A Circularly Polarized Planar Antenna Modified for Passive UHF RFID

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Abstract— **The majority of RFID tags are linearly polarized dipole antennas, but a few use a planar, dual-dipole antenna that facilitates circular polarization, but requires a three-terminal IC. In this paper, we present a novel way to achieve circular polarization with a planar antenna using a two-terminal IC. We present an intuitive methodology for design, and perform experiments that validate circular polarization. The results show that the tag exhibits strong circular polarization, but the precise axial ratio of the tag remains uncertain due to lack of precision in the experimental system.**

I. INTRODUCTION

The majority of UHF RFID tags are based on dipole antenna designs [1] because of the convenient, long and narrow geometry of the antenna and low cost of manufacture. Most commercial dipole antennas are linearly polarized (LP). Because of its simplicity, dipole antennas can interface easily with two-terminal RFID ICs. Reader antennas commonly use circularly polarized antennas in order to increase orientation diversity at the cost of polarization mismatch losses of 50%. At least one commercial RFID IC vendor provides a three terminal IC [2] that can interface to two, orthogonal dipoles. If properly designed, the two dipoles can provide either left- or right-hand circular polarization, which reclaims the polarization loss and improves orientation diversity.

To date, the majority of RFID antennas have either been linearly polarized dipole-like antennas, or orthogonal dual-dipole antennas. In this paper, we present a quad-pole antenna that is based on the work of Nesic [3], which provides good circular polarization, and is modified for a two-terminal RFID IC. Provided the tag and circularly polarized (CP) reader antenna are properly oriented, this antenna allows the same orientation diversity of a dipole but maintains a polarization match, and thus a 100% performance improvement that will result in a 41% increased read distance. If oriented opposite of the CP reader antenna, the polarization mismatch varies with frequency from as little as 16 dB to more than 23 dB measured with commercial equipment. We present a simple design methodology and test results that validate that the tag is strongly circularly polarized.

II. BACKGROUND

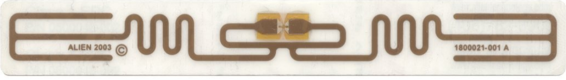

Fig. 1. Commercial linearly-polarized dipole antenna.

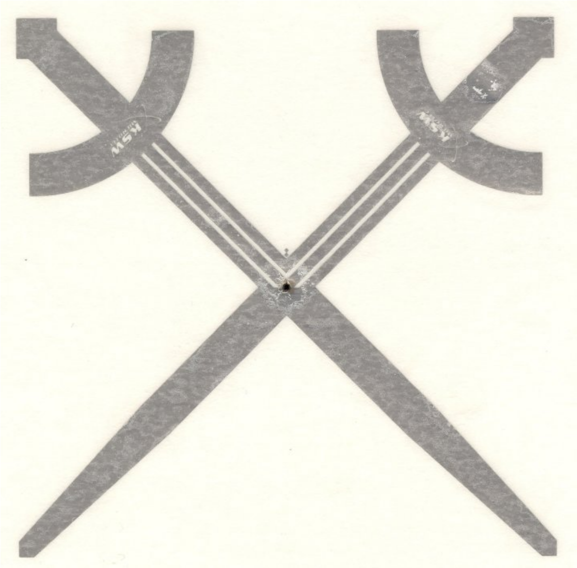

Fig. 2. Commercial dual-dipole antenna.

A common RFID tag is a modification of a dipole antenna (see Fig. 1). The antenna can include features such as a meandering segments and tip loading, often used to create a more compact resonant dipole. Less common but still of commercial interest is the dual-dipole antenna (see Fig. 2). The elements of the dual-dipole RFID tag antenna are explained in [4] and summarized here. The antenna consists of four poles and a special IC that has three terminals: *RF1*, *RF2*, and ground. As shown in Fig. 2, the IC connects to the antenna at three locations. The top two poles are connect to the two RF feeds, and the bottom two poles are connected to the IC ground and each other. Because the two dipoles are spatially orthogonal, they can operate independently with minimal coupling. In this configuration, the IC has the ability to operate in either linear or CP (either left or right) mode, and thus provide an especially good polarization match with a CP reader antenna. However, this approach requires a three-terminal IC, and thus may not be used with the more common two-terminal ICs.

