Magnetic Materials for RFID Antenna Isolators

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***Abstract*— In this paper, we review candidate antenna technologies for isolating RFID tag antennas (HF, UHF, and microwave) from the objects on which they are attached. Our primary focus is the incorporation of magnetic materials into RFID tag substrates, which hold the greatest potential performance enhancements, but is fraught with several physical limitations. We conclude by reviewing new breakthroughs in superparamagnetic materials that could revolutionize future RFID tag antenna isolators.**

I. Introduction

THE recent surge in UHF RFID applications and research has also resurrected interest in RF magnetic materials. These materials would allow RFID tags to operate efficiently on the full gamut of metallic, lossy, or dielectric objects while retaining low cost, flexibility, and sufficiently broadband for worldwide operation. Materials that maintain significant permeability at radio frequencies are still elusive, but several breakthroughs among scientists working with nanocomposites promise to achieve significant permeability at microwave frequencies. These new materials rely on *superparamagnetism* to achieve high-frequency permeability beyond the conventional limits of bulk materials.

This paper reviews the need for magnetic materials in RFID and presents candidate magnetic materials for RF operation. We begin by demonstrating why RFID tags – both inductive HF tags and their far-field UHF counterparts – would benefit from RF magnetic materials that, when placed on conductive and/or dielectric objects, would isolate the RF tag from the object-induced degradations in power and information transfer [1]. The magnetic isolator is discussed in the context of a host of conventional RFID tag solutions, all of which are either prohibitively expensive or intrinsically narrowband. Magnetic-based solutions may be the only realistic way to achieve *broadband* isolation at reasonable commercial costs [2], [3].

What follows is an overview of different forms of magnetism in materials. Unlike dielectric permittivity, the mechanisms that exhibit magnetic permeability in a material are diverse. An engineer's understanding material permeability is also frustrated by a lack of clearly-articulated explanations that illuminate how these different mechanisms compare to one another in terms of strength and frequency response. To facilitate this discussion, there is a plain-spoken tutorial section on magnetic materials that culminates in the presentation of superparamagnetism. We then discuss how recent breakthroughs in superparamagnetism have pushed the envelope in cut-off frequency and permeability that can be achieved in the microwave bands. It is hoped that a coherent fusion of RF engineering and material science will help spark more interest in RF magnetism research.

II. RFID Isolator Fundamentals

A. HF Isolator Operation

Relying entirely on inductive coupling of magnetic near-fields, the high frequency (HF) RFID tag collects the magnetic flux circulating around a square or circular loop reader antenna. The flux that makes it *through* the RFID tag's coils excites a voltage around the coil path, which powers-up the terminals of the tag's RFIC. As the magnetic field sketch in Figure 1 illustrates, it becomes extremely difficult to get magnetic flux through the RFID tag coil when it rests on a metallic object. One way to construct the total magnetic field solution of an RFID reader antenna operating in the presence of a flat metal surface is to use the method of images. Thus, in Figure 1 (left), the total magnetic field above the conductive surface is the sum of the free-space fields due to the RFID reader antenna and its virtual, mirror-image current on the other side of the material interface. The net effect is that surface fields are forced to travel parallel to the metal plane.

