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New Manufacturing Techniques for Antennas

Michael Nash

A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2009

Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this _____ day of _____ 20___

_____

Michael Nash

Abstract

This paper is a discussion of new manufacturing techniques for antennas. Many existing manufacturing methods, including conductive ink printing, plastic plating, hot foil printing, etching, sintering and die cutting, are investigated to determine their usefulness in the manufacture of antennas. The advantages and disadvantages of each are discussed, and the most promising method—plating on plastic—is further analysed. The method of adapting the plating technique so that it can be used for antennas is discussed. Two prototype antennas (a PIFA and omni antenna) were manufactured to test the plating method's effectiveness as a manufacturing technique for antennas. Results showed a frequency shifted VSWR pattern for the PIFA antenna of 10% on each notch. The gain plot for the omni antenna showed a higher gain for the plated antenna at a frequency shifted by approximately 0.4 GHz. A cost analysis was also performed to complete the investigation of the new manufacturing method. A saving of up to 4 000% can be realised on the substrate material, and the metal costs can be lowered by 700% for each PIFA antenna.

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Preface

This dissertation is presented to the University of the Witwatersrand, Johannesburg, for the degree of Master of Science in Engineering.

The dissertation is entitled *New Manufacturing Techniques for Antennas*.

This document complies with the university's *paper model format*. The paper contains the main results of the research. The appendices present in detail the work conducted during the research.

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Part 1

Paper: New Manufacturing Techniques for Antennas

New Manufacturing Techniques for Antennas

Michael Nash

***Abstract*—This paper is a discussion of new manufacturing techniques for antennas. Many existing manufacturing methods, including conductive ink printing, plastic plating, hot foil printing, etching, sintering and die cutting, are investigated to determine their usefulness in the manufacture of antennas. The advantages and disadvantages of each are discussed, and the most promising method—plating on plastic—is further analysed. The method of adapting the plating technique so that it can be used for antennas is discussed. Two prototype antennas (a PIFA and omni antenna) were manufactured to test the plating method's effectiveness as a manufacturing technique for antennas. Results showed a frequency shifted VSWR pattern for the PIFA antenna of 10% on each notch. The gain plot for the omni antenna showed a higher gain for the plated antenna at a frequency shifted by approximately 0.4 GHz. A cost analysis was also performed to complete the investigation of the new manufacturing method. A saving of up to 4 000% can be realised on the substrate material, and the metal costs can be lowered by 700% for each PIFA antenna.**

***Index Terms*—Antennas, Manufacturing Techniques, Plastic Plating**

I. Introduction

In all forms of industry there are obvious advantages to having cutting-edge and leading methods for producing superior merchandise. There are many ways to accomplish this, for example by using new designs, superior materials, and more efficient production methods. This paper discusses the current techniques for manufacturing antennas, why they are not optimal, and discusses how other manufacturing techniques could be applied to antenna manufacturing. These manufacturing methods are already in use in other areas of production, but could possibly be modified in order to be used in efficiently and cheaply manufacturing antennas. The advantages and disadvantages of each method are discussed, and one of the methods—plastic plating on polystyrene—is concluded to be the most promising technique. This technique is then used to manufacture a few prototype antennas, which are tested to see whether the method is viable. The cost and ease of manufacturing of the new method is also examined and compared to the existing methods of manufacturing to determine the usefulness of the technique in a competitive manufacturing environment.

II. Background Information

The current methods of planar antenna manufacture, which include PCB (Printed Circuit Board) manufacturing, are predominantly subtractive processes and are standard, well-known processes. Subtractive manufacturing methods are acceptable in the circuit industry as there are many tracks and few open spaces. Antenna manufacturing is different in that there are often very few feed tracks and large areas of copper need to be etched away. This means that a subtractive process in antenna manufacturing is a very wasteful process, and an additive process where no material is wasted is preferred. In order to gain an edge in manufacturing antennas, it is useful to review some manufacturing techniques which are not specific to antenna manufacturing, but that could be modified to suit that purpose. The new process would ideally be an additive process, as well as have the potential to be cheaper, easier and more reliable than current methods of producing antennas.

III. Discussion of Researched Technologies

The following section gives very brief descriptions of some manufacturing techniques that were researched with the possibility of modifying them and applying them in the manufacturing of antennas. For a considerably more detailed description of each of these technologies, refer to [1].

A. Etching

Etching is included in the research of technologies to provide definitive proof that it is a technology that needs to be replaced. The advantages and disadvantages of etching techniques will be discussed as with the other technologies.

Etching is used as a stage in the manufacture of PCBs to remove unwanted copper. PCB manufacturing is a well known, reliable and understood process—this is both an advantage and a disadvantage. It is beneficial in that it is easy to set up a manufacturing process and there are many people/companies that could assist with all the manufacturing requirements. The downside is that using this technology in manufacturing antennas will not necessarily provide an edge in the market. The substrates used in PCB manufacturing are also not ideal for high frequency applications. FR4 (Fire Resist 4, a fibreglass epoxy-resin), which is the usual substrate, is lossy. With a loss tangent of 0.025 it is only really useful up to about 1–2 GHz [2], while Rogers board—a substrate made for antenna applications, with a dissipation factor of around 0.002—is very expensive (approximately R 1/cm^2 for processed Rogers board [3]).

For these reasons it is beneficial to seek a new method for manufacturing antennas which will be less wasteful, cheaper and will provide better electrical characteristics than is currently available. Using another technology is also advantageous in giving a technological and marketable edge for a company that implements a new manufacturing technique.

B. Conductive Ink Printing

Conductive ink printing is a relatively new technology which was first considered as an elegant approach to printing electric circuits in the beginning of the digital printing era in the 1980s [4]. Since its inception many companies have used the technology to produce flexible circuits, RFID (Radio Frequency Identification) tags, and more recently OLED's (Organic Light Emitting Diodes) [4], [5]. A conductive ink consists of metal particles, such as copper or silver, in a retaining matrix. The retaining matrix is non-conductive, and needs to be reduced after printing (usually by curing) to increase the conductivity [6].

By using inkjet printers, there is the significant advantage that any shape of antenna can be printed without tooling (which is not the case in most other types of printing—including screens, offset, and gravure) [4]. This means that any changes to an antenna design can be made quickly and easily, and it also makes prototyping an easy task.

The major problems with using inkjet printing as a viable method of manufacturing antennas at the moment are threefold. Firstly, commercially available inks are expensive: at time of research a typical conductive ink from Epoxies Inc. cost R 15.10 per gram [7]. With a theoretical coverage of 720 sq.ft/gal/mil (7.10 m^2/kg) [8] a few simple calculations indicate that it will cost R 2 127 to cover 1 m^2. The coverage could be increased by decreasing the thickness of the ink, but this would lead to worse electrical conductivity and an inferior antenna. With the cost of processed FR4 at approximately 10 c/cm^2, the cost of the conductive ink (approx. 21 c/cm^2) is just too expensive at present. Other inks, including Carbon Nanotubes (CNT's) and other environmentally friendly inks, have been researched but have been found also to be expensive and do not offer satisfactory electrical characteristics. More detailed information on these inks can be found in [1].

The second problem with inkjet printing is resolution. In order to get a sufficiently conductive pattern, the antenna may have to be printed more than once. This may lead to small errors in the boundaries of the antenna if the substrate is not fed identically each time.

The third problem is that a typical conductive ink is difficult to solder, this makes attaching a feed difficult, although not impossible. The feed could be coupled capacitively, but this adds unnecessary complexity.

Conductive ink printing, therefore, is a technology to keep an eye on. When prices decrease it will almost certainly be a viable antenna manufacturing process. For now though, it will remain a useful method of manufacturing flexible RFID circuits, switches, displays and membranes [4], [8].

C. Plastic Plating

The process for plating on plastics is a well known and established process. The are a number of plastics which have better electrical characteristics than FR4, and a method whereby a sheet of plastic is plated with copper in the shape of an antenna could be a suitable manufacturing technique.

The most common plastic for plating is ABS (Acrylonitrile-Butadiene-Styrene); this is due to the fact that ABS contains butadiene molecules that are easily chemically etched away [9]. This chemical etching leaves small holes on the surface of the plastic which enables the electroless metal (metal that is deposited without using electrical current) to adhere to the plastic. ABS is typically electroplated to give plastic parts the more decorative finish of metals such as chrome, gold, silver and brass [10].

Plating on plastics follows a generic set of procedures. These procedures allow the surface of the plastic to become receptive to the initial electroless metal plating, which will further allow the plastic to be electro-plated. The following steps are necessary in plating plastic [11]:

- **Clean:** Removes any foreign particles which may hinder plating.
- **Etch:** Produces small holes in the surface to enable the metal to adhere.
- **Neutralise:** Neutralises the corrosive etch which would otherwise negatively affect the chemicals used in the subsequent steps.
- **Catalyst:** Enables the electroless metal to form on the surface of the plastic, usually a tin-palladium mixture.
- **Electroless Plate:** Deposits a thin layer of metal on the surface of the plastic.
- **Electroplate:** The layer of metal can be thickened by normal electroplating methods.

The advantages of using this manufacturing method include the fact that it can be an additive process—the metal can be 'grown' on the substrate in the required shape of the antenna, minimising waste. The process can be predominately automated, requiring labour only in the handling of the beginning and end products, which decreases the costs involved. Disadvantages include the fact that a process would have to be found to try and plate on plastics with better electrical characteristics, like polystyrene. Polystyrene has a loss tangent (dissipation factor) of only 0.05–0.4 ($\times 10^{-3}$) at a frequency of 1 MHz whereas ABS has a loss tangent of 2–15 ($\times 10^{-3}$); two orders of magnitude worse [12]. There could also be difficulty in trying to mask the required antenna shape.

D. Hot Foil Printing

Hot foil printing is a dry printing method used to transfer a shiny/metallic image onto the surface to be printed by a combination of heat and pressure [13]. Instead of using magnetism, plates, or inks to print words and shapes, foil stamping uses dies or sculpted metal stamps. The heated dies seal a thin layer of metallic leaf onto a surface and the leaf then adheres only in the intended places, where it has been heated [14].

This method of manufacturing could, in theory, mass produce thousands of antennas in a small amount of time. It is a completely dry process and therefore the finished products could be handled soon after production. It is also a fully automated process requiring very little user input. Machines used in the printing process are also fairly cheap, with a hot foil printing company, Kobo, selling hot foil printers ranging from approximately R 8 000 for a simple hand operated machine to R 60 000 for a large, fully automated machine [15].

Unfortunately there are some obstacles that would need to be overcome if this technology is to be adopted for the manufacturing of antennas, one of these is the foil. Commercially available foils are non-conductive, this means that a new foil would need to be developed that is both conductive, and has the required shear strength (the shear strength of the foil is important for the metal stamp to cleanly cut and separate the design from the excess material). Due to the required shear strength, conventional foils are also very thin. This will make soldering difficult and will adversely affect the conductivity of the foil [13].

These obstacles may prove insurmountable in the quest to use hot foil printing to manufacture antennas, but the only way to know conclusively is to attempt to manufacture a suitable foil and test the resulting antenna's effectiveness.

E. Sintering

The ISO definition of sintering is as follows [16]:

> The thermal treatment of a powder or compact at a temperature below the melting point of the main constituent, for the purpose of increasing its strength by bonding together of the particles.

Sintering is usually used in the manufacturing of metal parts. The metal particles are placed in a mould and then sintered until they form a strongly bonded part. In terms of antenna manufacturing, sintering would probably be most useful in improving the characteristics of antennas produced by other means, i.e. conductive ink printing or plastic plating. Since sintering forms bonds between the metal particles it would be a very useful process to apply to a printed circuit. The metal particles in a printed circuit are usually not properly bonded, and the improved bonding would both increase the strength of the antenna, as well as increase the conductivity between the particles.

F. Solder Paste

Solder paste is an alloy or pure metal which, when heated, liquefies and melts to flow onto the space between two close fitting parts, creating a soldered joint. Solder paste has suitable melting and flow properties to permit distribution by capillary attraction in properly prepared joints [17]. In order to make a suitable antenna, the solder paste will need to melt and form into a specific shape. This provides a challenge in choosing a suitable substrate and in getting the solder paste to form the correct pattern.

The first thing required of the substrate is that it must be able to withstand the temperatures necessary to melt the solder paste (about 230 °C) [18]. The melting point of polystyrene is about 190–260 °C [19]. Heating the entire board to the required temperature will thus result in the melting of the substrate. Either a substrate with a higher melting point must be found, or alternatively a heating method could be used which specifically targets the solder paste and not the substrate (e.g. laser heating). This, however, will add extra complexity and cost to the manufacturing process.

A simple test using solder paste was performed, and it was found that the paste tended to coagulate in the mould when heated rather than fill the entire space. The polystyrene also warped slightly at the high temperatures. To use this as a suitable manufacturing method would require too much altering of the method, and is thus not considered any further.

G. Die Cutting

Die cutting services use a variety of die cutting methods to fashion materials into predefined shapes or sizes. Several different types of die cutting are available, including flat and rotary laser die cutting, blade type rotary die cutting, steel rule die cutting, and ultrasonic die cutting. The method used can vary, depending on such factors as material and end product configuration [20].

Die cutting is an attractive manufacturing method as it can be used to produce many antennas of the same size and shape in a short space of time.

Die cutting, however, does not adequately address the problems that are present in current manufacturing techniques; namely, there will be a waste of material, as the antennas will need to be cut from a large sheet of metal. There are ways to minimise and reuse this waste, but no waste is preferable [21]. Other problems with this method of production include the fact that the antenna will have to be transferred to the substrate after cutting. This introduces a large amount of labour which increases the cost, and decreases the repeatability and efficiency of the process. The final problem is that creating dies is meticulous work, as they must be designed so that an absolute minimum of waste is produced [21], something that may not be easy with complex antenna designs.

IV. Description of Chosen Method

The technology that showed the most promise in being used as a new manufacturing technique for antennas is the masked plating method, described in section III-C. This method, however, needs to be modified in order to be useful for the manufacturing of antennas. This is because the material properties of ABS make it less suitable for antenna applications. A far superior substrate to use is condensed polystyrene. Polystyrene is preferable in that it has a low dielectric coefficient and it has low losses at high frequencies with a dissipation factor of 0.00005–0.0004, [22] at about 1 MHz. This is compared to ABS which has a dissipation factor of 0.005-0.019 [23]—many orders of magnitude higher than polystyrene. The low dissipation factor minimises losses of electrical energy to heat [24]. Polystyrene is also cheap; it costs less than 1 c/cm^2 for extruded 1 mm polystyrene. The one problem with polystyrene is that there is no commercially available method for plating it, and therefore some tests and experiments needed to be performed in order to find a suitable process.

V. Making the Prototypes

The main problem with using polystyrene as the substrate is that there is no easy method of etching it, like there is for ABS. It was therefore necessary to perform many experiments to determine the best method of making the surface of the polystyrene suitable for plating. To accomplish this a simple plant was set up with chemicals which were generic for plating on plastic, excluding the etching chemicals. The etching chemicals that were experimented with were suggested by consulted plating experts, as well as by trial and error. A complete description of these chemicals and the results that they produced can be found in [1].

Figure 1 shows the small plant that was set up in order to test the plating and etching methods. It consists of a few ten litre tanks each with separate temperature controllers, containing the chemicals needed to electrolessly plate copper onto plastic. The sample was then moved sequentially through each tank for the required amount of time, and the plated sample is tested to see whether the process is working (for detailed tests on the metal deposits see [25]).



Fig. 1. A view of the small testing plant.

The roughening (etching) procedure, which is important to the success or failure of the metallisation process, has two fundamental purposes:

1) To roughen the surface microscopically to remove glaze from the plastic article, and
2) To remove the ‘flash’ or feather-edge from the moulded piece [26].

The best etching method for polystyrene was found to be a combination of mechanical etching (using an abrasive cloth) and a solution of sulphuric acid and hydrogen peroxide, which removes any organic residues from the surface of the polystyrene.

The second important step in plating polystyrene (after etching) to make an antenna is the masking stage. The copper needs to be formed in the shape of the antenna; if it can be plated already in the correct shape it means that there will be no wasting of copper or extra work involved. It was found through experiments that a barrier layer applied to the surface of the polystyrene directly after the catalyst stage of

plating prevents the copper from forming on the polystyrene where the barrier has been applied. Initial tests used a variety of masks, including permanent marker, spray paint, and vinyl stickers. All of them worked in preventing copper growth where they were applied, but the deciding factor on which method to use is dependent on which method is easier and more cost effective to apply in bulk. For the prototypes, the designs were drawn on in permanent marker. This is the easiest method for small scale testing but a commercial printing process would probably be the best method to use for manufacturing.

VI. Testing the Prototypes

There are a number of physical tests that need to be performed on the plated plastic to check whether the deposits are bonded strongly enough to ensure the long time survival of the antenna. Narcus, in his book *Metallizing of Plastics* [26], provides a number of simple qualitative and quantitative tests which can be performed on plated parts in order to test the strength of the bond. These tests include:

- **Bend Tests:** Probably the most simple of the qualitative tests. If the material can be bent over a radius of the same order of magnitude as its thickness without cracking or fracturing the metallic surface, then the adhesion should be considered acceptable. A further test is to bend the material backwards and forwards a number of times to see if the coating separates from the base material.
- **Scratch Tests:** A method of determining adhesion which is described by Halls [27], employs a scratching tool of certain dimensions. The scratching tool is drawn vertically to the surface with firm hand pressure so that it just cuts through the metallised coating. If adhesion is suitable, a clean-cut line with the absence of jagged edges will be evident. Furthermore, if two such cuts are made which cross each other at an acute angle, there should be no flaking of the coating from the included angle.
- **Buffing Test:** A final qualitative test is to polish or buff the surface. Adhesion can be confirmed visually if the deposit does not separate from the base plastic after polishing without too much pressure.
- **Quantitative tests:** If the qualitative tests described above do not give either useful or accurate enough results, there are methods of quantitatively comparing the adhesion strength of the metal plating. Burgess [28] provides a method of quantitatively testing the adhesion strength of deposits by attaching a device to both sides of the plastic and then measuring the amount of force necessary to remove the deposit from the plastic.

Only once the metal deposits have passed all of the above tests can the plating process be described as a success. In this case, it took many attempts (see reference [25] for full details of the experiments), but eventually an adequate etching/plating solution was found. There are, however, other qualities that are required of the metallic deposits, specifically for antenna manufacturing.

Thickness Tests:

The thickness of the plating is very important for antenna applications for two main reasons. The first reason is because, at high frequencies, the electric current does not penetrate deeply into a conductor. The depth that it penetrates is dependent on the skin depth. Skin depth is a measure of how far electrical conduction takes place in a conductor, and is a function of frequency [29]. Skin depth can be measured using:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{1}$$

Where:

ω :	Frequency of interest in radians/sec
σ :	Conductivity of the material in Siemens/m
μ :	Permeability of the material in H/m

This shows that the higher the frequency, the thinner the antenna needs to be. A useful characteristic of plating on plastic is that the thickness of the deposit is directly related to the amount of time that the part is subjected to the plating process. In electroplating, the copper grows at a rate of about 1 μ/min [30]. Using equation 1, copper, at a frequency of 900 MHz has a skin depth of 2.2 μm. A useful rule of thumb states that for maximum efficiency the conductor should be about five times the skin depth [29], this equates to a plating time of about 10 minutes. This time decreases for any frequencies higher than 900 MHz.

The second factor dependent on the thickness of the antenna is the ease of soldering. If the metal layer is too thin, then a soldering iron will melt and strip away the metal layer. The thicker the layer, the easier it is to solder. There are ways to avoid soldering antennas, for example the antenna could be designed to be capacitively fed, but it is a good idea to be able to solder the antenna if necessary.

In order to get the required thickness on a plated part it is necessary to electroplate the electrolessly deposited metal. This has the added advantage of protecting the finish of the part. Unplated samples which were left for a few days oxidised very quickly and the finish became green/grey instead of a copper colour. This is important in antenna manufacturing, as the finish must stay in good condition long after the product has been made, in case the antenna enclosure needs to be opened.

VII. Results

Once the plating process had been refined and adequately tested, prototypes of two different antennas were produced to test the effectiveness of the new manufacturing method. The two antennas were chosen to represent two very different antenna types, with different substrates and uses. These two antennas are currently manufactured using different methods and therefore they give a broad test of the method's potential.

