Circularly Polarized Patch Antenna with High Tx / Rx-Separation

Lukas W. Mayer and Arpad L. Scholtz
Vienna University of Technology
Institute of Communications and Radio-Frequency Engineering
Gusshausstrasse 25/389, 1040 Wien, Austria
Email: lukas.mayer@nt.tuwien.ac.at

***Abstract*—In this contribution an antenna is described that allows simultaneous transmission and reception in the same frequency band. Circular polarization is employed for a most reliable communication with radio frequency identification (RFID) transponders that typically have linearly polarized antennas. To achieve high separation between transmitted and received signals, a square patch antenna originally transmitting horizontally and vertically polarized radiation is combined with a 3 dB-hybrid circuit. With this hybrid circuit the antenna can simultaneously radiate a right-hand circularly polarized wave and receive a left-hand circularly polarized wave. Furthermore, the transmit signal that is unintentionally leaking into the receive path can be compensated by tuning the hybrid circuit with two variable capacitance diodes. At 866 MHz a maximum Tx / Rx-separation of 65 dB was achieved in a static scenario. In a time variant indoor scenario with a metal object moving on a conveyor belt a Tx / Rx-separation of more than 52 dB was achieved by continuously tuning the hybrid circuit with a minimum-search algorithm.**

I. Introduction

Antennas that are simultaneously used for transmitting and receiving signals at one single carrier frequency are required in a variety of applications like radar or radio frequency identification (RFID).

In RFID applications power and data are transmitted in the same frequency band. Transponders have to be continuously supplied with power radiated by the reader antenna—also during data transmission from the transponder to the reader. This data transmission is achieved by a modulation of the transponder antenna load which intelligibly causes a very weak returned signal—at least in comparison to the power continuously radiated to supply the transponder.

Thus, an important property of an RF-frontend or an antenna used for RFID readers is its ability to separate the received from the transmitted signal (Tx / Rx-separation α). The following options are commonly used to achieve Tx / Rx-separation:

- A directional coupler or a circulator can be used to separate the incident and the reflected wave at the antenna port. Imperfect matching—which comes along with every antenna—causes some of the transmit power to be reflected at the antenna input. Thus, with a directional coupler or a circulator the Tx / Rx-separation is limited to the antenna's return loss. A tunable antenna [1] might bring an improvement, but a further degradation of performance can be expected from the imperfect coupler or circulator. Typically, only a Tx / Rx-separation of $\alpha < 20\,\text{dB}$ can be achieved.
- Antennas that transmit and receive waves having different polarization are usually a better choice to achieve decent Tx / Rx-separation. Such antennas have more ports—one for vertical and one for horizontal polarization, for instance—and are optimized for high cross-polarization ratio. Often, hybrid circuits are used to feed such antennas which provides different polarization modes [2], [3]. Tx / Rx-separation of $\alpha \approx 30\,\text{dB}$ can be achieved with such antennas [4].
- If Tx / Rx-separation is to be improved beyond that, active decoupling methods are necessary. Basically, a version of the transmitted signal that can be adjusted in delay and amplitude is added to the signal returned from the antenna. If delay and amplitude are correctly set, the transmit signal that leaks into the received signal is canceled [5], [6].

For best Tx / Rx-separation as required in future RFID applications, we combined a dual-polarization antenna with an active Tx / Rx-decoupling circuit. The decoupling circuit is directly mounted on the antenna.

The operation principle of the antenna is described in Section II. A modified 3 dB-hybrid circuit (Section III) is used to feed the antenna inputs. The hybrid can be connected to the transmit output of an RFID frontend. The receive output of the hybrid then provides the received signal to the frontend. Measurement results of the antenna performance are presented in Section IV. Methods for optimizing the antenna for RFID systems are described in Section V. Section VI discusses the applicability and benefits of the antenna in future RFID systems and draws conclusions.

II. Antenna principle

Since in RFID systems circularly polarized radiation is favored to account for the unknown orientation of transponder antennas, an antenna was built that transmits right-hand circularly polarized waves and receives left-hand circularly polarized waves. This is achieved by a combination of a cross-polarized antenna originally radiating horizontal and vertical polarization and a 3 dB-hybrid circuit also known as a branch line coupler. The basic property of the hybrid is splitting the power incident at one of its ports into two equal parts with a phase difference of $+90\,^\circ$ or $-90\,^\circ$—depending on which port was chosen. This can be exploited to achieve right-hand and left-hand circular polarization by using a dual-input cross-polarized antenna. Due to the theorem of reciprocity, the antenna with the hybrid can be used to either transmit or receive circularly polarized radiation. For this application a right-hand circularly polarized wave is radiated by applying

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power to the first port of the hybrid. The second port of the hybrid on the other hand will be used to receive a left-hand circularly polarized wave.

