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(Article begins on next page)

Multi-resonant Unit Cell for Efficient Smart electromagnetic Skins

S. Ayaz, M. Beccaria and P. Pirinoli
Department of Electronics and Telecommunications, DET
Politecnico di Torino
Turin, Italy
shahid.ayaz@polito.it, michele.beccaria@polito.it, paola.pirinoli@polito.it

***Abstract*—Recently, passive Smart Electromagnetic Skins (SESs) have gained popularity for their capability to enhance the performance of a communication system without increasing its complexity. Since the focus was initially on the design of the structure at the whole, less attention was paid to the effects that the unit cell used for discretizing the surface itself has on the SES performance, just making a distinction between the use of resonant or sub-wavelength elements. Conversely, in this communication a multi-resonant unit cell is introduced and some preliminary numerical results on its application to the design of a smart skin are shown: they confirm its effectiveness and capability to improve the performance of the SES in comparison with other unit cells.**

***Index Terms*—5G, 6G, Passive Smart Electromagnetic Skins, Reflectarrays, mmWave communications.**

I. Introduction

In the recent years, Smart Electromagnetic Skins (SESs) have been emerged as one of the key-enabling technologies for the next generation of communication systems thanks to their capability of wave manipulation, that can be exploited to improve the coverage and to mitigate the path losses at millimeter and sub-THz frequencies without the introduction of new Base Stations (BSs) [1]- [3], or either to allow the system to facilitate other functionalities as indoor/outdoor localization [4]. This is possible because of the local properties of the surface, that is actually discretized with a suitable number of Unit Cells (UCs), having either a (almost) resonant or a sub-wavelength size. These considerations highlight the strong correlation between the performance of the SES and that of the adopted UC. As an example, it is possible to consider the case of a static SES [5]- [9], for the realization of which it is sufficient to use a passive cell, as opposed to the request of a dynamically reconfigurable smart skin [10], in which case it is necessary to introduce into the UC some controllable components.

However, despite of the strict connection between the SES and the unit cell, most of the work carried out in the past years were devoted to the design of the SES at the whole. Sporadic examples of activities focused on the unit cell are represented by [11], where a technique for the design of the "meta-atoms" used to discretize a SES is presented or by [5], [12], were suitable unit cells are discussed and applied to the design of smart skins. In most other cases, UCs have been derived from previous analyses of structures similar to SESs, as for instance ReflectArrays (RAs) if the surface is supposed to be discretized with resonant cells.

RA UCs have been thoroughly investigated and several solutions have been proposed with the aim of improving the reflectarray radiation characteristics. Different technologies has been proposed for their realization, including the use of single or multi-layer printed elements [13]- [24], eventually with complex shapes and several degrees of freedom, dielectric-only configurations, where the control of the reflection coefficient is achieved with perforations [25]- [28], variable-height blocks [29], [30], or exploiting dielectric resonator elements [31]- [32] or either metal-only structures, using as geometrical varying parameter different types of slots [33], [34], variable-size [35], [36] or waveguide-based elements [37]. However, their direct use in the design of a smart skin could not represent the optimal solution, for several reasons. First, either if they would be integrated in an indoor or outdoor scenario their footprint must be minimized: this means that multi-layer configurations or dielectric only solutions cannot be the best choices, since they are generally thick. From the point of view of the working principle, the main difference between a reflectarray and the SES consists in the fact that in the second case the reflecting surface is in the far-field region of the base station, and therefore the incident field can be modeled with a plane wave. Since the position of the BS is fixed as well as that of area to cover, the cells must be able to provide a satisfactory performance even under strong oblique incidence in order to guarantee that pointing in the correct direction and its good stability over the considered frequency range. Moreover, if the angles defining the pointing and incidence directions are very different from each other, i.e., they are very far from satisfying the condition of specular reflection, the re-radiation pattern is affected by the presence of lobes comparable with the main lobe that are due to the effect of specular reflection.

To mitigate these drawbacks, here the use of a multi-resonant unit-cell is proposed. It consists in a square patch and a concentric square ring printed on a single layer substrate, to minimize the UC thickness. The multi-resonant nature of the unit cell has several benefits: it allows to obtain a range of variation of the phase of S_{11} of 360°, it guarantees that its magnitude is never lower than -0.2 dB and it keeps stable these features with respect to the variation of the angle of incidence. The performance of a planar SES, designed to feature a significant slant in the direction of maximum radiation, obtained through its numerical analysis, confirms the effectiveness of the unit cell.

