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# Microwave Antennas and Heterogeneous Substrates using Nanomaterial Fabrication Techniques

*Invited Paper for ICEA11:*

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**Abstract** — By exploiting the enhanced physical properties of nanomaterials and the advancement in nanotechnology, alternative methods of fabricating microwave antennas can be conceived. This paper will discuss the potential manufacturing advantages as well as different fabrication methods. By controlling the location of metallic and dielectric particles, integrated antennas and substrates can be made in one process. Electromagnetic advantages result from being able to add inclusions with different electrical properties into the host substrate and thereby create a new effective permittivity and permeability. This paper will review and analyse methods for calculating these effective properties.

## 1. INTRODUCTION

The world is becoming ever more dependent on wireless communications which by necessity requires antennas. As technology advances, there are financial and social drivers which desire smaller products. However, there are physically limiting factors which mean that the antenna itself can not be miniaturized at the same rate without compromising the performance. Market forces also demand that the antennas operate in cluttered environments with reduced manufacturing costs, for example a multi-band antenna for a modern mobile phone must be manufactured for less than \$0.10. Furthermore, to manufacture a traditional PCB antenna, an entire surface of copper is created and then selected parts are etched away by costly and environmentally damaging chemicals and several iterative processes are used to create the whole antenna system. As labour and material costs continue to increase, these costs will become ever more significant.

### 1.1 Proposed structure and nanofabrication techniques

This work aims to investigate a novel method of fabricating antennas by using nanomaterials in an additive rather than a destructive process, see [1-37] for more background information. Nanomaterials have a very high surface area to volume ratio which means they can exhibit interesting characteristics such as improved electrical conductivity, scratch resistance and strength. These properties have led to nanomaterials becoming a multi-trillion dollar

industry where the technology is developing at a rapid rate. Historical products that inadvertently used nanomaterials include Samurai swords and the pigments in stained glass windows, however, now we have the technology to understand and control the nano-geometry and hence the properties. Existing products that include nanotechnology include; stain resistant clothing, stronger car components and metal cutting tools, computer screens, scratch resistant coatings, batteries and optically transparent sunscreens [36]. Experts predict that nano-manufacturing could inspire the next industrial revolution with future products including faster computer chips, medical devices, water filters and more efficient solar cells [37].

It is expected that it will soon be possible to build an antenna system using bottom-up design by appropriately positioning metallic and non-metallic cuboids (each composed of many micro-sized nanoparticles). This will potentially enable the entire antenna system including the conductor, the substrate, the feed and the radome to be integrated into one process [16]. Note, the overall size of the antenna will still be of the millimetre scale at microwave spectra. However, small scale structures can increase the electrical length of simple antennas which reduces the resonant frequency at the expense of bandwidth [12].

Nano-technology fabrication techniques include electrodeposition and self-assembly [13-15]. Additional nanofabrication facilities available at Loughborough include Spin coating and screen printing methods to generate mesoporous interpenetrating nanocomposites of TiO<sub>2</sub> (metal oxides) and metal particle composites with particle sizes from 10nm to 100nm; 2) Spin coating techniques used to create thin films of homogeneous solution of metal, insulator, carbon nanotube nano-composites; 3) Nano templating of metal-polymer structures using a network of block copolymers; 4) Nano templating of metal-polymer structures using sputtering or evaporation patterns of metal on a base insulator created by using an appropriate mask; 5) using laser scribes to create patterns with 50µm spacings, 6) patterns deposited using ion beam microtoning and 7) nano-lithography. As an alternative to using metallic conducting sections, single walled or multi-walled carbon nanotubes (CNTs) can be used which can have very high conductivities when they are aligned in parallel.

An example of a heterogeneous nanostructure is shown in Fig. 1. These nano-scale perforated aluminium oxide discs contain holes arranged in a hexagonal lattice. These holes can be potentially filled with metallic particles. The volume fraction of the holes and hence the macroscopic properties can be controlled by altering the fabrication process [31]. In this example, the heterogeneity would be on a nano-scale not a micro-scale.

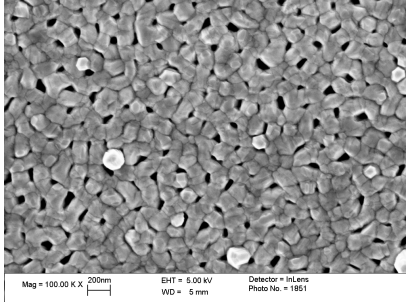


Fig. 1. A nano-scale heterogeneous sample made using vacuum evaporation techniques.

