DESIGN OF 5G MM-WAVE COMPATIBLE COVERS FOR HIGH END MOBILE PHONES

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Abstract

Next generation 5G networks will provide reliable high-speed data links between base stations and mobile devices. Base stations featuring antenna arrays with a large number of elements operating at high millimeter wave frequencies (e.g. 28 GHz) will use beam forming to allow efficient, targeted communication with mobile phone handsets. In the handsets themselves, the use of several small chip-integrated arrays in each device becomes feasible due to the small physical size of antennas at these high frequencies.

Spatial and material constraints make the integration of such antenna arrays into mobile phone handsets challenging. Chip based arrays may be accommodated below the back cover of the device, which, for high-end phones, may be made of metal or glass. A metal cover would act as a very effective shield, preventing communication entirely. Glass may allow electromagnetic energy to propagate through it, but its electrical thickness at high mm-wave frequencies may influence the array performance substantially.

This paper investigates approaches for the design of the back cover of a mobile phone when integrating a chip based antenna array by providing adequate scanning behavior across the frequency of interest. The methods and constraints described here will allow 5G antenna engineers to suggest mechanical and electrical designs that will work optimally to provide the efficient high data-rate connections that users require without sacrificing aesthetics and the tactile experience while handling the device.

The phone backing is treated here as a radome, and radome techniques commonly used in aerospace applications are applied. For dielectric materials, the enclosure design has to take into account the material properties and thickness of the cover. For the example of a metal-backed phone, a loaded radome incorporating a frequency selective surface (FSS) is designed and integrated in the phone cover, allowing electromagnetic radiation to pass in the frequency range of interest.

1. Introduction

5G connectivity will make use of millimeter wave technology (at frequencies above 20 GHz) to allocate more channels and alleviate the ever increasing demand of wireless capacity. The smaller wavelengths at mm-wave frequencies results in smaller antennas, arrays of which can be installed in compact end user devices like

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mobile phones. Beam steering of such small arrays is a key enabler of the 5G vision, since it allows the device to select the best direction to establish communication with another device or base station, while improving the link budget by making a more focal usage of the radiated power.

The mm-wave antenna module can be manufactured in a package which integrates both the small antenna array and the radio frequency front-end. This antenna-in-package design (AiP) approach mitigates the high losses in the transmission lines at high frequencies [1-2].

AiP modules can be produced at scale and can in principle be installed in any device. In this paper we handle the integration scenario in which the antenna module is designed in-house and intended to be used in a range of products, or bought as a components-off-the-shelf (COTS) from a supplier. In the millimeter frequency range the enclosure found in most consumer electronic devices is too thick to be ignored. In Figure 1 the transmission characteristic of a dielectric slab is shown as a function of its thickness in wavelengths.

