Textiles for Signal Transmission in Wearables

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ABSTRACT

The future trend in wearable computing is to integrate electronics directly into textiles. Our approach is to use conductive textiles for signal transmission. We investigated the electrical performance of textile transmission lines. We present methods for measuring as well as for modeling the high frequency properties of textiles. With the results it is possible to predict the electrical properties of different textiles and to optimize the fabrics and the signal line configurations.

1. INTRODUCTION

The goal of our knowledge-based society is to integrate intelligence into our everyday environment. Clothing is an important and special part of our environment as it is personal, comfortable, close to the body and used almost anywhere and anytime. Nowadays clothing already has more functions than just a certain climatic protection and a good look, but it is far away from taking full advantage of the potential of information technology services. If clothing had intelligent features, it could serve us in a very unobtrusive and natural way. Being close to the body it enables an intimate man-machine interaction. This interaction is necessary for any kind of computer intelligence as for example context awareness or intuitive interfaces. The WearNET demonstrates how a sensor system attached to the body can provide a wearable computer with a wide range of context information [1].

Humans prefer to wear textiles, as they are flexible, soft, lightweight, breathable, robust and washable. These textile characteristics strongly differ from the properties of conventional electronics. The special geometrical and mechanical properties are not only challenging researchers but also offer new fascinating possibilities in creating information systems [2][3]. So the idea emerged to develop smart fibers and fabrics that can be used for electronic functions. Advances in textile technology and material science have lead to new possibilities in the area of conductive textiles. Apart from electrical conductive material also optical conductive fibers are investigated [4][5]. Optical fibers have some advantages, as there can be no shortings, no corrosion and no parasitic field effects. But electrical conductors are still better to handle in textile fabrication processes and the costs are lower. EMI shielding and static dissipation are examples of already existing applications of electrically conductive fabrics. The idea of 'electronic textiles' goes one step further. Electronic means that textiles are capable of exchanging information. If textiles would have the ability to record, analyze, store, send and display data, a new dimension of intelligent high-tech clothing could be reached.

This paper presents the results of an interdisciplinary research work of textile and electrical engineers. We developed methods for electrical characterization of textile transmission lines. Our aim is to replace conventional wires and even whole circuit boards with textile fabrics. We wanted to find out up to which frequencies textile transmission lines can be used. Therefore we applied methods of microwave technology. That means that wires are not only characterized by their resistance but by wave effects depending on the line geometries and the surrounding material. Therefore we had to consider also the geometrical structures that are created in the textile fabrication processes.

2. TEXTILE GEOMETRY

The geometry of textile materials is characterized by a hierarchical structure: bundles of fibers are twisted to create yarns; yarns are e.g. woven or knitted to create fabrics. Fabrics for signal transmission in wearables have to meet special requirements concerning the conductivity, the processability and the wearability:

- We need individually addressable conductors that are insulated to prevent shortings.
- These insulated fibers have to withstand textile typical handling as for example weaving, washing and wrinkling without a damage of the insulation or the conductor.
- Fibers that are used for clothing have to be fine and to some extent elastic in order to achieve a high comfort of wearing. Fabrics need to have a low resistance to bending and shearing so that they can be easily deformed and draped. The more the textiles are close to the body the more they have to be flexible and lightweight.

These demands are partly inconsistent with the materials and geometries that are needed for an electrical conductivity. Metal, carbon and conductive polymers are quite rigid and brittle materials.

Nevertheless textile technologies have been developed to manufacture processable fibers and yarns out of these materials [6]. Methods of creating conductive fibers are:

- the filling of synthetic fibers with carbon or metal particles,
- the coating of fibers with conductive polymers or metal,
- the use of continuous or short fibers that are completely made of conductive material.

For our experiments we fabricated yarns that contain insulated metal filaments and fulfill the aforementioned requirements. The characterization methods that we developed can be applied for all kinds of conductive textiles. We chose woven fabrics with a plain weave in our experiments because this construction represents the most elementary and simple textile structure. In addition to that such kind of material can provide a tight mesh of individually addressable wires that can be used for basic transmission lines as well as whole circuits.

The examined fabrics contain polyester (PES) yarns that are twisted with a copper (Cu) filament. The copper filaments have a diameter of 40µm and are insulated with a polyesterimide coating. PES yarns with two different finenesses ($167\cdot10^{-4}$g/m resp. $334\cdot10^{-4}$g/m) have been used to create six different fabric types (Table 1). All fabrics have about 20 threads per cm in both directions but the density is different according to the used PES fineness. Two of the fabrics have metal filaments in both directions (warp and weft), two of them have metal filaments just in one direction (warp) and two of them are without metal. Figure 1 shows fabric 4.