### 1.2 Potential electromagnetic advantages

Further to the potential time and cost benefits outlined above, there are also electromagnetic advantages. Over 60 years ago, Lewin showed that the dielectric properties of a material could be changed by adding/inserting obstacles (much smaller than a wavelength) in a regular lattice formation within a host medium [1]. Now with the advancement in nanotechnology, these heterogeneous structures may be realisable. By varying the size and spacing of the included objects, the permittivity, the permeability and the losses of the substrate can be suitably controlled. Therefore, substrates with novel and bespoke properties can be considered – thus allowing a new degree of freedom in the antenna design process. Moreover, heterogeneous substrates can improve miniaturisation, bandwidth and efficiency by locating a lower permittivity material in regions of high electric field strength [29]. A lower effective permittivity can be achieved by increasing the spacing between the inclusions. Nanomaterials will not only enable this but will allow a smooth transition between separate regions which has been hypothesized to further improve the performance [29]. In addition, it has been theoretically demonstrated that creating a substrate with equality of permittivity and permeability can lead to improved electromagnetic performance [30]. As yet these materials do not exist without substantial losses but the use of heterogeneous nanomaterials may enable them.

Generally, the inclusions will have a higher permittivity than the host and therefore increasing the local volume fraction of the inclusions will increase the effective permittivity. However, the same theory would be applicable to a host with a high permittivity (for example barium titanate) which had small holes placed in a regular lattice. In this case

the holes would reduce the effective permittivity in certain locations depending on the size and spacing of the holes.

### 1.3 Interactions on a atomic and quantum level

Thus far we have only considered the behaviour of these structures using classical electromagnetic and have previously shown that micro-sized metallic cuboids can capacitively couple with each other to form larger structures [32]. However, as the scale of the structures decreases, atomic and quantum physics will begin to dominate over classical electromagnetics. Investigation of electromagnetic and transport properties of granular, fractal media and metamaterials is also a well-developed science and has attracted much attention in the area of condensed matter physics. However, within the cuboids in order to obtain the required range of  $\epsilon_r$ ,  $\mu_r$  and conductivity, important phenomena such as Coulomb blockade (CB), kinetic inductance and the effects of quantum coherence will be taken into consideration by our colleagues in the Physics Department at Loughborough University [33-35].

## 2. CANONICAL EQUATIONS

Several authors [1-11] have investigated the concept of controlling the effective permittivity and permeability by adding inclusions into a host medium and have developed canonical equations to describe such behaviour. The equations assume that the inclusions are much smaller than a wavelength. The equations are typically only valid for semi-infinite media where the inclusions are spheres and are equally spaced in a cubic lattice. The electromagnetic fields at each sphere are influenced by two fields: the incident field and the “mutual” field, which is the sum of all the fields due to all the other spheres. Since the total field varies in a complex exponential form, the problem is reduced to the scattering of a plane wave by a spherical object. The effective permittivity of such a mixture is given in equation (1) [1] where  $\epsilon_1$  is the host permittivity,  $f$  is the volume ratio of the spheres and  $\epsilon_p$  is the permittivity of the sphere which is different from its bulk value due to its small size and the equation for  $\epsilon_p$  can be found in [1]. Note there is an equivalent expression for the effective permeability.

$$\epsilon = \epsilon_1 \left( 1 + \frac{3f}{\frac{\epsilon_p + 2\epsilon_1}{\epsilon_p - \epsilon_1} - f} \right) \quad (1)$$

An examination of (1) shows that the maximum effective permittivity occurs when there is a high volume fraction. If we assume that the sphere has a much higher permittivity than the host, then the denominator simplifies to  $1-f$ . If the spheres are touching each other, the volume fraction is 0.52. Therefore, the highest possible value of the effective permittivity of the mixture is 4.3 times the permittivity of the host. Equation (1) also shows that the effective permittivity will be similar with

small or large spheres as long as the volume fraction is the same. Note, the results will not be identical as the effective permittivity of the sphere will change depending on its size [1].

The equations in [1-11] appear to be different on first analysis, however, algebraic manipulation and employing some assumptions to simplify the equations, show that they are numerically similar. Note, [5] does not include the permittivity of the host in the equations and hence is only valid for hosts which are electromagnetically close to air.

Metallic spheres can also be considered by using the Drude model to obtain the dielectric constant,  $\epsilon_r$  of a metal, see equation (2) [19].

$$\epsilon_r = \epsilon_d - \frac{\omega_p}{(2\pi f)^2 + \nu_e^2} \left( 1 + j \frac{\nu_e}{2\pi f} \right) \quad (2)$$

where  $\omega_p = \frac{N(ch)^2}{\epsilon_0 m_e}$  is the plasma angular frequency,  $\epsilon_d$  is the dark dielectric constant,  $\nu_e$  is the collision angular frequency,  $m_e$  is the mass of the electron,  $ch$  is the electron charge,  $\epsilon_0$  is permittivity of free space,  $f$  is frequency. The Drude model typically produces large values for the equivalent permittivity [27 -28].

