Progress In Electromagnetics Research Letters, Vol. 60, 101–106, 2016

Characterisation of Copper Nanoparticle Ink Printed FSS for Cellular Signals Suppression

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Abstract—This paper proposes a copper nanoparticle ink printed frequency selective surface (FSS) for cellular signals suppression. The FSS pattern is deposited on a polyimide film by using an inkjet printing technique. The printed FSS elements undergo the post-processing called sintering, where the optimum exposure duration and temperature are determined in order to form a conductive path across the metal pattern. Later, the conductivity of the printed FSS structure deposited on polyimide film is observed. The signal suppression ability of the printed FSS is conducted using the Computer Simulation Technology (CST) Microwave Studio software.

1. INTRODUCTION

The explosive growth of smart phones and other mobile devices causes the cellular networks coverage to be provided almost everywhere. However, in certain areas, these cellular signals might harm the security as well as the performance of the system, such as in airports and hospitals. Thus, there is a need of deploying a cellular suppression system in order to provide an isolation area [1]. There are various techniques that can be used to attenuate the cellular signals including the employment of mobile phone jammer [2]. Nonetheless, this technique is not environment friendly and less efficient as it requires power supply to operate. Therefore, the deployment of frequency selective surfaces (FSS) is one of the potential alternatives. In the indoor environment, FSS can be realized by transforming the wall into a frequency-selective wall, thus, modifying the electromagnetic architecture of the buildings.

FSS has been widely employed in microwave system designs such as dichroic reflector [3], antenna radomes [4] and spatial filters [5]. Recent research studies have investigated the application of frequency selective surface in constructing an electromagnetically quiet environment [1, 6]. In order to ease the integration of FSS onto the walls, deposition of FSS structure on flexible substrate is preferable. The utilization of silver-based double square loop FSS structure deposited on a paper substrate using manual stencil technique with dual-band stop behavior is discussed in [7]. However, there is an uncertainty of the uniform conductivity distribution of the FSS pattern due to the manual fabrication technique implemented. Therefore, in this study, copper nanoparticle ink is deposited on the preferable substrates by using an inkjet printing technique. At the beginning of the study, the copper nanoparticle FSS pattern is deposited on paper. Nevertheless, since the post-processing, which is the thermal sintering, requires high temperature to operate, the paper substrate is not compatible. Thus, the polyimide film is chosen as the substrate as it can sustain high temperature. In [8], a double square loop FSS is designed to attenuate the cellular signals at 900 MHz, 1800 MHz, and 2100 MHz frequency bands as specified by the Malaysian Communication and Multimedia Commissions (MCMC) [9]. Since the aim of this study is to determine the optimum exposure duration and temperature during the sintering process, a dipole FSS is chosen as the FSS element due to its simplicity. The electrical properties of the nanoparticle

Received 1 March 2016, Accepted 18 May 2016, Scheduled 27 May 2016

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copper printed dipole FSS on polyimide film is observed after the sintering process is conducted. The organization of the paper is as follows; the details of the FSS geometry design are described in Section 2; the approach to characterize the electrical conductivity of the FSS pattern is explained in Section 3; the performance of the FSS is discussed in Section 4.

2. FSS DESIGN AND REALISATION TECHNIQUES

The main focus of this study is to characterize the electrical properties of the nanoparticle copper ink using the Dimatix Materials Printer. Consequently, the focus of the study is to optimize all the parameters involved throughout the sintering process. In this study, a simple dipole FSS is chosen as the FSS element as it provides the required bandwidth. Besides, due to its simplicity, it can be deployed easily once the optimization of the sintering process is achieved. Figure 1 shows the FSS geometry of the dipole FSS that is printed on 0.5 mm (t) thick Kapton Polyimide (PI) film, with the dielectric permittivity, ε_r of 3.4. In order to tune the resonance frequencies at 900 MHz, the element length, L and element width, w is optimized to 37 mm and 1 mm, respectively. Similarly, the length and width of the substrate, P is optimized to 39.4 mm. The FSS patterns are realized on the polyimide film using the Dimatix Materials Printer. After the printing process is done, the pattern needs to be sintered in order to transform a non-conductive printed pattern to a conductive one [10]. By sintering the printed pattern, the solvent and dispergents are removed [11]. As a result, a conductive path is formed across the printed pattern. In this study, copper nanoparticle ink is used due to its high electrical conductivity and low cost compared to silver and gold [11–14]. However, since copper has a high rate of oxidation, the sintering process must be performed in an inert atmosphere [15]. Unlike silver oxides, copper oxides are non-conductive material [15].

