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Correlation of printing faults with the RF characteristics of coplanar waveguides (CPWs) printed on nonwoven textiles

Hasan Shahariar, Jesse S. Jur*

Fiber and Polymer Science Program, North Carolina State University, Raleigh, NC 27606, USA

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ABSTRACT

Printing high-resolution microwave passive devices directly on textile surfaces presents many challenges due to the high surface roughness and porosity of textile materials. This paper explains in detail physical and electromagnetic characterization of screen-printed coplanar waveguides (CPWs) on nonwoven textiles with a surface roughness of approximately ~18 μm. Three different screen mesh counts (mesh opening unit) are used to screen print CPWs with five different resolutions. A screen printable silver paste is used as a conductive ink during the screen printing process. The difference in screen mesh counts affects the line resolution, thickness, conformity, and overall power transferring capacity of printed CPWs. A print resolution of 220 μm as the gap between the parallel lines of CPWs is achieved in this work without any surface modification of textile media. The surface roughness of the printed silver track is very similar to the base fabric (18 μm) when the screen with 305 mesh-count is selected for printing. Additionally, the thickness of the ink on the fabric is most conformal and lowest (23.4 μm) for the similar selection of screen mesh count. Fabricated CPWs are characterized for signals from 0.5 GHz to 10 GHz and compared to electromagnetic 3D simulation results. This paper also identifies minute printing faults in the 3D structure of the printed CPWs and correlates that with the scattering parameters of the transmission lines. Simulated and experimental data prove that a well-designed and process optimized printed nonwoven-based CPW works well (i.e. below 3 dB of insertion loss) for frequencies ranging from 0.5 GHz to 7 GHz.

1. Introduction

Printed electronics have recently gained the attention in both academic and industrial research for their ease of fabrication and low-cost margin. A wide range of device applications are possible by printing electronics on conformal substrates like plastic films, textiles etc. For example, printed conductive textile sensors are used in research for the wearable applications, such as tracking biometric information of human body [1–4]. With the emergence of internet of things (IoT), these printed sensors are now connected to each other by the local area network using different communication protocol such as Bluetooth, Wifi or ZigBee. Hence, printing RF (Radio Frequency) devices along with the sensors is essential towards fabricating truly wearable and conformal device systems. Printed RF transmission lines can potentially be used to connect ultra-high frequency communication devices onto a flexible and wearable platform. The electromagnetic characterization of transmission lines are analyzed when they are fabricated by inkjet printing [5,6] and 3D printing [7]. The effect of the conductivity of printed lines with external effect like heat, different dielectric flexible or nonflexible materials, and print resolution on the transmission characteristic of RF signal have been discussed in literature [8–10]. However, the transmission lines were printed on planar plastic film which is very different than the porous and rough textile surfaces. The fabrication of transmission lines using conductive yarns and fibers on textiles have also previously been studied [11,12]. The characteristic impedance of textile transmission lines is difficult to predict and design, especially when the conductive threads or yarns are used for the device design. The spacing between the conductive threads can be affected by regular handling of the material. On the other hand, screen printing transmission line on textiles and nonwovens show better promise for having superior RF characteristics such as achieving the lower characteristic impedance (up to ~75 Ω) than that of transmission lines made with conductive yarns or threads by better controlling the physical dimension of the transmission line in the printing process [13–15]. However, the surface roughness and the porosity of

* Corresponding author.
E-mail addresses: hshahar@ncsu.edu (H. Shahariar), jsjur@ncsu.edu (J.S. Jur).

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the textile surface contribute for the bleeding of the ink, which can hinder achieving sharp and precise resolution during printing.

