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Review of Metal-Resistant Structures for Radio Frequency Identification Tag Antennas

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Abstract: Amidst the rapid expansion of e-commerce and the consequential surge in industries such as transportation, logistics, and supply chain management, there has been remarkable growth. Radio Frequency Identification (RFID) technology, along with its associated tags, plays a pivotal role in the transmission and tracking of crucial information within these sectors. However, the presence of metallic components within RFID systems poses a significant obstacle to efficient antenna transmission. Consequently, there is a pressing need for the development of RFID tag antennas endowed with metal-resistant properties. This paper undertakes a comparative analysis of existing designs and structures for metal-resistant RFID tag antennas, providing valuable insights into their prospective developmental trajectories and potential applications. Such analysis serves as a pertinent reference for research and engineering endeavors across related domains.

Keywords: RFID; Tag Antenna; Metal-resistant; Antenna Structure.

1. Introduction

Radio Frequency Identification (RFID) technology employs radio frequency signals for contactless automatic identification [1]. Its key functionalities encompass the identification, tracking, and management of individuals or items, rendering it applicable across diverse domains including anti-counterfeiting, military, logistics, healthcare, and industrial production [2]. Within RFID systems, the antenna assumes a pivotal role as a conduit for information exchange, constituting an integral component. In practical settings, RFID tag antennas are frequently positioned in metallic environments, where metals can reflect or scatter electromagnetic waves, resulting in several adverse effects when in proximity to metal objects:

(1) Electromagnetic waves encountering metal reflections precipitate a sharp decline in the antenna's radiation resistance, leading to impedance mismatch.

(2) The presence of metals within the antenna's electromagnetic field induces eddy currents while simultaneously absorbing RF energy, thereby significantly reducing the antenna's detection range and rendering it unrecognizable. Such interference culminates in signal loss and an escalation in errors, consequently diminishing the antenna's transmission efficiency.

Given these considerations, enhancing the performance of RFID antennas in metallic environments and mitigating the interference of metals on signal transmission have emerged as significant challenges for researchers and engineering professionals. In recent years, in response to the imperative for metal-resistant design and optimization of RFID tag antennas, scholars both domestically and internationally have proposed a myriad of solutions and innovative structures. This paper furnishes an overview of the technological advancements in this domain, with the aim of providing a theoretical foundation and technical support for further research and application of RFID antennas.

2. Introduction to Radio Frequency Identification Antennas

2.1. The Role of Radio Frequency Identification Antennas

In the bidirectional communication process of RFID systems, antennas function as the medium for information transmission, establishing a communicative bridge between readers and tags. The fundamental role of an antenna is to receive radio frequency signals emitted by the reader and convert them into electrical signals for processing by the embedded chip. Likewise, tags can employ the antenna to reconvert the chip-processed signals back into radio frequency signals, thus enabling feedback to the reader.

2.2. Classification of Radio Frequency Identification Antennas

RFID antennas are classified into various types based on specific application requirements. They are categorized by frequency range, including low frequency (LF) ranging from 125kHz to 135kHz, high frequency (HF) at 13.56MHz, ultra-high frequency (UHF) at 433MHz and 860–960MHz, and microwave (MW) at 2.45GHz and 5.8GHz [3]. Moreover, antennas can be distinguished by their form, encompassing linear antennas, coil antennas, patch antennas, and PCB antennas. In the design process of RFID antennas, it is essential to meticulously consider multiple factors such as operating frequency, gain, impedance matching, directionality, polarization, and size. This consideration aims to enhance antenna performance and optimize the read/write efficiency of RFID systems. The significant impact of metallic environments on antenna performance in practical applications has spurred the development of RFID antenna structures capable of effectively countering metal interference, thus becoming a focal point of academic interest.

2.3. Current Research Status of Metal-Resistant Radio Frequency Identification Antennas

Due to the significant advantages of RFID systems, including their longevity, ability to contactlessly identify multiple targets, and reusability [3], global interest in RFID technology research has been steadily increasing, particularly in the study of metal-resistant RFID antennas. A seminal discovery by Foster and P.R. in 1999 highlighted the potential distortion and reflection of electromagnetic fields near antennas caused by metallic objects, thereby affecting RFID antennas through interference and signal reflection [4]. Subsequent investigations by scholars such as Zhang Yimin and Lingfei Mo have further elucidated the detrimental effects of metal surfaces on RFID antennas, emphasizing the interference with RF signals and the weakening of signal strength when the phase of reflected waves opposes that of incident waves [5-6].

In recent years, there has been a surge in publications on metal-resistant RFID antennas internationally, signifying a growing body of research in this field. While research on the metal-resistant properties of RFID antennas in China commenced later, Chinese scholars have made significant strides, with over thirty related journal articles published in recent years. Presently, international research on metal-resistant RFID tag antennas is progressing towards high frequency, wideband, and low-profile directions, with novel findings continuously emerging in prominent journals. Meanwhile, in China, the primary research focus lies in the design methods of metal-resistant antennas, optimization design algorithms, and manufacturing technology for metal-resistant antennas.