"Readers" or interrogators interact with RFID tags through electromagnetic radiation. Often in commercial settings, one must choose the type of antenna system. The most common choices are: monostatic (a single antenna used to transmit and receive) or bistatic (two physically separated antennas, one for transmit and the other for receive), and linearly polarized or circularly polarized antennas. If the tags are or may be

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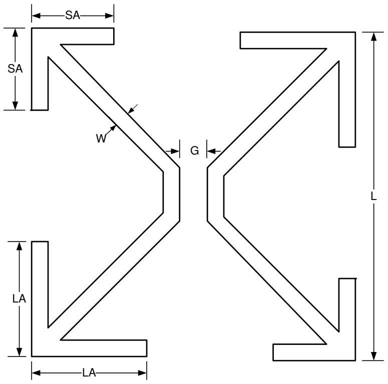


Fig. 3. Geometry of the quad-pole antenna.

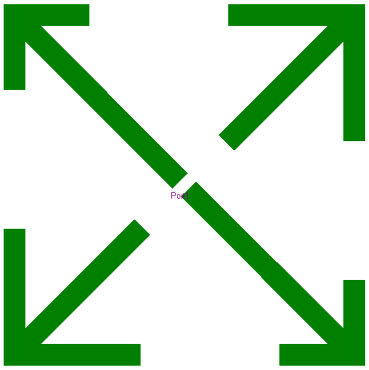


Fig. 4. Geometry used to determine dipole parameters.

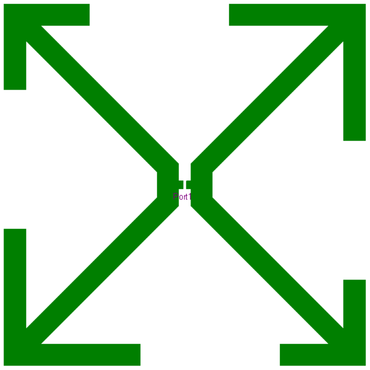


Fig. 5. Resulting quad-pole antenna.

linearly polarized and the angle of the dipole orientation is not known, e.g., sometimes oriented vertically and sometimes oriented horizontally, a circularly polarized reader antenna can be used to provide orientation diversity at the expense of a 50% polarization loss.

Nesic [3] has shown that by reactively loading four poles, similar to the dual dipole design, one can achieve circular polarization. To differentiate from the dual dipole antenna, we call this a *quad-pole antenna*. As opposed to the three-terminal IC and dual dipole antenna that accepts both left- and right-hand circular polarization, the quad-pole can work with a two-terminal IC, but receives radiation only in one polarization hand. This a novel compromise that facilitates the use of circularly polarized tag antennas with the more common two-terminal IC, while giving up the polarization diversity of dual-dipole antennas with a three-terminal IC.

III. DESIGN PROCESS

In this section, we present the process by which we developed the circularly polarized quad-pole RFID tag design. This begins with first developing the dipole components of the antenna, then converting it into the quad-pole, adding the matching circuit, and finally tuning for maximum axial ratio and minimum return loss. We use the definition of axial ratio as

$$AR = 20\log\frac{E_{max}}{E_{min}}\,.$$

A. Step 1: Two Dipoles

The substance of the circularly polarized quad-pole antenna are four poles that are conceptually related to two dipoles. Informally, the concept is to construct two dipoles that present an impedance with phase angle of +45° and $-45°$. These poles are then rearranged to form the antenna. The general antenna geometry of the final antenna is shown in Fig. 3.

To determine the parameter values, we used a MoM simulation tool [5] to determine the geometry for each of the diagonal dipoles. Fig. 4 shows the antenna used to determine the short dipole. With $L = 85$ mm, $W = 5$ mm, and $SA = 16.0$ mm, we found the dipole to have an input impedance of $44.2 - j43.8$ Ohms, i.e., a phase angle of $\approx -45°$. Similarly, we found $LA = 28.7$ with an impedance of $57.2{+}j57.4$ Ohms, i.e., a phase angle of $45°$. Better results are likely obtainable by further modifying the geometry so as to present a conjugate impedance between the two dipoles.