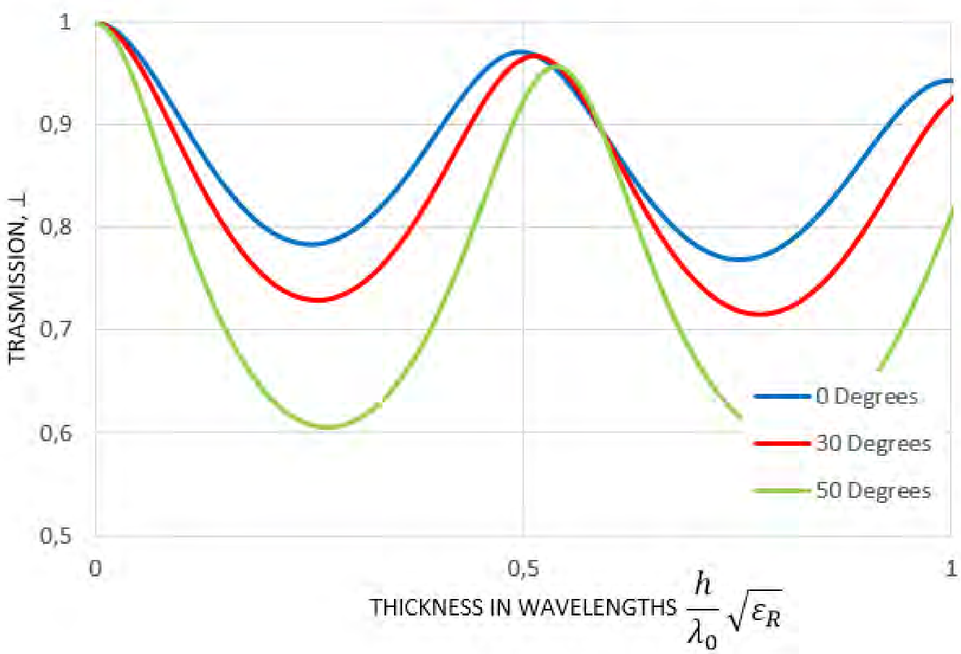

Figure 1: Transmission characteristic of a dielectric slab with thickness, h, and permittivity ε_R, for different angles of incidence, as a function of the slab thickness normalized by the wavelength inside the material.

As an example, we can consider the back of a modern mobile phone to be made of glass with a permittivity of 6.84. At 28 GHz the optimum thickness for maximum transmission – about half a wavelength, depending on the scanning angle – would be 2.05 mm. If the total thickness of the device is around 8.0 mm, this optimum design thickness would certainly be too bulky to be of practical use.

In this paper we address the integration problem by applying radome design techniques to a high-end phone back cover. For thedielectric cover, or monolithic radome designs, we provide a set of equations that can be used to support the material and thickness selection. For the metal back, an electromagnetic window is designed using FSS technology commonly found in loaded radome designs for the aerospace industry [3].

2. The dielectric cover

The dielectric cover can be divided into two categories: *thin* radomes and *thick* radomes. Thin radomes are characterized by a dielectric slab not thicker than 10% of the wavelength of interest. For our glass backed phone example, being *thin* would require the radome to have maximum thickness of 0.65 mm. A cover this thin may lack the mechanical toughness to be used in the phone. Thick radomes, on the other hand, are designs in which the dielectric slab has multiples of half of the wavelength of interest. If h is the optimum thickness, the design equation is given by [4]

Equation 1

$$h = \frac{n\lambda_0}{2}\frac{1}{\sqrt{\epsilon_r - \sin^2\theta_i}}; \quad n = 1, 2, 3, \ldots$$

In Equation 1, n is the order of the radome and θ_i is the angle of incidence. In general, the first order thick radomes are preferred. We can also re-write Equation 1 to find the optimum ϵ_r values if the thickness h is given.

Equation 2

$$\epsilon_r = \frac{\lambda_0^2}{4h^2} + \sin^2\theta_i$$

From Equation 1 and 2 we can conclude that:

- for a design with constant permittivity, the higher the permittivity the smaller is the optimum thickness dependency to the incident angle;
- for a design with constant thickness, the lower the design thickness the higher is the required permittivity.

To better visualize those results Figure 2 shows the thickness and permittivity for optimum transmission properties given three different materials and three different design thickness, respectively.

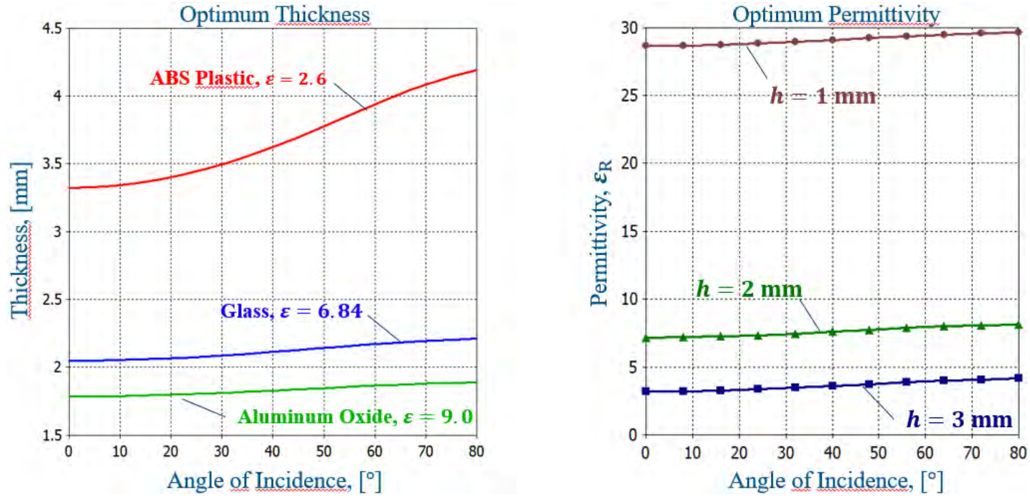

Figure 2: (left) Optimum transmission thickness as a function of the incident angle for ABS plastic (red curve), glass (blue curve) and aluminium oxide ceramic (green curve). (right) Optimum transmission material permittivity as a function of the incident angle for a material with 1 mm (brown), 2 mm (dark green) and 3 mm (dark blue) of thickness.

