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Capacitive coupling of discrete micro-sized gaps for RF applications

W. G. Whittow

School of Electronic, Electrical and Systems Engineering
Loughborough University, UK
w.g.whittow@lboro.ac.uk

Abstract: This paper investigates the performance of a passive thin metallic object containing micro-sized gaps exposed to a plane wave excitation. This work has potential applications for emerging antenna fabrication techniques where the conducting sections are made from discrete metallic sections. This includes antennas composed from nanomaterials and conventional inkjet printed antennas. Electromagnetic simulations showed metallic sections separated by a micro-sized gap were found to capacitively couple. The coupling can be enhanced by reducing the size of the gap, increasing the width of the metallic object or by filling the gap with a permittivity greater than unity. It should be noted that the DC value of parallel plate capacitor is not strictly valid at radiofrequencies – however, this paper shows that the DC value of capacitance is a reasonable approximation and is useful to understand the behavior.

1. Introduction

Planar antennas are typically made by printing a continuous layer of copper and then using environmentally damaging and expensive chemicals to etch away the unwanted metallic sections. This is a labour intensive process involving multiple steps. As the cost of the raw materials and labour continues to increase, the inefficiency of this process will become more evident and alternative processes need to be explored. Furthermore, there will be increasing public and political pressure to fabricate antennas and electronics in more environmentally friendly and efficient way. The aim of this work is to investigate the feasibility of a new method of designing and manufacturing microwave antenna systems using metallic and non-metallic micro and nanomaterials. By exploiting the rapidly improving nanomaterial technological advances, for example [1, 2], new structures can be envisioned and are expected to be realisable in the near future. As with any new technology, the financial costs will be large initially but these will decrease as the technology matures. In this work, conducting and insulating micro-sized cuboids will be created from many nanomaterials, depending on the techniques used, it is possible that the conducting millimetre/centimetre-sized sections may be composed from many discrete micro-sized cuboids. At the scale of the micro-sized cuboids, classical electromagnetics will dominate over atomic and molecular forces.

The proposed fabrication of using nanomaterials concept is advantageous because the entire antenna system including the radiating structure, the dielectric substrate, the ground plane and feed system can be integrated into one fabrication process. This work consists of two parallel research paths: 1) to examine the capacitive coupling of discrete metallic sections which will be addressed in this paper and 2) to investigate the dielectric substrate opportunities [3-5].

The properties of the dielectric substrate can be controlled with the ratio of conducting and non-conducting micro-cuboids which will allow an extra degree of freedom for antenna engineers to control the substrate height, the permittivity, permeability and losses which can be tailored for specific applications. It has been known for several decades that inserting uniformly spaced spheres, which are either conducting or have a high permittivity, into a host medium will result in higher effective permittivities [6]. The author has previously reported that the effective permittivity can be altered with heterogeneous mixtures containing micro-sized cuboids or spheres [3-5]. By suitably arranging the conducting and insulating micro-sized cuboids, the local concentration will be altered as will the local permittivity. This can be electromagnetically exploited to create a small size high efficiency antenna by creating a low permittivity region where the currents are large and a higher permittivity region elsewhere [7]. The authors in [7] hypothesised that further performance improvements could be obtained by introducing a smooth variation in the dielectric properties. Previously, it has been shown that if an as yet unrealisable substrate with equality of permittivity and permeability and low losses could be fabricated, then a small size, high efficiency and high bandwidth antenna could be designed [8]. This research will work towards enabling such structures.

In related work, Mittra [9] has reviewed the area of small antennas and concludes that the key future challenges are size reduction, directivity enhancement, bandwidth widening and backlobe. While Caloz [10] has shown that using smaller unit cells of materials can improve the homogeneity and the isotropy, extend the bandwidth and reduce refraction and diffraction losses at interfaces with other media. To achieve these electromagnetic advantages, new techniques need to be explored which may enable the next major advancement in antenna design.

This work also has relevance to other existing antennas that have been fabricated from discrete elements or have been physically extended and hence gaps have been created. Low cost antennas can be printed on a range of substrates using conducting ink [11-16]. This technique creates conducting patterns and tracks from discrete conducting ink droplets using inkjet or screen printing. These ink droplets are then sintered to ensure that the solvent evaporates leaving just the solid conducting flakes. The sintered ink is brittle and repeated stretching and bending can form permanent cracks. Conductive inks can be printed on a range of substrates including flexible materials paper and textile substrates which can be extended which means temporary gaps between the conducting ink flakes will be created. This paper will be of assistance to explain the behavior of printed antennas.

Integrating electronic systems into clothing is a concept that is currently a popular research topic. Future technology will allow the electronics to be stretched and bent around curved surfaces. These futuristic electronic systems will also incorporate antennas which will need to remain on frequency when they are stretched. Antennas composed of conducting elastomers have been recently considered in [17, 18]. This paper will show that the addition of micro-sized gaps will increase the resonant frequency. With careful material design, this increased frequency can be counter-balanced by the extended length of the antenna which will have a tendency to reduce the frequency.

This paper will analyse how discrete objects can couple to form larger objects and how the performance of the structure changes with regards to the geometry and is an extension of the work in [19, 20].

