A Dual-band HF / UHF Antenna for RFID Tags

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***Abstract*—Conventional RFID (radio frequency identification) systems operating at one single carrier frequency can hardly handle the great variety of shapes and materials that occur in products and packaging. In this contribution a dual-band antenna is presented that allows operation in the 13.56 MHz band as well as in the 868 MHz band. This provides two options to establish a data link to each object equipped with a dual-band RFID tag. The credit-card sized antenna consists of a very thin copper-plated polyimide substrate that is flexible and can be integrated into packaging. Measurements revealed that the antenna provides a quality factor of 54 in the 13.56 MHz band and a gain of −4.69 dBi in the 868 MHz band.**

I. Introduction

Product identification is probably the most relevant application for RFID (radio frequency identification) technology. In the supply chain of the automobile industry, for instance, a reliable RFID system has to cope with a variety of materials contained in products and packaging. Throughout the system design, the field of application has to be considered carefully. Particularly, the choice of operating frequency enables or rules out certain features of the final system. The tag antenna is a critical factor in this context because it is the weak point in the data and energy transmission. A poorly designed tag antenna reduces the available power to operate the chip and causes high backscatter modulation losses.

For low-cost applications in the HF band (3 MHz to 30 MHz) wound and printed coil antennas are used at the interrogator and the tag, respectively. The two coils form a transformer, so inductive coupling allows energy transmission between them. The antennas produce a dominantly magnetic field H that decays with the distance d to the power of three ($H \sim 1/d^3$) and thus can not bridge large distances. The read range of an HF system is closely related to the size of the interrogator antenna [1]. The advantage of using the HF band is that the dominantly magnetic field is able to penetrate water and other dielectric and lossy materials better than electromagnetic fields in the UHF regime.

The demand for reliable long-range ($d > 1\,\mathrm{m}$) interrogator-tag communication has led to the development of RFID systems operating at higher carrier frequencies. When increasing the frequency to the UHF band (300 MHz to 3 GHz), antennas that radiate electromagnetic field approach practicably small size to be used in tags. The electromagnetic field decays linearly with distance ($E, H \sim 1/d$) and thus provides higher read range compared to HF systems. On the other hand, high losses are encountered when the waves pass through water or lossy materials. Furthermore, reflections introduce multipath propagation and the subsequent fading impairs the reliability of the energy transmission.

In Section II, our antenna structures for the 13.56 MHz band and the 868 MHz band are presented. Based on these structures a low-profile, electrically small (largest dimension $D < \lambda_{\mathrm{UHF}}/4$), and flexible antenna that operates at both frequency bands is developed. Section II-D discusses how the input impedance of the antenna can be adjusted to match a dual-band RFID chip at both frequencies. In Section III, the antenna performance in either band is verified by measurements on antenna prototypes that are matched to a dual-band RFID chip [2] developed by Infineon Technologies Austria AG. A summary of our achievements is given in Section IV.

II. Antenna Design

This section describes the two antenna structures serving the HF and the UHF frequency bands. Furthermore, it is explained how the two antennas are combined into one dual-band antenna.

A. HF Antenna

In the 13.56 MHz band, a printed spiral antenna is used. The alternating magnetic field excited by the reader penetrates the spiral in an arbitrary angle. The part of the magnetic field that is aligned perpendicular to the spiral plane induces a voltage in the winding. According to the law of induction, the voltage can be increased by enlarging the diameter of the winding in order to collect more magnetic flux. It is therefore important that the HF antenna coil is placed at the outermost region of the available space.

The quality factor Q_{HF} of the HF antenna is determined by the resistive losses in the antenna coil. Q_{HF} is a measure for the voltage and current step-up at the antenna output. The quality factor is related to the antenna's center frequency $f_{0,\mathrm{HF}}$ and 3 dB bandwidth B_{HF} according to $Q_{\mathrm{HF}} = f_{0,\mathrm{HF}}/B_{\mathrm{HF}}$. This makes the quality factor available for measurement. The resonant frequency is determined by the total inductance and the total capacitance of the printed spiral.

