Design of an UHF RFID Antenna on Flexible Substrate Magnetically Coupled to the Tag

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Abstract: UHF RFID antennas that are magnetically coupled to the tag by using a transformer are designed and fabricated on flexible materials. The primary and secondary windings of the transformer are implemented on the antenna substrate and in the chip, respectively. In this way, galvanic contacts between the antenna and the tag are not required and the tag can be assembled on the antenna substrate by means of a mere placing and gluing process: the wire-bonding and the soldering processes are avoided reducing the production costs. Another important feature is the use of a flexible substrate. These features make this antenna attractive to the market of RFID and other applications, where the flexibility and the placing tolerances are mandatory. The design process of a bow-tie antenna with transformer, based on flexible substrate and operating in the UHF frequency band, is described step by step and validated by means of accurate full-wave simulations.

Keywords: Flexible Antennas, RFID, Magnetic Coupling, CST Microwave Studio, Computer-Aided Design (CAD), Non Ohmic Interconnection

1. Introduction

Nowadays, the Radio Frequency IDentification (RFID) systems play an important role in Automatic IDdentification (Auto-ID) technologies based on radio waves. They allows objects to become self-describing by communicating their identity. RFID is used in a wide spectrum of applications and it is evolving as a major technology enabler for tracking goods and assets around the world. For these reasons, they represent an important field of research with many technical challenges.

RFID systems usually require an electronic circuit, which can be integrated into a chip or tag, and an antenna, which enables the chip to transmit the identification information to a reader. The chip and the antenna are directly connected by means of galvanic contacts, requiring a wire-bonding or a soldering process. To avoid galvanic contacts, a novel method to connect antenna and tag, based on magnetic coupling, was proposed in [1-4]. This coupling mechanism is realized by means of a transformer with one of the two windings realized on the antenna substrate and the other in the chip, respectively. This allows mounting the chip by a self-assembly process [5, 6]. In this way, the chip is pad-less and completely passivated, avoiding wire-bonding, reducing the tag production costs, and eliminating the soldering process which can be critical for certain materials.

This paper deals with the application of the above described approach to structures based on flexible materials. An antenna-transformer prototype was designed, fabricated and measured. The transformer's primary winding was integrated onto antenna and implemented on the same flexible substrate without loss of generality. The secondary winding is realized on flexible substrate, not on chip, for test purposes only. The design of the antenna and the transformer aims at maximizing the power transfer between the antenna and the load (representing the chip in the actual application) connected to the secondary winding. The design, supported by the full-wave electromagnetic simulator CST Microwave Studio, is described step by step. The first step consists of the design and the optimization of the transformer. Next, a bow-tie antenna is designed. The antenna is matched to the transformer's optimum impedance, resulting in a transmission coefficient equal to the Maximum Available Gain (MAG). Finally, the prototype is realized and measured and the results are compared with the simulations to validate the design process.

2. Transformer and Antenna Design

In this section, the steps required for the design of the system antenna-transformer are described. The design is supported by full-wave electromagnetic simulations performed with CST Microwave Studio. In particular the frequency solver is used.

The structure is made using various materials. The antenna and the one turn primary winding are realized on flexible substrate (DuPont Pyralux) [7]. The one turn secondary winding is realized on a Rogers RO4003 [8] substrate and its terminals are connected to an UFL connector, required to characterize the antenna-transformer system by means of the Vector Network Analyzer (VNA). The use of Rogers material to realize the secondary winding, instead of an implementation directly on chip, allows easy validation of the design process, while demonstrating the feasibility of this coupling topology, provided one keeps in mind the further implementation that will include a chip. The materials stack, starting from the antenna substrate, is: Pyralux, copper (antenna and primary winding transformer), bi-adhesive tape, copper (secondary winding), Rogers and copper (connector pads). The properties of the materials used are listed in Table 1.

Table 1: Materials Properties

Materials	Thickness [μm]	Permittivity ε_R	Conductivity σ [S/m]	Loss tangent
Bi-adhesive tape	100	3	-	0
Copper	18	-	$5.8 \cdot 10^7$	-
Pyralux	50	3.2	-	0.001
Rogers RO4003	305	3.55		0.0027

A. Transformer Design

The first step consists of designing the transformer. The transformer is heterogeneous because the substrate materials, the dimensions and the number of turns are different for the two windings. The windings' dimensions result from a compromise between performance (MAG) and reliability, given the fabrication constraints (design rules). The primary and the secondary windings are implemented on the flexible substrate and on the Rogers substrate, respectively, and a sheet of bi-adhesive tape avoids direct contact of the windings.

