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Flexible antenna design for semi-passive HF RFID transponder in ink-jet technology

***Abstract**. The synthesis process of flexible antenna dedicated to semi-passive transponders of HF RFID system with inductive coupling is presented in the paper. The problem of antenna matching to a chip is considered in details. The emphasis is put on the possibility of manufacturing the antenna in the ink-jet technology. The impact of technology on antenna parameters is also discussed as it is important for transponder operation in a target application. The validation study of the synthesis method and samples behaviour in inhomogeneous magnetic field has been carried out.*

***Streszczenie.** W artykule omówiono proces syntezy elastycznej anteny dedykowanej do pracy w półpasywnych, indukcyjnie sprzężonych systemach RFID pasma HF. Szczegółowej analizie poddano problem dopasowania anteny i chipu. Przeanalizowano także możliwość wykonania zaprojektowanej anteny w procesie druku strumieniowego, zwracając szczególną uwagę na wpływ parametrów technologicznych na działanie identyfikatora w docelowej aplikacji systemu RFID. W artykule omówiono również proces syntezy układów testowych oraz ich pracę w niejednorodnym polu magnetycznym. (**Projekt elastycznej anteny półpasywnego identyfikatora RFID pasma HF realizowanej w procesie druku strumieniowego**).*

Keywords: flexible antenna, ink-jet technology, RFID system, HF semi-passive transponder.
Słowa kluczowe: antena elastyczna, technologia druku strumieniowego, system RFID, półpasywny identyfikator HF.

Introduction

The Radio Frequency IDentification (RFID) technique is still developed for improving automated processes in industry, logistics, science, medicine and many other fields of people's activities [1-4]. The automated identification is based on electronic transponders that are attached to marked objects. The typical passive RFID transponder consists of an antenna and a chip [5]. Besides it, there is a semi-passive construction (called active transponder) that has also an extra energy source built-in (e.g. lithium battery or other accumulator that collects energy from the environment). This power unit can be used for supplying blocks of additional autonomous functions such as measuring physical quantities, writing gathered data in a built memory, assigning time intervals, etc. [5, 6].

The need for integrating objects and their identifying markers causes that transponders should be fabricated on different substrates (flexible, rigid, resinous, ceramic etc.) that are compatible with a material to which they are fixed. Contemporary progress in the technology of modern electronic hybrids allows designers to realize passive and even semi-passive constructions straight on a surface of the consumer goods. It has to be emphasised that the employed technological processes and materials have significant influence on final parameters of electronic devices especially on that operating in radio-communication systems of high frequency (HF) range.

The antenna is the main component of the transponder. There are several techniques like screen printing, milling copper, chemical etching or ink-jet printing that can be used for fabricating the electric circuits of this element. It should be noted that the ink-jet printing is a very promising method and it is considered potential replacement of the other conventional technologies. It is predicted that it will be possible to realize more advanced applications, mainly thanks to the progress in the material science. With respect to RFID applications, the ink-jet printing may be utilized to manufacture the transponder (antenna, sensors and other blocks of additional autonomous functions) in the near future [7-9].

The part of synthesis (connected with design and fabrication in the ink-jet technology) of the semi-passive transponder that operates in a HF RFID system with inductive coupling is presented in this paper.

Transponder antenna construction

The RFID transponders are manufactured as labels, ISO cards, disks or coins, glass tubes, plastic encapsulations and other forms that are adequate to a given application [5]. The encapsulation shape, applied materials and manufacturing technology determine the pattern of internal antenna and further they influence an electronic circuit structure and its parameters. The system has to be carefully designed and aligned because the antenna and RF front-end has to be able to convey data transmission as well as to convert energy that is passed by radio-communication system working in a given frequency band.

