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2-Dipoles Circularly-Polarized Antenna Integrated in Lamp Holder for Fixed RFID Reader

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ABSTRACT The paper presents a solution to integrate a circularly polarized antenna in a tracklight housing that contains both a lamp and a UHF-RFID reader. The antenna is located outside the tracklight housing since the cylindrical lamp holder is metallic and small in terms of wavelength, and there is no space enough inside it. Furthermore, the antenna does not interact with the lamp, so no specific lamp is required. The solution makes use of a standard print-circuit-board fabrication technique combined with a low-cost metal sheet cavity, that can be also drilled for aesthetical reasons. An antenna prototype has been designed for the North America market. The measurements showed a reflection coefficient less than -15dB and a gain greater than 6dBi in the band of interest (902-928 MHz).

INDEX TERMS UHF-RFID reader, circular polarization, antenna, lamp.

I. INTRODUCTION

The rapid expansion of RFID applications, such as asset tracking, security systems, remote wireless identification, identification of objects, people and animals, baggage localization and tracking at airports, purchasing, logistics and supply chain management, Internet of Things (IoT), library management systems, industrial automation, and wireless sensor networks (WSNs), has driven the research on UHF radio frequency identification (UHF-RFID) systems [1], [2]. In particular, a new wave of interest on RFID has been generated by the world of retail. In 2016, research showed that 73% of retailers had implemented or were currently implementing or piloting RFID. That number had nearly doubled from 2014 [3]. Indeed, retailers are beginning to see how this tech can directly benefit their bottom line in unexpected ways. Here, a few examples. RFID tags are serialized, enabling the unique identification of each item in the supply chain, inventory, and store. So, the inventory counts, which traditionally is a tedious exercise done manually about once a year, can be avoided. Indeed, thanks to the RFID technology, retailers can monitor stock in real-time with reduced staff costs, increasing drastically the inventory accuracy, sales, and customer satisfaction, that will not experience the out-of-stock of the item he likes. Furthermore, the use of RFID tags can prevent theft and track assets that are frequently moved and often misplaced. RFIDs can be used for payments and checkouts shortening queues and speeding up the checkout process. Finally, if the RFID tag is inserted in the RFID loyalty card, the retail can detect customers in a store. Even small and midsize retailers with a single store or a few stores can benefit from using radio frequency identification technologies [4]. The RFID technology has also other advantages: an RFID reader can count several items per second and it can identify items several meters away, even if the item is behind a wall or in a cardboard box. However, the key factor for a successful RFID in retail strategy is how the technology is implemented and deployed in the store.

Till now, we have seen store employees armed with handheld RFID readers and the research has been focused on finding a compact, low-profile, lightweight, and cost-effective solution for the antenna [5]-[10]. However, handheld RFID readers still require personnel to use them. The current trend is using fixed RFID readers installed in ceilings and doorways to automatically collect a continuous stream of valuable real-time data [11], [12]. So, the research call now is designing antennas that can fit in fixed pieces of furniture. In this regard, the antenna has to be hidden, or at least it has to have an aesthetically pleasing appearance. A possibility is to integrate the ensemble of antenna and RFID reader in a

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tracklight housing already present in most of the stores/warehouses (see for example Figure 1). A bulb that integrates directly the system has been recently proposed in the literature [13], although with a lower gain. However, this type of bulb cannot be inserted in the tracklight since this one is metallic and significantly degrades the radiation in the 900MHz band.

FIGURE 1. **Possible scenario of application: RFID reader integrated in tracklight housings used in a clothing store.**

Since RFID tags usually use linear polarization (LP) and they are also commonly hand-held and so randomly orientated, the reader uses circular polarization (CP) to ensure that the transponder can receive energy regardless of the tag orientation [14], [15].

This paper presents the design process, manufacturing, and testing of a circularly-polarized antenna to be used in a fixed RFID reader integrated into a tracklight housing. The solution allows us to take advantage of the power plugs already existing in the store/warehouse. The readers are then connected via WiFi between them and the processing unit.