If the hybrid circuit and the antenna inputs are well matched and the antenna is operating in free space—ideally—no power is present at the left-hand circular port when transmitting on the right hand-circular port of the hybrid. In practice however, a Tx / Rx-decoupling of approximately 30 dB has been achieved with a generic hybrid circuit and a square patch antenna built in house. The measurement was carried out in an anechoic chamber.

In the real world manufacturing tolerances and—more importantly—the reception of electromagnetic waves that are reflected at objects in the proximity of the antenna impair the Tx / Rx-separation. It is in the nature of RFID systems that the environment around the antenna changes versus time. Consequently, the signal power at the receive port changes as well and makes the detection of weak signals returned by a transponder more difficult. In this case the Tx / Rx-separation can be improved by adaptively tuning the hybrid circuit.

III. Tunable hybrid

The use of variable capacitance diodes inserted in hybrid couplers has been known for long. Most recent advances are presented in [7], where the center frequency of a coupler is adjusted to allow switching between several narrow frequency bands. Varactor diodes were also used in a hybrid circuit by Ferrero [8] to reconfigure an antenna to allow different polarization modes. In this work however, the maximization of the Tx / Rx-separation of an antenna is achieved by inserting two variable capacitance diodes into a hybrid circuit. By applying two reverse voltages to the varactors the RF signals that are passing through them can be controlled separately. The diodes are placed across gaps in each of the two transmission lines of the hybrid that lead to the receive port (see Figure 1). Furthermore, the diodes are placed a quarter wavelength apart from each other (equivalent to a $90\,^\circ$ phase shift) which enables to separately control the in-phase and the quadrature component of the signal that is coupled from the transmit port to the receive port of the hybrid. The control voltages are applied to the diodes by quarter wavelength transmission lines that isolate the RF signal from the control voltage source. With every diode there is also a bypassing capacitor that blocks the control voltages from the ports of the hybrid.

To allow a cancelation of signals with arbitrary phase shift and power, the hybrid was simulated in ADS and modified in it's dimensions. It was optimized to work similar to a generic hybrid with both varactors set to the middle of their tuning range. The full tuning range of the varactors allows to couple a small part of the transmit signal to the receive port with any phase shift between $0\,^\circ$ and $360\,^\circ$. The maximum power of this coupled signal is 20 dB below the input signal power. This allows to fully compensate a similarly weak parasitic signal that is leaking into the receive port by adjusting the two varactor voltages. With this arrangement, imperfections of the patch antenna as well as received sinusoidal signals caused by

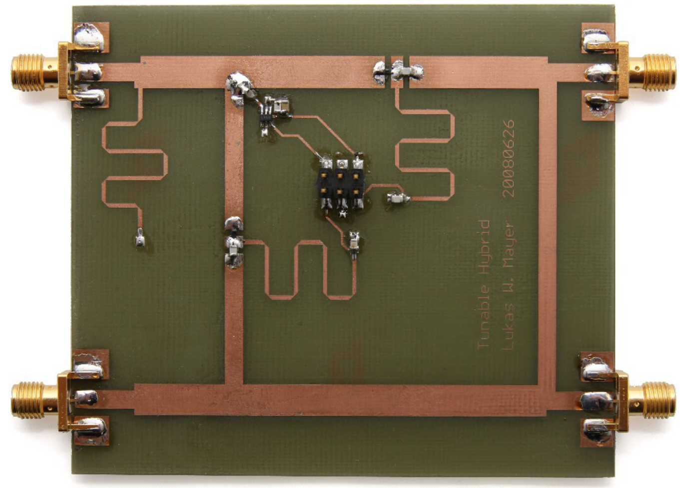

Fig. 1. Tunable 3 dB-hybrid circuit. The Tx-input connector is on the lower left (port 1), the Rx-output connector is on the upper left (port 2). The vertical and horizontal input of the cross-polarized antenna is wired to the upper right and the lower right connector, respectively (port 3 and port 4). The detector is seen in the upper left corner of the hybrid. Varactor diodes are placed in the middle of the upper and in the middle of the left transmission line of the hybrid. Thin meandered quater-wave microstrip-lines are used to apply the control voltages to the varactors. The connector in the center is used to interface to an automatic tuning hardware.

reflection of the radiated signal in space can be compensated. Please note the thick microstrip lines that extend to the left of the hybrid circuit (Figure 1). These lines were inserted to improve matching between the microstrip patch antenna and the input and the output port.

