Rapid prototyping lightweight millimeter wave antenna and waveguide with copper plating

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We present a novel method of rapid prototyping waveguide and antenna using plating on plastic technique. The part is created by high precision 3D printing and plated with copper using both electroless plating and electroplating. The performance is comparable with industry made waveguides and antennas but the time and cost for creating these parts are largely reduced.

I. INTRODUCTION

TRADITIONAL waveguides and antennas are made with pure metal, which suffer from heavy weight and high manufacturing cost. Lightweight and low cost waveguides and antennas are thus much desired, especially for mobile and aerospace applications. This trend has driven the research in fabricating microwave components by metalizing plastic parts [1, 2]. With the fast advance of the rapid prototyping technologies, 3D printers are able to print with adequate precision for making microwave components dedicated for high frequency applications [3]. Rapid prototyping allows freedom in designing components and also reduces the time and cost for building customized pieces, while maintaining low insertion loss and desired radiation patterns [4, 5].

However, previous metalization for rapid prototyped lightweight microwave components was either done by spraying conductive coating [4] or by depositing copper with electroless plating [5]. The former method suffers from non-uniform deposition, and the performance of the resulting plating may not suffice for fabrication of low-loss waveguide sections. While the latter method does generate a uniform coating, the resulting plated copper is very thin, the process itself is slow, and the electroless plating produces more chemical waste than electroplating. Furthermore, the method described in [5] does not employ a split block design, thus requiring electrodeposition inside a tube making a waveguide. Since accessing the interior of a convoluted waveguide becomes progressively more difficult as the number of bends in the waveguide increases, this technique is limited to relatively simple structures. For the case of manufacturing a complicated network, it is hard to ensure a good surface deposition without exposing the inside of the structure.

Here we present a novel method for manufacturing lightweight metal plated waveguides and antennas that addresses the above problems. A 3D model for a waveguide or an antenna is designed and printed using high resolution 3D printer. A copper seed layer is then deposited onto the surface of the part by electroless deposition. Electroless deposition ensures the plated area has a uniform thickness over the entire surface, but is usually very thin with a short period of plating. To strengthen the plated copper layer, the part is then electroplated with copper. The finished parts are then treated with a protective layer of benzotriazole and acrylic to prevent the part from oxidation and scratches.

II. METHOD

A WR42 waveguide is designed in the split-block fashion by cutting the waveguide along the center of its E-plane, i.e. across the broad wall. The dominant TE_{10} mode confines all electric fields are transverse to the direction of propagation and perpendicular to the broad wall, thus cutting across the middle of the broad wall ensures good construction of the narrow walls that short electric field at both ends, as shown in Figure 1a. The waveguide features a 0.42 inch x 0.17 inch channel, 200 mm in length, and standard UG-599/U flanges. The parts are joined together using bolts that are inserted into the holes along the substrates. A K-band pyramidal horn with a WR42 adapter is designed featuring a standard flange pattern. The horn is 190 mm long with a 4.13 inch x 3.11 inch aperture. The pyramidal horn is also split from the E-plane. The prototypes are created using a Stratasys Object350 Connex 3D printer with 0.016 mm layer resolution and 0.1 mm lateral resolution.

The metalization method we developed is based on traditional electroless copper and electroplating procedures, with modifications to adapt to manufacturing microwave devices in an academic lab environment. To prepare the part for metalization, the support material must be removed and the parts must be cleaned thoroughly with strong degreaser such as trisodium phosphate. Any amount of residual grease on the surface will prevent the part from successful metal plating. After the part is cleaned, the next step in metalization is etching the surface with a strong oxidizer. This step is necessary because the 3D printed plastic material needs to be made hydrophillic so that the coating adheres to the plastic surface. A strong oxidizer such as hydrogen peroxide will oxidize the part's surface and produce microscopic pores that function as bonding sites for the catalytic material. The part must be rinsed with deionized water following each step in the procedure. The next step, electroless plating, utilizes an oxidation- reduction chemical reaction rather than electrodeposition. The plastic surface needs to be catalytically

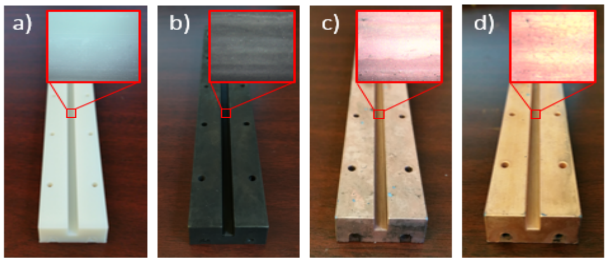

Fig.1 a) The half WR42 waveguide block during the plating process, the insets show the microscopic image of the part surface. a) after cleaning support material and grease. **b)** with silver deposited as catalytic agent for electroless copper plating. **c)** after electroless copper plating **d)** after electroplating and coated with benzotriazole.

