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A METALLIC RFID TAG DESIGN FOR STEEL-BAR AND WIRE-ROD MANAGEMENT APPLICATION IN THE STEEL INDUSTRY

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Abstract—In recent years, RFID solutions are finding an increasing number of applications in a wide variety of industries. There are some natural limitations when applying RFID technology in the steel industry, because the tags do not function well in metallic environments. Even though some commercial RFID metal tags are available in the market, they are found to be too expensive by steel companies. This paper proposes a useful and practical RFID tag design for management applications involving steel-bar and wire-rod products manufactured by the steel industry. The dual-function metallic RFID tag, comprising of both an RFID code and a barcode, involves technology advancement in RFID design, and named Window-Tag (WinTag). The maximum read range of this tag can reach about 5.7 m for the radiated power of 4.0 W EIRP in free space. In the practical application, the maximum read ranges are about 2.3 m and 5.0 m for the worst and best case, respectively. The design methodology as well as simulation and measurement results of the WinTag are presented in this paper. The low profile and low cost features of the WinTag makes the RFID tag well suited for metallic type tag of labeling system that requires integration of RFID technology.

1. INTRODUCTION

Radio Frequency Identification (RFID) is a technology used for object identification, which finds numerous applications in retail, transportation, manufacturing and supply chain systems. While successful RFID applications are constantly being announced in many

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areas, the steel industry remains an exception. Both the metallic objects as well as those containing liquids represent two major bottlenecks when considering the design of RFID tags [1]. Obviously, all steel products fall into the metallic category and pose a challenge in the tag design, especially since the commercial RFID solutions are not workable for the steel or iron products. While RFID solutions for metallic objects have been developed and are available in the market, their cost is relatively high, and this poses a real barrier to their use in the steel industry. Since the typical steel products are large and heavy, and since they operate in a high temperature environment, scanning the barcode information poses a danger to the operators since they must get close to the products. Consequently, the RFID solutions are very important and much desired in the steel industry. Though there are many different types of products manufactured by the steel industry, the steel-bar and wire-rod products are the ones that are manufactured in large quantities. This has prompted us to develop and deploy the RFID solution for these products in the initial stages of our RFID effort for this industry.

In a typical RFID system, an RFID solution is comprised of tags, readers and information management systems [2–4]. If an RFID tag is attached directly to a metallic object, or to a package containing metals, it may function rather poorly [5]. For instance, when dipole-type of RFID tag adheres to a metallic object without the presence of a gap or a substrate, they function relatively poorly. Thus designing an RFID tag antenna that performs well when operating in close proximity of a metallic object is of critical importance.

Over the past few years, a considerable number of studies have been conducted on the topic of RFID design [6, 7], with emphasis on good performance in practical applications [8]. An RFID tag is composed of an RFID chip and an antenna, which transforms the received electromagnetic fields into electrical energy for the chip that sends out digital information, embedded within it, back to the reader. A successful antenna design provides a conjugate impedance match between the chip and the antenna [9].

Several papers on RFID tag antenna design have appeared in the literature in recent years. The dipole-type RFID tag antenna is very common and simple to design [10, 11], though it cannot be used on metallic objects. The inverted-F antenna (IFA), planar inverted-F antenna (PIFA), and patch-type antenna all can be designed for RFID applications involving metallic objects [12–14]. However, the thickness of these antenna structures must necessarily be larger than 3 mm, or even greater. This makes these antenna structures unsuitable for use where a tag with a bulge is not acceptable. In addition, those RFID metal tag antenna all possess a ground plane structure to immune the interference from the metallic objects, therefore, the radiation patterns of those tags cover only the semi-spherical space or a certain direction. This reduces the benefits of applying RFID technology in the practical applications. Therefore, an RFID tag whose thickness is smaller than the available metallic tags and the radiation pattern is close to omnidirectional needs to be developed for steel-bar and wire-rod type of RFID applications.

In this paper, we propose an inductively-coupled slit structure with a small loop antenna to form an RFID tag antenna, called the WinTag, for metallic objects. The antenna structure and its characteristics are detailed in Section 2, which also includes the simulation and measurement results. Section 3 presents a practical WinTag design and its implementation. Finally, some conclusions are presented in Section 4.