The transformer layout (see Fig. 1) was simulated in order to find the optimum impedances and the MAG; its dimensions are listed in Table 2. A one turn primary winding was chosen in order to avoid the use of vias in the flexible substrate. Several simulations were performed, varying the distance of the windings (or tape thickness) in order to verify the MAG and the optimum impedances. The results are plotted in Fig. 2. For a distance of 100 μm the optimum impedances are $Z_{S\_OPT} = 6.9–j13.7\ \Omega$ and $Z_{L\_OPT} = 32.4–j80.5\ \Omega$, whereas the MAG is -0.24 dB at 868 MHz. The optimum impedances would be equal if the transformer has the same number of turns and the same dimensions. However, here we deal with a heterogeneous transformer.

Table 2: Transformer Dimensions

Winding	Materials	Number of turns	Tracks width and spacing [mm]	Inner radius [mm]
Primary	Copper	1	0.2	0.55
Secondary	Copper	3	0.1	0.25

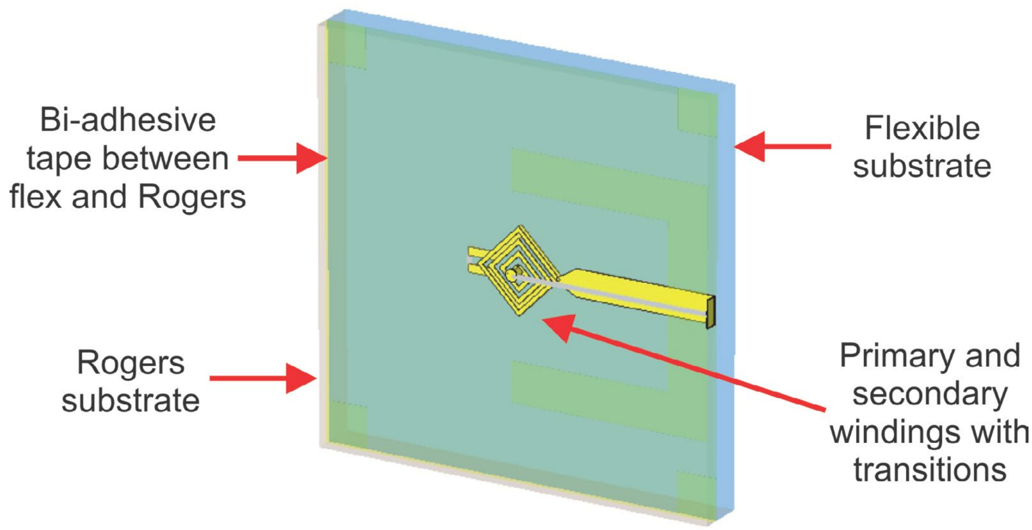


Fig. 1. Heterogeneous transformer layout: the primary and the secondary windings are implemented on a flexible and a Rogers substrate, respectively. They are separated by a sheet of bi-adhesive tape.