II. READER ANTENNA DESIGN REQUIREMENTS

In the following, the several different requirements of the antenna will be shown and the criticalities will be highlighted.

A. EM REQUIREMENTS

The antenna has to be used in an RFID reader for the North American market, thus it will work in the frequency band 902-928MHz (approximately 3%). It is worth noting that the decision of the European Community (EU) 2018/1538 has extended the usage of the 915-921 MHz band for RFID applications also to the EU territories. Thus, the proposed antenna could also be used in Europe. The radiation pattern has to be as broad as possible, since wider HPBW (in both azimuth and elevation planes) is adequate for easy item scanning [16], and the gain larger than 6 dBi.

B. SIZE

The lamp holder that we are going to consider is a metallic (steel) cylinder that can hold a commonly used BR30 led lamp. The tracklight housing has a diameter of 110 mm, while the height is 160 mm. Moreover, it uses a halo insert on the top of the cylinder, i.e. it has a flange that extends beyond the diameter of the tracklight housing. The outer diameter of that flange is about 160 mm.

The antenna cannot be located inside the lamp holder mainly because of the cylindrical holder is metallic and the reader working frequency is not sufficiently high to allow the propagation of the fundamental mode in the circular waveguide that the holder creates. Then, there is not enough space to room the antenna neither around nor beyond the bulb because of the electronics. Thus, the antenna has to be conformal or has to extend in front of the lamp holder, but its structure has to be robust and low-cost.

Moreover, the antenna design has not to be limited by the peculiarity of the used lamp housing designs since they will change from one retailer to another. Finally, the antenna must not hide the light.

C. FEEDING MECHANISM

A RG316 coaxial cable will be used to feed the antenna. The coax is connected to the RF unit using an MMCX straight edge mount connector.

D. COST

The expected wide diffusion of the device requires a limited antenna cost. This favors the use of low-cost materials and technologies as standard print-circuit-board fabrication techniques.

E. AESTETICS & RECOGNIZABILITY

The presence of the antenna on the lamp has not to be recognized from the customers for two reasons: first to avoid sabotage, and second for not discouraging the attendance of those customers that are scared by electromagnetic radiation or by any kind of control. The ensemble of the tracklight holder and the antenna has to be aesthetically pleasing, even if the lamp is not in plain sight. In fact, it is supposed located between three and four meters from the floor.

F. FASTENING OR MOUNTING

As the RFID reader lamp will be deployed in a controlled indoor environment, the environmental requirements such as temperature, humidity, salt mist, solar radiation, and wind survival are insignificant. Furthermore, the presence of the antenna must not change the mounting mechanism of the lamp to the existing electrified track.

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III. ANTENNA DESIGN

The simplest antenna solution would be a helix operating in the axial mode. However, here it is impractical since it would require a large radial distance of the helix from the metallic cylinder, and this would certainly result in being unaesthetic. Thus, a loaded dipole configuration has been used.

Figure 2 shows the antenna geometry: four dipoles serially fed with a stripline, located around the tracklight housing cylinder, and backed by an open cavity of diameter 178 mm, 67 mm deep. The effect of the cavity is to create an equivalent magnetic reflector close to the dipoles to enhance the antenna gain and to reduce the back radiation. The stripline is made by using two 0.785mm thick FR4 substrates (Figure 3).

Figure 4 explains the antenna working mechanism: four dipoles are fed with a current having equal amplitude and a progressive phase shift of 90°. Due to the narrow band of the specific RFID application, this can be done by using a series feeding network. In Figure 4 the red segments are the actual radiating elements of the quad dipoles configuration [17]. They are very short in terms of wavelengths. Specifically, each radiating element has a length of about $\lambda_0/20$, where λ_0 is the wavelength in air, and of about $\lambda_d/10$, where λ_d is the wavelength in the dielectric substrate (FR4, $\varepsilon_r = 4.4$). When considered in isolation, each element shows an input impedance characterized by a very low resistive part and a high reactance. To overcome this drawback, two arms (metallic chord), that act as a capacitance, have been added (see Figure 4b). These, practically, increase the electrical length of the radiating element and allows us to obtain an almost real input impedance R_d of about 33Ω.