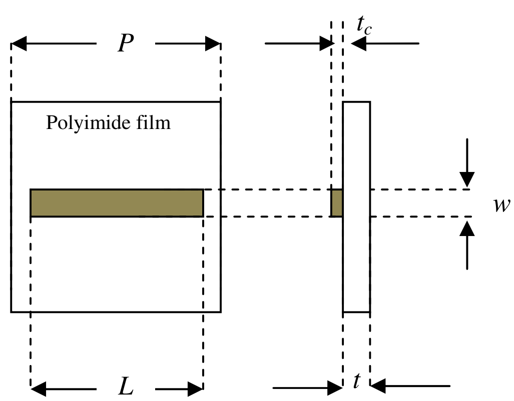

Figure 1. The unit cell of the dipole FSS.

3. SINTERING AND CHARACTERISATION OF COPPER NANOPARTICLE INK

The sintering process is performed right after the deposition of dipole FSS on polyimide film. During the sintering optimization stage, both sintering temperature and duration are varied. The sintering temperature is varied from 150°C to 300°C. The FESEM images with magnification of 50 k as illustrated in Figure 2 demonstrate that higher sintering temperature results in better surface treatment. It can be seen that the particles size dramatically increases as the sintering temperature increases. The heat treatment that is applied lead to the reduction of pores which indirectly causes the grain size to be increased [10]. Besides, when the temperature increases up to 300°C, the surface contact between the copper nanoparticles ink improves. Indirectly, the efficiency of the electron transfer can be enhanced, which will then increase the conductivity of the copper nanoparticle ink. The duration of sintering is varied from 10 to 30 minutes. For 300°C, the duration of sintering needs to be minimized to 10 minutes in order to prevent surface cracks from happening. Comparison of FESEM images of printed FSS

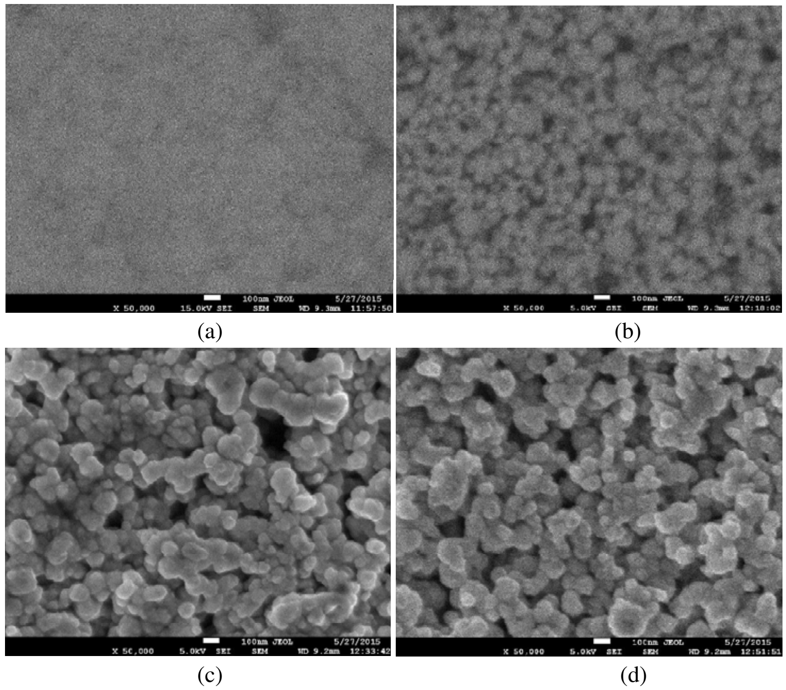

Figure 2. FESEM images of printed FSS element after sintering at (a) 150°C, (b) 200°C, (c) 250°C, and (d) 300°C.

element before and after sintering is illustrated in Figure 2. This figure proves that by implementing thermal sintering, conductive path can be formed across the printed pattern of the copper nanoparticles ink. It is found that the grain size of the copper nanoparticle ink is sintered perfectly when the FSS pattern is exposed at 300°C for 10 minutes in an inert atmosphere.

The investigation of the actual conductivity of the nanoparticle copper printed FSS is realized through the observation of the electrical resistance, R, by using a two-point probes method. Then, the electrical conductivity, σ, is calculated from the value of the electrical resistivity, ρ, according to Equations (1) and (2) as follows;

