A Polarization- and Power-agile Interrogator Antenna for UHF RFID Systems

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Abstract – **We present an active interrogator antenna for UHF RFID (radio-frequency identification) systems which is capable of transmitting electromagnetic radiation at any desired polarization and with adjustable transmit power. We use a dual-polarized patch antenna originally radiating linear polarization in +45° and -45° direction and feed each input with signals that can be adjusted in both phase and amplitude by two vector modulators. The vector modulators are controlled by a microprocessor that provides an RS-232 interface. The antenna also comprises power amplifiers to achieve a maximum transmit power of 2 W at any desired polarization mode. For testing we perform measurements that determine the radiation pattern and polarization mode of a commercially available transponder and find very good agreement with simulation results.**

1 INTRODUCTION

In RFID (radio-frequency identification) systems transponders that consist of a transponder chip and an antenna are used to track and identify objects or individuals remotely, without the need for visual or physical contact. Therefore, a passive transponder (or tag) is placed into the electromagnetic field produced by an antenna which is connected to an interrogator (or reader). The energy received by the transponder antenna is used to power the transponder chip which can then communicate with the interrogator by the mechanism of passive backscattering [1][2].

The most challenging task in making an RFID system reliable is to optimize the radio transmission between the interrogator and the transponder. Since the maximum transmit power of the interrogator is limited by local authorities and the minimum operating power needed by a modern transponder chip is very high compared to the sensitivity achieved with externally powered receivers, a radio transmission loss of some 40 dB to 50 dB must not be exceeded. This is particularly difficult in RFID applications because in most cases the orientation of the objects and hence the transponder antenna in space is unknown and polarization mismatching can lead to an increased path loss. A common technique to avoid polarization mismatching is to use linearly polarized transponder antennas and circularly polarized interrogator antennas (or vice versa). However, this measure comes with an increase in the radio transmission loss of 3 dB—theoretically. In fact, when transponder antennas are put onto the object that is to be identified their radiation behavior will change. This is a result of the transponder antenna interacting with the conducting, dielectric, or ferromagnetic materials contained in the object. A dipole-like transponder antenna may then radiate some elliptically polarized waves instead of pure linear polarization. Furthermore, some transponders—like the one investigated in this paper—radiate linear, circular, or elliptical polarization depending on the angular region that is investigated, even when placed in free space.

It is thus obvious that the radio transmission can be made much more reliable if one controls the polarization mode of the interrogator antenna or—equivalently speaking—granting polarization matching between the transponder antenna and the interrogator antenna. However, this demands to produce any elliptical polarization mode. Polarization-agile antennas that allow to switch between some pre-defined modes like the ones presented in [3] or [4] are not sufficient. Furthermore antennas that utilize varactor diodes [5] can hardly handle the transmit power required for RFID systems without producing significant spurious emissions.

The design of the active antenna used to achieve polarization matching and the simple means of calibrating the antenna is described in Section 2. The measurement procedure that was invented to determine the radiation pattern and polarization mode of any passive transponder is explained in Section 3. Test results of an AD-840 transponder by Avery Dennison are given in Section 4 and are compared to simulation results obtained with HFSS by Ansoft. In Section 5 further applications that are enabled by this new antenna are itemized and conclusions are drawn.

2 ACTIVE ANTENNA

The active antenna consists of a cross-polarized square-patch antenna that has separate inputs for linear polarization in +45° and -45° direction. We feed each input with signals that can be adjusted in both phase and amplitude by two vector modulators. The vector modulators can be electronically controlled by a

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measurement host. The antenna also comprises power amplifiers to achieve a maximum transmit power of at least 2 W at any desired polarization mode.

2.1 Patch antenna

A microstrip square-patch antenna serves as a radiator to produce linearly polarized radiation in +45° and -45° direction. The 45° tilt of the patch antenna axis with respect to the horizontal/vertical measurement coordinate system was chosen to allow a total radiated power of 4 W for either pure horizontal or pure vertical polarization. This is achieved by constructively superposing the 2 W of transmit power delivered to each antenna input by the two power amplifiers.

The antenna is manufactured of two aluminum plates—the ground plane and the patch. The plates are separated by a 6 mm thick layer of acryl glass with a relative permittivity of $\varepsilon_r = 2.51$ that accounts for some size reduction. Nylon screws are used to hold the stack together. Two metal screws are used to directly feed the patch. These screws reach through holes in the acryl glass layer and the ground plane and are electrically connected to the printed circuit board that is mounted to the back of the antenna. The patch antenna has a center frequency of 864 MHz and a bandwidth of 15 MHz. The axial ratio is well above 30 dB.