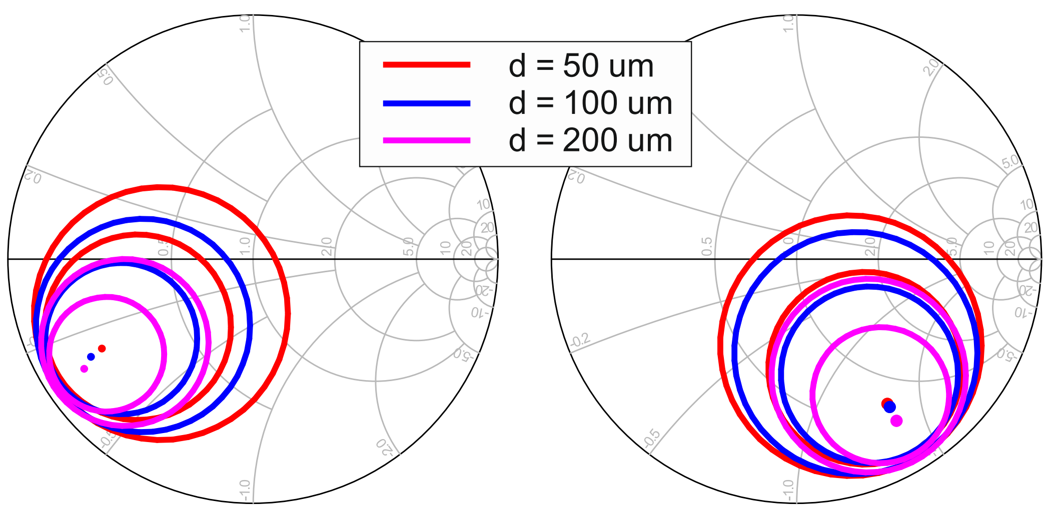
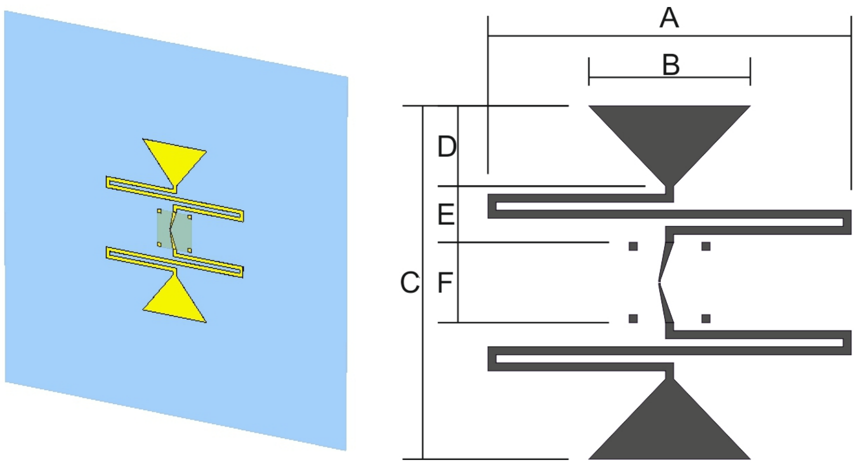


Fig. 2. Transformer simulation results: source (on the left) and load (on the right) optimum impedances and gain circles (step -0.25 dB) of the transformer with UFL connector transitions plotted on a Smith chart with 50 Ω reference impedance and computed varying the distance *d* between the windings (or tape thickness). Values obtained at 868 MHz.

B. Antenna Design

Knowing the optimum impedance required from the transformer, the next step is the design of the antenna. The antenna must have an input impedance equal to Z_{S_OPT} and must operate in the Short Range Devices (SRD) frequency band 868÷869.2 MHz. The bow-tie antenna topology exhibits a simple single layer structure, avoiding the use of vias.

Several EM simulations were performed to match the antenna impedance to the optimum source impedance of the transformer. A meander line was inserted between the feed point and each arm to tune the input impedance [9]. Fig. 3 shows the resulting layout and the optimum dimensions. The antenna simulation results, the radiation pattern and the reflection coefficient S_{11}, are shown in Fig. 4. The antenna impedance is equal to 6.38–j20.9 Ω at 868 MHz and this value is close to the optimum impedance 6.9-j13.7 Ω required from the transformer (the mismatch between the two impedances generates a reflection of magnitude -14.2 dB). The estimated antenna efficiency radiation is -1.14 dB (77 %) and its maximum directivity is 1.92 dB.



A = 45 mm	
B = 20 mm	
C = 44 mm	
D = 10 mm	
E = 7 mm	
F = 10 mm	

Fig. 3. Bow-tie antenna layout and dimensions. The two feeding points of the antenna are spaced 1 mm and, in the layout of the system antenna-transformer, they are connected to the primary winding terminals. The four squares are used to aligne the substrate with the secondary winding.