II. Unit Cell Design

The unit cell here introduced is sketched in Fig.1. It is a multi-resonant configuration, consisting of a grounded DiClad 527 single-layer dielectric substrate ($\varepsilon_r = 2.55$, $\tan_\delta = 0.0022$) with thickness $h = 0.8$ mm, with a square ring and an inner square patch printed on the top side. The size of the UC is 3.5 mm, which is slightly smaller than $\lambda_0/3$ at the operating frequency $f_0 = 27.5$ GHz.

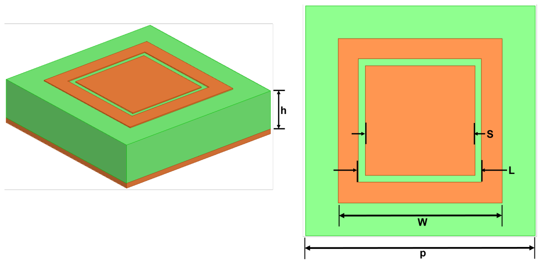

Fig. 1. Unit cell structure.

The unit cell has several degrees of freedom, that could vary independently to better control the behaviour of the UC itself and consequently of the SES; as a first example, however here the simplex case in which the outer side W of the square ring is taken as variable geometrical parameter, while the other sizes are expressed in terms of it, is considered. In particular, the inner size of the outer ring L depends on W according to the relation $L = W - W/3$ while the side of the inner square patch S is given by $S = W - W/4$.

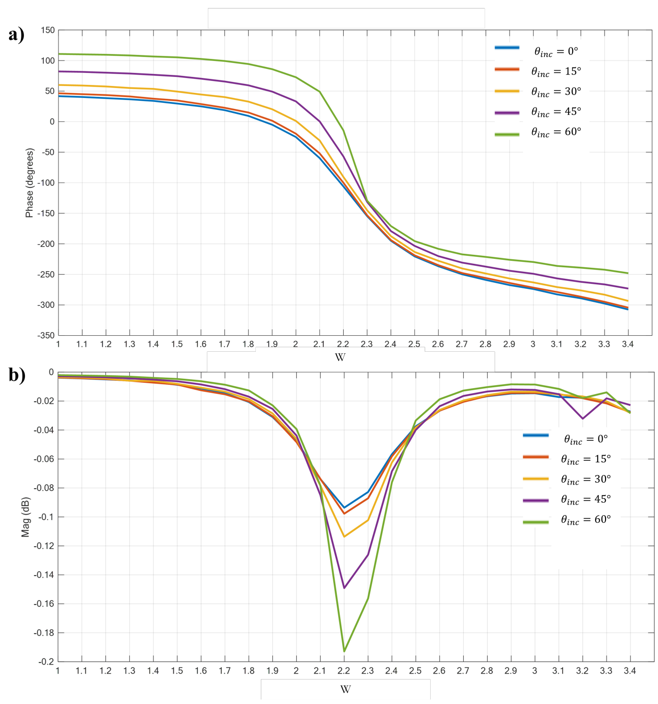

Fig. 2. Phase (a) and magnitude (b) of the reflection coefficient S_{11} as a function of W for different direction of arrival of the incidant wave.

The variation of both the phase and amplitude of S_{11} as a function of W, for five different angles of incidence in the range $0° < \vartheta_{inc} < 60°$ discretized with a step of 15°, is plotted in Figs. 2a, 2b. As can be seen, the phase of S_{11} shows a smooth S-shaped variation over a range of 360°, while $|S_{11}|$ is never lower than -0.2 dB also for the largest among the considered incidence angles. The capability of the unit cell to provide the variation for $\angle S_{11}$ of 360° is related to its multi-resonant characteristic.

III. SES design

In view of its behaviour, the UC has been used for the design of a planar smart skin. The considered structure is rectangular, with size of 180 mm $\times$267 mm and it is discretized with 51×76 unit cells. Under the, realistic, hypothesis that the SES is in the far field region of the base station, the incident field is modeled with a plane wave that impinges orthogonally on the smart skin, while the desired pointing direction for the reflected field is identified by $(\vartheta_{max} = -45°, \varphi_{max} = 90°)$ in the adopted reference system. With the aforementioned specifications, the phase delay that must be provided by the smart skin in order to produce the desired beam pattern has been computed and is shown in Fig. 3a. The layout of the

