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A UHF RFID Tag with Improved Performance on Liquid Bottles

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***Abstract*—The effect of liquid on the performance of a UHF RFID tag is investigated in this paper. It is found that the presence of the liquid increases the loss resistance in the equivalent circuit of the antenna. This leads to impedance mismatching with a narrower bandwidth and degraded return loss. The proposed solution for compensating this effect is to add a resonant RLC circuit with smaller resistance in parallel to the antenna body. This resistance corrects the increased loss resistance when the resonant frequency of the added part is close to the working frequency of the tag. The simulation and measurement results confirm an improvement in impedance matching which leads to the increase of the reading range.**

***Index Terms*—Equivalent circuits, Impedance matching, Radio frequency identification (RFID), RFID tag antennas.**

I. Introduction

TRACKING of objects using passive radio frequency identification (RFID) tags has been replacing other methods of tracking in recent years since they are easy to read and provide a long read range with enhanced data capacity [1]. There are various designs of these tags with different sizes for different applications but label types are more favorable as they are low cost and easy to use. In addition, in many applications like tagging goods in stores it is required to hide the tag from the surface of the object for security and appearance reasons. Thus, label type tags are the best choice. One drawback of these tags is the sensitivity to the adjacent material. Their performance is affected as a result of detuning the antenna when they are in proximity to metals and dielectrics such as water [2]. Liquid filled bottles and containers are among the most challenging objects which seriously affect the performance of label type tags placed on them. High permittivity and conductivity of water are the main reasons for this effect [2], [3]. Although there have been designs with a ground plane that can tolerate liquid bottles, they are costly and bulky compared to label type tags [4], [5]. There has been some work in the literature to solve the problem of label type tags used on liquid bottles. One way is to avoid the liquid by placing the tag on the neck of the bottle

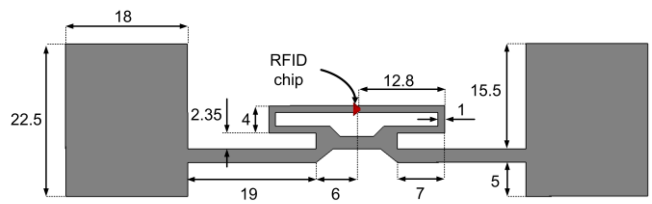

Fig. 1. Physical structure of ALN-9768 with dimension details. All values are in millimeters.

[6]. However this tag only works when the bottle is in a standing position. Another solution is to embed the tag inside the cork [7] but due to the complicated design, the fabrication process would be very costly. Other efforts for improving the performance are done with the cost of using a combined dipole antenna or reflector plate on the back of the bottle [8], [9]. The performance of commercial tags seriously deteriorates when they are placed on liquid bottles [2]. Although there are some tags which are specially designed for liquids, they are normally large, costly, and not easy to use.

In this paper, the performance of one of the latest commercial designs on a thin liquid bottle is investigated first. The effect of water on the frequency response is studied from the equivalent circuit point of view and a new design with an improved reading range and bandwidth is then proposed. Finally, the performance of the proposed prototype is tested and compared with the commercial tags.

II. Analysis of ALN-9768

ALN-9768 which is known as “Wonder Dog” is one of the latest products of Alien [10]. It is a general purpose tag particularly designed for RF reflective and absorbing materials such as metals and bottled liquids. The performance of this tag in free space and on a thin liquid bottle is studied by simulation and circuit analysis in the following subsections.

A. Structure Simulation

The physical structure of ALN-9768 is analyzed and simulated by using CST software. The passive tag is composed of a chip and an antenna which are connected together by a matching loop as shown in Fig. 1. The matching loop provides the required inductive impedance for conjugate matching to the capacitive impedance of RFID chip. This is to achieve the maximum power transfer [11]. The short dipole antenna is loaded with capacitive plates at both ends. This facilitates the impedance matching and also increases the average current on the radiating wire leading to an

This work is supported by Aeternum, LLC.