2. Simulation methodology

In this paper, finite-difference time-domain (FDTD) EMPIRE XCcel™ software (www.empire.de) is used to examine the effects of micro-sized gaps at the centre of thin metallic sections. These metallic sections were passive objects and will be referred to as dipoles in this paper. A vertically polarised plane wave excitation incident on the passive vertically orientated dipoles was implemented using the total field scattered field technique. The advantage of using a plane wave source compared to a lumped port is that there is no variation in the source when thin dipoles are considered. In this paper the cross section of the dipoles was always square and therefore the term “100 micron wide dipole” refers to the width of the cross section. The geometry of the dipole is shown in Figure 1. Various widths of dipoles and different sizes of gaps were investigated. Care was taken to ensure that both the dipole and the gap were meshed finely. The length of the dipole was 5000μm (5mm) unless started otherwise.

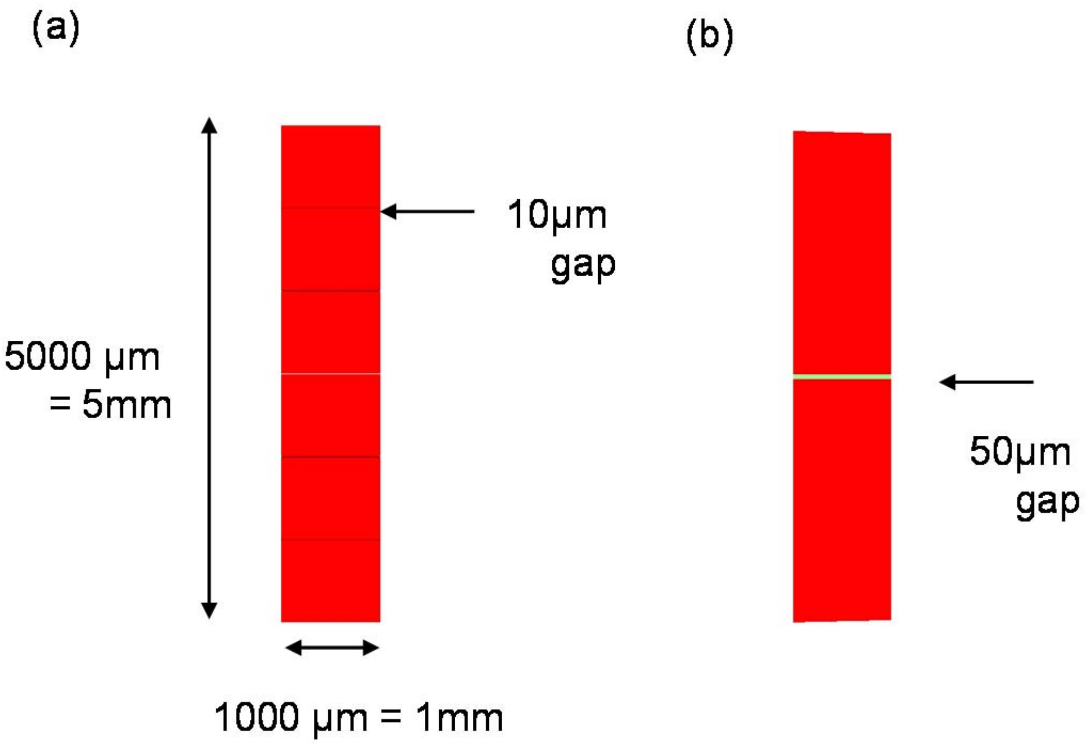

Figure 1. (a) A 5mm long, 1mm wide dipole with five 10 micron gaps and (b) the same dipole with one 50 micron gap at the centre.

3. Results

3.1. Coupling of single and multiple gaps

Results with different widths of dipoles and different sizes of gap at the centre are shown in Figure 2. As expected, the resonant frequency increases as the size of the gap increases.

The relative frequency increase is the resonant frequency divided by the resonant frequency of the continuous dipole (no gaps) of the same width and length. Therefore, when the relative frequency is close to one, the gap has negligible effect on the overall performance and there is strong coupling between the two sections. When the relative frequency is approaching two, the two sections separated by the gap behave as two separate sections and hence do not exhibit coupling. This coupling gap threshold was determined by the dipole thickness. Figure 2 shows that the coupling increases with smaller gaps and also thicker widths of dipole. These results suggest that the effect is due to capacitive coupling. The DC capacitance of the gap can be found using equation (1). This equation assumes an ideal capacitor where the fringing effects are zero.

$$C_{DC} = \frac{\varepsilon_0 \varepsilon_r A}{g} \qquad (1)$$

Where ε_r is the permittivity of the material in the gap, *A* is the area of the dipole (≡dipole width^2) and *g* is the gap between the metallic sections. This expression is not valid at radiofrequencies (RF); however, it has been used in this paper as it helps explain the results. Results later in this paper will show that the DC capacitance is a reasonable approximation to the RF Capacitance.

Of particular interest is the fact that large gaps behave similarly to multiple 10μm gaps of the same total size – see the 500 and 1000 micron wide dipole results in Figure 2. This is consistent with the standard equation for capacitors in series.

In the case when the gaps are all the same size, the total capacitance can be obtained by dividing the capacitance of one gap by the number of gaps. Specifically, one 50μm gap has the same behaviour as 5 x 10μm gaps. Therefore, one gap at the centre of the dipole was used in this paper to simplify the simulations and reduce the computational requirements. The single gap can also represent the ratio of non-metal to metal sections.

In this paper, the structure is said to couple strongly if the frequency of the dipole with the gap is less than 1.2 times the frequency of the continuous dipole. If the frequency doubles, there is negligible coupling. Therefore, if the relative frequency increase is larger than 1.8, the structure is said to weakly couple. These values of 1.2 and 1.8 have been chosen by the author to represent a reasonable level of performance and are shown in green and red throughout this paper. To enhance the usefulness of this paper, strongly coupling regions in the graphs have been highlights in green while weakly coupling sections are highlighted in red.