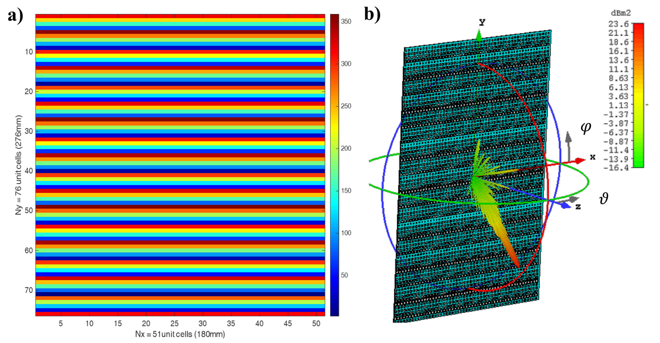

Fig. 3. a) Required phase distribution map. b) Sketch of the SES layout with the 3D-pattern of the reflected RCS at the design frequency of 27.5 GHz.

corresponding SES is sketched in Fig. 3b, with overlapped the 3D-pattern of the reflected field, expressed in terms of the Radar Cross Section (RCS) at 27.5 GHz, obtained through its full-wave simulation carried out with CST Microwave Studio.

In Fig. 4 the behaviour of the RCS in the H-plane ($\varphi = 90°$) evaluated in correspondence of several frequencies in the interval [26,29] GHz, is plotted. The well-defined and focused main beams in the given pointing direction confirms the effectiveness of the SES design. Moreover, good pointing stability can be observed: the beam deviates only by 3° from the desired pointing direction of $\vartheta_{max} = -45°$ within the considered frequency band. The side lobes are well controlled, also the specular ones, that could represent a drawback in the use of SESs especially when they are used for localization. As it appears from the curves in figure, the specular lobe is definitely low at the lower frequencies, but also in the upper part of the considered band it stays below -9 dB with respect to the maximum.

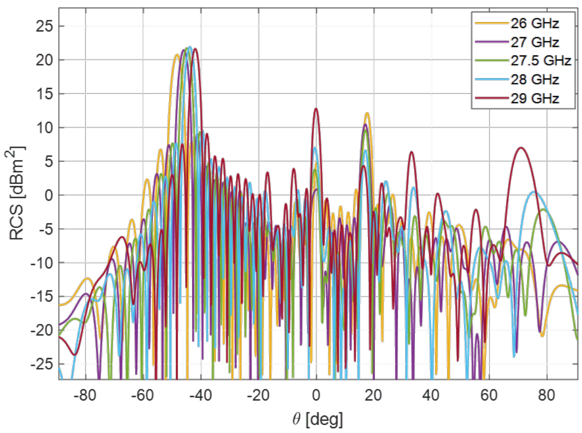

Fig. 4. RCS behaviour in the H-plane evaluated for several frequencies.

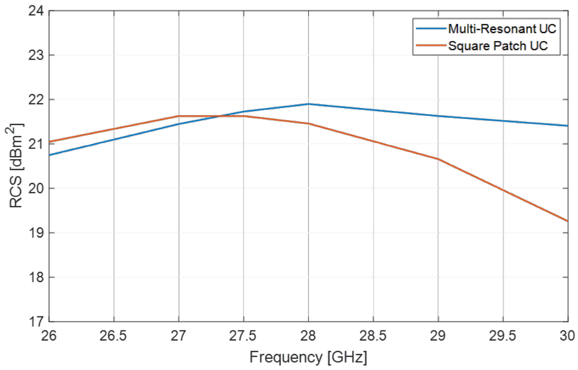

Fig. 5. Comparison of maximum RCS variation between the considered SESs with the multi-resonant UC and those designed with square patch UC in the analysed frequency band.

Finally, in Fig. 5 the variation of the maximum RCS with frequency is shown, together with that characterizing another smart skin, with the same size and designed to focus the reflected field in the same direction, but discretized with a different unit cell, whose behaviour is controlled varying the size of a square patch [7]. The use of the multi-resonant UC significantly improves the value of the maximum RCS, particularly at higher frequencies, with a remarkable enhancement of 2.2 dBm^2 at 30 GHz, while the square patch unit cell works slightly better at the lower frequencies. Note that the variation with frequency of the maximum RCS in the case in which the multi-resonant UC is used si so smooth that it stay within 1 dB over almost the entire considered frequency range.

IV. Conclusions

In this communication, the preliminary results on the design and analysis of a planar smart skin discretized with a multi-resonant unit cell are presented. They show that the re-radiated field presents a well-defined main beam in the desired direction, quite stable over the considered frequency band; moreover, the comparison with the results obtained with the numerical analysis of a similar configuration adopting a different unit cell, confirms that the here introduced UC helps to increase the bandwidth. For all these reasons it seems to be a good candidate for the design of smart skins to be used in indoor scenarios. Further results will be discussed at the conference time.

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