# Selective Laser Sintering of Patch Antennas on FR4

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***Abstract*** *- This paper investigates the fabrication of microwave components using the Selective Laser Sintering (SLS) on FR4. This technique has exciting potential for the metallization of low-temperature substrates. The effects of the laser process parameters on the DC conductivity are examined. These results are applied to produce fabricate a patch antenna which is compared to simulation and an identical patch antenna fabricated with traditional manufacturing.*

## Introduction

This paper investigates Selective Laser Sintering (SLS) of planar metallic microwave components on FR4. Conventional thick-film inks require thermal processing after deposition by screen printing or other means. This usually involves placing the entire component in a high temperature furnace in order to sinter the metals. The current standard manufacturing process is based around an 850°C sintering temperature and this limits the choice of substrates to only those which can withstand these temperatures such as alumina. There are commercial inks that require a processing temperature of 525°C which is still higher then the damage threshold of low temperature polymer substrates.

In SLS, the laser allows precise control of the thermal profile with respect to time as well as in both the normal and lateral directions. This allows the laser to not only thermally process the ink but also pattern it. The applicability of the SLS process to high frequency antennas has not been thoroughly investigated. At high frequencies almost all of the current is carried along the surface of a pattern. Therefore a line that has good conductivity at DC or very low frequencies may exhibit poor performance at high frequencies because of poor surface or edge quality.

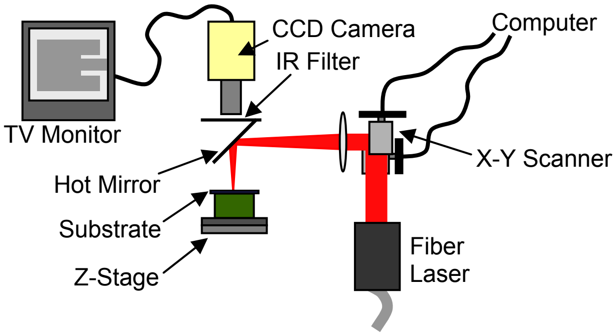

Figure 1. Schematic of SLS setup.

By moving the laser beam relative to the substrate, the laser can also be used to generate the pattern. A schematic of the setup used for the experiments in this paper is shown in Fig. 1. The X-Y scanner consists of two servos and mirrors which can be coordinated such that the laser beam can write a pattern. This offers the advantage of very high write speeds since the mirrors have very little mass. Because the laser beam is moved very rapidly the lateral heat diffusion in the lateral direction is minimized and only the ink in the region of the laser spot receives the energy necessary to be solidified. This allows feature sizes below 40 μm to be created. This paper examines the SLS process for the development of thick film patch antennas. The patch antenna was selected because it has a low profile, is simple, and has been studied thoroughly. FR4 is a very inexpensive and

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an accessible low temperature substrate. Although its dielectric loss is not as good at high frequencies, it is a good challenge material because its glass transition temperature, $T_g$, is 140°C. A patch antenna was fabricated on FR4. Another antenna was milled on double sided FR4 to give a physical reference for the laser sintering. A parametric search using DC test patterns written with SLS on FR4 was used to identify the laser parameters (speed and power) for maximum conductivity. These parameters were used to fabricate the patch antenna.

## Theory

The goal is to bring the temperature throughout the ink layer as close to the sintering temperature (500ºC) while maintaining the substrate temperature below its damage threshold (140ºC). This criterion is difficult to completely satisfy but through careful selection of the laser speed and power a satisfactory thermal profile with minimum damage to the substrate can be produced. The complete analysis of the heat transfer in the interaction between the laser, ink, and substrate is very complex and requires a rigorous numerical simulation. As the laser scans the pattern the ink properties change from previous interaction with the beam and the sintered material has different thermal properties from the unsintered material. However, insight can be gained into the general phenomena and the effects of the different process parameters by considering simple approximations.

The ink absorbs energy from the focused laser beam according to Lambert's law. The ink consists of silver suspended in organic material and as a first order model it can be assumed that the laser energy is primarily absorbed by the silver and then transferred via conduction to the organic material. For pure silver almost all of the energy is absorbed within a 100 nm of the surface of the ink. This energy is dissipated through the ink via conduction because of the large thermal gradients in the direction normal to the surface of the ink (the thickness of the ink is on the order of 7.5 µm) so the heat transfer due to conduction will dominate the other two modes of heat transfer. The thermal gradients in the lateral directions are much smaller then in the normal direction. However, when the laser is used to pattern as well as thermally process the ink, the thermal conduction in the lateral directions ultimately dictates the minimum limits the feature size that can be produced by the technique and quality of the sintered pattern [1].