activated before electroless deposition. However, traditional electroless copper plating requires palladium as catalyst [6], which imposes a high cost to manufacturing waveguides and antennas in a lab environment. Instead, in our procedure we choose to use silver (Ag) - a cheaper and more accessible alternative [7]. Colloidal silver is deposited on the part using repeated submersion of the part in tin(II) chloride and silver nitrate solutions. The concentrations of reactants and the temperature are two important factors that control the reaction rate and must be carefully controlled. The detailed method and procedure for electroless copper deposition is described in [6, 7] Successful electroless plating is able to deposit copper of a few microns, which is enough to act as a seed layer for electroplating.

Following the electroless deposition, the part is plated using electrolytic deposition to enhance surface copper deposition. Common techniques employ acidic electroplating using sulfuric acid or fluoboric acid [8], but a weaker acid that dissolves copper such as acetic acid can be used when less hazardous chemicals are preferred. Electroplating microwave devices such as waveguides requires the inner surface of the channel to have a bright finish, indicating a smooth surface with low loss. One key factor in achieving smooth and bright copper deposition is introducing additives in the plating solution. To achieve this goal, we adapted the additive recipe introduced by IBM in the damascene process, which has been widely used in on-chip metalization[9]. In common damascene process, copper sulfate based electroplating bath utilizes small amounts of chloride ions and polyethers such as polyethylene glycol (PEG) as suppressor, a sulfur-based organic compound such as 3-mercapto-1-propanesulfonic acid as brightener, and an aromatic nitrogen based polymer such as Janus Green B as leveling agent to produce mirror-flat surface [10]. Another key factor is the agitation of the plating bath. Good agitation ensures uniform copper deposition, and reduces the current density needed for the electroplating.

The finished part is then immediately rinsed and transferred to a benzotriazole bath, which inhibits corrosion due to surface oxidation. To further protect the soft copper, diluted acrylic latex suspension solution is applied to the part. Figure.1 depicts the results and the surface finishing of a WR42 waveguide part after each procedure.

III. RESULTS

We demonstrate the deposition results and performance of the pyramidal horn and the K-band waveguide section. The performance of the plated rectangular horn is tested with near-field scanning, as shown in Figure 2a. The scans are performed at 20cm away from the horn at 18GHz and 26.5GHz respectively. As shown in Figure 2b-2c, the results are compared with an identical rectangular horn made by Quinstar. The comparison shows that the rectangular horn made with our technique has almost identical radiation patterns at different frequencies compared with an industry made horn. Figure 2d shows the plated plastic WR42 waveguide section. The waveguide is connected to a network analyzer from both end for transmission measurement from 16GHz to 27GHz. We then measure the transmission parameter connecting only the two adapters and calculate the insertion loss of the waveguide. As shown in Figure 2e, the insertion loss over the 20cm waveguide section is around 0.3 dB, i.e. 0.015 dB/cm. One reason the performance is not perfect is that the plastic parts deform when heated during the metalization, especially when the part features a thin wall. This results in a slight deviation from the desired feature size, and slightly bent waveguide sections.

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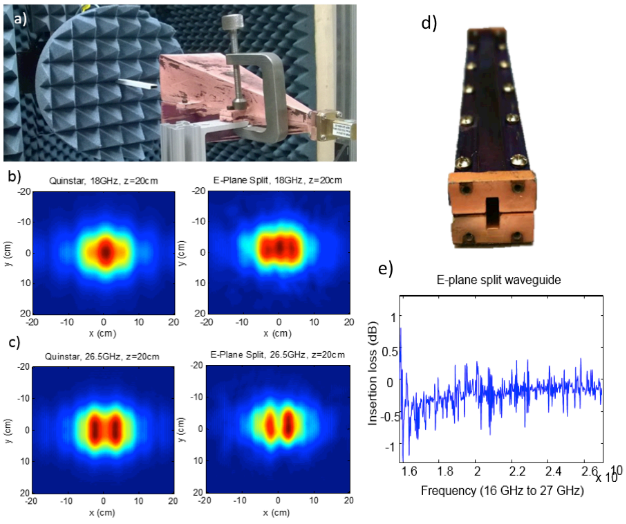

Fig.2. a) 3D printed plastic pyramidal antenna plated with copper in near-field scanning setup. b-c) Near-field scans performed at 20cm away from the horn at 18 GHz and 26.4GHz respectively and compared with same measurement done with industry made rectangular horn. d) A 3D printed WR-42 waveguide plated with copper in transmission measurement setup. e) The insertion loss of the 200mm waveguide measured from 16GHz to 27GHz.

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