Spiral Antennas in RFID and Their Size Reduction and Performance Enhancement

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ABSTRACT: This paper reviews the state of the art of the spiral antenna used in RFID, and discusses design approaches and techniques for its performance enhancement, size reduction, as well as compatibility with operating environments, by using techniques including the slow-wave antenna and the magneto-dielectric antenna.

INTRODUCTION

RFID (Radio Frequency Identification) is considered a prominent emerging technology in future telecommunications [1]. As a wireless system, RFID relies heavily on its antennas. Therefore, research in antennas for RFID has been so active that an outcry of "oversupply of RFID antenna technology" popped up [2]. Indeed, there are so many papers on RFID antennas that it is difficult to single out some of them for background referencing in this short paper, since they seem to be equally worthy. Meanwhile, the antenna community recognizes the severe challenges of the RFID antenna problem and must continue to search for better solutions.

It is noted that RFID tag antennas in the global marketplace have largely gravitated toward the spiral antenna. Yet there is a lack of analytical and synthetic work, either theoretical or empirical, for RFID spiral antennas at a fundamental level. This paper will review the merits of the spiral antenna for RFID, attempt to formulate the problem at a more fundamental and rigorous level, and highlight present and future research in spiral antennas that should lead to major performance improvements in RFID and other similar wireless systems.

THE SPIRAL ANTENNA AS A COMMON SOLUTION FOR RFID TAGS

An RFID system has a reader/writer and a tag, each with an antenna. We will focus on the tag antenna because of the serious design challenges in dealing with its complex and varying operating environments and user mandates. In particular, the antenna for a passive tag (without a battery) must meet not only the RF performance requirements, but also the severe constraints in size, shape, weight, cost, etc. The planar spiral antenna has been widely adopted in passive RFID tags due to its form factor and the following unique merits not available in most other antennas. As a receive antenna, the unique and rich multimode feature inherent in the spiral antenna makes it a uniquely efficient sensor and collector of RF power for the passive tag. As a transmit antenna, the spiral can operate either in single mode or multimode feature for optimal RF link coverage.

At present, there are three major frequency bands in RFID: HF (primarily at 13.56 MHz), UHF (primarily 865-928 MHz), and microwave (primarily 2350-2450 MHz and 5400-6800 MHz). The performance of RFID improves with the frequency largely because the tag antenna becomes more efficient and broadband (a well-known fact that will be discussed later). At present, The RFID industry is moving toward fewer frequency bands in its consolidation and standardization, while the wireless industry (with the RFID merely as a component) gladly accommodates multiple bands in its movement toward convergence and multimedia.

PLANAR SPIRAL ANTENNA'S STABLE BROADBAND MULTIMODE FEATURE IN FAR AND NEAR FIELDS

In an RFID system, the distance between the tag antenna and the reader/writer antenna varies widely with their operating environment. As a rule, simple antenna theories are rendered inaccurate or even invalid in treating RFID problems as the distance decreases to the antenna's near-field region. The near-field region of an antenna consists of two sub-regions: a reactive near-field region immediately surrounding the antenna, wherein the reactive field predominates, and a radiating near-field region between the reactive near-field region and the far-field region. The outer boundary of the reactive near-field region is at a distance R from the surface of the antenna, generally given by $R = 0.62 (D^3/\lambda)^{1/2}$, where D is the largest dimension of the antenna and λ is the operating wavelength.

It must be pointed out that the reactive near-field region extends only to a very small distance from the antenna surface. Even at the HF band of RFID (13.56 MHz), R is merely 0.15 or 0.77 cm for an antenna with $D = 5$ cm or 15 cm, respectively. Therefore, an RFID generally operates in its radiating regions, near-field or far-field, rarely in its reactive near-field region. Thus the design of an RFID antenna is a complex full-fledged electromagnetic problem which encompasses both far-field and near-field issues, and often needs to take account of nearby structures.