A. PIFA

The first antenna to be tested is a dual-band Planar Inverted F Antenna (PIFA). The PIFA typically consists of a rectangular planar element located above a ground plane, a short circuiting plate or pin, and a feeding mechanism for the planar element. The Inverted F antenna is a variant of the monopole where the top section has been folded down so as to be parallel with the ground plane. This is done to reduce the height of the antenna, while maintaining a resonant trace length [31]. In addition to cellular applications, PIFAs have become attractive candidates in a variety of commercial applications such as Bluetooth and mobile satellite communications [32].

Figure 2 shows the plated PIFA antenna. As discussed above, the pattern for the prototype antenna was drawn on the substrate using permanent marker.

The substrate used for the PIFA antenna is injection moulded polystyrene. The plated metal adheres very well to the substrate, and the finish is bright and shiny. The advantage of the moulded item is that it is possible to achieve any shape required for an antenna design and the moulding process is cheaper than extruded polystyrene. Injection moulding has little or no waste of material.

The connector was successfully soldered on to the antenna with minimal effort, showing that the plating is thick and sturdy enough for soldering.

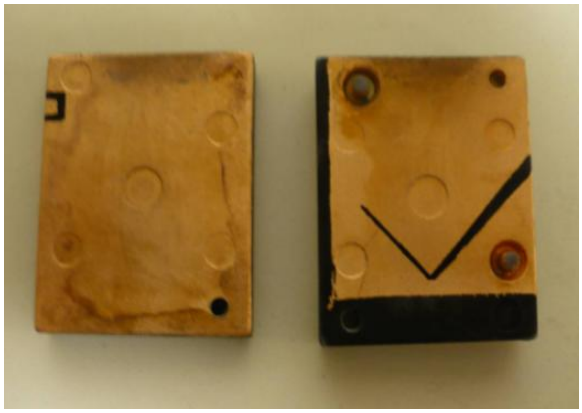


Fig. 2. Front and back view of the plated PIFA antenna.

Figure 3 shows the plot of the VSWR (Voltage Wave Standing Ratio) vs. frequency for the plated PIFA antenna and the original PIFA antenna. The original PIFA antenna was designed to be a dual-band cellular planar inverted F antenna. Normally it would be mounted inside an enclosure where the resonant frequencies would shift to the required cellular band. The original PIFA has two characteristic resonant frequencies. These show up as two deep notches in the VSWR plot at about 1 010 MHz and 1 950 MHz. The plated PIFA also shows these two characteristic resonant frequencies, except at 910 MHz and 1 750 MHz. The percentage error between the lower frequency notches is 9.9%, and 10.2% between the higher frequency notches. This means that the plated PIFA antenna is simply frequency shifted, a simple process to alter in antenna design. The main property of the antenna, i.e. the notches, are actually more defined than for the metal stamped antenna and thus the plated antenna will probably perform better than the original. The cause of a frequency shift is usually due to incorrect lengths of the antenna tracks. Since the plated antenna is plated directly on to the substrate and the metal stamped antenna attaches above the substrate, this could account for the slight frequency shift. These factors indicate that it will work well as a PIFA antenna, even though this protype is out of band. An antenna specifially designed with the plating process in mind can then be made to operate at the correct frequency.

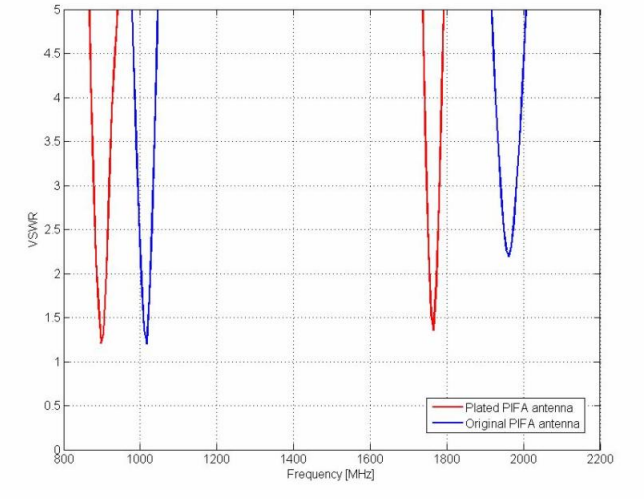


Fig. 3. Graph of VSWR vs. frequency for the two PIFA antennas.

B. Omni Antenna

The second antenna that was tested is an azimuthal omnidirectional antenna.

Omnidirectional antennas are generally realised using collinear dipole arrays. These arrays consist of half-wavelength dipoles with a phase shifting method between each element that ensures the current in each dipole is in phase [33].

The reasons for the choice of this omni antenna for the second prototype are as follows:

- The tracks for the antenna are relatively thin—this will give a good idea of the strength and stability of the plating on longer/thinner tracks. It will also serve to give an idea of the resolution that can be achieved with the plating.
- The substrate used for the omni antenna is extruded polystyrene, which is thinner and more flexible than the substrate used for the PIFA antenna. This gives an idea of the strength of the plating on a less rigid substrate.
- The original omni antenna is produced using ordinary PCB etching methods using Rogers board, so it serves as a direct comparison to a different, existing, manufacturing method.

Figure 4 shows the plated omni antenna. The antenna proved to be difficult to solder, as the plating tended to lift away from the substrate if the connector was pulled too hard. To combat this a bit of putty was used to stop the connector from pulling away from the antenna. It must be noted that the underside of the omni antenna has a similar pattern of dipoles to what can be seen in the figure, which makes it an omnidirectional antenna.

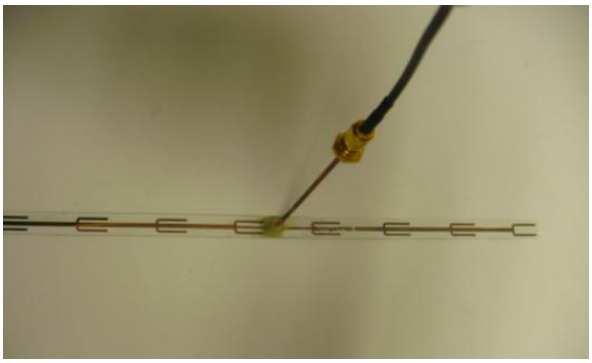


Fig. 4. The copper plated omni antenna.

The S21 plot in *Figure 5* shows a comparison between the FR4 based antenna and the polystyrene based antenna. The two antennas were made directly from the simulated data and were not physically optimised. It can be seen that the FR4 antenna operates over a much larger band, but with a lower gain. This can be attributed to the lossy FR4 material and the smaller aperture of the FR4 antenna. The polystyrene antenna has a much larger aperture with the same number of antenna elements. The lower dielectric constant allows a better element distribution due to the lower velocity factor of the material. This allows the transmission lines between the elements to be longer on the polystyrene substrate so to achieve the correct phasing and thus a much larger, increased aperture, antenna.

C. Cost Analysis

It has been shown in sections VII-A and VII-B that the new plating method for producing antennas is viable in terms of the resulting electrical characteristics of the antennas, but there is still one final

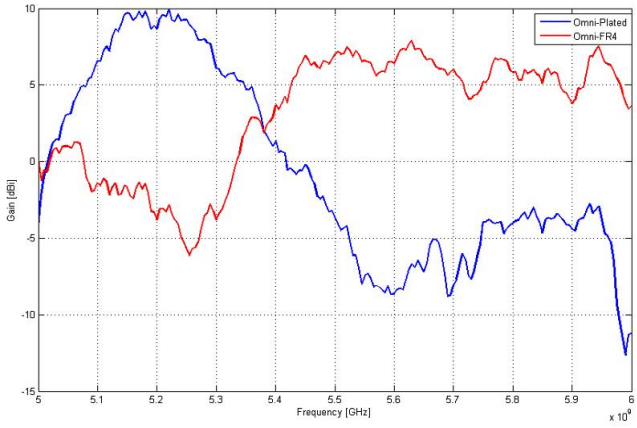


Fig. 5. Graph of gain vs. frequency for the two omni antennas.

aspect to examine before it can be seen whether the manufacturing method is truly viable. That is the cost of production.

For the PIFA antenna, a simple cost comparison is the cost of the stamped metal plate compared to the cost of the chemicals needed to plate the antenna. The detailed costs of the chemicals can be seen in [34]. The cost of the stamped metal is R 0.70; the cost of metal for plating is R 0.10. The substrate is the same in both cases, but the plating method will probably require less labour. Added to the saving in metal, it is significantly cheaper.

The omni antenna gives even better savings, due to the massive savings on the substrate. Processed Rogers board costs around R 0.40/cm^2, whereas polystyrene costs less than R 0.01/cm^2.

These prototypes show that using the new plating technology will realise a significant reduction in costs of materials. One thing that needs to be factored in to the cost is the set up of a manufacturing plant. Chemserve, a chemical plating company [35], has quoted a price of R 1.8 million for the complete set-up of an automated plating plant. To factor in this cost, one would have to know the volume of antennas that are expected to be produced, as this will determine if the cost is an acceptable one. It must be noted, however, that the test plant that was set up to manufacture the prototypes was relatively inexpensive (around R 1 000). Obviously this would not be sufficient for manufacturing, but a plant that is set up with less complex equipment will be significantly cheaper.

VIII. Conclusion

This paper has presented a number of different manufacturing techniques which could be applied to antenna manufacturing. The many manufacturing techniques all have advantages and disadvantages in terms of their use in the manufacturing of antennas. The most decisive factors in choosing an appropriate technique are cost, ease of use and time required to make the antenna. The most suitable technique (for the purpose of replacing PCB type antennas) was decided to be plastic plating on polystyrene. This process, however, had to be modified and adapted to properly fit the manufacturing of antennas. An experimental plant was set up so that prototypes could be produced in order to test whether the new method is indeed suitable. Two prototype antennas were produced and tested to see whether they perform adequately as antennas. The manufactured antennas performed well in the tests—although they were frequency shifted—indicating that the process is suitable to the manufacturing of antennas from an electrical characteristic view. The technique was also critiqued with cost and ease of manufacturing in mind. In these two areas it is also likely to be a good candidate as a new manufacturing technique for producing antennas—savings of up to 4 000% can be realised on the substrate of a normal antenna, along with 700% savings in metal costs. The objectives of the experiment were met conclusively with the success of the plating of metal on polystyrene, with the subsequent tests confirming the usefulness of the new method.

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Part 2

Appendices

Appendix A

Research into Available Technologies

Abstract This appendix gives a detailed discussion of manufacturing techniques that were researched for their potential use in antenna production. The methods that are discussed include: conductive ink printing, sintering, hot foil printing, plastic plating, etching, die cutting, and solder paste. A detailed description of each is given, along with cost analysis and advantages and disadvantages for each method. After examining all the technologies, plastic plating is decided to be the most promising method.

A.1 Introduction

This document provides detailed descriptions of all manufacturing methods that were researched to determine which is most suited for use in antenna manufacturing. Each manufacturing method is described in detail, examples are given on where the technique is currently used, advantages and disadvantages of each method are discussed and finally (if applicable) the potential cost of each method is discussed.

This is a supporting document for the main paper. It therefore provides more details on each of the methods described briefly in the main paper, and is useful in determining exactly which method is the most suitable for antenna manufacturing.

An important advantage for any new technology is that it should be an additive process. This means that the metal used should be just the right amount needed, as opposed to a subtractive process like PCB (printed circuit board) etching, where a sheet of copper is masked and the unwanted copper is removed. Subtractive processes obviously are more wasteful than additive processes. This is not much of a problem in PCB manufacture, however, where there are many tracks, and the unwanted copper is minimal. In antenna manufacture there are often large areas of open space, with tracks far apart. This means that there will be more wasted material—this increases the cost, and is inefficient.

A.2 Technologies

The following section describes in detail the various technologies that were researched in order to arrive at a suitable and effective method of manufacturing antennas.

A.2.1 Conductive Ink Printing

Conductive inks are typically made of metallic particles (often silver or copper) or carbon particles in a retaining matrix [1]. The retaining matrix is generally non-conductive, and must therefore be removed after the ink has been printed so that the particles make contact, which is done by curing. Traditionally, the matrix used was a ceramic such as glass frit (a finely ground, porous glass substance). Increasingly, use is made of a polymer (known as Polymer Thick Film or PTF) [1]. The curing process limits the choice of substrate as, for example, the ceramic based retainer needs to withstand temperatures of up to 650 $^{\circ}$C for a number of minutes—this requires expensive substrates. PTF, on the other hand, has a lower cure temperature requirement of about 150 $^{\circ}$C. Therefore less robust and cheaper substrates, like PTF, can be used.

However, there are alternatives to high temperature curing. The Office of Technology Management at the University of Illinois has developed a process which uses graphite ink with anisotropic properties to enhance conductivity. Upper limit conductivity is achieved after four to sixteen hours of curing at room temperature. Typically, an increase in conductivity during ink curing is attained due to the aggregation of conductive particles above a percolation threshold. However, this technology's operating mechanism allows for the orientation of graphite planes, which gives the ink specific conductivity [2]. The bulk conductivity of the printed inks depends greatly on the composition of the ink, but can be improved with a number of methods including microwave sintering [3] and compression methods [4]. The inks can be transferred to the substrates in a number of ways, which include inkjet printing, spraying and dip coating [5].

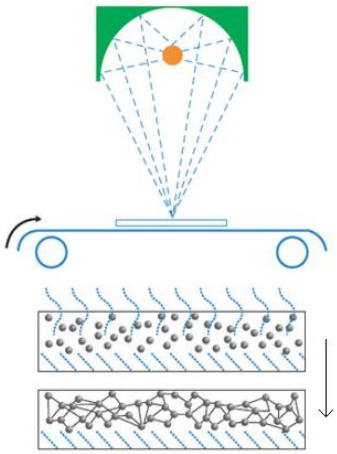


Figure A.1: Curing process for conductive inks [6].

Figure A.1 shows how curing increases the connectivity between the separate particles. This increases the conductivity as well as the strength of the printed circuit.

A.2.1.1 Current Uses and Advances in Conductive Inks

Apart from the variations which can exist in different ink compositions, there are a number of other factors which will affect the performance, cost and suitability for using conductive ink printing methods to manufacture antennas. The following section describes processes which are being used to improve the characteristics of conductive ink printing. The performance of an antenna manufactured with conductive ink will be dependent on four main factors: the ink used, the method of transferring the ink to the substrate, the substrate, and any process applied to the ink once it has been printed.

Ink: Using an off-the-shelf inkjet printer, a team of scientists from Rensselaer Polytechnic Institute has developed a simple technique for printing patterns of carbon nanotubes on paper and plastic surfaces [7]. Carbon nanotubes (CNTs) have many advantageous properties, such as excellent thermal conductivity, good mechanical strength, optional semiconducting/metallic nature, and advanced field-emission behaviour [8]. Recent advances in nanotube chemistry enable both the dissolution and dispersion of CNTs in various solvents [9]. *Figure A.2* shows how multi-walled carbon nanotubes (MWCNTs) can be functionalised so that they become dispersible in water.

This means that a solution of carbon nanotubes can be printed, using an ordinary inkjet printer, onto a substrate—forming an antenna. Reference [8] provides a method of dispersing these nanotubes in a solution which can be injected into the cartridge of an inkjet printer and an electrically conductive surface can be printed.

The chemistry department at the University of the Witwatersrand has the capability to produce carbon nanotubes. Sableo Mhlanga, a post graduate student in the chemistry department, has produced a batch of nanotubes for experimentation purposes. The method of production of the nanotubes is outlined below:

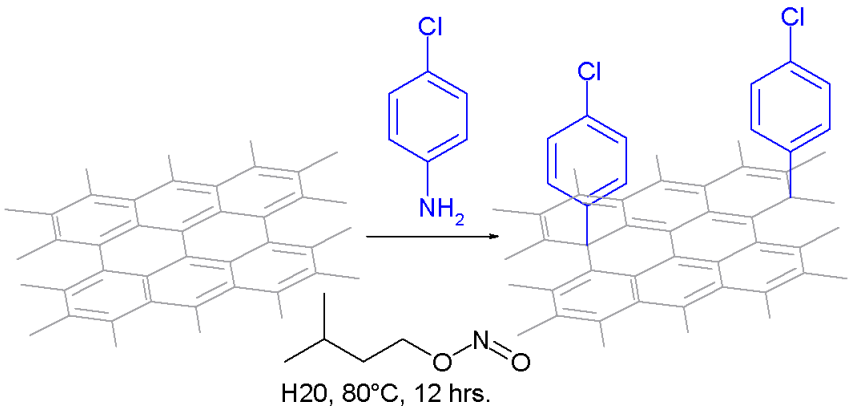


Figure A.2: Schematic of MWCNT functionalisation [8].

1) Preparation of catalysts:
   $Fe(NO_3)_3 \cdot 9\,H_2O$, $Co(NO_3)_2 \cdot 6\,H_2O$, $Fe(CH_3CO_2)_2$ and $Co(CH_3CO_2)_2$ from Sigma Aldrich were used to prepare the different catalysts. A calculated amount of the Fe and Co salts were mixed, ground to a fine powder and dissolved in distilled water to make a 0.3 M 50:50 Fe-Co precursor solution. This solution was added to the support and the mixture was left to age for 30 minutes under stirring. The mixture was filtered to form a homogeneous mixture of the metals on the support. The resulting slurry was allowed to semi-dry at room temperature, after which time it was dried in an air oven at 120 °C for 12 hours, cooled to room temperature, ground and finally screened through a 150 mm sieve. The fine powder (the catalyst) was then calcined at 400 °C for 16 hours.
2) Carbon Nanotube Synthesis:
   Carbon nanotubes (CNTs) were synthesised by the decomposition of acetylene (C_2H_2) (AFROX) in a tubular quartz reactor (51 cm x 1.9 cm internal diameter, see *Figure A.3*) that was placed horizontally in a furnace (see *Figure A.4*). The furnace was electronically controlled such that the heating rate, reaction temperature and gas flow rates could be accurately maintained as desired. The catalyst (0.2 g) was loaded into a quartz boat (120 mm x 15 mm) at room temperature and the boat was placed in the centre of the quartz tube. The furnace was then heated at 10 °C/min while N_2 was allowed to flow over the catalyst at 300 ml/min. No pre-reduction of the catalyst was necessary since the catalyst was reduced in-situ by the H_2 released from the decomposition of the feed stock gas (C_2H_2). Once the temperature had reached 700 °C, the N_2 flow rate was reduced to 240 ml/min and C_2H_2 was introduced at a constant flow rate of 90 ml/min. After 60 minutes of reaction time, the C_2H_2 flow was stopped and the furnace was left to cool down to room temperature under a continuous flow of N_2 (40 ml/min). The boat was then removed from the reactor and the product (carbon deposit) formed along with the catalyst was weighed. In the study, the activity of the catalysts was based on the measurement of the total amount of carbon deposit (% C) formed. The selectivity (% selectivity) was calculated based on the amount of CNTs formed with respect to the total % C produced. Generally, there was little formation of amorphous carbon deposit. The crude CNTs were purified by treatment with 30% HNO_3 (24 hour, room temperature) and then washed until the washings were neutral.

Other advances in ink technology include:

- Acheson is developing water-based inks which are environmentally friendly and inexpensive because they do not require expensive solvent recovery equipment during processing [10].
- Silver nanoparticle ink from Cabot, which can obtain a sheet resistivity of 0.1–0.5 Ω/square [6].
- Researchers at Leeds University have printed electrically conductive patterns using a desktop printer loaded with a silver salt solution and vitamin C [11]. Two separate chambers in the printer's cartridge, which normally contain different ink, were loaded with the metal solution and the reducing agent. Using silver nitrate solution as the 'metal ink' and ascorbic acid (vitamin C) as the reducing agent proved to be the most successful combination. The process is also environmentally friendly as the base is totally soluble. After a circuit is printed using silver nitrate, vitamin C is overlaid a few minutes later. Water can then be used to wash away other products, leaving the silver behind. Scanning electron microscope images reveal a rough surface of silver nanoparticles [11].



Figure A.3: Examples of the quartz reactors.



Figure A.4: Furnace used to produce carbon nanotubes.