The inductively coupled HF RFID systems operate at the frequency f_0=13,56 MHz. An inhomogeneous magnetic field generated into the read/write device (RWD) antenna is a medium for transferring energy (from RWD to transponder) and wireless data exchange (in both direction RWD - transponder). The communication mechanisms are implemented in adequate protocols (for the HF band: ISO/IEC 15693, ISO/IEC 14443, ISO/IEC 18000-3 and others). The transponder antennas in the high frequency band are made in the form of a small loop in relation to the wavelength ($\lambda \cong 22$ m at f_0=13.56 MHz). The antenna loop is typically designed as a square [10], rectangle [11, 12], circle [13] or other polygon that is suitable for the target object. It can be fabricated as an air-loop [14], loop with a ferrite material (rod or foil) [15] and first of all as a planar structure by using various technology processes [6, 8, 9, 11-13].

If the RFID antenna is fabricated in the ink-jet printing technology, the special attention should be devote to selection of materials and equipment adjustment. The adequate dielectric substrate, conductive ink and integrated circuit (chip) are needed in order to prepare a complete transponder [16]. Since the conductive ink has to be compatible with a surface on which it is printed, polyethylene terephthalate (PET) and polyimide (PI) [17-19] materials are the most often used for realizing flexible transponders. It is hard to reach any other assemblies because commercially available conductive inks are limited only to principal applications. In order to creating an untypical transponder, e.g. on the paper, the own ink composition has to be developed. And here, the next problem appears – the material compatibility with technological equipment [20]. The ink-jet printing process (continuous CIJ or drop-on-demand DOD technique) is tremendously sensitive to chemical composition of the ink and set parameters of an ink-jet printer.

The low maximal temperature in the technological processes on flexible substrates leads to the next problem that has to be taken into consideration while the antenna and RF front-end are being designed. The resistance of conductive loops printed on polymers is far higher (e.g. it is equal 50 mΩ/square for NPS-J Harima) than it is achievable for copper-clad laminates. Since the high value of antenna quality factor Q_T for semi-passive transponder is crucial for transferring energy effectively [21] (the high value Q_T can be obtained at low resistance of electric wire [22]), this requirement is hard to meet [23].

It should be mentioned, that planar structures on elastic substrates and their diverse modifications are currently the subject of intensive research. The permanent progress is possible due to availability of new materials, technologies and also software tools that significantly support antenna designers. It allows researchers to develop e.g. 3D antennas of RFID transponder [24, 25] or transponder antennas operating in two frequency bands [12] and following to integrate these antennas with very thin objects such as tickets, banknotes, valuable and identity documents, etc. [26].

Antenna design

The antenna loop (Fig. 1a) is represented by a parallel circuit where L_T is the self-inductance and R_T characterizes the resistance of wires that are used for creating the winding and it also includes the ohmic losses (C_{TS} denotes inter-turn capacitance). The R_{TS} and L_{TS} quantities denote respectively the resistance and inductance of series antenna circuit. The source U_{RT} represents the voltage induced in the antenna loop when the transponder is in the magnetic field of RWD antenna. The maximum value U_T across loop antenna terminals is obtained for the parallel resonance between the inductance L_{TS} and the capacitance C_{TC} of an active chip. This phenomenon is used to supply the chip and also to harvest additional energy from RFID system environment. These operating principles concern the semi-passive transponders with the extra harvester that recovers energy from the magnetic field (characterised by the field strength H – Fig. 1a) of RWD antenna. The harvested energy can be accumulated and used for powering blocks of additional autonomous functions.

The flexible square antenna that is dedicated to the STM M24LR16E-R transponder chip [27] has been synthesised in the research. The selected chip operates according to the communication protocol ISO/IEC 15693. It is equipped with the 16 kb EEPROM with password protection. The memory map depends on the access mode: 2048 B in I^2C mode and 512 blocks of 32 bit in RF mode. The energy harvesting block can operate in four configurable ranges of current sink (6 mA, 3 mA, 1 mA, 300 μA). The internal tuning capacitance (C_{TC}=27.5 pF for 1 V_{pp}) is included at loop antenna terminals. The presented design is a development base for flexible construction of autonomous semi-passive transponders dedicated to operation in anti-collision dynamic RFID systems.