2. METALLIC RFID TAG ANTENNA DESIGN

There are two approaches to designing tags for applications to metallic objects. The first one is to reduce the effects of interference from the metallic surface, which is achieved for instance by inserting the tag in a high permittivity substrate or embedding it with a HIS (High Impedance Surface) ground plane [15]. An alternative approach is to insert a conductive ground plane in the antenna structure to reduce the effect of the metallic surface on the performance of the antenna. However, these designs are not suitable for metallic tag applications, even though they may perform well on other metallic objects. The reason for this is that these antennas have a semi-spherical radiation pattern, and require additional space when they are attached to metallic objects. Thus, these features together with their cost aspect, renders them unsuitable for steel-bar and wire-rod RFID applications. This motivates us to develop a metallic RFID tag, proposed in this paper to mitigate these problems. The configuration of the tag, its characteristics and the basic design concepts of the proposed metallic RFID tag are described below in detail.

2.1. Configuration of the WinTag

The proposed metallic RFID tag is comprised of a slit metallic plate and a small loop antenna. Since its shape has the appearance of a window, it has been named the Window-Tag (WinTag). Figure 1. shows the configuration of the WinTag. The slit in the metallic plate is designed to have a special shape and it serves as the radiator of the

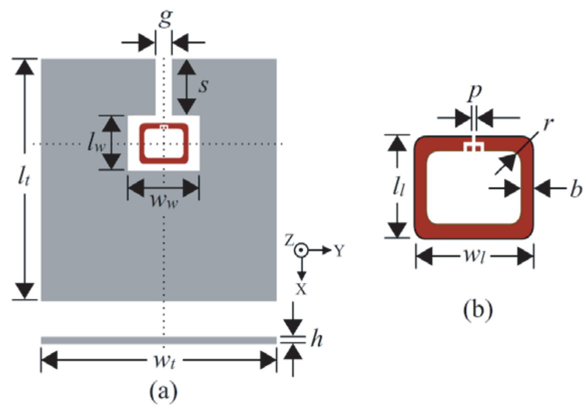

Figure 1. (a) Configuration of the WinTag antenna, (b) small loop antenna.

proposed WinTag antenna. The small loop antenna inductively couples the energy to the radiator to form the metallic RFID tag antenna. The advantages of this design are that the slit can be directly cut in the original metallic tag, and the small loop antenna can be produced by using a commercial RFID tag manufacturing process, which renders the proposed metallic RFID tag very suitable for steel-bar and wire-rod RFID applications when compared to the conventional other RFID metal tags.

2.2. Characteristics of the WinTag

In this paper, the WinTag antenna is designed for a TI UHF RFID chip, whose input impedance is about $(10.7–j62.8)\,\Omega$ at 925 MHz. The chip conforms to the EPC Class 1 Gen 2 standard and provides a 96-bit read/write EPC ID memory block. We note at this point that the design do not follow the 50-Ω rule, but a complex conjugate match to the chip. The inductively coupling between the small loop antenna and the slit metallic plate makes it convenient to implement the impedance match, especially when we require a small resistance and a large reactance value for the RFID chip impedance. The small size of the loop antenna also provides freedom for adjusting the imaginary part of the impedance and this is a very important feature of conjugate impedance matching type of design, which is achieved by tuning the geometrical parameters w_l, l_l, and b. After a satisfactory imaginary part has been realized, the slit metal plate is added to the design model to further tune geometrical parameters w_w, l_w, s, and g, to realize the desired real part of the impedance, and to tune w_t and l_t to achieve the desired level of the gain for the WinTag antenna. Thus, the design methodology of the WinTag antenna is simple and easy to implement.

2.3. Small Loop Antenna Design

In developing the design procedure, we first consider how to design the small loop antenna. It is well known that a small loop has a poor radiation efficiency and, hence, it is not suitable for an RFID tag with a long read-range in this design. Nevertheless it can be used as an inductively-coupled, useful feed antenna [16, 17], and we use the small loop antenna for this purpose of this design. Figure 2 shows the impedance characteristics of the small loop antenna as we vary its size. Since the small loop antenna has poor radiation efficiency, the real part of its impedance is approximately zero, and varies as we change the area of the small loop. However, the inductance does vary in proportion to the area of the loop. The larger the area we used, the larger the inductance we can obtain. The coupling strength is dependent upon the distance between the loop and the slit window of the metal plate.

