Piotr JANKOWSKI-MIHUŁOWICZ, Mariusz WĘGLARSKI

Rzeszów University of Technology, Department of Electronic and Communications Systems

Synthesis of Read/Write Device Antenna for HF Proximity Range RFID Systems with Inductive Coupling

Abstract. *The effective synthesis process of a complete RF output circuit in a proximity range single RFID system with inductive coupling has been presented in the paper. The synthesis also incorporates problems connected with designing read/write devices constructed on the basis of integrated circuits from different manufacturers. The presented method can be applied to any process of automatic identification requiring the proximity range RFID system operating at the frequency of 13.56 MHz and using any communication protocol.*

Streszczenie*. W artykule zaprezentowano efektywny proces syntezy kompletnego obwodu wyjściowego RF, w którym uwzględniono jego poprawne działanie w systemach identyfikacji pojedynczej, w czytnikach/programatorach skonstruowanych na układach IC różnych producentów. Zaprezentowana metoda może zostać zastosowana dla dowolnego procesu automatycznej identyfikacji obiektów, gdzie wymagana jest aplikacja systemu RFID bliskiego zasięgu, działającego z częstotliwością 13,56 MHz i wykorzystującego różne protokoły komunikacyjne. (****Synteza anteny czytnika/programatora indukcyjnie sprzężonego systemu RFID bliskiego zasięgu funkcjonującego w paśmie HF****).*

Keywords: RFID, HF band, antenna, Read/Write Device
Słowa kluczowe: RFID, pasmo HF, antena, czytnik/programator

Introduction

Antennas of Read/Write Devices (RWD) are the main executive components of Radio Frequency IDentification (RFID) systems [1]. The knowledge of methods for their proper synthesis not only makes possible to design the proper output circuit but also enables to determine the Interrogation Zone (IZ) which is the primary parameter of RFID system applications [2]. This knowledge allows a smooth implementation of automatic identification processes in various areas of socio-economic activity [1, 3-7]. Two operating ranges are defined with regard to the established characteristic of electromagnetic field in RFID systems. The near field occurring in proximity range RFID systems means the transmission distance up to about a dozen centimeters, whereas the far field in long range RFID systems is the distance from few dozen centimeters to several meters [8].

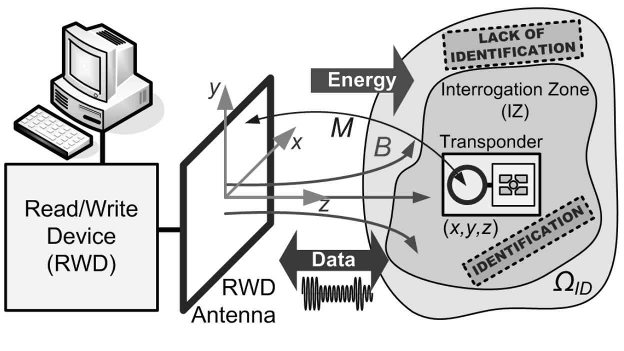

Fig.1. RFID system with inductive coupling

The inductively coupled RFID systems operate using area in which an inhomogeneous magnetic field (characterized by the induction B or magnetic field strength H) and strong coupling (characterized by the mutual inductance M) between antennas of the communication system built from the RWD and transponders occur (Fig.1). Since the proximity range RFID system working in the HF band utilizes the typical operating frequency f_0=13.56 MHz, the wavelength λ is about 22 m. For this reason, the antennas with unmatched impedance are made in the form of small (relative to λ) loop. The inhomogeneous magnetic field generated into the RWD antenna vicinity is the medium for both transferring energy and wireless data transmission. Most common means of data transmission by this medium is the amplitude-shift keying by using load modulation. But, the load modulation with subcarrier is used in above mentioned RFID systems because of the necessity for transferring energy correctly to the passive transponders. These communication mechanisms are implemented in adequate protocols (for the HF band: ISO 15693, ISO 14443, ISO 18000-3, and others).