It is important to point out that conventional single-band HF transponders usually feature an essentially inductive antenna that is tuned to the desired resonant frequency by a capacitor ($\approx 25\,\mathrm{pF}$) that is integrated into the transponder chip. For a combined HF and UHF transponder chip with one single port, such a capacitor would present a short circuit at the chip input for UHF and thus inhibit operation. Here it is essential to minimize the input capacitance of the chip like in a pure UHF design (today, typical UHF chip input capacitances are in the range of a few 100 fF to 1 pF). As a consequence, the HF antenna coil cannot be tuned by a chip capacitance, but rather has to be resonant on its own. This is achieved by the

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substrate capacitors C1, C2, and C3 (see bottom drawing of Fig. 1 and a detailed explanation in Sec. II-C) that create a parallel resonance with the coil at approximately 13.56 MHz.

B. UHF Antenna

The challenge of the comprehensive antenna design was to find a UHF antenna shape that

- has minimal mutual interaction with the HF coil antenna,
- and can be combined with the HF coil antenna consuming as little additional space as possible.

The shorted loop slot antenna ([3], [4]) was found to best fit these requirements because it is electrically small and features a closed ground plane at its circumference. The closed ground plane allows to place the HF coil around the shorted loop slot antenna. Since the conducting strips of the coil run in parallel to the outer edge of the ground plane, performance of the loop slot antenna is weakly impaired. The structure (not to scale) of a shorted loop slot antenna is shown in the top drawing of Fig. 1.

The main design parameter of the shorted loop slot antenna is the length of the slot-line resonator, which is folded into a rectangle. The length determines the self resonant frequency $f_{0,\mathrm{UHF}}$ of the antenna. A standing wave can be excited in the resonator by applying electric energy somewhere along the slot-line. The position of this feed with respect to the ends of the slot-line determines the feedpoint impedance. The highest input impedance is achieved by placing the feedpoint into the center of the resonator. Moving the feedpoint closer to either of the resonator ends (closer to the short) yields lower input impedance. The input impedance of the antenna also depends on the slot width—where a narrow slot causes smaller input impedance and also higher losses in the resonator. Radiation is mainly caused by the electric current present in the short.

C. Combination of Antennas

To reduce HF eddy currents in the UHF antenna elements, the big metal area surrounded by the loop slot has to be removed. This leads to a modified version of the shorted loop slot antenna consisting of two rings. Induced HF currents in the rings push the magnetic field to the outside. This reduces the magnetic flux collected by the HF coil and consequently impairs its quality factor. To remove the closed loops a narrow gap is inserted into each of the loop slot antenna rings. This makes the UHF antenna compatible with the HF antenna. The modified antenna with the cutout and the gaps is shown in the middle drawing of Fig. 1.

For UHF each gap is bypassed by a conducting strip formed by the top metallization. The substrate capacitors C1, C2, and C3 bridging the gaps are chosen to sufficiently conduct the UHF, while only weakly conducting the HF. This allows a reuse of the UHF antenna rings as two inner turns of the HF coil antenna. Furthermore, the substrate capacitor C2 ($\simeq$ 55 pF) is used to adjust the coil antenna to its center frequency. Fine-tuning is done by proper choice of C1 and C3.