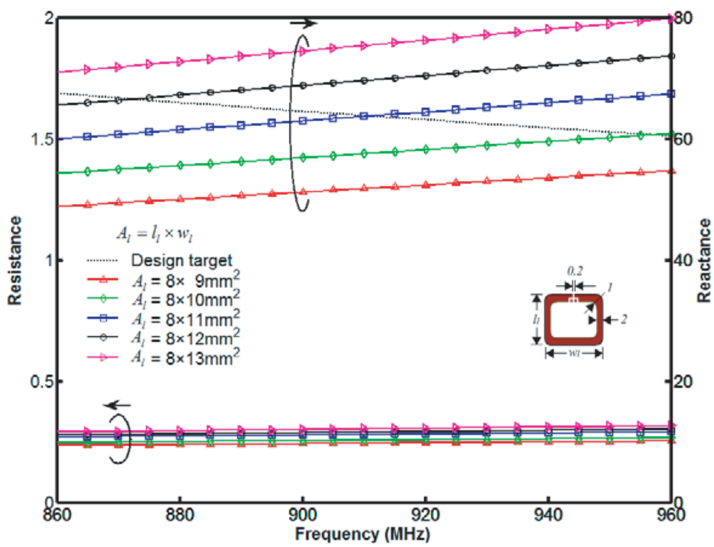

Figure 2. The simulation results of different dimensional small loop antennas.

On the basis of the simulation results of the small loop antenna, the size is chosen to be $8 \times 11\,\text{mm}^2$ ($l_l \times w_l$), and the width of the copper line is 2 mm. The impedance of the loop antenna operating at

925 MHz is about $(0.3 + j64.9)\,\Omega$; hence, its imaginary part is close to our design target of $j62.8\,\Omega$. Although the real part impedance of this loop antenna is very small, it will increase when the loop is inserted in silt metal plate.

2.4. WinTag Antenna Design

The characteristics of the WinTag antenna, which combines a small loop with the slit metal plate, will now be examined in detail. The imaginary part of its impedance is determined primarily by the inductively coupled source, namely the small loop antenna. However, the primary source of the radiation is the slit metallic plate, and we use it to adjust the real part of the impedance of the antenna and to enhance its gain. We will now examine below the effects of varying the different parameters on the WinTag.

2.4.1. Slit Width, g, of the WinTag

Figure 3 shows the simulation results as we vary the size of the slit width, s. The imaginary part impedance of the loop antenna is affected little when we change the slit width. However, the real part of the impedance is inversely proportional to its width, and the smaller the

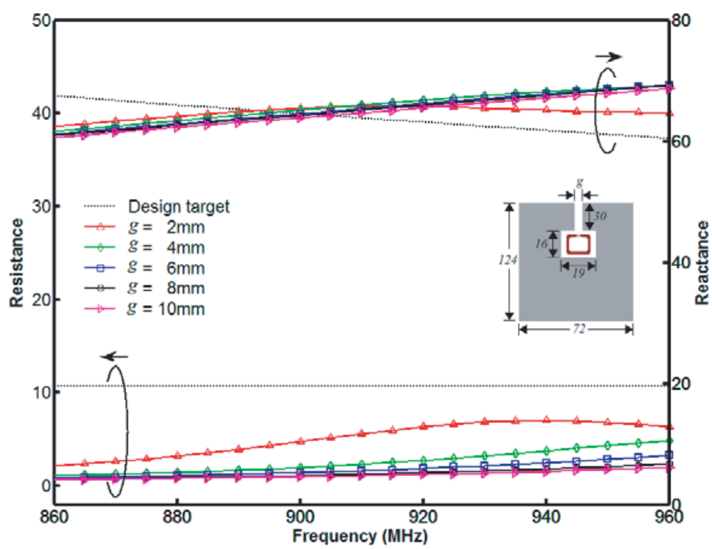

Figure 3. The simulation results of different dimensional slit width, g.

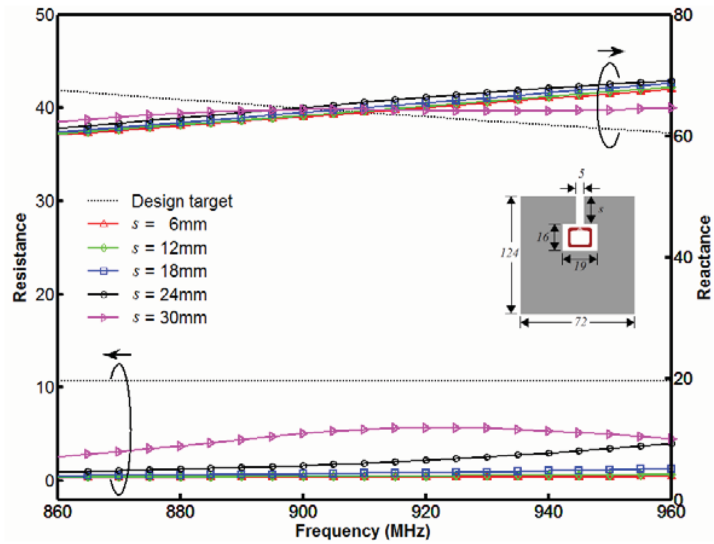

Figure 4. The simulation results of different dimensional slit length, s.