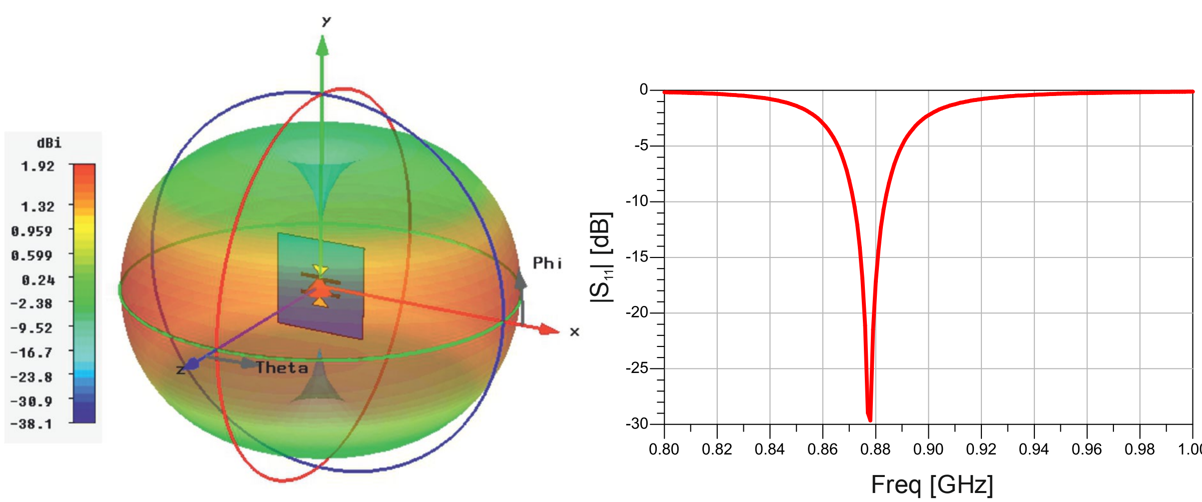


Fig. 4. On the left: directivity diagram at 868 MHz. On the right: reflection coefficient S_{11} simulated and normalized with respect to the complex conjugate source impedance of the transformer $Z_{S\_OPT}^* = 6.9+j13.7$ Ω.

3. Prototype Measurement

Finally the overall system antenna-transformer was simulated, fabricated, and measured. The prototype is shown in Fig. 5. The radiation efficiency and the maximum directivity, obtained from the EM simulation of the entire system, are equal to -1.94 dB (63.9 %) and 1.92 dB respectively. The reflection coefficient S_{11} was measured by means of the VNA and normalized with respect to the optimum load impedance Z_{L_OPT}, obtained from the transformer simulation. The results are plotted in Fig 6. Note that the magnitude of the reflection coefficient is below -10 dB in the frequency band 868÷869.2 MHz.

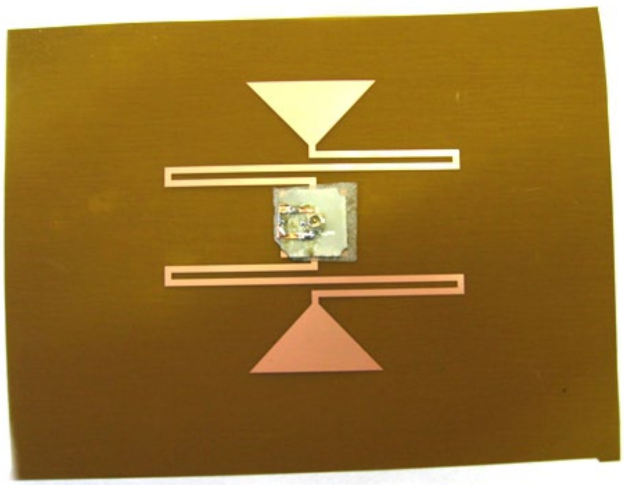


Fig. 5. Prototypes of the antenna-transformer: flexible substrate with dipole antenna and primary winding, and Rogers substrate with UFL connector and secondary winding separated by bi-adhesive tape.