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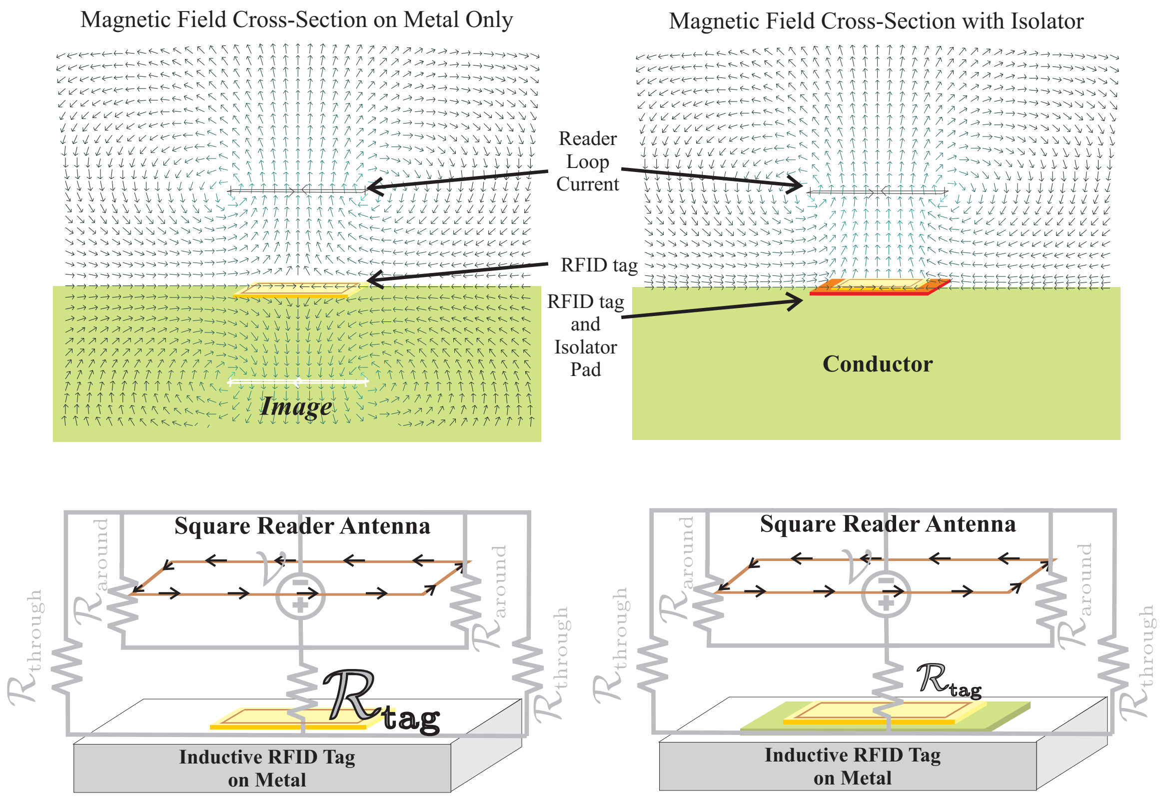

Fig. 1. Example of on-metal HF RFID tags excited by a square loop with equivalent magnetic flux circuits. The left case demonstrates how a simple tag struggles to collect enough magnetic flux through its tag coils to operate. The right case demonstrates how a high-permeability isolator allows additional flux through the tag.

The on-metal degradation of HF RFID tags (those operating from 3-30 MHz) can best be explained using magnetic flux circuits. In a flux circuit, magnetic flux takes the place of electrical current in a conventional circuit; instead of voltage sources, the magnetic circuit is excited by *magneto-motive force*, $\mathcal{V}$ – a loop or coil of current that effectively energizes the magnetic flux. Because magnetic flux is neither created nor destroyed, it follows a Kirchhoff current law just like electrical current. The net magnetic flux into any node within the flux circuit must be zero. Likewise, magneto-motive force satisfies the same conservation properties as its counterpart, voltage, in electric circuits. When summed around any arbitrary loop, the quantity we define as total magneto-motive force must equal zero in the magnetic circuit – just like Kirchhoff's voltage law.

To complete the analogy, we need a physical quantity in a magnetic circuit to serve as the analogy to resistance; then we can apply Ohm's law and calculate how magnetic flux might distribute itself in an inhomogeneous collection of materials. This resistive term is called *reluctance*, $\mathcal{R}$, in a flux circuit and quantifies how easily magnetic flux is conducted through an object. Reluctance is inversely proportional to material permeability and has the same relationship to geometry as resistance. For simple objects with prismatic structure – a cross-sectional area A and a length L – the reluctance takes on the following approximate form:

$$\mathcal{R} = \frac{L}{\mu A} \tag{1}$$

Note the similarity in the definition of Equation (1) to the formula for resistance in an electrical circuit, where permeability, μ, is simply replaced by conductivity, σ, for a structure with identical geometry. In most flux circuits, Equation (1) serves as rough guideline, since the overall reluctance is difficult to calculate for an irregular, non-prismatic object.

