ELECTRICAL CHARACTERIZATION OF PRINTED COPLANAR WAVEGUIDE TRANMISSION LINES ON SPECIFIC NONWOVEN TEXTILE SUBSTRATES

C.R. Merritt, B. Karaguzel, T. Kang, J.M. Wilson, P.D. Franzon, H.T. Nagle, B. Pourdeyhimi, E. Grant

ABSTRACT

The focus of this paper is the electrical characterization of coplanar waveguide (CPW) transmission lines that are printed onto nonwoven textile substrates using conductive inks, to determine their suitability for wide-band applications, e.g. digital signaling. The conductive ink line characterization tests included DC resistance, impedance characterization, and frequency characterization. The transmission line test samples were screen printed onto two different types of nonwoven textile substrates using two different conductive inks, i.e. inks with different viscosities. Tests showed that the variations in the continuity of the transmission lines varied, giving rise to geometrical variations in the CPW structure; and in the characterization of the same.

Key Words: Nonwoven e-textiles, conductive inks, electrical characterization, printed electronics, polymer thick film, electronic textiles.

1. INTRODUCTION

Electronic Textiles for wearable computing present considerably greater challenges to researchers than those presented by a traditional printed circuit board (PCB). According to Marculescu et al (2003), an electronic textile must be flexible, unobtrusive, robust, small, inexpensive, washable, biocompatible with human skin, and aesthetically acceptable, yet very few wearable computing devices exhibit any of the desired characteristics expressed in. Most wearable computing devices are bulky, non-conformal, expensive, and cannot be washed without removing complex electronics (Marculescu et al, 2003). Some devices even include wires, which are used to connect to external components; these wires obstruct natural movement. Electronic textiles are mostly made conductive through weaving or knitting conductive yarns into the fabric during their fabrication (Marculescu et al, 2003; Cottet et al, 2003; Tröster et al, 2003). The geometrical limitations associated with the conductive lines also increases the difficulty of integrating electronic components into clothing since they lack the footprint patterns of the electronic components that are normally found in traditional PCB's (Marculescu et al, 2003), requiring designers to develop alternate means of assembly (Tröster et al, 2003).

Our research adopts the technologies used in the polymer thick film (PTF) industry and adapts and applies them to our nonwoven textiles project. Instead of weaving or knitting conductive yarns with fabrics, we are currently screen printing conductive inks onto nonwoven textile substrates. In order to determine the capabilities of these inks as they have been printed onto the nonwoven substrates, the electrical properties of the printed conductive traces. This first paper reports on the tests that were carried out to determine the suitability of this approach for use in wide-band applications. These tests include measuring the DC resistance, impedance characterization, and frequency characterization.

2. SCREEN PRINTING CONDUCTIVE INKS

Screen printing is the preferred manufacturing process of the PTF industry. This process delivers a thick ink deposit under controllable conditions while maintaining print clarity (Gilleo, 1996; Gupta, 2003). In addition, PTF inks can be screen printed onto almost any flexible substrate without resorting to the use of environmentally hazardous and harsh chemicals used in traditional copper circuitry methods. Overall, PTF is a simple and low cost process that has an extremely low impact on environmental issues related to the use of hazardous chemicals for such a manufacturing process (Gilleo, 1996). For these reasons, we chose to screen print with the same conductive inks that are used in PTF. For our research we choose to use two types of silver inks: Creative Materials' CMI 112-15 and Precisia's CSS-010A.

The screen printer used for the experiments is a DeHaart EL-20 flatbed semi-automatic screen printer with a dual squeegee print head. The screen printing parameters used for printing onto the selected nonwoven textiles are shown in Table I. For our experiments we screen printed with two 41º angle double beveled polyurethane squeegees. The durometer and print speed of the squeegees, which were the same for both printing and flooding, are given in Table I.