From Figure 2 we can see that back covers of a thickness between 1 and 2 mm thick would require the material permittivity to in the range of 8 to almost 30. This essentially excludes the usage of plastics like ABS, and calls for harder materials like ceramics.

3. The metallic cover

Ceramic monolithic radome designs might present a possible solution, but mechanical requirements may hinder their application. In older high-end mobile phones, metal back covers were widely used. Wireless communication was enabled by inserting dielectric slots to act as electromagnetic windows in the enclosure. The slots could also separate different regions of the metallic housing allowing the usage of the enclosure as an integrant part of the antenna design. At mm-wave frequencies the electromagnetic window can be realized by a frequency selective surface (FSS). The FSS is a 2D periodic structure which can be designed to be transparent in a given frequency band. frequency ranges.

The FSS loaded back cover is designed for an enclosure of 1 mm of thickness. The FSS layer has a thickness of 0.1 mm and is sandwiched between two layers of dielectric with a relative permittivity of 9. The same material composes the non-conductive areas of the FSS layer, as shown in Figure 3.

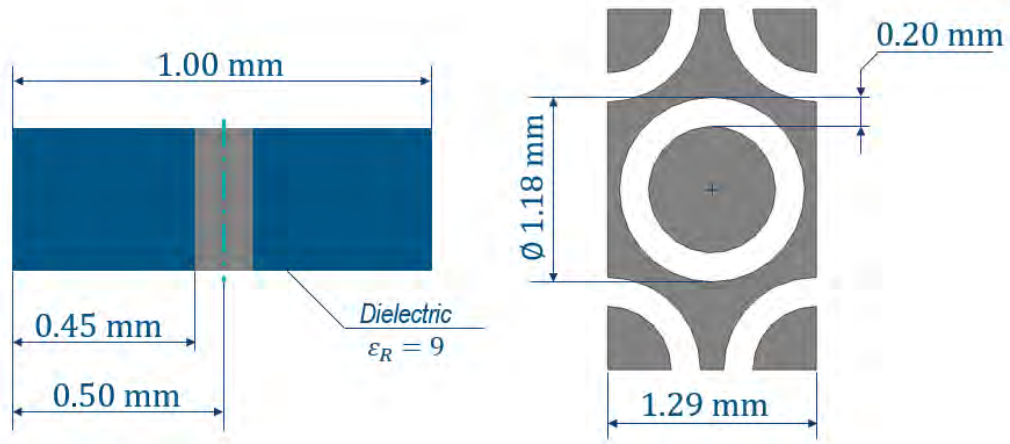

Figure 3: (left) View of the layers of the back cover. (right) view of the unit cell of the FSS design, the dimensions here shown are the final values of the design.

The chosen geometry for the FSS is a circular loop design, since it offers a more compact design and stability over frequency and angle of incidence. A triangular lattice is used to increase the density of elements, and by keeping the inter element distance small we avoid issues with grating lobes [3].

The FSS was optimized at unit cell level. For a ring dielectric width of 0.2 mm the goal function was

$$\begin{aligned} &\text{Return} < -10\ \text{dB} \\ &s.t. \quad 26.5\ \text{GHz} < f < 29.5\ \text{GHz} \\ &\qquad\ \ 0^\circ < \theta < 30^\circ \end{aligned}$$

The final geometry had a ring diameter of 1.18 mm and inter element spacing of 1.29 mm, as shown in Figure 3. The performance results for the return loss for both polarizations are shown in Figure 4.