For a planar spiral antenna, a full-wave solution in the spectral domain has long been established and was applied in the design of the SMM (spiral-mode microstrip) antenna [3]. The fields of a planar spiral antenna lying in a plane perpendicular to the z-axis can be completely expressed in terms of wave functions Ψ_n given by

$$\Psi_n = \exp(jn\phi) \int_0^\infty g\,(k_\rho)\, J_n(k_\rho \rho)\, \exp(jk_z z)\, k_\rho\, \mathrm{d}k_\rho \qquad (1)$$

where n specifies the spiral mode number, and ρ, ϕ and z are the cylindrical coordinates. A planar spiral per se radiates to both sides of the spiral ($z > 0$ and $z < 0$), that is, bidirectionally. Fig. 1 depicts the far-field radiation patterns of lower-order spiral modes Ψ_n given by (1) for the upper half space ($z > 0$). (The patterns for the lower half space ($z < 0$) are similar.) As can be seen, a planar spiral can generate directional (mode-1) as well as omnidirectional (mode-0, mode-2, and mode-3) radiation patterns in the far field, and a combination of spiral modes 0 and 1 covers the entire space.

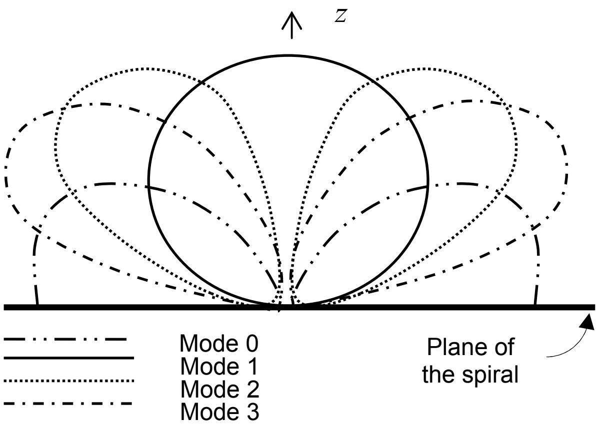

Fig. 1. Far-field patterns of spiral-modes in upper half-space.

The radiating near fields of a spiral antenna have graceful transition to the far fields. This observation is consistent with an earlier observation that fields in the antenna's radiating near-field zone can be accurately computed numerically by a finite collection of plane waves using an FFT (Fast Fourier Transform) algorithm sampled at Nyquist rate [4]. The fairly stable field characteristics of the spiral antenna are rooted in the stable field patterns of the small electric and magnetic dipole and loop ($D < \lambda/2$), which are the building blocks of the spiral antenna radiator.

PLANAR SPIRAL ANTENNA PRIOR TO THE SMM ANTENNA — USING DISSIPATIVE LOADING OR A CONDUCTING PLANE SPACED λ/4 APART

In the preceding section, it was shown that a planar spiral structure per se radiates on both sides of the spiral, + z and – z. This bidirectional pattern of a spiral is undesirable for nearly every application. Generally an antenna is mounted on, or positioned near, a platform, which can disrupt a bidirectional beam and brings a host of EMC/EMI problems. For over three decades since the conception of the first spiral antenna in mid-1950s, there were only two types of remedies for this undesirable bidirectional pattern: (1) Broadband approaches in which an absorbing structure is used to absorb the beam on one side of the spiral, (2) Narrowband approaches in which a conducting plane is spaced $\lambda/4$ apart to constructively reflect the power on one side of the spiral to effect unidirectional radiation to the other side. The dissipation methods lose half the power and thus are not suitable for transmit. The methods using $\lambda/4$-spaced ground plane are narrowband. In addition, both methods lead to a bulky spiral antenna.