Table I Screen Printing Parameters

Mesh	250ss
Emulsion	25.4 µm
Mesh Angle	90º
Squeegee Durometer	70
Print Pressure	275.8 kPa (40 PSI)
Print/Flood Speed	3.5 cm/s
Snap-off	76.2 µm

The nonwoven textiles selected for this project are a surface treated Tyvek® designed for ink jet printing and Freudenberg's Evolon®. The Evolon® fabrics consisted of three different weights 80, 100, 130 g/m^2. Since we intended on curing the inks printed on the nonwoven substrates we had to determine the curing temperatures that were safe for the fabrics and high enough to cure the inks effectively. Table II shows the curing temperatures that were safe for the fabrics and satisfactory for curing the silver inks.

Table II Curing Temperatures

Substrate	**Temperature (ºC) at 5 minutes**
Tyvek®	110
Evolon®	140

The screen printing process consisted of first flooding the screen with sufficient ink in one direction and then printing in the opposite direction. The printed samples were then run through a second flood-print cycle for sufficient ink coverage. The most likely reason for poor coverage of ink is due to the restricted volume of ink delivered by the screen, since the screen was fabricated using a high mesh count. Decreasing the mesh count will solve this problem since decreasing the mesh count increases the thickness of ink (Gilleo, 1996; Gupta, 2003; Hoff, 1997). The nonwoven fabrics used in the experiments exhibited discrepancies in their two-sidedness. Tyvek® was surface treated on one side; giving it a rough side and a smooth side. Evolon®, on the other hand, was untreated, yet it appeared to have a rough side and a smooth side. Also, the machine direction of Evolon® is prevalent meaning that the surface of the fabric has a periodic roughness caused by the belt motion during fabric manufacture. To accommodate for these periodic variations in surface geometries we decided to print the majority of the conductors parallel to the machine direction. The front sides of the fabrics were chosen as the print side to maintain consistency among all of the printed samples.

3. TEXTILE TRANSMISSION LINE DESIGN

Coplanar waveguides (CPWs) were chosen for this research because they offer several advantages. These advantages include: simple fabrication, straight forward surface mount component assembly, no need for via holes, and reduced radiation loss (Wadell, 1991; Simons, 2001). Also, the ground planes of CPWs separate adjacent signals, which effectively reduce the crosstalk commonly encountered when conductive lines are in close proximity to each other (Simons, 2001). The design of a coplanar waveguide transmission line consists of a center conductor, which acts as the signal (S), surrounded by two ground planes (G). Figure 3.1 shows the cross-section of a coplanar waveguide ground-signal-ground (GSG) structure indicating the dimensions that influence the characteristics of the line. In the figure, *a* stands for the signal width, *W* stands for signal-ground gap, *h* stands for the height of the substrate and *t* stands for line thickness.

The time-domain-reflectometry (TDR) measurements for impedance characterization were reported in this paper for a line length of 10 cm. The CPW lines consisted of five groups with an initial signal width *a* = 600 μm. These five groups are distinguished by constant *b* values equal to 800, 1200, 1600, 2000 and 2400 μm. Within each line group, with the exception of groups one and two, the signal widths increased starting from *a* equal to 600 μm in 100 μm increments until *W* reached 400 μm. The screen printed samples with 10 cm lines are shown in figure 3.2.