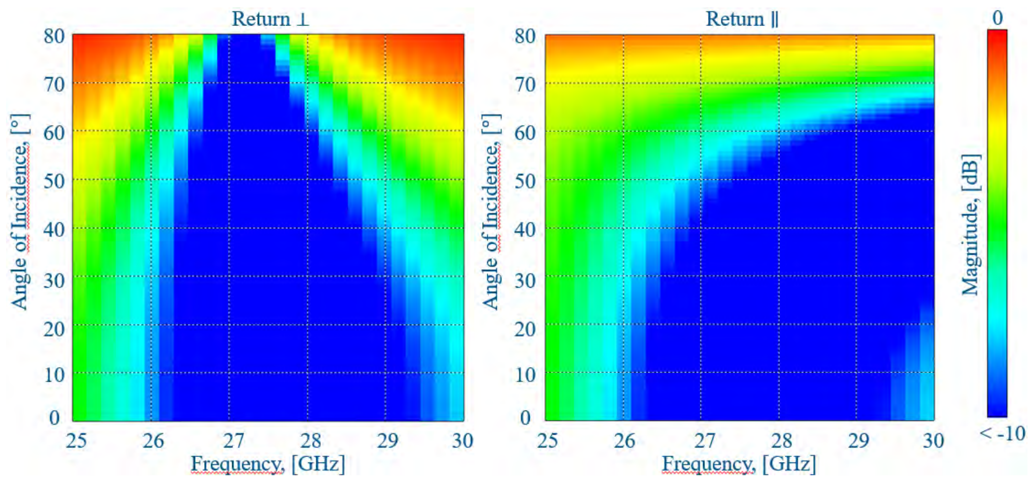

Figure 4: The reflection coefficient of FSS unit cell analysis is shown. In both graphs the vertical axis represents the angle of incidence and the horizontal axis represents the frequency, while the magnitude of the return loss is depicted by the color ramp. The left map shows the result

for the perpendicular polarization, and the right map shows the result for the parallel polarization.

4. Full model integration

The equations and statements provided thus far are derived from well-known practices for radome engineering, and thus assume that the radome is illuminated by a plane wave. In other words, they consider the radome to be in the farfield zone of the antenna: the gap between the antenna module and the back cover is assumed larger than 17 mm at 28 GHz. This condition is clearly not met in this application. Therefore, the full model integration should be an important step not just in the validation process, but also in the design to allow fine tuning of the design parameters.

The AiP used consists of a 2x2 array of stacked patch antennas designed to operate in the 26.5-29.5 GHz frequency range, and to steer the beam to +/- 30 degrees in both axes with dual polarization. It is square with a length of 10.71 mm along one edge. The module is installed in the upper right corner quadrant of the back of the phone, as shown in Figure 5, with a gap of 1 mm between the module and the cover.

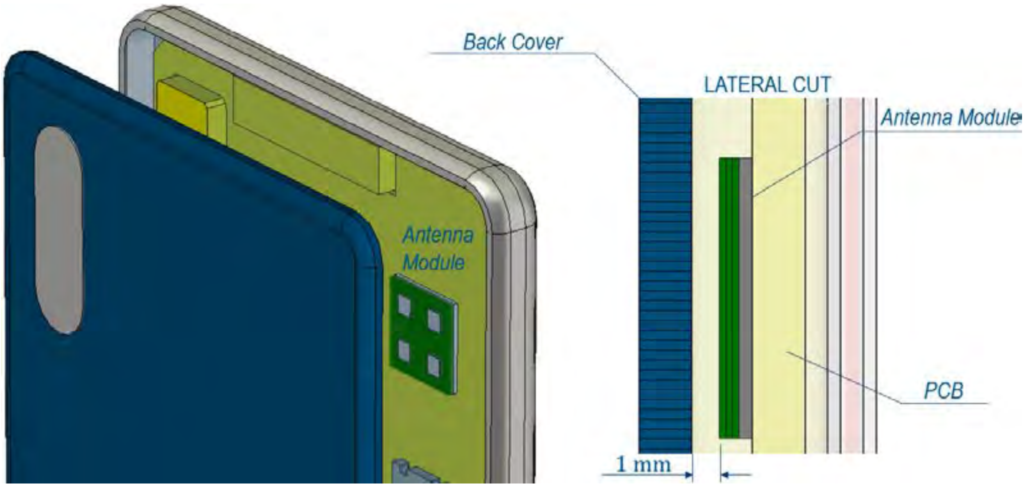

Figure 5: (left) Perspective view of the phone with the back cover lifted showing the position of the antenna module. (right) Lateral cut at the antenna module showing the stack up arrangement of the phone PCB, antenna module and the back cover.

