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Reflection and Transmission Coefficients of Nano-metamaterial Antennas at Microwave Frequencies

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Abstract

The hypothesis of this paper is that when metallic nanoparticles are grouped together by suitable field coupling they can behave like larger objects which will resonate at microwave frequencies. This means that sheets of nano-materials can be designed that are largely transparent at these spectra except where an antenna has been created from densely grouped clusters of metallic nanoparticles. Simulations, based on actual samples composed of nano-metamaterials, show the behaviour of the reflection and transmission coefficients of antennas. The resonant frequency can increase or decrease depending on the geometry.

1. Introduction

This research is part of a new field domain of nano-electromagnetics which is growing rapidly in popularity [1, 2]. Due to their size, nanomaterials find applications in electromagnetics at extremely high frequencies (many GHz or THz) where the wavelengths are very small. Examples include nano-waveguides, nano-antennas, semiconductors, nano-scale resonators [2]. However, all this research is undertaken at very high wavelengths and not in the microwave range as used in communications devices. Previous work by the authors have shown that antennas composed of very small conducting dots have very interesting properties, depending on their size and the gaps between them [3, 4].

This uniform sub-wavelength repetitive structure is expected to behave similarly to a metamaterial and will exhibit the same remarkable metamaterial phenomena such as negative refraction and phase-shifting [1, 5]. Caloz [1] has shown that using smaller unit cells of metamaterials can improve the homogeneity and the isotropy, extend the bandwidth, enhance the functionality and reduce refraction and diffraction losses at interfaces with other media. Therefore, constructing antennas using nanomaterials has enormous potential in antenna designs for many different applications.

Additional advantages of using such nano-metamaterials for microwave antennas include being able to build the antenna, the substrate and RF circuitry in one process, therefore, exploiting the flexibility of nanomaterials to create novel and specific substrate properties, such as permittivity, permeability and low losses. Using nanomaterials also means microwave antennas can be constructed in a variety of very complex intricate antenna designs such as spirals or fractals. A further advantage of creating antennas from nanomaterials is that very thin layers are formed and therefore smaller volumes of the metal are needed. This is beneficial to the environment and may reduce the manufacturing costs.

2. Fabrication of Samples

The design of a novel method of fabricating antennas using nano-metamaterials is an iterative interactive process between simulated results and samples that can be practically manufactured. This paper considers two different fabrication techniques. Samples 1, 2 and 3 are simple 'dipoles' (2mm x 4mm), i.e. strips of metal vacuum-evaporated on 1 mm thick glass, see Fig. 1 (a) – (c). The silver layer is 500 nm, but there is a 50 nm gold layer on top of it for passivation (to prevent oxidation). Sample 1 is con-
tinuous, but Samples 2 and 3 have a ~60μm gap in the middle. In Sample 2, the gap goes down to the glass substrate. In Sample 3 there is some residual silver inside the gap.

Sample 4 is essentially a perforated metal film disc on top of a 60μm thick porous dielectric (alumina-oxide, εr = 5). The silver film thickness is ~200 nm (plus a 50 nm gold passivation layer, so ~250 nm overall). The holes, arranged in a loosely hexagonal pattern, are about 200 nm in diameter and the mean distance between their centres is 300 nm, see Fig. 1 (e). Around 30-40% of the surface area is covered by holes. This can be varied using different fabrication processes and film thicknesses. The metal layers were deposited on the surface of a porous alumina sample (employed as a template) using vacuum evaporation techniques at a pressure of 5 x 10^-6 Torr and a deposition rate of 20 ± 2 nm/min.

Fig. 1. (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4 from front and back compared to a British 1 pence coin. (e) is an Scanning Electron Microscope image of Sample 4 - the bar in the bottom right corner is 500nm.

3. Simulation Methodology

In this paper, EMPIRE commercial FDTD code (www.empire.de) has been used in simulations. A vertically polarised plane wave was created using an air-filled microstrip line which acts as a parallel plate waveguide. The cut off frequency of the cavity, fc=c/MAX(W or H) and therefore, at 40GHz, the (maximum) height and width of the waveguide is 7.5mm. Perfect electric conductors and perfect magnetic conductors are used at the two sides and top and bottom boundaries respectively. This means the sample is infinitely periodic in two dimensions.

Fig. 2. Simulation setup: (a) Sample 1 in microstrip line. (b) and (c) are approximate representations of Sample 4 using 300μm spacings. (b) 50μm silver strips (holes = 250μm) and (c) 250μm silver strips (holes = 50μm).

4. Results

When the microstrip cavity was empty the S11 was < -70dB and the S21 was ~ 0dB up to 40GHz. The S21 results for Samples 1 and 2 are shown in Fig. 3 (a). Sample 3 behaved like Sample 1 if 10μm thick of metal resided in the gap. Note that the S11 can be found using $S_{11}^2 + S_{21}^2 \approx 1$ as the losses were negligible. As the size of the gap increased, the resonance frequency increased logarithmically, see Fig. 3 (b). The results in Fig. 3 (a) considered adding a gap at the centre of a 4mm dipole. Increasing the depth of the dipole had little effect. Decreasing the width of the dipole, increased the resonance frequency and increased the sensitivity of adding small gaps. Note, the resonance frequency of the 0.5mm and 1mm wide dipoles (without gaps) were 23.9GHz and 24.3GHz respectively. An alternative to this is to add a gap in-between two 2mm sections so the total length of the dipole increases. This causes a lower resonance frequency, which is noticeable with larger gaps.

The results in Fig. 4 represent Sample 4. A thin section of silver was added surrounding the 5mm square sample so that the exterior dimensions were constant. The spacing in-between the silver strips
was 300μm (see Fig. 2 (b) and (c)) and 600μm. As the thickness of the silver strips decreased (i.e. larger holes), the resonant frequency decreased with both 300μm and 600μm spacings, see Fig. 4.

![Graph showing transmission coefficient and resonant frequency](image1)

**Fig. 3.** (a) The transmission coefficient of Samples 1 and 2 and similar samples with larger gaps. (b) shows the resonant frequency of the S21 of different samples as a function of the size of the gap.

![Graph showing transmission coefficients of different metal strip widths](image2)

**Fig. 4.** The transmission coefficients of a 5mm square disc with different widths of metal strips (a) at 600μm spacing and (b) at 300μm spacing. NB The size of holes equals the spacing minus the strip width.

### 5. Conclusion

The possibility of producing antennas from nano-metamaterials has been investigated and representative real samples have been simulated. It is very computationally expensive to electromagnetically simulate nanostructures on the mm/cm scale. However, these results indicate their performance. As gaps were added to a dipole, the resonance frequency increased logarithmically. When holes were added to a metal disc the resonance frequency decreased. This may be particularly relevant to wearable antennas which require the antenna to be lightweight, flexible and to allow the skin to breathe. Future work will measure the S11 and S21 of samples placed in-between two horn antennas as in [5].

### References