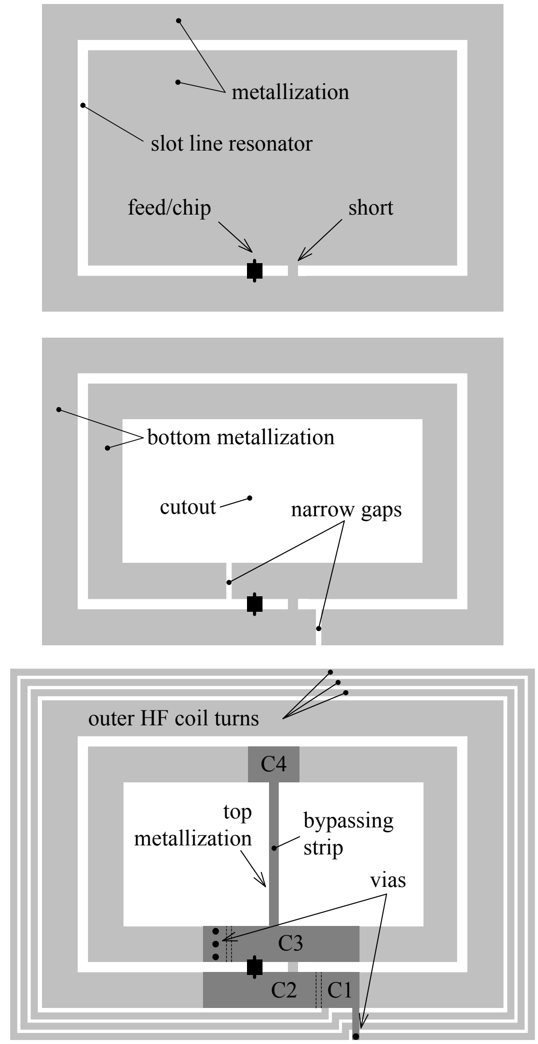

Fig. 1. Antenna evolution
Top: Generic shorted loop slot antenna.
Middle: Modified antenna with center cutout and narrow gaps to reduce eddy currents.
Bottom: Dual-band antenna with outer HF coil, top metallization, and substrate capacitors (C1 C2 C3) bridging the gaps for UHF currents. The bypassing strip and the capacitor C4 conduct surface currents former present in the cutout area.

Finally, a bypassing strip is introduced to conduct the UHF surface currents former present in the cutout. This strip consists of top metallization and is connected to the inner ring by the substrate capacitors C3 and C4. Simulations with Ansoft HFSS showed that such an arrangement well preserves the characteristics of the shorted loop slot antenna.

The shape of our HF antenna coil differs from standard geometries treated in literature because of:

- two wider innermost turns,
- a wider gap between those two turns, and the
- substrate capacitors C1 to C4.

With the procedure described in [5], the inductance of the coil at HF was determined. Based on this result, the capacitors that tune the HF antenna on the one hand and conduct UHF currents on the other hand were calculated. The resulting

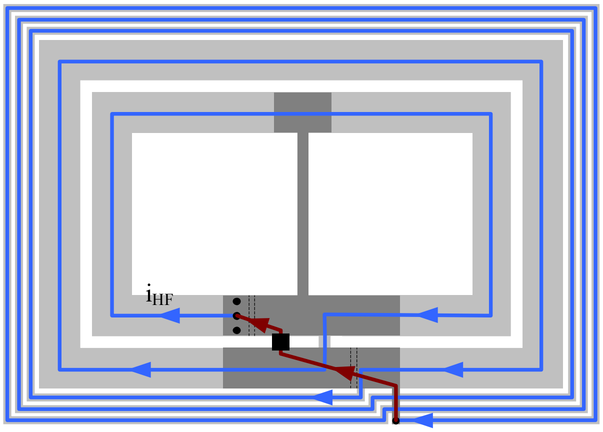

Fig. 2. Path of the HF current i_{HF} through the dual-band antenna. Current on the top metallization is shown in red, current on the bottom metallization is shown in blue. The transponder chip is mounted on top of the substrate.

capacitor values are some 10 pF to 60 pF. Given the area available for the substrate capacitors, a very thin dielectric substrate has to be used. For the prototypes presented in this paper a 25 μm polyimide substrate (relative dielectric constant $\varepsilon_{\mathrm{r}} = 3.1$, loss-tangent $\tan(\delta) = 0.007$) with double sided 18 μm copper cladding was used and processed in house by a standard PCB manufacturing process.

The final antenna structure can be seen in the bottom drawing of Fig. 1. Please note that for UHF the metallizations on top and bottom of the substrate are well connected by substrate capacitors. Except for the outer HF coil turns and the cutout that is replaced by the bypassing strip, there is no significant electrical difference to the generic shorted loop slot antenna shown in the top drawing of Fig. 1. Conversely, at HF, currents between top and bottom metallizations are conducted by vias. This allows integration of the HF antenna into the shorted loop slot antenna by sharing the two inner rings. To summarize, the path of the HF current i_{HF} through the dual-band antenna is shown in Fig. 2.

