account the fringing effect it should be modified to include the effects on the edges and should be changed to,

$$q \frac{c}{2L \sqrt{\varepsilon_{r}}}$$

(5)

Where,

$$q = \frac{f_{r\text{h}0}}{f_{r0}}$$

(6)

The actual length of the patch can be computed by solving equation (5),

$$L = -2\Delta L \frac{1}{2f_{r} \sqrt{\varepsilon_{\text{eff}} \mu_{0} \varepsilon_{0}}}$$

(7)

To have an efficient radiator, we have the following width expression that leads to good radiation efficiencies,

$$W = \frac{1}{2f_{r} \sqrt{\mu_{0} \varepsilon_{0}}} \sqrt{\varepsilon_{r} + 1} = \frac{c}{2f_{r} \sqrt{\varepsilon_{r} + 1}}$$

(8)

### D. Feeding of planar antennas

The transfer of energy between the source and the radiating element is a key issue in the planar antenna specification. In order to obtain maximum energy efficiency input impedance should have a good relationship with the source or with the transmission line impedance, ideally 50 $\Omega$ (typical value output impedance of the power supplies). Thus, to minimize reflected power and make the reflection coefficient close to zero, the antenna input impedance should be very close to 50 $\Omega$.

In this project it was used the microstrip line type feeding. Using this technique it is possible to feed the antenna using a characteristic impedance line designed to relate to the source impedance. Both the line and the antenna are supported by the same dielectric substrate, making the antenna seem like a natural extension of microstrip line.
E. Feeding architecture

Antenna arrays are highly versatile and are used, among other things, to achieve patterns which could not be achieved with a single antenna element. They can be arranged as a series or parallel power supply.

In a series power feeding architecture several elements are arranged linearly in series and fed by one transmission line. It can have two different configurations: in-line feed, where all the elements are aligned, from feed point to the termination, and also out-of-line feed, where some or all elements are not aligned with the defined transmission line.

There is also the possibility of having series feeding arrays with two dimensions. A series fed array can be classified into two types, a resonance array if the termination is a short circuit or an open circuit, or a phase wave array if to the feed line is terminated with a matched load. On the other hand, a parallel two dimensional feeding is also possible. In this case, with symmetrical or asymmetrical configuration. The latter feeding type is also called corporate feed, because a network is used to provide power division with order $2^n$ (i.e., $n = 2, 4, 8, 16, 32$, etc.).

Finally, there is also the possibility where the feeds are coupled in parallel and in series. These are referred to as hybrid feeds and give the opportunity of balancing the bandwidth and insertion losses. With this configuration larger bandwidths are achieved. However, it is also evident that, having a parallel parallel feed, the hybrid assembly insertion losses will be greater than a purely series fed array.

F. Deformable antennas

An essential part of an array is its curvature. The shape of the array can be classified in two different ways, taking into account the radius of curvature of the surface in which it is inserted. When the conformal array occupies only a small portion of a curved body and has a much smaller opening size than the surface curvature radius, conforming effects are felt only in terms of patterns and excitation and not at the impedance level. In such cases the whole unit may be considered as planar, but with a conformal phasing. On the other hand, arrays that are considered large in comparison with the surface radius of curvature are designated individually curved or doubly curved, such as ring-shaped or cylindrical arrays. The latter, due to their complexity and the potential level of sizes, shapes, and types of elements requirements are more challenging to analyze.

G. Cylindrical and circular array patterns

Circular and cylindrical arrays have the advantage of being symmetrical in the azimuth, which makes them ideal for a full 360° coverage. This same advantage has been exploited for the development of transmission antennas and direction-finding antennas. In the Figure 3, a group of elements arranged in the circle is displayed. The pattern for a circular aggregate (or ring), with radius $a$, consisting of $N$ local elements $\phi = n \Delta \phi$ is given by,

$$ r_n = R_0 - a \sin \theta \cos (\phi - n \Delta \phi) $$

Where $R_0$ is the required distance in which the far field approach can be used, given by

$$ R = 2L^2 / \lambda $$

Which results in the pattern,

$$ F(\theta, \phi) = \sum_{n=0}^{N-1} I_n f_n(\theta, \phi) e^{j \beta \sin \theta \cos (\phi - n \Delta \phi)} $$

(11)