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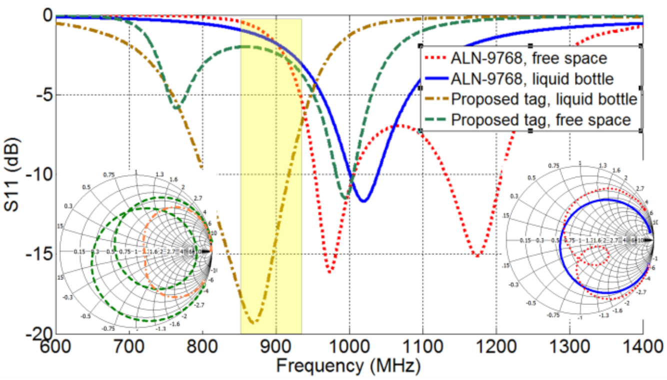

Fig. 2. S11 and the Smith chart of ALN-9768 and the proposed tag in free space and on a plastic bottle filled with water.

improvement in the radiation efficiency [12]. It is known that the radiation efficiency of the tag is severely limited by the presence of water [3]. Thus, perfect impedance matching with a sufficient bandwidth plays an important role in having a reliable universal tag that covers UHF RFID EPC Gen 2 band (860-960 MHz, but most countries use either 865-868 or 902-928 MHz bands). The reflection coefficient S11 parameter of the tag in free space and on a plastic bottle with relative permittivity of 2.3, thickness of 1 mm and dimensions of 80 mm×80 mm×200 mm is simulated and the result is plotted in Fig. 2. The S11 is at the chip input port and matched to the chip impedance. It is observed that the tag is out of tune. In general purpose tags, the antenna is usually designed to resonate slightly higher than the required bandwidth. This compensates for the effect of the dielectric material on the tag [13]. As can be seen in Fig. 2 the frequency response of the tag is affected by the liquid bottle with a smaller bandwidth and smaller return loss. This not only affects the reading range but also makes the tag sensitive to any changes in the environmental temperature, the material and thickness of the bottle. The reason of this phenomenon can be found by studying the equivalent circuit of the tag in the next subsection.

B. *Equivalent Circuit Analysis*

The physical structure of the tag in Fig. 1 can be translated into the equivalent circuit of Fig. 3 by applying the electric wall concept [13], [14]. Due to the mutual inductance and radiation from the matching part it is difficult to have an accurate prediction on the values of the elements in the circuit. However it is possible to have approximate estimation on the values. The inductances can be found by:

$$L = \frac{\mu_0}{2\pi} l \left(\ln\left[\frac{l}{w}\right] + \frac{\pi}{2} \right); \ \mu_0 = 4\pi \times 10^{-7} H/m \qquad (1)$$

where l and w are respectively the length and width of the conductive trace [13]. The calculation of the inductances for the antenna divided by the electric wall results in: L_{ser} = 10.5 nH, L_{sh} = 3.2 nH, and L_{ant} = 19.3 nH. The antenna capacitance is mostly provided by the plates at the end of the dipole. A study done in [13] shows that a disk with radii of around 1 cm

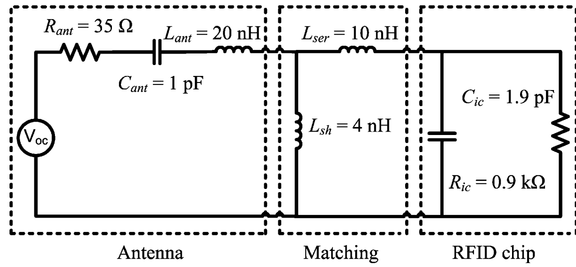

Fig. 3. Equivalent circuit of ALN-9768. The values are for the tag working in free space.