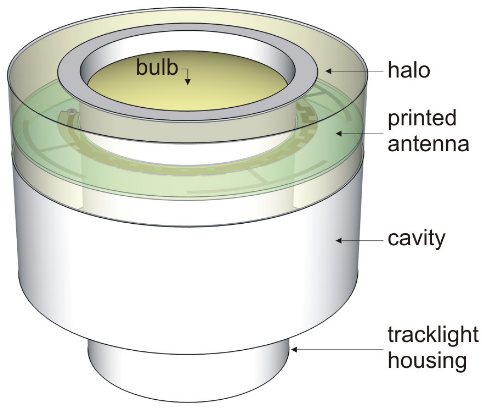

FIGURE 2. RFID reader and lamp system. The antenna is made by four stripline serial-fed dipoles located around the tracklight housing and backed by a quarter wavelength open cavity, that creates an open condition at the end nearest the antenna.

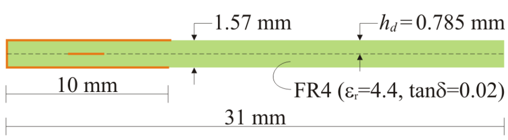

FIGURE 3. Transverse section of the antenna PCB.

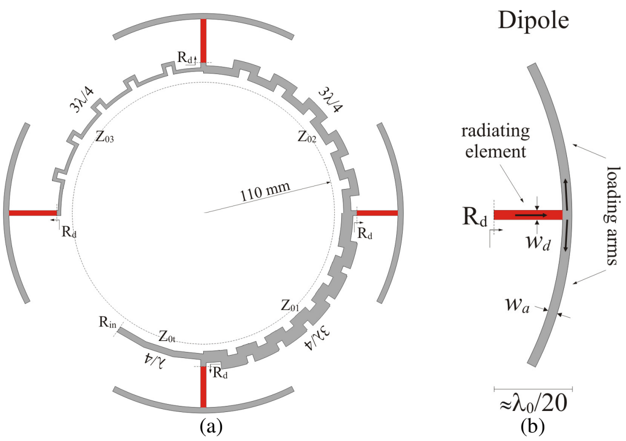

FIGURE 4. (a) Four dipoles are serially fed with equal amplitude and 90° shift phase by using a stripline. (b) Dipole configuration: the radiating element ($w_d = 2.3\text{mm}$) is the red segment while the two arms ($w_a = 2.3\text{mm}$) have been inserted as loading capacitors to obtain an input impedance $R_d \simeq 33\Omega$.

A. ANTENNA MODEL

Figure 5 shows the equivalent circuit of the feeding network. All the dipoles are characterized by an input impedance R_d that can be considered real for the effect of the capacitive load. The easiest way to provide a progressive phase shift of −90° between the currents feeding the dipoles is to choose a length of the transmission line, that joins two consecutive dipoles, equal to $\lambda_d/4$. However, the geometrical arc between two consecutive dipoles is greater than $\lambda_d/4$. As a matter of fact, since the minimum circumference is equal to $345.6\,\text{mm}$, the inter-dipole distance is about $\lambda_d/2$, being $\lambda_d = 156.3\,\text{mm}$ the wavelength in the stripline. Thus, the electrical length of the transmission line has been increased to $3\lambda_d/4$ with a meander line, providing a progressive phase shift of 90°.

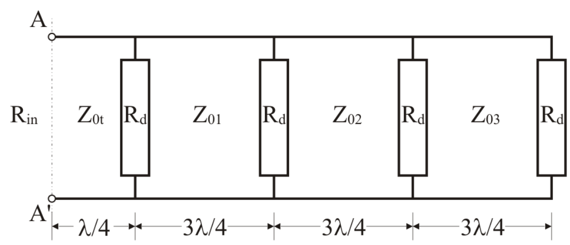

FIGURE 5. Equivalent circuit model of the antenna. Each resistive load represents a dipole.