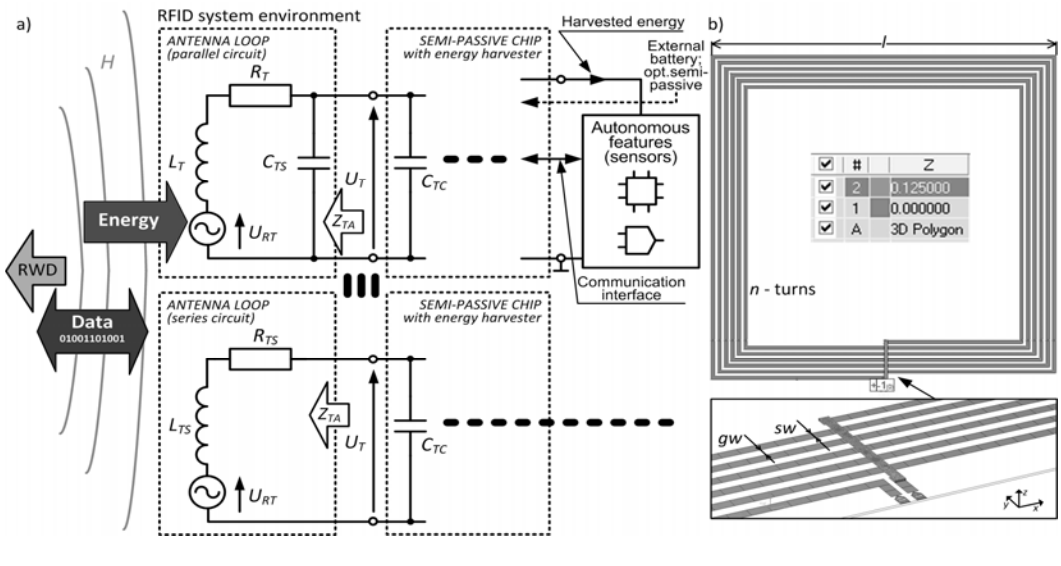


Fig.1. HF RFID semi-passive transponder: a) diagram of antenna circuit, b) HL3DEM design model

The numerical model of loop antenna (Fig. 1b) was developed in the Mentor Graphics HyperLynx 3D EM (HL3DEM). The project was prepared for the selected DuPont Kapton HN-500 substrate (thickness: 125 μm, relative permittivity: 3.5, loss tangent: 0.0026) and the Harima NPS-J silver nanoparticle ink (assumed thickness for 3 layers: 3 μm, assumed resistance: 3 μΩ·cm). The calculation of model parameters were carried out to obtain the parallel resonance between the L_{TS} and the C_{TC} at the f_0=13.56 MHz (for the C_{TC}=27.5 pF, the L_{TS} should equal 5 μH). The calculations were completed for the following geometric parameters of the HL3DEM design model: the number of turns n=6, side length l=63.125 mm, the gap width gw=0.6 mm, the strip width sw=0.6 mm.

Antenna fabrication

The antenna fabrication process was carried out at the test stand in the author's HYBRID laboratory. The test antenna (Fig. 2a) was realized practically by using PixDro LP50 ink-jet printing system (Fig. 2b). The Kapton substrate was preconditioned before the ink-jet printing process [28]. The special cleaning procedure was elaborated in order to ensure effectiveness of next steps. The substrate was washed at 50°C in deionised water with 3% detergent as well as deionised water and next in acetone. After that, it was dried at 80°C for 30 minutes.