For testing, a version of the tunable hybrid with SMA connectors was manufactured and characterized with a 4-port vector network analyzer. Prior to the measurement, the hybrid was tuned to achieve best isolation at 866 MHz. The measured scattering parameters of the hybrid circuit at 866 MHz are

$$S = \begin{pmatrix} -38.1\,\mathrm{dB} & -52.1\,\mathrm{dB} & -4.0\,\mathrm{dB} & -3.3\,\mathrm{dB} \\ -68.8\,\mathrm{dB} & -11.1\,\mathrm{dB} & -4.0\,\mathrm{dB}\angle-168.8\,^\circ & -4.5\,\mathrm{dB}\angle 83.6\,^\circ \\ -4.0\,\mathrm{dB}\angle 95.7\,^\circ & -4.0\,\mathrm{dB} & -15.1\,\mathrm{dB} & -27.2\,\mathrm{dB} \\ -3.3\,\mathrm{dB}\angle 166.1\,^\circ & -4.5\,\mathrm{dB} & -28.2\,\mathrm{dB} & -24.0\,\mathrm{dB} \end{pmatrix}$$

where port 1 is the transmit input and port 2 is the receive output. The cross-polarized antenna is connected to port 3 and port 4. The less relevant S-parameters are shown in grey.

From the S-parameters it can be seen that the hybrid circuit introduces losses of approximately 1 dB for the transmit and also for the receive path. This shows that a very power efficient tuning of the branch line coupler is achieved. The losses caused by the varactor diodes in the receive path are similar to the losses caused by the microstrip lines in the transmit path. Furthermore, there is a slight deviation from the expected 90° phase shift between the two antenna ports. In practice, this will result in a not perfectly circularly polarized transmitted and received wave. However, the cross-polar discrimination is still 15 dB for transmitting and 16 dB for receiving [9]. For RFID applications where the circular polarization is only required to gain independence of the transponder's orientation, this is fairly enough.

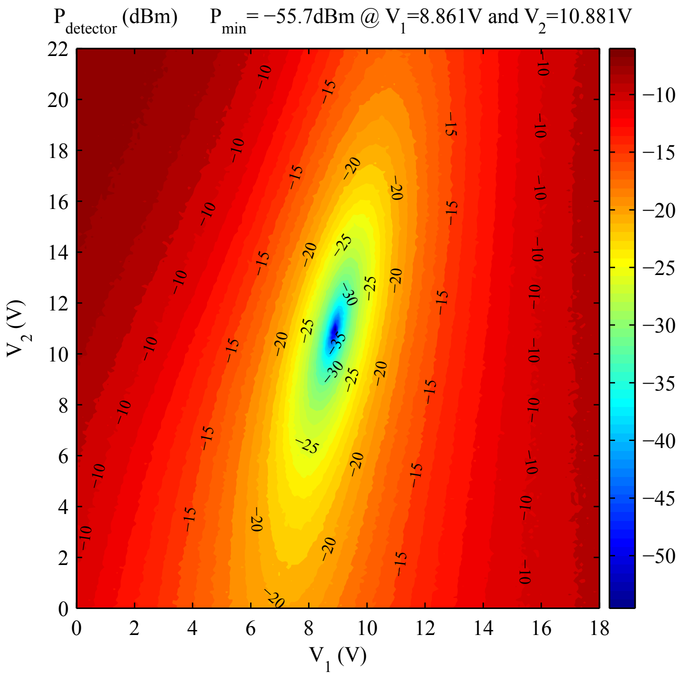

Fig. 2. Output power versus diode tuning voltages V_1 and V_2.

For monitoring the power at the receive port, a power detector is placed in the corresponding corner of the hybrid. The detector provides an output voltage that is proportional to the logarithm of its input power. It's output voltage can be used to optimize the Tx / Rx-separation by setting the varactor voltages automatically with a minimum-search algorithm.

IV. Performance testing

By measurement in an anechoic chamber, the basic behavior of the cross-polarized microstrip patch antenna with the hybrid circuit attached was determined. Therefore, the detector power—or equivalently speaking the power at the receive port—was measured versus the varactor tuning voltages V_1 and V_2. In Figure 2 it is seen that a minimum detector power of $P_{\text{detector}} = -55.7\,\text{dBm}$ is achieved at $V_1 = 8.86\,\text{V}$ and $V_2 = 10.88\,\text{V}$. The measurement was taken with a 10 dBm sinusoidal signal at the transmit port. Thus, a maximum Tx / Rx-separation of 65.7 dB was achieved in this static scenario.