Exploiting the property of a transmission line with characteristic impedance Z_{0i} and electrical length of $3\lambda_d/4$, that presents an input impedance $Z_{in} = Z_{0i}^2/Z_L$ when closed on a load Z_L, it is possible to calculate the characteristic impedance of each section between two consecutive dipoles that provides the correct power flowing in each of them (i.e. provide equal current magnitude in each dipole). This results in: $Z_{03} = R_d$, $Z_{02} = R_d/2$, $Z_{01} = R_d/3$. Then, the last section is a simple quarter-wave transformer with characteristic

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impedance $Z_{0t} = \sqrt{R_0 R_d}/2$, where $R_0 = 50\Omega$ is the input impedance of the connector.

B. SEMPLIFIED GEOMETRY

The proposed solution is quite robust and ensures good performances even for not very accurate manufacturing. However, it is not affordable from a manufacturing point of view. In fact, the four dipoles solution requires to cut an annulus of the dielectric substrate with a significant waste of material, since the central part occupied by the tracklight housing (a substrate disk of 110 mm diameter) has to be removed. For the reason described above, a simplified version that makes use of two dipoles only has been developed, as shown in Figure 6. The idea concerning the feeding network is analogous to the 4-dipoles solution, but now the symmetry of the lamp is exploited. In particular, the two dipoles excite mainly two orthogonal TE_{11} modes in phase quadrature. The cavity depth ($h_c = 67$ mm) and the position ($h = 15$ mm) of the dipoles with respect to the cavity top (open section) have been numerically optimized to simultaneously maximize the gain and the polarization purity (i.e. the amplitude of the TE_{11} with respect to the undesired fundamental TEM mode in the coaxial cavity). Furthermore, the cavity is located 50 mm above the bottom of the holder to allow the insertion of the tracklight bracket.

The antenna performance of the 2-dipoles solution is very similar to those of the 4-dipoles configuration. In fact, if we consider the manufacturing of both the stripline and the dipoles with a low-cost substrate, characterized by a typical loss tangent of about 0.02 (e.g. FR4), the gain of the 2-dipoles solution will be only 0.5-0.4 dB lower than the 4-dipoles one (since the latter, even if more directive, makes use of a longer feeding network, with higher losses). However, the 2-dipoles solution has two main advantages: it is less sensitive to manufacturing inaccuracies, and there is no waste of dielectric substrate.

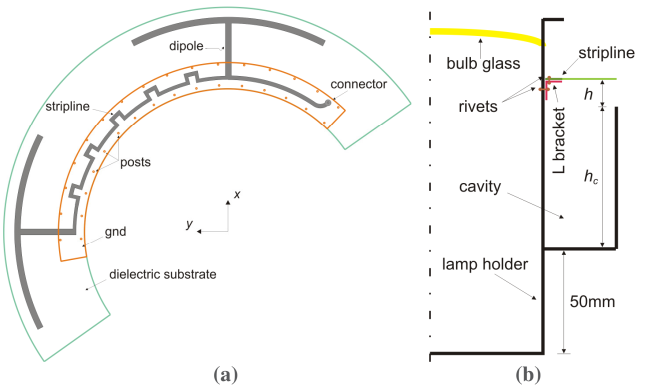

FIGURE 6. **(a) 2-dipoles solution. (b) antenna mounting (half section).**

B. ANTENNA PERFORMANCES

As shown in Figure 7, the simulated reflection coefficient of the 2-dipoles antenna solution is less than −25dB in the 902-928MHz frequency band of interest both using CST Microwave Studio (dash dot red) and Ansoft HFSS (dash blue).