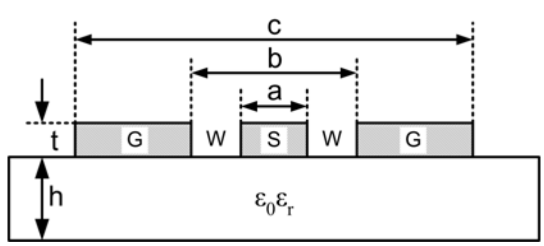


Figure 3.1 Cross-section of GSG coplanar waveguide

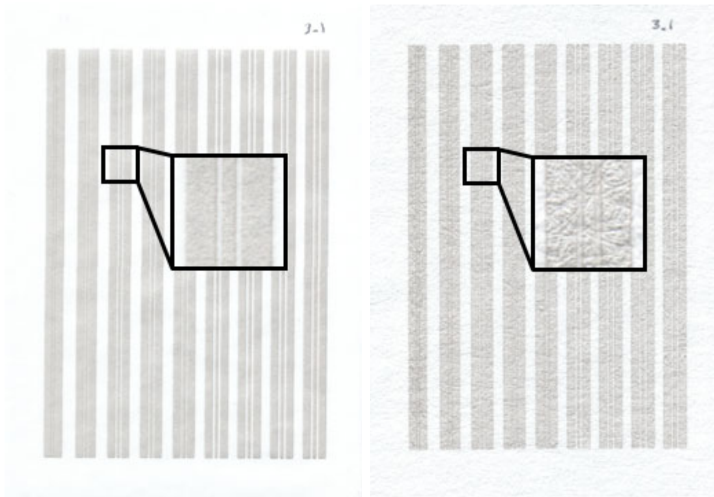


Figure 3.2 Screen Printed Sample of CPWs on Evolon

4. ELECTRICAL CHARACTERIZATION RESULTS

The textile transmission lines were characterized by DC resistance, impedance characterization, and frequency characterization. The DC resistance of the line will give an idea of the overall conductivity of each line while the impedance characterization will graphically show the variations of impedance throughout the lines. In addition, the frequency characterization will show frequency dependant parameters like attenuation and insertion loss. This will allow us to evaluate if the printed lines using conductive inks on nonwoven textiles have the potential for use in high-speed signaling applications.

4.1 DC Resistance

The DC Resistance of the lines was measured to provide a more definite comparison of the two inks and to quantify the role that each substrate played in conductivity, see Figure 5.1. For the DC resistance measurements, we printed on Evolon® and Tyvek® with the same parameters outlined in Section 2. The results obtained show that the CMI 112-15 ink performed better than the CSS-010A ink possibly because it possessed a higher viscosity and larger percentage of silver. From figure 4.1 it is apparent that CMI 112-15 printed on Tyvek® produces the best results in terms of DC resistance. However, the Evolon® fabric had become a major focus in the research as it had progressed because it is a softer fabric, and it had been decided that Evolon® will more likely be made into a wearable computing garment because of such inherent properties.

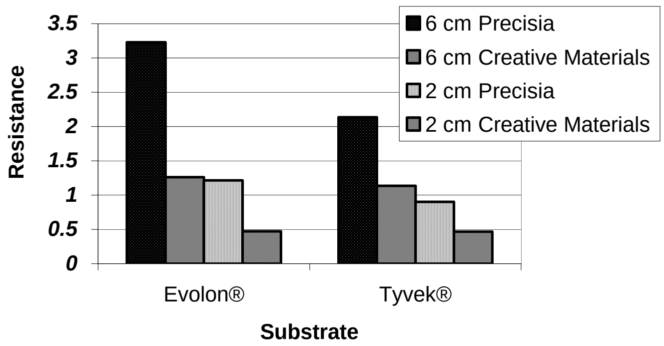
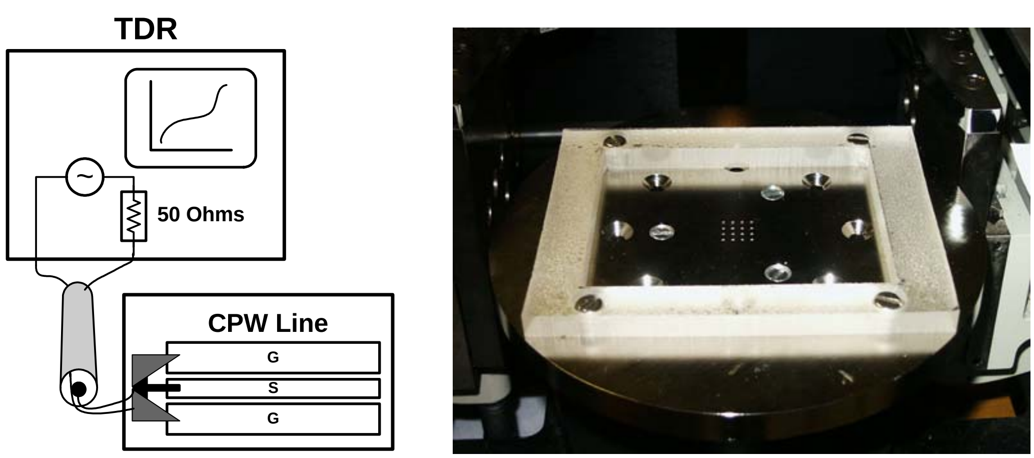