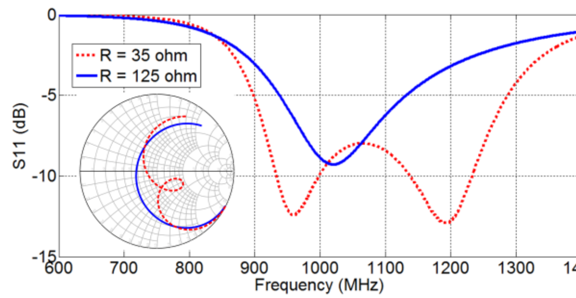

Fig. 4. The effect of increasing R_{ant} from 35 Ω to 125 Ω on the frequency response of the equivalent circuit.

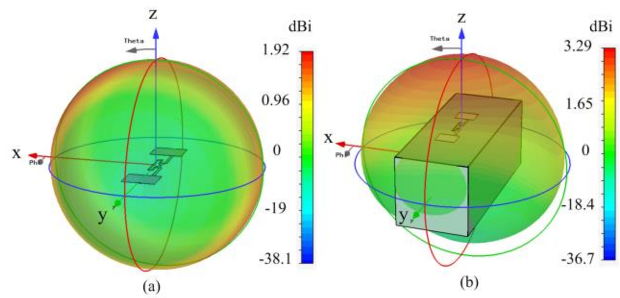

Fig. 5. The radiation pattern of ALN-9768 in: (a) free space and (b) on a plastic bottle filled with water.

provides capacitance of about 1 pF. The antenna resistance is the sum of the radiation and loss resistance ($R_{ant} = R_{rad} + R_{loss}$). The loss resistance is usually negligible in comparison to radiation resistance in free space. The radiation resistance for a small dipole can be approximated by:

$$R_{rad} = 80\left(\frac{\alpha \pi l}{\lambda}\right)^2 \qquad (2)$$

where l is the length of the antenna and α is a factor between 0.5 and 1 depending on the current distribution along the antenna [12]. By considering the working frequency of the tag at 866 MHz, the radiation resistance is supposed to be between 12.17 Ω and 48.66 Ω. The equivalent circuit for Higgs-4 RFID chip is a 1.8 kΩ resistor in parallel with a 0.95 pF capacitor. These values are respectively divided and multiplied by 2 after applying the electric wall concept. ADS software is used to simulate the equivalent circuit and the value of elements that achieved by fine tuning is given in Fig. 3. They are in good agreement with the predicted values by calculation. These values are for the tag working in free space. It is observed that by increasing the value of R_{ant} from 35 Ω to 125 Ω the frequency response of the circuit resembles the effect of the liquid on the tag. The result is depicted in Fig. 4 which is

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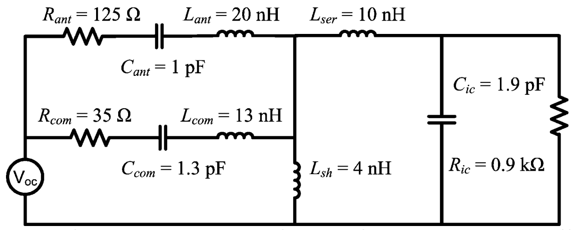

Fig. 6. Modified equivalent circuit of the tag for compensating the effect of liquid on the frequency response.

similar to Fig. 2. As shown in Fig. 5 the directivity of the tag is increased from 1.92 dBi to 3.29 dBi in presence of liquid but the total radiation efficiency is decreased from -0.17 dB to -22.17 dB. Thus it can be concluded that the liquid causes an increase in R_{loss} leading to a total increase in R_{ant}. This results in the impedance mismatch and reduced bandwidth.