With the flux circuit analogy in mind, consider what happens when an RFID tag approaches a metallic surface in Figure 1. Almost all of the magnetic flux circumvents the tag's coil aperture because the fields would have to travel through an area of extremely high reluctance, $\mathcal{R}_{\text{tag}}$: through the very narrow opening between the metallic surface and the coil traces of a tag. One way to improve the flux coupling is to place a magnetic isolator pad underneath the RF tag. Such a pad is usually a polymer impregnated with iron oxide or tiny iron particles that yield a high permeability in the HF bands. The additional spacer, coupled with the larger μ-value, dramatically lower the reluctance through the tag. Now a significant amount of magnetic flux will travel through the RFID tag coils instead of entirely through the return paths, $\mathcal{R}_{\text{around}}$.

B. UHF Isolator Operation

In UHF RFID, on-object degradations result from field boundary conditions similar to the on-metal HF RFID case [2]. Consider the normal-incident electromagnetic wave on a dielectric substance in Figure 2(a). The field boundary conditions dictate that the reflection coefficient at the air-dielectric interface becomes

$$\Gamma = \frac{\sqrt{\mu_r} - \sqrt{\epsilon_r}}{\sqrt{\mu_r} + \sqrt{\epsilon_r}} \tag{2}$$

For the majority of dielectric materials, relative permittivity is greater than unity ($\epsilon_r > 1$) and relative permeability is nearly its free space value ($\mu_r \approx 1$). Under this scenario, the reflection coefficient in Equation (2) will *always* be negative, implying a reflecting electric field that will partially or completely cancel the electric field due to the incoming wave. It should be noted that the opposite is true of the magnetic field, which will constructively reinforce along the reflection surface as illustrated in Figure 2(b).

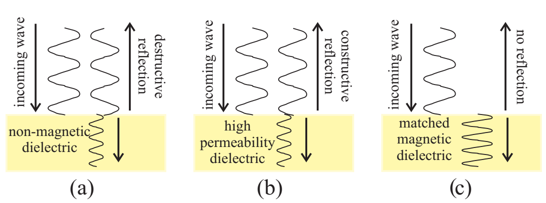

Fig. 2. Three categories of interface: (a) non-magnetic, where electric field cancelation occurs (similar to a conductive interface), (b) magnetic ($\mu_r > \epsilon_r$), where electric field reinforcement occurs, and (c) matched ($\mu_r \approx \epsilon_r$), where no reflection occurs.

This electric field behavior has serious implications for UHF RFID antennas. Thin peel-and-stick RFID tag antennas are trapped in the two-dimensional plane of their object surface. These antennas must use their metallic traces to accumulate enough electric field along the surface of the object to provide a power-up or communicative voltage to its RFIC. With significant cancelation of tangential electric fields, this becomes nearly impossible. In terms of far-field antenna properties, the on-object degradation most significantly manifests itself as a precipitous drop in the RFID antenna's radiation impedance, making impossible to couple power into a typical RFIC. Figure 3 illustrates this drop in real and imaginary radiation impedance as a half-wave dipole is brought closer and closer to a metallic surface.

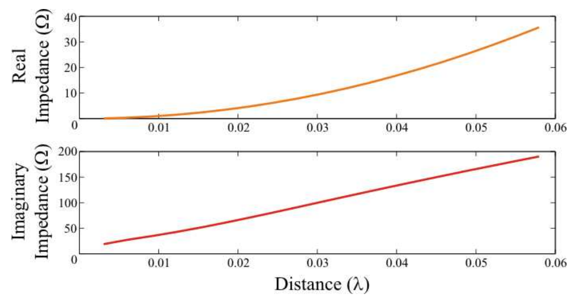

Fig. 3. Illustration of how real-valued radiation impedance drops for an ideal half-wave dipole as it draws closer to a conductive metal surface [4].

There are a number of techniques used by antenna engineering to circumvent this problem solutions, with Table 4 summarizing some of the most common types and their relative trade-offs. The only truly broadband solutions for antenna isolation involve using engineered RFID substrates where the dielectric has significant relative permeability, $\mu_r > 1$. In fact, if $\mu_r > \epsilon_r$, we can see from Figure 2 that there would actually be a *constructive* electric field reflection coefficient at the material interface where the RFID tag antenna is placed. This would dramatically increase the efficiency of the antenna at *all* frequencies.