slit width, the larger the real part of the impedance. However, a small slit width is difficult to work with, in practical production, and a large one compromises the robustness of the metal plate. In view of this, we fixed the slit width to be $g = 5\,\text{mm}$ for the practical design.

2.4.2. Slit Length, s, of the WinTag

Figure 4 shows the relationship between the slit length and the input impedance of the small loop antenna. The reactance of the WinTag changes little when the slit length, s, is varied from small to large. But the resistance increases to the maximum value for a certain length and then decreases to the minimum value as the length is increased beyond the turning point. To improve the power transmission coefficient (PTC), the impedance of the WinTag antenna impedance should be close to conjugate impedance of the PFID chip. Moreover, a large slit makes the tag rather fragile. Given this background, we choose the slit length to be $s = 30\,\text{mm}$ in this paper.

2.4.3. Window Slot Size, $l_w \times w_w$, of the WinTag

The window-shaped slot, which connects to the slit, is used to inductively couple the energy from the small loop antenna to the slit

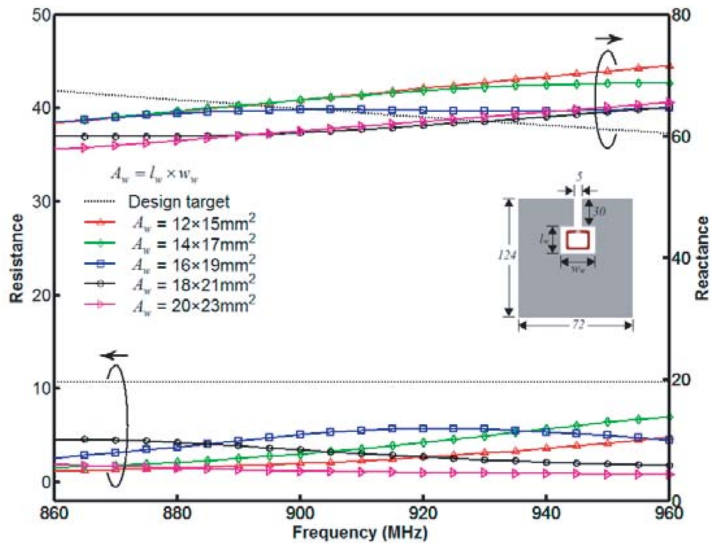

Figure 5. The simulation results of different dimensional window size, $l_w \times w_w$.

metal plate. The coupling strength is mainly controlled by the distance between the window slot and the loop antenna. Figure 5 shows the effects of the different window size on the input impedances of the loop antenna. Simulated results indicate that if this size is small, both the resistance and reactance of the loop will change, but the impedance values are not affected significantly large when this distance is too wide. However, as seem from Figure 6, the choice of a large distance case reduces the antenna gain, but the simulated results show that the window slot size of $16 \times 19\,\text{mm}^2$ is better than the other choices for its dimensions. We note that the real part of the input impedance of the small loop antenna has increased, but its imaginary part remains relatively original unchanged from its value. In addition, the antenna gain is also maintained; hence, we choose $16 \times 19\,\text{mm}^2$ as the size of the window slot for the WinTag to achieve a good performance.

2.4.4. Slit Metal Plate Size, $l_t \times w_t$, of the WinTag

The most important point to realize in designing the slit metal plate is that the choice of its size depends upon the practical application in which it would be used. For example, some steel companies use metal tags with the size of a business card, namely $86 \times 60\,\text{mm}^2$, whereas others choices for specific sizes are $100 \times 70\,\text{mm}^2$ or $124 \times 72\,\text{mm}^2$. To