Transferring the Ink: There are many different techniques used in the printing world: inkjet, screens, offset, gravure, and others. All of them, except for inkjet, require tooling to create the printed image. While there are advantages and disadvantages to each technique, the ability to digitally create an image without tooling is the main advantage of inkjet printing [12]. High-speed printing techniques, such as lithography, are more economical than screen-printing for high-volume printing applications. High-speed printing techniques can be used at up to 600 metres per minute on wide web platforms. A 20-micron resolution is achievable with many high-speed printing techniques. Lithographic printing is able to produce an antenna that is approximately 3 μm in thickness. This reduces drying time with negligible impact on the performance of the antenna as compared to traditional metal antennas [13].

The Choice of Substrate: Just as the substrate on which ink is printed affects the appearance, the substrate on which conductive ink is printed impacts the achievable conductivity. Smooth surfaces such as glass and polyethylene terephthalate (PET) enable the greatest possible conductivity. Rough surfaces, such as that of newspapers and untreated cardboard, will provide a significantly lower maximum conductivity [13].

Conductive inks are commercially available in formulations suitable for a range of printing processes such as flexography, gravure, lithography, screen, and rotary screen, and substrate quality such as kapton, mylar, glass, PET and some coated papers [13].

Post Print Processes: There are many different ways to improve the conductivity of the conductive ink once the antenna has been printed. Some of these methods are useful in reducing the cost of producing printed antennas, and others are useful more for the electrical benefits that they provide.

The first and simplest method for improving conductivity in a printed antenna is to print the pattern more than once as more particles will overlap and there will be more contacts between the tiny metallic particles. This is because desktop printers make images from tiny dots of ink that do not overlap, but bleed slightly into each other. An industrial ink printer would be more efficient and require fewer passes [11]. Printing more than once is not ideal, as conductive ink is presently fairly expensive and requires more ink than other methods.

A second method of significantly improving the performance of a printed antenna is to print a thin layer of conductive ink and then, using electrolysis, plate the antenna with another metal (which could be copper, cobalt, nickel, gold or other metals) [14]. Printable conductive metal pastes have always had to reach a compromise between the rheological (flow properties) and conductive properties of the material. Binders and carriers used to provide flow during printing and adhesion to substrates impact the conductivity of the final composite layer and impede current flow through the conductive track. A process has been developed that can support the direct creation of solid-copper designs using an additive, inkjet printing line [12]. The solution is a web-based, high speed digital printing system combined with an innovative tank-based electroless copper plating process that allows for the creation of solid-copper printed circuits at speeds of up to 30 m/min. With web widths of up to 305 mm on the current generation of equipment, this system has the capability of producing enormous quantities of material rapidly and at a low cost [12]. *Figure A.5* shows this continuous process.

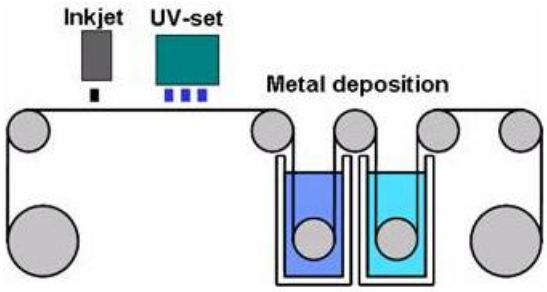


Figure A.5: Inkjet printing with electroless plating process [12].

To further thicken the antenna (if necessary), electroplating can be used to add 5 microns of metal to the antenna per minute [14]. *Figure A.6* shows radio-frequency identification (RFID) antennas produced by QinetiQ using the process described above. The technology has the potential to be widely and rapidly adopted across both new and emerging sectors, such as RFID. The ink can be applied using inkjet, rotary and flat-screen, spray, gravure, flexo and offset printers [14].

A third, fairly simple method of improving the properties of conductive paste is to compress the material. Studies performed by members of the Dresden University of Technology have shown that area resistance can be reduced by more than 70 %. The reliability can be improved and the adhesion strength of the paste is increased 2.4 times. If the temperature of the material is increased whilst it is being compressed, then the conductive particles are forced into closer contact. They are hence more strongly interlocked within the substrate material. This means that antennas can be made using conductive ink with comparable performance to traditional metal etched antennas [4].

A fourth method of improving the properties of a printed antenna is to sinter the ink once it has been printed. Since the polymer substrate is virtually transparent to microwave radiation, a negligible amount of energy is absorbed by the substrate, whereas the conducting silver nanoparticles, with a high dielectric loss factor, absorb the microwaves strongly [3]. This process significantly lowers the resistance of the conductive ink

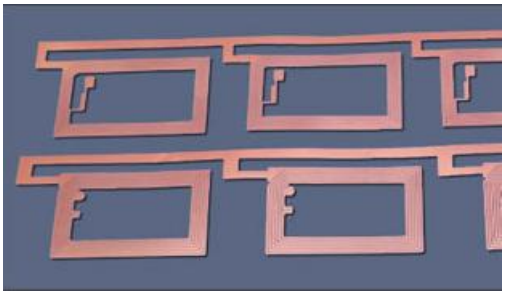


Figure A.6: Antennas which have been produced by inkjet printing of conductive ink and then plated with copper [14].

layer as shown in *Figure A.7*. The process of sintering is more clearly explained in the section on sintering technology.

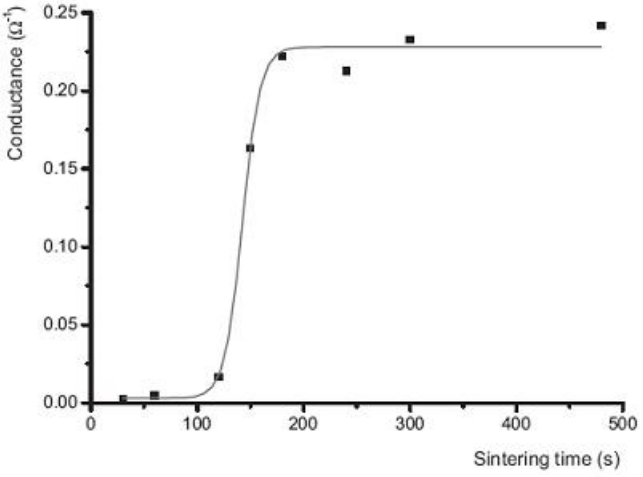


Figure A.7: Conductance as a function of time for the microwave sintering of tracks made from silver paste from Harima Inc. which has been inkjet printed onto a polymide (PI) substrate [3].

A.2.1.2 Advantages and Disadvantages of Conductive Inks

Advantages: Conductive ink printing negates the cost and struggle associated with photoresist application and definition, etching, stripping and the waste treatment challenges associated with other processes. Maybe more importantly, the time between circuit development and actual production is minimised as, with digital printing, changes can be performed quickly and easily [22]. Nanotube technology is a rapidly growing area of research, both in South Africa (with Sasol [15]) and the rest of the world. This means that advances in this field will be quickly realised and the cost of production and manipulation of carbon nanotubes will decrease significantly and swiftly. Other advantages include:

- Digital non-impact printing method, additive.
- All kinds of substrates.
- Rigid or flexible substrates.
- Rough or smooth surfaces, 3D surfaces.
- Accurate, high resolution, high speed.
- Possibility for mass customisation.
- Low material consumption [6].

Disadvantages: The cost of the technology, at present, is quite high, but with all the research into the area of conductive ink and nanotube technology these prices are likely to fall in the near future. There is a possibility that the antenna will not perform as well as some of the more established methods because of the reduced conductivity of the material, but experiments need to be performed to verify this.

A.2.1.3 The Cost of Conductive Inks

The cost of commercially available conductive inks is relatively high and it is not foreseen that their use will result in an inexpensive manufacturing process.

HARAEUS PC 86006, a conductive adhesive from EIS, is R 48.20 per gram.

A single gram of adhesive will cover about 100 cm^2, thus resulting in a cost per square centimetre of 48 cents. The cost of processed FR4 (Fiberglass Epoxy-resin) is roughly 10 cents per square centimetre and is hence considerably cheaper.

Another typical conductive ink from Epoxies Inc. costs R 15.10 per gram [16]. With a theoretical coverage of 720 sq.ft/gal/mil (7.10 m^2/kg) [17] a few simple calculations indicate that it will cost R 2 127 to cover one m^2 (equivalent to 22 cents per cm^2).

The idea of using carbon nanotubes as a basis for a conducting ink could be one of the new technologies in the manufacture of antennas. The current commercial price for nanotubes is high as illustrated in Table A.1.

Table A.1: The current price of carbon nanotubes as of May 2007.

Company	**Description**	**Price per gram** ($)	**Approx price in ZAR**
n-Tec	approx 65 wt% carbon nanotubes, approx 35 wt% graphite nanoparticles	40	290
Namocs	High purity MWNTs	80	570
Bucky USA	Multiwall nanotubes 80 wt%, 8-15 nm diameter, 1-10 m length	55	390
MER	Arc-produced MWNT with 30-40 wt% nanotube content	15	70

The cost of making nanotubes is, however, considerably cheaper and works out to about R 4.30 per gram. It is not currently known what surface area will be covered by a gram of nanotube-based ink, but if we assume the same coverage as achieved with the commercially available inks, then the cost per square centimetre is about 4 cents. The cost of producing the carbon nanotubes using CVD (chemical vapour deposition) was computed as follows:

Nitrogen usage:

- 300 ml/min for 70 min.
- 240 ml/min for 60 min.
- 90 ml/min for 30 min.

Total nitrogen usage: 36 600 ml, which works out to R 1.14

Acetylene usage:

- 90 ml/min for 60 min

Total acetylene usage: 5 400 ml, which works out to 35 c.

Catalyst:

- Cobalt Nitrate: R 4.50
- Iron Nitrate: 50 c

Total raw material cost to manufacture approximately 1.5 g of carbon nanotubes: R 6.49.

This cost obviously does not include labour costs (labour is necessary in preparing the catalyst as well as making the nanotubes) or the costs associated with running the furnace.

Prices for gases obtained from Afrox and the chemical catalysts from Sigma Aldrich.

Although CNT's are definitely an option for the future, presently they are not ideal for conductive ink printing. The purity of the lab-made CNT's were not high enough to give suitable conductivity, especially when printed in thin layers. The CNT's from the lab also tend to be more conical in shape rather than cylindrical, and this makes them more suited for semi-conductive applications as opposed to producing a conductive layer [18].

A.2.2 Sintering Methods

The ISO definition of sintering is as follows [19]:

> The thermal treatment of a powder or compact at a temperature below the melting point of the main constituent, for the purpose of increasing its strength by bonding together of the particles.

Although sintering does occur in loose powders, it is greatly enhanced by compacting the powder, and most commercial sintering is done on compacts. Compacting is generally done at room temperature, and the resulting compact is subsequently sintered at an elevated temperature without application of pressure. For special applications, the powders may be compacted at elevated temperatures and therefore simultaneously pressed and sintered. This is called hot-pressing or sintering under pressure [20].

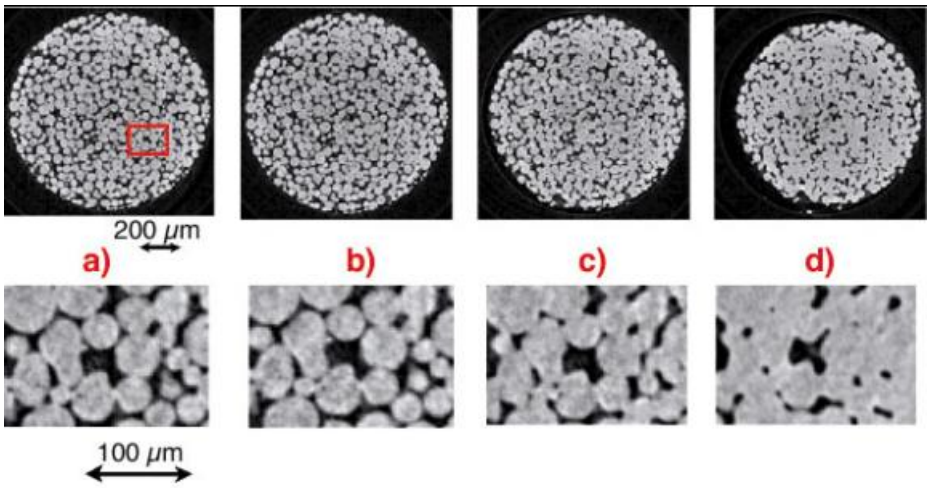


Figure A.8: Illustrating the sintering process [21].

Figure A.8 shows the sintering process, it can be seen that bonds are formed between the powder particles which strengthens and binds the material.

A.2.2.1 Current Uses of Sintering

Sintering is currently used in the production of metallic parts from powder. It is also used as described in the conductive ink section above, where it is used to improve the bonds between printed particles, and thus improve the conductivity.

There are three main techniques that can be used to sinter metals. These are outlined below.

Pulse Plasma Sintering (PPS): This is a new sintering technique involving the action of an electric field. This method utilises pulsed high electric current discharges to heat the powder subjected to pressing. The PPS process has a very high thermal efficiency, since the powder is heated directly by the pulse arc discharges. Its main feature is the high power (of the order of 600 MW) delivered in a short pulse. The main advantages of the sintering enhanced by strong electric-current impulses are: the short process duration (a few minutes) and energy-savings.

The PPS sintering technique can be used for producing dense sinters from a wide variety of materials such as metals (wolfram, titanium, iron and its alloys), ceramics (Al_2O_3, TiN, TiB_2), composites (WC-Co, WCu, Cu-diamond, NiAl-TiC, NiAl-Al_2O_3) and functionally graded materials. Using the PPS technique it is possible to obtain sinters of nano-crystalline powders after a few minutes, the sinters having the density close to the theoretical value. This method can also be used for conducting reactive processes with the participation of the SHS reaction (Self Propagating High Temperature Synthesis), which permit producing NiAl from nickel and aluminum powders [22].

Microwave Sintering: Microwave heating and sintering is fundamentally different from conventional sintering, which involves radiant/resistance heating followed by transfer of thermal energy via conduction to the inside of the body being processed. Microwave heating is a volumetric heating involving conversion of electromagnetic energy into thermal energy, which is instantaneous, rapid and highly efficient.

Most research and industrial activities employ electromagnetic heating at 2.45 GHz and 915 MHz frequencies. Based on their microwave interaction, most materials can be classified into one of three categories—opaque, transparent and absorbers. Bulk metals are opaque to microwave and are hence good reflectors. However, powdered metals are very good absorbers of microwave energy and heat up effectively, with heating rates as high as 100° C/min. Most other materials are either transparent or absorb microwave energy at varying rates at ambient temperature [23].

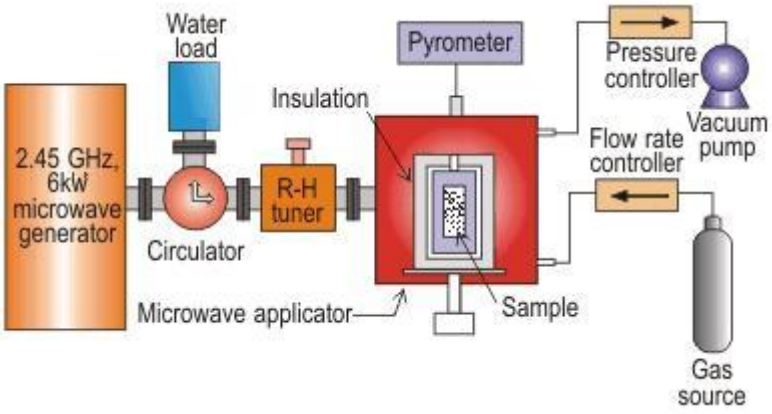


Figure A.9: Components needed for microwave sintering of metals [23].

Figure A.9 shows the components needed to microwave sinter metals. These components are fairly sophisticated, and would need to be assembled and manufactured by professionals, incurring extra costs.

Thermal Sintering: During sintering, the pressed parts move through a controlled-atmosphere furnace. The pressed powder particles fuse together, forming metallurgical bonds. The type of furnace most generally favoured is an electrically heated one through which the compacts are passed on a woven wire mesh belt. The belt and the heating elements are of a modified 80/20 nickel/chromium alloy and give a useful life at temperatures up to 1 150 °C. For higher temperatures, walking beam furnaces are preferred, and these are increasingly being used as the demand for higher strength in sintered parts increases. Silicon carbide heating elements are used and can be operated up to 1 350 °C [24]. For special purposes at still higher temperatures, molybdenum heating elements can be used, but special problems are involved, notably the

readiness with which molybdenum forms a volatile oxide. Molybdenum furnaces must operate in a pure hydrogen atmosphere [19]. Compax, Inc. has high temperature sintering capabilities of up to 1 650 °C. Sintering powders at these temperatures enable the sintered item to achieve its maximum strength [24].

A.2.2.2 Advantages and Disadvantages of Sintering Methods

Sintering will probably have more advantages in the process of improving printed antenna characteristics than in fully producing antennas. This is due to the fact that the powders used in sintering are expensive. There are similar problems with getting the material into the correct shape and onto the substrate as there is with solder paste methods (see section A.2.6 on solder pastes for more information).

A.2.3 Hot Foil Printing

Instead of using magnetism, plates, or inks to print words and shapes, foil printing uses dies, or sculpted metal stamps. The heated dies seal a thin layer of metallic leaf onto a surface. The foil comes in a wide roll, large enough for several passes, backed by Mylar. The hot die works similarly to a letterpress. Once heated, it presses the foil against the substrate material with enough pressure that the foil sticks only in the intended places, leaving a slight imprint [25].

Metallic hot stamping foil is manufactured by application of a number of coatings to a polyester carrier film. The polyester film thickness normally used is 12 microns and is chosen because of its dimensional stability when heated and resistance to stretching and shrinkage during the hot foil manufacturing process.

The coatings normally applied to a hot metallic stamping foil are:

1) RELEASE: The release coat is applied first to the polyester, and is the coating which allows the foil to release from the carrier. Without the release coat, the lacquer coat would adhere to the polyester and not release when stamped. Most release coats are based on waxes, although resin releases are also used for specific applications. They are very thin; thicknesses below 0.005 g/m^2 are not uncommon.
2) LACQUER: The lacquer gives the colour to the foil and also the body and resistance properties. There are many different lacquers which can be used for specific hot foil properties, such as heat resistance, product resistance and conformance to environmental and toxicity requirements.

Hot foil printing can be applied to many surfaces, including paper, card, leather, plastics, fabrics and wood [26]. The basis of a hot foil printing machine is a heated block with a template inserted in to it, and stamping down by means of an air cylinder through a printing foil which is made up of a silicone carrier to which a carbon pigment is attached [27].

Figure A.10 shows an example of a manually operated small scale hot foil printing machine which is easy to use and fairly inexpensive (around R 15 000 [28]). A machine like this would be used to make small quantities of stamped items. Much larger automated machines exist which are suitable for producing large quantities in a small amount of time. A machine like this could be used to produce prototypes to test new designs and procedures quickly and easily.

A.2.3.1 Current Uses of Hot Foil Printing

Hot foil printing is currently used in all fields of plastic decoration ranging from consumer electronics, automotive interiors and exteriors, furniture, toys, packaging and many other industries. It is recognised as the most durable form of marking or decorating once-off or volume parts, which can be flat or have a complex, tubular, convex or concave surface [43]. Examples include:

- Product badges
- Keyboard keycaps
- Automotive components
- Thumbwheels
- Terminal blocks



Figure A.10: Example of a foil printing machine [28].

- Warning plates

It is suitable for use on:

- Thermoplastics
- Duoplastics
- Paper
- Real and imitation leather
- Textiles
- Wood [29].

The machines involved with this technology are well established and readily available. The most important feature of hot foil printing with regards to antenna manufacture is the availability of the conductive foil. The metallic foils currently in use are too thin to act as a suitable conductor for this application. In the literature, there is mention of foils that have been specifically designed for printing conductive circuits. One of these authors is Bauser et al. [30].

The basic layout of the foil suggested by Bauser [30] is similar in make up to that of ordinary foils. Figures *A.11* and *A.12* shows a possible make up of a foil which has a conductive layer that is thick enough to properly conduct an electric current. It must also have a shear strength low enough that, when the shape is stamped, the material is bonded to the substrate with straight and adequately defined edges.