III. Overview of Magnetic Materials

Before continuing, it is necessary to review the basics of magnetic material phenomenon to illustrate why high-frequency RF isolators are difficult – but not impossible – to realize in practice.

Fig. 4. A summary of techniques used to isolate UHF RFID antennas from dielectric and conductive objects. Table is meant to show *qualitative* differences in techniques.

	Planar-F Antenna	PCB Patch Antenna	Printed Dipole Folding	Super Permittivity Spacer	Magnetic Spacer	Absorptive Spacer	Surface-Coupled Antenna	Artificial Magnetic Conductor
low cost	poor	poor	excellent	good	good	good	good	terrible
on-metal improvement	excellent	excellent	poor	poor	fair	good	good	excellent
on-dielectric improvement	fair	excellent	terrible	good	good	fair	poor	excellent
thinness	terrible	fair	excellent	good	good	excellent	excellent	poor
industry acceptance	good	good	good	poor	poor	poor	poor	fair
RFIC integration	poor	poor	excellent	excellent	excellent	excellent	fair	poor
high bandwidth	fair	poor	poor	terrible	excellent	good	fair	poor
omni radiation	excellent	excellent	excellent	good	good	fair	good	good
small footprint	excellent	fair	poor	fair	good	fair	good	fair
printability	terrible	terrible	excellent	excellent	excellent	excellent	fair	terrible
radiation efficiency	excellent	excellent	excellent	excellent	good	good	good	excellent
flexibility	terrible	terrible	excellent	excellent	excellent	excellent	excellent	terrible

○ **terrible** ◢ **poor** ◖ **fair** ◕ **good** ● **excellent**

Planar-F Antenna	The general shape of this antenna – 90° bent metal flange attached and tuned in a compact space – still requires some vertical protrusion above a surface and does not lend itself to the peel-and-stick functionality of RFID.
PCB Patch Antenna	Patch antennas on printed circuit board (PCB) function well on materials, but are too costly and inflexible for most RFID applications. Thinness is difficult to achieve for 1 GHz systems and lower [5].
Printed Dipole Folding	Folded dipole antennas on a 2D plastic surface is a common way in RFID to make a thin tag antenna with increased radiation impedance. The free-space radiation impedance of this antenna increases for each fold incorporated in the dipole. Thus, by starting with a large value in free space, the folded dipole's radiation impedance drops to a value that can still couple some received power into the RFIC [6].
Super-Permittivity Spacer	Use of a high-permittivity dielectric substrate of a few millimeters or less allows resonant antennas, such as a patch, to radiate on objects; this solution tends to be extraordinarily narrowband [5].
Magnetic Spacer	A magnetic spacer (a dielectric substrate with high permeability) would allow constructive field reinforcement on its surface across a broad band [2], [3].
Absorptive Spacer	An absorptive spacer is a low-conductivity substrate between object and antenna that tries to accept and attenuate an incoming wave. Often relying on a matched interface, illustrated in Figure 2(c), this is also the principle behind low-observability materials in radar. Ideally, this partially suppresses field cancelation along the surface, unless the spacer is *too* conductive.
Surface-Coupled Antenna	In some circumstances, it is possible to ground the antenna against a metal object with an electrical connection. This is obviously not practical for general RFID tag use.
Artificial Magnetic Conductor	PCBs with tessellated conductive elements and metallic vias create resonant structures that mimic a substance with magnetic current (similar to high permeability). Such PCBs allow antennas to radiate directly on their surface at the resonant frequency [7].

A. Diamagnetism

Diamagnetism results from the partial cancelation of impressed magnetic fields due to a countervailing deformation in molecular electron clouds. Note that *all* electron clouds will produce countervailing magnetic fields when moving through an impressed magnetic field – even bound orbital electron pairs with no net magnetic moment. Thus, every material exhibits some form of diamagnetic behavior. The behavior is strongest in metal atoms with large atomic numbers, as these have dense collections of electron orbitals packed around their nuclei.