It should be noted that the minimum power at the receive port can in fact be much smaller than the detector readout. This is due to the limited dynamic range of the detector chip which has an RF input power range between -60 dBm and 0 dBm. In fact, measurements with a spectrum analyzer and manual tuning of the varactor reverse voltages led to a Tx / Rx-separation of more than 80 dB. We thus see great potential in this design when equipped with a more sensitive power measuring device.

In time variant scenarios where objects moving in space introduce reflections, the varactor voltages V_1 and V_2 have to be continuously adjusted to keep the Tx / Rx-separation as high as possible. In the contour plot shown in Figure 2 time variance will cause a movement of the minimum power position.

Digital signal processing hardware was used to implement a simple minimum-search algorithm that continuously tunes the varactor voltages V_1 and V_2 based on the detector power P_{detector}. Testing the automatic tuning algorithm was done with the following measurement procedure:

- The antenna with the tunable hybrid and the automatic tuning circuit was mounted on a pole in an anechoic chamber.
- 15 cm in front of the antenna a half-wavelength copper strip mounted on a conveyor belt was placed. This metal causes a very strong reflected signal and is used to fathom the antenna performance. When the conveyor belt moves, the metal sweeps past the antenna. At $x = 0\,\text{m}$, the metal resides directly in front of the antenna.
- The transmit port of the antenna is fed with a 10 dBm sinusoidal signal.
- The power at the receive port was recorded by reading the detector voltage while the metal was swept past the antenna.
- The conveyor belt with the metal was moved from $x = -0.5\,\text{m}$ to $x = 0.5\,\text{m}$ twice. First with constant varactor voltages that were tuned to achieve best Tx / Rx-separation in the empty chamber. This case is equivalent to a patch antenna fed by a generic hybrid circuit that is optimized to have best Tx / Rx-separation in free space. In the second sweep, the hybrid circuit was continuously adjusted by tuning the varactor voltages with a minimum-search algorithm.

The result of the measurement is seen in Figure 3. For the case with constant varactor voltages, a 45 dB variation of received power is encountered while the reflecting metal is moving. Especially at $x = 0\,\text{m}$, where the reflecting metal is closest to the antenna, a strong signal is present at the receive port. Still, a Tx / Rx-separation α of 20 dB is retained. This is due to the highly optimized antenna and hybrid circuit.

Secondly, during the sweep with the continuous minimum-search algorithm switched on, the detector power remains below $-42\,\text{dBm}$. With the transmit power set to 10 dBm, this corresponds to a Tx / Rx-separation α well above 52 dB. This is an improvement of 32 dB compared to fixed varactor voltages (or a generic antenna of this kind). The ripple in the detector power is caused by the minimum-search algorithm. We are confident that this ripple can be reduced to less than 1 dB by implementing a better algorithm. With this, a Tx / Rx-separation of approximately 60 dB will be achieved.

In Figure 4 the varactor tuning voltages V_1 and V_2 are shown as a function of conveyor belt position x. Four test scenarios have been characterized. First, a metal reflector was placed on the conveyor belt. Because the reflected signal that has to be canceled by the hybrid circuit is strong, the varactor voltages vary most for this test case. Furthermore one single RFID transponder was put on the conveyor belt. Since the signal reflected by this tag is by far weaker than the signal reflected by the metal, the varactor tuning voltages vary less. A similar result is obtained with six different transponders attached to