The low shear strength of the foil can be achieved by using a crystalline structure that has fibers which are orientated at right angles with the surface of the foil, as well as containing doping agents such as carbon, sulphur and nitrogen [30].

The exact details of the construction of a foil like this can be found in the literature by Bauser [30], but it is sufficient to know that it is possible. It would, however, mean that the foil would need to be specially manufactured, as it is not used in any current commercial processes. This means that manufacturing a prototype becomes laborious, and quite probably expensive.

A.2.3.2 Advantages and Disadvantages of Hot Foil Methods

Hot foil printing is a well established manufacturing process. This means that machines and templates can be obtained easily, cheaply and will be reliable.

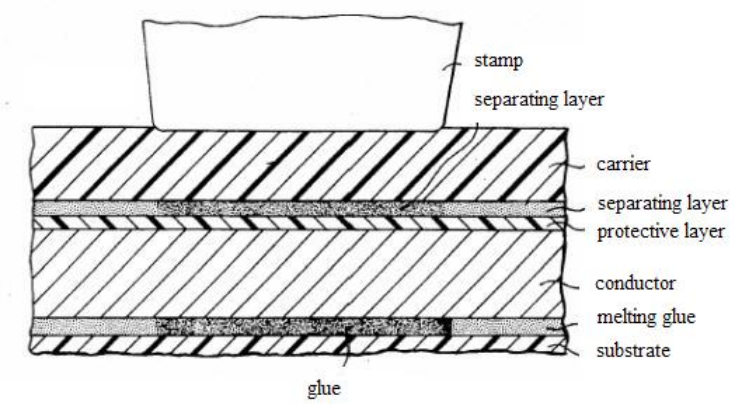


Figure A.11: Schematic cross-sectional diagram of a conductive hot-stamping foil [30].

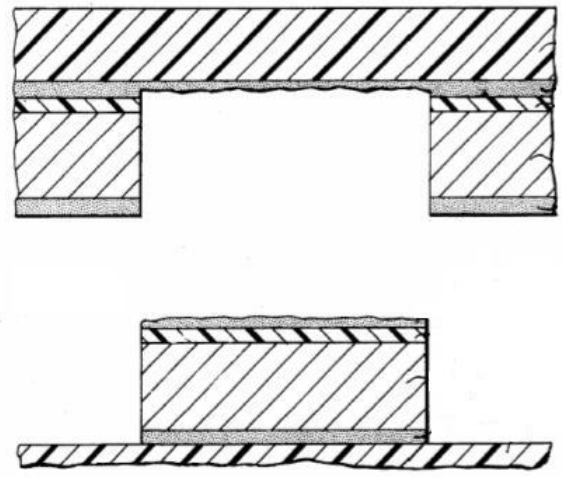


Figure A.12: Schematic cross-sectional diagram of a conductive hot-stamping foil directly after stamping and separation [30].

Foil printing is quite unique in its application as it is an odour-free, dry transfer process that does not require ink, hence the product is completely dry after printing and can be handled and re-packaged immediately. In addition, the machine does not require cleaning after completing a print run [31].

Disadvantages include the fact that new foils may have to be manufactured, which could be initially expensive. Testing and manufacturing a prototype using this method will also be a difficult task, requiring the development of a conductive foil (if it cannot be sourced) as well as the outsourcing of a foil printing machine and template.

The majority of the hot foil methods are not suitable for the production of antennas because conventional foils have a maximum thickness of 0.1 μm which may be too thin. A film of such a thickness has a low electrical conductivity when compared to the materials' bulk conductivity. The conductivity may also be inconsistent across its surface due to variations in quality and to the diffusion of bonding agents into the layer. The thickness of the conductor is an important consideration as the conductance of a material decreases with decreasing thickness. The parameter used to determine the resistance of a metal sheet is the skin depth which can be computed using equation A.1.

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{A.1}$$

Where:

ω :	Frequency of interest in radians/sec
σ :	Conductivity of the material in Siemens/m
μ :	Permeability of the material in H/m

The skin depth is the depth below the surface of the conductor at which the current density decays to about 37% (1/e) of the current density at the surface. A metal whose thickness is more than the skin depth is perfectly adequate for the manufacture of an antenna at that frequency.

In order to get a feel for the minimum thickness of a foil, the skin depth of copper at various frequencies is tabulated in Table A.2.

From this table it can be seen that a foil thickness of roughly 2μm would be satisfactory for most antenna applications as long as the adhesive does not influence the electrical performance of the foil.

Table A.2: The skin depth of copper at various frequencies of interest

Frequency (MHz)	Skin Depth (μm)
900	2.2
2500	1.3
6000	0.9

Another disadvantage of the commonly used hot foil methods is that the foil cannot be easily soldered. This is partly due to the thickness of the material and partly due to the quality of the surface of the foil. Such a limitation is not insurmountable from an antenna manufacturing point of view, as the antenna can normally be designed to be capacitively fed; however there are instances where construction from a solderable foil is beneficial (the provision of DC grounding, for example) [32]. One route to circumvent the poor conductivity of the commonly used foils is to improve the conductivity by electroplating. Problems may well arise from this approach as the process would have to be achieved with poor electrical contacts. In addition, the adhesive bonding the foil to the substrate may contaminate the plating bath and the plating may not be uniform due to the variation in conductivity of the foil. The severity of these problems will have to be investigated in more detail if this approach is to be followed.

A.2.4 Plastic Plating Techniques

There are a number of plastics that have considerably better electrical characteristics than an FR4 board. A process whereby metal is plated onto a plastic substrate and then processed in a fashion similar to a normal PC board could be an attractive method of antenna manufacture.

One cannot use an electrolysis process to deposit metal onto plastic. The generic metal plating process involves depositing a thin conductive layer on the plastic using electroless plating and then using electrolysis to bolster the thickness of the conductor. It is apparent that virtually any plastic can be plated by following a moderately generic series of steps [33]. The main differences between the processes used for different plastics are to be seen in the use of different chemicals.

The most popular plated plastic is acrylonitrile-butadiene-styrene (ABS) which is used in the production of, for example, automotive parts including grills and decorative trims. Other plastics such as nylon, polysulfone, and polycarbonate have all been successfully commercially plated. Exact details of these plating processes are available from either the manufacturer of the plastic or from the suppliers of plating chemicals. The plating process for ABS (*Figure A.13*) will be described as an illustrative example of the process [34], [35].

Cleaning: Alkaline detergents are commonly used to remove foreign materials from the plastic that might have a detrimental effect on the efficacy of the chemicals used in the plating process. Impurities such as oil and dust left on the plastic surface can affect the peel strength of the metal deposit.

Etching: ABS is typically etched in a strong oxidising solution for a period of 5 to 10 minutes at a temperature between 60 °C and 70 °C. This process is used to roughen the surface by selectively attacking

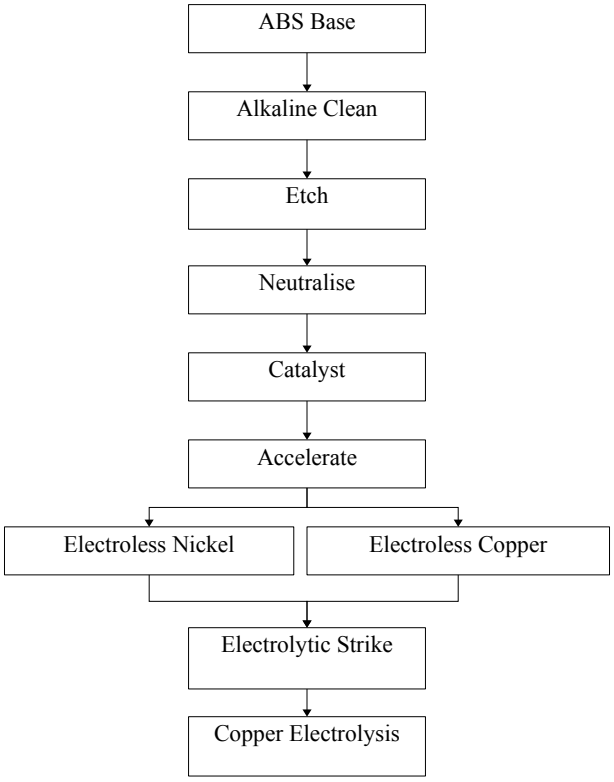


Figure A.13: The plating process for chemical plating on ABS.

some of the components of the plastic and to render it hydrophilic. The success of this process affects the strength of the bond between the plastic and the metal coating. Oxidising solutions used include chromic acids and sulfuric acid.

Neutralising: If a chromic acid is used in the etching phase, then it is necessary to remove as many of the resulting chromium compounds as possible. Chromium salts have a detrimental effect on the absorption of the catalyst or activator used in the following step.

Catalysing: The ABS is immersed in a strong acidic mixture of tin and palladium salts which are suitably diluted (1–10% by volume) for a period of between 2 and 10 minutes. The catalyst is attracted to the plastic forming a film on the surface. This film is used to initiate the electroless deposition process.

Accelerating: A dilute acid or alkaline solution is used to remove any excess tin compounds thereby exposing the palladium. The temperature of these solutions is controlled to sit between 20 $^{\circ}$C and 50 $^{\circ}$C and the plastic is immersed for about 2 minutes.

Electroless plating: This is the process that results in a thin nickel or copper layer being deposited over the entire surface of the plastic. It typically takes 5 to 10 minutes to deposit a layer of about 0.5 μm.

Electroplating: The electroless plating process results in an extremely thin conducting layer over the plastic. The layer plated over the strike layer is normally a ductile copper which acts as a stress-absorbing layer which is used to counteract the difference in the thermal expansion of the plastic and plated metals. The copper layer could be the final coating on the plastic or subsequent layers could be deposited depending on

the application. The final thickness of the deposit can be controlled but is typically between 15 and 25 μm. The conductive layer on the plastic can be etched to form the required shape by a process similar to that used to process PC boards.

A.2.4.1 Current uses of ABS plating

ABS is typically electroplated to give parts with the more decorative finish of metals such as chrome, gold, silver and brass. The plating can increase the rigidity of a moulding as well as scratch resistance. The metal layer screens radio waves and conducts electricity. It is currently used in applications such as sanitary ware, automotive or radiator grilles, wheel covers, headlight bezels, interior and exterior trim and knobs, marine hardware, radio and TV parts, shavers, light fixtures and appliance housings [36]. Rather than using traditional copper etching methods, Atotech Global use an ABS plating technique to produce inductive payphone cards and smart cards. The advantage of this is that there is no etching of excessive and unwanted copper involved, as is the case with common card inlet laminates. The concept offers substantial cost savings as it minimises the amount of copper to be etched and hence the amounts of etch waste to be treated [37].

New research by JP Laboratories has revealed that alternatives to chromic acid (which is commonly used in the ABS plating process and is highly toxic) are available [38].

A.2.4.2 Advantages and Disadvantages of ABS Plating Methods

Advantages:

- Additive—by using the resist and only plating where the copper is needed, one can save on material costs. ABS is a fairly cheap substrate, and it offers better electrical properties than other substrates such as FR4.
- The process could be modified to plate on plastics like polystyrene, which have superior electrical characteristics to that of ABS [39], [40].
- Plating processes can be easily automated. This will reduce labour costs.
- The plating process could be used to replace many other current processes (PCB manufacture, foil cutting, metal stamping) as it can be used on different substrate forms and shapes.

Disadvantages:

- ABS is usually the substrate of choice in most plating applications that are only interested in the ease of plating and subsequent plating adhesion strength. A new method of plating would need to be researched in order to plate on other materials like polystyrene.
- Plating involves potentially hazardous chemicals, which need careful handling and then special removal once they are used. This means training workers to handle the materials and costs will be incurred in the waste removal.
- The number of antennas that can be made at one time will be restricted by the tank size and the size of the framework necessary to move the substrate through the plating baths.

A.2.4.3 Anticipated Cost of Set Up and Manufacture

Chemserve (a plating chemical supplier) has estimated that a full scale automated plant would cost in the region of R 1.8 million [41]. To factor in this cost, one would have to know the volume of antennas that are expected to be produced, as this will determine if the cost is an acceptable one. The manufacturing costs, however, are expected to be far cheaper than existing methods. Polystyrene (if it can be used as the substrate) is cheaper than FR4 and Rogers board. The cost of plating chemicals is also fairly cheap in terms of the amount of copper deposited per square metre (see [42] for accurate manufacturing costs).

A.2.5 Etching Techniques

A.2.5.1 Current Uses of Etching

PCB Etching is one of the processes that is currently being used in the manufacturing of antennas. This method of manufacturing has been researched as extensively as the other methods to determine whether it is a technology that needs to be replaced. PCB boards are typically made from FR4 [43]. These boards are coated in copper and are then chemically etched to form a specific pattern, removing unwanted copper from the board. There are a few general steps that need to be performed in order to fabricate a PCB [43]. These are:

- Step1: PCB Data acquisition. The pattern for the PCB needs to be made and the photo-tool for image transfer is made.
- Step 2: Preparation of PCB core. The FR4 is coated with either with copper foil or electrolytically deposited copper and is then sheared and cleaned.
- Step 3: Inner layer image transfer. The copper is coated with photoresist and then exposed to light. The unwanted copper is then etched using chemicals.
  After this step a pattern is formed from the remaining copper; for antenna manufacturing processes, this is enough. For normal PCB applications, further steps are necessary for lamination, drilling of holes, through-plating and layer integration.

A.2.5.2 Advantages and Disadvantages of Etching

Etching is a well established and understood process, it can be fully automated and thus provides a high-quality, fast turn-around and a moderately cost effective method of manufacturing [44]. There are many companies offering etching services and machinery; knowledge on the subject is thus readily available should any problems arise. Manufacturing a prototype to test the effectiveness of the method is a simple matter as etching can be performed using common equipment—a laser printer, an iron and a few chemicals [45]. A problem with etching is that it is a subtractive process—the board starts completely covered with a metal (say copper) and the unwanted copper is then etched away to produce the required pattern. This means that there is a lot of waste produced in the method. It also means that the process is theoretically more expensive than say an additive plating process (as described in previous sections), where only the metal which is necessary for the pattern is plated onto the substrate. The chemicals used in the wet etching process are also potentially hazardous.

Dry etching, on the other hand has the following advantages and disadvantages [46]:

Advantages:

- Eliminates handling of dangerous acids and solvents.
- Uses small amounts of chemicals.
- Isotropic or anisotropic etch profiles.
- Less undercutting.
- No unintentional prolongation of etching.
- Better process control.
- Ease of automation (e.g., cassette loading).

Disadvantages:

- Some gases are quite toxic and corrosive.
- Re-deposition of non-volatile compounds.
- Need for specialised (expensive) equipment.

Either way, both wet and dry etching techniques are still subtractive processes, and there is therefore always going to be wasted copper. Another problem with both processes is that they are limited to either FR4 board or a substrate called Rogers board. These substrates both have disadvantages when used for antenna

manufacture. FR4, which is the usual PCB substrate, is lossy. With a dissipation factor of 0.025 it is only really useful up to about 1–2 GHz [47], while Rogers board—a substrate made for antenna applications, with a dissipation factor of around 0.002—is very expensive (approximately R 1/cm^2 for processed Rogers board [32]).

It is therefore anticipated that a cheaper and better solution can be found.

A.2.5.3 Anticipated Cost of Setup and Manufacture

There are many companies that produce PCBs in bulk. These companies will have all the necessary equipment and will probably make antennas cheaper than could be done in-house (this depends on the quantity of antennas needed). One of the problems, however, with external manufacturing is that lead times (time taken from design to prototypes and then full scale manufacturing) could be fairly long. PCB costs, as mentioned earlier, are very much dependent on quantity, but to give an idea of some prices for various quantities ASPiSYS Ltd. provides the following estimates [48]:

- 1 PCB (i.e. a prototype) 10 cm x 16 cm—R 1 000.
- 500 PCBs (a fairly small run)—R 50 each.
- 10 000 PCBs—R 39 each.

This shows that producing a prototype may be fairly expensive, but producing a batch of products will significantly decrease the cost per single PCB.
Rogers board, as mentioned earlier, is R 1/cm^2. This works out to around R 160 for a PCB of dimensions similar to the one quoted above. This is more than three times as expensive as normal FR4 PCBs.

A.2.6 Solder Paste

Solder paste is an alloy or pure metal which, when heated, liquefies and melts to flow onto the space between two close-fitting parts, creating a soldered joint. Solder paste has suitable melting and flow properties to permit distribution by capillary attraction in properly prepared joints [49]. In order to make a suitable antenna, the solder paste will need to melt and form into a specific shape. This provides a challenge in choosing a suitable substrate and in getting the solder paste to form the correct pattern.

The first thing required of the substrate is that it must be able to withstand the temperatures necessary to melt the solder paste (about 230 °C) [50]. The melting point of polystyrene is about 190–260 °C [51]. Heating the entire board to the required temperature will thus result in the melting of the substrate. Either a substrate with a higher melting point must be found, or alternatively a heating method could be used which specifically targets the solder paste and not the substrate (e.g. laser heating). This, however, will add extra complexity and cost to the manufacturing process.

A simple test using solder paste was performed, and it was found that the paste tended to coagulate in the mould when heated, rather than fill the entire space. The polystyrene also warped slightly at the high temperatures. To use this as a suitable manufacturing method would require too much altering of the method, and is thus not considered any further.

Figure A.14 shows an experiment with solder paste that confirms the solder paste coagulates on heating and does not fill the mould as hoped.

A.2.7 Die Cutting Techniques

Die cutting services use a variety of die cutting methods to fashion materials into predefined shapes or sizes. Several different types of die cutting are available, including flat and rotary laser die cutting, blade type rotary die cutting, steel rule die cutting, and ultrasonic die cutting. The method used can vary, depending on such factors as material and end product configuration [52]. Flat bed die cutting (or steel rule die cutting) is an efficient and cost effective method to die cut less complex part designs. It is typically used for smaller production quantities. Parts are manufactured in a reciprocating die-cut press using a steel rule die that is



Figure A.14: The solder paste coagulates in the surface indentation.

bent to form the desired part. A synthetic board holds the steel rule in place. The board is laser cut to ensure accuracy [53].

A.2.7.1 Current Uses of Die Cutting

Many different materials can be processed by suppliers of die cutting services for a wide variety of applications. Materials include felt, fabrics, fiber, cork, paper, metals and alloys, plastics, rubber, foam and sponge, composites, electrical insulating materials, and EMI/RFI shielded foils and laminates. Examples of products manufactured by die cutting include gaskets and seals, shims, templates, inserts, washers, and puzzle pieces [52], [54].

A.2.7.2 Advantages and Disadvantages of Die Cutting Methods

Similar to foil cutting, once the conductive material has been cut, it will need to be transferred to the substrate. This could be done manually (not cheap or repetitive) or a way needs to be found to automate the process. Cheap and easy to use machines are available to use for testing and the manufacturing of a prototype.

Die cutting, however, does not adequately address the problems that are present in current manufacturing techniques; namely, that there will be a waste of material, as the antennas will need to be cut from a large sheet of metal. There are ways to minimise and reuse this waste, but no waste is preferable [55]. Other problems with this method of production include the fact that the antenna will have to be transferred to the substrate after cutting. This introduces a large amount of labour which increases the cost, and decreases the repeatability and efficiency of the process. The final problem is that creating dies is meticulous work, as it must be designed so that an absolute minimum of waste is produced [55], something that may not be easy with complex antenna designs.

A.3 Conclusion

A detailed review of some current manufacturing methods has been presented. These methods were chosen for the possibility that they could be useful in finding new techniques for manufacturing antennas. The most useful procedure differs according to the specific need for the process as most of the methods have advantages which make it suitable for certain applications. For instance, a hot foil printing method is ideal for producing large quantities of planar antennas, but the cost of tooling and changing the design is fairly high. On the other hand, with a process like plating on plastic, the antenna design can be changed quickly, and prototypes can be made easily to test new designs. Another important thing to look for in the new manufacturing process is adaptability: it is useful if it can be used to produce many kinds of antennas using the same method. It

was decided that the plating of plastics method is the most promising. However, it will need to be modified in order to be suitable for plating antennas. It allows for the use of low loss substrates like polystyrene; it is an additive process; and it will hopefully be cheaper than the current PCB manufacturing processes, as well as cheaper, easier and more effective than the other methods described above.