The HFSS simulated antenna gain is greater than 6.25dBi in the 902-928MHz frequency band, while the simulated axial ratio is less than 0.35dB at the central frequency and less than 0.45dB in the band. Figure 8 shows the gain pattern at the central frequency of 915 MHz in the orthogonal planes $\phi = 0°$ and $\phi = 90°$. It should be noted that the high cross-polarized back lobe is expected since the entire antenna has a dimension that is slightly greater than $\lambda_0/2$. Figure 9 shows the simulated antenna gain and axial ratio versus frequency. It is worth noting that they both vary a little in the frequency range of interest.

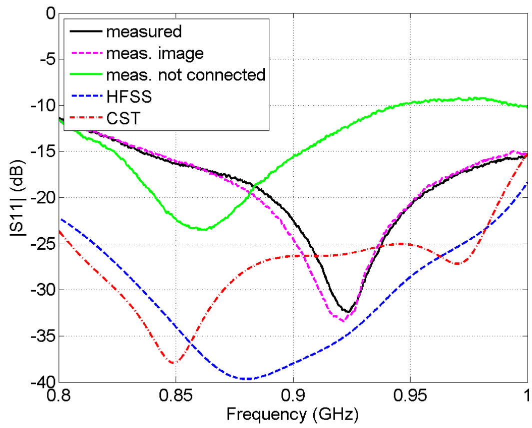

FIGURE 7. **Simulated and measured reflection coefficient versus frequency for the 2-dipoles antenna solution.**

A sensitivity analysis has been carried out by using HFSS on several antenna geometrical parameters to understand manufacturing reliability. The results of the analysis are reported in Table I. It is evident that the solution in the frequency band of interest (902-928MHz) is very robust with respect to the dielectric constant substrate value ε_r, the substrate thickness h_d, the lines width $w \pm \Delta w$, and the position of the dipoles with respect to the cavity $h \pm \Delta h$. We also analyzed the effect of a not perfect electric contact between the stripline ground plane and the cylindrical holder (a 0.5 mm gap has been considered). Full-wave simulations have shown that a continuous connection is not necessary, but it is sufficient to guarantee a good electric contact only in corresponding with the sections of the two dipoles. In particular, we discovered that it is mandatory to have good electric contact between the holder and the stripline ground in correspondence with the dipole closer to the feeding input point. As a matter of fact, if this condition is not verified the gain drops by 3dB, while if we disconnect the point close to the further dipole the gain lowers of only 0.5dB.

Thus, to secure the antenna to the holder we have used two L shaped metallic brackets just in correspondence of the dipoles. They have been fixed to the holder and to the stripline ground with rivets (see Figure 6b).

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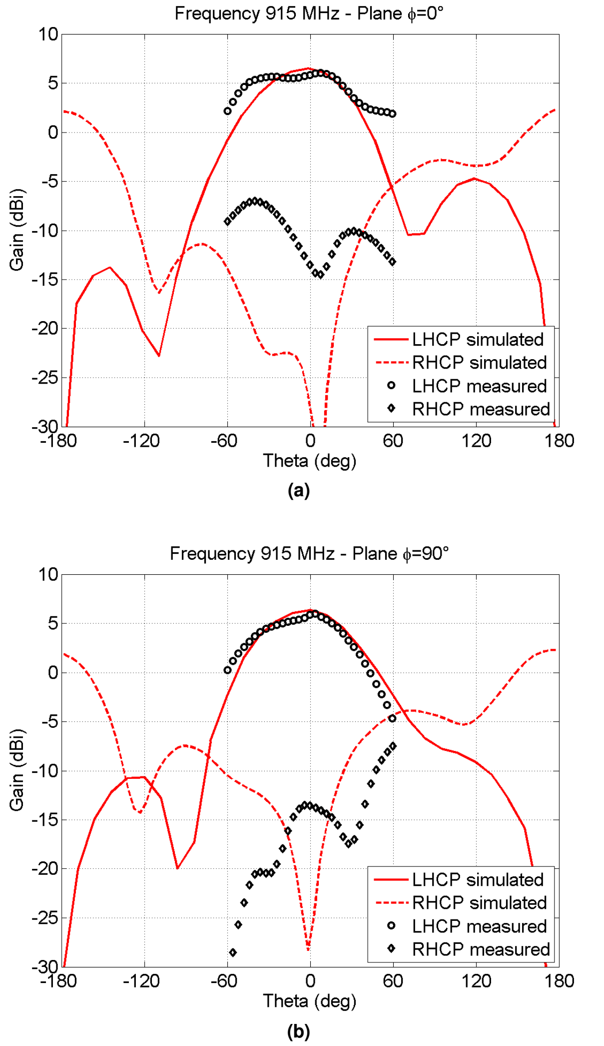