Screen-printing is currently the preferred fabrication process for printed electronics on rough and porous textiles surfaces due to its ability to deposit highly viscous inks in an easy manner. It also allows for higher conductivities of printed patterns when printing viscous conductive inks or pastes, compared to inkjet printing, which yields lower conductivities when printing thin conductive inks. Additionally, the range of viscosity and particle size in the conductive inks that are used in the inkjet, gravure, and transfer printing processes, cannot create sufficient electrical percolation networks on porous, rough textile surfaces. However, the resolution of screen-printed patterns is greatly influenced by the process parameters [16]. The resolution of the screen printing process is limited by the screen mesh size, ink rheological properties, and the substrate properties. A higher mesh count means that the weave of the screen is finer, which allows less ink material to pass through the screen during printing. However, predicting the resolution of screen printed pattern is very difficult when it is printed on rough and/or porous materials. The conductivity, resolution and the durability of the printed line are fundamentally affected by the ink-to-nonwoven interaction for screen printing CPWs on nonwoven textiles [17,18]. The high density of solid materials and the smooth surface of the fabric helps to achieve higher conductivity upon printing conductive traces; however, the porosity of the fabric to some extent improves the durability of the conductive traces [19]. In the case of printed CPWs on nonwoven textiles, the variation of the characteristic impedance from TDR data has a direct correlation with the surface roughness of the nonwoven fabric. The thickness of the conductive ink is uniform on the smooth surface of the fabric, which contributes to the uniform impedance profile [19]. However, the effect of fabric surface profiles and screen-printing variables play vital roles in attaining a uniform 3D resolution of the printed traces. Very limited research has been done on optimizing screen printing parameters to print high-resolution RF devices and transmission lines [16,20,21]. It is expected that finer resolution of printed patterns can be achieved when a screen with higher mesh count is selected. On the other hand, higher mesh count (finer mesh opening) restricts transferring highly viscous ink through the mesh opening to the substrate. Additionally, the adhesion force of the ink with substrate should be greater than the elastic force exerted by the screen during the stroke of squeegee for the successful transfer of the ink onto the substrate [16]. Thus, the screen mesh count should be selected in an optimized way for transferring the ink through the mesh as well as achieving a good resolution of the pattern. The adhesion force of the ink is also dependent on the surface properties of the print media. It can be further hypothesized that the surface roughness and the porosity of the print media or substrate would require a higher amount of ink deposition on it than that on a planar substrate (like films) to attain the optimum adhesion force for successful ink transfer. Unfortunately, the experimental proof to this point has not been addressed in the previous literature. In this paper, we experimented with printing coplanar waveguide (CPW) on a nonwoven Evolon® textile substrate using different screen mesh count to understand the effect of mesh opening on the print resolution. Analyzing printed transmission lines on textiles provides the opportunity to explain the variation and anomalies of RF performance of the transmission line due to printing faults or problems. Defects on transmission lines can change the local area impedance by changing the resistance and reactance values of unit areas. Additionally, defects in local areas of printed transmission lines can also result in undesirable high pass filtering effects [22]. Computational models have shown that periodic faults in microstrip transmission lines were responsible for a dip trend or suck out effect in insertion loss [23], which could be a common problem for printed transmission lines. The correlation between the printing resolution of transmission lines on textiles along with detailed RF-characterization is very important to understand the performance of printed RF devices.

The purpose of this research is to understand how changes of screen mesh count, cause deviations in print resolution on the Evolon® textile material, and how that, in turn, affects transmission line performance for the transmission of RF signals in the frequency range from 0.5 GHz to 10 GHz. Note that the goal of this research is not to develop the best-printed transmission line, but rather to understand the optimization process of screen printing conductive ink on textile substrates for transmission line applications with the considered sets of variables in this paper. To our best knowledge, very little or no significant research has been done to resolve or understand this problem.

2. CPW design

Fig. 1 illustrates the design and different layers of coplanar waveguide (CPW) transmission line from a cross-sectional view. In a CPW, an electromagnetic field is guided by two parallel "ground" conductive lines on either side of the signal line while an RF signal is transferred from one port to another port. The physical dimensions of the CPW such as the width of signal and ground lines, the spacing between signal and grounds, the thickness of the conductor (metal ink) and the dielectric substrate define the characteristic impedance of the transmission lines. The following mathematical equations are used to calculate the characteristic impedance for a CPW from the physical parameters of the materials.

$$Z_0 = \frac{60^*3.1416}{\sqrt{E_{eff}}} \cdot \frac{1}{\frac{K(k)}{K(k')} + \frac{K(kl)}{K(kl')}} \quad \text{(i)}$$

$$k = \frac{a}{b} \quad \text{(ii)}$$

$$kl = \frac{\tanh(\frac{3.1416^*a}{4^*h})}{\tanh(\frac{3.1416^*b}{4^*h})} \quad \text{(iii)}$$

$$k' = \sqrt{\left(1 - k^2\right)} \quad \text{(iv)}$$

$$kl' = \sqrt{\left(1 - kl^2\right)} \quad \text{(v)}$$

$$E_f = \frac{1 + E_r \left(\frac{K(k)}{K(k')}\right) \frac{K(kl)}{K\left(kl'\right)}}{1 + \left(\frac{K(k)}{K(k')}\right) \frac{K(kl)}{K\left(kl'\right)}} \quad \text{(vi)}$$

Here, Z_0 is the characteristic impedance of the CPW line. kl, k, k', and kl' are constants that depend on parameters a, b, h and t which are the width of the signal line, width of signal line plus the width of the gaps between the conductors, height of the dielectric, and thickness of the metal or conductive ink, respectively. E_{eff} and E_r are the effective permittivity and the dielectric permittivity of material, respectively.

It is possible to tune the physical parameters such as width, length, gap resolution and the thickness of printed lines to change the characteristic impedance and RF characteristics of CPWs using Eq. (i). [24] CPW transmission lines were designed based on the above mathematical model in this paper. Table 1 lists the dimensions of CPWs printed on Evolon®. The gap width between signal and grounds was designed to be 100, 200, 300, 400 or 500 μm to observe the differences in resolution of the screen-printed CPWs using three screens with different mesh counts, and also to determine the resulting changes in RF characteristics for the printed CPWs. The corresponding change of characteristic impedance by