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Appendix B

The Plating Process

Abstract

A detailed description of a new manufacturing technique for antennas is provided. The new technique is the plating of copper on polystyrene. It is similar to normal plastic plating on ABS (Acrylonitrile Butadiene Styrene). The only modification to the process is in the etching step of the plating process, which needs to be modified so that the copper adheres to the polystyrene surface. Experiments are presented to verify the new technique, as well as masking tests which ensure that an accurate pattern of an antenna can be plated on the polystyrene. The results show that the plating technique is adequate for use on polystyrene, which makes it suitable for antenna applications.

B.1 Introduction

This document, describes the chosen method for antenna manufacturing—plastic plating. The plating process is described in detail, along with how it can be used to manufacture antennas. In order for established plating techniques to be useful in manufacturing antennas, the process needs to be modified slightly (for use with polystyrene as the substrate). The experiments that were conducted to test the modifications are discussed, and the details of the best method are presented. Another important step in manufacturing antennas using the new technique is masking. The experiments conducted to establish the best masking techniques are also discussed in detail.

B.2 Description of the Plating Process

The manufacturing process chosen for further investigation and testing is that of selectively plating copper on polystyrene. The process of plating copper onto plastics like ABS is a very standard process, and is used extensively in industry [1], [2]. The difficulty in plating polystyrene as opposed to plating ABS is in the etching step. This is because of the differences in the chemical make-up of the two plastics. ABS has butadiene particles on the surface of the plastic which are easily removed using a chromic acid etch. Polystyrene, however, has no such chemical that can be easily removed in order to roughen the surface. Ordinarily, plating on plastic involves the following general steps:

- **Cleaning:** This is to remove any excess dirt/oils from the surface of the plastic to avoid contamination of the plating solutions as well as to provide a good clean surface for the chemicals to act on and the copper to adhere to.
- **Etching:** The plastic needs to be microscopically etched in order for the copper to adhere to the surface of the plastic. If the surface is too smooth, then the adhesion of the copper to the plastic is not great enough and the copper will simply peel away. To etch ABS, a solution of chromic acid and sulphuric acid removes the butadiene particles on the surface of the plastic, creating a rough surface, as seen in *Figure B.1*.
- **Neutralise:** The chemicals used in the etching process are reactive and, if chromic acid is used, then it is necessary to remove as many of the resulting chromium compounds as possible. Chromium salts have a detrimental effect on the absorption of the catalyst or activator used in the following step.
- **Catalyst:** The ABS is immersed in a strong acidic mixture of tin and palladium salts which are suitably

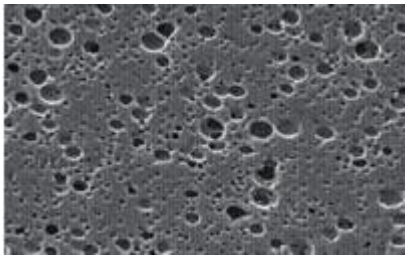


Figure B.1: The ABS surface that was mildly etched is slightly roughened with individual cavities [2].

diluted (1-10% by volume) for a period of between 2 and 10 minutes. The catalyst is attracted to the plastic which forms a film on the surface. This film is used to initiate the electroless deposition process.
- **Electroless Plating:** The plastic is immersed in the electroless plating solution which deposits a thin layer of copper (≈ 0.5 μm) on the surface where the catalyst has been applied.

B.2.1 Additional Steps

The above steps describe the general steps necessary for electroplating plastics, specifically those designed for use with ABS, a commonly plated plastic. For antenna manufacturing it is preferable to use polystyrene as the substrate as it has better electrical/dielectric characteristics than ABS. This means that the process needs to be modified slightly. Most importantly, the etching of the surface needs to be modified, as the chromic acid and sulphuric acid combination is specifically designed for ABS. The experiments used to determine a suitable etching solution are outlined in this document. The other steps that need to be added are a masking step—necessary to plate the copper in the required shape for the antenna—and electrolytic plating to thicken the copper layer, which will enable soldering on the copper layer as well as provide more durability and strength.

- **Masking:** Making can be performed in a number of different ways; there are the usual methods of masking PCB (see [3] for more information). But these methods are, firstly, expensive to set up and, secondly, are subtractive rather than additive processes. A new/different method of masking the pattern of the antenna needs to be found. An approach to this problem is discussed in more detail in section B.4 of the report, which outlines experiments used to determine a suitable method of masking, as well as the results of those findings.
- **Electrolytic Plating:** Electrolytic plating is a standard method of increasing the thickness of an electroless plated metal. The Britannica Concise Encyclopedia gives the following definition for electroplating [4]:

  > Process of coating with metal by means of an electric current. Plating metal may be transferred to conductive surfaces (e.g. metals) or to nonconductive surfaces (e.g. plastics, wood, leather) if a conductive coating has been applied. Usually the current deposits a given amount of metal on the cathode (workpiece) and the anode (source of metal) dissolves to the same extent, maintaining a fairly uniform solution.

  In this case, electroplating is necessary to increase the thickness of the copper to enable soldering, to strengthen the plating and also to give the antenna a durable and shiny surface.

B.2.2 Etching Methods

Narcus, in his book *Metalizing of Plastics* [5] gives the following information regarding the formation of a suitably conductive and adherent film on a plastic surface. It involves these steps:

1) Slight roughening or deglazing of the plastic surface
2) Cleaning the surface
3) Sensitising the surface

These preparatory treatments of the inert plastic surface govern the success or failure of any process for application of the initial chemically-reduced film, since the chemical structure of the plastic determines the procedure to be employed for application of this conductive film.

The roughening (etching) procedure, which is important to the success or failure of the metallisation process, has two fundamental purposes:

1) To roughen the surface microscopically to remove glaze from the plastic article, and
2) To remove the 'flash' or feather-edge from the moulded piece [5].

This roughening procedure can be accomplished by either mechanical or chemical means. Mechanical methods can include any procedure which roughens the surface physically, namely sand blasting, abrasive rubbing, wet tumbling etc. Chemical methods, on the other hand, are obviously ones in which the etchant is a chemical solution which will roughen the surface. Care must be used with chemical roughening methods to ensure that the etchant does not cause too severe an etching action.

Narcus [5] provides the following chemical solutions to chemically etch different types of plastic surfaces:

- Plastic of the phenol and urea-formaldehyde types as well as the cellulosics can be treated in the following acid etch, provided the excess acid is immediately rinsed away and the parts are immersed in a neutralising solution, such as 10 per cent sodium carbonate:
  - 256 parts (by volume) Sulphuric acid
  - 128 parts (by volume) Nitric acid
  - 1 parts (by volume) Hydrochloric acid
  - 32 parts (by volume) Water
- Treatment for 1-5 minutes in a 5 to 10 per cent sodium hydroxide solution may be used for etching plastics of the cellulose ester group; organic reagents such as 10 per cent acetone may also be used for this type of plastics.
- Many thermoplastic materials have been successfully etched in the following chemical solution:
  - 100 ml Sulphuric acid
  - 15 g Potassium dichromate
  - 50 ml Water

  A two minute treatment in the above solution will etch the plastic surface, making it suitable for metallisation.
- A three minute treatment in the following solution will produce a desirable etching of thermosetting type plastics:
  - 400 ml Hydroquinone
  - 100 ml Pyrocatechin
  - 4000 ml Acetone
- Consultation with a plating expert [6] also offered the following chemical solution which might be effective at etching the surface of polystyrene:
  - 75 ml Sulphuric acid
  - 25 ml Hydrogen peroxide

  This solution is also called a piranha solution and is most commonly used to remove organic residues from substrates, particularly in micro-fabrications labs. The solution may be mixed before application or directly applied to the material, applying the sulphuric acid first, followed by the peroxide. Piranha solutions are extremely energetic and may result in explosion or skin burns if not handled with extreme caution [7].
- A typical etchant used in the plating of ABS is a mixture of chromic acid and sulphuric acid. This tends to 'dissolve' the butadiene particles on the surface of the ABS, creating a rough surface. The purpose of the etching step is two-fold. Firstly, the plastic is etched in such a fashion to increase surface area. Secondly, the plastic is made hydrophilic, making the surface receptive to subsequent activating and plating stages [8]. It was suggested that this solution might aid the process of plating on polystyrene not necessarily only for etching, but also for acting as a cleaning agent.

B.2.3 Suitability of the Process

The process described above was chosen to be further researched as a viable method for manufacturing antennas for a number of reasons. These reasons include economic considerations, ease of manufacture,

electrical characteristics, as well as repeatability in the manufacturing.

- Using good masking techniques should get good repeatability with antenna manufacturing compared to foil methods which require manual placement of the foil onto the substrate.
- Polystyrene is a good substrate to use compared to that of ABS (better electrical characteristics) and Rogers board (cheaper).
- It is a fairly simple process to set up almost completely automated plant, thus eliminating a lot of excess labour.
- The substrate can be of any dimension and shape (depending on the tank size) thus enabling greater flexibility in the manufacturing process.

B.3 Experiments

B.3.1 Initial Plant Setup

Initial experiments were performed using very basic equipment and small solution and prototype sizes. This is so that any parameters can be changed quickly and cheaply, and it enabled a better understanding of the plating process. The figures below give an indication of the set-up for the experiments, using glass beakers and plastic tubs to hold the solution and a basic element for heating the electroless copper solution.

The temperature controller is a digital temperature controller allowing the temperature to be set to the required number. The thermocouple, which switches off the heating element when the required temperature is reached, monitored the temperature of the solution. It was found that the temperature controller was accurate to within 3 °C, which is adequate as the temperature of the plating solutions need to be within 5 °C of the specified temperatures.

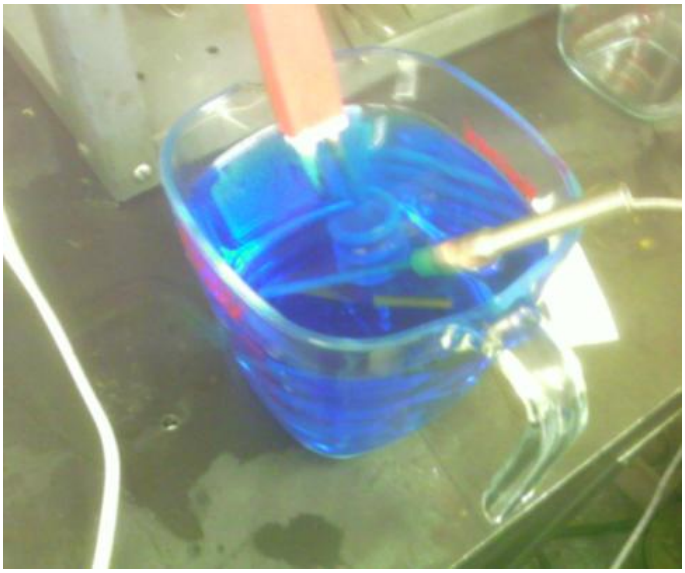


Figure B.2: The glass beaker with the electroless copper solution showing the heating element and the thermocouple.

A glass beaker (*Figure B.2*) was used for the electroless copper plating solution as it needs to be heated to 48 °C and thus the heating element will get very hot and will melt the plastic containers if it comes into contact with them.

The first two plating chemicals were placed in 5 l polyethylene baths (as seen in *Figure B.3*) and the samples were either floated or held down in the baths. Experiments as described in section B.3.2 show that this initial setup is adequate for very basic testing, but is not repeatable or accurate enough for proper tests.

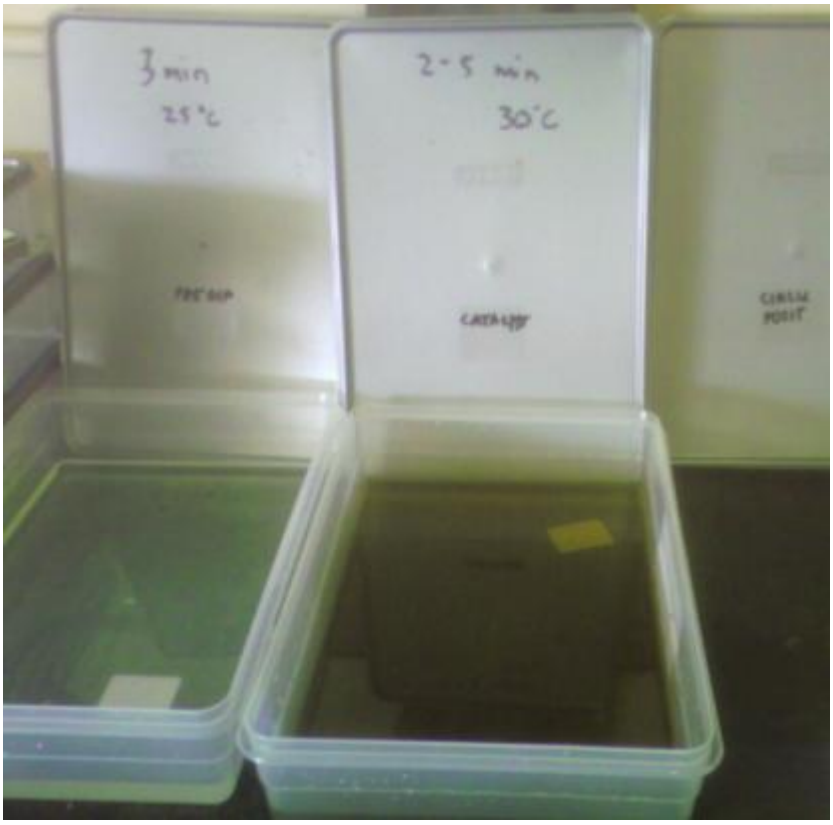


Figure B.3: The pre-dip and catalyst solutions.



Figure B.4: Electroless nickel solution.

The electroless nickel solution shown in *Figure B.4* was used to determine whether adhesion, using electroless nickel as the initial deposit and then copper plating the electroless nickel, would prove to have better adhesion than the electroless copper. The test was inconclusive as the initial preparation for the electroless nickel was inadequate and therefore no coverage or adhesion was noticed. This process could be repeated if necessary using the proper preparation chemicals but is not absolutely required for the initial prototyping experiments.

B.3.2 Initial Etching Experiments

The following section will give a brief description of the experiments as they were performed as well as the results and conclusions drawn from each experiment. These were experiments that were performed using the equipment and conditions described above and helped lead to the final plating method. The substrate used for these experiments was 3 mm thick polystyrene. It must be noted that initially there was only one temperature controller and thus the catalyst solution which is supposed to be at 30 °C was at room temperature (around 22 °C). All the samples went through the same procedure except the first step—the etching—so as to determine the most effective etching method.

- Rubbed gently with abrasive cloth.
  - Very little adhesion except on what was most probably the recently cut edge—which had excellent adhesion and coverage. This edge was fairly rough and clean.

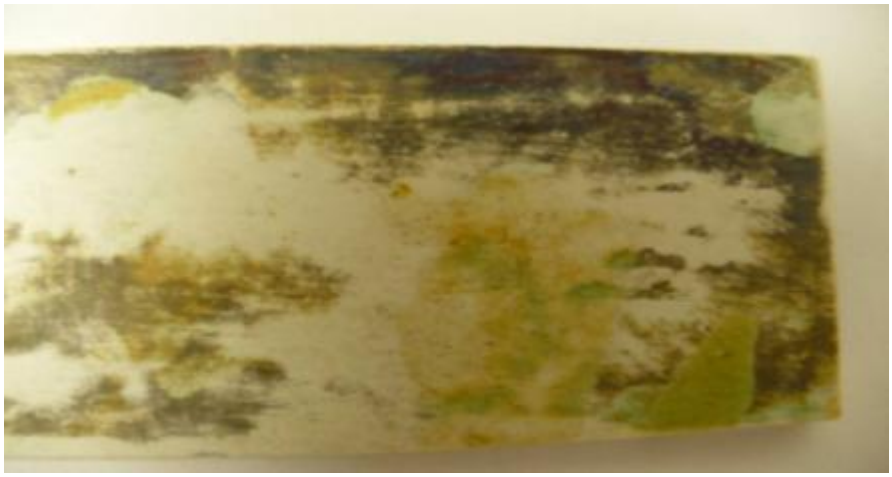


Figure B.5: Early plating sample—very little adhesion.

- Dilute mixture of sulphuric acid (H_2SO_4) and Hydrogen Peroxide (H_2O_2) immersed for approximately 5 minutes.
  - Small amount of coverage with minimal adhesion, edge effect still noticeable (see *Figure B.5*).
- Rubbed with abrasive cloth and long (15 minutes) immersion in dilute (1:4) H_2SO_4 and H_2O_2 solution.
  - Much better coverage and adhesion than previous attempts although the coverage is still patchy.

- Rubbed with rough sandpaper.
  - Speckled coverage, very good adhesion, but the surface was made too rough by the sandpaper (see *Figure B.6*).

- Second try abrasive cloth (same piece of polystyrene as the first test—so was rougher than in the previous test).
  - Good coverage and adhesion, still small patches of uncovered polystyrene. This is probably where the surface of the polystyrene was touched (either with fingers or the tongs) while moving through the process.

- Rough sandpaper and dip in dilute H_2SO_4 and H_2O_2 solution.
  - Very bad coverage, worst result so far (see *Figure B.7*).



Figure B.6: The piece of polystyrene showing the patchiness of the copper after rubbing with rough sandpaper and then plating (sandpaper also shown in the picture for reference).

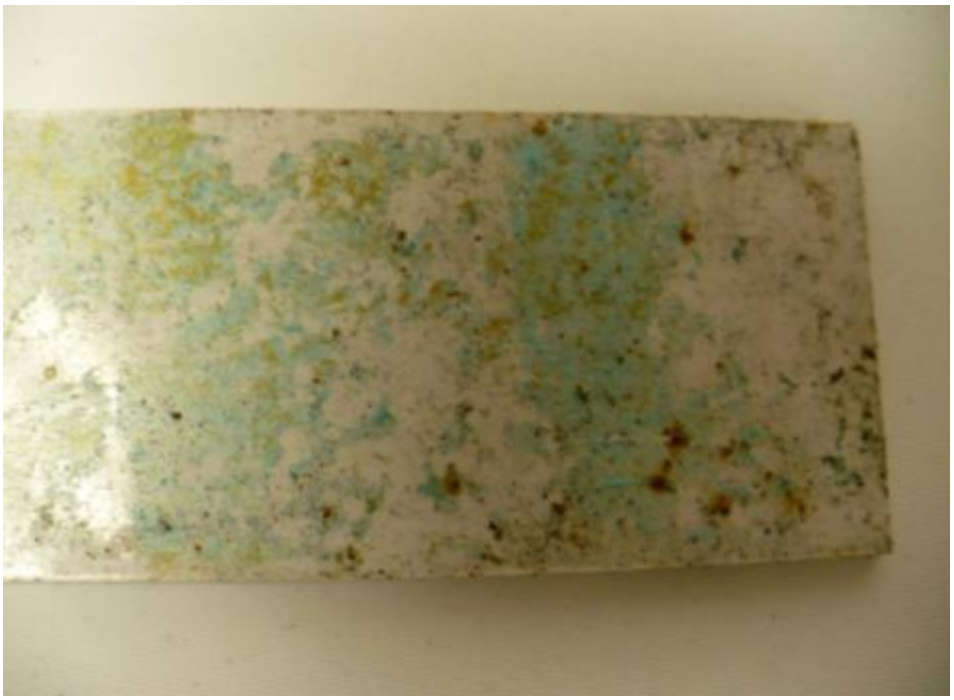


Figure B.7: Very little coverage or adhesion, showing the ineffectiveness of the dilute etching solution.

- Fine sandpaper.
  - Good coverage but still patchy. Adhesion is good in some places, average in others (see *Figure B.8*).