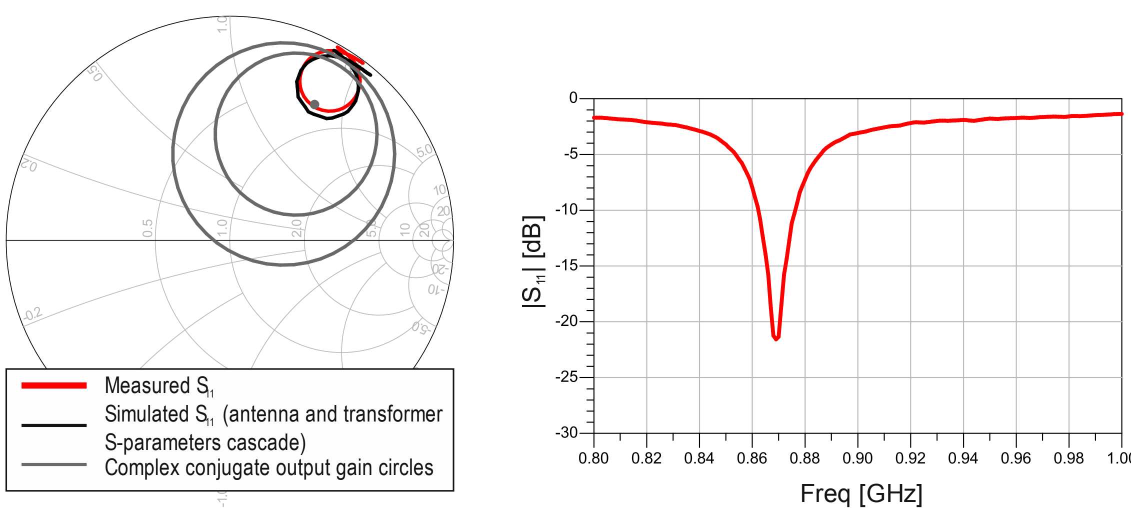


Fig. 6. On the left: measurement vs. simulations of the antenna-transformer prototype; the reflection coefficients S_{11} are plotted on the Smith chart with 50 Ω reference impedance in the frequency range 800÷1000 MHz; the complex conjugate of the load optimum impedance and of the gain circles (step of -0.25 dB) are obtained at 868 MHz. On the right: measured reflection coefficient S_{11} plotted with respect to 32.4–j80.5 Ω (optimal load impedance transformer); S_{11} magnitude is below -10 dB in the frequency band 868÷869.2 MHz.

4. Conclusions

A flexible antenna with a transformer based feeding topology was simulated, fabricated and measured. The system operates in the UHF RFID frequency band (868÷869.2 MHz) and provides a measured reflection coefficient below the -10 dB in the overall operating frequency band. All the steps of the design process, supported by the EM simulator CST Microwave Studio, were outlined. The simulations and the measurements show a good agreement, validating the design approach and the feasibility of the described coupling technique between antenna and tag.

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References

[1] A. Finocchiaro, G. Ferla, G. Girlando, F. Carrara, and G. Palmisano, "A 900-MHz RFID system with TAG-antenna magnetically-coupled to the die," *IEEE Radio Frequency Integrated Circuit Symposium*, *IEEE RFIC 2008*, Atlanta (GA), USA, 17 Apr. 2008, pp. 281–284.

[2] F. Alimenti, M. Virili, P. Mezzanotte, V. Palazzari, M. M. Tentzeris, and L. Roselli, "Low-cost assembly of UHF RFID chips and flexible substrate antennas by magnetic coupling approach*", IEEE International Microwave Symposium Digest (MTT), IEEE MTT-S 2010*, Anaheim (CA), USA, 23-28 May 2010, pp. 1532–1535.

[3] F. Alimenti, M. Virili, G. Orecchini, P. Mezzanotte, V. Palazzari, M. M. Tentzeris, and L. Roselli, "A New Contactless Assembly Method for Paper Substrate Antennas and UHF RFID Chips", *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, n. 3, pp. 627–637, Mar. 2011.

[4] F. Alimenti, G. Orecchini, M. Virili, V. Palazzari, P. Mezzanotte, and L. Roselli, "Design of Paper-Substrate Dipole Antennas Magnetically Coupled to UHF RFID Silicon Chips", *IEEE International Conference on RFID-Technology and Applications, IEEE RFID-TA 2011*, Sitges, Barcellona, Spain, 15-16 Sep. 2011, pp. 219–222.

[5] Alien Technology, "*Alien Technology Corporation white paper: Fluidic self-assembly*," http://www.alientechnology.com, Oct. 1999.

[6] C. Landesberger, E. Yacoub-George, W. Hell, and K. Bock, "Self-assembly and self-interconnection of thin RFID devices on plasma-programmed foil substrates," *IEEE Electronic System-Integration Technology Conference, IEEE ESTC 2010*, Berlin, Germany, 13-16 Sep. 2010, pp. 1–5.

[7] DuPont, "*DuPont Pyralux AP All-Polyimide Flexible Laminate*," http://www.dupont.com/fcm, Jun. 2012.

[8] Rogerscorp, "*RO4000® Series High Frequency Circuit Materials*," http://www.rogerscorp.com, Nov. 2011.

[9] G. Orecchini, F. Alimenti, V. Palazzari, A. Rida, M.M. Tentzeris, and L. Roselli, "Design and fabrication of ultra-low cost radio frequency identification antennas and tags exploiting paper substrates and inkjet printing technology", *IET Microwave Antennas and Propagation*, vol. 5, iss. 8, pp. 993–1001, 6 Jun. 2011.