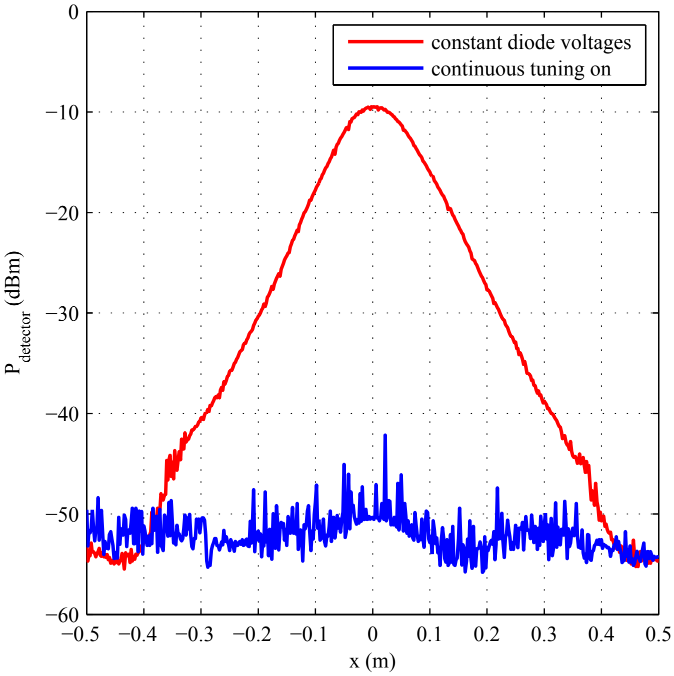

Fig. 3. Detector power (equivalent to receive port power) versus position of a metal reflector sweeping past the antenna on a conveyor belt. At $x = 0$ m the metal resides directly in front of the antenna.

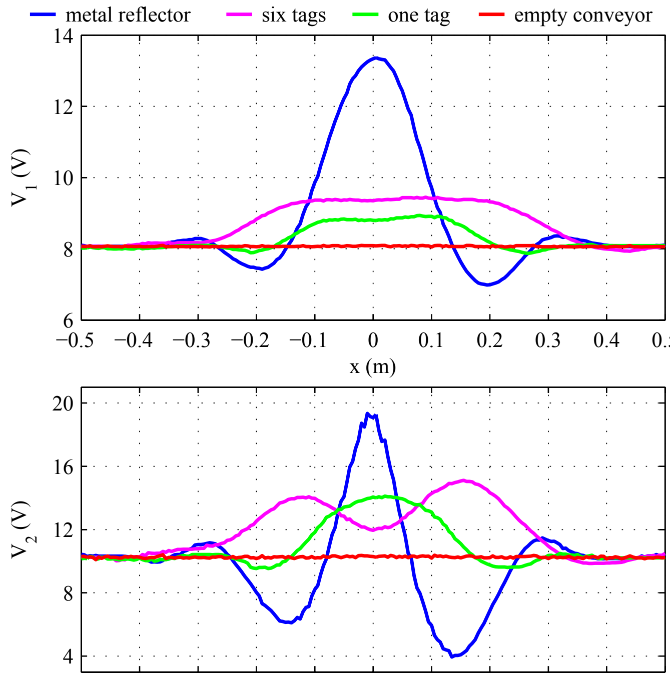

Fig. 4. Automatically tuned varactor voltages V_1 and V_2 during test runs with a metal reflector, one single RFID transponder, and 6 transponders positioned next to each other on the conveyor belt passing by the antenna. For reference, a measurement with the empty conveyor belt is also shown.

the conveyor belt with some 80 mm distance from each other. For reference, a measurement with the empty conveyor belt is also shown. During all four measurement runs, the Tx / Rx-separation remained well above 52 dB.

V. Considerations for Automatic Tuning

With this antenna an improvement in reading RFID transponders is achieved because imperfections of the antenna itself as well as parasitic sinusoidal signals that fade in and out versus time are suppressed. The response of a transponder on the other hand is a fast modulated reflected signal only present for a short period of time. Of course—in theory—a very fast minimum-search algorithm could cancel the response caused by a transponder too. However, if the designer of the algorithm has good knowledge of the temporal behavior of the scenario, a minimum-search algorithm can be parameterized that levels out reflected signals that do not carry information, while letting signals returned by transponders pass directly to the receive port. Another option is of course to halt the minimum-search algorithm for the time a tag's response is expected (e.g. after an inventory command) and engage it afterwards. This also eliminates possible interference of the minimum-search algorithm during a tag's response. Whichever way is preferred, the result is that the superimposed carrier signal is strongly reduced while the transponder's response passes directly to the receive port which makes detection a lot easier.

VI. Conclusion

The employment of this antenna with high Tx / Rx-separation in an RFID system enables to receive weak signals returned from transponders at less effort compared to conventional antennas. This allows cheaper RF-frontends because an expensive circulator or directional coupler are not required and—as long as digital signal processing hardware is used—less dynamic range is needed at the receiver. Furthermore, the suppression of the transmitted signal is directly done at the antenna where the received signal has the best signal-to-noise ratio. With a low-noise amplifier directly connected to the receive port of the antenna this signal-to-noise ratio can be well preserved, even if the antenna cable leading to the RFID reader frontend is long and lossy.

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