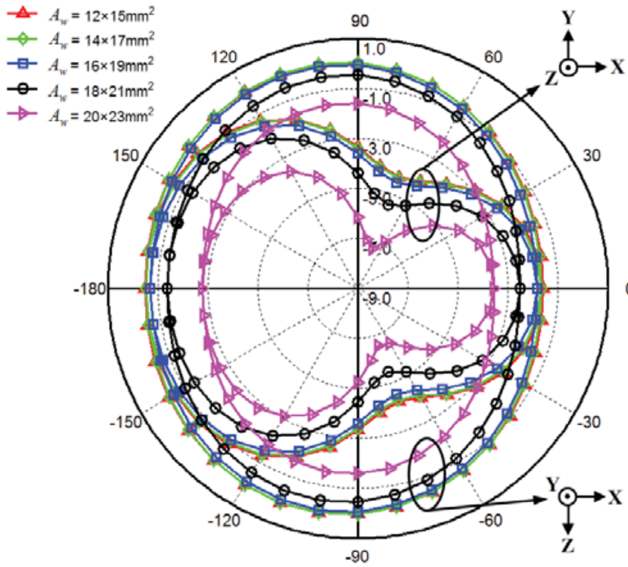

Figure 6. The simulated radiation pattern of WinTag with different window size, $A_w = l_w \times w_w$ (operating frequency = 925 MHz).

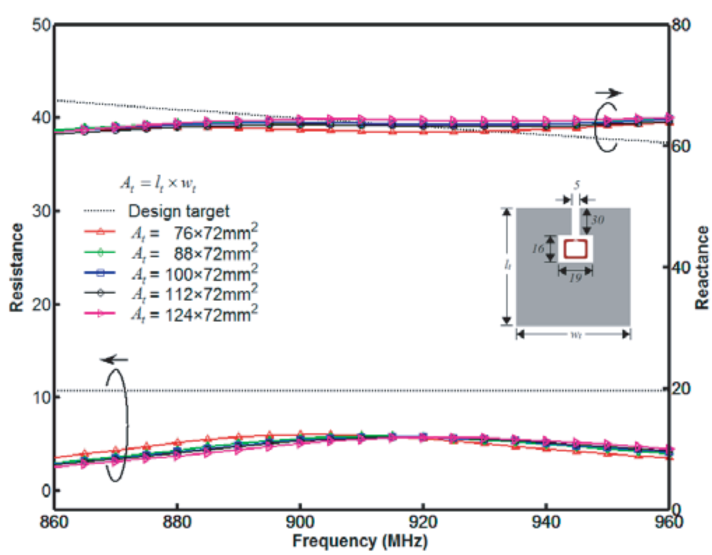

Figure 7. The simulation results of WinTag with different plate size, $A_t = l_t \times w_t$.

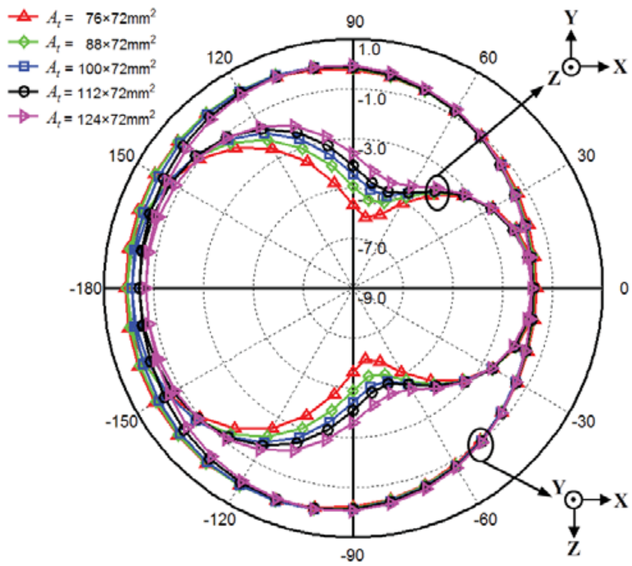

Figure 8. The simulated radiation pattern of WinTag with different plate size, $A_t = l_t \times w_t$ (operating frequency = 925 MHz).

be cost-effective, it is necessary to design the metallic RFID tag to be compatible with the available facilities for printing. It is also highly desirable to choose the size of metallic RFID tags to be the same as that of the original metal tag. Figures 7 and 8 show that the size of slit metal plate does not significantly affect the impedance of the small loop antenna, though it does change its radiation pattern and the antenna gain. We note from Figure 8 that a larger slit metal plate yields a higher antenna directivity in some directions. We choose the slit metal plate to $124 \times 72\,\text{mm}^2$ in size for the design in this paper.

