Extraction of 13.56 MHz NFC-Reader Antenna Parameters for Matching Circuit Design

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Abstract: The maximum operating distance and the optimum performance (good coupling, lower/moderate power consumption) of even the well-designed NFC-reader-antenna in an RFID system depend largely on the good matching circuit. With the aforementioned objective, the paper presents here a modeling and computer aided design and then parameter extraction technique of a NFC-Reader Antenna. The 3D geometry model of the antenna is then simulated in frequency domain using Comsol multiphysics tool in order to extract the Reader-Antenna parameters. The extracted parameters at 13.56 MHz frequency are required for further RF-simulation, based on which matching circuit components (damping resistance and series & parallel capacitances etc.) of the Reader-Antenna at above frequency have been selected to achieve the best performance of the antenna.

Keywords: RFID, NFC-Reader Antenna, Parameter Extraction, RF-simulation, Matching Circuit Design.

1. Introduction

Radio Frequency Identification (RFID) systems have been used since long past and nowadays, they are part of our daily life.

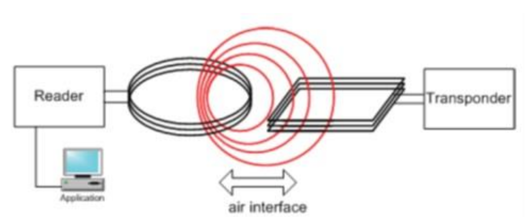

Figure-1: Principle of RFID Systems ([1])

Electronic Article Surveillance (EAS) systems are applied in most shops in order to protect the articles from theft or illegal removal from the shop. RFID technology based ticketing systems are used in several countries. Electronic passport (ePassport) uses also RFID based proximity coupling device [1].

RFID system uses a Transponder and the near field communication (NFC) antenna or reader antenna operating at 13.56 MHz frequency (Figure-1) which needs to be optimally designed for a higher efficiency, lower power consumption and larger operating distance (say, up to 9 cm). Typically, RFID antennas are flat rectangular/square/circular-shaped inductive coils with 2 to 4 turns and are often printed directly on the PCB. The larger antenna (diagonal) size implies larger operating distance and number of turns plays an important role in achieving target inductance from 1.0 µH to 3.0 µH. As per [3] larger inductance has no impact on coupling. RFID antenna can be built as a single layer or multiple layers coil.

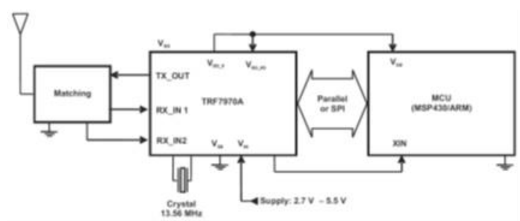

Figure-2a: NFC- antenna needs the matching circuit to interface with the TI-TRF7970, a high performance transceiver chip [2].

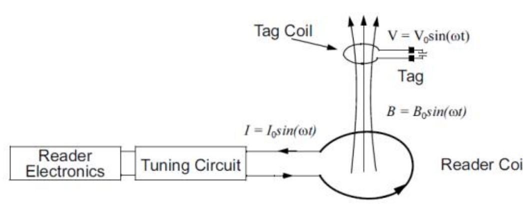

Figure- 2b: Mutual Coupling and energy transfer principle between Reader Coil and Tag Coil [5].