2.2 Feeding circuitry

The patch antenna is fed by a circuit that is realized on an 0.8 mm thick glass fiber enforced substrate with a relative permittivity of $\varepsilon_r = 4.4$. The circuit consists of a Wilkinson power divider that splits the input signal into two equal parts. Each signal is then fed through a vector modulator (AD8340 by Analog Devices) that allows electronic adjustment of amplitude and phase shift of the passing signal by two analog control voltages. After calibration a dynamic range of more than 30 dB and full control of the phase is provided. The signals are then fed through pre-power-amplifiers (MGA-30116 by Avago) and finally through power-amplifiers (ALM-32120 by Avago) that deliver 2 W to each of the antenna ports.

A small portion of each transmit signal is diverted to two power detectors by using resistive couplers. These detectors are used in a calibration process that corrects the major imperfections introduced by the nonlinear elements, which are

- zero-transmission setting of each vector modulator,
- a variation of the vector modulator gains versus phase setting,
- compression of the vector modulators, and
- compression of the power amplifiers.

The phase of the two output signals with respect to each other is calibrated by testing of a transponder with a linearly polarized antenna that resides vertically or horizontally in front of the antenna. While transmitting with equal power on both the +45° and -45° antenna input, the phase between the transmit signals is varied until no more response of the transponder is detected because of destructive interference of the transmitted waves along the transponder axis. Consequently this means that the transmitted signals have a phase difference of exactly 0° or 180° for horizontal or vertical alignment of the transponder, respectively. The so found phase relation is then used for calibration. This calibration is most accurate because it also mitigates phase shifts caused by imperfect impedance matching of the power amplifier outputs and the antenna ports.

Figure 1 shows a photograph of the patch antenna's rear side. The RF circuitry consisting of the Wilkinson power divider, vector modulators, pre- and power-amplifiers is seen on the left. The power detectors are connected to the outputs with SMA connectors. Some fixed attenuators are inserted to make full use of the dynamic range of the power detectors.

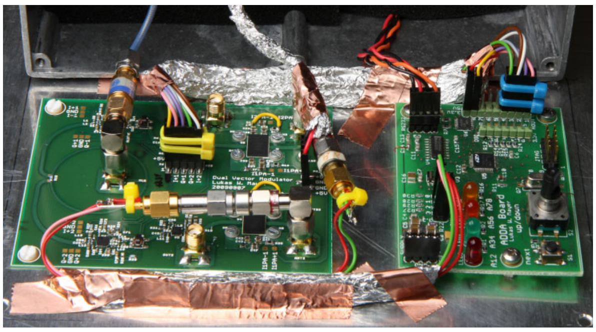

Figure 1: Photograph of the patch antenna's rear side with the RF feeding circuitry (left) and the microprocessor circuit board for analog control (right).

2.3 Control hardware

A second circuit board was designed to control the vector modulators and read the detector output voltages. A microcontroller (C8051F016 by Silicon Laboratories) provides 10 bit A/D converters and controls 12 bit D/A converters. The circuit has an RS-232 interface which allows to take full control of the antenna by use of a host computer running Matlab. The hardware for controlling the antenna is seen on the right in Figure 1.

3 TEST PROCEDURE

In this section we perform a test measurement with our interrogator antenna and present a novel method to characterize both the radiation pattern and the polarization mode of transponder antennas. For the transponder-under-test, we chose an AD-840 transponder by Avery Dennison that

- radiates different polarization modes—including elliptical polarization—and has a
- very simple structure to make possible accurate simulation to generate theoretical results for validating the measured data.

It consists of a rectangular aluminum metallization that has a meandered slot entering from the broadside. The transponder chip's terminals are connected across the slot at a certain position to achieve optimal impedance matching. The transponder antenna does not show narrow metal structures or fine meanders which would make simulation results less reliable because of the imperfect modeling of the losses in the thin conducting sheet. In Figure 2, the simulation model set up in HFSS along with the selected coordinate system for simulation and measurement is displayed.

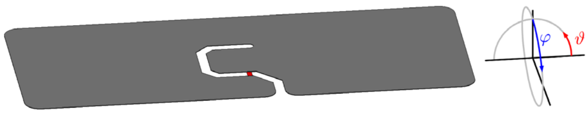

Figure 2: Simulation model of the AD-840 with coordinate system.

3.1 Measurement method

The measurement setup consists of the polarization- and power-agile interrogator antenna which is connected to a UHF RFID long-range interrogator (ID ISC.LRU2000 by Feig Electronic). This device uses one antenna port for simultaneous transmission and reception. Since this interrogator antenna cannot be used for signal reception, a circulator is used to split the transmitted and received signals. The transmit signal is fed into the interrogator antenna. A second antenna that picks up the transponders response is positioned below the interrogator antenna and provides the receive signal.

The transponder-under-test is mounted in a rotation apparatus that is manufactured of low permittivity foam material (Rohacell with $\varepsilon_r = 1.05$). The rotator can point the antenna at any azimuth and polar angle without interfering with the electromagnetic field. A similar setup with such a low-interfering rotator was already described in [6].