Table 1: Textiles used in the experiments

Yarn types	Woven fabric types
Yarn A: PES yarn $167\cdot10^{-4}$g/m + Cu filament *Yarn B:* PES yarn $167\cdot10^{-4}$g/m	*Fabric 1:* low density with Cu in both directions (XY) *Fabric 2:* low density with Cu in one direction (X) *Fabric 3:* low density without Cu
Yarn C: PES yarn $334\cdot10^{-4}$g/m + Cu filament *Yarn D:* PES yarn $334\cdot10^{-4}$g/m	*Fabric 4:* high density with Cu in both directions (XY) *Fabric 5:* high density with Cu in one direction (X) *Fabric 6:* high density without Cu

Taking a closer look to textile geometry one can observe that fibers follow a helical path within the yarn. The helical path of the metal threads can be seen in figure. When the yarns are woven into a fabric they are periodically crimped (Figure 2). That means that the length of the metal filament is greater than the length of the fabric. There are several irregularities concerning the location of the fibers within the yarn as well as concerning the location of the yarns within the fabric. These variations are caused by the deformability of the textile material and the degrees of freedom in the manufacturing processes. At the level of fibers and yarns there are e.g. variations of diameters and densities (along the thread but also from thread to thread). At the level of fabrics e.g. the distance between yarns varies (Table 2). As textile material has viscoelastic behavior, inner tensions relieve over time and the geometry may change (especially in washing treatments).

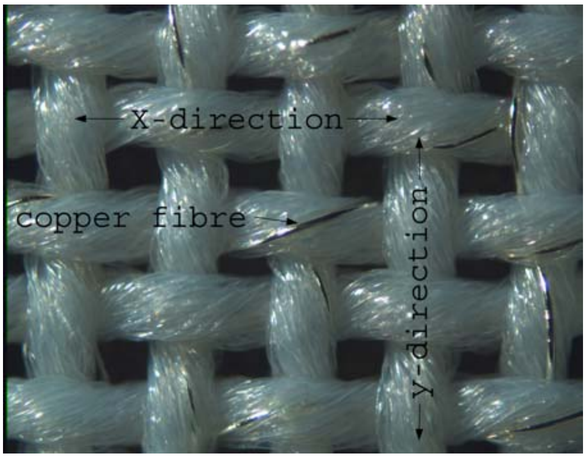


Figure 1: Woven fabric with metal fibers

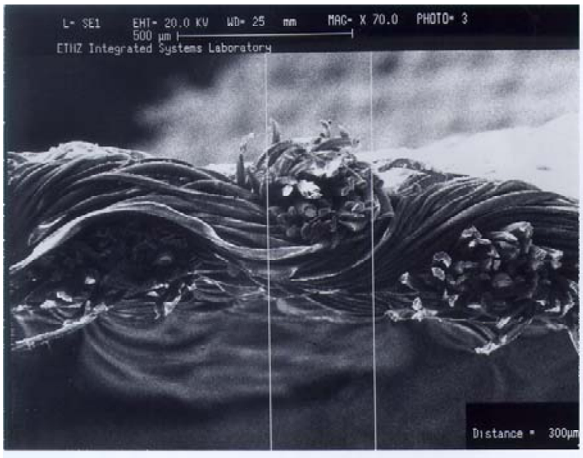
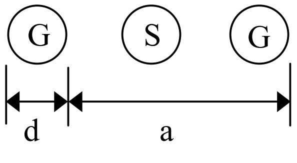


Figure 2: Fabric cross-section

Table 2: Variations of textile geometries used in the experiments

Fabric type	Dimensions	Variations
Fabric 1 (low density)	a=891µm d=228µm	σ=32.9µm σ=25.3µm
Fabric 4 (high density)	a=876µm d=334µm	σ=25.0µm σ=28.0µm

Explanation:
d=thread diameter
a=thread distance



3. ELECTRICAL CHARACTERIZATION

In order to evaluate the performance and limits of textile transmission lines we extracted the electrical parameters with time and frequency domain analysis and developed a theoretical model that describes the signal transmission in textiles.