$$\sigma = \frac{1}{\rho} \tag{1}$$

$$\rho = \frac{RA_c}{L} \tag{2}$$

where R is the electrical resistance, A_c the cross-sectional area and L the length [14]. Note that A_c is a multiplication of $t_c \times w$. The electrical resistance is measured by pointing two probes of the digital multimeter at the two edges of the fabricated dipole FSS. In order to determine the cross-sectional area, A_c, the thickness of the copper printed on polyimide film, t_c is measured precisely by using a surface profiler. The electrical conductivity of 10 samples is selected randomly, as tabulated in Table 1. It is observed that the average thickness of the printed FSS is about 7.2 µm while the resistance between the two edges of the FSS varies between 20.7 to 95.9 Ω. The value of the resistance varies due to the variation of the thickness of the fabricated dipole FSS. Correspondingly, the measured electrical conductivity of the FSS element is calculated to be in a range of 11.8 to 47.1 kS/m, depending on the combination of the average thickness of the metallic pattern and the resistance between the two edges. The electrical resistivity of the printed FSS measured with a two-point probes method which is a DC parameter is applicable even tough the FSS patterns operates at microwave range [16, 17]. This is inline with the specification of the copper nanoparticles ink where the conductivity is 8.7 nΩm for the track thickness of 300 to 400 nm.

Table 1. Electrical resistivity of the printed FSS element using copper nanoparticle ink.

Sample #	Average thickness (μm)	Resistance (Ω)	Resistivity (nΩ m)	Conductivity (kS/m)
1	9.214	49.61	70327.136	14.219
2	6.579	73.15	74042.055	13.506
3	6.661	20.73	21244.529	47.071
4	6.391	27.87	27402.070	36.494
5	8.017	68.61	84623.926	11.817
6	6.932	66.15	70543.717	14.176
7	6.278	54.13	52284.583	19.126
8	7.135	51.22	56225.639	17.785
9	5.326	95.87	78550.962	12.731
10	9.452	54.85	79756.119	12.538

4. FSS PERFORMANCE AND DISCUSSION

The calculated conductivity of the copper nanoparticle as shown in Table 1 is included as the parameter in the numerical simulation. The electromagnetic performance of the FSS is performed numerically in frequency domain solver by using the Computer Simulation Technology (CST) Microwave Studio software. Adaptive Tetrahedral Mesh refinement is employed where the convergence criteria is met where the threshold value between discrete sample is less than 0.01. Figure 3 shows the simulated transmission frequency response of the dipole FSS under different electrical conductivity values of the printed FSS element at normal incidence. The effects of varying the angle of incidence have been clearly discussed in [7, 8]. As the angle of incident increases, the resonant frequency is shifted upwards. The optimum electrical conductivity of the copper as defined in the computer software is equal to 58000 kS/m. From this figure, it can be seen that as the conductivity is varied, the resonance frequency as well as the attenuation of the signal vary. Nonetheless, the attenuation of the signal is still below −10 dB at the resonance frequency. Due to the size limitation of the furnace used during the sintering process, the printed FSS pattern is sintered in a smaller size. Subsequently, these simulated results cannot be validated experimentally.

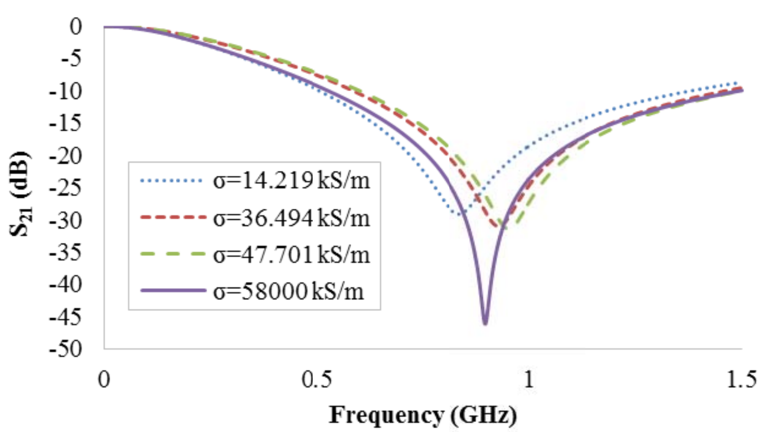

Figure 3. Simulated transmission frequency responses of loop FSS under different electrical conductivity values at normal incidence.

5. CONCLUSION

The performance of a copper nanoparticle printed FSS is demonstrated. The proposed FSS can be used to attenuate cellular signals operating at 900 MHz frequency bands while transmitting other microwave signals. It is shown that the copper nanoparticle ink is sintered perfectly when the FSS pattern is exposed at 300°C for 10 minutes in an inert atmosphere. The simulated results show a good performance though the measured conductivity of the printed FSS pattern varies.

ACKNOWLEDGMENT

The authors would like to thank the Ministry of Education Malaysia for supporting this study under the Research Supporting Grant Scheme (RSGS/1/2014/TK06/UTHM/02/1/U103). Much appreciation also goes to the Microelectronics and Nanotechnology — Shamsuddin Research Centre (MiNT-SRC), Universiti Tun Hussein Onn Malaysia for providing the measurement facilities.

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