For a series of azimuth and polar angles, the transponder is radiated with differently polarized waves that are modulated with an inventory command which is issued by the interrogator. A successive approximation routine is used to find the exact transmit power at which the transponder barely responds. The polarization modes investigated are:

1. linear horizontally polarized (LINH),
2. linear vertically polarized (LINV),
3. left hand circularly polarized (LHCP),
4. right hand circularly polarized (RHCP), and
5. +45° linearly polarized (LIN45).

From the results, the parameters of the generally elliptical polarization are calculated. The magnitude of the horizontal and vertical electric field components comes directly from the measurement with LINH and LINV, respectively. The phase offset Ψ between the horizontal and the vertical electric field component is calculated twice, once from the results of the LINH, LINV, and LHCP measurements, and once using the respective result from the RHCP measurement. The so determined phase offset angels are then compared and the mean value is used. Please note, that the phase offset angle Ψ determined from these factors yields a range of -90° to +90° only. To determine whether the major axis of the polarization ellipse has positive or negative tilt, the LIN45 measurement is used to extend the Ψ range to full -180° to +180°.

4 TEST RESULTS

4.1 Visualization of antenna pattern and ellipticity

For easy perception, we compile the acquired data into a two-dimensional plot that unwraps the surface of a sphere around the antenna into a rectangle. Each measurement at a certain azimuth angle φ and polar angle ϑ is represented by a square within this rectangle. On the one hand, the color of the square maps to the total normalized field that is radiated in the given φ and ϑ direction, regardless of the polarization mode. The polarization mode on the other hand is depicted by a small ellipse showing the path of the electric field vector in the plane orthogonal to the direction of propagation. An arrow somewhere on the ellipse gives the direction of rotation.

4.2 Interpretation of the measurement results

Figure 3 and Figure 4 show the simulated and measured results of the AD-840 transponder. It can be seen that there is excellent agreement which confirms the measurement method on the one hand and the functionality and calibration of the interrogator antenna on the other hand. It is hard to determine whether the residual deviation is caused by a minor interfering of the rotation apparatus with the transponder antenna, or by imperfect calibration of the interrogator antenna.

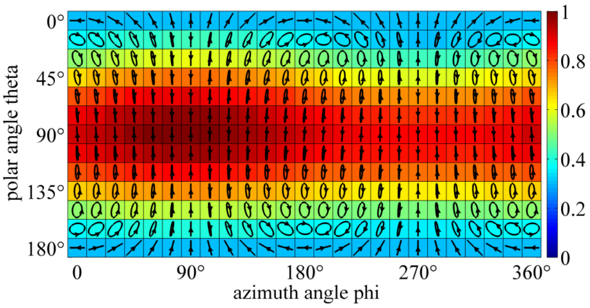

Figure 3: Simulated radiation pattern and polarization mode of the AD-840 transponder versus φ and ϑ.

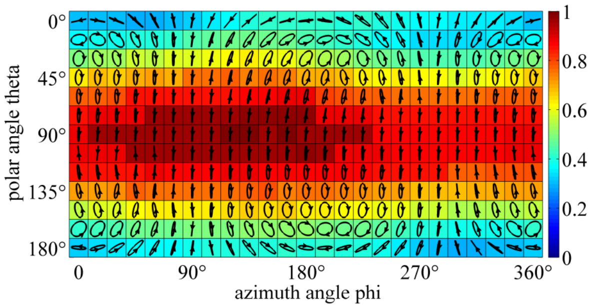

Figure 4: Measured radiation pattern and polarization mode of the AD-840 transponder versus φ and ϑ.

It is seen that the AD-840 radiates dominantly vertical polarization in the H-plane (ϑ = 90°) which is very similar to a dipole. This radiation is caused by a strong surface current that flows *along* the rectangular antenna metal. But, it also radiates elliptic polarization at angles closer to the poles. This is caused by additional surface currents flowing along the meandered slot and mainly *across* the rectangular antenna metal. At the poles at ϑ = 0° and ϑ = 180°, only these surface currents contribute to radiation which is why linear polarization is observed that rotates with the azimuth angle φ.

5 CONCLUSION

The antenna described in this contribution is considered very versatile. First, it was shown that it can be used as a measurement device for characterizing the radiation pattern and the polarization mode of transponder antennas with high accuracy at reasonable effort. To the knowledge of the authors, no such measurements on RFID tags have been completed so far. Second, its deployment in an RFID system allows to achieve polarization matching with transponders. This reduces the required transmit power or enables higher read-range without violating the emission limits set by local authorities. Third, it can bring totally new functionality to RFID systems like

- the estimation of the physical orientation of transponders, or
- inhibiting the response of a particular transponder by radiating its orthogonal polarization.
- Scanning different polarization modes one after another requires only transponders with matching polarization to respond which reduces collisions and allows shorter inventory rounds.
- With the elimination of the polarization mismatching loss, there might even be the possibility to estimate the distance between a transponder and the interrogator antenna.
- When more such polarization-agile antennas are used for transmitting, the individual phase and amplitude adjustment enables transmit-beamforming at any given polarization mode which allows to scan selected spatial regions one after another, or to estimate a transponder's position.

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