Microwave Performance of Composite Conductors for Fused Filament Fabrication of Electronics

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***Abstract*—Fused Filament Fabrication (FFF) now offers some useful performance for functional materials including conductors. These are generally composites of highly conductive particles embedded in a weakly conducting , or insulating host material. The conducting structures thus formed are not continuous but rather a percolative network of weakly connected conductive particles. Whilst their DC conductance can often be good enough for useful circuits the RF performance may be degraded by the impact of the frequency dependent impedances of the weak links. In this paper we are beginning the evaluation and modelling of such materials with a view to exploring resulting design constraints and their ultimate performance for the successful production of RF systems like antennas, resonators and filters up to the top of the Ku band using FFF methods.**

I. Introduction

Fused Filament Fabrication (FFF) is a method of 3D fabrications utilising extrusion of thermoplastic materials thorugh a heated nozzle.Until recently it was only applied to the production of mechanical components and solid models but is now being used for electronics [1]. This has largely been facilitated by the development of new filaments which offer more than merely structural properties [2] [3]. In particular the use of FFF for electronics is enabled by conductor loaded or conductive filament materials and inks that are compatible with the FFF method (extrusion through a heated nozzle). The majority of these materials are composites of highly conductive particles and a weakly conducting or insulating host. Generally it is the host material that melts to enable the extrusion and fusion with the solid higher melting point particles carried along with the melt. A conductive solid results as long as the particles are in adequate contact to provide a DC current path across the entire structure being fabricated as shown in figure 1. Such structures are usually described by percolation theory which has been extensively used to study random networks of resistances and impedances [4].

The connections between conducting particles are the key limitation and source of most of the problems for this type of conductor. Current crowding occurs at these bottlenecks (figure 1b) and their dimensions are critical to the overall performance, even for DC. When considering the high frequency AC conductance of the material then the impact of skin effect on the weak links variable cross section may become significant. Consider for example a matrix made from a highly conducting material, consisting of isolated blocks linked by thin wires as shown in figure 1c. Whilst the whole matrix may be many times larger than the skin depth for conduction in the material the thin wires are each similar in size to the skin depth. For each of them the skin effect will tend to pinch off conduction resulting in a rapid rise of their resistance at the frequency when the skin depth starts to approach their radius. In addition the skin effect also imposes a phase shift on the current as a function of depth into a conductor which results in a complex ac impedance.

The aim of this paper is to explore the potential impact this frequency dependent impedance has on FFF fabricated RF devices like antennas, resonators and ultimately, metamaterials.

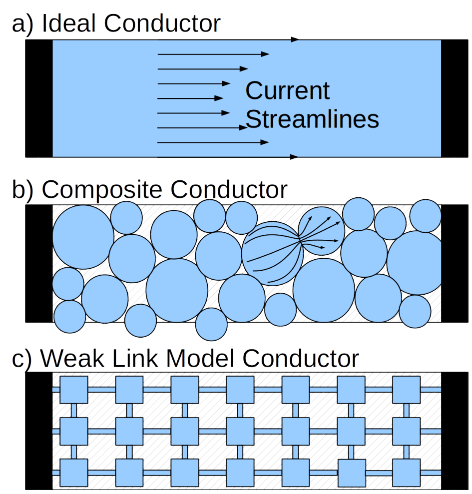

Fig. 1. Comparison of current paths in a continuous solid conductor (a) whose thickness is greater than the skin depth, a composite formed from conducting particles (b) and the weak link model os a random impedance matrix (c).

II. Modelling a weak link

We first consider the RF model for a weak conducting link, like those of the third part of figure 1, between particles in the composite conductor. We suppose that this weak link is a cylindrical wire linking two much larger conductive particles so that the properties of the wire dominate the composite behaviour. In general for a solid cylindrical conductor, the impedance resulting from skin effects is given by [5]

$$Z = \frac{(1-j)}{2\pi a\delta}\frac{J_0([1-j]/\delta)}{J_1([1-j]/\delta)} \quad (1)$$