2.4. Methods for Metal Resistance in Radio Frequency Identification Tag Antennas

In recent years, scholars have pursued various methods to tackle the issue of signal interference induced by metallic objects in RFID tag antennas. One relatively straightforward approach involves the utilization of electromagnetic absorbing materials. By positioning these materials between RFID tag antennas and metal surfaces, they can absorb the electromagnetic waves reflected by the metal surfaces, thereby alleviating the signal interference caused by reflected waves [7]. However, the cost of electromagnetic absorbing materials is relatively high, and RFID tag antennas typically prioritize cost-effectiveness, rendering these materials unsuitable for widespread application in RFID tag antennas. As a result, researchers have redirected their efforts towards designing novel antenna structures, such as the inverted-F structure, artificial magnetic conductor (AMC) structures, and electromagnetic band gap (EBG) structures, to achieve metal-resistant effects in antennas.

3. New Metal-Resistant Structures for Radio Frequency Identification Tag Antennas

The interference of metallic objects with tag antennas arises from two fundamental aspects: the reflection of radio waves by metals and the influence of eddy currents generated by metals on the antenna's magnetic field. Currently, there are primarily four methods aimed at enhancing an antenna's resistance to metal: firstly, utilizing absorbing materials to absorb excess electromagnetic waves; secondly, increasing the distance between the metal surface and the antenna; thirdly, expanding the antenna's bandwidth; and fourthly, employing a grounded antenna structure. However, taking into account practical applications and cost considerations, researchers currently lean towards exploring innovative structural designs for antennas to address these challenges.

3.1. Planar Inverted-F Antenna and Planar Inverted-L Antenna Structures

The Planar Inverted-F Antenna (PIFA) structure [8] and the Planar Inverted-L Antenna (PILA) structure [9] are widely utilized antenna designs. The PIFA typically consists of a metal radiator, insulating medium, and ground plane. Capacitive coupling between the radiator and ground plane achieves the antenna's resonance and radiation. The presence of the insulating medium partially mitigates metal interference, thereby facilitating metal resistance [8]. On the other hand, the PILA comprise a metal radiator and metal feed line. While offering less effective mitigation against metal interference, the PILA can achieve various polarization modes such as horizontal, vertical, or circular polarization [9].

Some scholars have proposed enhancing the PIFA structure with tunable via-hole patch-loaded designs. In this configuration, the patch utilizes insulating material to isolate the metal object from the antenna's electrical signals, thereby achieving metal resistance [10]. Others have improved upon the PIFA by incorporating loaded inductive elements to modify the distribution of the antenna's capacitance and inductance. Additionally, employing PIFA arrays can alter the antenna's radiation pattern, thereby minimizing the impact of metal objects [11]. Lee and colleagues have advanced research on metal-resistant antenna structures by adopting an annular feeding method to evenly guide the current onto the PILA structure. This reduces electromagnetic coupling between the antenna and metal objects, thereby enhancing the antenna's metal resistance [12].

3.2. Antenna Array Structures

Building upon the design principles of PIFA and PILA structures, scholars have explored spatial arrangements or combinations of these structures to form antenna arrays, thereby further enhancing the antennas' resistance to metal.

Lee and colleagues employed a rotational symmetry approach to assemble PILA units into an antenna array. This unique layout enhances the antenna's response on metal surfaces and reduces interference strength from the metal [12]. Additionally, many researchers have designed metal-resistant antennas based on the antenna array approach. For example, some have utilized arrays composed of dual-unit PIFAs for proximal coupling feeding to patches loaded with metal short-circuiting via holes, thus enhancing the antenna's metal resistance [13]. Horng-Dean Chen and Yu-Hung Tsao improved the metal resistance of RFID antennas based on a PIFA array structure by incorporating planar waveguide structures, adding dielectric layers, optimizing the antenna structure, and employing broadband technologies [14]. Qu Yuanjun and others devised an antenna array with a metal grid, consisting of six antenna elements stacked along the y-axis to enhance its radiating capability and thereby reduce signal attenuation caused by metal [15]. Chen Xuemeng investigated a rectangular waveguide slot array antenna based on T-shaped resonators, introducing periodic T-shaped resonators into the bottom wall of the rectangular waveguide to effectively eliminate interference from metal-reflected waves on the antenna [16].

3.3. Artificial Magnetic Conductor (AMC) Structures

AMC structures are commonly employed in research on metal-resistant antennas due to their ability to manipulate the propagation characteristics of electromagnetic waves, including reflection, transmission, and absorption [17].