In order to achieve the proper operation of the RWD antenna in an inductively coupled proximity range RFID system in the HF band, it is necessary to connect together the loop antenna with unmatched impedance and a balanced output of transmitter/receiver. The effective synthesis process of this complete RF output circuit has been presented in the paper. Problems connected with designing RWD on the basis of ICs from different manufacturers (NXP, Texas Instruments, EM Microelectronic and others) and with implementing them into single identification RFID systems have been considered in this process. The requirements of electromagnetic compatibility EMC have been also taken into account. This synthesis yields the possibility of determining the interrogation zone in which the proper operating conditions for passive transponders are established irrespective of their location and orientation in space. Such considerations in the RFID area are rare in the literature, but this problem very often happens in practice and then a trial-and-error method is used to find the place for correct operation of the transponders. The reason of these troubles arises from the difficulty in analytical description of numerous parameters affecting the energy transfer and data transmission in a non-uniform magnetic field. Moreover, values of the parameters are strongly dependent on the synthesis process of RWD antenna which is dedicated to a given RFID system.

The presented method can be applied to any process of automatic identification requiring the proximity range RFID system operating at the frequency of 13.56 MHz and using any communication protocol.

Model of an antenna unit

An efficient antenna system is required for proper operation of the read/write device in the inductively coupled proximity range RFID system working in HF band. Its generalized form can be represented by a combination of: a loop antenna and impedance matching components as well as an EMC filter and a signal detection circuit for data transmission in transponder – RWD direction (Fig.2).

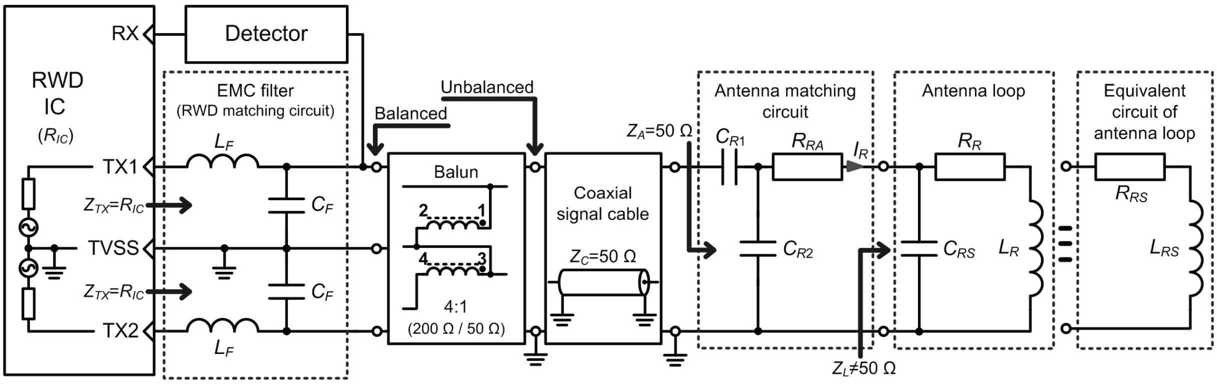

Fig.2. Block diagram of antenna unit connected to RWD

The diagram shown in the figure 2 is adequate for any antenna system design solution in which there is a necessity to separate its individual modules by using wire connectors. On its basis it is possible to synthesize the effective antenna that can work with the integrated circuit such as: TRF7960, CLRC632, EM4094, AT88RF1354, AS3910 [9-13] and many others. Factors influencing the energy transmission to a passive transponder, radio communications and application of a single proximity-range RFID system in HF band have been considered complementary in the following parts of this chapter.

In the inductively coupled RFID system the magnetic field is a medium for energy transmission and conducting radio communication so the loop antenna is a fundamental element that influences its synthesis. In the block diagram shown in the figure 2, L_R is the self-inductance of the loop antenna and R_R represents the resistance of the wire which is used for creating the winding; R_R also characterizes ohmic losses which cause the wire heating. Capacity C_{RS} is the resultant of all capacities between the coils; it results from a uniform distribution of wire electrical parameters along the entire length of the loop of the RWD antenna. In the general scheme (Fig.2), an equivalent circuit has been also included in order to facilitate a subsequent experimental verification; R_{RS} and L_{RS} denote the serial resistance and inductance of the loop antenna.