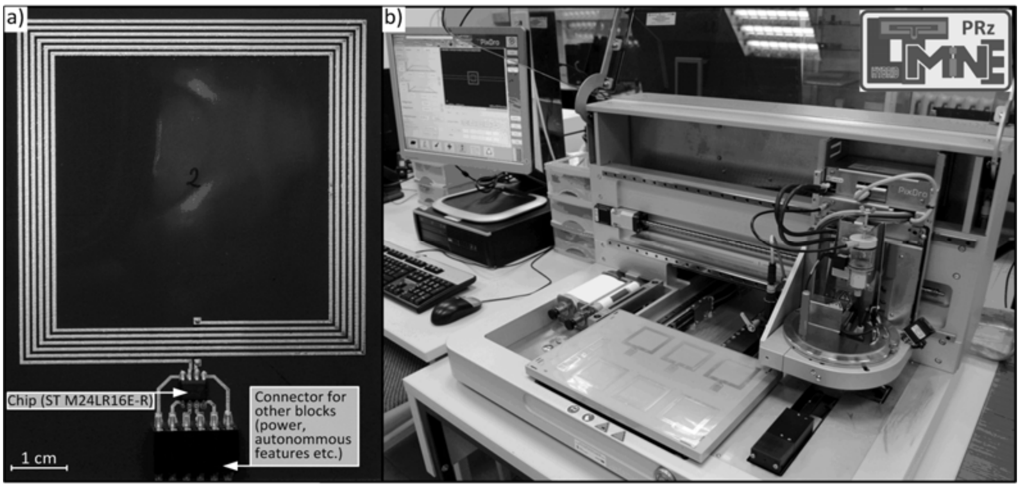


Fig.2. HF RFID semi-passive transponder: a) sample, b) ink-jet printing stand in the author's HYBRID laboratory

The nanoparticle ink was warmed up to the room temperature in order to obtain suitable rheological parameters. The used PixDro LP 50 inkjet printer was equipped with Spectra SE-128 AA print head. This print head combines 128 piezoelectric nozzles with 35 microns in diameter. It is fully compatible with the NPS-J inks and can generate drops with calibrated volume of 30 pl.

The antenna ink-jet printing process begins from setting initial parameters that were experimentally adjusted during manufacturing samples. In order to obtain satisfactory results it is necessary to achieve the greatest number of nozzles that generate the stable stream of drops (with a fixed time interval and volume). It is performed by using purge procedure and wiping the nozzle plate. The results of the initial procedures and adjusting electrical parameters of print head control waveforms can be observed in a drop view system. Finally, fallowing parameters were set-up in the experiment: pulse duration of 5/12/6 μs for rise/plateau/fall time, pulse amplitude of 59 V, Y-normal uni-directional print with resolution of 400 dpi and print speed of 300 mm/s. The Kapton sheet was warming to temperature of 60°C in order to prevent excessive ink spreading. It should be emphasized that the tracks of antenna coil have to be narrowed down by 80 μm on each side in relation to the design model. The special physicochemical treatment of the substrate and correction of track width eliminates undesirable ink spreading.

Since the generated drops in consecutive nozzles have somewhat diversified parameters (volume, velocity), only the one nozzle (1-N) was selected to perform the ink-jet printing process (samples 1-6). To compare the accuracy, the same process was repeated with more nozzles (8-N) (sample no. 7 and 8). Two layers of geometrical model were transferred on both sides of the Kapton material. The silver layers were printed one by one (SL) on the top and bottom surface with using an alignment positioning system. The samples were dried at 60°C for 30 minutes between the top and bottom prints then they were once again treated with temperature at 60°C for 30 minutes and cured at 220°C for 60 minutes. The connections (vias) between the top and bottom layer were made after singulation. They were drilled with diameter of 0.5 mm. The Elpox AX-15S silver conductive adhesive was used to create the vias and to mount the M24LR16E-R transponder chip and an electrical connector for connecting external blocks. The glued samples were dried at 60°C for 120 minutes in order to reduce stresses.