Since the induced magnetic polarization field countervails the impressed field – a microscopic Lenz's law at work – the total magnetic field is slightly less than the impressed field, resulting in a negative susceptibility, χ_v:

$$\vec{B}_{\text{tot}} = \vec{B}_{\text{imp}} - \vec{B}_{\text{pol}} = \mu_o \underbrace{(1+\chi_v)}_{\mu_r} \vec{H}_{\text{tot}} \qquad (3)$$

Therefore, relative permeability μ_r is actually *less* than 1, but only slightly as diamagnetic effects are extremely weak. The elemental metal with the highest known diamagnetic response is bismuth, with $\chi_v = 16.7 \times 10^{-5}$, resulting in a permeability of 0.99983 relative to free space. Classically, the magnetic energy density (units of J/m^3) of a simple material is given by the expression

$$\text{Magnetic Energy Density} = \frac{\|\vec{B}_{\text{imp}}\|^2}{\mu_r \mu_o} \qquad (4)$$

which implies that, for a constant impressed magnetic flux, energy density *increases* if μ_r decreases. Therefore, diamagnetic materials will be *repelled* by a strong, DC magnetic field, as the material is pushed away to a region of lower flux density to minimize energy. Countervailing diamagnetic material is also illustrated in Figure 5.

Because diamagnetism is extremely weak and countervailing, it is of little use as an antenna isolator. This is unfortunate, because the mechanism of diamagnetism will persist in medium for extremely high frequencies. These effects are just as pronounced in the microwave bands as they are at DC.

B. Paramagnetism

In general, the response of paramagnetic materials is an order-of-magnitude or more stronger than that of diamagnetic materials. The polarization field is *reinforcing* instead of countervailing, which leads to a positive susceptibility. To see why, first recognize that the atoms of a paramagnetic atom or molecule usually have single, un-paired electrons that impart a net magnetic moment to each atom. Like diamagnetic materials, there is no permanent, net magnetic polarization in the bulk material. The polarizations of paramagnetic atoms are randomly distributed by thermal energy. If the unpaired electrons are modeled as loops of current around an atom, we would also see that adjacent atoms tend to favor countervailing orientations compared to their neighbors that quench the net magnetic polarization of the material.

In an impressed field, the magnetic dipole of the paramagnetic atoms or molecules partially aligns with the impressed field. In classical electromagnetism, if each particle is modeled as a loop of equivalent current, then magnetic forces act on the loop to produce a torque, which is illustrated in Figure 6. This torque will push the equivalent loop of current such that its own magnetic dipole moment is matched to the north-south orientation of the impressed magnetic field. (Note that a magnetic *north* corresponds to the direction in which magnetic flux is *leaving* the dipole and follows the right-hand-rule with respect to a current loop.)

Since the classical magnetic fields of a current loop bend back from north to south *outside* the current loop, the total magnetic field surrounding the atom or molecule is reduced (see the top case of Figure 5). In a bulk material with many such particles, this will result in a net increase of magnetic flux *through* the material and a net decrease of magnetic flux immediately *outside* the material. We may write the total interior flux density as the sum of an impressed (free-space) field and a polarization-response field:

$$\vec{B}_{\text{tot}} = \vec{B}_{\text{imp}} + \vec{B}_{\text{pol}} = \underbrace{(1+\chi_v)}_{\mu_r} \mu_o \vec{H}_{\text{tot}}$$

Thus, the paramagnetic medium's relative permeability should be *greater* than unity ($\mu_r > 1$).

Paramagnetism often persists at microwave frequencies, but does not provide enough increase in permeability to make an effective antenna isolator. However, there are other stronger magnetic phenomena involving paramagnetic atoms that can lead to significant RF antenna isolating behavior. These other forms of magnetism require some quantum