The antenna loop should be made in PCB technique because it is usually mounted in the close vicinity of RWD circuits. It is typically created on a separate layout which is placed on or below the PCB of RWD. Therefore a one side of the layout should be shielded against the influence of electronic components, whereas the other side with the loop antenna must be easily accessible for transponders. The antenna can be any shape (Fig.3) and must be fitted into an individual RFID application according to its requirements.

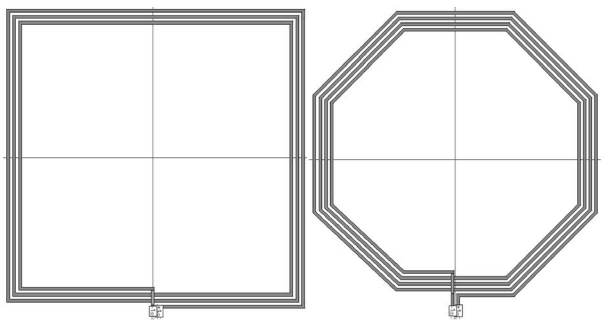
Fig.3. Examples of RWD antenna loops

When designing the loop antenna and its shield it is important take care of a resonance. In the considered RFID system the own resonance frequency must be greater than 30 MHz. The resonance occurs between the inductance L_R and capacitance C_{RS}. This inductance is within a range of a few hundred of nH to a few of μH for antennas with several coils and typical linear size (from several to a few tens of centimetres). Parameters specified in the mentioned ranges ensure the transmission of energy to common transponders that are a few centimetres away from the antenna.

The proper use of the RWD antenna requires a connection of unmatched (in impedance and wave) antenna loop to a symmetric (with respect to ground) input with mismatched impedance in the read/write device (TX1-TVSS-TX2). It is realised by using a coaxial signal cable with the wave impedance of Z_C=50 Ω as well as using a symmetric EMC filter on the RWD side and an asymmetric matching circuit on the side of the antenna loop. Both systems are connected by a balancing transformer with configuration 4:1 (200 Ω / 50 Ω), where a turns ratio is equal n=2.

The impedance matching circuit of the antenna loop consists of a capacitive divider C_{R1}, C_{R2}. It has been integrated with a resistance R_{RA} which lowers a Q_R factor of the RWD antenna. The Q-factor can not exceed the maximum value Q_{Rmax} which directly results from the data rate required by a communication protocol. On the basis of this dependence the minimum resistance R_{RAmin} can be determined:

$$(1)\qquad Q_R \le Q_{Rmax} \Rightarrow R_{RAmin} = \frac{\omega L_{RS}}{Q_{Rmax}} - R_{RS}$$

If values of the Q-factor are smaller than the maximum Q_{Rmax}, the RWD device is more resistance to detuning due to e.g. environmental influences. However, it reduces the size of the interrogation zone and thus limits the usefulness of the designed RFID system in which there is usually tendency to obtain the maximum distance for recording or reading information to or from transponder memory.

The parameters C_{R1}, C_{R2} of the capacitive divider can be obtained on the basis of a dependence describing the antenna impedance:

$$(2)\quad Z_A = R_A + jX_A = \frac{1}{j\omega C_{R1}} + \frac{\left(R_{RD} + j\omega L_{RS}\right)\cdot \frac{1}{j\omega C_{R2}}}{R_{RD} + j\omega L_{RS} + \frac{1}{j\omega C_{R2}}}$$

for fallowing conditions:

$$(3)\qquad \begin{cases} R_A = R_0 = 50\ \Omega & \longrightarrow C_{R2} \\ X_A = 0 & \longrightarrow C_{R1} \end{cases}$$

where R_{RD}=R_{RA}+R_{RS}.

The solution of the system of equations gives final dependences and on their basis it is possible to calculate the values of the divider elements:

$$(4)\qquad C_{R2}=\frac{\omega L_{RS}-\sqrt{\dfrac{\omega^2L_{RS}^2R_{RD}+R_{RD}^3-R_{RD}^2R_0}{R_0}}}{\omega^3L_{RS}^2+\omega R_{RD}^2}$$

$$C_{R1}=\frac{C_{R2}L_{RS}-\dfrac{1}{\omega^2}}{\omega^2L_{RS}^2C_{R2}+R_{RD}^2C_{R2}-L_{RS}}-C_{R2}$$

If the capacitances are calculated on the basis of the equals (4), the impedance matching of the antenna and the asymmetric coaxial signal cable with impedance of 50 Ω is provided.