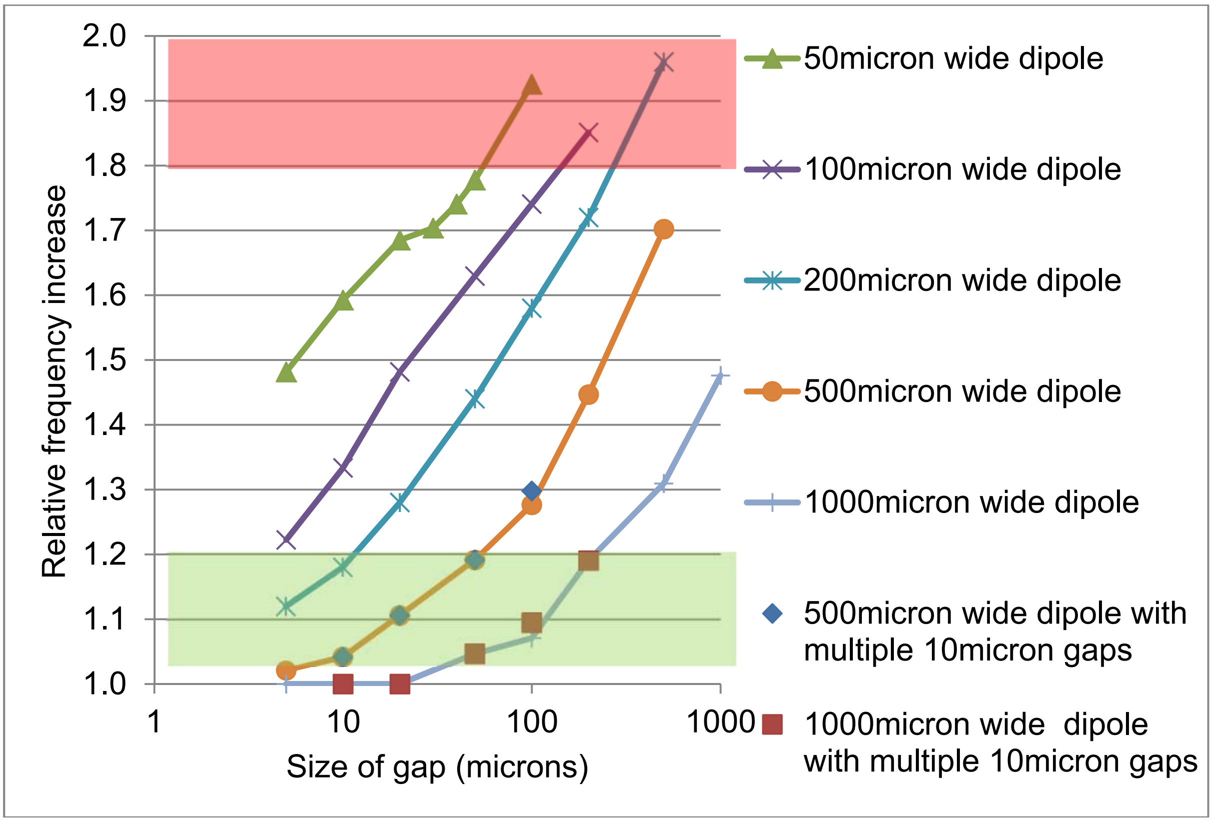

Figure 2. The relative increase in frequency of a 5000µm long passive dipole of different widths with varying sizes of gap.

To insightfully understand the data, it is helpful to think of the results in Figure 2 in terms of the DC capacitance. When the capacitance is small as is the case with large gaps or thin dipoles; there is little coupling and the resonant frequency is significantly increased. As expected, as the width increased or the gap decreased, the capacitive coupling increased. With larger capacitance values, the resonant frequency converges to the case of the continuous dipole. Further increases in the capacitance did not reduce the frequency beyond the continuous dipole. Thin dipoles with small gaps are equivalent to wide dipoles with larger gaps which emphasizes the usefulness of examining the structures in terms of their capacitance.

For the same capacitance value, thinner dipoles couple marginally better (the relative frequency increase is smaller) than thicker dipoles with larger gaps. This was thought to be due to edge effects of the finite sized capacitor where the electric fields between the two dipole sections are all parallel also bend around the gap at the edges, see Figure 3 (a). These edge effects are more significant for smaller dipoles hence the improved coupling, see Figure 3 (b) and (c).