Figure 4.1 Average DC Resistance for 2 cm and 6 cm lines

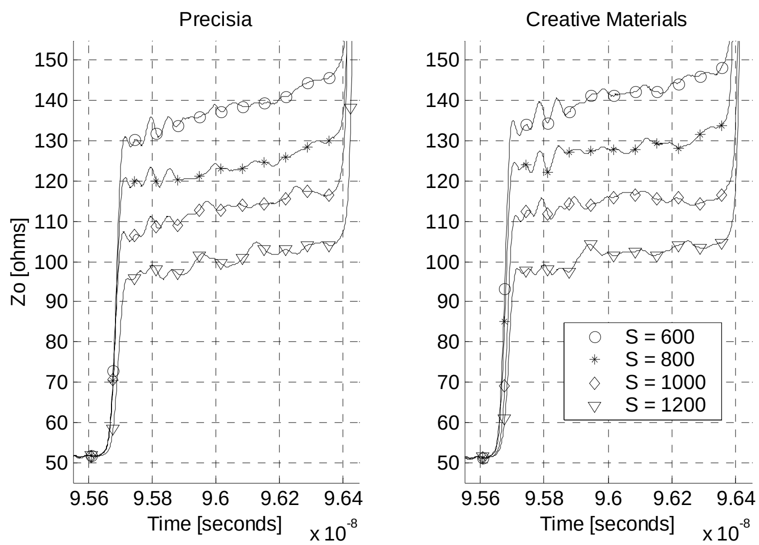
4.2 High Frequency Characterization – Time Domain and Frequency Domain

The impedance characterization was performed by using time-domain-reflectometry (TDR) techniques. We used a Tektronix 11801 with a SD-24 TDR Sampling Head and a GGB Industries PicoProbe Model 40A GSG Probe with a 1250 µm pitch. According to the block diagram of the experimental setup in Figure 4.2a, the probe is landed on only one side of the transmission line with the other side left open. A test fixture was designed to reduce artifacts in the electrical measurements caused by measurement interconnect. By designing our own test fixture we were able to place the probe directly down onto the fabric without the need to use conductive epoxy or SMA connectors like in Cottet et al (2003). As a result, the impedance profile is free of any artifacts that are a result from discontinuities between the test equipment and device under test (DUT). The test fixture shown in figure 4.2b was designed to test 10 cm line lengths with an air bridge beneath the lines, so that the characteristics of the line would not be influenced by conductors or dielectrics below the transmission lines.



(a) (b)

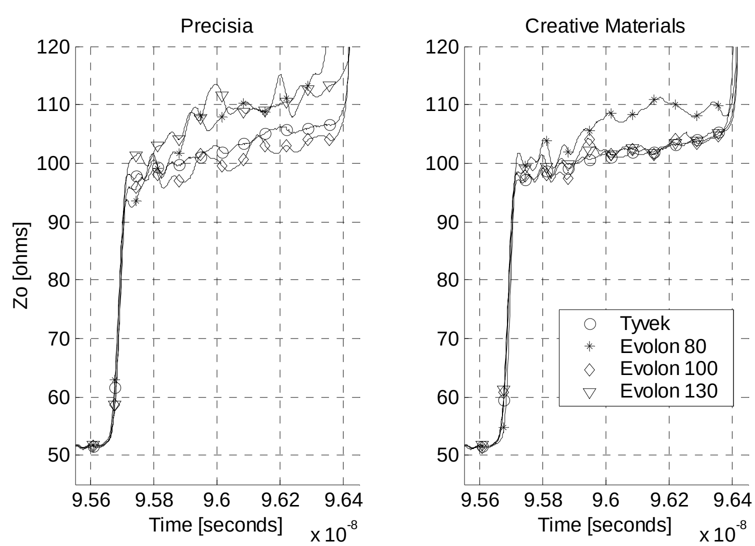
Figure 4.2 Experimental Setup (a) block diagram (b) test fixture for probing 10 cm line length



(a) (b)

Figure 4.3 TDR Profile for varying signal width S = 600,800,1000,1200 μm and *b* = 2000 μm on Evolon 100 g/m^2 with (a) Precisia ink (b) Creative Materials ink