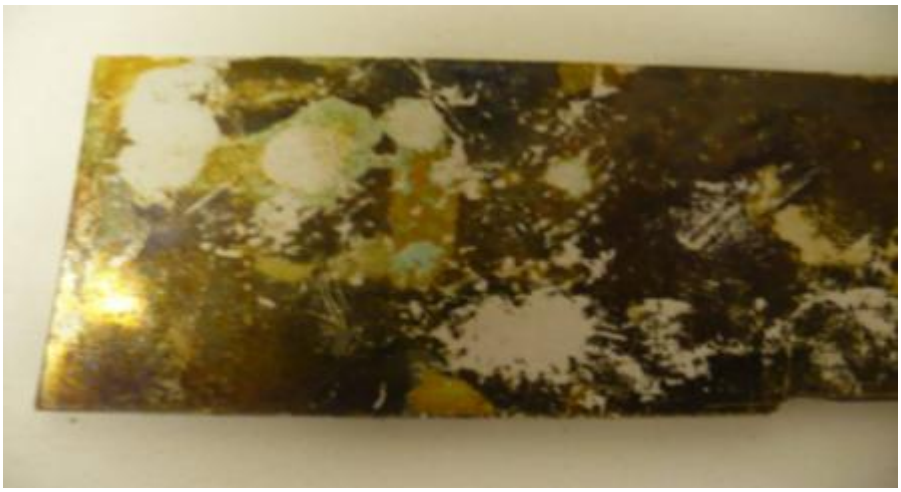


Figure B.8: Test part showing the patchy coverage as well the differences in adhesion on different parts of the polystyrene.

New mixtures of catalyst and copper sulphate solutions (solutions were left for a couple of days and became discoloured).

- Replication of scotch brite abrasion.
  - First attempt with old (discoloured) catalyst solution produced no coating.
  - With new catalyst solution coverage was almost 100% on both sides (rough and smooth) although the rough side shows much better adhesion.

- Pure sulphuric acid etch.
  - Excellent coverage (100%); adhesion was poor on one side, good on other side. Perhaps one side was more submerged in the acid than the other? More tests necessary to get good adhesion.

- Pure Hydrogen Peroxide etch.
  - Poor coverage and adhesion; the hydrogen peroxide did not seem to etch the surface of the polystyrene at all.

- Sulphuric acid and hydrogen peroxide mixture (3:1 respectively).
  - Good adhesion; coverage is once again patchy, possibly due to handling or inefficient cleaning of the polystyrene prior to etching.

- Abrasive cloth together with one minute immersion in the same H_2SO_4 and H_2O_2 solution.
  - Again good adhesion but still not very good coverage. The copper sulphate solution may be running low, and even with care the tongs are making too much contact with the surface of the polystyrene in between stages. The polystyrene also floats in the solutions and must therefore either be manually submerged otherwise only one side is acted on by the chemicals.

- Surface of the polystyrene dabbed with MEK (methyl ethyl ketone) which dissolves polystyrene; the surface was then rubbed with the abrasive cloth.
  - This produced absolutely no adhesion of copper to the surface. The MEK melted the polystyrene and formed a smooth exterior which did not allow the tin palladium catalyst to adhere to the surface.

- Immersion of polystyrene in recently combined solution of sulphuric acid and hydrogen peroxide causes the polystyrene to warp (see *Figure B.9*); this is probably due to the fact that the temperature of the reaction can reach 120 °C [9]. Once the mixture has been allowed to cool to room temperature the surface of the polystyrene does not get etched at all, therefore the solution needs to be heated to a

temperature of around 60–70 °C so that it does not melt the polystyrene but still has an effect on etching the surface.



Figure B.9: The sulphuric acid and hydrogen peroxide solution when recently mixed causes the polystyrene to warp at high temperatures.

- Abrasive cloth on one side of the polystyrene, then immersion into heated sulphuric acid and hydrogen peroxide solution, as well as no rinse after the catalyst stage, gives excellent adhesion and coverage, the best result so far. The side which was not abraded with the cloth has not got as good adhesion.
- Note: After speaking to plating experts it was found that the rinse stage after the catalyst is very important as the tin palladium in the catalyst solution will contaminate the electroless copper bath, and therefore the result described above is inapplicable.

It was decided that in the previous tests, the sample was being handled too much; the solutions were possibly being contaminated by repeated use of tongs to get the sample from one solution to the next; and both sides of the sample were never completely submerged in the solutions as the polystyrene floats. The ‘jig’ used was a simple strip of polystyrene with a hook which hooked into a hole drilled into the sample pieces of polystyrene. An initial test sample, etched using just the abrasive cloth gave 100 % coverage and good adhesion, confirming the usefulness of the holding apparatus.

A second task is to see how the temperature of the catalyst affects the coverage and adhesion of the electroless copper. Thus far, the temperature has been around 22 °C whereas the recommended temperature is 30 °C. The catalyst solution was brought up to the correct temperature using a gas burner. Although not the most efficient way, the temperature was monitored using a temperature ‘gun’ (an infrared temperature sensing device) and it seemed to be fairly accurate. The new methods (holding jig and heating the catalyst) seem to have helped in that samples are now consistently achieving 100% coverage and good adhesion as seen in *Figure B.10.*

The results obtained above showed that there is potential for electroless plating copper on polystyrene. In order to obtain more accurate tests, as well as to calculate the cost of plating the copper, a new plant setup was needed. The new setup enables more accurate tests to be performed, more consistently and in a better working environment.



Figure B.10: The samples are now achieving 100% coverage along with good adhesion.

B.3.3 New Plating Setup

The new setup uses 10 litre tanks, each one having a temperature controller, timer and pump to ensure that the solution is at the correct temperature and that the solution is agitated to fully cover the sample.

The new plating setup allows more accurate and controlled tests to be performed, this helps to establish repeatability in the experiments, as well as to provide a quick and easy method to test new ideas. One such idea is to try a different etch from the ones used in the initial experiments, i.e. the chromic acid etch. It was found that to get better and more accurate results, a small well-controlled setup was required. Due to the fact that toxic chemicals are being used, the need for ventilation and a safer work environment was necessary.

The heaters (as shown in *Figure B.11*) are modified glass fish tank heaters. They were opened up and the bimetal strip was bypassed so that the external temperature controllers were able to control the temperature.

Figure B.12 shows one of the polyethylene tanks which measure 15 cm x 30 cm x 15 cm, and holds 10 l of the plating solution. The holding apparatus consists of a polyethylene strip with stainless steel clips to hold the samples in place. Each tank is marked with the name of the solution, the time needed for the sample to be submerged, as well as the temperature of the solution. Each tank had a heater and temperature controller so that all the solutions were at the correct temperature for optimum performance. The electroless copper tank had two heaters as it requires the hottest temperature (48 $^{\circ}$C) and two heaters heat the solution much quicker than one.

Figure B.13 shows the entire plant with all the plating solutions in the order that they are used in the plating process, as well as two rinse/clean stages. The room was equipped with extractor fans to remove any chemical fumes that are emitted from the tanks. Fumes are especially emitted from the electroless copper tank as bubbles form on the plating surface and release gas into the air when agitated.

Figure B.14 shows how the samples are held by the jig. The smaller samples of the PIFA substrate needs to be extended by using wire to ensure that the entire sample is completely immersed in the plating solutions.

Figure B.15 shows the temperature controller and timer which are used on every tank. The timers are set every time a sample is put in the plating solution and the alarm sounds when the time is up. This ensures that all tests are accurate and repeatable. The temperature controllers have thermocouples to monitor the temperature of the solutions and switch off the heaters when the correct temperature is reached.

The rectifier shown in *Figure B.16* has both current and voltage control. To get good copper plating, a current of 0.025 Amps per square centimetre is required. For smaller antennas a smaller current is required otherwise



Figure B.11: The glass heaters.



Figure B.12: Electroless copper plating tank with two heaters.



Figure B.13: A view of the testing plant.



Figure B.14: The pre-dip tank with a test sample held by the jig.



Figure B.15: The temperature controller and timer.



Figure B.16: Rectifier and plating solution.

the copper tends to bubble and does not plate either evenly or properly.



Figure B.17: Two samples plated using the test plating plant.

Figure B.17 shows two pieces of polystyrene plated using the new setup. Both the coverage and the adhesion of these samples are excellent, and proves that the new setup is beneficial to producing high-quality and reliable results.

B.3.4 Testing the Metallic Deposits

The characteristics of the metallic film formed on non-conductors depend greatly on the process used for the formation of the film. In the manufacturing of antennas, the adhesion strength of the film, the thickness of the film, as well as the electrical characteristics of the film are all important. Methods of testing these characteristics are described below. In order for any of the plating tests/prototypes to be considered a success they must conform to all the tests described.

B.3.4.1 Adhesion Tests

In terms of antenna manufacturing, the adhesion of the copper to the surface of the plastic is probably the most important characteristic, as any peeling/flaking of the antenna will result in inferior performance of the antenna. There are both qualitative and quantitative methods for determining adhesion strength.

- Qualitative tests: A variety of qualitative adhesion tests have been developed for electrodeposited metal coatings on metallic basis materials (e.g. tensile and impact tests), but these cannot be adapted to deposits on plastics. There are, however, many which can be used on a plastic based material [5].
  - Bend Tests: Probably the most simple of qualitative test. If the material can be bent over a radius of the same order of magnitude as its thickness without cracking or fracturing the metallic surface, then the adhesion should be considered acceptable. A further test can be to bend the material backwards and forwards a number of times to see if the coating separates from the base material.
    Figure B.18 shows the adhesion of the electrolessly plated samples is more than adequate. There is no peeling, cracking or separation of the copper from the polystyrene.
  - Scratch Tests: A method of determining adhesion which is described by Halls [10] employs a scratching tool of certain dimensions. The scratching tool is drawn vertically to the surface with firm hand pressure so that it just cuts through the metallised coating. If adhesion is suitable, a clean-cut line with the absence of jagged edges will be evident. Furthermore, if two such cuts are

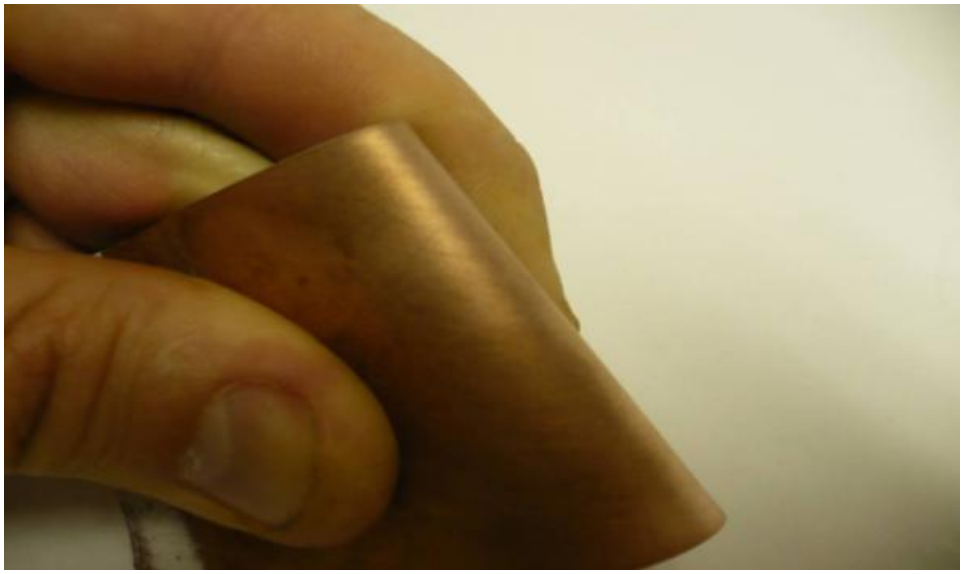


Figure B.18: A sample of plated polystyrene bent to test the adhesion.

made which cross each other at an acute angle, there should be no flaking of the coating from the included angle.
Early samples (as shown in *Figure B.19*) did not pass even basic scratch tests, as the copper peeled from the surface easily once scratched, and jagged lines were observed along the scratch line.

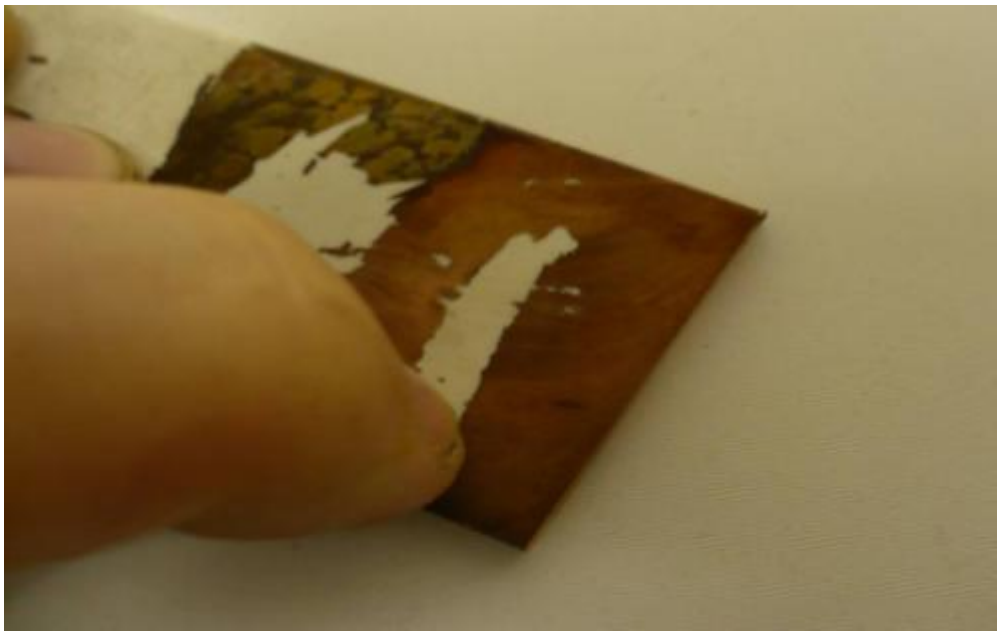


Figure B.19: Scratching of earlier samples produced a peeling effect.

Figure B.20 shows how later samples improved to the point that the polystyrene could be cut/torn and no peeling of the copper occurs. There are also no jagged edges on the side of the copper.

- Buffing Test: A final qualitative test is to polish or buff the surface. Adhesion can be confirmed visually if the deposit does not separate from the basis plastic after polishing without too much pressure.

- Quantitative tests: If the qualitative tests described above do not give either useful or accurate enough results, there are methods of quantitatively comparing the adhesion strength of the metal plating. An apparatus, as used by Burgess [11], can be used to quantitatively test the adhesion strength of the metal to the plastic. Tests like these serve to confirm the theory that copper films show better adhesion to

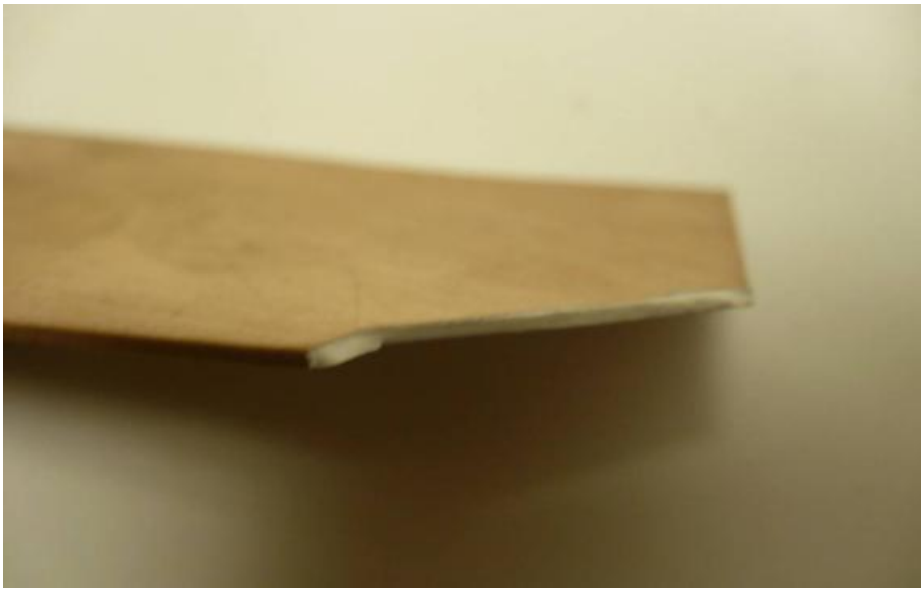


Figure B.20: Later sample with torn corner shows the straight tear of the copper, with no peeling.

roughened surfaces rather than smooth surfaces. Hence the advantage of roughening plastics prior to film formation for subsequent electro-deposition is again made noteworthy [5].

B.3.4.2 Thickness Tests

A variety of thickness tests have been developed for evaluating the thickness of the electrodeposits on metallic basis materials, of which not all are directly applicable to metallised coatings on non-conductors [5]. This, however, is not of the utmost importance in antenna manufacturing, as the only importance for the thickness is in the solderability of the coating. If the electrolessly deposited coating is not thick enough to solder on, then either the whole thing can be electrolytically plated to increase the thickness, or just the end of the antenna which needs to be soldered can be plated. Of course, electroplating the entire antenna surface has the additional benefit of protecting the surface from corrosion and oxidation, giving it a bright and shiny surface. Soldering experiments are described in more detail in Section B.3.4.4 below.

The extra electroplating of the sample thickens the copper deposit, but this leads to an increase in likelihood of peeling and cracking when bent. This phenomenon can clearly be seen in *Figure B.21* below.

B.3.4.3 Electrical Characteristics

The antenna obviously needs to be able to perform adequately with regard to its electrical characteristics. Using copper as the metal deposit, the main area of interest is whether the antenna is thick enough for the entire current to propagate properly. This factor is dependent on the frequency of the signal, and can be determined by looking at the skin depth of the material. The skin depth is defined as the depth to which the current is attenuated to 1/e of its original intensity [12]. Skin depth can be measured using:

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{B.1}$$

Where:

ω :	Frequency of interest in radians/sec
σ :	Conductivity of the material in Siemens/m
μ :	Permeability of the material in H/m

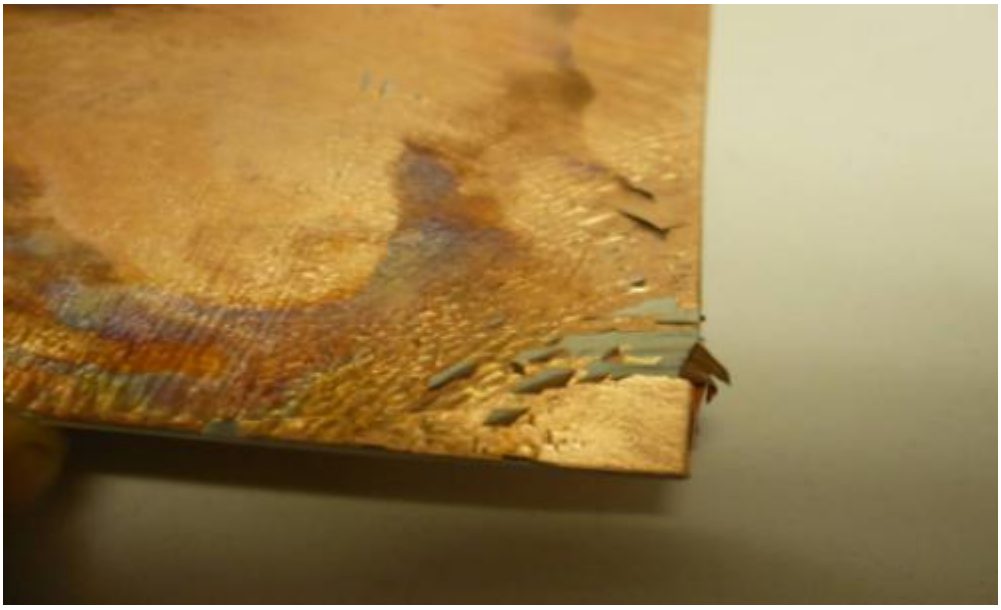


Figure B.21: Electroplated sample after bending.

This shows that the higher the frequency, the thinner the antenna needs to be. A useful characteristic of plating on plastic is that the thickness of the deposit is directly related to the amount of time that the part is subjected to the plating process. In electroplating, the copper grows at a rate of about 1 μ/min [13]. Using equation B.1, copper, at a frequency of 900 MHz, has a skin depth of 2.2 μm. A useful rule of thumb states that for maximum efficiency the conductor should be about five times the skin depth [14]; this equates to a plating time of about 10 minutes. This time decreases for any frequencies higher than 900 MHz.