The Geometry/shape and size etc. of the antenna are important factors for achieving a target operating distance. Therefore, based on the selected geometry/shape and size (91 mm × 15 mm) the NFC Antenna is designed starting with 2 or more turns. The fabricated NFC antenna parameters must be measured with high accuracy/precision generally, with an Impedance analyzer or with a Vector Network Analyzer (VNA: ZVL from Rhode & Schwarz GmbH, Germany, miniVNA-pro from mini Radio Solutions). The Smith Chart plot by VNA can deliver the S11 parameters/coil-inductance value (L_a), series-resistance (R_a) and parallel-capacitance (C_{pa}) value of the antenna at 13.56 MHz. First two parameters are applied for the computation/RF-simulation of matching circuit [2, 3]. The optimal matching circuit design is difficult without the information of NFC antenna parameters. Even if the NFC reader antenna is designed and fabricated by a third party, to get the best efficiency (e.g., maximum operating distance with minimum power consumption) from the NFC-antenna a suitable matching circuit (**Figure-2a and 2b**) has to be designed that together with NFC Antenna shows a typically 50 Ohm (real) impedance at the end of EMC filter circuit (TI-TRF7970A transceiver). The arbitrarily designed matching circuit based on the incorrect antenna parameters values will lead to a very poor performance (slow data rate, less operating distance or very high power consumption etc.) of the NFC-reader antenna. Therefore, accurate information/measurements of antenna parameters are necessary for an optimal design of antenna-matching circuit. With the aforementioned objective in the paper the frequency domain modeling of a selected antenna with the use of Comsol multiphysics tool has been described in section-2, whereas the simulation results and parameter extraction techniques have been described in Section 3. The extracted parameter values were also compared with the Smith Chart plot of Vector Network Analyzer (VNA) in section 3. The extracted values are further used in the (freely available RF99) RF-simulation for the determination of matching circuit components, which is also briefly shown in section 3. Thereafter, the simulation results were discussed and finally in section 4 paper concludes with brief remarks..

2. Use of COMSOL Multiphysics

As mentioned earlier in Section-1 the NFC-reader-antennas are flat rectangular/square/ circular or even elliptical shaped inductive coils with 2 to 4 turns and are often printed (etched) directly on the PCB. If the single-layer coil is used as antenna, based on the geometric shape of the coil the antenna inductance can be calculated by different methods. In the proceeding section we will discuss a few of them.

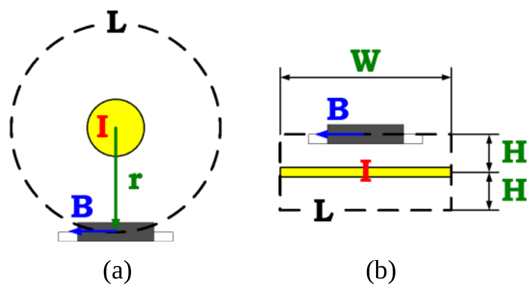

Figure-3: a) Magnetic flux density (*B*) at the Hall-sensor IC located at a distance *r* away from the center of a round conductor, b) Strip conductor of width **W** and at **H** distance away from a Hall-sensor IC ([6]).

The magnetic field intensity or magnetic field strength (H_{mf}) in Ampere-per-meter around a conductor is given by:

$$H_{mf} = I / L_{field}, \quad (1)$$

where (I) is the current flowing through the conductor and as shown in Figure-3a

$$\mathbf{L} = L_{field} = 2\pi r, \quad (2)$$

is the length of the field line around the straight, infinitely long, ideally thin and round conductor. Since the *length* (**L**) of the field line *increases* with the distance (r) to the conductor, the magnetic field strength (H_{mf}) is inversely proportional to the distance (r) and also related to bus bar (conductor) geometries e.g. round or strip conductor etc. as shown in Figure-3a and 3b respectively. The magnetic flux density B is related to H_{mf} by the factor of permeability of the medium, $\mu = \mu_0.\mu_r$ where the absolute permeability $\mu_0 = 4\pi \times 10^{-7}$ [V.s/A.m], $\mu_r = 1$ (approximately) for air medium and therefore, magnetic flux density is given by:

$$B = \mu_0 \mu_r H_{mf}. \quad (3)$$

Since for the strip conductor of width (**W**) located at a (**H**) distance apart from Hall-sensor IC, as shown in Figure 3(b), gives the length of field line as shown in (4):