Measurements of four different line geometries printed on Evolon and Tyvek with Precisia and Creative Materials inks are presented in the paper. All CPW lines had a ground-to-ground spacing (*b*) of 2000 μm, and signal line widths (*S*) of 600, 800, 1000 and 1200 μm, with a length of 10 cm. Increasing the signal width of a CPW transmission line decreases its characteristic impedance (Z_0), and the measurements indicate that the line impedance decreased from approximately 130 Ω to 95 Ω as the signal line width was increased from 600 μm to 1200 μm, see Figure 4.3. The measurements in Figure 4.4 are for 100 g/m^2 Evolon® with both inks. These TDR measurements show that these techniques can be used to produce controlled impedance CPW lines.



(a) (b)

Figure 4.4 Fabric comparisons of 10 cm CPW with *b* = 2000 μm and S = 1200 μm using (a) Creative Materials ink (b) Precisia ink

Shown in Figure 4.4 are TDR measurements of a particular line geometry across variations in textile substrate and conductive ink. There are significantly more variations of impedance in the Evolon® fabrics compared to Tyvek®. These variations are most likely due to the surface roughness of the fabric, which would cause an uneven deposit of ink onto the surface. There are also small regions where ink did not deposit completely when printed on Evolon®. These regions produced discontinuities that showed up as variations in the line impedance because of the reflections they cause. Since the characteristic impedance of a CPW line is strongly dependent on the gap between the signal and ground conductors, it is likely that the rough trace edges also cause variations in the line impedance.

After examination of Figure 4.4, it is also apparent that the overall coverage of ink for Creative Materials appears to be more consistent, since the TDR profile is much smoother. In general, ink with a high surface tension tends to attract more to itself instead of to the fabric. Thus, the Creative Materials ink, having a higher surface tension, tends to remain on the surface of Evolon® thereby producing a more continuous surface for conductivity. The Precisia ink, having a lower surface tension, most likely absorbs into the fabric leaving a thinner conductive surface. The electrical characteristics of the thinner surface are therefore more influenced by the fabrics' surface roughness.

We also measured the scattering parameters (S_{11}, S_{21}, S_{12}, S_{22}) of the CPW lines using a Hewlett Packard 8510B Vector Network Analyzer (VNA). The characteristic impedance and attenuation as a function of frequency, from 100 Mhz to 10 GHz, was extracted using the method reported in Mondal et al (1988). The same probes were used for the VNA measurements along with a similar Plexiglas test fixture. The test fixture for these measurements had a 2.5 cm air bridge instead since we were examining 2.5 cm CPW lines. The characteristic impedance values extracted from the frequency domain measurements match closely with those obtained using TDR, and these values are compared in Table III.

Table III – Characteristic Impedance (Ω) from TDR (10 cm lines) and VNA* (2.5 cm lines)

Signal Width (Method)	600 µm (TDR)	600 µm (VNA)	800 µm (TDR)	800 µm (VNA)	1.0 mm (TDR)	1.0 mm (VNA)	1.2 mm (TDR)	1.2 mm (VNA)
Evolon 80**	136 Ω	136.2 Ω	126 Ω	124.5 Ω	112 Ω	111.3 Ω	101 Ω	98.3 Ω
Evolon 80***	131 Ω	130.5 Ω	117 Ω	118.6 Ω	105 Ω	104.5 Ω	93 Ω	91.2 Ω
Evolon 100**	135 Ω	140.4 Ω	124 Ω	123.9 Ω	112 Ω	108.0 Ω	97 Ω	96.5 Ω
Evolon 100***	131 Ω	134.1 Ω	120 Ω	119.6 Ω	106 Ω	104.7 Ω	95 Ω	95.0 Ω
Evolon 130**	135 Ω	137.8 Ω	125 Ω	123.9 Ω	109 Ω	109.9 Ω	98 Ω	95.5 Ω
Evolon 130***	132 Ω	132.4 Ω	120 Ω	118.0 Ω	112 Ω	109.0 Ω	102 Ω	95.8 Ω
Tyvek**	135 Ω	139.4 Ω	124 Ω	123.6 Ω	109 Ω	108.3 Ω	97 Ω	96.2 Ω
Tyvek***	133 Ω	138.5 Ω	124 Ω	123.9 Ω	109 Ω	109.2 Ω	97 Ω	96.9 Ω