A circuit of the symmetric low-pass EMC filter (L_F, C_F) serves an additional function of impedance matching Z_{TX} to an IC input. The impedance value depends on the type of chip and should be only the real part (close to the required value of R_{IC}). It ensures the effective transfer of power from the circuit of RWD to its antenna. Typically, the R_{IC} values are in the range of a few to several tens of Ω. According to the assumptions, the impedance Z_{TX} can be written as:

$$(5)\qquad Z_{TX}=R_{TX}+jX_{TX}=j\omega L_F+\frac{\dfrac{n^2Z_A}{2j\omega C_F}}{\dfrac{1}{j\omega C_F}+\dfrac{n^2Z_A}{2}}$$

where Z_A – according to (2)-(4) – is equal 50 Ω.

In order to obtain proper impedance matching of the whole circuit to the inputs TX of the IC, it is necessary to meet following conditions:

$$(6)\qquad \begin{cases}R_{TX}=R_{IC}\longrightarrow C_F\\ X_{TX}=0\quad\longrightarrow L_F\end{cases}$$

The solution of the system of equations (6) leads to the final dependencies. The values of EMC filter elements can be determined using these formulas:

$$(7)\qquad C_F=\sqrt{\frac{2n^2Z_A-4R_{IC}}{n^4\omega^2Z_A^2R_{IC}}}$$

$$L_F=\frac{n^4Z_A^2C_F}{n^4\omega^2Z_A^2C_F^2+4}$$

After determining the value of C_F and L_F, it is necessary to check whether the designed EMC filter meets all its functions. Beside the impedance matching, the EMC filter has to ensure an elimination of higher harmonics during energy transmission, improve signal to noise ratio for transmission between a transponder and a read/write device and also improve conditions for transferring data to a transponder. The resonant frequency f_{EMC} should be also taken into consideration in design process. It can be calculated from the formula:

$$(8)\qquad f_{EMC}=\frac{1}{2\pi\sqrt{L_FC_F}}$$

The required value of the frequency f_{EMC} results from the signal spectrum for subcarrier modulation. In this process, the transmitted information should be recovered from the side bands. The frequencies of the side bands are strictly defined according to the used communication protocol (e.g. f_0/16, 32, 64 gives approximately 847, 424, 212 kHz, etc.). For example, if the bit rate equals 106 kb/s, the frequency of the filter is f_{EMC}=14.4 MHz (13.6 MHz+847.5 kHz).

The circuit of signal detection of data sent from a transponder is the last module presented in the figure 2. This module is characteristic for the IC [9-13] and therefore the detailed electronic diagram is not specified. It must be emphasised that the proper design of the whole circuit connected with energy transfer from the RWD to the transponder is very important in determination of the interrogation zone of a read/write devices especially that which works in the near field of the HF band. If the specificities of each discussed element are correctly taken into consideration the proper synthesis of the magnetic field is possible. Then, any implementation process of identifying any object at a distance of several centimeters from the antenna system of RWD is feasible [8, 14].

Synthesis of RWD Antenna

The octagonal antenna has been synthesised in order to verify the presented experimental method. The antenna is dedicated to a multiprotocol circuit of a read/write device of the proximity-range RFID system in HF band. The diagram of the antenna model is presented in the figure 4-a. The diagram has been prepared in IE3D package (Mentor Graphics). The test antenna has been realised practically on the PCB substrate and is presented in the figure 4-b.