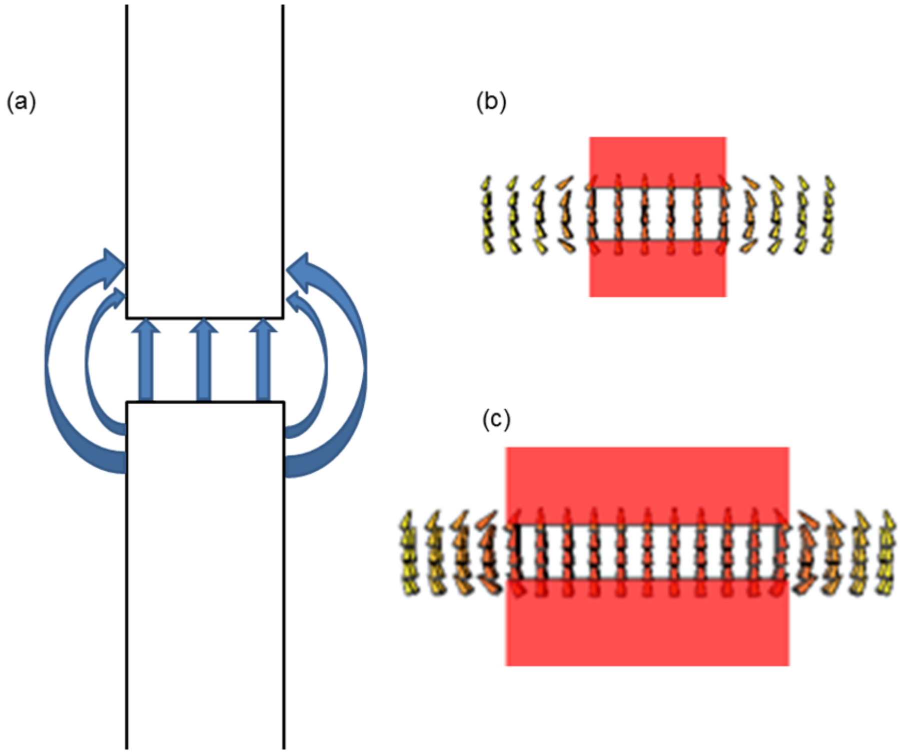

Figure 3. (a) Sketch showing electric fields in a thin perfect electrically conducting capacitor; (b) the electric fields in a 20 micron gap at the centre of a 50 micron wide dipole and (c) the electric fields in a 20 micron gap at the centre of a 100 micron wide dipole.

3.2. Reactance of micro-sized capacitors

For capacitors at RF spectra, the capacitance can be calculated using equation (2):

$$C_{RF} = -\frac{1}{\omega X} \tag{2}$$

Where ω = 2πf and X is the reactance = V/I (ohms).

The reactance can be calculated from the simulations by recording the voltage (V) in the gap as well as the displacement current (I) from the four magnetic field components surrounding the gap at the centre the dipole. Figure 4 shows that there is a linear relationship between the reactance and the relative frequency increase for each width of dipole examined. The gradient of this line is dependent on the width of the dipole with wider dipoles having larger reactances. Generally, a large displacement current in the gap is required for the two metallic sections to couple which will produce a smaller reactance.

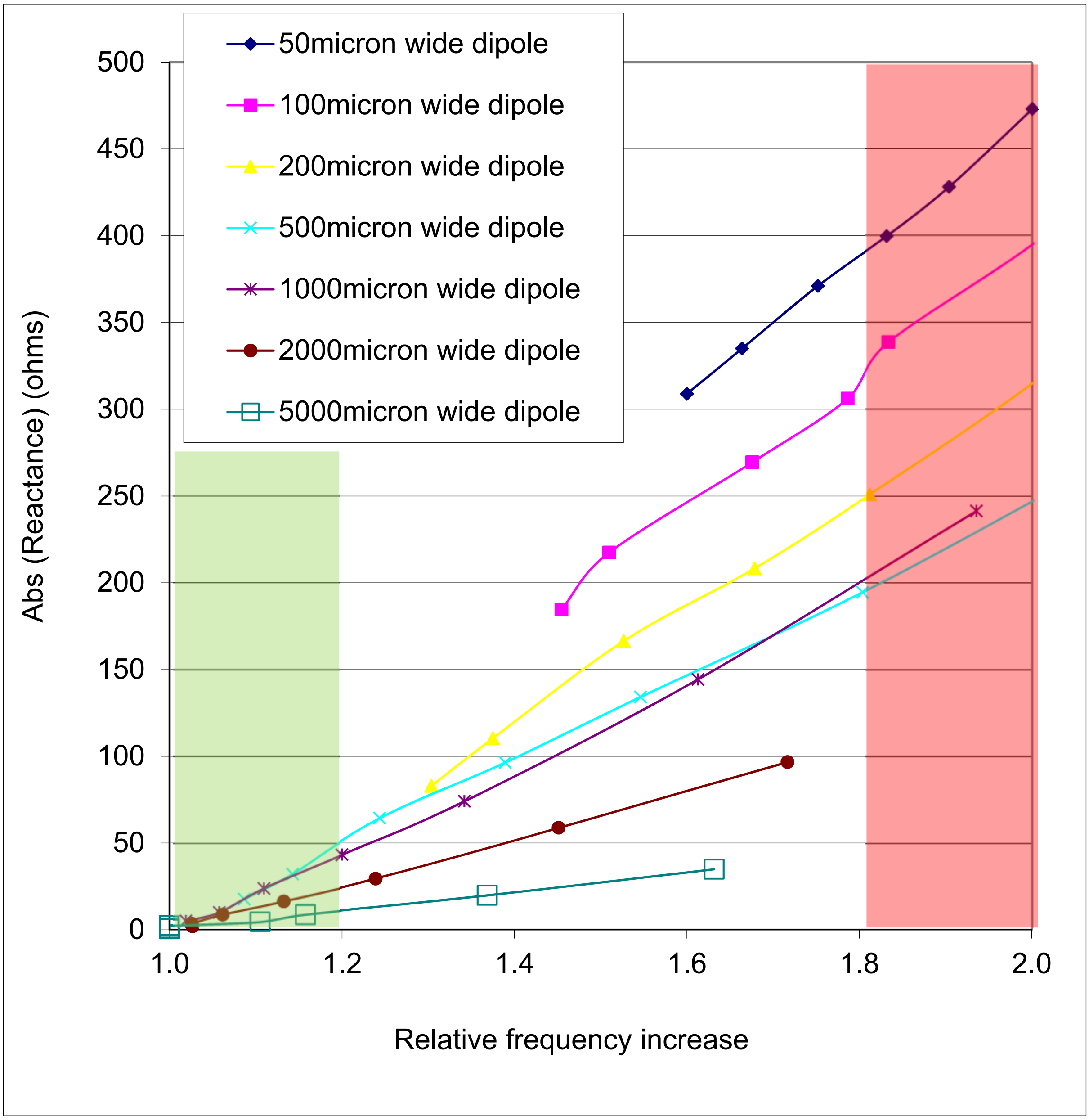

Figure 4. Reactance of the micro-sized gap as a function of the relative frequency increase of a 5000µm long dipole.