2.4.5. Offset Tolerance between Loop Antenna and Slit Metal Plate

The characteristics of the WinTag and how they relate to the dimensional parameters have been discussed in detail above. All of these parameters can be controlled accurately for small loop antenna, and the slit metal plate can be mass-produced separately. We should remember that the accuracy of the barcode printer of labeling equipment is approximately ± 1.5 mm. Thus we should investigate the effect of the offset of the labeling location of the small loop antenna. The structure of the WinTag antenna is symmetric along the X-axis, therefore we only show the simulated results of the offset location on

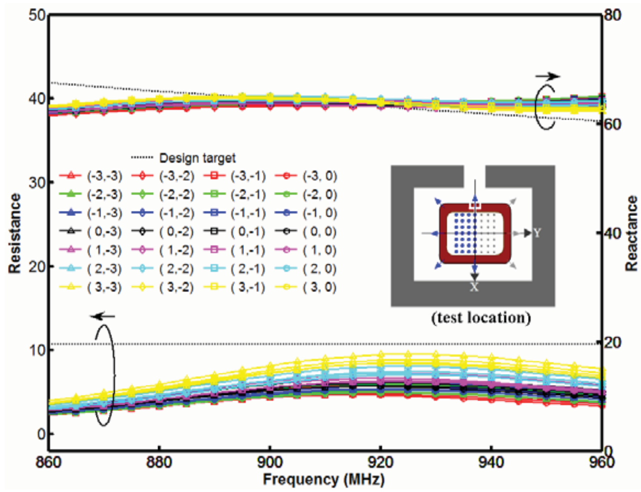

Figure 9. The simulated results of location tolerance for small loop antenna.

the left-hand side of Y-axis. Figure 9 shows the simulated results for the offset-location-tolerance for the small loop antenna. The maximum offset location tolerance is ± 3.0 mm both in the X- and Y-directions. For the reactance part, it is not affected by the offset location of the small loop antenna as long as it is within ± 3.0 mm. The resistance of the small loop antenna improves when it gets closer to the slit metal plate in either the $+X$ direction, or to $-Y$ and $+Y$ directions. These results lead us to conclude that any offset within ± 3.0 mm of small loop antenna labeling location can improve the WinTag performance compared with the case when the label is locale at the center location. This feature is very important from the point of view of the practical applications in the steel industry.

3. PRACTICAL DESIGN AND IMPLEMENTED

We will now consider a practical design example of the WinTag in this section. The physical dimension of the proposed WinTag antenna is adjusted to provide sufficient impedance to match conjugate impedance of TI RFID chip with input impedance of $(10.7–j62.8)\ \Omega$ and sensitivity about -12 dBm at 925 MHz. The WinTag antenna design is also modeled and simulated by using the software Ansoft HFSS. The antenna impedance measurement was performed by using an Agilent vector network analyzer ENA 5071B and the measurement platform for measuring impedance of RFID tag antenna [18].

Parameters	Length (mm)
l_l	8
w_l	11
b	2
r	2
p	0.2
l_t	124
w_t	72
h	0.4
l_w	16
w_w	19
g	5
s	30

Figure 10. The photograph and physical dimensions of the implemented WinTag antenna.

For the test antenna, a slit shaped like a window was directly cut out of a metal plate, which was a compound of iron and carbon, with a thickness of 0.4 mm. The dimensional parameters and a prototype photograph of implemented WinTag antenna are shown in Figure 10. The circular hole in the plate is introduced so as to make it convenient to hang the tag on steel-bar and wire-rod products by using a small iron hook.

The simulation and measurement results of the WinTag antenna, so designed, are shown in Figure 11. The results are in good agreement as a general trend, though they are some differences because of fabrication and measurement errors. It is evident from the figure that the reactance part of the implemented antenna is close to the design target, but is a bit lower. This difference is probably due to the different sizes for a pitch of the fed port between simulation model and practical measurement. The pitch sizes of the fed port are 0.2 mm and 2.5 mm used for the simulation and measurement. We note that the resistive part is higher than the design target. It is likely that the offset of the small loop antenna and the probe above the WinTag antenna affect the measurement results, especially the resistive part of the impedance of the WinTag antenna. The simulation results of the radiation pattern of the WinTag antenna is shown in Figure 12. From the radiation pattern on the X-Y plane, we note that it has a minimum radiation gain in the