*VNA measurements collected at 2 GHz
**Creative Materials Ink (CMI 112-115)
***Precisia Ink (CSS-010A)

The attenuation as a function of frequency was extracted for various CPW lines printed on both nonwoven fabrics. The results for both fabrics were nearly identical and showed only slight differences in attenuation for the Precisia ink printed lines, see Tyvek results in figure 4.5. According to the figure, the Precisia ink transmission lines exhibited a slightly steeper attenuation curve. The attenuation plots also show that CPW lines printed on nonwoven textiles can be used in multi-gigabit per second applications over distances from up to 2 m, depending on the data rate. For example, a typical equalized serial link can easily tolerate 20 dB of attenuation. If the edge rate in the system were 70 ps, the majority of the energy in the signal would be below 5 GHz. A 70 ps edge rate is fast enough to represent a non-return to zero (NRZ) signaling rate of 3 Gb/s. The fundamental frequency for a 3 Gb/s NRZ signal is at 1.5 GHz and it has a third harmonic at 4.5 GHz. One meter of the CPW line with the lowest loss would attenuate a signal with these characteristics by 8 - 16 dB.

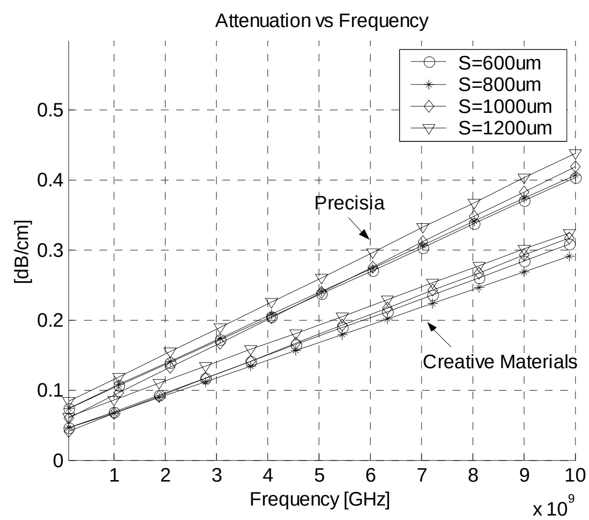


Figure 4.5 Attenuation vs frequency for various CPW lines printed on Tyvek

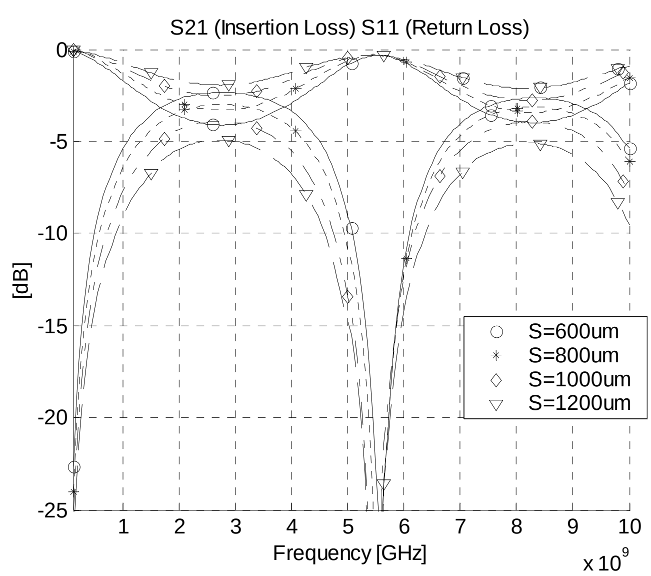


Figure 4.6 Insertion and return loss for various CPW lines printed on Tyvek

Figure 4.6 shows the measured insertion loss and return loss (S_{21} & S_{11}) for various 2.5 cm lines printed on Tyvek. The return loss for these CPW lines is higher than most acceptable transmission lines for most applications. However, this is to be expected given that these lines had characteristic impedances between 95 Ω and 140 Ω, and were measured in a 50 Ω system. In order to reduce the return loss and decrease attenuation, new line geometries with controlled lower characteristic impedances will be designed.