As can be analyzed in Figure 3, all integral elements of the array are considered identical, symmetrical and are equally spaced and distributed along the radius. Thus, the pattern element in azimuth can be expressed as a function of $[\Phi - \beta]$. This pattern is dependent on elevation angle $\theta$. Assuming that the phase center is located in the element the gain is given by,

$$ G(\phi - \beta, \theta) = |G(\phi - \beta, \theta)| \exp \left[ j k \cos \theta \cos (\phi - \beta) \right] $$

(12)

And the far field is given by,

$$ E(\phi, \theta) = \sum_{r} \sum_{n} I_n G(\phi - \beta_r, \theta) \exp (j qu) $$

(13)

Where $u = kd \sin \theta$ and $d$ represent the spacing between elements in the axial direction.

III. DESIGN OF A CONFORMAL ARRAY

A. Design of a planar element

In order to proceed with the simulation of the desired design of an antenna array we will initially measure and analyze in detail only a planar element design, comparing different types of possible substrate and the structure to be used to maximize the antenna.

Thus, to calculate the width of the patch the expression (8) was applied. For the length was used (7) and the for effective dielectric constant (1).

We then defined an element consisting of a linear array of planar patches shown.

Then a working frequency band of 58.8 GHz was set up since with this band with 5 mm of free space wavelength the antenna structure can be physically small. The width of 9
GHz band available in the range of 58.8 GHz provides a high data rate and a possibility to avoid co-channel interference.

B. Choice of substrate

In order for a substrate to provide support to an antenna on a cylindrical surface it is essential to have good flexibility. Initially we analyzed the Taconic substrate (TLY-5) because of its low losses and good flexibility. This substrate consists of PTFE glass fabric coated by a resin layer. It is also chemically inert and has high tensile strength. It is easy to see that it grants low losses at high frequencies and small values of dielectric permittivity.

In a second phase of the simulations, Kapton substrate was chosen and the logical comparisons were made between the two types of materials in order to conclude which one was most suitable for the final simulations. This film, developed by US Company DuPont, has a set of features that make this ideal for a variety of applications in different industries.

Table 1 show some of its physical, chemical and electrical proprieties that were used in the simulations performed in CST Microwave Studio software. The values for Kapton are for 3 GHz frequency. From this, it was extrapolated to 58.8 GHz.

<table>
<thead>
<tr>
<th></th>
<th>Taconic (TLY-5)</th>
<th>Kapton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>0.127</td>
<td>0.05</td>
</tr>
<tr>
<td>Dielectric loss tangent</td>
<td>0.0009</td>
<td>0.002</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Maximum operating temperature</td>
<td>-75 a 260 ºC</td>
<td>-269 a 400 ºC</td>
</tr>
</tbody>
</table>

Table 1 - Characteristics of Taconic and Kapton substrates

C. Design of a planar array

To study the two-dimensional array formed by planar elements a 4x4 mesh was used, series fed, as shown in Figure 5. In order to get the correct design for the proposed problem the transmission line model on a rectangular patch was used.

From the design of the planar element in IIIA., the problem was escalated for an array we come up to the values shown in below.

As mentioned before, microstrip line feed was chosen. In this type of technique, a conductive strip is connected directly to the microstrip patch edge. The conductive tape is considerably smaller in width compared with the main patch, and can be implemented directly on the substrate.

Within this type of feed we opted for a central line feed, placing the conductive strip in the center of the patch.

D. Numerical simulation

With Taconic substrate (TLY-5) the reflection coefficient has a value of -37.2 dB, lower than the -34.2 dB obtained with Kapton substrate, thus ensuring lower power reflection values for the antenna. With Taconic substrate obtained also, to close, a larger bandwidth.

A shift in the frequency range can be seen. For the case of Kapton, due to its features, flexibility and a higher electrical permittivity, this difference was even more pronounced, thanks to the even more intense "fringing fields" that are felt at the antenna neighborhood.

Thus, it can be said that the reference element for Taconic is adapted to the frequencies between 57.72 and 58.4 GHz, while the Kapton is adapted to the frequencies between 55.45 and 55.85 GHz. Although both are not in the desired working frequency the Taconic showed a better suitability for the final conformal structure.

E. Radiation patterns

The radiation pattern is a graphical representation of the variation and defines the energy that is radiated by an antenna in the far zone of the antenna. This power variation as a function of angle of arrival is observed in the far field of the antenna.