The SMM antenna is an innovation in which a conducting ground plane is spaced a small distance from a planar spiral, with the resulting antenna gain pattern essentially like those in Fig. 1 and no fields in the lower half-space ($z < 0$). The SMM antenna overcomes the planar spiral's problem of bidirectional radiation while maintaining its multioctave bandwidth. The multiplicity of radiation patterns in a well-designed spiral antenna, such as the SMM antenna, provides the unique capability of multifunction rarely available in other antennas. The advantage of circular polarization is an additional advantage of the spiral antenna, especially for operation in changing complex environments.

Since 1990, significant progress has been made in the SMM antenna and additional techniques for the spiral antenna and other similar traveling-wave antennas, notably the miniaturized slow-wave antenna, have been developed [5-7]. A common feature of these designs is a ground plane placed very close to a planar broadband traveling-wave structure, including the spiral type. The inclusion of a conducting ground plane allows conformal mounting on any platform and enhances the antenna gain/directivity. Today, SMM antennas for spiral-modes 0, 1, and 2 have reached a considerable degree of maturity, achieving desired performance over broad instantaneous bandwidths of up to 10:1 or more.

TO HAVE OR NOT TO HAVE A GROUND PLANE — THAT IS THE QUESTION FOR SPIRAL ANTENNA!

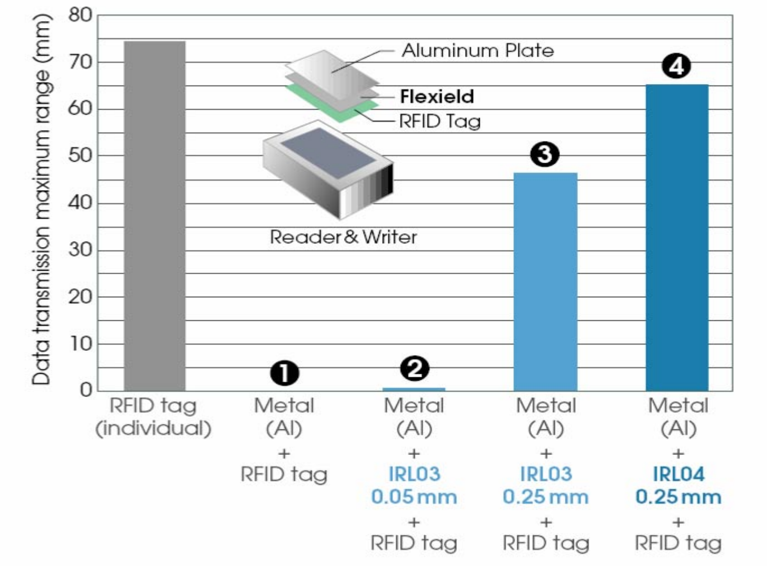

Fig. 2. Effects of conducting ground plane and ferrite substrate on RFID spiral antenna. (TDK data)

For an RFID tag to be placed close to an object, and especially a metallic surface, an antenna having a conducting ground plane is highly desirable and even necessary. For a "free-standing" tag, the inclusion of a conducting ground plane can make the antenna pattern more directional, thus increase the range between tag and reader.

For a spiral antenna used in RFID, a ground plane can be destructive or beneficiary to its performance. This is well demonstrated in Fig. 2 [8]. (The full paper is available on TDK Corporation website.) It shows measured maximum range between RFID tags and reader/writers at 13.56 MHz HF-RFID band for four mounting variations with the tag on a folding-type RFID mobile phone. An aluminum plate of the same size as the RFID card is attached to the surface of the battery case of the phone. In cases 2, 3 and 4, a certain TDK ferrite substrate, called Flexield, is inserted between the aluminum plate and the tag. As can be seen, the alumimum plate effectively killed the RFID function when it was directly placed on the RFID card (Case 1). And the disruptive effect of the aluminum plate was mitigated by a judicial use of a ferrite substrate of certain thickness (optimized in Case 4).

The technique used by TDK is apparently a dissipative loading approach discussed earlier since the range achieved in the optimal Case 4 is still shorter than the Case "Individual" (no aluminum plate), and since the Flexield has "high magnetic loss (μ'')." As will be discussed in the next section, the techniques in [5] and/or [9] can potentially increase the communication range considerably beyond that of Case "individual."