D. Antenna Tuning

The comprehensive RFID tag antenna has to be optimized when integrated into packaging, designated to an RFID chip, and assigned to a certain field of operation. In detail, the unknowns are

- material parameters of the antenna cladding (cardboard, plastic, paper, adhesive tape, ...),
- transponder chip parameters like input resistance, input capacitance, maximum input voltage, chip size, bonding / gluing techniques, and
- required bandwidth to take care of detuning effects in multiple tag scenarios and in proximity of products and materials.

The following paragraphs discuss the effects of the design parameters that are available for antenna optimization.

1) HF: Detuning effects and the chip input capacitance lower the center frequency of an HF tag antenna. This impairs the performance, especially when the antenna has small bandwidth, or equivalently, high quality factor. More reliable operation of an RFID tag can be achieved by choosing a center frequency slightly above 13.56 MHz and a qualitiy factor of $Q_{\mathrm{HF}} \simeq 40$. These values provide sufficiently high output voltage and practical robustness to detuning effects.

The center frequency can be coarsely adjusted by the number of outer turns and fine tuned by the substrate capacitors. A decrease in capacitance is achieved by shortening the top metallizations along the UHF antenna rings. This increases the center frequency of the HF antenna. The quality factor of the HF antenna can be deliberately decreased by choosing smaller conductor width of the outer turns.

2) UHF: Matching to RFID chips, that typically show small input resistance and strongly capacitive behavior, can be achieved by choosing the self resonant frequency $f_{0,\mathrm{UHF}}$ of the antenna higher than the desired operating frequency. The antenna then shows inductive behavior and small input resistance. The ratio of input reactance and input resistance is set by the frequency offset. For transponder chips, typical ratios of $-\mathrm{Im}\{Z_{\mathrm{chip}}\}/\mathrm{Re}\{Z_{\mathrm{chip}}\}$ range from 4 (Infineon) to 34 (Atmel ATA5590). For testing with currently developed Infineon chips, a ratio of 4 was chosen for the first antenna prototypes. Scaling the real and imaginary part of the input impedance can be done by choosing the distance between the feeding point (or equivalently speaking the chip position) and the short circuit.

Addressing most general results, our comprehensive antenna was optimized to best operate in free space. Prototypes with a resonator circumference of 174.4 mm and a distance of 10 mm between the feedpoint and the short were built. The dimensions of the final antenna are $71 \times 46\,\mathrm{mm}^2$. Compared to the dual-frequency RFID antenna described in [6] an area reduction by a factor of 4 is achieved.

III. Measurements

In this section measurement procedures and results for the HF and the UHF band are reported.

A. HF Measurements

Antenna characteristics in the HF band were determined in a transmission experiment. The dual-band antenna was positioned coaxial to a wide-band test antenna (16 turns, coil diameter 67.5 mm) at a distance of 30 mm. The open circuit voltage at the tag antenna terminal was measured to determine self resonant frequency $f_{0,\mathrm{HF}}$ and quality factor Q_{HF}. A 3.3 pF SMD capacitor was inserted between the antenna and the measurement cable to minimize influence of cable capacitance and measurement equipment. A self resonant frequency of $f_{0,\mathrm{HF}} = 13.49\,\mathrm{MHz}$ and a maximum quality factor of $Q_{\mathrm{HF}} = 54.1$ was determined. This shows that an HF performance as good as that of single-band HF antennas can be achieved. Tuning the quality factor to the optimum of $Q_{\mathrm{HF}} = 40$ can be achieved by reducing the conductor width of the outer HF antenna coil turns. The resonant frequency can be adjusted by changing the length of the conducting strips

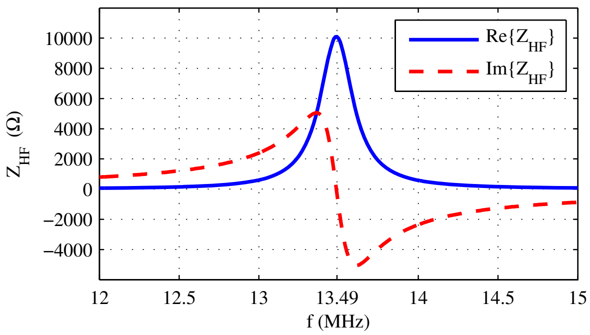

Fig. 3. HF: Measured antenna input impedance versus frequency.