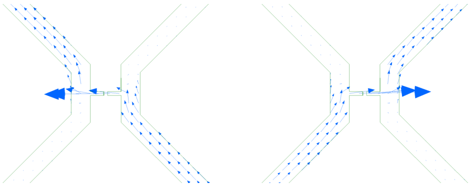
B. Step 2: Converting dipole into quad-pole antenna

Once the physical geometry of the dipoles are known, we modify the geometry of the antenna to form the quad-pole antenna. The antenna geometry is modified to that shown in Fig. 3 with $G = 8$ mm. Then, we added short inductive feed lines to the center of the antenna as shown in Fig. 5 to create a center-fed quad-pole antenna.

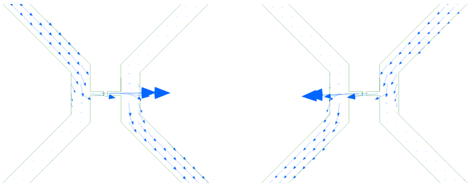
When placed together, the two poles of conjugate phase approximately cancel so that the input impedance is predominantly real, but the current flow in each pole is $\pm 90°$ out of phase with respect to the adjacent poles. We used the MoM tool to simulate the currents at various phase angles. A snapshot of the currents on the center of the antenna at 90° intervals shown in Fig. 6 demonstrate a very strong left-hand transmit circular polarization.

C. Step 3: Adding an impedance matching circuit

The IC impedance we chose to use has a parallel resistance of 350 Ohms and a parallel capacitance of 2.5 pF, which produces a series resistance of 13.3 Ohms and a reactance of $-j66.9$ Ohms at 915 MHz. The quad pole shown in Fig. 5 produces a resistance of 50 Ohms with a small series



(a) 60°	(b) 150°



(c) 240°	(d) 330°

Fig. 6. Simulated currents on antenna at four phase angles: 60°, 150°, 240°, and 330°.

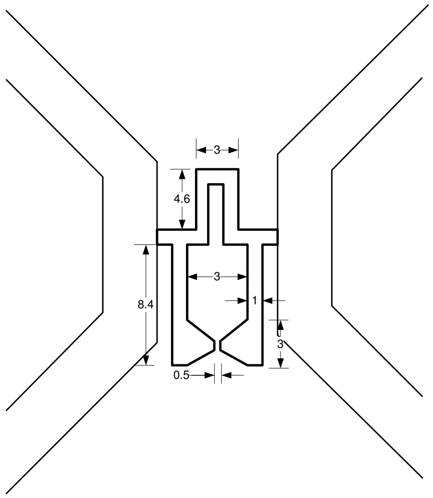


Fig. 7. Geometry of matching circuit. All units are millimeters.

inductance of $j25$ Ohms. A modified T-match [1] is used to provide the impedance matching, shown in Fig. 7.

D. Step 4: Optimize

Note that the antennas are modified to accomodate the matching network, so we expect some small modifications necessary to achieve the desired axial ratio and impedance match. Using simulation, we found the axial ratio was best at 912 MHz with $AR = 0.2$ dB. We were able to further improve the axial ratio to essentially zero at 916 MHz by making small changes to the parameters as follows: $L = 85$ mm, $LA = 28.8$ mm, and $SA = 15.5$ mm.

The resulting return loss of the simulated antenna design with the IC impedance is presented in Fig. 8. Measuring impedance is challenging and error-prone, involving issues outside the scope of this paper, so we rely primarily on simulation for impedance validation. We calculate the power reflection coefficient $|s|^2$, where

$$s = \frac{Z_c - Z_a^*}{Z_c + Z_a},$$

Z_a is the antenna impedance, and Z_c is the IC impedance. The calculated return loss, $20 \log |s|$, of the tag over the frequency band is given in Fig. 8. The tag bandwidth is wide because of its relatively large size.

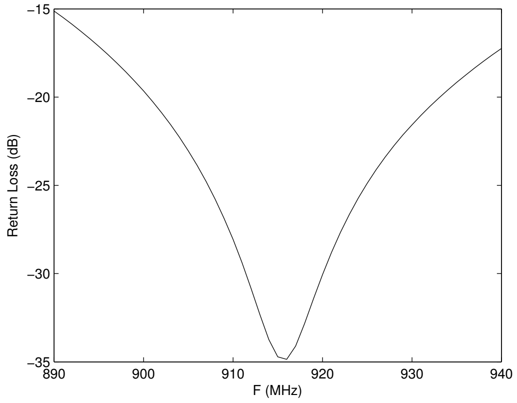


Fig. 8. Return loss of simulated antenna to stated IC impedance.