Equation (2) allows the RF capacitance to be compared to the DC capacitance which can be easily calculated from the size of the dipole and the gap. These results are shown in Figure

5. As the DC capacitance increases, the coupling increases and the RF capacitance converges to the DC capacitance. If the capacitance of the 5000 micron long dipole is greater than approximately 100fF, the frequency increased by less than 20% of the frequency of the continuous dipole. Figure 5 shows that above this range, the ratio of the RF capacitance to the DC capacitance is less than two. Therefore, the DC capacitance provides a reasonable indication of the RF performance if the structures couples well. As expected, when the coupling is weak, the displacement current is very small and hence the RF capacitance is very large. The figure shows that the ratio of RF capacitance to DC capacitance increases with smaller values of DC capacitance which one might expect to increase the coupling. However, it is worth noting that the X-axis scale in Figure 5 is a logarithmic scale and hence the DC capacitance must decrease by a factor of ~1000 for a ten times increase in the ratio of RF to DC capacitance and hence the relative increase in the RF capacitance does not contribute to strong coupling.

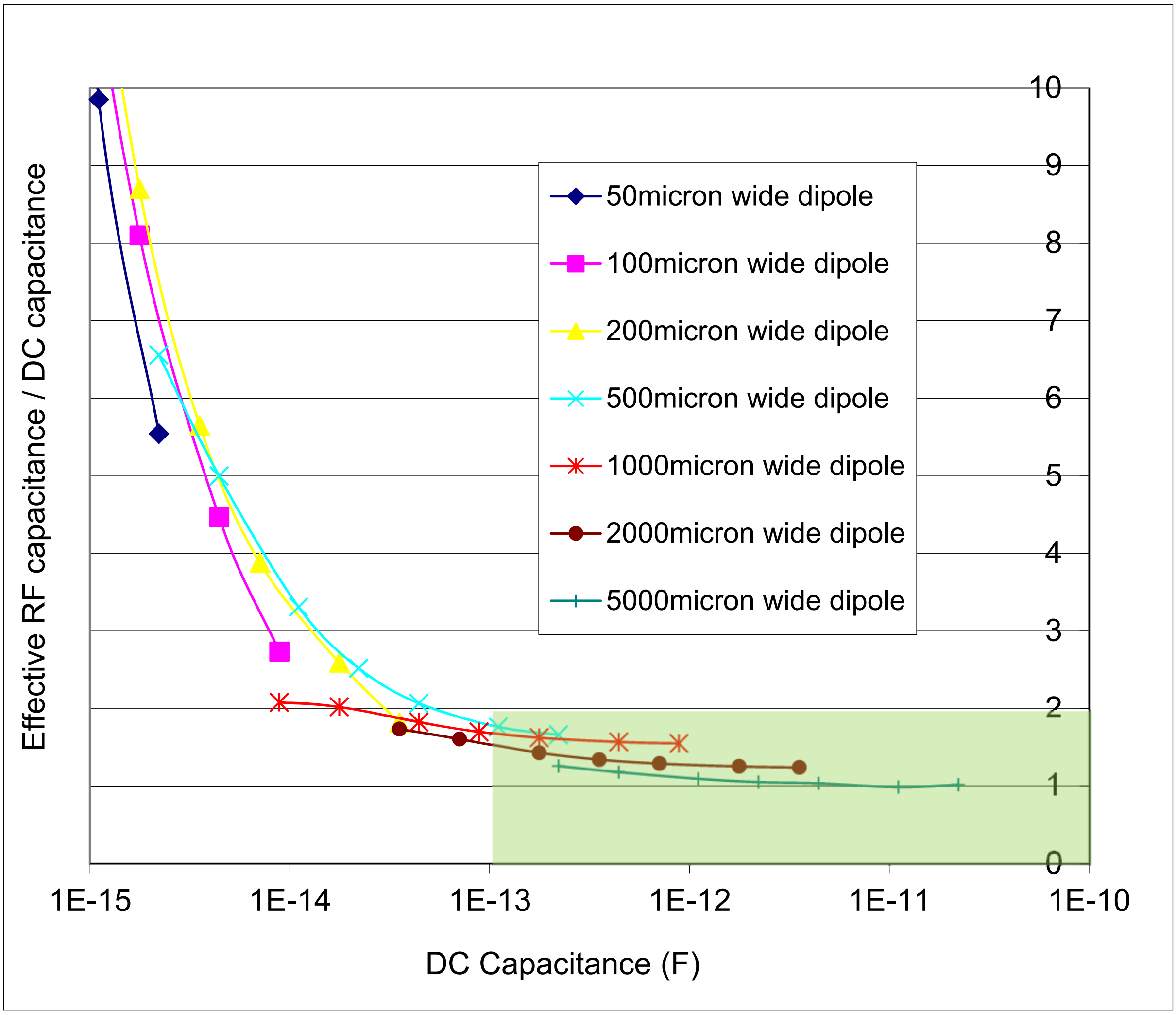

Figure 5. The ratio of RF capacitance to DC capacitance as a function of DC capacitance.