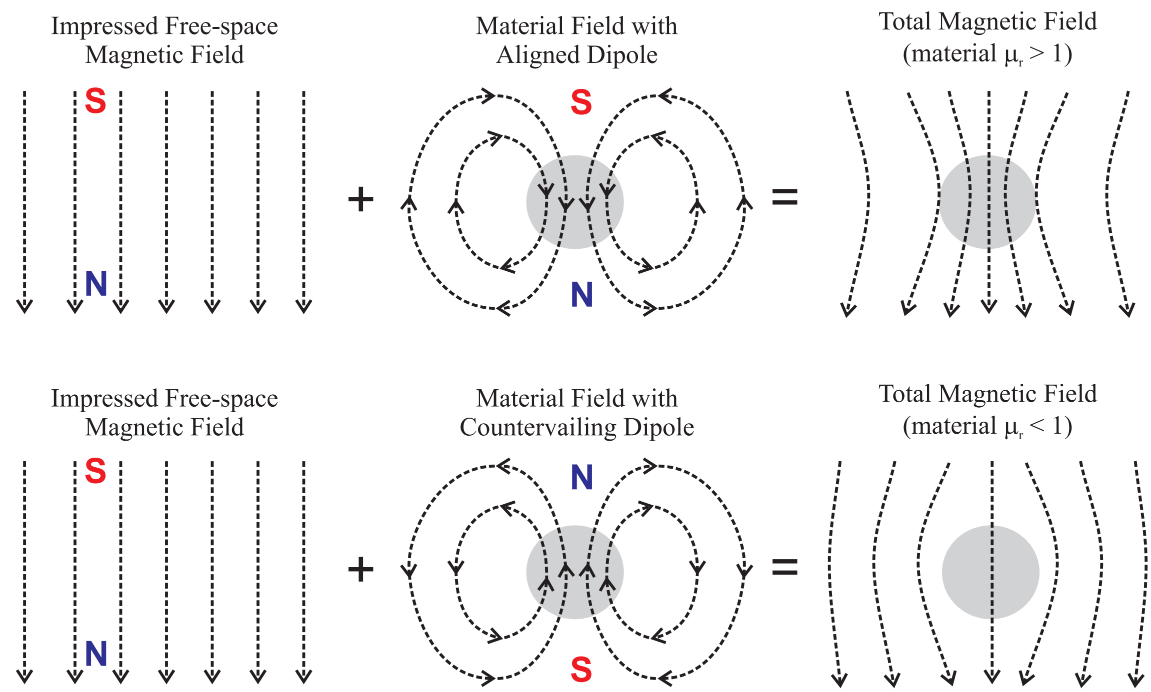

Fig. 5. Particles that aligns their magnetic dipoles with an impressed field (top) result in total magnetic flux that appears to increase inside the particle. Particles that countervail the impressed field (bottom) result in a total magnetic flux that appears to decrease inside the particle.

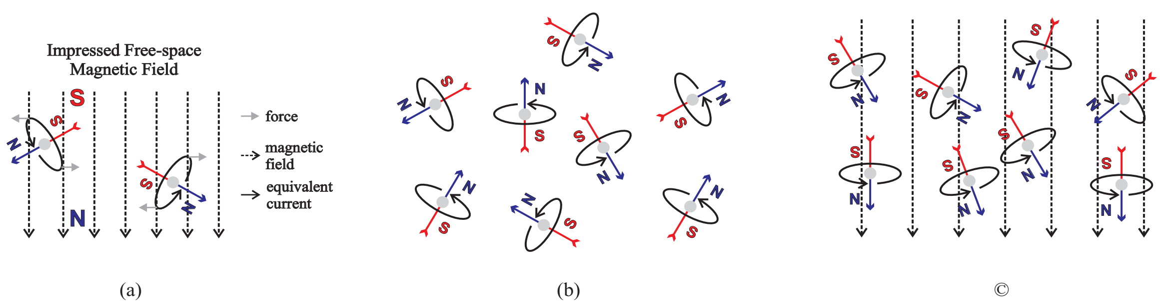

Fig. 6. Forces on particles with permanent magnetic dipoles (left) result in torques that align the particle's dipole moment with the polarity of the impressed field. Based on this principle, paramagnetic particle dipoles are randomly distributed (center) until an impressed field begins to impart a net bias in their orientation (right).

mechanical explanations.

C. Ferromagnetism

In a crystalline material, some types of paramagnetic atoms have a way of overcoming the classical magnetic dipole repulsion forces and aligning their magnetic moments with neighboring atoms. This type of material – a *ferromagnet* – relies on a purely quantum mechanical phenomenon called *exchange energy* between neighboring atoms in a lattice. To understand the nature of exchange energy, recall that electrons have a wave function that permits even a bound electron to exist at far distances from its "home" nucleus.