where Z is the impedance per unit length, a is the radius of the cylinder, δ is the skin depth with $J_0 \& J_1$ being Bessel functions of the first kind. To visualise the impact of the skin effect on our weak link figure 2 plots the result of (1). Z is in general complex except when skin depth is infinite. Skin depth varies as the inverse root of frequency so tends to infinity as frequency tends to zero. Figure 2 shows the normalised value of $2\pi a^2 Z$ versus the ratio of radius to skin depth. As skin depth decreases from its infinite DC value with increasing frequency, the weak links' resistance increases with the reduction of its effective cross section. At the same time the imaginary component representing an inductive character increases. Hence the weak links will tend to reduce the overall conductance and generate a net phase shift between current and voltage.

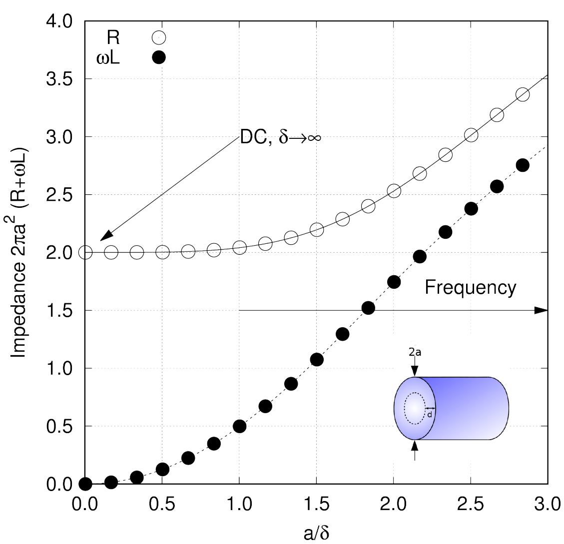

Fig. 2. Impedance components $Z = R + j\omega$ of a cylindrical conductor as a function of the ratio radius to skin depth. R is resistance and L is inductnace. DC behaviour is produced for $a/\delta = 0$ and increasing frequency results in a rising value for the imaginary component which is inductive in character

Figure 2 clearly shows that when the skin depth becomes smaller than the radius ($R/\delta > 1$) then the loss and phase of the weak link currents will begin to change rapidly.

RF devices formed including weak links like this can thus be expected to exhibit an anomalously poor high frequency performance as compared to that expected based on their DC resistance. The work to be reported in the full paper includes a random network model investigation of the probable impedance behaviour of the composite conductor using the regular model of figure 1c.

III. Measurements

To help develop the use of composite conductive materials for high frequency applications we have undertaken a measurement campaign to compare the frequency dependent conductance of several promising conductive filaments and inks. Using stripline methods as shown in figure 3 we have measured "Electrifi" filaments (copper nano-particle loaded polyester), Silver nanoparticle inks (Voxel 8) and Copper-Latex paint. Measurements have been made up to 18GHz. the full paper will report the details of these measurements and the results. In brief the conductors are printed onto a substrate carrying a standard $35\mu m$ thick copper ground plane and connected using SMA strip launchers. A Vector Network Analyser is used to measure scattering parameters of the line over a wide bandwidth and the conductor performance derived from them.

Initial results show that all three materials have RF performance consistent with their DC conductivity up to 1.7GHz. Further refinement of the methods to explore the higher frequency regime is ongoing at the time of writing this abstract. Our full paper will report these results in full along with performance of some metamaterial waveguide structures fabricated using them.

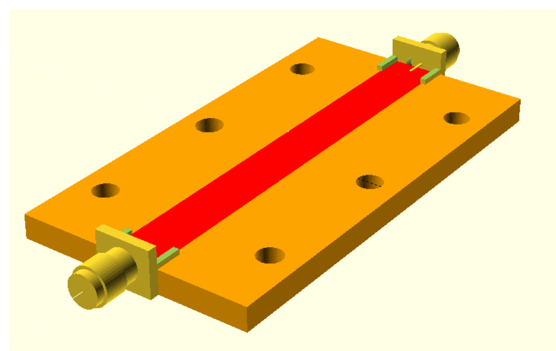

Fig. 3. Stripline design with printed composite conductor as the primary waveguide.

Acknowledgement

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