We estimate the antenna Q_a using the expression

$$Q_a = \frac{1}{2R_a}\left(\omega \frac{dX_a}{d\omega} + |X_a|\right)$$

to be approximately 5.6, and is coupled to an IC with a Q of approximately 5, so we anticipate and observe excellent return loss over band.

IV. EVALUATION OF PROPOSED TAG

We generally assume that an RFID tag-reader system is limited by the reader-to-tag (forward) channel. Thus, in a multi-path free environment, the maximum read distance of an RFID tag can be determined by the following [6]

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r) p \tau}{P_{th}}},$$

where λ is the free space wavelength, P_t is the transmit power, G_t is the transmit antenna gain towards the tag, G_r is the tag antenna gain towards the reader, p is the polarization mismatch, τ is the power transfer efficiency defined earlier, and P_{th} is the minimum (threshold) power required by the IC to respond.

Formally, p can be defined as [7]

$$p = \frac{1 + \rho_t^2 \rho_r^2 + 2\rho_t \rho_r \cos(\vartheta_t - \vartheta_r)}{(1 + \rho_t^2)(1 + \rho_r^2)},$$

where $\rho_t e^{j\vartheta_t}$ and $\rho_r e^{j\vartheta_r}$ are the complex polarization ratios of the reader (transmit) and tag (receive) antennas, respectively.

If the reader is circularly polarized and the tag is linearly polarized, which is commonly the case in practice, then $p = 1/2$. Similarly, when the reader is linearly polarized and the tag circularly polarized, then $p = 1/2$. If both the reader and tag are circularly polarized, then $p = 0$ or 1, depending on whether the polarization handedness is matched or mismatched.

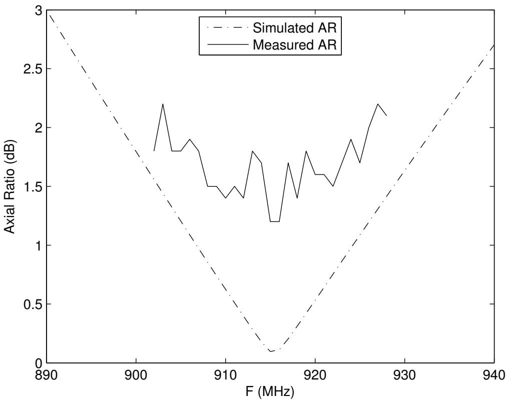


Fig. 9. Simulated and measured axial ratio.

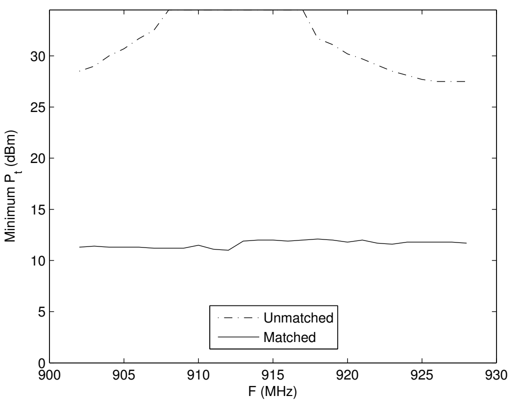


Fig. 10. Measured performance when polarization matched and unmatched with CP transmit antenna.

A. Direct Measurement of Polarization

To test the circular polarization of the tag, we used a variation of the Rotating Source method [7]. We placed the tag one meter in front of the transmit antenna of a bistatic reader system, both antennas oriented broadside. The transmit antenna was a linearly polarized "patch" type antenna with a gain of 6 dBi. The receiver antenna was a circularly polarized antenna with matched polarization. The reader antenna was fixed and the tag was rotated at ten degree intervals from 0° to 180°. At each rotation, we varied the frequency in 1 MHz intervals and the power settings in 0.1 dB intervals. For each angle of rotation, frequency, and power setting, the reader attempted to read the tag for 0.5 seconds. For each angle of rotation and frequency, we noted the minimum power setting necessary to detect the tag at least once.