III. Equivalent Circuit Modification

Having identified the problem, a novel solution is proposed in this section by compensating the effect of the liquid: a smaller resistance in parallel to R_{ant} is added. In this way it is possible to correct the total resistance in the antenna body in order to make the optimum impedance matching with the chip. The parallel resistance is added to the circuit in the form of another series resonant *RLC* circuit as shown in Fig. 6. The resonant frequency of the added *RLC* circuit should be close to the resonant frequency of antenna body. To show the effect of the new added resistance, a high value of about 1 kΩ is considered first. Such a high resistance in parallel to 125 Ω should not make a significant change on the frequency response. For the next step, the value of resistance is set to be about 35 Ω. Compensation takes place at this point as depicted in Fig. 7.

In an optimum tag design the impedance of antenna should be matched at the working resonant frequency. The circuit of Fig. 3 is simply translated from the physical structure and it cannot clearly reflect the manner of the system in resonance. This circuit can be transformed to a simpler form by using the method introduced in [15]. For the proposed circuit in Fig. 6, another stage of transformation is needed. It is found that the proposed circuit can be simplified to the circuit shown in Fig. 8. The parameters β, x, and y can be found by:

$$\beta = \frac{L_{sh}}{L_{sh} + L_{ser}} \tag{3}$$

$$x = 1 + \frac{Z_{ant}}{Z_{com}} \quad , \quad y = 1 + \frac{Z_{com}}{Z_{ant}} \tag{4}$$

where Z_{ant} and Z_{com} are the input impedances of the antenna body and the added part for compensating the effect of liquid.

$$Z_{ant} = R_{ant} + j\omega L_{ant} - \frac{j}{\omega C_{ant}} \tag{5}$$

$$Z_{com} = R_{com} + j\omega L_{com} - \frac{j}{\omega C_{com}} \tag{6}$$

The transformed circuit depicted in Fig. 8 is comprised of two series resonators and one parallel resonator. The series

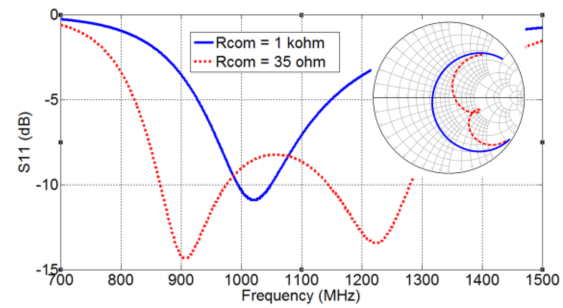

Fig. 7. Determining the effect of R_{com} on the frequency response by changing the resistance from 1 kΩ to 35 Ω.

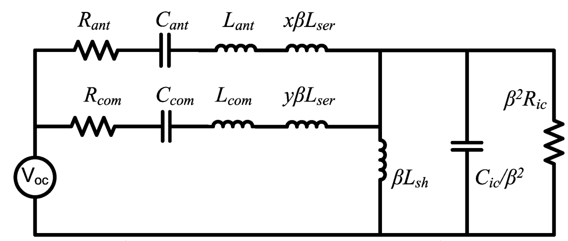

Fig. 8. The modified equivalent circuit can be transformed into a simple circuit consisting of parallel and series resonators.

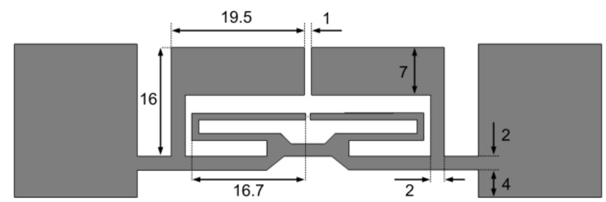

Fig. 9. Proposed modified structure of the tag for compensating the effect of liquid on the frequency response. All values are in millimeters.

resonators act as a short circuit at the resonant frequency and the parallel resonator acts as an open circuit. So, the circuit simply converts to a new arrangement of resistors. The maximum power transfer occurs when R_{ant} in parallel to R_{com} is equal to $\beta^2 R_{ic}$.