GAIN BANDWIDTH LIMITATION, SIZE REDUCTION, AND PERFORMANCE ENHANCEMENT ISSUES

At HF RFID band of 13.56 MHz, where $\lambda = 2212$ cm, the size of the tag antenna is generally electrically small, and thus confronts a well-known fundamental limitation for the gain-bandwidth of a lossless antenna of a given size, known as the Chu limitation [10]. However, this author noted shortcomings and ambiguities in the Chu theory when applied to real-world problems, and made some revisions [11]. When an antenna is mounted on a platform, it is generally inseparable from the transceiver/platform. Thus, the extent and size of the antenna become ambiguous. Also, the Chu theory is valid only for high-Q (Quality factor), thus narrowband, antennas. Since a real-world antenna has inherent and even contrived losses, the zero-loss premise in the Chu limitation can also be used to circumvent it.

With the realm of the Chu limitation confined, research in size reduction and performance enhancement for antennas under size constraints becomes vastly more promising and active. Techniques pursued by this author and his colleagues include the miniaturized slow-wave antenna [5] and the use of magneto-dielectric substrate [9]. However, these techniques have been hampered by the lack of practical low-loss high permittivity/permeability materials at high RF frequencies. Fortunately, propelled by the global commercial research in recent years, practical materials with high-permittivity/permeability and suitable for antenna applications are becoming more and more available. With the advent of LTCC (low-temperature co-fired ceramic), LCP (liquid crystal polymer), and high-permeability ceramic materials, etc., research in antenna size reduction has become very active, and promising results have been reported.

Most noteworthy is perhaps the use of magneto-dielectrics with approximately equal relative permittivity and permeability to reduce the physical size of traveling-wave antennas, including the spiral antenna, as had been first taught in [9]. Recent research using this technique showed that antenna size reduction by a factor of 4 to 16 in linear dimensions can be achieved with acceptable performance degradation [e.g., 12, 13]. Thus, at 13.56 MHz, an antenna 221-cm (1/10-wavelength) in maximum linear dimension can be reduced to 14 cm after a 1/16 reduction in linear dimensions using a substrate whose effective relative permittivity and permeability are both 16. (It is worth commenting that no "real" magnetic source has been found to exist. Therefore, the word "dielectric" has sustained its original definition (a nonconductor for electric current) to mean a material with complex permittivity and permeability (generally in tensor form) whose imaginary components are not so large as to be considered a conductor.)

SPIRAL ANTENNAS IN FUTURE RFID AND OTHER WIRELESS SYSTEMS

The unique multimode feature of the spiral antenna will be exploited to enhance performance, and add new features, for RFID spiral antennas. Smart high-directivity features, such as adaptive pattern-diversity, will increase the range and improve security for the RFID system. Recent availability of low-loss magneto-dielectric materials for frequencies up to 1 to 3 GHz, as well as a variety of such materials derived using techniques in metamaterials, artificial materials, nanotechnology, etc. holds great promise for advances in the performance of antennas for RFID.

Obviously, spiral antennas developed for RFID can be applied to other wireless systems having similar antenna requirements. For example, the bendable radio without an external battery being developed by SEL and TDK at 13.56 MHz is an obvious extension from RFID to radio [14]. It is noted that the antenna shown in the photograph of the radio is a spiral antenna, and that its range can be increased significantly by using techniques just discussed.

CONCLUSIONS

Based on a review of the state of the art of the spiral antenna used in RFID, there is considerable room for significant performance improvements. Specifically, the slow-wave antenna technology and the magneto-dielectric antenna technology have shown promise for major performance improvement and/or size reduction in spiral antennas, based not only on the research by this author but also on the direct and relevant findings at other laboratories using newly available electromagnetic materials.

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