A Novel Planar Microstrip Antenna Design for UHF RFID

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ABSTRACT

Passive UHF RFID tags generally do not work well near metal or water. Microstrip antennas offer a potential solution, but suffer from manufacturing complexity because a need for via or some other reference to ground. We present a new antenna and matching circuit design using a balanced feed that eliminates any reference to ground and thus simplifies the antenna's construction.

Keywords: *UHF RFID, Microstrip Antenna, Matching network, balanced feed.*

1. INTRODUCTION

Radio frequency identification tag (RFID) has emerged as a promising technology for increasing visibility and efficiencies in the supply chain. In particular Passive UHF (860-960 MHz) tags represent a near optimal combination of cost and performance. Passive UHF RFID systems are increasingly being employed in distribution and supply chains like Wal-mart and Tesco [3]. Recently several government agencies including US-DOD and FDA have issued mandates requiring suppliers to use RFID on their products [4] [5]. Apart from the industrial applications, RFID was used for baggage tracking and access control. Passive RFID tags are available at $0.10 US and can be detected 4 - 7 meters away. Asset tracking is a particularly useful application, since RFID can help in automated tracking of high-value assets. RFID tags perform well in free space [9], but undergo performance degradation when attached to different materials [11]. This loss of performance is because the material characteristics affect critical antenna properties such as substrate dielectric constant and loss tangent, radiation efficiency, radiation pattern, and radiation impedance. UHF RFID tags show performance degradation when placed near high dielectrics and lossy materials (e.g. water) and conductors. Unfortunately many assets are metal made or encased in metal containers.

Active RFID systems offer an alternative to this, but are considerably more expensive. Several attempts [6, 7, 8] have been made to create UHF RFID tags that perform well when attached to metal or plastics. They are mostly, specific models that are pre-tuned to work on different materials [7, 8]. For example a tag designed to work well near metal will still be de-tuned when placed on plastic or near water. Or they are ordinary dipoles or some variation of it encased in rugged plastic cases to shield from the effects of metal and water. One way to achieve uniform performance with different materials is to design an antenna that is electrically separated from the material. Microstrip antennas have a top antenna layer, a substrate and a ground plane. The ground plane separates the microstrip antenna from the material to which it is attached. Microstrip antennas thus offer a potential the metal-water problem of passive UHF RFID.

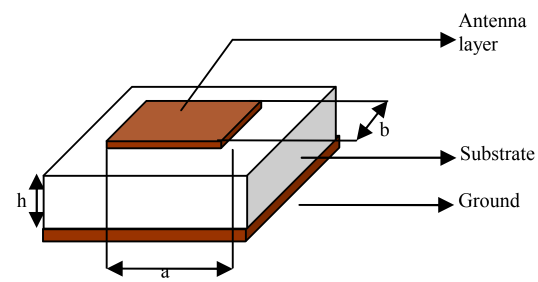

Fig. 1: Basic rectangular microstrip patch antenna construction.

Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. Since the propagating EM fields lay both in the substrate and in free space, a quasi-TEM mode is generated. The length and width of the patch are given by a and b respectively. The substrate thickness is given by h. When $a > b$, the TM_{10} mode is the fundamental resonant mode and TM_{01} is secondary. If dimension along $b > a$, then the order is reversed. Microstrip antenna designs, however, suffer from manufacturing complexity. Most microstrip designs use feed techniques that require connection between the antenna layer and the ground plane. Furthermore, the microstrip patch impedance has to be matched to the conjugate IC impedance in order to enable efficient power transfer. The traditional techniques used for constructing matching networks is by a cross-layered structure, such as a via or a shorting wall. Cross-layer structures require more complex and costly construction. Recently, passive tags that use the inverted F antenna were proposed [1]. These are three layer structures with via connecting across the layers. A more recent advancement was the use of shorting metal plates [2] that eliminates the need for a via. The shorting wall can be viewed as a continuous conductive layer that crosses three layers. While this is an improvement in some ways, it still requires 3-D structure in which the conductors pass between the substrate.