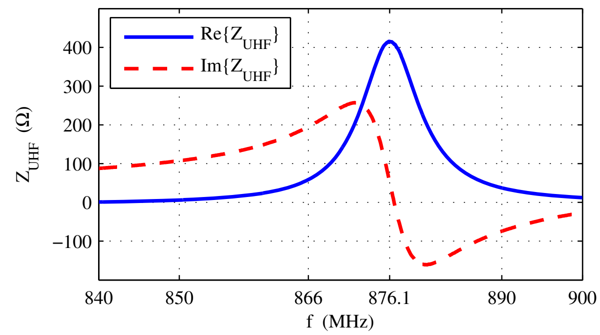

Fig. 4. UHF: Measured antenna input impedance versus frequency.

formed by the top metallization or—equivalently speaking—changing the capacitance of C1, C2, and C3. An input impedance measurement with a vector network analyzer was additionally performed to verify the results from the quality factor measurement (Fig. 3).

B. UHF Impedance Measurements

Impedance measurements in the 868 MHz band were performed by means of a vector network analyzer. The antenna was connected via a thin coaxial cable. The electrical length of this cable was deembedded during the calibration process. Due to the slot line structure, the antenna can be fed single ended. The shield and the center conductor of the coaxial measurement cable are soldered to the inner and outer ring of the antenna, respectively. The measurement cable extends along the antenna plane to minimize proximity effects. Fig. 4 shows real and imaginary part of the input impedance Z_{UHF} versus frequency.

A self resonant frequency of $f_{0,\mathrm{UHF}} = 876.1\,\mathrm{MHz}$ was achieved by a resonator circumference of 174.4 mm. It is also seen from Fig. 4 that for frequencies below $f_{0,\mathrm{UHF}}$, the input reactance $\mathrm{Im}\{Z_{\mathrm{UHF}}\}$ shows inductive behavior and the input resistance $\mathrm{Re}\{Z_{\mathrm{UHF}}\}$ is reduced to $59\,\Omega$ as discussed in Section II-D. The desired ratio of 4 between real and imaginary part of the input impedance is approximately achieved.

C. UHF Gain Measurements

In this section, two versions of the dual-band antenna, one with, and one without the outer HF antenna coil turns, are explored. Gain and directional pattern measurements of the antennas are described and compared.

The cable that connects the tag antenna with the measurement equipment introduces the following disadvantages when characterizing an RFID tag antenna:

- Currents induced along the shield of the measurement cable will corrupt the measurement of directional pattern and of the input impedance. In particular, these currents will seriously impair the measurement results for small, and low-directivity antennas.
- A measurement cable complicates antenna pointing when 3D radiation patterns are to be determined.

To avoid these drawbacks, gain measurements were performed with a miniaturized, battery-driven, crystal-stabilized oscillator that generates the transmission signal at 866 MHz directly at the antenna. A tunable matching network built into the oscillator unit provides a source impedance equal to the complex conjugate input impedance of the antenna. Prior to the characterization of each antenna variant, this matching network was tuned to deliver all the available oscillator power to the antenna. This was done by maximizing the radiated power. After each gain measurement the available oscillator power was determined by using a microwave tuner and a power meter. Fig. 5 shows the dual-band antenna with the battery driven oscillator. For characterization the antenna was clamped into a polystyrol test fixture.

A precision, low-loss half-wavelength dipole that was fed by an identical oscillator was used as a reference antenna. Gain figures were then determined by comparing the antenna prototypes with the dipole. A more detailed description of the gain measurement method can be found in [7].