3.1 Material Properties

The DC resistance of single metal filaments is 0.15Ω/cm for yarn A and 0.17Ω/cm for yarn C. These measured DC resistances and the actual diameter of the metal filaments allow calculating the effective metal filament length compared to the textile length. For the thinner yarns (type A) the metal filament is about 7.5% longer than the corresponding textile, with a tolerance of 0.5%. For the thicker yarn (type C) where the metal fiber runs a larger helical path, this difference increases to about 25.5% with a tolerance of 2.0%.

The dielectric permittivity ε_r of the mixed PES-air textile structure was extracted by means of parallel plate capacitors of known dimensions and using the yarn types B and D (without metal fibers). The obtained results range from $\varepsilon_r = 1.4$ to 1.6. These inaccurate values are due to the fact that the measured permittivity strongly depends on the ratio of polyester and air. Introducing the copper fibers will also affect the total permittivity as the polyesterimide used for the isolation coating of the copper shows an $\varepsilon_r \approx 3$.

3.2 Transmission Line Configuration

To minimize parasitic coupling at high frequencies the ground line should be close to the signal line. In conventional circuit boards often a whole ground layer is used, but creating such a construction in textile fabrics would have several disadvantages. We decided to take metal filaments in warp direction (X-direction) as signal lines and the neighboring metal filaments on each side as ground lines. These configurations are similar to conventional coplanar waveguides (CPW) on printed wire boards. The transmission line configurations differ by the number of signal fibers S or ground fibers G. The space between the ground and the signal line is given by the textile construction and cannot be modified. The attempt to skip copper fibers to increase the space would yield floating lines evoking undesired parasitic coupling effects. A list of all investigated configurations is given in Table 3.

Table 3: Transmission line configurations

Configuration	Number of signal lines	Number of ground lines
GS	1	1
GSG	1	2 (1 on each side)
GSSG	2	2 (1 on each side)
GSSSG	3	2 (1 on each side)

3.3 Impedance Measurement

We investigated the typical, achievable characteristic impedance of the textile transmission lines. As we expected the textile geometrical variations to have influence on the impedance, we measured the signal reflections along the transmission line with time domain reflectometry. We had to develop suitable connectors for the measurement of textile lines. FR4 laminate-based interposers with patterned 50Ω CPW solder pads on one side and SMA connectors on the other side allowed reliable connection of the textile samples with the measurement equipment (Figure 3, Figure 4). The block diagram of the measurement setup is depicted in Figure 5.