There are several plans that can be used to analyze these patterns. For the simulations the following were used

- Horizontal plane (XY): Phi=0º, with Theta angle variation
- Vertical plane (YZ): Phi=90º, with Theta angle variation
- Vertical plane (XY): Theta=90º, with Phi angle variation
Taconic (TLY-5) Simulations

![3D Diagram](image)

a) 3D Diagram

![Polar representation](image)

b) Polar representation

**Figure 7 - Gain in logarithmic units (ABS)**

Kapton Simulations

![3D Diagram](image)

a) 3D Diagram

![Polar representation](image)

b) Polar representation

**Figure 8 - Gain in logarithmic units (phi)**
Analyzing the radiation pattern is easy to see that these are directional diagrams, or are diagrams symmetrical in the XY plane. This is largely due to the symmetry of the array structure, with XY symmetry, as visible in Figure 5.

The values of the gain, directivity, power and electric field are in accordance with expected, taking positive values in zones close to the center power feed line chosen, dispersing as the current propagates through the elements. The properties of the Taconic substrate caused these parameters to concentrate their maximum values in the center of the patch. Instead, with the Kapton substrate, the electric field, the power and the gain showed a much more dispersed behavior and showed maximum values along the supply line (x = 0).

As noted in Table 2 shown below the Taconic substrate topped Kapton in all analyzed aspects in the simulations, presenting itself as the most efficient solution. Despite having more than twice the thickness as Kapton, Taconic can compensate for this thanks to better values of dielectric permittivity and dielectric loss tangent.

When an antenna is not tuned with the receiver the energy is reflected. This gives leads to a “reflected wave voltage”, which creates standing waves along the transmission line. It is possible, analyzing the results of simulations for both substrates to realize that they have quite different behaviors thanks to the different frequencies in which they operate and their properties.

The VSWR ratio directly relates to the reflection coefficient and is defined by,

$$\text{VSWR} = \frac{V_{\text{max}}}{V_{\text{min}}} = \frac{1+|S_{11}|}{1-|S_{11}|}$$

For Taconic standing wave ratio reaches the lowest value, and therefore has a better adaptation - VSWR=1 - to the 58 GHz frequency, and is very close to the value we intend to study and optimize. With Kapton, VSWR reaches the lowest values for 55.75 GHz and 58.6 GHz, revealing a big shift in the optimal frequency. For the frequency we are running, it takes approximate value of 3. That is an acceptable value however it shows that there is a reflected power of -6 dB, leading to an approximate loss of 25% of the power that is initially generated.

Therefore it is possible to conclude that for this type of project the Taconic substrate is more efficient than the Kapton and will used for conformal simulations displayed next.

F. Cylindrical conformal array in free space

The first case study involves characterizing the conformal array behavior in a free space environment (Figure 13). The cylinder has been filled with a PEC (perfect electric conductor) material for that purpose. Several curvature radius of the cylinder will be tested and the results will discussed. For these simulations a frequency domain solver was used.
The curvature radius was analyzed from 5mm to 10mm, with 1mm intervals. The reflection coefficient is shown above.

**Table 3 - Parameter values for the cylindrical array at 58.8 GHz**

<table>
<thead>
<tr>
<th>Radius [mm]</th>
<th>$S_{11}$</th>
<th>Maximum surface current [A/m]</th>
<th>Radiation efficiency [%]</th>
<th>Global efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-15.98</td>
<td>1296</td>
<td>97.04</td>
<td>95.56</td>
</tr>
<tr>
<td>6</td>
<td>-18.00</td>
<td>1716</td>
<td>97.61</td>
<td>96.07</td>
</tr>
<tr>
<td>7</td>
<td>-18.32</td>
<td>1665</td>
<td>97.86</td>
<td>96.42</td>
</tr>
<tr>
<td>8</td>
<td>-19.02</td>
<td>2774</td>
<td>97.87</td>
<td>96.65</td>
</tr>
<tr>
<td>9</td>
<td>-19.0</td>
<td>2074</td>
<td>96.64</td>
<td>95.43</td>
</tr>
<tr>
<td>10</td>
<td>-18.74</td>
<td>2765</td>
<td>95.39</td>
<td>94.12</td>
</tr>
</tbody>
</table>

To the chosen frequency, 58.8 GHz, and as can be seen in Table 3, the cylindrical array with $r = 8\text{ mm}$ radius has proved the most effective in all parameters. Thus, the results will be studied in greater detail for the most effective case, $r = 8\text{ mm}$.
The above results are in accordance with what was initially expected. The optimal working frequency, analyzing the reflection coefficient chart for 8mm radius (Figure 14), is between the 58.43 and 59.17 GHz, with peak efficiency at 58.84 GHz, -19.38 dB. We therefore consider the selected frequency of 58.8 GHz as very close to the project goal.