B.3.4.4 Ability to Solder

The ability to solder to an antenna is crucial as most antenna feeds are connected to the antenna by means of soldering. *Figure B.22* shows a test of soldering on the plated polystyrene.



Figure B.22: Electroless plated sample being soldered. If the solder is applied quickly then the copper does not burn away.

When soldering on the electroless copper deposition, the copper tends to burn very easily. This can be counteracted by adjusting the temperature of the soldering iron, but this is a limited solution due to the fact that lead free solder (which is environmentally friendly) requires a higher temperature compared to normal leaded solder. A solution to this problem is to electroplate the antenna. Electroplating can be done exclusively on the part of the antenna which needs to be soldered. This is useful as it uses less copper, and is viable since the solder point is normally near the end of the antenna. The other problem with electroplating is that the copper tends to break and peel if bent too much. This problem is also negated if one only plates the part that needs to be soldered and leave the rest as electroless copper.

B.3.5 Protecting the Finish

Figure B.23 and *Figure B.24* show the contamination of the electroless copper after only a few days. Although this will not adversely affect the electrical characteristics of the plating, the aesthetics of the antenna will be severely compromised.

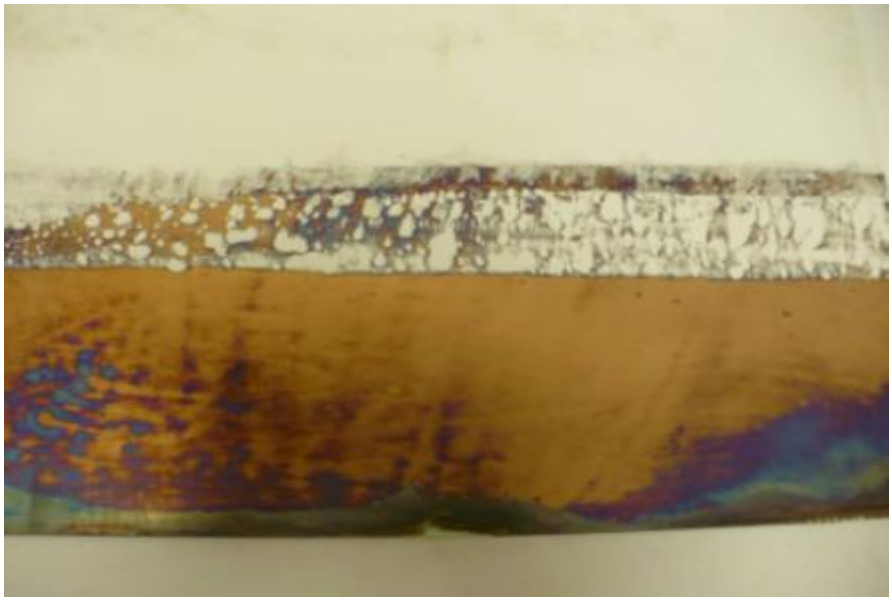


Figure B.23: A sample after one day showing the oxidation of the coppers

There are many ways to combat this phenomenon, and it remains only to determine which method is the cheapest and easiest method to implement. Some of these methods include nickel plating, clear lacquer spray, and electro copper plating. The copper electroplating has the advantage of making the copper deposit thicker, and thus easing soldering. The most useful and sufficient method will most likely be to electro copper plate the antenna where it needs to be soldered and then tin plate the entire antenna to prevent corrosion and keep the finish bright.

B.3.6 Heating to Increase Bonding

A fan oven with a temperature range of 0–250 °C was used to heat the plated polystyrene to determine whether this had any effect on the bonding of the plastic and the metal deposit. The fan ensures that the temperature of the oven is even throughout. The oven is used to determine both whether heating does in fact increase the bond between the copper and the polystyrene and what temperature is the optimum for the bonding.

Table B.1 shows that a temperature of 150 °C gives the best results for increasing the bond between the copper plating and the polystyrene substrate.

Figure B.25 shows the warping that occurs when the temperature of the oven exceeds 160 °C. *Figure B.26* below proves that the bond strength has been increased by the heating as indicated by the scratch test.

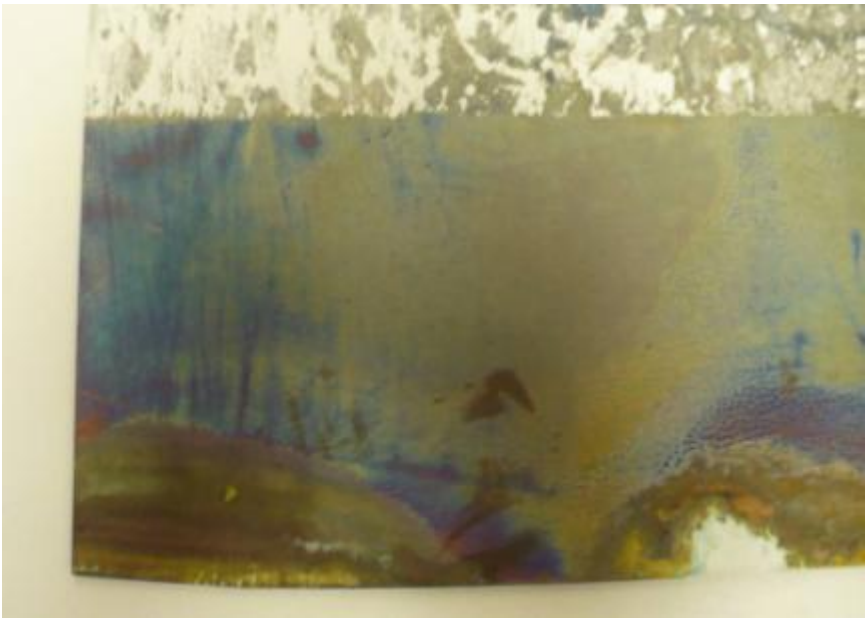


Figure B.24: The copper continues to oxidise and turns grey after about two days.

Table B.1: Results of the temperature tests on bonding between copper and plastic

Temperature (°C)	**Result**
70	No change
110	Slightly better adhesion, still not great
120	Adhesion still improving
140	Good adhesion, could possibly be slightly better
150	Best adhesion, optimum temperature
160	Good adhesion, but slight warping of the plastic
170	Excessive warping, temperature is too high

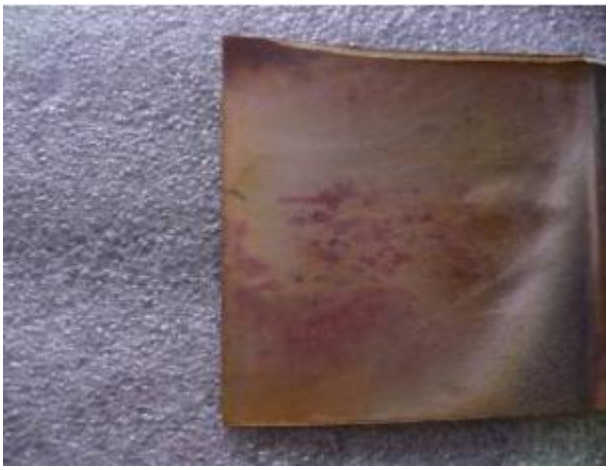


Figure B.25: Warping of the sample occurs at high temperatures.

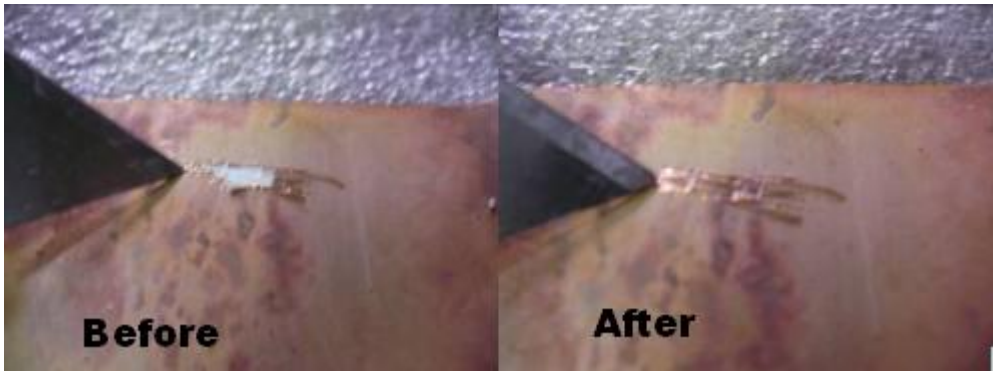


Figure B.26: Scratch test before and after heating.

A bend test performed on the sample after it has been in the oven shows that the copper does not delaminate, but it does become brittle and loses some of its strength. After heating, it is noted that the properties of the plastic alter slightly as it is now not as bendable – it breaks more easily than before. This brittleness is not a huge problem as the antennas will not be bent to such a degree once plated.



Figure B.27: Bend test after heating.

B.3.7 Preparing the Surface

In order for effective and complete plating to occur on the polystyrene, the glazed surface, as well as any oils and dirt on the surface, must be removed. During testing this was accomplished by manually sanding the surface with a scouring abrasive cloth. This is obviously not useful or efficient when dealing with large volumes. A machine could be manufactured to perform this function; it would roughen and clean the entire surface of a sheet of polystyrene quickly and easily with very little labour requirements [15].

B.4 Masking Tests

- A first simple test was to draw a pattern with a permanent marker on the polystyrene after it has been cleaned and roughened by the abrasive cloth.
  - The copper was deposited all over the surface of the polystyrene, but it was patchy where the permanent marker had been applied. This copper could easily be washed off (along with the permanent marker) using whiteboard cleaner (see *Figure B.28*). It also came off with fairly gentle rubbing. The pattern that was left was clearly defined and had good adhesion. This solution is not ideal, however, as it uses more copper than is necessary, and it requires an extra cleaning step after the antenna has been electrolessly plated.



Figure B.28: First basic permanent marker masking test.

- Next, the permanent marker mask was applied after the polystyrene had been in the catalyst solution. The mask serves to block the catalyst and, in theory, no copper will be deposited on the masked area.
  - The theory was proved correct as no plating occurred on the marker. This is a good result, as the coverage and adhesion around the mask is excellent. The only extra step that is required using this type of process would be to dry the polystyrene before the mask is applied—a simple task. It also leads to different ways of applying the mask as the antenna pattern can obviously not be drawn on by hand. These other methods are discussed below.

- A further masking test was done by putting tape over the polystyrene and then spraying with lacquer based spray paint.
  - This method did work, but not quite as well as the permanent marker, possibly due to the fact that the sticky tape contaminated the catalyst surface and thus the adhesion was not as good as it may have otherwise been. This shows that the mask should not use any form of sticky contact with the substrate.

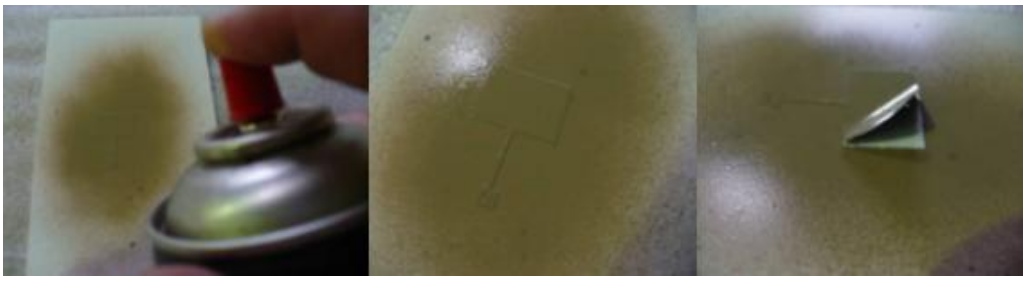


Figure B.29: Masking using spray paint.

Masking using spray paint as shown in *Figure B.29* works, but the paint is too thick and does not provide a good straight line on the sides of the mask. A similar approach of spraying ink rather than paint could be used to better effect.

Figure B.30 shows an attempt at masking a PIFA (Planar Inverted F Antenna) using a fine tipped permanent marker. This test showed the accuracy and precision that can be obtained with an ink based masking technique. It must be noted, however, that one masking test—using a water based ink stamped onto the surface of the polystyrene—was a failure as the ink washes off in the electroless plating solution. Therefore, oil based or permanent type ink must be used when masking the antenna pattern.

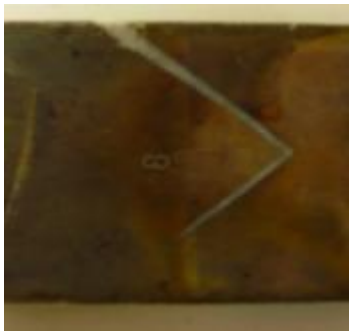


Figure B.30: First attempt PIFA antenna.

B.5 Conclusion

A detailed description of the plating process has been provided, along with all the experiments conducted to ensure that the process is viable for the production of antennas. Modifications to normal plating processes were needed so that polystyrene could be used as the substrate. Experiments showed that by using different etching techniques than for normal ABS plating, polystyrene can be adequately plated. Masking tests also confirmed that an accurate shape of an antenna can be plated on the polystyrene.

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Appendix C

Prototypes and Results

Abstract

Two prototype antennas (a PIFA and an omnidirectional antenna) were manufactured using a new plating on polystyrene method. They were tested to see whether they satisfy electrical, physical and cost characteristics compared to antennas manufactured using older methods. The antennas were compared to others using VSWR and gain plots and were found to be more than adequate. There was a slight frequency shift of 10% on the VSWR plot for the PIFA antenna, and a frequency shift of 0.4 GHz on the gain plot of the omni antenna. The new method is also found to be cheaper than other methods, with calculated savings of up to 4 000% on the substrate over Rogers board, and savings of 700% on metal costs.

C.1 Introduction

This document provides details on the production of two prototype antennas which were manufactured using a plating on plastic process. The intention is to verify that the new method is viable as a new manufacturing technique. This is accomplished by testing the two antennas electrically and physically, as well as by an analysis with regard to cost.

C.2 Prototypes

The following prototype antennas have been manufactured using the plating method described in [2]: PIFA antenna, and an azimuthal omnidirectional antenna.

C.2.1 PIFA

PIFAs (Planar Inverted F-Antennas) are internal antennas which have the desirable features of compactness, moderate range of bandwidth, higher gain in principal planes for both states of polarization, are less prone for breakage, and reduced power absorption with the user as compared to external antennas. In addition to cellular applications, PIFAs have become attractive candidates in a variety of commercial applications such as Bluetooth and mobile satellite communications [6].

The substrate used for the PIFA is an injection-moulded polystyrene. It is thicker and more sturdy than the extruded polystyrene that was used in the plating tests. This injection-moulded polystyrene plates with similar ease to that of the extruded polystyrene, and the sturdiness adds to the adhesion strength of the plated copper. The surface has a fine ‘spark’ finish (a textured surface which is created by the injection mould) which also helps the plating to adhere. The advantage of the moulded item is that it is possible to achieve any shape that is required for an antenna design and that this moulding process is cheaper than extruded polystyrene. Injection moulding has little or no wastage of material [3]. The PIFA has a 6 mm thick substrate and a relatively small surface area. This was found to be advantageous as the antenna is rigid. This helped with the peel strength of the antenna and the electroplated material showed good adhesion to the substrate surface.

Figure C.1 shows the plated PIFA antenna prototype. The slightly rough edges on the plating of the antenna, as seen in *Figure C.1*, are due to the impreciseness of the permanent marker pen, as well as the inherent roughness of the injection moulded plastic base.

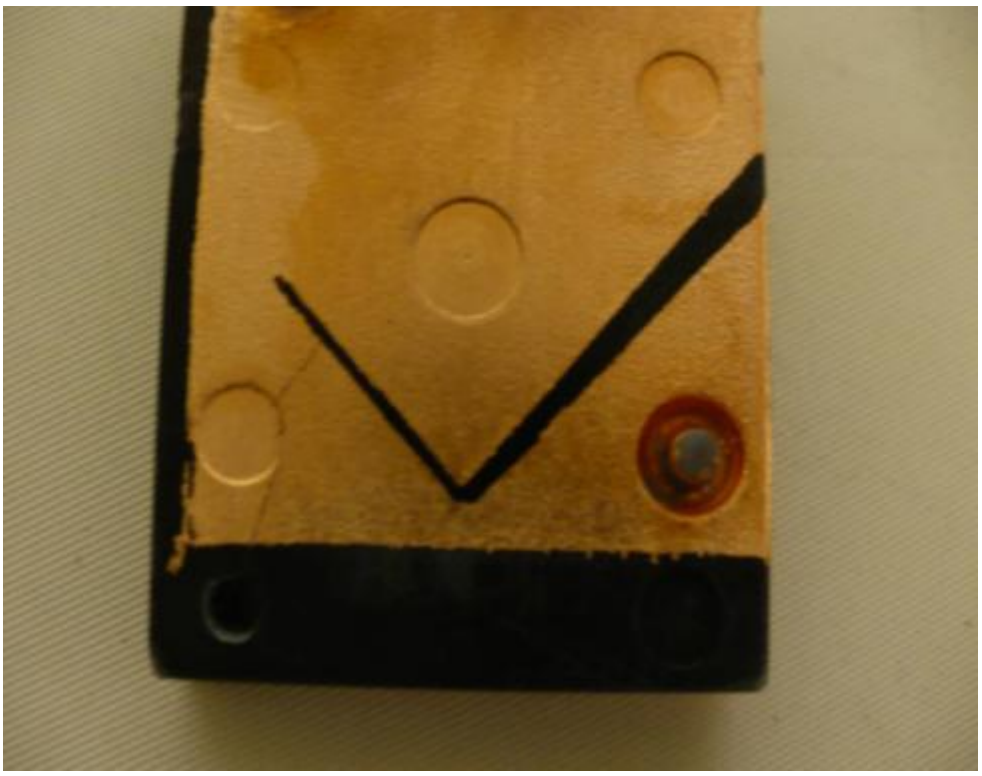


Figure C.1: PIFA antenna prototype.

The antenna was masked by placing a metal piece cut out in the shape of the antenna over the polystyrene substrate (shown in *Figure C.2*).

Figure C.3 shows the prototype PIFA antenna with connector soldered on to it. This is used to test the antenna's properties and shows that the copper is thick enough to solder. *Figure C.4* shows the original metal stamped PIFA antenna used as a reference for tests to determine the effectiveness of the plating technique to manufacture antennas.

Figure C.5 shows the plot of the VSWR (Voltage Wave Standing Ratio) vs. frequency for the plated PIFA antenna and the original PIFA antenna. The original PIFA antenna was designed to be a dual-band cellular planar inverted F antenna. Normally it would be mounted inside an enclosure where the resonant frequencies would shift to the required cellular band. The original PIFA has two characteristic resonant frequencies. These show up as two deep notches in the VSWR plot at about 1 010 MHz and 1 950 MHz. The plated PIFA also shows these two characteristic resonant frequencies, except at 910 MHz and 1 750 MHz. The percentage error between the lower frequency notches is 9.9%, and 10.2% between the higher frequency notches. This means that the plated PIFA antenna is simply frequency shifted, a simple process to alter in antenna design. The main property of the antenna, i.e. the notches, are actually more defined than for the metal stamped antenna and thus the plated antenna will probably perform better than the original. The cause of a frequency shift is usually due to incorrect lengths of the antenna tracks. Since the plated antenna is plated directly on to the substrate and the metal stamped antenna attaches above the substrate, this could account for the slight frequency shift. These factors indicate that it will work well as a PIFA antenna, even though this protype is out of band. An antenna specifially designed with the plating process in mind can then be made to operate at the correct frequency.