3.3. Capacitive micro-sized gaps at different frequencies

The results in the previous sections have been made with a 5000μm long dipole. Theory indicates that the capacitance will be frequency dependent and therefore the behaviour with the same sized gap will be dependent on the length of the dipole. The results in Figure 6 indicate the coupling between two halves of different length dipoles with a 10 micron gap. As the length of the dipole increased, the frequency decreased and the relative frequency increase due to the gap increased. 5mm long dipoles coupled better than 15mm long dipoles as shown in Table 1. Even though the frequency was approximately three times lower for the longer dipole, the change in coupling was approximately 10%, hence the change in performance was small compared to the change in length.

As the capacitive gaps can be considered to be lumped elements and therefore the ratio of the gap to the total length is not a suitable metric. As the frequency decreased, the capacitor behaves like an open circuit, hence the coupling decreased and the resonant frequency increased compared to the continuous case – as shown in Figure 6. Conversely, as the dipole becomes shorter, the frequency increases, the capacitor behaves more like a short circuit and the coupling improves. The absolute value of the reactance at the centre of the dipole increases linearly with the length of the dipole as shown in Figure 7. Therefore, the reactance is proportional to 1/frequency as in equation (2). These results show that a large reactance value indicates that the two halves of the dipole are not coupling – which was also shown in Figure 4.

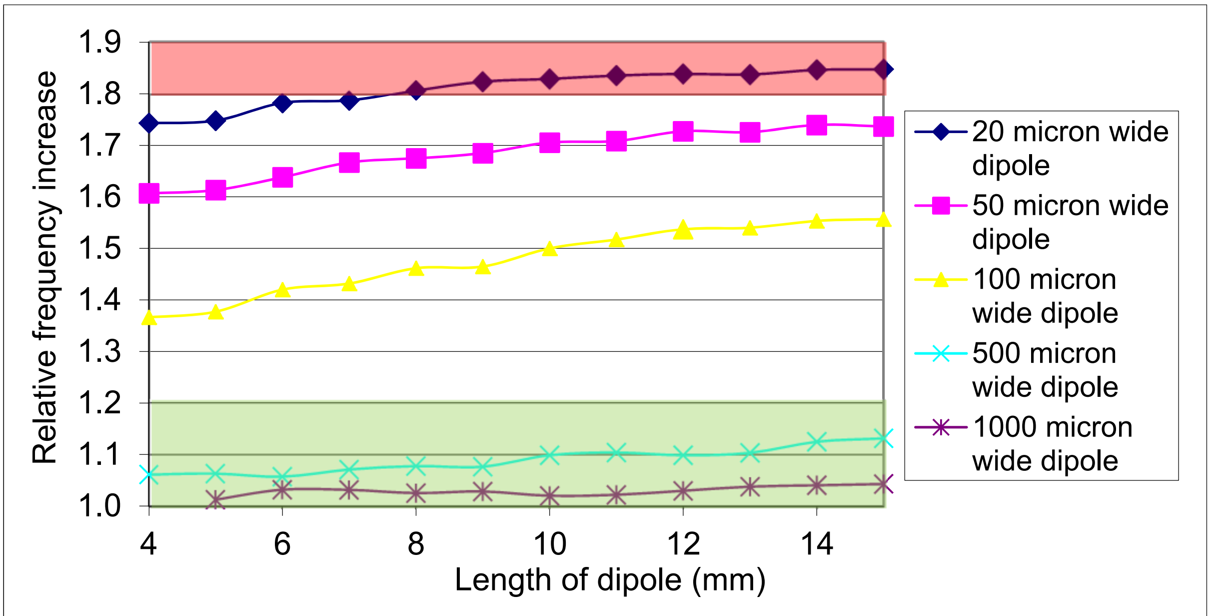

Figure 6. The relative frequency increase of different lengths of dipole with a 10micron gap at the centre.

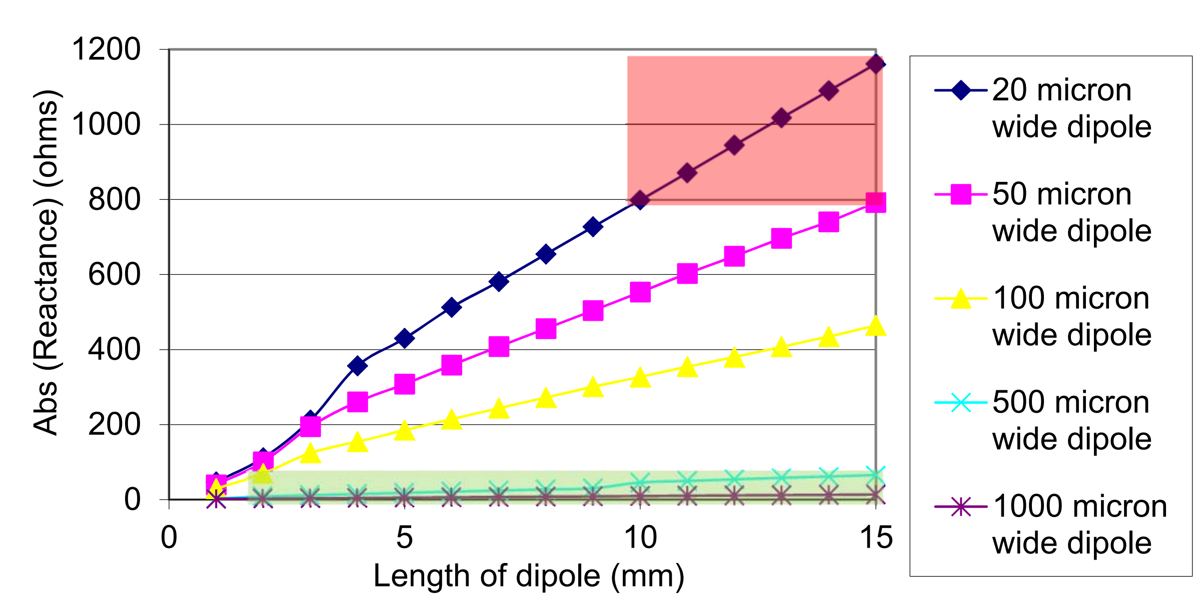

Figure 7. The absolute value of the reactance with different lengths of dipole with a 10 micron gap at the centre.