Kim and colleagues utilized AMC as the bottom surface of a metallic cavity in their antenna design, modifying the ground plane's reflection phase to increase recognition distance and reduce electromagnetic interference from metals [18]. Hong and colleagues mounted cross-dipole tag antennas on phase-correlated AMC structures, reducing interference from metal electromagnetic waves and achieving high gain [19]. Additionally, some researchers inserted a symmetrical patch into the middle of rectangular patch-type AMC units with offset via holes, creating a dual-layer symmetrical Electromagnetic Band Gap (EBG) structure [20]. The EBG structure, known for its ability to truncate the propagation of electromagnetic waves, also contributes to metal resistance when applied in antennas [21]. Wang et al. utilized a ground plane with EBG and a double-layer substrate structure to reduce coupling and reflection between the antenna and metal objects, achieving metal-resistant characteristics [22]. Some scholars employed a double-layer rectangular mushroom-type EBG structure to increase the total inductance of EBG, enhancing its resistance to metal, although the suppression of surface waves was not sufficiently strong [23]. Improvements have been made by transforming a single-layer mushroom-type EBG structure into a jigsaw-shaped mushroom-type EBG structure, thereby expanding the suppression effect on surface waves [24]. Additionally, researchers have explored EBG array structures capable of achieving metal resistance while enabling circular polarization, thus broadening the antenna's range of applications [25].

3.4. Coupled Feeding Structures

Researchers have proposed coupled feeding structures, which, when applied to tag antennas, can mitigate the coupling effect between the antenna and metal, thereby facilitating metal resistance and enabling circular polarization.

Liu Hui and colleagues suggested embedding the feeding structure within the gaps of the antenna's radiating structure, which increases the antenna's bandwidth and diminishes the impact of metal [26]. Yan Yi and others utilized a Wilkinson power divider feeding network to expand its radiating range, enabling the antenna to function atop metal columns [27]. S. -R. Lee and his team designed a ring inductor embedded into the antenna's feed line. This ring coupling structure decreases both the electric and magnetic field coupling between the antenna and metal surfaces, thereby minimizing the metal surface's effect on the antenna [28]. Incorporating metal in the antenna design not only achieves metal resistance but also enhances the antenna's stability and increases its recognition distance. However, this design approach results in larger and less flexible structural dimensions for the tag antenna.

3.5. Foldable Patch Tag Antenna (FPTA) Structure

In recent years, scholars have introduced the Foldable Patch Tag Antenna (FPTA), a novel antenna design where the radiating part, short-circuiting part, and the ground plane are all processed on one side of a flexible substrate. Following processing, the substrate is bent and wrapped around soft foam, yielding a semi-flexible tag antenna [29-33].

In research by Abdelaziz Hamani et al., a folded antenna structure was proposed, amalgamating the antenna's radiating body and ground plane into a compact configuration. This method involves optimizing parameters like antenna size, shape, and position to bolster its interference resistance against metal surfaces [34]. Shin-Rou Lee and colleagues proposed an antenna design merging a folded patch structure with a T-shaped L-probe feeding method. Through adjustments in the coupling position and size between the T-shaped L-probe and the folded patch antenna, they succeeded in broadening its bandwidth and achieving metal resistance [35].

However, FPTAs require specific raw materials, mandating extremely thin flexible dielectrics (0.05 mm) and conductive layers (9 μm). Manual wrapping may lead to issues such as inadequate adhesion and misalignment of antenna edges during bending, resulting in significant manufacturing errors and frequency resonance shifts in the FPTA [3].

Furthermore, while offering high design flexibility, the FPTA structure entails a complex design and manufacturing process, potentially leading to escalated manufacturing costs and time. Nonetheless, despite these challenges, the FPTA structure has attracted widespread attention owing to its superior performance in specific applications, particularly its efficient operation in metallic environments.

4. Conclusion

With the continuous evolution of RFID technology and its expanding application spectrum, various innovative solutions have emerged for tag antenna designs tailored to metallic environments. These solutions encompass integrating Artificial Magnetic Conductor (AMC) structures with arrays, amalgamating Electromagnetic Band Gap (EBG) structures with arrays, embedding feed coupling structures into antenna designs, utilizing metal as the antenna substrate, and integrating coupled feeding metal cavities into antenna structures. Such endeavors not only augment the reading efficiency and stability of RFID systems but also set the stage for technological advancements in critical domains like logistics management and smart manufacturing. However, these designs may entail increased dimensions of tag antennas or diminished recognition distances. Thus, surmounting the challenges posed by metallic environments on tag antennas, while bolstering their performance stability, reducing costs, and achieving multipolarization and miniaturization, stands as a significant breakthrough challenge.

Moving forward, research on metal-resistant tag antennas will increasingly pivot towards the deep integration of material science and electromagnetic field theory. For instance, further exploration of novel nanomaterials and graphene, renowned for their exceptional electromagnetic properties, holds promise in significantly enhancing antenna performance. Additionally, leveraging multiphysics simulation technology will expedite the optimization process of antenna design by accurately simulating the interactions between electromagnetic fields and metallic materials, thus providing a more scientific framework for antenna design.

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