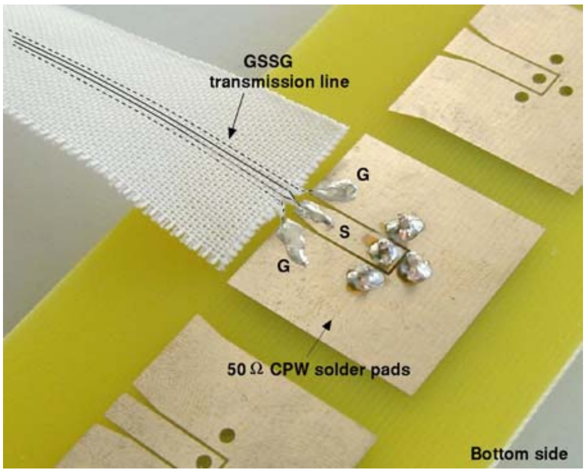


Figure 3: Textile solder-pads as 50 coplanar waveguide

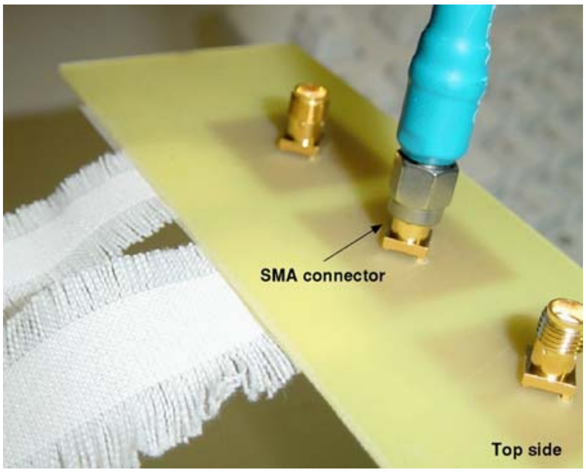


Figure 4: SMA connectors

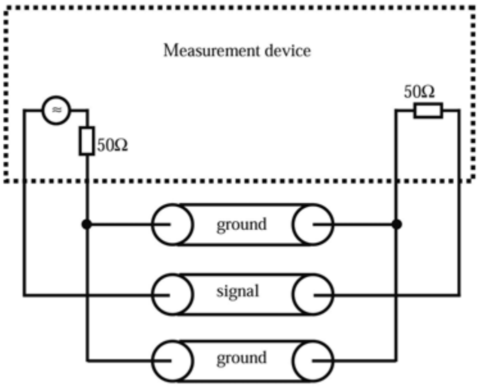


Figure 5: TDR measurement setup

Figure 6 shows typical measured line impedances for the investigated transmission lines. Results for the same yarn and fabric types are connected with lines to illustrate the relation between configuration and line impedance. The XY-fabrics (metal fibers in both directions) have lower impedances due to a higher capacitance that is caused by coupling effects to the floating lines in Y-direction. The textiles with metal only in X direction have lower capacitance and inductance and therefore provide faster signal propagation than the textiles with metal in XY direction.

The results of the four configurations are comparable to coplanar waveguides on PCBs: increasing the signal line width by adding more parallel copper fibers decreases the line impedance. Using fabrics with smaller distances between the threads (that means between signal and ground lines) would enable a lower line impedance, but 50Ω lines seem difficult to achieve. However, it is more important to achieve a defined impedance value. The measurements show impedance variations along the textile signal lines (see Figure 7). These variations are caused by the geometrical irregularities in the fabrics. In the following we investigated the effects of these variations on the predictability of the line impedance.

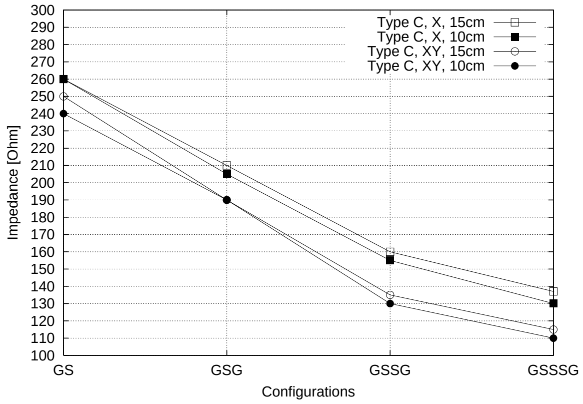


Figure 6: Measured impedance of the different transmission line configurations

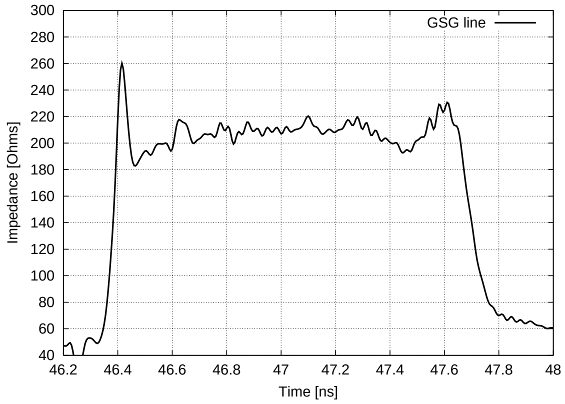


Figure 7: Impedance profile of 15cm transmission line

3.4 Impedance Simulation

In order to predict the impedance of different fabrics and line configurations we modeled the textile transmission lines with a 2.5 dimensional electromagnetic field solver (Sonnet EM Suite 7.0). In this way we wanted to get better understanding of how the textile fabrication tolerances affect the line impedance. To simplify the modeling and to reduce the computation time, the woven fabric structure was regarded as homogenous material with an equivalent dielectric permittivity as previously measured in section 3.1. In effect the textile model consists of two dielectric layers with a permittivity of $\varepsilon_r = 1.5$ and a thickness of 2mm each (see Figure 8). The metal fibers are modeled as planar metal strips between the two textile layers. To compensate for the sinusoidal helical shape of the metal fiber within the yarn, the width of the metal stripes is averaged to $w = d/\pi \approx 110\mu m$.