Firstly, the antenna version without the extra HF coil turns was characterized. A maximum gain of $-1.92\,\mathrm{dBi}$ (gain compared to the isotropical radiator) was determined for this variant. Compared to a well optimized single-band shorted loop slot antenna also operating in the 868 MHz band with a proposed gain of $-0.4\,\mathrm{dBi}$ [4], a gain reduction of approximately 1.5 dB is encountered for this version of the antenna. The reason for this is that the focus of the dual-band antenna design was put on the HF antenna performance. The gain reduction is explained as follows:

- The small slot width (1 mm) leads to high surface currents along the edges of the slot line resonator and thus to increased losses. A widened slot would increase the overall size of the antenna and decrease the area covered by the innermost winding of the HF coil antenna.
- Confinement of the ground plane (3 mm wide) reduces the directivity of the antenna and causes a more omnidirectional radiation pattern which has an impact on the maximum gain.
- Removing the metal area in the center of the bottom metallization and replacing it with a bypassing strip concentrates the surface current into a small cross-section which also increases losses.

At this point it is obvious that—in comparison to a generic shorted loop slot antenna—some of the gain reduction can

Fig. 5. Dual-band tag antenna prototype with battery driven oscillator.

be recovered at the cost of overall antenna size and HF performance by widening the slot width, increasing the ground plane size, and introducing more than one bypassing strip.

The characterization of the complete dual-band antenna (with the outer turns of the HF coil) revealed a maximum tag antenna gain at UHF of -4.69 dBi. Obviously, induced currents in the outer HF winding cause an additional loss of UHF performance by approximately 2.8 dB. This loss can also be reduced at the cost of HF antenna performance by moving the outer HF-coil turns to the inside of the UHF antenna rings. The gain pattern obtained for horizontal and vertical polarization is shown in Fig. 6.

Tab. I compiles the measurement results of the reference dipole and the two antenna variants as well as simulation results of the optimized, single-band shorted loop slot antenna presented in [4].

IV. Conclusion

A new antenna structure operating in both, the HF and the UHF band, was found. The antenna structure consists of a shorted loop slot antenna serving the UHF band and a coil antenna serving the HF band. It was explained how the antenna can be matched to state-of-the-art tag chips by tuning a few geometric parameters. A very thin and flexible laminate was used to allow easy integration into product packaging.

For verification, two prototypes—one for dual-band operation and one without HF capabilities—were manufactured. By measurement, a comparison to conventional single-band antennas showed that performance at UHF is degraded by some few dB, while performance at HF is very well preserved. The possibilities and limits in finding a trade-off between HF and UHF performance for a given application are explained. For this dual-band antenna, a U.S. patent [8] was filed.

TABLE I
Comparison of UHF gain figures

antenna type	max. gain
reference dipole	2.15 dBi
optimized shorted loop slot antenna	-0.4 dBi
dual-band antenna with HF winding removed	-1.92 dBi
dual-band antenna with HF winding	-4.69 dBi

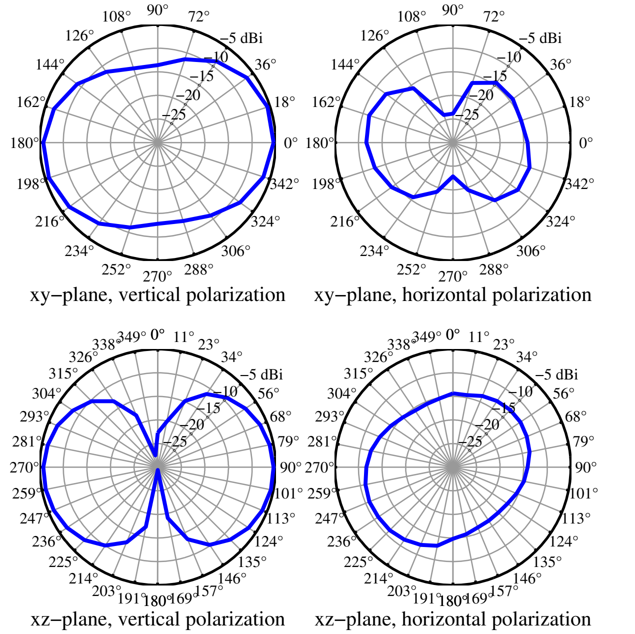

Fig. 6. Measured gain of the dual-band antenna in horizontal and vertical polarization at 866 MHz. The upper plots show the gain in the xy-plane with respect to the azimuth angle starting at the x-axis. The xz-plane plots are drawn versus the polar angle starting at the z-axis (see Fig. 5).

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