A more in-depth analysis of these canonical equations can be found in [16]. This paper also includes numerical results of varying the sphere size, spacing and permittivity.

### 3. ELECTROMAGNETIC SIMULATIONS

The canonical equations are very useful to understand the electromagnetic mechanisms that explain the effective properties and give a quick estimate of the values that different geometries would produce. However, they are only valid for spheres that are evenly spaced in an infinite medium. In reality, our samples will be of finite size and the inclusions may not be spherical or evenly spaced. Therefore, to understand how realistic structures behave and to quantify the accuracy of the canonical equations, electromagnetic finite-difference time-domain (FDTD) simulations were used. Specifically, Empire XCcel™ was used to create a plane wave travelling along a transmission line. The sample can be placed half way along the transmission line and this produces S11 and S21 results over a range of frequencies. The effective  $\epsilon$  and  $\mu$  of a mixture can be calculated from the S-parameters using a “Resonant Inverse Scattering Formalism” as shown in [18]-[23]. More details of the FDTD simulations and the rectification algorithm can be found in [17].

Initially, the FDTD simulation and retrieval algorithm were validated by simulating 10mm thick homogeneous samples with known values of permittivity: 1, 2, 3...10. The results are shown in Fig. 2. At frequencies where the thickness of the homogeneous sample is less than half a guided

wavelength ( $\lambda_g$ ), the retrieval algorithm produces very accurate results for the calculated permittivity which is the same as the simulated permittivity. This shows that the algorithm is robust.

For all ten materials considered, there is a local spike in the calculated permittivity where the thickness is  $\sim 1/2 \lambda_g$ . At these frequencies, the slab is transparent to an incoming plane wave as  $d_{slab} = n\lambda_g/2$  where  $n = 1, 2, 3, \dots$  [20, 22, 24]. At these points, the  $S_{11}$  values are very close to zero while the  $S_{21}$  is close to unity and these values produce numerical errors in the retrieval algorithm. Note, the effective permittivity of the real material does not change at these points. The accuracy of the algorithm is reduced when the thickness is greater than  $\sim 1/2 \lambda_g$ . Further details about the retrieval algorithm can be found in [24 - 26].

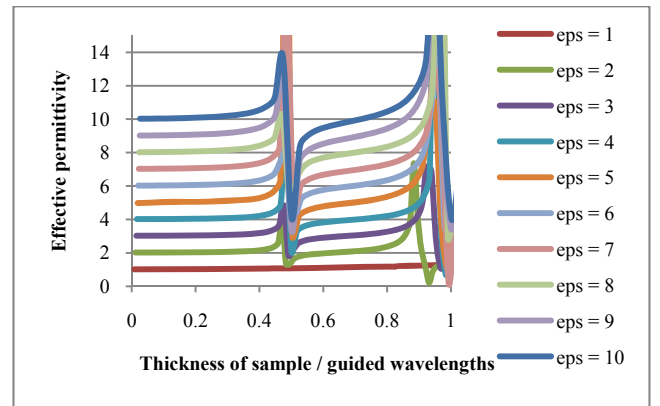


Fig. 2 The effective relative permittivity derived from the rectification algorithm and simulated scattering parameters. The sample was 10mm thick, homogeneous and had permittivity values of 1, 2, 3...10.

The same process can be applied to heterogeneous mixtures. Please see [17] for simulated results of these structures which produced effective permittivity results that closely agreed with the canonical equations. As mentioned above, a higher effective permittivity was found when the permittivity of the inclusions was increased and they were more closely spaced. The simulations allowed cubic inclusions to be included. The cubes behaved similarly to spheres when the size was adjusted to enable a similar volume ratio. Note, the cubes require less computational resources.

Validating the simulation and algorithm system by comparing it to a homogeneous sample as well as with the canonical equations, gives confidence that it can now be applied to more complicated geometries. Simulating structures with small scale inclusions is computationally expensive, but computers are continually developing and hence these fine-scale simulations will become more manageable. If the inclusion spacing and hence the local effective permittivity varied, a smoothly graded dielectric substrate could be designed. Once the local effective permittivity is known, the

antenna can be quickly simulated by replacing the inclusions with the equivalent homogeneous material.

#### 4. CONCLUSIONS

This paper has reviewed analytical and simulation design tools that can be used to understand and predict the electromagnetic behaviour of heterogeneous substrates. While the canonical equations have the advantage of taking a few seconds to calculate, they are limited to idealised structures of spheres in a uniform lattice. By contrast the simulations are much slower but more flexible. The two techniques have been found to produce a good level of agreement. The effective permittivity was found to be strongly dependent on the volume fraction of the inclusions. Future work will include: - simulating patch antennas with uniform and non-uniform lattices, fabricating samples and increasing the permeability.

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