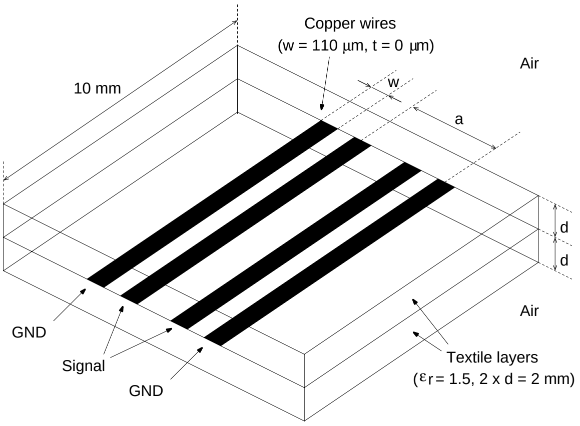


Figure 8: Textile model for Sonnet showing a GSSG configuration

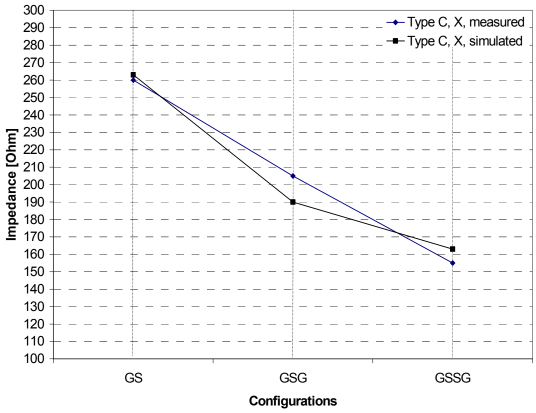


Figure 9: Comparison of measured and simulated impedances

Figure 9 shows the comparison of measured and simulated impedances and demonstrates that it is possible to predetermine the textile line impedances with the developed model. The achievable tolerances caused by geometrical variations are accurate enough for an implementation where a textile signal bus must be effectively terminated.

3.5 Frequency Characterization

To investigate the frequency characteristics of textile transmission lines we measured the transmission properties with a vector network analyzer (VNA) up to 6GHz. The textiles were connected with the network analyzer ports by means of the same FR4 interposers proposed earlier.

As mentioned before the textile lines are not reflectionless but continuously and stochastically change their impedance value. The variations of wire lengths and distances are able to unequalize the phases and excite parasitic waves ("odd-modes"). As the ground wires and signal wires are shorted at the beginning and the end of the transmission line these odd-modes have an effect when the line length is a multiple of the half-wavelength of the signal. In Figure 10 one can clearly observe some deep minima in the line transmission even down to -18dB being the result of these parasitic resonances.

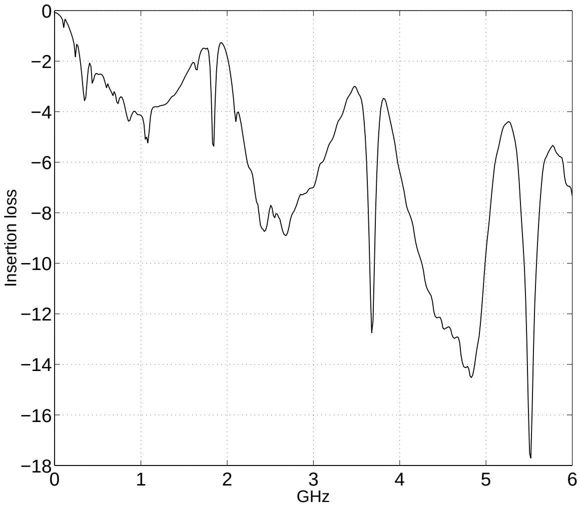


Figure 10: Measured insertion loss in [dB] of the 5cm GSSSG line (fabric 5)

We extracted the attenuation constants for the different configurations. The extracted values show that in the lower frequency range the coupling to the odd-modes is weak and single mode propagation can be reasonably justified. One can observe that the extracted attenuation even in this frequency range shows non-monotonical frequency behavior, which is not typical for uniform transmission lines. This is the effect of non-uniform characteristic impedance profile along the line caused by large geometrical tolerances. The frequency behavior of the tested configurations show the same dependence with the same maximum attenuation of 0.05--0.1dB/cm in the frequency range of single mode propagation.

We can arrive at the very important conclusion that the insertion loss of the textile lines is not determined by the dielectric and ohmic losses, but by the reflections along the line in the lower frequency range and coupling to the parasitic modes at higher frequencies above half-wavelength. Although the textile wires feature very high conductivity, it plays no role in determining the loss factor of the lines. the XY configurations show slightly lower losses in the single mode propagation range and weaker but more irregular coupling to odd modes. This is the effect of the orthogonal wires which are able to destroy the constructive resonances of the odd modes to some extend.