FIGURE 8. **Antenna gain patterns at 915 MHz in the ϕ=0° (a) and ϕ=90° (b) planes.**

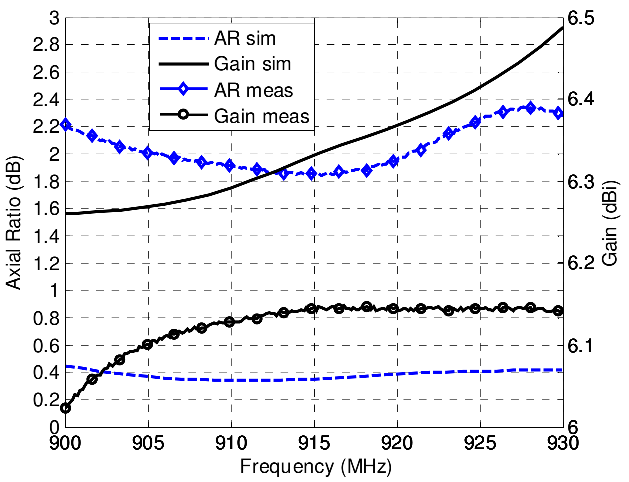


FIGURE 9. **Simulated/measured axial ratio and antenna gain versus frequency.**

TABLE I
SENSITIVITY ANALYSIS

900-930MHz	S_{11} (dB)		Gain LHCP (dBi)		Axial Ratio (dB)	
	MIN	MAX	MIN	MAX	MIN	MAX
nominal	-38.0	-33.4	6.25	6.49	0.34	0.45
ε_r= 4.17	-32.5	-32.0	6.35	6.45	0.50	1.30
ε_r = 4.30	-36.0	-33.5	6.75	6.85	0.35	1.20
ε_r = 4.50	-41.0	-33.0	6.70	6.80	0.40	1.10
h_d = 0.735	-36.0	-32.0	6.20	6.30	0.70	1.20
h_d = 0.835	-30.0	-28.0	6.30	6.35	0.45	0.95
$\Delta w = -50\mu$m	-36.0	-30.0	6.25	6.35	0.05	0.70
$\Delta w = +50\mu$m	-40.0	-39.0	6.25	6.35	0.25	1.05
$\Delta h = -2$mm	-47.5	-39.0	6.15	6.25	0.80	1.80
$\Delta h = +2$mm	-38.0	-30.5	6.30	6.40	0.25	0.90
Cond. losses(*)	-38.0	-33.5	6.1	6.15	0.10	0.70

* the strips have been supposed made of copper, while the lamp holder and the additional cavity of tin.