In the monolithic radome design glass is used as the material. Instead of thickening the entire back cover, we borrow the idea of the electromagnetic window, and apply a local thickening to the region of the radome immediately above the antenna to achieve the required 2.05 mm of thickness (see Figure 6).

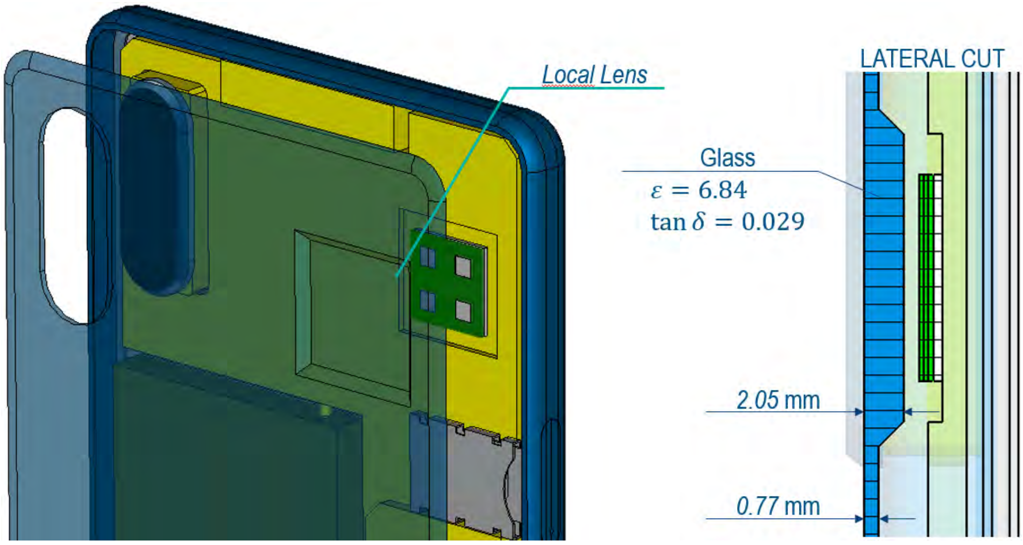

Figure 6: (left) Perspective view of the phone showing the local thickening of the glass back cover. (right) Lateral cut at the antenna module showing the stack up arrangement of the design.

The electromagnetic performance of this enclosure is sub-optimal. Although an improvement in the antenna matching and efficiency is observed, the radiation pattern is quite distorted by ripples (Figure 7), as part of the energy is guided inside the dielectric cover, or propagates along the surface of the PCB before being radiated.

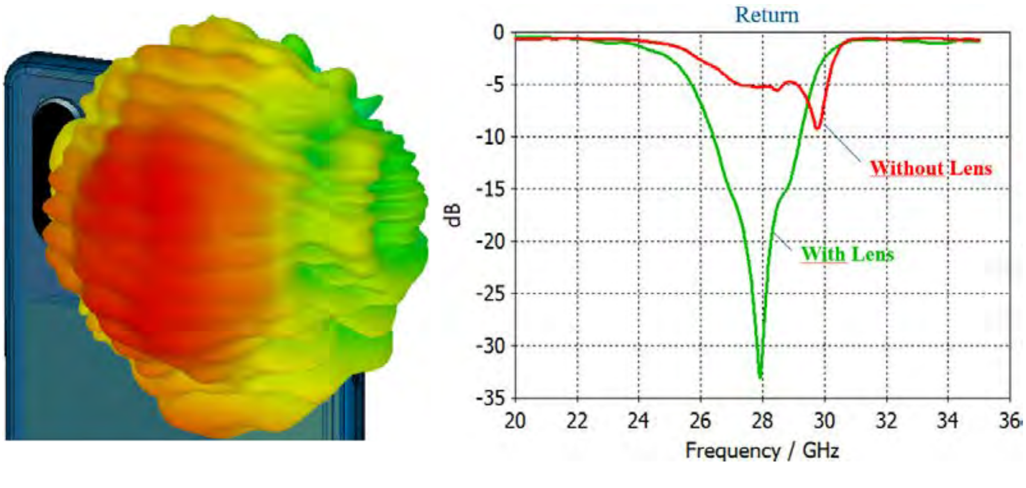

Figure 7: (left) Directivity pattern of the phone at the boresight, the rippled look of the pattern is due to part of the energy being propagated along the PCB surface and part being guided inside the dielectric. (right) Return loss response of the module with and without the local dielectric lens for a back cover with 0.77 mm thick glass.