For these simulations we obtained a radiation efficiency of 97.87% and an overall efficiency of 96.65%. This radiation efficiency concerns the relationship between the power absorbed by the antenna and the power that is radiated while the overall efficiency takes into account the effects of maladjustment and antenna dissipation. Finally, a realized gain of 35.5 (15.5 dB) was obtained alongside with a maximum power of 2,828 W/m². We consider these results very satisfactory and with room for a possible execution.

G. Cylindrical conformal array in a dielectric structure

A dielectric material is a substance that is an electrical insulator but offers effective support to the electrostatic field. If such material experiences the action of an electric field above its rigidity levels, it allows the flow of electric current.

For the choice of dielectric layer surrounding the array, the relative parameters of the electric and magnetic permittivity, \( \varepsilon_r \) and \( \mu_r \), must be defined. In order to be able to simulate an insulating layer, a traditional rubber was chosen with values of \( \varepsilon_r = 3 \) and \( \mu_r = 1 \). Again, the simulation was done using a "solver" in the frequency domain.

The above results are in accordance with what was initially expected. The optimal working frequency, analyzing the reflection coefficient chart for 8mm radius (Figure 14), is between the 58.43 and 59.17 GHz, with peak efficiency at 58.84 GHz, -19.38 dB. We therefore consider the selected frequency of 58.8 GHz as very close to the project goal.

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As one would expect with the use of an electrical insulator, particularly rubber, there has been a natural decline in the array global efficiency. However this slight drop did not prove to be significant. Despite the decrease in the directivity from 15.7 to 15.3 dB, there gain reveals a different output, showing a slight increase, from 15.5 to 16.1 dB. As expected, both parameters reach minimum values inside the structure due to the lack of conductivity of the latter. The radiation efficiency has a value of 95.43% and the global efficiency is at 93.22%. The maximum power displayed in the simulation was 2,416 W/m².

The reasons behind this small drop in overall performance is mainly due to the surrounding of the ground plane - copper - and the Taconic substrate, both with considerable thickness compared to the global size of the project, and with also good conductive properties. Thus, despite the visible differences in radiation patterns presented, it was possible to conclude that the initial goal set to apply this adaptive array to human skin is achievable and may therefore be subject to further future study in order to optimize and improve all the processes involved, from the mesh to the materials.

IV. CONCLUSIONS

The objectives and main scope of this project was to study an array, conformal to a cylindrical structure, operating in the 58.8 GHz band. With this configuration the goal was to apply the set of adaptable patch antennas on the human body, particularly on the wrist.

For this, a microstrip antenna study and design was conducted. Based on previous work, a linear array of planar elements was designed. After that, we resized the problem to a two-dimensional array of planar elements and finally to a cylindrical conformal array.

To optimize the problem, two substrates with different characteristics were tested, namely the Taconic and Kapton. The first proved to be the most efficient and the most suitable substrate for the desired project, showing the most favorable results in terms of gain, directivity and reflection coefficient. Therefore, Taconic was chosen for the final simulations with the cylindrical structure.

To get the ideal structure various simulations were conducted, initially within a free space environment in order to get the optimal cylinder radius. Then, a dielectric structure was applied and the appropriate comparisons were made.

In free space environment, simulated with a perfect electric conductor material, after analyzing the S11 parameters, the current surface and the radiation efficiencies, it is concluded that the most appropriate radius of the cylinder was 8mm. For this array we obtained a reflection coefficient of -19.02 dB, a gain of 15.5 dB and an overall efficiency of 96.65%.

Finally, in the last simulations a rubber was used to fill the cylinder with an isolating material. It was concluded that the rubber did not significantly affect the array overall performance - the structure efficiency has dropped only 3.43%, confirming why the feasibility of the proposed design.

Due to the small dimensions of the designed structure this may apply to a human finger. So that it can be adapted to a wrist, the mesh must be replicated proportionally, however at risk of compromising the overall efficiency

REFERENCES