Based on measured different line configurations we can conclude that the longest possible line length is equal to the half-wavelength of the lines at the maximal desired frequency of usage. It allows the lines to be 10cm long for maximal frequency of approximately 1.2GHz and 1GHz for X and XY configurations, respectively. For 100MHz signals the allowable line lengths are tenfold and are in the range of 100cm.

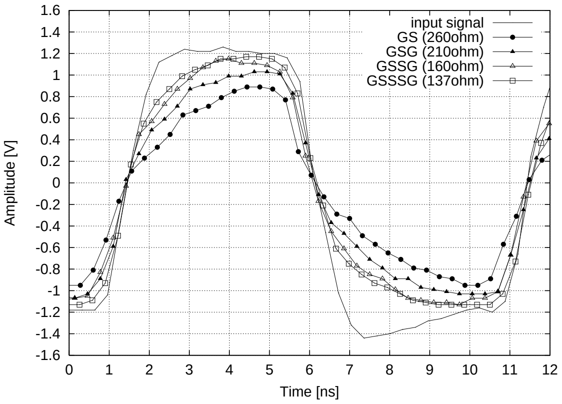


Figure 11: 100MHz clock signals measured through four different 20cm long textile transmission lines

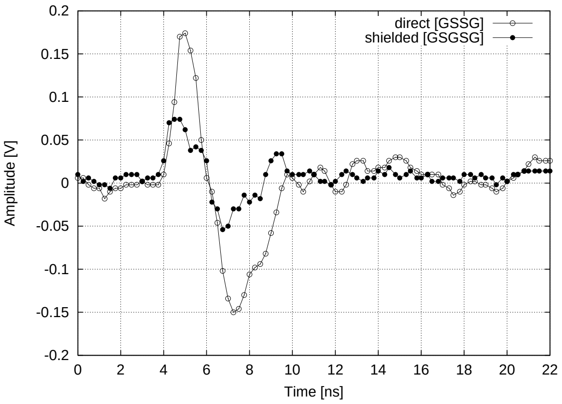


Figure 12: Far-end crosstalk measured on 20cm matched load lines with and without shielding

3.6. Signal Integrity and Crosstalk

Figure 11 shows a 100MHz clock signal measured at the end of 20cm textile transmission lines in different configurations and demonstrates the signal integrity.

Figure 12 presents the results of the far-end crosstalk for the two neighboring lines in GS and GSG configurations. The measurements were performed on two 20cm long lines terminated in a matched load. The amplitude of the aggressor signal was 2.5 Volts with a rise time of 6 ns. The ground fiber between the neighboring lines in the GSG configuration, acting as a shield, allowed to reduce the cross-talk from 7.2% in GS configuration down to 2.8%.

4. CONCLUSIONS

This paper presents for the first time the extensive characterization of textile transmission lines for use in wearable computing applications. The proposed textiles are fabrics with copper fibers in one or both directions and with different yarn fineness. This variety of fabrics opens a wide range of possible transmission line topologies and allows finding a configuration that fits the target application.

The FR4 interposer with coplanar solder pads and SMA connectors allowed reliable connection of the textile samples to the measurement equipment. TDR measurements showed that the achievable characteristic impedances lie between 120Ω and 320Ω. To study the influence of fabrication tolerances, the textiles were modeled with Sonnet, an EM-field simulation tool. The simulation results showed that with the given geometry variations an accuracy of ±5% to ±10% for the characteristic impedances is achievable.

High frequency network analyzer measurements were performed up to 6GHz. The extracted frequency characteristics revealed that the dielectric and ohmic losses do not determine the line insertion loss. The loss is mainly influenced by non-uniform impedance profile along the lines up to the half-wavelength and by coupling to parasitic modes above this frequency point. This results in cut-off frequencies of 1.2GHz and 1GHz for 10cm long lines in X and XY configurations, respectively. Good signal transmission for a 100MHz clock signal was proved through 20cm textile lines. Experiment showed also that a grounded copper fibers between two neighboring lines reduced crosstalk from 7.2% to 2.8%.

The final conclusion of this work is that the conductive textiles provide much more than EMI shielding and power supply. Transmission lines with controlled characteristic impedance and high signal integrity up to several 100MHz enable new options of interconnect for wearable computers.

5. ACKNOWLEDGEMENTS

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