For the metallic back, it was studied how big the FSS coverage should be, since the antenna module is more likely to be placed close to corners and edges which would limit the possible extent of the coverage. The three different coverage areas shown in Figure 8 were compared. The result of the different coverages for radiation pattern in the azimuth cut and antenna matching is shown in Figure 9. For this application, the FSS has to be at least slightly larger than the antenna footprint to perform adequately. The integration of the FSS in the phone's back cover provides an excellent electromagnetic window which allows the antenna module to radiate efficiently with the desired – almost ripple-free – farfield pattern shown in Figure 10.

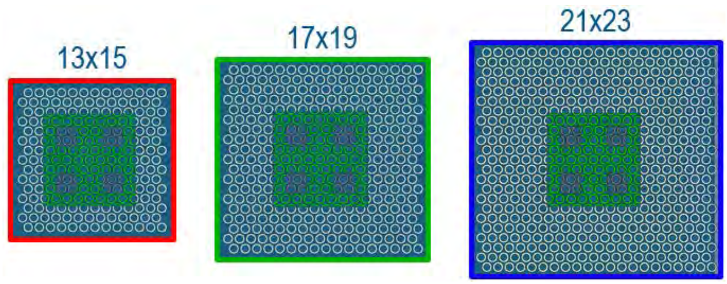

Figure 8: Size of the FSS coverage when compared to the antenna module in the background. Three configurations are used and the size of the ring matrix is shown above each FSS.

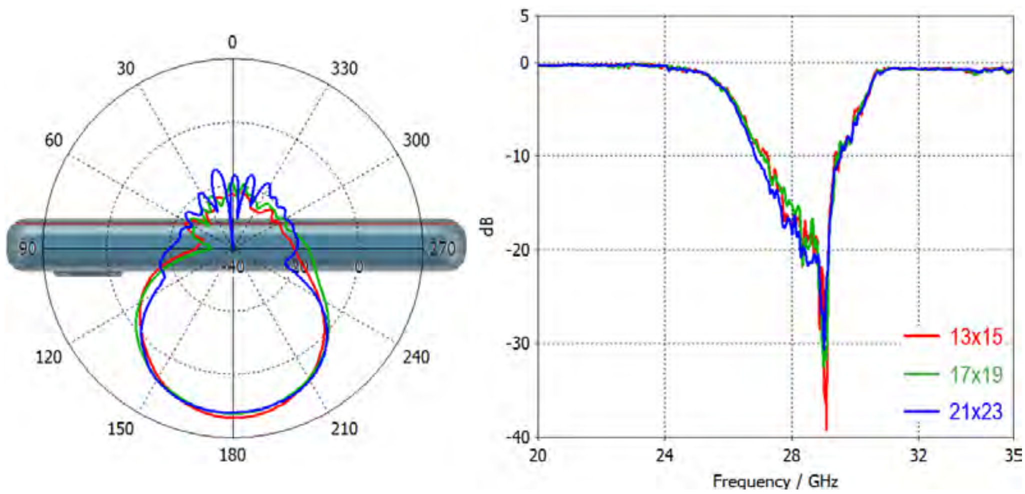

Figure 9: (left) Directivity pattern of the phone with FSS loaded metallic back for a boresight radiation at the azimuth plane. (right) Matching of the antenna module.