We present here a completely planar microstrip RFID tag design. This implementation does not require any cross-layered structures and hence greatly simplifies tag construction. The new antenna and the matching circuit design using the balanced feed approach eliminates any reference to ground. Current RFID tag technology uses simple tag manufacturing techniques. The tag antenna is printed or etched on an inlay, and the RFID IC is attached to the antenna. The inlay is then attached to a substrate with adhesive. Our design allows microstrip RFID tags to be easily incorporated into such a manufacturing process.

2. APPROACH

Traditionally microstrip antennas are viewed as unbalanced devices. A microstrip feed is single feed that can be designed as probe, edge feed, or aperture feed. The reference is always given with respect to the ground plane. Thus, one end of the RFID IC is connected to the antenna plane while the other end is grounded. (One exception is when a single line feed is split into two feeds 90° out of phase with respect to each other in order to achieve circular or elliptical polarization.) We believe it is this perspective that has lead to various complex microstrip designs.

In contrast, we view the microstrip as a capable balanced-feed device. The premise of our approach is that we use two feeds and two unbalanced transmission lines to effectively create a single (virtual) balanced transmission line. Most microstrip designs use a single microstrip line to feed the patch antenna. Now, instead of using a single microstrip line feed, we use two feeds connected symmetrically about the vertical central axis of the patch as seen in Figure 3. The differential feed to the patch antenna is achieved by using the two symmetric feed lines. The RFID IC is connected to the two feeds.

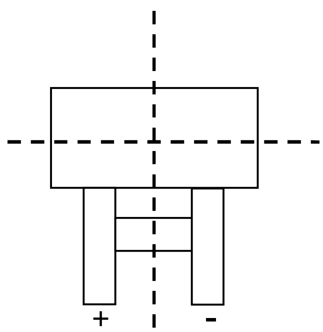

Fig. 3: Dual microstrip line differential feed with shorting stub.

Circuit analysis: From Figure 3 we observe that the patch antenna has E-plane symmetry and is represented by two sections of λ/4 length transmission line sections, where λ is the effective wavelength. In order to make the circuit completely symmetric about the vertical axis, the induced voltage (V_I) along the fringing fields is divided into two equal halves across the plane (see Figure 4). The rectangular patch is a λ/2 transmission line section with both ends having open circuit (Z_R). Applying boundary conditions and using even/odd mode analysis, in even mode the axis of symmetry is an open circuit and current flow due to even mode does not contribute to the radiation of the rectangular patch. The voltages V_1 and V_2 are both equal to zero. In the Odd mode the plane of symmetry is now a virtual ground. The voltage V_1 is equal to V_I / 2 and V_2 is equal - V_I / 2. Therefore, we see that the fundamental solution is where the vertical axis of symmetry is a short circuit. Even mode symmetry does not satisfy these conditions. We can now extend the plane of symmetry to the matching circuit and the load. Therefore odd mode analysis alone is sufficient to describe this circuit. The odd mode representation of the circuit is given my figure 4. As we can see here the E-plane line of symmetry represents the virtual short circuit.

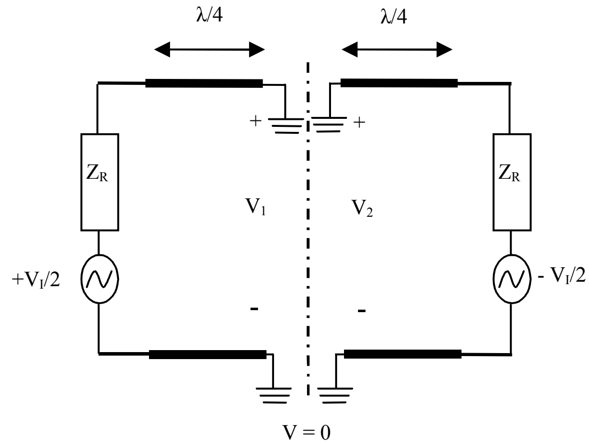

Fig. 4: Odd mode symmetry circuit model

Along with the antenna the two microstrip feed lines also have odd mode symmetry. Here, we conceptually divide the antenna and IC into two halves as shown in Figure 5. The dashed line represents the line of symmetry, and is a line of a virtual short circuit. If one views only the top half with the source impedance, characteristic impedance of the transmission line, line lengths, and the dashed line as a ground, it is apparent that this is a simple, single shorting stub matching circuit. We call this design the dual feed mechanism with a shorting stub matching network.