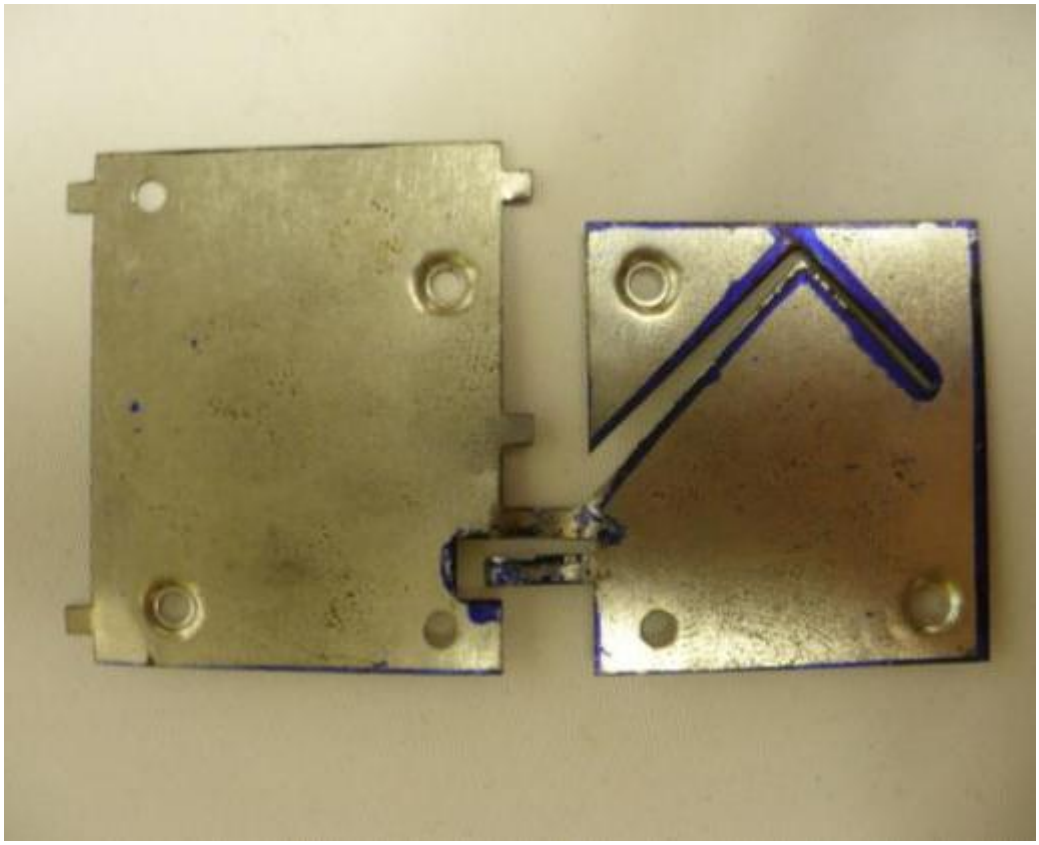


Figure C.2: Metal mask used to get PIFA pattern.

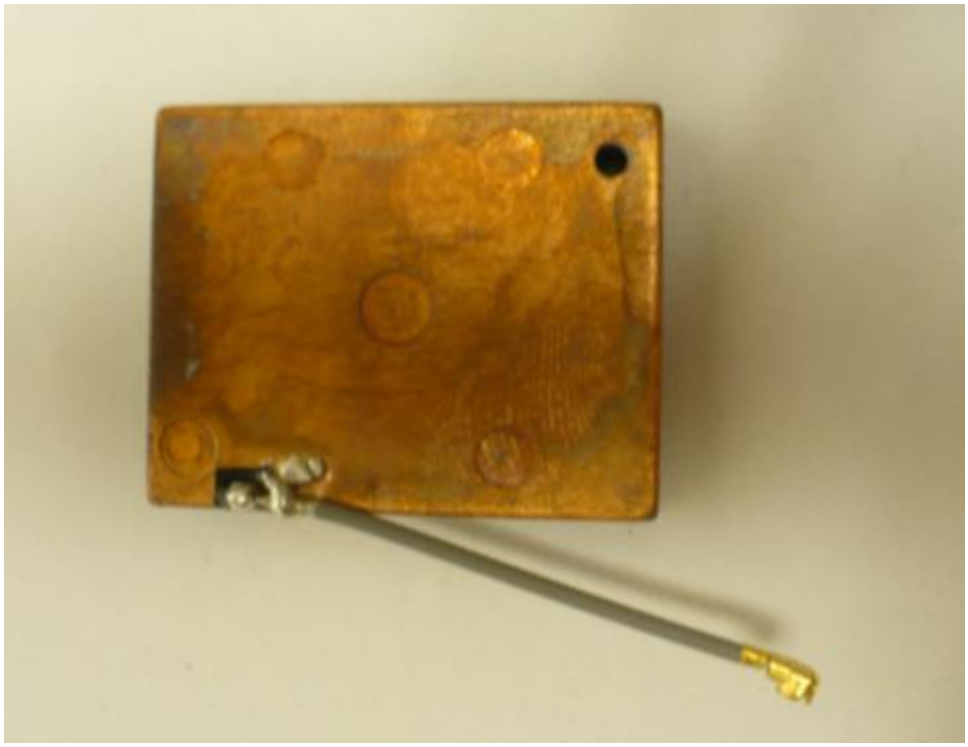


Figure C.3: The PIFA antenna with connector soldered on to it.

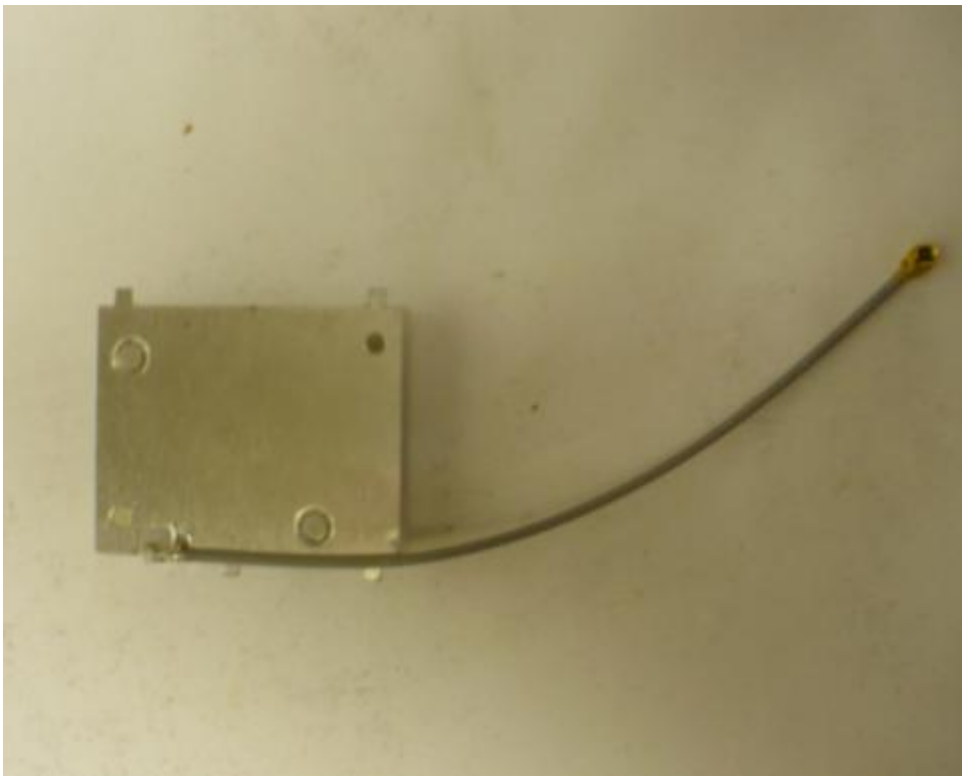


Figure C.4: Original PIFA antenna.

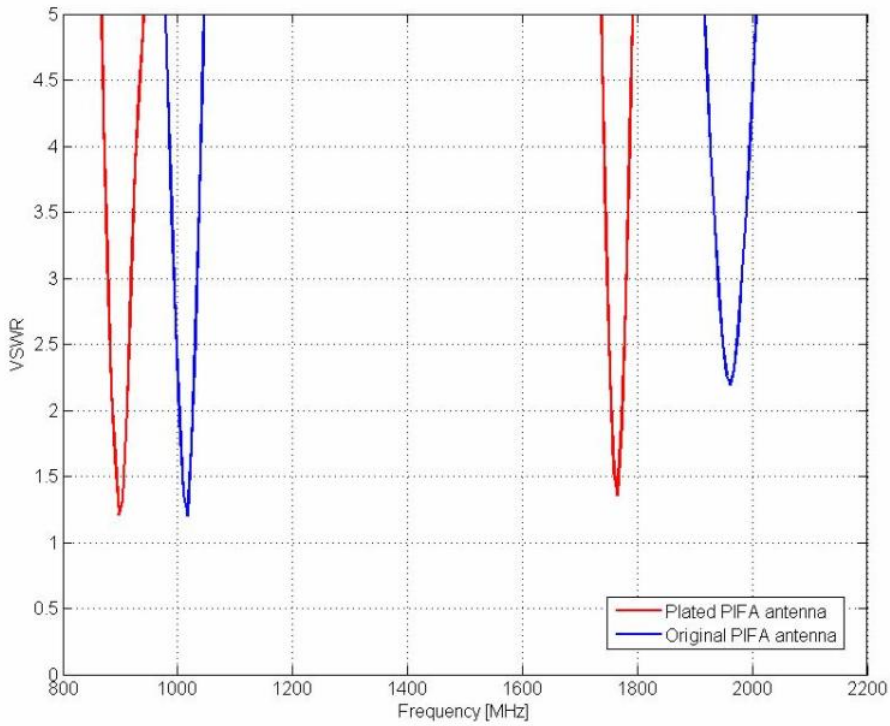


Figure C.5: Graph of VSWR vs. frequency for the two PIFA antennas.

C.2.2 Omni Antenna

Omnidirectional antennas are generally realised using collinear dipole arrays. These arrays consist of half-wavelength dipoles with a phase shifting method between each element that ensures the current in each dipole is in phase [1].

Figure C.6 shows the copper plated omni antenna, with polystyrene as the substrate. The copper is too thin to solder, but after electroplating the copper is thick enough for soldering. *Figure C.7* shows the original FR4 manufactured omni antenna, which is the old technology which needs to be replaced.

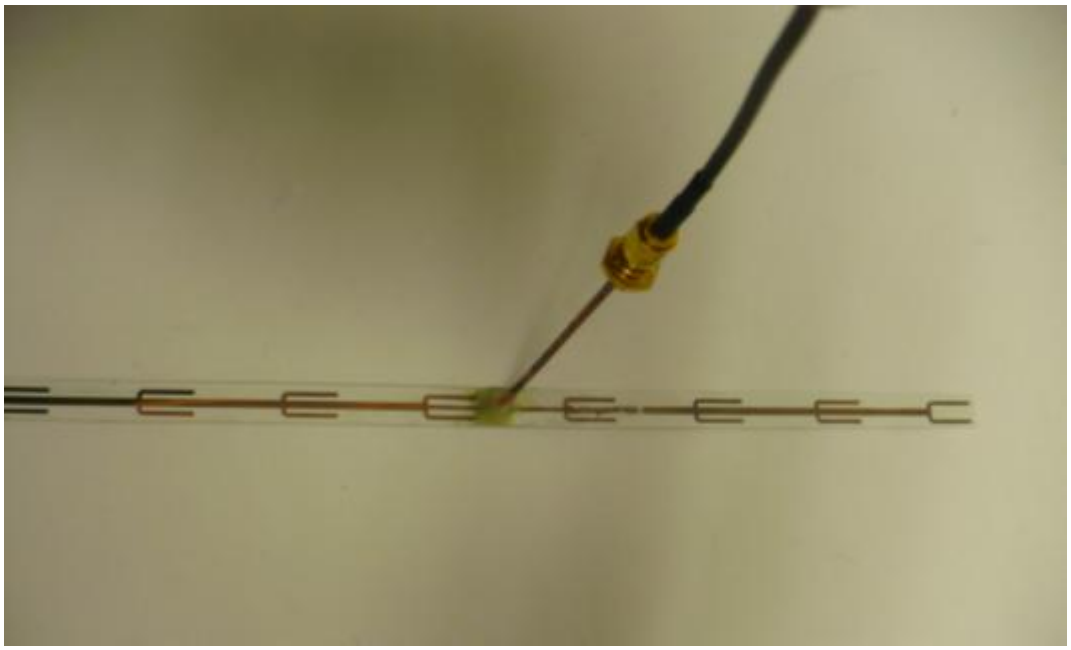


Figure C.6: The copper plated omni on polystyrene.

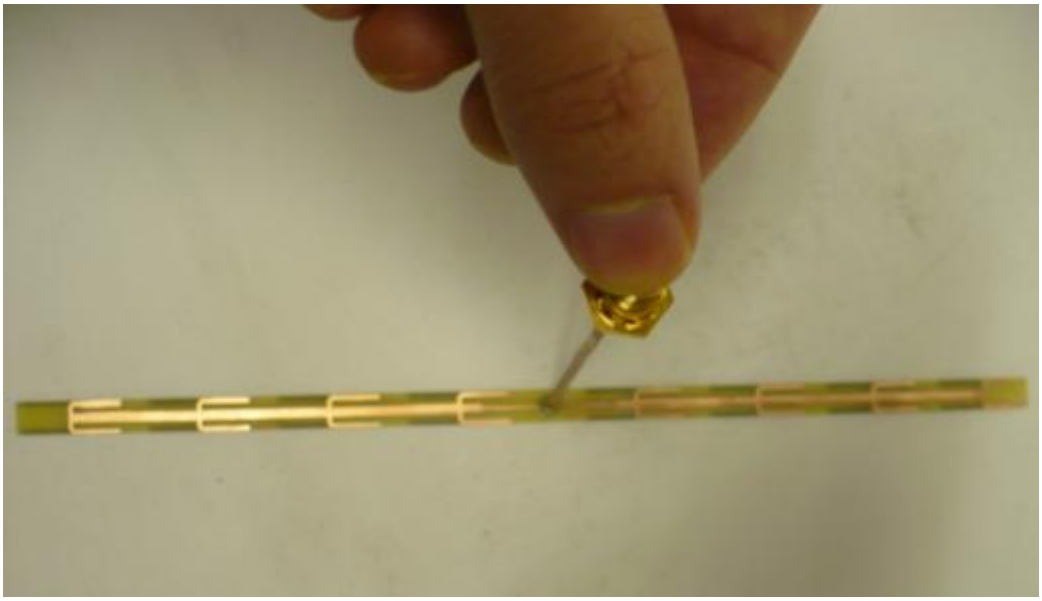


Figure C.7: The FR4 based omni antenna.

The S21 plot (*Figure C.8*) shows a comparison between the FR4-based antenna and the polystyrene-based antenna. The two antennas were made directly from the simulated data and were not physically optimised. It can be seen that the FR4 antenna operates over a much larger band, but with a lower gain. This can be

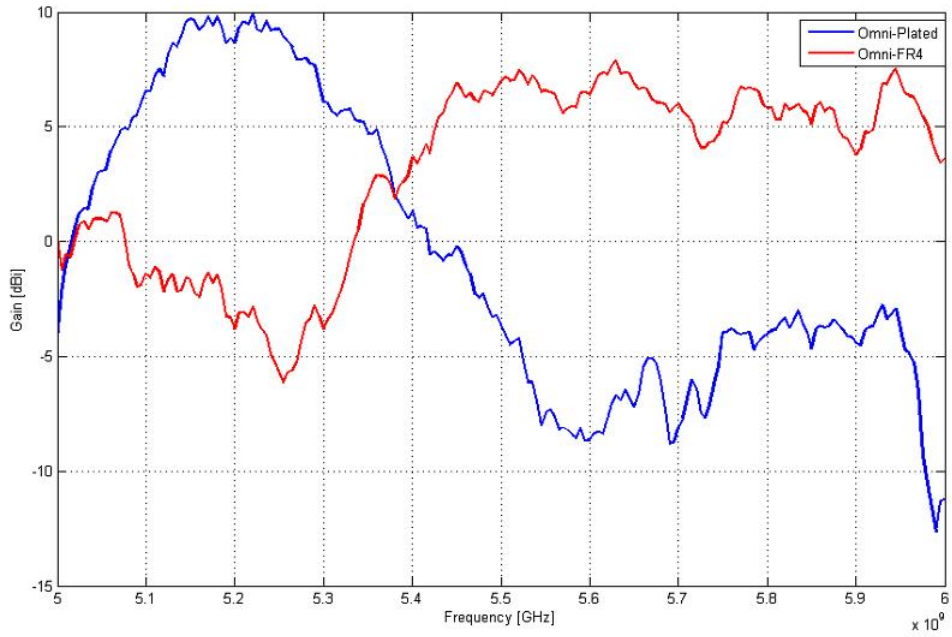


Figure C.8: Graph of gain vs. frequency for the two omni antennas.

attributed to the lossy FR4 material and the smaller aperture of the FR4 antenna. The polystyrene antenna has a much larger aperture with the same number of antenna elements. The lower dielectric constant allows a better element distribution due to the lower velocity factor of the material; this allows the transmission lines between the elements to be longer on the polystyrene substrate to achieve the correct phasing and thus a much larger, increased aperture antenna [4].

C.3 Comparison of Costs with Old Methods of Manufacture

The estimated costs for copper plating on plastic are outlined in detail in Tables C.1 and C.2.

Table C.1 shows the costs associated with electroless plating copper on polystyrene. If it is deemed necessary to electroplate the antenna for extra thickness and durability, then the chemical costs associated with this process are shown in Table C.2.

To get an approximation of the saving in cost using the plating technique compared to that of the old method used in manufacturing the PIFA antennas, the following results were obtained.

The cost of metal to make the PIFA antenna using stamped metal is R 0.70, the plastic substrate is R 0.73, and the labour cost is R 3.48. This gives a total cost of R 4.91.

The plating method costs are as follows: 3.5 cm $\times$ 2.5 cm $\times$ R 58.18 /m2 = R 0.10, the labour costs are minimal and can therefore be halved from that of the original antenna. This gives a total cost (for materials, excluding connectors) of R 1.84. The savings from the cost of the metal coating is obvious—down from R 0.70 to R 0.10—but the set-up costs for the manufacturing plant are significant. This is obviously a once-off payment and can only be factored into the cost once an estimate is made of the number of antennas which can be made using the plating process.

A better comparison would be to compare the cost of a Rogers board antenna (a material with similar characteristics to that of polystyrene, but significantly more expensive) which costs 40 c/cm^2. Polystyrene on the other hand is priced as follows:

Table C.1: Costs of chemicals needed to electroless plate copper onto polystyrene [5].

Step	Process	Chemical	Cost per m^2 (R)
1	Surface Etch	Demineralised Water	0.05
		Chromic Acid	0.67
		Sulphuric Acid	0.05
2	Neutralise	Demineralised Water	0.05
		Hydrochloric Acid	0.03
3	Predip	Demineralised Water	0.05
		Predip 3340	0.32
4	Catalyst	Demineralised Water	0.05
		Circuposit 3340	0.80
		Catalyst 3344	0.75
5	Electroless Deposit	Demineralised Water	0.05
		Circuposit 3350 M	0.46
		Circuposit 3350 A	19.94
		Circuposit 3350 B	0.19
		Circuposit 3350 C	11.89
		Circuposit 3350 R	12.02
		Cuposit Y	1.50
		Cuposit Z	1.35
		Total:	**R 50.22**

Table C.2: Costs of electroplating chemicals [5].

Step	Process	Chemical	Cost per m^2 (R)
6	Copper Plating	Demineralised Water	0.05
		Sulphuric acid	0.12
		Copper Sulphate	0.10
		Coppergleam Part A	4.00
		Coppergleam Part B	3.69
		Total:	**R 7.96**

Cost of Polystyrene: 3mm polystyrene sheet R 349.41
Sheet size 2 500 $\times$ 1 250 mm

1mm polystyrene sheet R 116.49
Sheet size 2 500 $\times$ 1 250 mm

This works out to less than 1 c/cm^2.

So an antenna made with 0.8 mm Rogers board will cost 40 c/cm^2 for the substrate whereas an antenna made with 1mm polystyrene will cost less than 1 c/cm^2. This is a saving of 4 000% on the substrate. The process for calculating total cost of manufacture is obviously more complex, but the savings on the substrate alone make the copper plating method viable and cost attractive.

C.4 Conclusion

A new method of manufacturing antennas has been presented. This method has been tested by manufacturing two prototype antennas. These antennas were analysed with regard to their performance when compared to other antennas produced using standard techniques. The antennas produced using the new method performed favourably with regard to electrical characteristics; and the cost and material savings that could be realised is substantial. The savings in material are up to 4 000% on the substrate, 700% on metal costs. These savings need to be offset against any additional equipment costs, but it is certainly a manufacturing technique worth investigating further.

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