Table 1. The relative frequency increase of dipoles with a central gap compared to the same size continuous dipole for 5mm and 15mm long dipoles.

		Width of dipole (microns)			
		100	200	500	1000
Size of gap (microns)	10	1.33; 1.56	1.18; 1.33	1.04; 1.03	1.00; 1.06
	20	1.48; 1.67	1.28; 1.44	1.11; 1.11	1.00; 1.11
	50	1.63; 1.78	1.44; 1.56	1.19; 1.22	1.05; 1.15
	100	1.74; 1.87	1.58; 1.67	1.28; 1.41	1.07; 1.25
	200	1.85; 1.89	1.72; 1.78	1.45; 1.49	1.19; 1.38
	500			1.70; 1.72	1.31; 1.50
	1000				1.48; 1.63

3.4. Measured results

To verify the simulated results, monopole antennas were fabricated and measured. The monopole was an 80mm long copper cylinder of diameter of 2.36mm. The ground plane was 200 x 200mm with a small hole drilled at the centre through which the inner pin of an SMA connector was soldered to the monopole. The bottom of the monopole was placed 2mm above the ground plane. Two variants of the monopole were made: i) continuous and ii) two 40mm long sections with faces machined so they formed flat parallel faces. Small sections of 50 micron thick Mylar film were placed between the two monopole sections to create the gaps. The monopoles were securely embedded in a Rohacell cuboid to provide structural support and to ensure the monopole halves did not move when the Mylar sections were removed. Different sizes of gaps were considered by temporarily placing multiple layers of Mylar between the monopole sections and then removing them. The fabricated monopoles are shown in Figure 8.

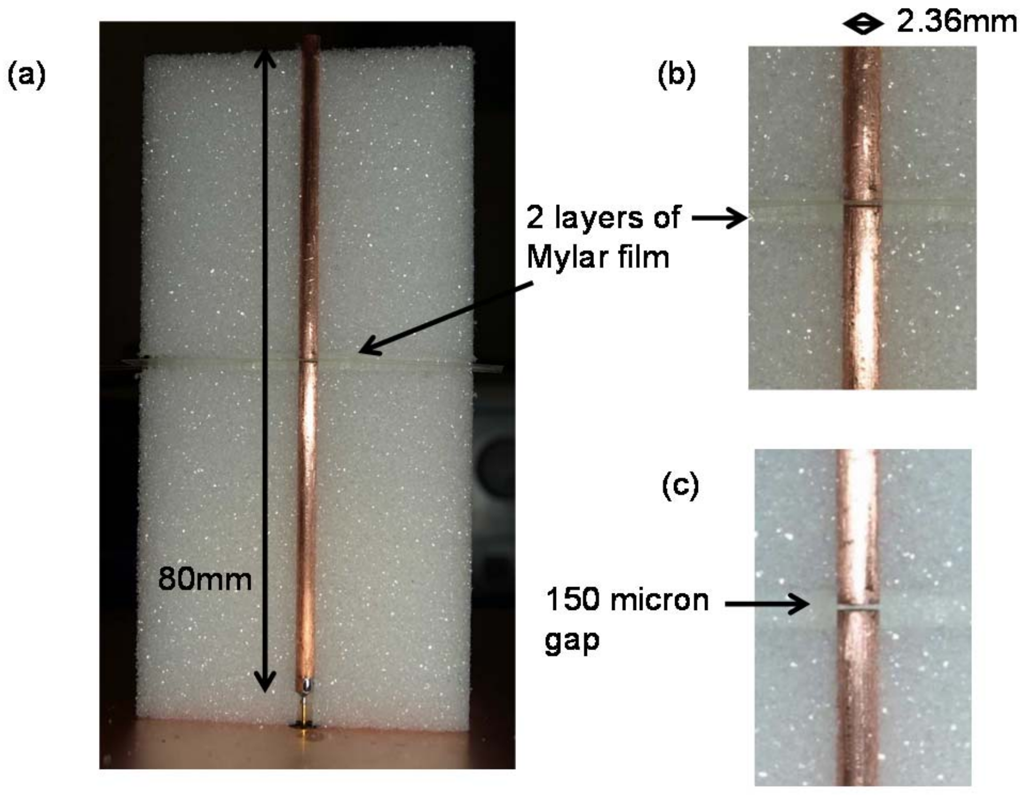

Figure 8. The measurement setup of the monopole antennas: (a) monopole with two 50 micron Mylar layers at centre; (b) zoomed in view of gap with two Mylar sheets and (c) 150 micron air gap.

The measured return loss results are shown in Figure 9. As expected, the frequency increases with the size of the gap. The measured results show good agreement with the simulations.