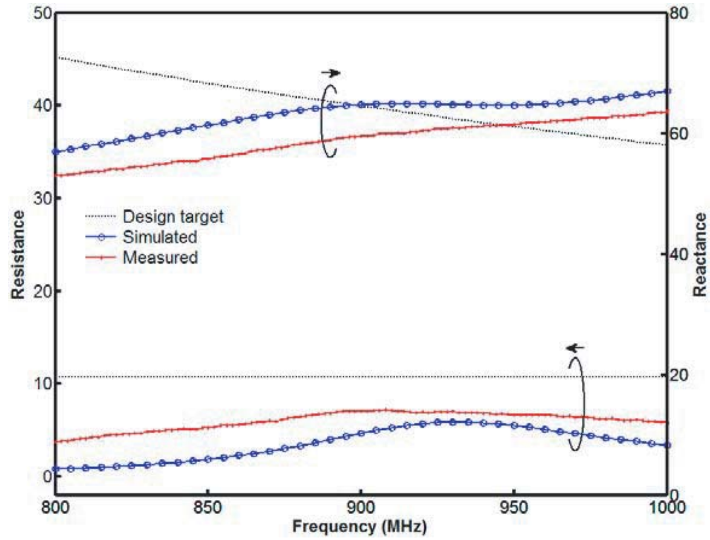

Figure 11. Simulated and measured results of the input impedance of the implemented WinTag antenna.

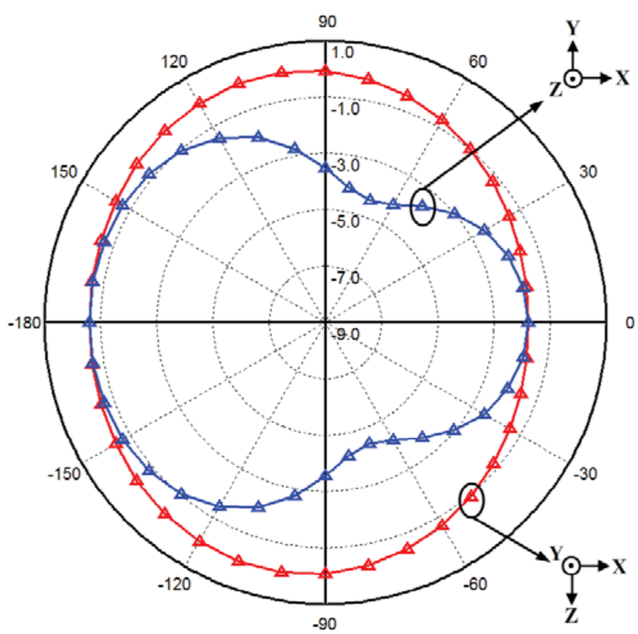

Figure 12. Simulated results of the radiation pattern of the implemented WinTag antenna (operating frequency = 925 MHz).

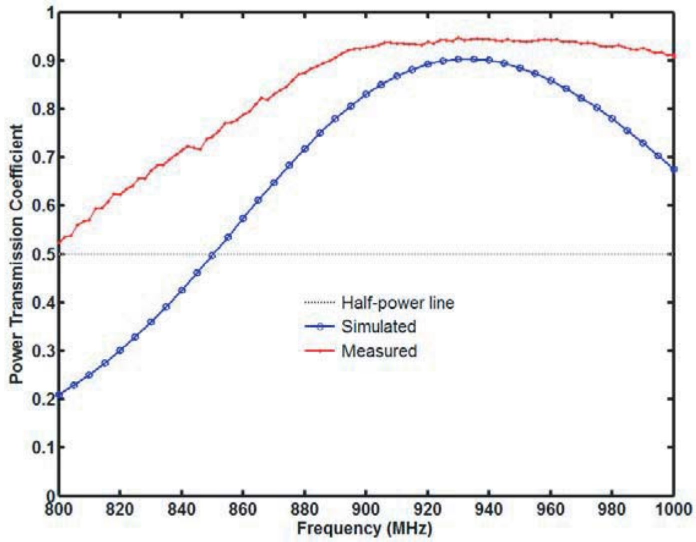

Figure 13. Simulated and measured results of the PTC of the implemented WinTag antenna.

Y-direction and also has a smaller radiation gain in the $+X$-direction than in the $-X$-direction. However, this does affect the performance of the WinTag used for steel-bar and wire-rod applications, because the hanging hole is also in the X-direction, and when the WinTag is hung on the products, the reader does not sense from that direction. For the Y-direction, the problem can be overcome by appropriately choosing the location of the antenna of the reader.