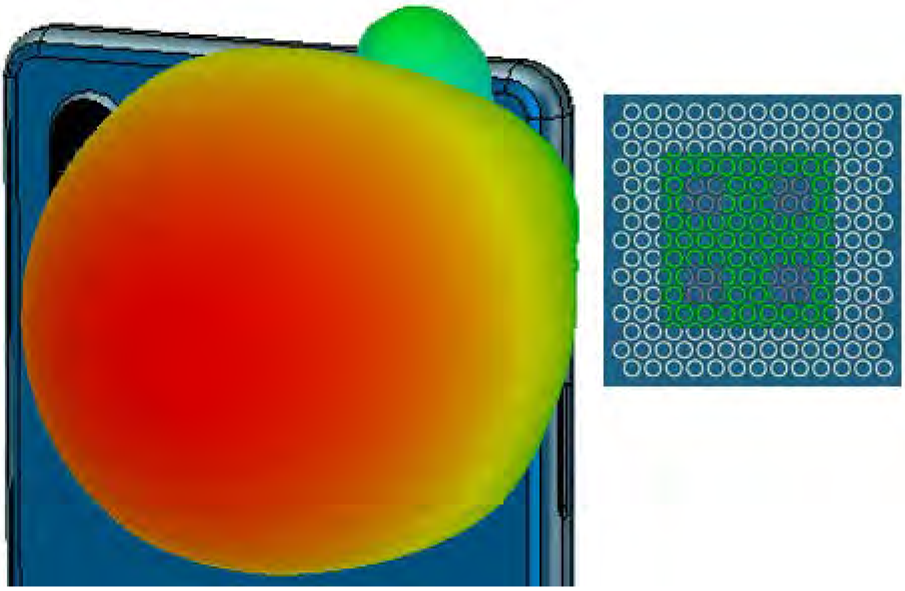

Figure 10: Directivity pattern in 3D for the phone with FSS with 13x15 elements loaded metallic back. The radiation pattern shown is for the boresight radiation, minimum distortion of the 3D pattern is observed, and the same holds when the beam is steered.

5. Conclusions

This paper focused on the problem of integrating an antenna-in-package module capable of 5G connectivity at 28 GHz inside a high end mobile phone. Radome techniques common in the aerospace industry were applied to the back cover design.

The monolithic radome design was found to be a sub-optimal solution for this application, since it produced a rippled radiation pattern. However, the applicability of dielectric enclosures cannot be completely discarded for all end user devices, since it has the potential to deliver the desired performance if the gap between the antenna module and the enclosure can be increased.

The metal cover loaded with an FSS is a promising solution, at least in terms of electromagnetic performance, since antenna matching and beam steering requirements can be met even for small gaps between the enclosure and the antenna module. This performance comes at the cost of design and manufacturing complexity.

6. References

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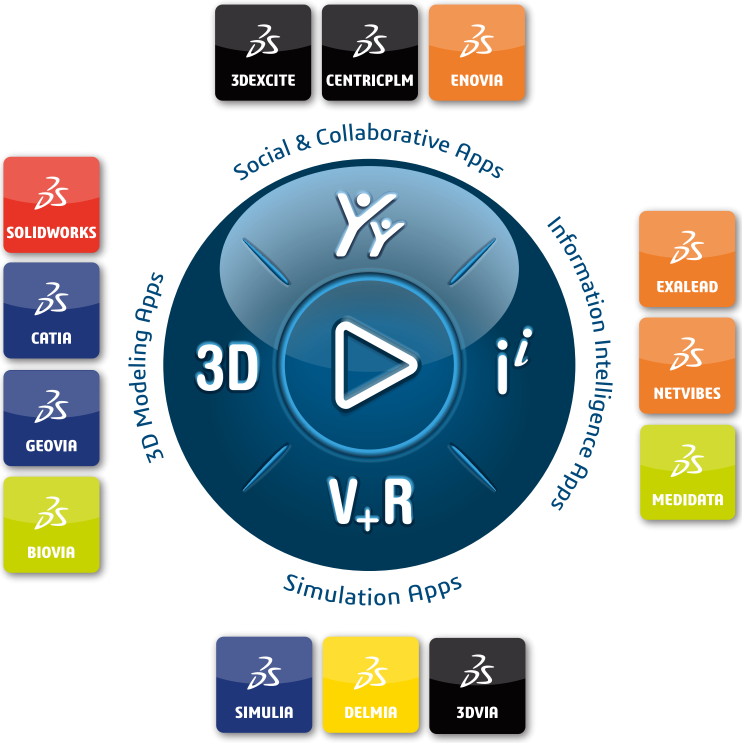

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