Here, we note that our measurement system was not precise. For example, without altering any of the physical setup, we would re-run the identical experiment and get, at times, significantly different results. For a certain orientation and frequency, the minimum power to detect a tag was frequently the same, but sometimes varied by as much as 0.6 dB, even after every effort was made to remove any external bias. We conclude that the variance lies within the instrumented reader. More accurate results will require more sensitive equipment than we had available. Despite the challenge of reader precision, we performed the complete experiment. Then, for each frequency, we determined the largest and smallest minimum power setting. The difference between the largest and smallest minimum power setting, along with the axial ratio determined from the MoM code, are plotted in Fig. 9.

We note that the data does indicate that the tag has some axial ratio that is minimum near 915 MHz and appears to be increasing at the edge of the band. The data contains significant "noise," which is consistent with the level of precision observed earlier. While these measurements are somewhat crude, we can conclude that the tag antenna is predominantly circularly polarized, and that the measured minimum axial ratio of 1.2 dB is likely an upper bound.

B. Indirect Measurement of Polarization

Next, we attempt an alternative method to evaluate the polarization of the tag antenna using circularly polarized reader antennas. Using a bistatic antenna in a single orientation, we again changed the frequency and found the minimum reader power required to detect the tag. The reader antenna is an Andrew RFID-900-SC, which is a bistatic circularly polarized "patch" antenna designed to operate over the 902–928 MHz band. We emphasize that these antennas are not highly circularly polarized, and as a patch antenna, is likely to have a significant axial ratio off the center frequency, as well as cross polarization. The two antennas have opposite polarization handedness. We performed two experiments: one in which the transmit antenna was matched to the tag (and the receive antenna mismatched), and one in which the transmit antenna was mismatched (and the receive antenna matched). The results of the two experiments are shown in Fig 10.

We note two important features. First, we note that in the middle of the frequency band, in the mismatched transmit antenna case, the tag became completely unreadable at 1 meter of read distance with a maximum transmit power. This suggests a very high polarization mismatch, indicating that the tag has a very small axial ratio near 915 MHz. Second, we note the minimum read power differs by at least 16 dB over the band, and by as much as 23 dB (and likely more). It is likely that both the reader and tag antennas have significant cross polarization and non-zero axial ratio, which is what we are likely observing here. Again, the difference between the two is a strong indication that the tag polarization is circular with a small axial ratio. If the antenna was linearly polarized or had a strong linearly polarized component, then the difference between the matched and unmatched performance of Fig. 10 would be identical or small.

It is interesting to note that when the tag and receiver antenna experienced a very large polarization mismatch (this happens when the tag and transmit antenna are matched), apparently by more than 23 dB, that did not appear to negatively impact the reader performance. It is also worth pointing mut that the minimum turn-on power in the matched condition at 912 MHz was 11.0 dBm and at 914 MHz was 12.0 dBm; it is unlikely that the tag and reader antenna characteristics vary that rapidly, which again is an indication of the precision of the measurement method.

Since the commercial antennas were not fully characterized and the reader exhibited considerable variance, it is difficult to draw any conclusions with more than 1 dB of precision. Given that margin of error, we can conclude that the tag is indeed circularly polarized. The 23 dB or more difference in minimum detection power between the matched and unmatched case indicates a difference in read distance of a factor of approximately 16 or more, which has very practical significance. More precise testing equipment are necessary to obtain greater confidence.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we present a novel circularly polarized quadpole antenna that is adapted for use as a passive UHF RFID tag. We present a simple design process that can rapidly yield an effective design, and show that an antenna with a very low axial ratio can be achieved quickly and easily. The antenna has excellent return loss over the FCC UHF band.

Experimental measurement of the tag gives strong indication of good circular polarization. The data does indicate that the upper bound on the minimum axial ratio is about 1.2 dB, and that the axial ratio does increase at the edge of the band. Further, the difference between matched and unmatched tag performance varies bewtween 16 and more than 23 dB with commercial RFID reader antennas, which would yield a difference in read distance of a factor of approxiamtely 16 or more. The measured results are thus consistent with simulation results within the precision of available measurement equipment.

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