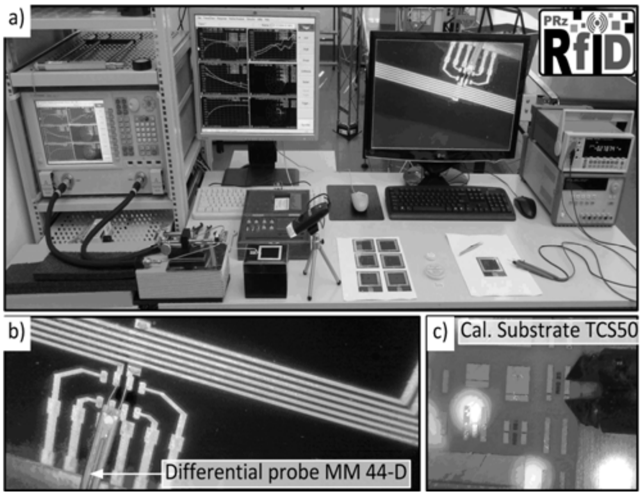


Fig.3. Measurement process: a) antenna measurement stand in the author's RFID laboratory, b) differential probe fixed to terminals, c) calibration set of test stand

Measurement

The measurements in the experiment were carried out in the specialized test stand of the author's RFID laboratory (Fig. 3a). The loop parameters of HL3DEM model were confirmed experimentally by measuring the test antenna

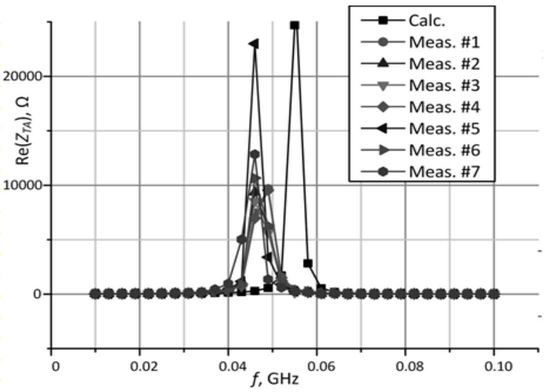
(AUT) using a two-port vector network analyzer (VNA) and a differential probe (Fig. 3b). The *S*-parameters of AUT were measured by using the VNA Agilent PNA-X N5242A and a passive differential probe Micromanipulator Model 44-D that was located at the XYZ positioner Model 110/210 (resolution 2.2 µm, max. travel each axis: 10 mm). This equipment was connected by flexible test cables – Agilent 85131F and Huber+Suhner (Astrolab) minibend. Firstly the test stand was calibrated at the probe tips (short, open, load, and thru procedure) using the PacketMicro TCS50 calibration substrate (Fig. 3c). After calibration, the *S*-parameters ware measured and results were used in the impedance parameter calculation according to [29].

The loop impedance Z_{TA} is presented in figure 4. The calculations of model parameters were carried out for the data described in chapter III. The measurement data were calculated from *S*-parameters for the eight samples by using the equation [29]:

$$Z_{TA} = 2Z_0 \frac{S_{12}^2 - S_{11}^2 - 2S_{12} + 1}{(1 - S_{11})^2 - S_{12}^2} \quad (1)$$

where the wave impedance Z_0=50 Ω.

The adhesion of the 3-layer silver test rectangle printed on the Kapton substrate was measured according to ASTM D3359 test method B [30]. The obtained result was 1B. The estimated thickness for 3 layers of silver was 3 µm (it was checked on the basis of test meander). The circuit parameters for the operating frequency f_0=13.56 MHz are summarized in table 1.