5. CONCLUSION

This paper presents the initial investigation of the characterization of transmission lines printed onto nonwoven substrates for wearable computing applications. Instead of using woven and knitted electronic textiles techniques we are adopting PTF to develop textile printed circuits. Applying PTF technologies onto nonwoven textiles will allow us to use a simple manufacturing process without adding complexities that would increase production costs.

For this paper we investigated printing various conductive silver lines onto Evolon® and Tyvek® substrates. We also used two conductive inks of different viscosities and percentages of silver. The DC measurements showed that the higher viscosity ink with a larger percentage of silver produced the best results in conductivity and appearance. In addition, the conductivities of the inks printed onto Tyvek® were noticeably higher than Evolon®. The lower conductivities in Evolon were most likely due to higher ink absorption and greater surface roughness.

The impedance and frequency measurements required a customized setup utilizing a specially made Plexiglas test fixture to hold the substrates in place. The TDR results showed that Tyvek® produced a much smoother impedance profile meaning that there were few variations of impedance throughout each line. These initial TDR measurements showed that these techniques could be used to construct controlled impedance CPW lines by varying line geometries. These transmission lines will also support multi-gigabit per second applications for distances up to 2 m since the lines exhibit low attenuations as a function of frequency. In addition, frequency domain measurements showed insertion losses and return losses that where higher than most accepted transmission lines. Although, adjusting the line geometries to yield 50 Ω characteristic impedance transmission lines will reduce the insertion loss and return loss. Overall, the impedance and frequency measurements demonstrated improved characteristics when compared to woven technologies for wearable computing (Marculescu et al, 2003; Cottet et al, 2003).

6. REFERENCES

Cottet, D., Grzyb, J., Kirstein, T., and Tröster, G. (2003) ‘Electrical Characterization of Textile Transmission Lines’, *IEEE Transactions on Advanced Packaging*, Vol. 26, No. 2, May 2003.

Gilleo, K. (1996) *Polymer Thick Film*, Van Nostrand Reinhold, New York.

Gupta, T.K. (2003), *Handbook of Thick- and Thin-Film Hybrid Microelectronics*, Wiley-Interscience, Hoboken, NJ.

Hoff, S.B. (1997) *Screen Printing: A Contemporary Approach*, Delmar, Albany, NY.

Marculescu, D., Marculescu, R., Zamora, N.H., Stanley-Marbell, P., Khosla, P.K., Park, S., Jayaraman, S., Jung, S., Lauterbach, C., Weber, W., Kirstein, T., Cottet, D., Grzyb, J., Tröster, G., Jones, M., Martin, T., Nakad, Z. (2003) 'Electronic Textiles: A Platform for Pervasive Computing', *Proceedings of the IEEE*, Vol.91, No.12, Dec. 2003.

Mondal, J. and Chen, T. (1988) 'Propgation Constant Determination in Microwave Fixture De-embedding Procedure', *IEEE Transactions on Microwave Theory and Techniques*, Vol. 36, No.4, April 1988.

Simons, R.N. (2001) *Coplanar Waveguide Circuits, Components, and Systems*, Wiley-Interscience, NY.

Tröster, G., Kirstein, T., and Lukowicz, P. (2003) 'Wearable Computing: Packing in Textiles and Clothes', *14th European Microelectronics and Packaging Conference & Exhibition*, 23-25 June 2003, Friedrichshafen, Germany.

Wadell, B.C. (1991) *Transmission Line Design Handbook*, Artech House, Boston, MA.

ACKNOWLEDGEMENTS

The authors would like to thank NTC for funding this research. We would also like to thank Freudenberg, DuPont™, Creative Materials, Precisia for their donations, Goulston Technologies for their help in the contact angle measurements, and the Electronics Research Laboratory at NCSU for the use of their TDR equipment.

RESPONDENCE ADDRESS:

Center for Robotics and Intelligent Machines
Campus Box 7911,
412 Daniels Hall,
North Carolina State University,
Raleigh, NC 27695-7911 USA