IV. ANTENNA MANUFACTURING

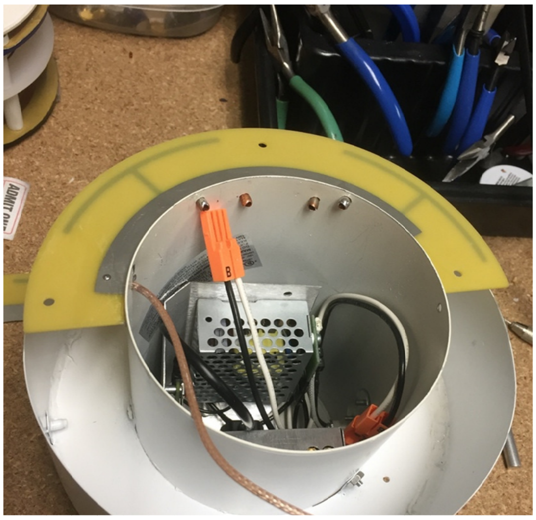
An antenna prototype has been manufactured starting from a commercial tracklight housing. In particular, the stripline substrate has been made by using two ISOLA 370HR substrates (ε_r=4.17, tanδ=0.0161@1GHz) 0.785mm thick and an ISOLA FR406 prepreg, as a binding layer. The dielectric constant substrate differs from the one used in the design by 3%. However, this difference does not affect significantly the antenna performances (see TABLE I). The stripline is fed via a coaxial cable through a hole in the metallic holder (CAN) where the RFID reader electronic is located. In the following, we show the results obtained by considering an H+S RG_316_/U coaxial cable directly soldered to the stripline, but analogous results are expected when a MMCX connector is used.

The cavity can be easily manufactured at low cost with mass production techniques. In particular, it has been made out of a sheet and roll, fastened at a lap joint. The manufactured antenna is shown in Figure 10.

V. ANTENNA MEASUREMENTS

Figure 7 also reports the measured reflection coefficient of the manufactured antenna (solid black). Furthermore, only for an investigative purpose, we have removed any electric connection between the stripline ground and the lamp holder. In the latter case the reflection coefficient increases and its minimum shift toward lower frequencies, but is anyway lower than −10dB in the band of interest.

The measured antenna gain is always greater than 6 dBi in the band of interest with a value of 6.14 dBi at 915MHz. Figure 11 shows the measured gain patterns of the 2-dipoles antenna in the two principal planes. The scanning angle is limited to ±60° because it represents the reliability range of the near-field scanner used for the measure. The same measured results have been superimposed on the simulated ones in Figure 8. Figure 11 also reports the gain pattern measured when an additional 2-dipoles passive printed circuit board is located symmetrically with respect to the fed



(a)

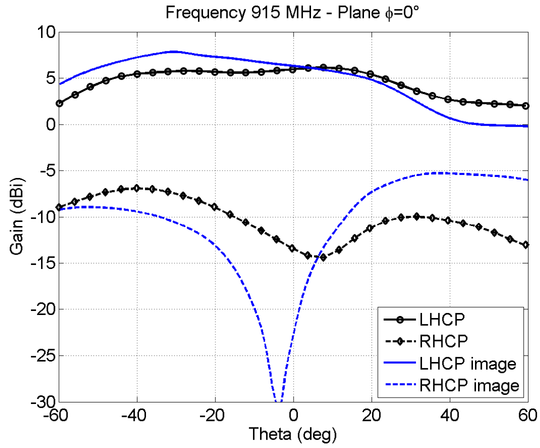
(b)

FIGURE 10. **Manufactured antenna integrated in the tracklight housing: the antenna and the electronics inside the tracklight housing (a), the lamp-RFID reader as a whole (b).**

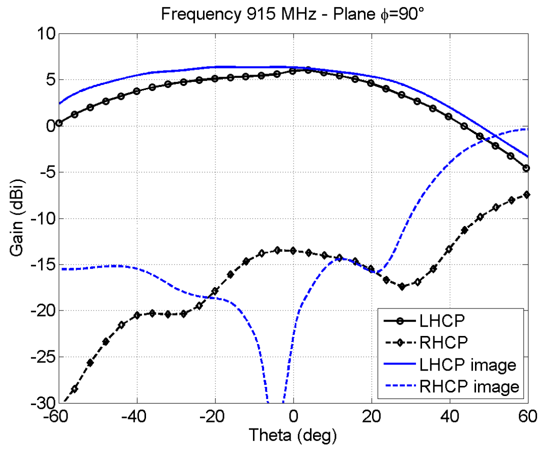
one. For the latter case, we have a polarization purity improvement and a slightly lower reflection coefficient (Figure 6, dash magenta). It is worth noting that for both cases a slight asymmetry of the gain pattern is present in the plane $\phi = 0°$. This represents an advantage since the installed lamp is commonly slanted of 15°÷30° with respect to the vertical axes.