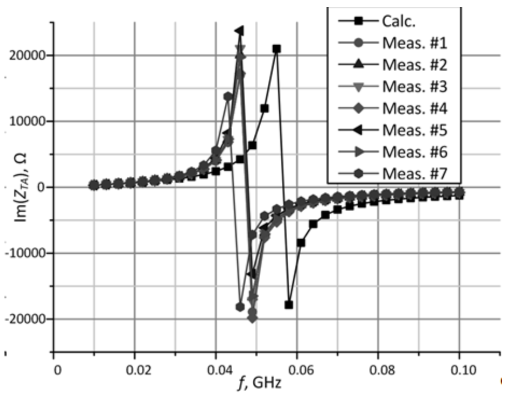


Fig.4. Impedance of antenna loop: Re(Z_{TA}) - real part; Im(Z_{TA}) - imaginary part

An increase of the strip width caused by excessive ink spreading can be observed in each case of the fabricated samples. It is especially visible for samples 7 and 8. A satisfactory result for R_{TS} is obtained for 1-*N* prints. The 8-*N* printing process is not stable because there are significant differences between the parameters of the drop streams generated by the used nozzles. This drawback causes that the printed patterns are not uniform – there are small unprinted gaps in the tracks.

Table 1. The parameters of the sensor

No. *S.*	R_{TS} [Ω]	L_{TS} [µH]	Q_T [-]	*sw* [mm]	*gw* [mm]	*SL*	*N*
Calc.	39.3	5.04	10.9	0.60	0.60	3	
M. #1	46.5	5.50	10.1	0.69	0.65	2	1-*N*
M. #2	39.5	5.52	11.9	0.73	0.58	2	1-*N*
M. #3	35.8	5.48	13.0	0.73	0.61	3	1-*N*
M. #4	35.3	5.46	13.2	0.70	0.63	3	1-*N*
M. #5	35.5	5.49	13.2	0.75	0.58	3	1-*N*
M. #6	41.0	5.48	11.4	0.73	0.61	3	1-*N*
M. #7	51.1	5.51	9.2	0.81	0.52	2	8-*N*
M. #8	-	-	-	0.82	0.50	2	8-*N*

No. *S.* – no of sample; *N* - no of nozzles; *sw* and *gw* was measured in print view system after curing, for first layer of silver; Calc. – calculation for the data from chapter III

The minor discrepancies (Fig. 4) that can be seen near the self-resonance between the inductance L_T and capacitance C_{TS} (Fig. 1a) are due to the fact that geometrical parameters of antenna loop after printing process slightly deviate from the values determined for the numerical model (Tab. 1). The tracks width *sw* of the test samples is larger than in the model and it influences the inductance of the antenna loops. On the other hand, the gap width *gw* is usually smaller and it leads to the increase of inter-turn capacitance C_{TS}. As a consequence, the frequency of sample's self-resonance is smaller than it is in the numerical calculations. Despite this, obtained values show a satisfactory convergence with respect to complete the process of flexible antenna design for HF RFID semi-passive transponder in ink-jet technology. The values of quality factor Q_T are satisfactory and the sample antennas can operate correctly. The antennas can be matched to the selected RFID chip both in communication and energy aspects [21]. The designed flexible antenna can be also utilized in other configurations with chips that are compatible with RFID communication protocols of HF band (i.e. ISO/IEC 15693, ISO/IEC 14443, ISO/IEC 18000-3 and others).

Conclusion

The process of flexible antenna design and validation study for HF RFID semi-passive transponder is presented in this paper. The main focus has been placed on the possibility of manufacturing RFID antenna in the ink-jet technology that is predicted to be widely used for integrating transponders with marked objects. The characteristics of materials (relative permittivity, loss tangent for the substrate and specific resistance for the ink) and ink-jet process parameters (layer thickness, effective in the realization dimensions for the gap and strip width) have been taken into consideration in the numerical model of flexible antenna construction. Antenna fabrication and quality tests have been performed in the complex of professional laboratories equipped with both electronic technology machines and measuring apparatus. The results of measurements and calculations have been compared and antennas suitable for operating in flexible RFID transponders has been worked out. The prefabricated sample antennas can operate correctly in the inhomogeneous magnetic field of RFID system and can be matched to any high frequency RFID chip both in communication and energy aspects.

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