$$L = L_{field} = 2(W + 2H) \cdot \quad (4)$$

Therefore,

$$H_{mf} = I/(2(W + 2H)) \cdot \quad (5)$$

Accordingly, for the strip conductor the magnetic flux density is given by:

$$B = \mu_0 \mu_r I/(2(W + 2H)) \cdot \quad (6)$$

In general, the magnetic field strength (H_{mf}) and/or magnetic flux density produced by a current carrying element at point P as shown in Figure-3c of a straight wire (round conductor) with a finite length is given by:

$$H_{mf} = I(\cos\alpha_2 - \cos\alpha_1)/4\pi r \quad (7)$$

and the magnetic flux density in the air medium is:

$$B = \mu_0 \mu_r \cdot I(\cos\alpha_2 - \cos\alpha_1)/4\pi r \quad (8)$$

Where, I = current flowing through the wire and r = distance of the point P from the center of the wire and μ_0, μ_r are the absolute and relative permeability.

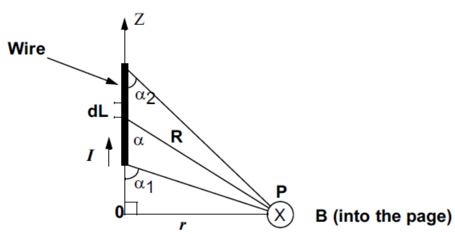

Figure-3c: Calculation of the magnetic flux density (B) or H_{mf} -field at the location P due to current I through a straight conducting wire [5].

In a special case with an infinitely long straight wire where, $\alpha_2 = 0°$, $\alpha_1 = 180°$ or equivalently, $\cos\alpha_2 = 1$, $\cos\alpha_1 = -1$ which will lead to

$$H_{mf} = I/2\pi r \text{ and } B = \mu_0 \mu_r I/2\pi r. \quad (9)$$

Therefore, magnetic flux passing through each turn of the coil can be written as:

$$\psi_{mf} = \int B \cdot dA, \quad (10)$$

where, B is the magnetic flux density given above, and A = surface area of the coil. Here, both B and surface area A are vector quantities and inner product (cosine angle between two vectors) is computed to get the total magnetic flux through each turn of the coil. Once the term ψ_{mf} is calculated for a single turn of the coil the inductance of the antenna L_a can be computed using the following relation:

$$L_a = N\psi_{mf}/I, \quad (11)$$

where, N = number of turns in the coil. Alternatively, one can compute the induced voltage using the following relations:

$$V = -L_a(dI/dt) = -N(d\psi_{mf}/dt), \quad (12)$$

Where, the negative sign comes from the Lenz's law. Thereafter, L_a can be estimated from the above two relations.

However, with the Comsol multiphysics tool using the Impedance Boundary Condition in frequency domain study the coil inductance is estimated from the total magnetic energy W_m using the following relationship:

$$L_a = 4W_m/I_0^2, \quad (13)$$

where, L_a = antenna coil inductance, I_0 = terminal current applied to the Lumped Port (*mf*-physics in Comsol). Note that here factor 4 instead of factor 2 has been used in coil inductance computation. The reason for the same is as follows: Comsol assumes that the applied terminal current (I_0) is the peak current, whereas the total magnetic energy W_m computed by Comsol is based on RMS value of current and therefore:

$$I_{rms} = I_0/\sqrt{2} \quad (14a)$$

and consequently:

$$L_a = 2W_m/\left(I_0/\sqrt{2}\right)^2 \quad (14b)$$

because,

$$W_m = \frac{1}{2} \cdot L_a I_{rms}{}^2. \quad (15)$$

Besides the coil inductance DC and AC resistances of antenna coils are also important, as the impedance of the coil (Z_a) depends both on coil-inductance (L_a) and coil-resistance (R_a) etc. The DC resistance of any conductor with uniform cross-sectional area can be written as $R_{dc} = l/(\sigma A)$, where, R_{dc} = DC resistance (Ohm),