A first order estimate of the thermal penetration depth of the laser is given by

$$d = \sqrt{4\alpha\tau} \qquad (1)$$

where the thermal diffusivity of the ink is $\alpha=\rho c_p/k$ and $\tau$ is the length of the exposure to the laser. The laser spot has a Gaussian profile and as the laser passes over a point it experiences a varying heat flux. However, the time of exposure is proportional to the laser spot size divided by the laser scan speed. The maximum temperature in the ink is proportional to the laser power.

## Experimental

The ink used for the experiments presented in this paper is Heraeus C8772. It is a commercial thick film fritted silver conductor paste that has been designed to be fired at 475-525ºC for a dwell time of 2-3 minutes. The sheet resistance for this ink is 5.0 mΩ/square at 14 µm fired film thickness which corresponds to a conductivity $\sigma$ of $1.43\times10^7$ S/m. Terpineol is added to the ink to thin it before it is applied to the substrate (FR4) using a wire-coater to form an ink film about 5-10 um thick. The substrate is then dried in a conventional oven for 10 minutes at 150°C. This drives off most of the volatile organic material from the ink. If the FR4 is left in the oven for much longer then 10 minutes its color begins to change indicating the onset of damage.

An SDL IFL9 Fiber Laser with a wavelength of 1.06 µm is used for these experiments. To create thick lines the laser beam is rastered back and forth with 20 µm between passes. After the pattern has been sintered with the laser the excess ink that was not sintered is removed with a solvent. Often it is desirable to add one or more layers of ink to a pattern to either build up its thickness and or repair defects in the pattern after the initial coating. This was done for the patch antennas but not for the DC patterns. The circuit is fully functional once the final layer is sintered and the un-sintered material removed. No additional post processing is required.

For this paper the process parameters were identified using a parametric sweep. A series of lines 1.5 cm long and 500 µm wide were written between two contacts. These lines were written with a single coat of ink the undamaged patterns had a measured thickness of 2 µm after processing. Fig. 2 shows the conductivity as a function for different writing speeds. The power is what was measured at the substrate after the beam had passed through all optics. When the power of the laser was set to 1.62W all of the patterns written at various speeds measured open. From this experiment the optimum power and speed for this ink layer are 1.07 W and 40 cm/s. These settings produced a line with 57% of the conductivity specified for the ink sintered using the standard procedure.

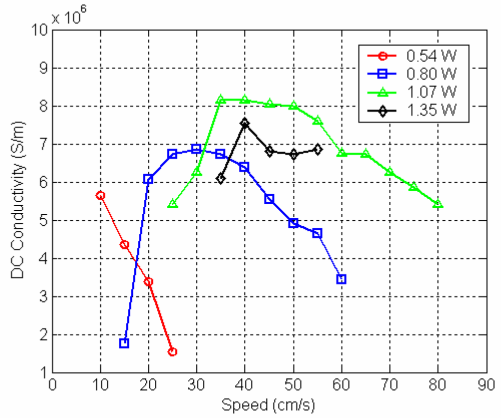

Figure 2. Results of DC Parametric Sweep.

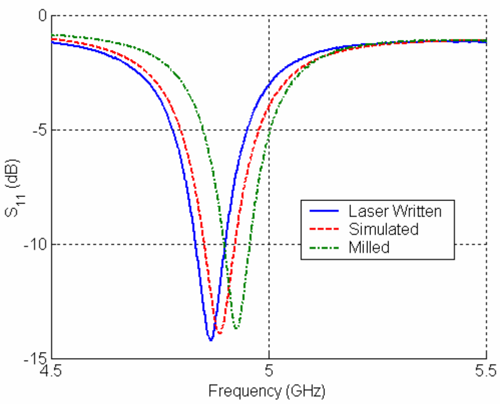

Figure 3. Antenna Comparison

This experiment illustrated several failure modes of the process. If the power is too high and or the speed too low too much energy is transferred to the substrate and it becomes burnt. If the power is too low or the speed too high then insufficient energy propagates to the ink/substrate interface and the pattern does not adhere to the substrate. Another significant problem is as the laser scans back and forth it must slow down to change directions at the edges of the pattern. This usually leads to excess damage at the edges where the laser dwells. This problem can be overcome by using a shutter to block the laser when it is not moving at a constant speed and forcing the laser beam to change directions outside the pattern. These failure modes can all be overcame by properly selecting the laser power and speed and by using a shutter and recoating the substrate.