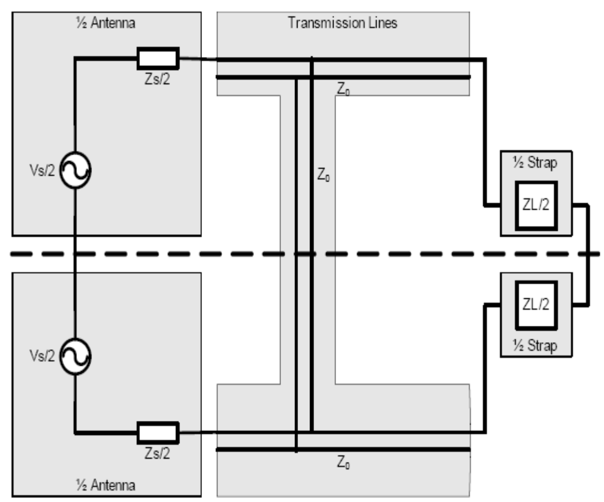

Fig. 5: Circuit model of microstrip patch antenna with balanced feed matching network.

A number of RFID ICs were measured to have resistive impedance in the range 10-50Ω, and reactive (capacitive) impedance of 120-160Ω. The particular RFID IC that we match to is assumed to have an impedance of approximately 15-j130Ω. The matched line lengths are calculated to match the real part of IC impedance and the shorting stubs are used to adjust the reactive component. Thus if we assume the IC impedance to be *R-jX* the load impedance to the patch is matched to *R+jX* (complex conjugate of the IC impedance). The tag design details are discussed in the following section.

3. DESIGN

Our initial design was based on the dual feed approach with a shorting stub matching network as described in Section 2. Here we present two variations of the tag.

Design 1: Our initial design used a pair of high-impedance lines each of 1mm wide and a shorting stub of the same width for the matching network. The entire matching network has a vertical length of 12.4 mm and a horizontal length of 30 mm. The patch length is chosen such that it resonates on the desired substrate between 865–875 MHz, which includes the UHF range of RFID in Europe (865-868 MHz). A 60 mils (1mil = 0.001 inch = 0.00254 cm) material with low loss ($\varepsilon_r = 2.31$, tan δ = 0.0023) is used as the substrate. The feed lines are attached to the non-radiating edge such that they are symmetric about the middle of the patch which acts as a virtual ground. The lines lengths are adjusted to provide the conjugate match to the strap impedance for maximum power transfer. The target port impedance (indicated by a dot in the smith chart) is 15+j150Ω for Design 1. For simplicity, we consider rectangular shaped tags. (Other geometries are planned for future work). The rectangular patch has area 114mm x 35mm. The ground plane is kept 15mm in excess to the antenna dimensions in order to create an infinite ground plane effect. Thus the total size of the antenna is 140mm x 72mm.

