A novel Hexagonal Excitation for a Multi-Layer Wearable Miniaturized Antenna

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***Abstract*—Microstrip antennas are widely used for Wireless Power Transfer applications both in medical and industrial environment, however, a trade-off between performance and dimensions must be set. This article proposes an hexagonal rectenna with enhanced radiation performance. The two-layer structure accounts for an hexagonal ring antenna equipped with concentric parasitic rings, fed by a microstrip line that couples with the antenna parasitic elements in order to achieve optimum matching conditions at 2.45 GHz. The second layer, made by metallized FR-4, allows for enhancing the radiation performance of the overall structure reaching for a 20 % and more than a +1.5 dBi increment in the antenna radiation efficiency and gain respectively, while maintaining overall small dimensions.**

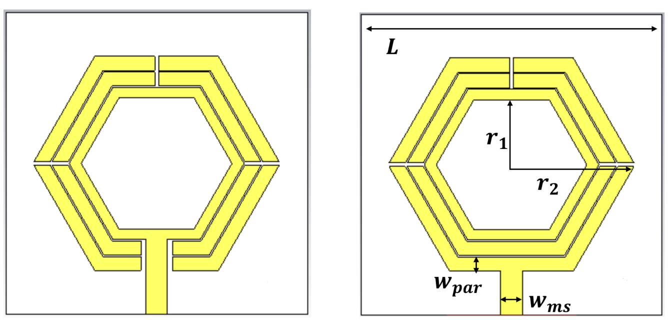
***Index Terms*—Superstrate antennas, WPT, wearable antennas.**

THE technological development and the extensive spread of modern IoT devices has increased the demand for battery less solutions [1]. Many are the fields in which IoT devices can have useful applications, from the logistics [2], to agriculture [3], as well as from the industrial [4], [5] to the medical environment [6]–[9]. In particular, when designing devices that are used in the a wearable context, wearability, lightness, compactness and energy autonomy become key points to be achieved. Wearable antennas play an important role inside an energy harvesting system due to the fact that their performance need to be maximized to provide a sufficient amount of power to the device to which they are connected. When designing wearable antennas, it is also important to allow a safe electrical decoupling from the body surface in order to avoid degradation in performance or possible antenna detuning. In [10], a lightweight textile rectenna is presented. The system is composed of a 2 x 2 and a 2 x 3 antenna arrays whose each element is connected to a rectifier circuitry to perform the $\eta_{RF-to-dc}$ power conversion. Being the system designed to be embedded in a garment, organza is used as textile substrate and conductive fibre [11] is used to create the radiating patch and the ground plane [10]. The embedded half-wave rectifier, that makes use of a Skyworks SMS7630 Schottky diode, results in a power conversion efficiency of about 20% for a -20 dBm input power. Using e-textiles is a good trade-off between flexibility and performance, however, they may not allow to create small-sized devices, especially when used to design microstrip patch antennas [12], due to the low dielectric constants of these substrates. It is worth noticing that patch antennas are one of the most widely used antenna typologies to be applied in wearable applications especially due to the presence of a ground plane that allows for a safe decoupling of the antenna from the human body, avoiding undesired detuning and drops on the radiation performance. To achieve optimum performance while reducing the encumbrance with respect to the e-textile implementations standard RF-substrate are still a matter of interests also for wearable applications, especially if they perform flexibility [13]. The radiation performance of these structures can be enhanced by using metasurfaces acting as a superstrate of the radiating element. In [14], the radiation performance of a patch antenna are increased by means of a phi-shaped slotted metamaterial superstrate. The metasurface is placed on top of the radiating element at a distance equal to 1.6 mm and it is derived on a Photonic Crystal substrate. The simulated gain of the antenna is computed in the case of having the metasurface derived on the same antenna substrate, FR-4 and on the proposed superstrate. The former show a 7.92 dBi gain, the latter performs a 9.67 dBi gain, showing how this technique can improve the antenna performance without drastically increase the overall dimensions.

This article presents the design of a wearable rectenna operating at 2.45 GHz for energy harvesting purposes. The presence of a background placed allows for decoupling from the body surface to avoid detuning when the antenna worn. The radiation performance are enhanced by means of a superstrate placed on top of the radiating element, at a fixed distance of 1.5 mm, that acts as a director, guaranteeing high radiation performance while maintaining a reduced overall dimension. With respect to [14], this proposed solution allows to obtain a further increased gain enhancement, of about 1.5 dB with a standard layer of commercial FR-4 substrate.

I. Antenna Design and Comparison

The antenna is realized on an RF-substrate, the Rogers 3003 (ε_r=3, $\tan\delta$=0.001) of a thickness of 1.52 mm. The operative steps start with the design of a ring antenna, fed by a microstrip line. The antenna is made of two parts: the ring antenna whose shape has been optimized to reduce the overall dimensions and the superstrate that is a simple metallized FR-4 layer with the same dimension of the antenna layer, used to enhance the radiating performance.