A sketch of a probabilistic wave function denoting position is shown in Figure 7. Note that the highest region of electron position probability exists close-in to its home nucleus – yet there is a non-zero probability that the electron will exist close to neighboring lattice nuclei. Each paramagnetic atom in the lattice has an unpaired electron (with a net magnetic dipole moment due to spin) that

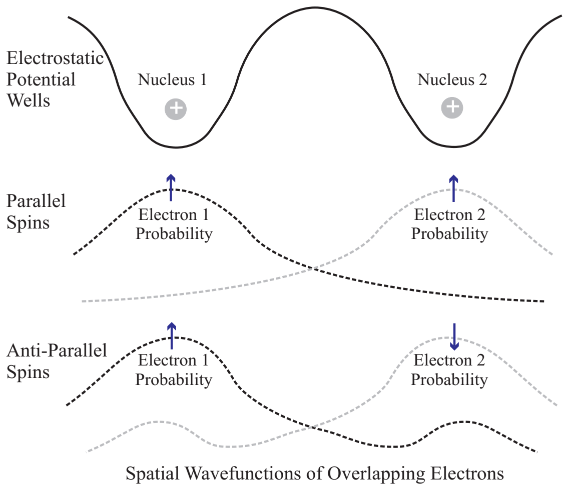

Fig. 7. In a ferromagnetic material, neighboring electrons prefer parallel spin alignments to minimize their spatial overlap and, subsequently, their mutual electrostatic repulsion.

follows a similarly shaped wave function; the only difference is that the wave function is translated in space by one spatial unit within the material's crystal lattice. Furthermore, as Figure 7 illustrates, neighboring electron-electron spin interactions dictate two different positional probability functions. If neighboring electrons have aligned or *parallel* spins, then they must have low-probabilities of overlap. If neighboring electrons have opposite or *anti-parallel* spins, then they are allowed to have higher probabilities of overlap. This is due to the quantum mechanical properties of electrons, which belong to a class of particles called *fermions* that cannot occupy the same space and state.

Thus, a bound electron may only spend significant amounts of time around a neighboring nuclei if it has an opposite nuclei. All else being equal, there should be no preference between these two wave functions for electrons – but we have not accounted for electron-electron *electrostatic* interactions. Since electrons are negatively charged and repel one another, there is an additional energy required to maintain the anti-parallel state in ferromagnetic materials. This is the exchange energy of the material and forces *all* electrons to align in a ferromagnetic material, over and against the classical forces of paramagnetism that would predict adjacent particles would orient their magnetic dipoles in opposite directions to minimize energy. The perfect regional alignment of magnetic dipoles, as illustrated in Figure 8, creates a *domain* within the ferromagnetic material that is capable of exhibiting extraordinarily high permeability. Furthermore, once aligned with an impressed field, the domains of a ferromagnetic material may remain aligned to form a permanent magnet.

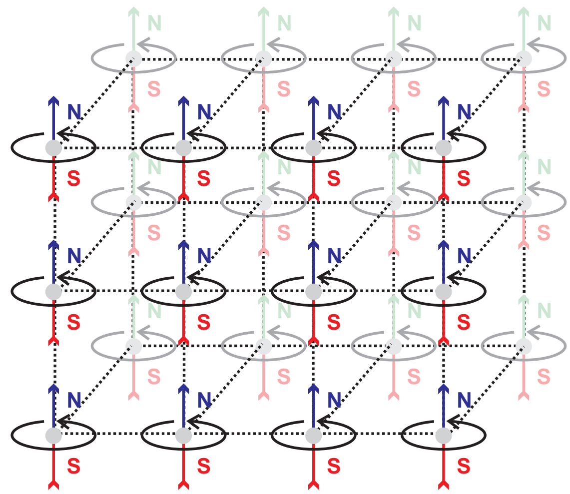

Fig. 8. Total magnetic dipole alignment of individual atoms in a ferromagnetic material.