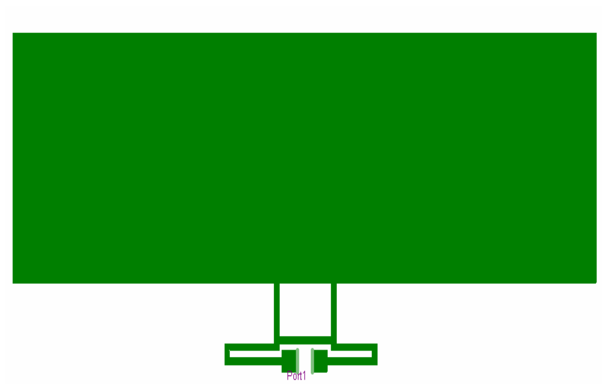

Fig. 6: Design 1- Europe Planar Microstrip RFID tag – top view

The microstrip antenna design was simulated using Ansoft Designer based on the method of moments. The simulation assumes that the antenna is traced on a substrate of given thickness and dielectric properties with an infinite ground plane on the other side. We assume that an infinite ground plane is well-approximated by a 15 mm excess on all sides of the trace for practical applications. The simulation results shown below are plots of the impedance (Ohms), return loss, and gain (in dBi) for designs 1 and 2 over the frequency ranges of 860–875 MHz and 900–930 MHz respectively. The impedance plots shows that the tag resonates at 867.5 MHz and the resistive impedance varies between 2 to 19Ω, and the reactive impedance is between 136 to 155Ω in the given frequency range. The return loss is given by S_{11}(dB). The return loss and gain plots are shown in Figure 8 and Figure 9 respectively.

The following plots show that the maximum power transfer occurs at 867MHz when the return loss is minimum (-43 dB). The matching network provides a narrowband match between 864 to 869 MHz, where the return loss is less than -30dB.

The return loss increases due to mismatch in the impedance and hence power transfer is not maximal, but since it is well under -10dB power transfer is optimal at all frequencies of operation. Simulation shows peak gain input at the resonant frequency. The simulated peak value corresponds to -5.45dBi. The 3dB bandwidth is measured to be 5.1 MHz between 866.2 to 871.3 MHz.

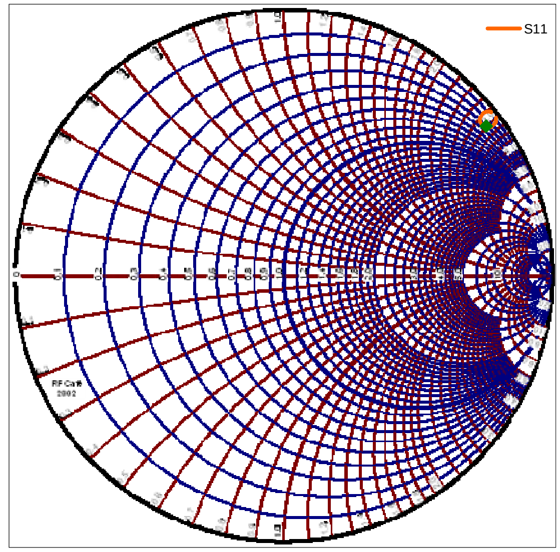

Fig. 8: Design 1- Impedance and S_{11} plotted in Smith chart [10]

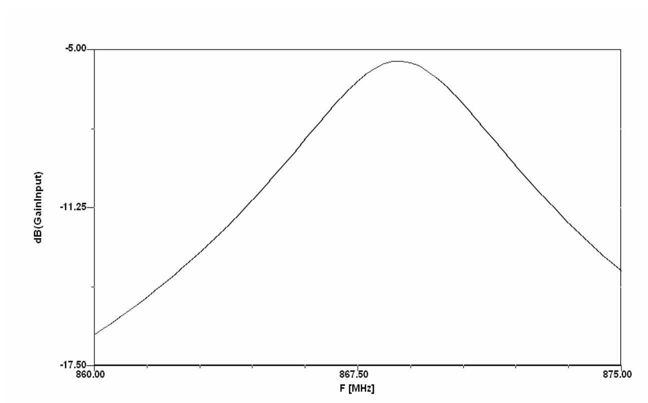

Fig. 9: Design -1 Gain plot

Design 2: This tag is designed to operate in the US Federal Communications commission (FCC) range for UHF RFID (902 to 928 MHz). Tag size is minimized by designing a notch in the rectangular patch thus electrically increasing the length of the antenna, and by imbedding the matching circuit within the patch dimensions as seen in Figure 7. The substrate is 62 mils thickness with ε_r = 2.32, tanδ = 0.0035. Design is optimized using lower impedance (wider) transmission lines to feed the antenna and in the construction of the matching network, thereby reducing conductive losses and maximizing gain. The target port impedance (indicated by a dot in the smith chart) is 30+j110Ω for Design 2.