(a) (b)

Fig. 1: (a) Hexagonal ring antenna with feeding (a) on the central ring and (b) on the external parasitic ring.

The overall project has been focused on the design of a system that boasts good performance avoiding excessive dimensions, so the operative constraints on the antenna dimensions have been set to 50 x 50 mm^2. Fig. 1a shows the preliminary design of the hexagonal ring antenna, made by a central ring, fed by 50-Ω microstrip line and surrounded by two rings of parasitic elements. Each parasitic element is fractionated into four sections, whose separation distance adds further degrees of freedom that can be used for matching purposes. The presence of these two parasitic rings identifies some well-matched resonances that are still far from the desired one at 2.45 GHz. This way, the best matching condition is found to be around 3.4 GHz, showing a radiation efficiency of 69% and a gain of 5.6 dBi. In order to further lower the resonance frequency, the feeding line is moved from the direct connection with the central ring to the external one, with a slight modification of the parasitic ring arrangement, as shown in Fig. 1b. In this way, in fact, a direct connection with the external path allows to guarantee a longer electrical length.

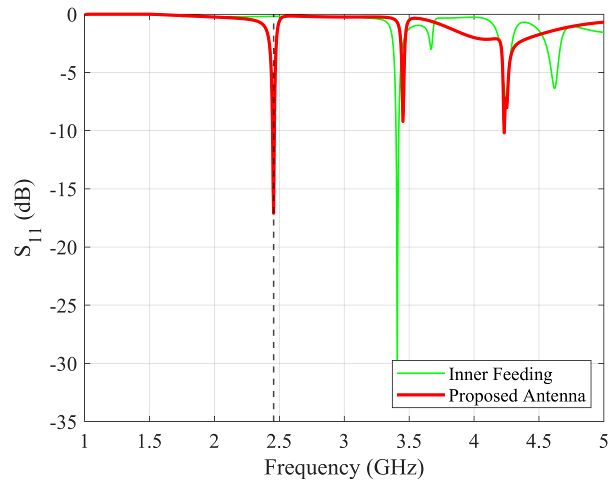


Fig. 2: Reflection coefficients at the antenna input port for the two different configurations shown in Fig. 1.

This last design allows for having very good matching conditions around 2.45 GHz. In this configuration the feeding is not provided directly to the central ring, but being the external ring the one to be directly fed, the radiating inner ring antenna is excited by means of coupling effects acting between the parasitic rings interposed from the feeding line and the central ring. This behaviour allows to tune the antenna to resonate at a lower frequency without enlarging the overall dimensions, due to the fact that the effective path followed by the current is significantly increased, mainly because of the fusion of the external lower parasitics.

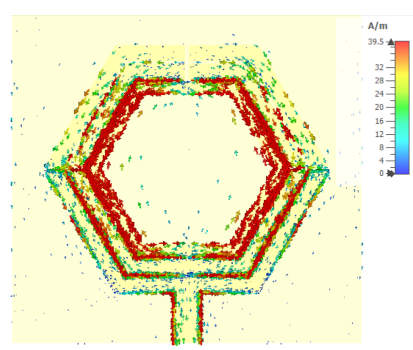


Fig. 3: Surface current on the Hexagonal ring antenna at the operating frequency of 2.45 GHz

Fig. 3 shows the surface current at the resonance frequency; it is clearly visible that the current follows a meandered path from the feeding line up to the central ring. The antenna experiences a radiation efficiency of about 65 % and a gain of 4.6 dBi. Although the radiation performance are in agreement with the expectations, further analysis to improve the system performance have been conducted. A director is placed on top of the hexagonal antenna, at a reference distance of 1.5 mm, and it is realized on standard FR-4 substrate (Dk= 4.5, tanδ=0.025), with a thickness of 0.6 mm. A preliminary version has considered a thinner substrate, however for realization compliances we opted for a more standard value that can be fabricated more easily, since no difference in the overall performance were highlighted. This superstrate acts as a director enhancing the radiation properties of the antenna that is placed underneath. The overall dimensions of the antenna are 42.5 x 42.5 x 3.72 mm^3, thus achieving good trade-off between dimensions and performance. The optimized parameters of the hexagonal antenna are reported in Tab. I

TABLE I: comparison on antenna radiation performance

Component	**Value**	**Component**	**Value**
L	42.5 mm	w_{par}	2.7 mm
w_{ms}	3.6 mm	r_1	10.5 mm
Substrate thickness	1.52 mm	r_2	18.5 mm
Metasurface thickness	0.6 mm	Air gap	1.5 mm

Full-wave simulations have shown a 20% improvement on the radiation efficiency, reaching a value of 85%, whereas the antenna gain varies from 4.5 to 6 dBi. The improved performance shows how this approach can be considered a valid option to increase the antenna radiating performance without the need to rearrange the entire layout or change the substrate. To consolidate the found results, the antenna is then compared with a standard patch whose substrate corresponds to a stack-up of different substrates: Fr-4, air and Rogers 3003 respectively, represented in Fig. 4.