IV. Superparamagnetic Spacers

A. *Superparamagnetism*

Despite its extraordinarily high permeability, ferromagnetism's principle limitation for antenna isolation is its sluggish inability to change the net orientation and intensity of magnetic polarization. Although a pure iron material may have a relative permeability of 5000 at DC, its permeability approaches free space at microwave frequencies. In fact, a bulk magnetic material with higher DC permeability will *necessarily* quench its magnetic behavior at a lower frequency. This fundamental limitation on the frequency response of magnetic materials is called the *Snoek limit*. The Snoek limit states that, for a given crystalline structure, the product of a material's DC permeability, μ_r, and its cut-off frequency, f_o, are conserved. Thus, higher-permeable materials lose their magnetic behavior at lower frequencies.

When ferromagnetic particles are reduced in size so that their diameters are less than 20nm, the small collection of atoms that constitute the particle no longer maintains magnetic "memory". At this size, ambient thermal energy in the particle is enough to break apart any remanent magnetic field over a short time period. The *coercivity* – the magnetic field strength required to reorient the moment of a ferromagnetic material – approaches 0 for particles of this size, making them respond to high frequency fields with ease. Yet the atoms in the particles are still capable of cooperative reinforcement in the presence of an external field, giving superparamagnetic media an unexpectedly large permeability, beyond the Snoek limit.

Superparamagnetism has been known for quite some time, having placed a fundamental limit on how many bits per square inch may be stored on magnetic media [8]. This *superparamagnetic effect* meant that the ferrous oxide regions of magnetic hard disks could only be made so small before they began to spontaneously reverse their "permanent" magnetic moments, which obviously leads to data loss. However, it is precisely this malleability of the material's magnetic dipole moment that permits superparamagnetic particles to exhibit permeability at radio frequencies. When the particles are incorporated into a polymer substrate, a high-frequency RF antenna isolator is possible. An added benefit is the suppression of eddy currents, which suppresses conductivity that would otherwise ruin the isolator behavior.

B. Superparamagnetic Spacer Construction

Construction of a superparamagnetic spacer for isolator antennas is illustrated in Figure 9. The magnetic nano-particles are dispersed through a polymerizing solution that forms the body of a thin, flexible substrate. Then an antenna pattern may be printed directly onto the surface or deposited through adhesive transfer of stamped foil. Carefully blending the permittivity of the dielectric and the permeability of the magnetic particles allow an engineer to achieve either a magnetic interface (Figure 2b) or a matched interface (Figure 2c) for the antenna

C. Future Research

Recent research has identified particle compositions, sizes, and geometries that allow magnetic relative permeability of $\mu_r = 2.0$ at a frequency up to 6 GHz [9] with theoretical models predicting achievable permeability of $\mu_r = 10.0$ at 20 GHz using ideal, finite rod-shaped particles [10]. The super-paramagnetic effect has been known for quite some time, but only recent work has revealed new particle compositions and shapes that achieve microwave permeability.

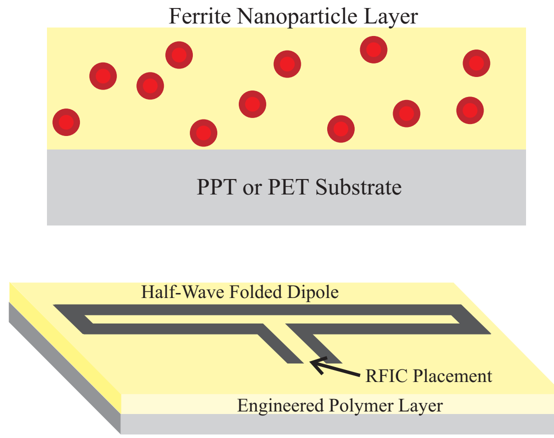

Fig. 9. Example cross-section of a superparamagnetic RF spacer using blade-casting and a printed or adhesive-transfer antenna trace.

There is much cross-disciplinary research to be conducted in terms of fabricating superparamagnetic isolators in a manner that is cost-effective, thin and flexible, and environmentally sound. It should also be noted that a major hurdle in this research is the *measurement* of RF magnetic materials. Because microwave permeability has been a relatively rare phenomenon, simply measuring this behavior above 1 GHz can be a research challenge.

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