Moreover, we drilled through the sheet-metal of the cavity several circular holes (see Figure 12) with a period of 9.57 mm, both for appearance purposes and for reducing the cost of the cavity manufacturing. From the full-wave simulations, we noticed that when the radius of the holes is less than 4.4 mm any significant difference is recorded between the perforated and the continuous case. Then, it is also possible to plug some holes to create a pattern.

To check the functionality of the antenna, we attached it to the ceiling of our laboratory at a height of 3.9m. The antenna axis was tilted about 15° with respect to the vertical direction



(a)



(b)

FIGURE 11. **Antenna gain measured in the two orthogonal planes ϕ=0° (a), and ϕ=90° (b), at 915 MHz when the 2-dipoles circuit is used and when an "image" parasitic 2-dipoles circuit is also introduced.**

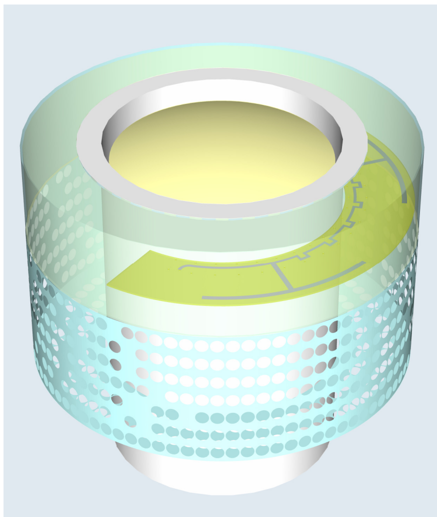


FIGURE 12. **RFID reader and lamp system with a perforated open cavity. The 2-dipoles antenna is integrated in the lamp holder. The cavity is perforated by circular holes of radius 4.4 mm; several holes have been removed with random pattern.**

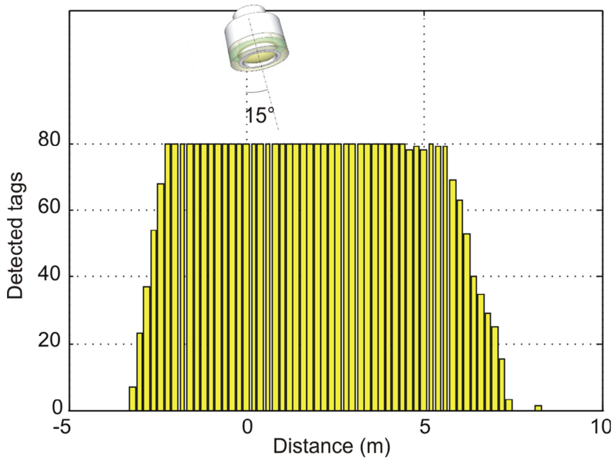


FIGURE 13. Number of detected tags versus distance from the vertical under the lamp holder.

and fed with an input power of 0.5 W (i.e. 27dBm). Then, we located 16 RFID tags (AD-383U7) on a swivel chair and moved it below the antenna with steps of 20cm. We repeated the procedure five times after changing the orientation and the position of the tags on the chair seat. Figure 13 shows the number of detected tags versus the position of the chair with respect to the antenna.

VII. CONCLUSION

A low-cost circularly-polarized antenna to be integrated into a tracklight housing has been worked out for UHF-RFID reader applications. Starting from a configuration with four dipoles backed by a quarter-wavelength open cavity, we showed that is possible to use only two dipoles with just a small degradation of the polarization purity. The proposed solution is robust and immune to typical manufacturing tolerances. Furthermore, the good antenna performances are maintained also when the walls of the cavity are perforated. This can be useful to embellish the cavity with some decorations made by opportunely arranging the holes.

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