σ = conductivity of the conductor, l stands for total length of the conductor, A = cross-sectional area of the conductor = $w \cdot h$, where w = width of the copper trace = 0.15 mm (say) and h = height (thickness) of the Cu-trace = 35µm = 0.035mm (say). In order to get higher Q-factor (quality factor of antenna) the resistance must be kept low (by using thicker and wider Cu-trace). AC resistance of the conductor is generally higher than the DC resistance because, at DC charge carriers (electrons) are evenly distributed through the entire cross-section of the Cu-trace or conductor. As the frequency increases the skin-effect also increases in the conductor forcing the charge carriers to move away from the center of the conductor towards the edge. As a result the current density ($J = I/A$) decreases in the center and increases near the edge. The depth into the conductor at which current density falls to 1/e or 37% of its value along the surface, is known as the skin depth and expressed as follows:

$$\delta = 1 / \sqrt{\pi f \mu \sigma}\,, \qquad (16)$$

where, f = frequency, μ = permeability of the medium (H/m) $= \mu_{0} * \mu_{r}$, and $\mu_r = 1$, is the relative permeability of Cu-trace. As before, here also σ = conductivity of the Cu-trace = $5.8*10^{+7}$ (Siemens/m). The skin-depth of Cu-trace at 13.56 MHz = 18μm = 0.018 (mm) implying that 63% of the RF current will flow in Cu-trace or Cu-conductor within a distance of 0.018mm of the outer edge of the conductor for 13.56 MHz frequency. The wire resistance increases with increase in frequency and the resistance due to the skin-depth is called AC resistance and approximated by the following formula [5]:

$$R_{ac} = l / (\sigma A_{active}), \qquad (17)$$

where, R_{ac} = AC resistance (Ohm) and

$$A_{active} = (w + h)\,\delta \qquad (18)$$

for Cu-trace with width w and thickness h [5]. Hence,

$$R_{ac} / R_{dc} = wh / (w + h)\delta, \qquad (19)$$

and this yields

$$R_{ac} = 1.57 \cdot R_{dc}. \qquad (20)$$

This means that AC resistance of the Cu-trace is 1.57 times higher than the DC resistance of the Cu-trace, which is calculated for w = 0.15 mm, h = 35µm and for above skin-depth of Cu-trace at 13.56 MHz.

2.1. Model building

In order to compute and/or extract the antenna coil parameters COMSOL Multiphysics tool has been used for model building. The Comsol modeling starts with first opening (double clicking) the Comsol Multiphysics model wizard window and then by selecting sequentially "new" and "3D Space Dimension" under "Model Wizard" menu. In the next step, under the add physics "AC/DC" and then the "Magnetic Fields (*mf*)" interface and also "Frequency Domain study" under the "Select Study" have been selected. Thereafter, geometric model building was performed with the following steps as shown in Figure-4a.

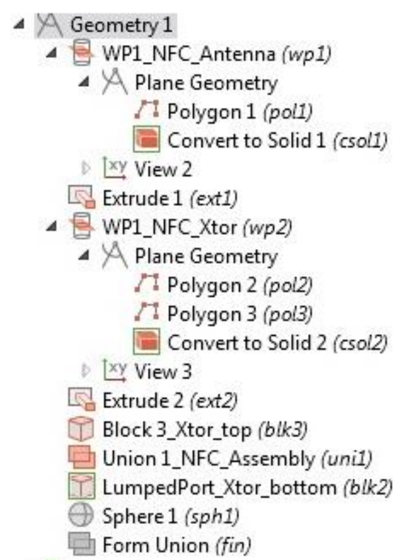

Figure-4a: Geometry building steps of NFC-antenna in model builder

Under the "WP1_NFC_Antenna (*wp1*)" the polygon 1 (*pol1*) represents the antenna coil (xw, yw) corner points in the table form (open or closed curve), which is then converted to solid using (*csol1*) operation. Thereafter, extrude operation was performed in order to have the 3D model of NFC-antenna. Remaining part of the geometry depicts the construction of lumped port, lumped port connectors of NFC-antenna etc. After the 3D model construction of NFC-antenna coil and lumped port element the entire coil is placed in a big sphere with diameter of at least 1.5 times as big as the NFC-antenna length. The aforementioned sphere "(*sph1*)" with layer thickness of 3 mm is used here as the infinite element domain. Thereafter, in this model only two types of materials were used.