The tag dimension of Design 2 is 95mm x 29mm. The overall dimension including ground plane is 105mm x 44mm. Prototypes of the novel planar microstrip tag for UHF RFID described above were fabricated and tested. The details of the simulated and measured performances are described briefly in the next section.

Fig.7: Design 2 – FCC Planar Microstrip RFID tag – top view

The tag dimension of Design 2 is 95mm x 29mm. The overall dimension including ground plane is 105mm x 44mm. Prototypes of the novel planar microstrip tag for UHF RFID described above were fabricated and tested. The details of the simulated and measured performances are described briefly in the next section.

Design 2 was also simulated using Ansoft Designer. The impedance, S_{11}, and gain plots for Design 2 are shown in figures 11, 12, and 13. The tag resonates at 918MHz where the real impedance is 84Ω and imaginary impedance is at 127Ω. The return loss however is maintained well under -10dB, enabling good power transfer to occur throughout the bandwidth. The maximum simulated gain is -1.13dBi at 920.5 MHz. The increase in gain is attributed to the use of low impedance feed lines and matching network.

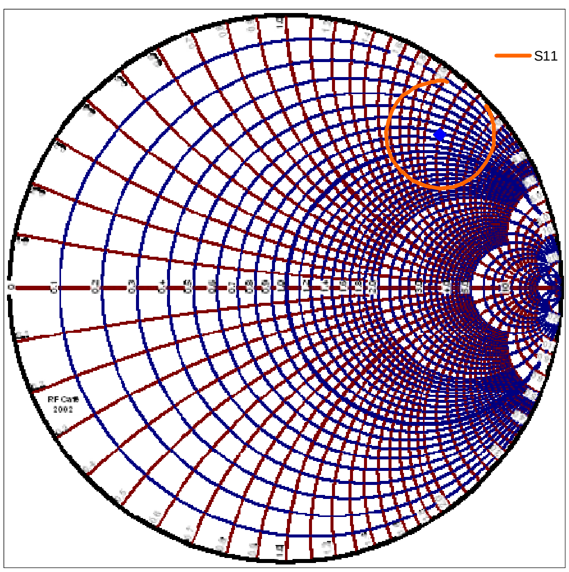

Fig. 11: Design -2 Impedance and S_{11} plotted on smith chart[10]

4. MEASURED RESULTS

Validation of the above simulations was done by fabricating prototype of the Design 1 tag and measuring its performance using readers that are configured to operate in the European and FCC UHF RFID frequencies. The performance characteristics of the tag were measured by comparing it against a commercially available passive UHF RFID tag. The commercial tag we choose is based on the bowtie design and is uses EPC Gen 2 [9] RFID IC technology. The 'turn-on' power is defined as the minimum reader's transmit power with which the tag can be detected at a fixed distance. Our tags and a commercial tag were tested in identical test environments to compare tag performance.

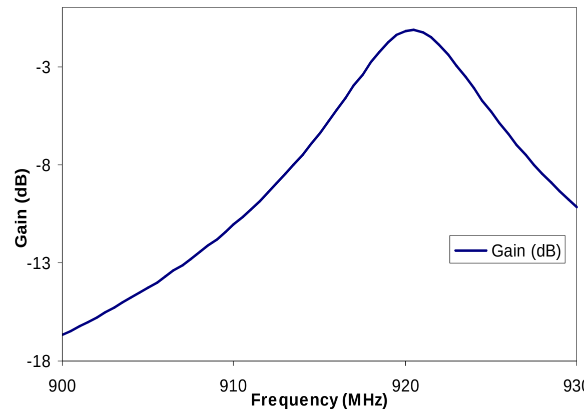

Fig. 12: Design -2 Gain plot

The comparison assumes commercial tag is designed to operate in the FCC frequency band. We performed a frequency sweep from 905 to 926MHz; with increasing attenuation applied to the reader transmit power. Design 1 tag is tested in the European frequencies from 865 to 870MHz. This tag shows a minimum turn-on power of 19 dBi between 865.5–866.5 MHz. The measured results showed that the tag performance was offset in frequency by 2 MHz compared to the simulation results (see Figure 10).