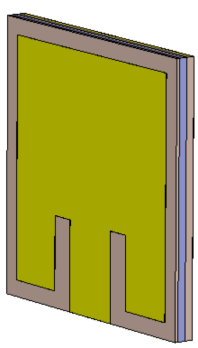


Fig. 4: Patch antenna realized with a layered stack-up, having the same overall thickness.

The aim of this investigation is to justify the correct behaviour of the antenna superstrate as a director and not attribute all the improved performance to the interposed layer of air. As can be noticed from Fig. 4, the substrate width is drastically reduced to a 50 x 50 mm^2 to allow a fair comparison with the designed hexagonal antenna system. Due to the reduced dimensions of the substrate the overall performance tent to decrease from 77%, in the case of having a larger substrate (80 x 80 mm^2), to 65% of radiation efficiency and a decrement of about 2.6 dB for the antenna gain, from 6.8 to 4.2 dBi, also because of an increased back-radiation. A summary of the compared performance is displayed in Tab. II.

TABLE II: comparison on antenna radiation performance

	Radiation Efficiency	**Gain**	**Dimension**
Standard multilayer patch with large ground plane	77 %	6.8 dBi	80 x 80 mm^2
Standard multilayer patch with reduced ground plane	65 %	4.2 dBi	50 x 50 mm^2
Proposed multilayered hexagonal antenna	**85 %**	**6 dBi**	**42.5 x 42.5 mm^2**
Proposed multilayered hexagonal antenna (on body)	**66 %**	**5.9 dBi**	**42.5 x 42.5 mm^2**

As can be inferred from the values shown in Tab. II, the proposed system can represent an interesting design layout for achieving not only high radiation performance, but also to guarantee them while being in compliance with some dimension constraints, that for wearable applications are of a paramount importance.

II. SIMULATIONS WITH BIOLOGICAL TISSUES MODELS

Being the antenna designed for wearable applications, an important step is to simulate the antenna performance when placed close to the body surface. In order to do this, a layered stack of biological tissues is designed and used to perform a full-wave simulation. The antenna topology has been chosen in order to minimize the decoupling and detuning due to the proximity to the human body, whose dielectric properties do have an influence, especially in the microwave or millimetre wave range. The biological tissues considered in the full-wave simulations are skin, fat and muscle, of a thickness of about 3, 10 and 20 mm respectively, as shown in Fig. 5.

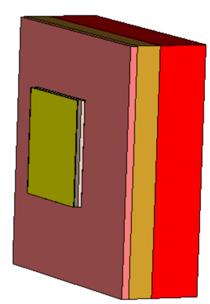


Fig. 5: Representation of the proposed antenna in the presence of a multilayer block of biological tissues.

The simulated separation distance is of 5 mm to account for the possibility of incorporating the antenna into garments or inside an holding case. The radiation performance when the antenna is placed in close proximity to biological tissues show a small decrement, however remaining well above accepted values for both the radiation efficiency and antenna gain. In particular the radiation efficiency decreases to 66% while the gain remains almost unvaried, 5.9 dBi. The dielectric properties of the biological tissue layers have been reported according to [15]. The radiation diagram of the proposed antenna is plotted in Fig. 6 for two simulated conditions: with the antenna in free space and when the antenna is placed in close proximity of the biological tissue layers, showing good agreement.

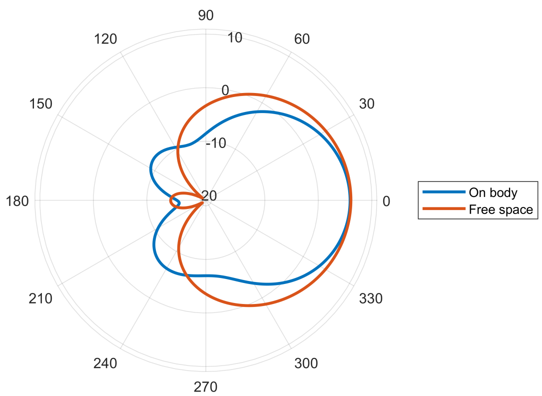


Fig. 6: Normalized radiation diagram for the proposed antenna: in air and when placed close to biological tissue layers.

The proposed antenna can also be equipped with a rectifier to perform a correct RF-to-DC power conversion efficiency. Given the antenna overall radiation performance, it is possible to safely design a rectifier with an optimized matching network. However, optimization are being conducted to further reduce the rectifier encumbrance and will be added to the final version of this paper.

III. Conclusion

This article presents the design of an hexagonal ring antenna equipped with a director placed on top of it, at a reference distance of 1.5 mm. The systems boasts enhanced performance with reduced overall dimensions and can be applied in wearable applications due to the decoupling introduced by the ground plane. The antenna is compared with a similar realization of a standard patch accounting for the same stacked layers as substrates, showing how the proposed design introduces a valid trade-off between dimension and radiation performance, reaching a value of 85% of radiation efficiency. Simulations are conducted also considering the antenna placed close to a stack of body tissues to investigate the performance simulating a wearable conditions, showing still encouraging results.

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