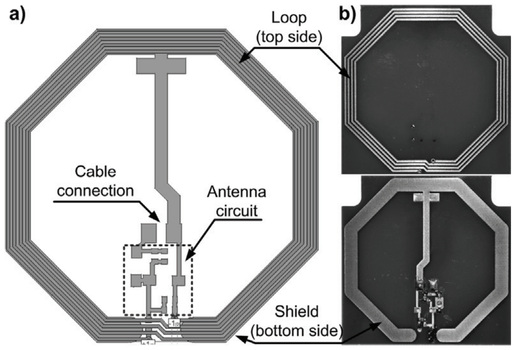

Fig.4. Octagonal RWD antenna: a) IE3D model, b) test PCB

The typical two-sided FR-4 laminate (laminate thickness: 1.55 mm, permittivity: 4.85, dielectric loss: 0.025 for f=10 MHz, thickness of copper: 17.5 μm) was used to prepare the model and test antenna. The shield connected to ground was placed on the bottom layer. The antenna has four terns located on the opposite side of the laminate. The shield covers the area of the antenna loop. The main function of the shield is to separate the electronic system from the magnetic field supplying a passive RFID transponder. The distribution of current presented in the figure 5 confirms this function. The maximum value of the current occurs at each segment of the loop, while the current value is less by several tens dB on the shield side.

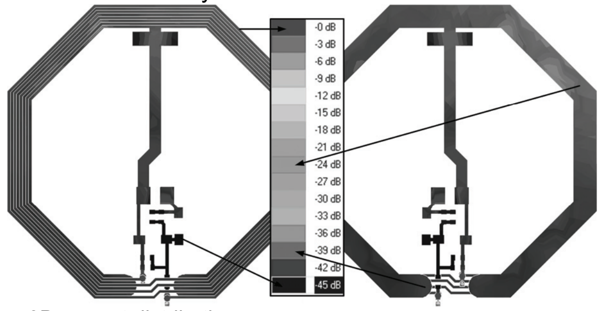

Fig.5. 3D current distribution

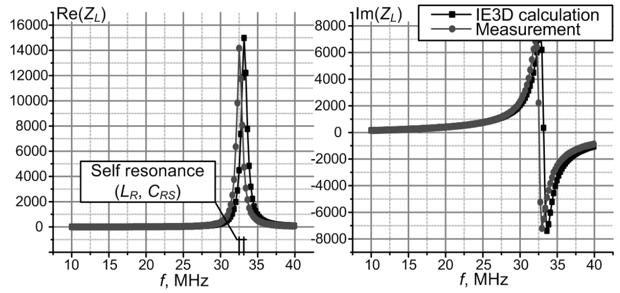

Fig.6. Impedance of antenna loop

The loop impedance Z_L is presented in the figure 6. It has been calculated for the model in IE3D package and practically measured with the test antenna, using a two-port network analyzer (Agilent PNA-X N5242A) and a differential probe [15]. The self-resonance (noticeable in the chart – Fig.6) between the inductance L_R and capacitance C_R is at a frequency greater then 30 MHz and it meets the previously defined criterion. Such separation from the operating frequency f_0=13.56 MHz gives the magnetic field with strength greater than the minimum value (H>H_{min}) which is required for typical RFID transponders at a distance of a few centimetres from the antenna loop surface [8]. The minor discrepancies noticeable in the figure 6 are due to the fact that material parameters have been assumed constant in whole frequency band in the numerical calculation.

Table 1. Calculated and measured parameters of the antenna circuit

Parameter	IE3D calc. results	Meas. results
L_{RS}	2.55 μH	2.51 μH
R_{RS}	3.65 Ω	3.48 Ω
Q_R	59.5	61.5
R_{RAmin} (Q_{Rmax}=22)	6.26 Ω	6.24
C_{R1}	24.1 pF	24.3 pF
C_{R2}	30.1 pF	30.7 pF
L_F (R_{IC}=12)	381 nH	381 nH
C_F	318 pF	318 pF
f_{EMC}	14.5 MHz	14.5 MHz

The circuit parameters which have been calculated from the relation (1)-(8) for IE3D model and measured for the test antenna are summarized in the table 1. The obtained values show a satisfactory convergence, especially for the parameters of EMC filters which are collated at the end. The achieved value of the resonance frequency f_{EMC}=14.5 MHz provides the ability to transfer data with a typical bit rate e.g. 106 kb/s for a protocol ISO/IEC 14443.