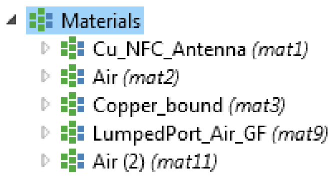

Figure-4b. Material lists of the NFC-antenna model.

The copper (Cu) is used as both NFC-antenna coil material and NFC-connectors including the two sides (boundaries) of the lumped port, which are connected to NFC connectors for electrical current conduction. The sphere walls (inner and outer walls) and lumped port materials are assumed to be of air materials. The material list is shown in Figure-4b. Once the materials are assigned to the different boundaries and domains/model elements then the magnetic field (mf) interface from the AC/DC physics is considered and described in subsection 2.2.

2.2. MF-Physics Interface

In the (*mf*) physics interface the following additional items e.g. "Impedance Boundary Condition (IBC)" and "Lumped Port (LP)" and "Discretization" etc. are used besides the default *mf-interfaces* such as "Ampere's law 1", "Magnetic Insulation 1" and "Initial Values 1" etc. as shown in (Figure-4c).

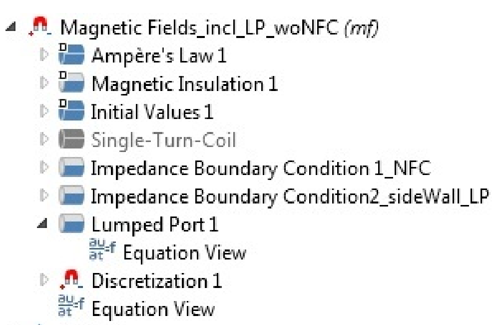

Figure-4c: Magnetic Field interface list used for NFC-antenna model simulation.

The domains and boundaries are assigned suitably under *mf*-interface. For instance, *mf*-interface "Magnetic Fields_incl_LP_woNFC" in Figure-4c includes all the domains (infinite elements/eight outer-walls of the sphere, inner-wall domain of the sphere and also the lumped port domain) ***except** the domain of NFC-antenna*. This means that "NFC-antenna" domain must be excluded from aforementioned *mf-interface*. The "Impedance Boundary Condition 1_NFC" includes all the copper-boundaries of NFC-antenna whereas the second IBC i.e., the "Impedance Boundary Condition 2_sideWall_LP" includes only the two copper side-boundaries of Lumped Port which are attached to NFC-antenna/copper connectors. The Lumped Port 1 includes the remaining four boundaries of Lumped Port which were earlier assigned as air in the material list. Discretization of Magnetic vector potential can be linear or quadratic. However, in the first instance linear discretization can be used.

2.3. Mesh Settings

Mesh settings assigned to various boundaries and domains are shown in Figure-4d. Sphere inner wall boundaries are meshed with "Free Triangular 1" meshes of normal element size.

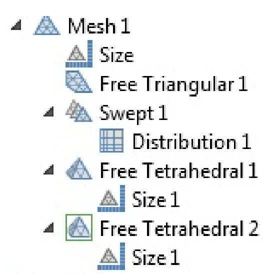

Figure-4d: Meshes used for NFC-antenna simulation.

Only the outer-walls (infinite elements domains) of the sphere are included under the domain selection of "Swept-1". The "Distribution" setting includes all domains including inner and outer walls and also the NFC-antenna and Lumped Port domains. Four (4) numbers of elements are assigned under "Distribution" properties. Tetrahedral meshes "Free Tetrahedral 1" with extra fine element sizes are used for meshing the NFC-antenna and the Lumped Port domains. The remaining (unassigned) domains of entire geometry are meshed with “Free Tetrahedral 2” meshes of normal element size.