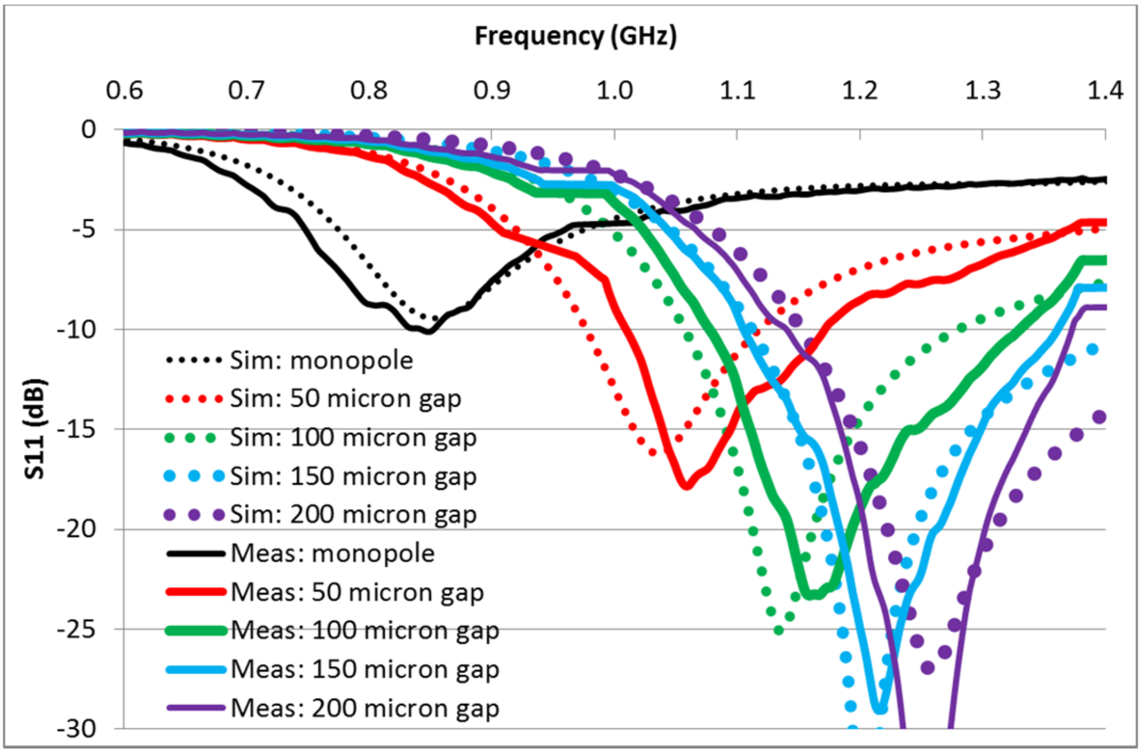

Figure 9. Measured and simulated return loss results of monopole antennas. Colour version is available online. (If viewing in black and white, the frequency increases with the size of the gap; see Table 2).

The earlier results show that the coupling is related to the capacitance of the gap. The capacitance can also be increased by filling the gap with a dielectric material with a permittivity greater than one. This is the same technique as used to model lumped capacitors in the FDTD method [21]. The measured results with Mylar sheets in the gap are shown in Table 2. The Mylar sheets increased the degree of coupling compared to the same sized air gap. Mylar has a reported relative permittivity of approximately 2.8 at 1GHz [22] or 2.45 at 100GHz [23]. A range of permittivity values were considered in the simulations. As the simulated permittivity increased, the capacitive coupling increased and the relative frequency increase is reduced. The measured and simulated results with the Mylar filled gaps show reasonable agreement as shown in Table 2.

Table 2. The measured frequency of the monopole with different gaps and simulated results with a range of permittivity values for Mylar.

	Measured frequency (GHz)	Simulated frequency (GHz) ε_{Mylar} = 2.0	Simulated frequency (GHz) ε_{Mylar} = 2.5	Simulated frequency (GHz) ε_{Mylar} = 2.8
Monopole	0.86		0.85	
50 micron gap (air)	1.06		1.03	
100 micron gap (air)	1.15		1.13	
150 micron gap (air)	1.21		1.20	
200 micron gap (air)	1.25		1.26	
50 micron gap with Mylar	0.96	0.95	0.94	0.93
100 micron gap with Mylar	1.06	1.04	1.01	1.00
150 micron gap with Mylar	1.10	1.09	1.06	1.04
200 micron gap with Mylar	1.14	1.14	1.10	1.09

4. Conclusions

This paper has investigated the performance of non-continuous conducting sections. This has relevance to systems where the radiating element is composed from many small elements. It also applies to antenna systems that can be stretched or damaged where cracks and gaps appear within the structure. Dipole-like structures with small micro-sized gaps have been shown to capacitively couple and can resemble one continuous object. The gaps cause the resonant frequency to increase which increases logarithmically with the size of the gap. The results have also indicated that many small gaps will produce a similar level of performance as one larger gap. The coupling is increased with smaller gaps or thicker dipoles. Different widths of dipoles with the same DC capacitance will exhibit similar levels of coupling. The results have shown that when the dipoles couple strongly, the RF capacitance value is a reasonable approximation to the DC capacitance to within a factor of two. As the length of the dipole with a central gap increased, the resonant frequency compared to the continuous dipole also increased. However, if the frequency is changed by a factor of three, the degree of coupling is only changed by only 10%. As the capacitance decreased, the coupling decreased as the displacement current in the gap decreased. Therefore, high reactance values indicate a low level of coupling. The capacitance can also be increased by filling the gap with a permittivity greater than unity which is an alternative method of improving the coupling. This enables an extra degree of control to the antenna designer and shows that the coupling can be increased by embedding the metallic sections in a high permittivity dielectric.

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