In addition to the impedance analysis, the power reflection coefficient (PRC) [19] or power transmission coefficient (PTC, PTC=1-PRC) value is yet another important performance indicator. Therefore, the PTC curve which calculated from the PTC equation with antenna impedance and RFID chip impedance is shown in Figure 13. The PTC curves show that the WinTag antenna is a wideband device and its half-power bandwidth covers the worldwide RFID frequency band ranging from 860 MHz to 960 MHz. This is very important for steel companies, because their products are almost always shipped to foreign countries around the world.

In order to verify the read range performance of the implemented WinTag, an Impinj RFID reader system was set up with the operating frequency of 902–928 MHz, radiation power of 30.0 dBm and a circularly polarized antenna gain of 6.0 dBi. Therefore, the total transmitted power is approximately 4.0 W EIRP (Effective Isotropic

Environment	The maximum read range (m)
Free space	5.7
Wire-rod : 0°	5.0
Wire-rod : 90°	3.8
Wire-rod : 180°	2.3
Wire-rod : 270°	4.2

Figure 14. Test scenario for the wire-rod product application and the test results of the maximum read range of the metallic RFID tag.

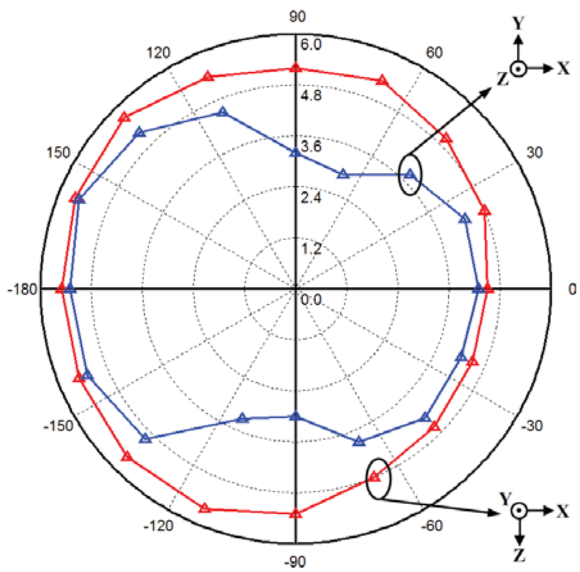

Figure 15. The measured results of the read pattern of the implemented WinTag in free space (frequency band = 902–928 MHz).

Radiated Power). The hang position of the metallic RFID tag on the wire-rod or steel-bar is very random and it is impossible to keep the tag at a fixed position in practical applications. In addition, the practical application on the wire-rod is more complicated than on the steel-bar. For this reason, a test scenario for wire-rod application was defined and shown in Figure 14. The maximum read ranges of the implemented RFID tag applied on the wire-rod product are also shown in Figure 14. The test result of the metallic RFID tag hanged at wire-rod 0° position is very similar to the tag in free space and shows a good read performance than other three positions. The worst case is the tag hanged at wire-rod 180° because the slit and the loop antenna are almost attached to the wire-rod body and consequently the read performance is dramatically decreased. The read pattern of the WinTag measured in free space is shown in Figure 15.

4. CONCLUSION

In this paper, we have proposed a metallic RFID tag antenna design for steel-bar and wire-rod applications, typical for the steel industry. The special design of the WinTag, is fabricated by directly punching out a slit in the original metal tag, and inductively coupled it to a small loop antenna. The characteristics of the WinTag have been analyzed and explained in details. In order to verify the proposed design method, a practical design based on the proposed WinTag structure is also simulated, implemented, measured and tested in this paper. The maximum read range of the implemented WinTag has been found to be 5.7 m with a 4.0 W EIRP and the RFID reader system located in free space. In the practical application on the wire-rod product, the maximum read ranges are about 2.3 m and 5.0 m for the worst and best case, respectively.

In the practical applications, the dual-function WinTag provides the same ID information with barcode label and the RFID chip. Both barcode scanners and RFID readers can be used to obtain the ID information. Therefore, there are no outstanding and unsolved issues encountered during the transition stage of the RFID system deployment or integration, from the upstream suppliers to downstream customers. Even those customers, who are not set up with the RFID facilities, can use the barcode scanners to scan the product ID information. The WinTag is suitable for hang-type metal tag labeling applications, but it cannot be attached directly to the metallic objects. For this reason, developing an attachable RFID metal tag for other steel products will be the major topic of research in the future.

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