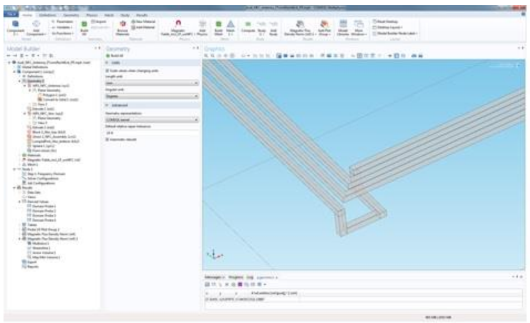

Figure-4e: Partial (zoomed) view of a large NFC-antenna (3 turns) modeled using Comsol

The total number of mesh elements generated in the model is 365748 and the average element quality of the generated meshes is 0.6553 as per the statistics. In Figure-4e the partial zoomed view of the NFC-antenna model is depicted.

3. Simulation and Parameter Extraction

After the successful model building and mesh generation the NFC-antenna model can be simulated by clicking the mouse on “study” and then “compute” button on Comsol model wizard window. Magnetic field (MF) interface from AC/DC physics with aforementioned settings has been used for such an antenna-model simulation.

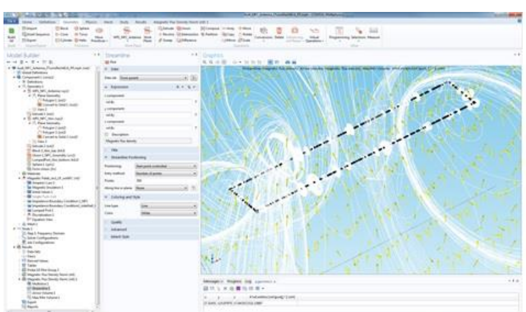

Figure-5: Frequency domain modeling of NFC Antenna (Comsol simulation results)

Figure-5 shows the simulation results obtained from a frequency domain modeling of NFC antenna at 13.56 MHz using Comsol multiphysics tool. Frequency domain modeling carried out with the above antenna shows the ring/circular shaped white lines representing magnetic flux density (B-field) and the yellow colored arrows show their directions. In addition to B-field, Comsol model also computes the coil inductance L_a = 1521 nH or 1.521 µH and series resistance R_a = 1.6 Ohm of the antenna, which are good starting values for the further computation of matching circuit components using RF simulation [2, 3].

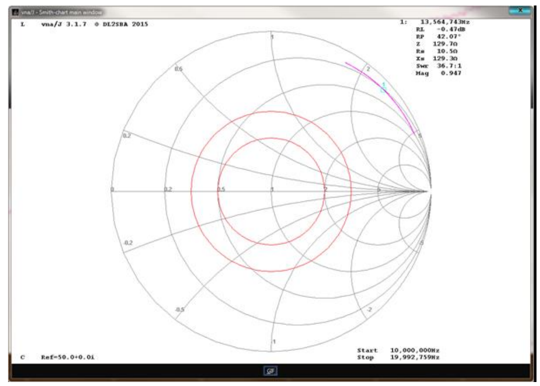

Figure-6: Vector Network Analyzer (VNA) measurement of the NFC-Antenna parameters.