IV. Tag Design and Measurement

The proposed equivalent circuit of Fig. 6 is translated into the physical structure shown in Fig. 9. The structure is designed and simulated using CST software. The overall structure of the proposed tag is based on the dimensions of ALN-9768 shown in Fig. 1. The dimension of the matching loop is increased in the proposed design to shift the resonant frequency of the tag down to the required band when it is on the bottle. The added series *RLC* circuit is translated into two arms in symmetry as can be seen in Fig. 9. The short gap of the arms provides enough capacitance and low loss resistance needed for impedance matching as discussed in the preceding section. The frequency response of the proposed design is depicted in Fig. 2 as well for easy comparison with the reference tag. The added arms increase the return loss and bandwidth of the tag in the working frequency. The -10 dB bandwidth is increased from 3.7 % to 13.5 % for the tag on the bottle. This is achieved without increasing the dimensions but using the available space in an efficient way. In general, if the size is limited in one or two dimensions, the performance can be improved by using more of the remaining space [12]. The

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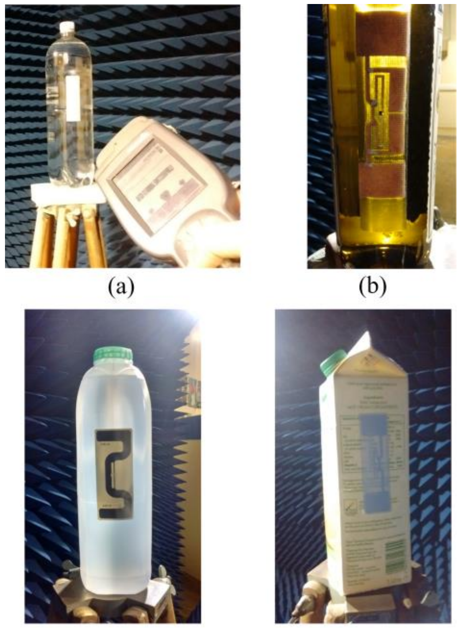

Fig. 10. (a) Determining the reading range of the tags in an anechoic chamber. (b) Proposed design on a glass bottle. (c) Wonder Dog on a paper bottle. (d) BAT on a plastic bottle.

S11 of the proposed design in free space is around -2 dB in the desired band as can be seen in Fig. 2. According to the high radiation efficiency of the tag in free space, this value is sufficient for most RFID applications in practice [16].

A sample of the proposed tag is made by etching the structure of Fig. 9 into a copper sheet. A Higgs-4 SOT RFID chip is soldered to the tag. The reading range of the tag is measured in an anechoic chamber using Nordic ID PL3000 UHF RFID reader which is a handheld device with 630 mW equivalent isotropic radiated power (EIRP). The performance of the tag is compared with ALN-9768 and ALN-9770 that is another tag from Alien known as BAT. This tag is specially designed for automotive batteries and other challenging metal, plastic, and fluid containers [10]. Three different types of water bottle are used for the experiment. The measurement setup and the tags on the bottles are illustrated in Fig. 10. The maximum reading range is measured in each case and the results are listed in Table I. The proposed design offers the longest reading range in all cases.

V. Conclusion

One of the latest commercial UHF RFID tag designs on liquid bottles has been analyzed in this paper. It was shown that by using equivalent circuit analysis and efficient use of available space it is possible to improve the performance without increasing the overall dimensions of the design. Both the simulation and experiment results have shown that the proposed low-cost compact label tag has demonstrated excellent performance and could become a new design for general RFID applications, even for liquid bottles. All the simulation and experiments were performed on water filled bottles. Therefore the result is valid for water based liquids but it should also be suitable for other liquids (such as oils and wine) due to the broadband feature of the tag.

TABLE I
Reading Range of the Tags in Centimeters

Material	BAT	Wonder Dog	Proposed design
Free space	110	150	220
Paper bottle	29	45	79
Glass bottle	13	22	31
Plastic bottle	16	23	54

Acknowledgment

The authors would like to thank Alien Technology (alientechnology.com) for providing RFID tag and chip samples.

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