In testing the commercial tag we assume that it is designed with a peak gain of -1.25dBi (predicted by our simulation tools, although it seems low). We performed the frequency sweep and found that the tag has a least turn on power of 21dBm. The difference between the peak gains of our Design 1 tag and the commercially available tag is 4.2 dBi. Hence, we expect that our tag will have at turn-on power ~4 dBm more than the commercial tag. However we notice that our tag turns on 0.5 dBm below the commercial tag. This could be due to the assumes based on which the commercial tag was simulated, conductive losses in etched silver inlay and RFID IC technology used which is different in our tags and the commercial tag, or errors caused by assumptions and approximations in the simulator.

We are currently investigating the causes for the difference in the measured and expected results. This variation could be attributed to the design imperfection in the prototype and also to the impedance mismatch due to manual RFID IC attachment.

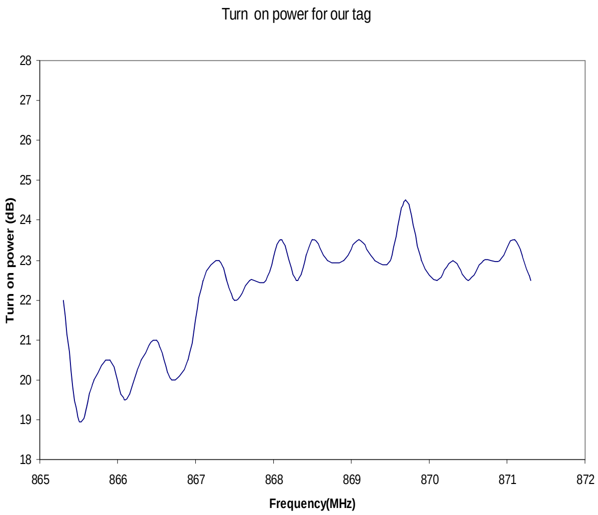

Fig. 13: Turn-power for our tag – Design 1

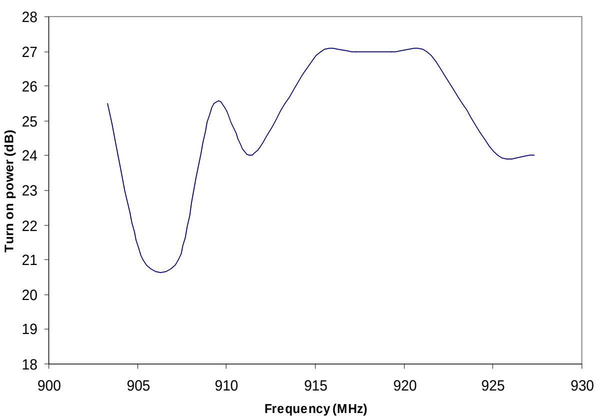

Fig. 14: Turn-power for commercially available tag

5. CONCLUSIONS

We have demonstrated a microstrip RFID tag that is thin and constructed completely of planar elements is possible. The simple, planar nature makes constructing the microstrip RFID tags significantly simpler than those requiring vias or shorting walls. We achieved this by using a balanced feed and matching circuit. Odd-mode analysis and traditional matching circuit techniques can then be used to design the matching circuit. Finally, we presented results that showed good overall performance, but expected narrowband operation.

In the future, we plan to explore matching network designs that are compact and will increase the peak gain. We believe that the tag read distance is gain limited and hence there is ongoing work to make these antennas that have optimal gain characteristics. We are also investigating antenna designs that are resonant at multiple frequencies as a means to obtain acceptable minimum gain over the entire ISM frequency range in both US and Europe. We are also investigating the interaction of the balanced feed and alternative antenna geometries, as well as other matching circuit techniques. We are also working towards developing rigorous test procedures to validate the performance of our tags and to test and compare Design 2 tag performance validation with various commercially available tags

6. REFERENCES

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