Patch antenna dimensions were calculated using a center frequency of 5.0 GHz on FR4 substrate using standard methods. To account for fringing fields empirical formulas were used from [2], these formulas have a given accuracy of 5%. The design was simulated in HFSS and the actual center frequency was 4.887 GHz, this difference corresponds to a 2.3% error and is due to the lack of accuracy of the empirical formulas. The simulation was used to improve the in fed coupling. Once the process parameters found for the ink substrate combination were used to fabricate the patch antenna. It took 20s to write the patch and after sintering the remaining material removed and an additional layer of ink was added. This process was repeated 4 times. The final thickness of the patch was measured 7 µm. The same dimensions were milled on double sided FR4.

In order to examine the quality of the antennas the resonance frequency and return loss are compared, from $S_{11}$. Measurements were done using an 8720ET network analyzer from Agilent. Comparison between the laser sintered patch, milled patch and simulation is in Fig. 3. The difference between the fabricated and simulated patches is negligible (0.4% laser sintered from simulated and 0.8% milled from simulated). The return loss is very similar for all the antennas with less then 1 dB variation.

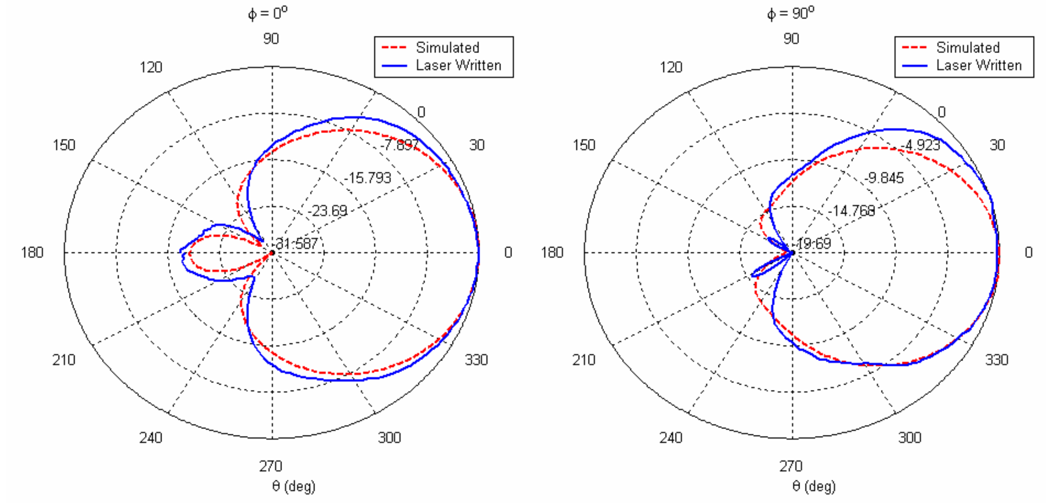

Figure 4. Radiation Pattern Comparison, Simulated and Laser Sintered Antennas.

To verify the radiation pattern of the laser sintered patch antenna, it was measured in an anechoic chamber. The pattern was them compared with the simulated pattern, to improve accuracy the test fixture was included in the simulation. The test fixture used extended the ground plane which reduced the back radiation. The resulting radiation patterns are in Fig. 4. The patterns match very well.

The gains for the milled and the laser sintered antennas were measured to be 1.39 dB and 1.042 dB respectively. The difference in gain results from higher conductor losses in the laser sintered patch antenna [3]. These losses are due to the conductivity of the sintered ink as well as the thickness of the patch. The low gain values are attributable to the high dielectric losses of FR4 at high frequencies.

## Conclusion

In this paper we investigated the use of selective laser sintering for the creation of thick film processing of microwave patch antennas. The thermal profile of the patterned metal during sintering can be controlled using the laser parameters and therefore a variety of substrates can be used. The DC resistance of a simple test pattern was determined on FR4 from a parametric sweep and the failure modes identified. The minimal resisitivity is further enhanced by multiple layering of the metal. A patch antenna was fabricated with these parameters and demonstrated to match both simulation and a patch antenna fabricated with traditional milling. While the conductivity is not as high as that with traditional screen printing techniques, this process allows for patterning on substrates that can not survive the high sintering temperature of traditional thick film processing.

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