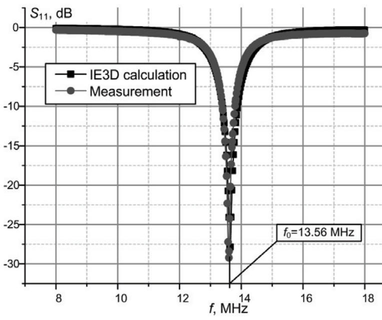

Fig.7. Calculation and measurement results of S_{11}

Reflection losses (S_{11}) which have been calculated for the model IE3D and measured for the test antenna are presented in the figure 7. The measurements have been realized by using network analyzer LA19-13-02 (LA Techniques), while the calculations have been made on the basis of a circuit model prepared in the MODUA editor from the IE3D package. The obtained value of the reflection losses S_{11}=-29 dB (VSWR=1.07) gives the full antenna impedance matching to designed circuit of RWD.

Conclusion

The process of the antenna synthesis for a read/write device working in an inductively coupled proximity-range RFID system operating in the HF band has been presented. The solution of the synthesis problem results from extensive research which are carried out by RFID technique team of the Department of Electronic and Communications Systems in Rzeszów University of Technology. Their practical implementation allows one to quickly estimate the efficiency of a RFID systems (in any application), complementary in the field, electrical and communications conditions. The determination of the interrogation zone in which there is possibility to place transponders on labelled objects in any position is the main practical result of these research.

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REFERENCES

[1] Finkenzeller K., *RFID Handbook*, 3-rd Ed., Wiley (2010)
[2] Jankowski-Mihułowicz P., Kalita W., Interrogation Zone - a Basic Application Parameter of RFID Systems, *Elektronika*, No. 8 (2010), 67-72
[3] Brown D., *RFID Implementation*, McGraw-Hill (2007)
[4] Weigelt K., Hambsch M., Karacs G., Zillger T., Hübler A.C., Labeling the World: Tagging Mass Products with Printing Processes, *IEEE Pervasive Computing*, 9 (2010), No. 2, 59-63
[5] Cheng S., Tom T., Thomas L., Pecht M., A Wireless Sensor System for Prognostics and Health Management, *IEEE Sensors Journal*, 10 (2010), No. 4, 856-862
[6] Jones E., Chung C., RFID in Logistics - A Practical Introduction, CRC (2008)
[7] Plessky V., Reindl L., Review on SAW RFID tags, *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, 57 (2010), No. 3, 654-668
[8] Jankowski-Mihułowicz P., Field Conditions of Interrogation Zone in Anticollision Radio Frequency Identification Systems with Inductive Coupling, *Radio Frequency Identification Fundamentals and Applications Bringing Research to Practice*, Turcu C. (Ed.), Intech (2010), Chapter 1, 1-26
[9] Texas Instruments, *TRF7960, TRF7961 Multi-Standard Fully Integrated 13.56-MHz RFID Analog Front End and Data-Framing Reader System*, SLOU186F, Rev. 2010
[10] NXP, *CLRC632 Multiple Protocol Contactless Reader IC*, No. 073935, Rev. 3.5, Nov. 2009
[11] EM Microelectronic - Marin SA, *EM4094 Analog Front End Integrated Circuit for 13.56 MHz RFID Base Station*, Rev. A, 09/03, 2003
[12] Atmel, *AT88RF1354 13.56-MHz CryptoRF Type B RF Reader*, No. 8547B–RFID–3/09, 2009
[13] Austriamicrosystems AG, *AS3910 13.56 MHz RFID Reader IC, ISO-14443 A/B*, Rev. 2.3, Oct. 2009
[14] Aerts W., De Mulder E., Preneel B., Vandenbosch G. A. E., Verbauwhede I., IEEE Dependence of RFID Reader Antenna Design on Read Out Distance, *IEEE Trans. Antennas Propag.*, 56 (2008), No. 12, 3829-3837
[15] Palmer K.D., van Rooyen M.W., Simple broadband measurements of balanced loads using a network analyzer, *IEEE Trans. Instrum. Meas.*, 55 (2006), No. 1, 266-272

***Authors**: dr inż. Piotr Jankowski-Mihułowicz, dr inż. Mariusz Węglarski, Rzeszów University of Technology, Department of Electronic and Communications Systems, ul. W. Pola 2, 35-959 Rzeszów, E-mail: pjanko@prz.edu.pl (http://pjanko.sd.prz.edu.pl), wmar@prz.edu.pl.*