The simulation results obtained from the Comsol multiphysics tool have also been compared with vector network analyzer (VNA) measurements. For this purpose NFC-antenna coil of above Cu-material, size and dimension have been fabricated on the test printed circuit board (PCB) and thereafter, the antenna is measured with the vector network analyzer after the usual calibration of VNA. Figure-6 shows the Smith chart plot of VNA with the frequency sweep around (13.56 ± 1.0) MHz frequencies. The same figure (Figure-6) also shows in the top right-hand corner side of the coil reactance at f = 13.56 MHz: $X_s = 129.30$ Ohm and coil resistance at f = 13.56 MHz: $R_a = 10.30$ Ohm. The coil reactance value when divided by the angular frequency, $\omega = 2\pi f = 8.52 \times 10^7$, yields the antenna-coil inductance value L_a (vector network analyzer-measurement): $L_{a\_VNA} = X_s/\omega = 1.52 \mu H$, where f =13.56 MHz. This means that the antenna coil inductance (L_a) value obtained from VNA-measurement is surprisingly identical with that obtained from Comsol multiphysics tool, although coil resistance value (R_a) for the same model differs significantly, as $\Delta R_a = (10.3 - 1.6)\Omega$, which gives: $\Delta R_a = 8.7\Omega$. The aforementioned results (L_a and R_a values) are then further applied for the design and simulation of matching circuit components (damping resistor and also series, parallel capacitance selection) using RF-simulation (see Figures-7a and 7b).

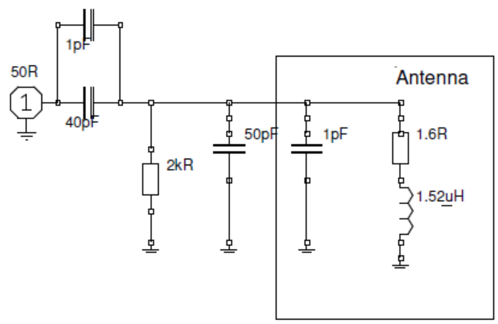

Figure-7a: RF-simulation of NFC-antenna coil for matching circuit design.

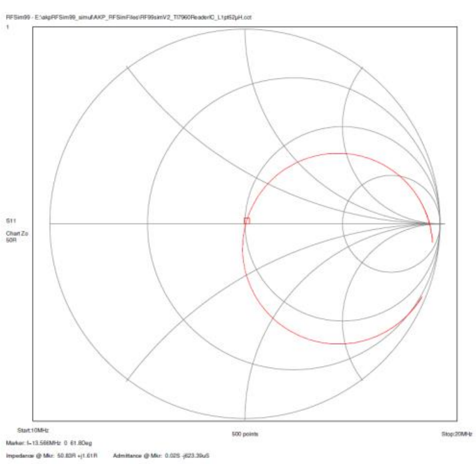

Figure-7b: Smith chart plot from RF-simulation of NFC-antenna coil for impedance matching.

RF-simulation circuit (Figure-7a) uses the antenna parameters $L_a = 1.52\mu H$ and R_a = 1.6 Ohm, which are extracted from the Comsol simulation. The Figure-7b shows the Smith chart plot of RF-simulation carried out with RFSim99 simulation tool. The Smith chart plot shows that 2k damping resistance along with 40pF and 50 pF capacitances deliver the (S11) parameter or impedance Z = (50.37+j1.61) Ohm at 13.566 MHz, which represents a very good match to 50 Ohm.

4. Concluding Remarks

An NFC-reader antenna was modeled using Comsol frequency-domain tool at 13.56 MHz operating frequency of the antenna. The antenna coil inductance (L_a in µH) and series resistance (R_a) in Ohm obtained from the frequency domain model of the antenna were further compared with the Vector Network Analyzer measurement. It was observed that measured coil inductance (La) value of the antenna resemblances very closely with the simulation results obtained from frequency domain modeling with Comsol multiphysics tool. However, the antenna series resistance (R_a) value differs significantly. Further antenna models were built and simulated with variations in physical dimensions of the antenna (not reported here) and they are in most cases within 10-15% error limit. Based on the above parameter values suitable matching circuit was designed and the performance of the matching circuit was also tested. It has been observed that matching circuit designed with Comsol multiphysics tool performs close to the matching circuit which was designed based on the VNA measurement. The simulation results were implemented in the prototype-development of an NFC-reader antenna used for automatic car door opening system.

5. References

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