Characterization of Inkjet Printed Coplanar Waveguides for Flexible Electronics

Yi Feng (1), Matthias Mueller (2), Jens Liebeskind (2), Qiang Chen (1), Li-Rong Zheng (1), Wolfgang Schmidt (3) and Werner Zapka (1,2), (1) iPack Vinn Excellence Center, KTH (Royal Institute of Technology), Forum 120, 164 40 Stockholm-Kista, Sweden, (2) Xaar Jet AB, SE-175 26, Järfälla, Sweden, (3) Felix Schoeller GmbH & Co. KG, Burg Gretesch, 49086 Osnabrück, Germany, yfeng@kth.se

Abstract

The low conductivity and thin layers of the inkjet-printed metal conductors have always been a big concern in paper-based printed electronics for high frequency applications. To provide the fundamental knowledge, the high frequency characteristics of inkjet-printed coplanar waveguides on paper substrate were studied experimentally in terms of characteristic impedance and conductor losses using the time domain reflectometry technique. The influences of different printing settings and of geometric parameters on the waveguide's properties were investigated. Considering the measurement accuracy in high frequency characterization, one sample with an impedance of 51.2 Ω was achieved. The electrical stability of the samples was also studied and explained. In addition, one waveguide sample was printed in a way that the pattern area with the highest current density is thickened. This variable ink-layer thickness approach has successfully been proven as a promising solution to reduce the conductor losses and yet consuming less ink.

Introduction

Paper has attracted great research interest as a substrate for flexible electronics in the last decade [1]. It is not only cheap and environmentally friendly, but can also be processed in a roll-to-roll fashion at high speed. As a direct-write technology, digital inkjet printing has been considered as a promising method for fabricating paper electronics on account of its additive, mask-less, non-contact and fast processing.

There have been several reports on high frequency electronic devices inkjet-printed on paper substrate, such as antennas and RFID tags [2-5]. However, there is no fundamental study on the high frequency performance of printed metal conductors on paper substrate so far. Moreover, the unknown electrical properties of new substrate materials and the non-uniform cross-section of printed conducting tracks make it difficult to achieve accurate evaluation using electromagnetic field simulation tools. Therefore the experimental study on high frequency characteristics of inkjet-printed coplanar waveguides (CPWs) on paper substrate would provide important parameters and knowledge to enable an efficient and elaborate design of printed electronics. The CPW was chosen in this study because its uniplanar structure requires only single-side process and eliminates the need of via holes. In addition, the CPW structure can be used in the future to build up microwave circuits and components such as, directional coupler, filters and conformal antennas [6, 7].

Experimental

The cross section view of a coplanar waveguide is illustrated in Figure 1(a), with g indicating the width of the outer ground conductors, s the width of the center signal conductor, w the gap size between the signal and the ground conductors, t the thickness of the conductors. The length of the conductors is indicated by l.

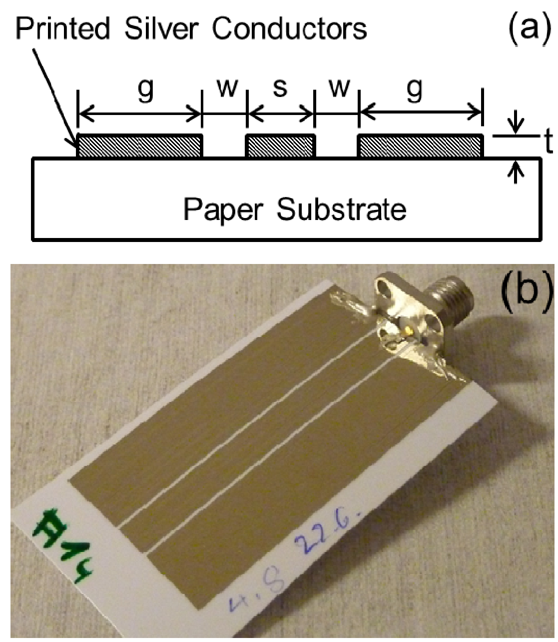

Figure 1. *(a) The cross section of a coplanar waveguide. (b) Photograph of an inkjet-printed coplanar waveguide on paper with a SMA coaxial connector*

The CPW patterns were inkjet printed with silver nano-particle ink SunTronic™ Solsys EMD 5603 from Sun Chemical Corp, which is ethanol based and contains 20 wt% silver. The substrate was PE-photopaper H72110 from Felix Schoeller GmbH & Co. KG. This paper is single-sided coated with a defined porosity intended to collect the silver nano-particles in the top surface while absorbing the fluidic carrier into the bulk of the paper. The paper substrate is 280 μm in thickness. A binary Xaar126 printhead with 50 pl drop volume was mounted on a flat bed printer and inclined to print at 360 dpi resolution across to the printing direction while the printing resolution in printing direction could be changed. The impacts of the resolution in the printing direction and of the number of layers printed on the high frequency performance of CPWs were to be investigated in this work. After printing the samples were cured at 90 ºC for 30 minutes in a convection oven. For measurement of their high frequency performance the CPW samples were assembled with the SMA coaxial connectors 32K441-600L5 from Rosenberger. During this assembly step the center and ground conductors were connected with the SMA by manually dispensing electrically conductive epoxy CW2400 from Circuit Works as can be seen in Figure 1(b).

Measurements and Discussion

Time domain reflectometry (TDR) measurements of the printed CPW samples were performed to determine the characteristic impedance by using an Agilent Infiniium DCA 86100b wide-bandwidth oscilloscope. In addition, TDR is also useful to compare the losses in the transmission lines [8]. The standard calibration was done before the measurements.

The TDR responses of the CPW samples with geometric parameters of s = 1.6 mm, w = 500 µm, g = 10 mm and l = 50 mm, using different resolutions in the printing direction and layers, are shown in Figure 2. The area A indicates the impedance of a 50-Ω short coaxial cable that connects the samples to the equipment. TDR responses of the CPW samples are shown in the area B. The exponentially rising characteristic in the curves reflects that the conductor losses predominate in the printed CPWs. Then in the area C the curves approach infinity sharply because all the samples are open-ended. As the magnitude of the curves' slope in the area B indicates the conductor losses, it can be seen that the losses basically goes down as the ink amount increases and thus the fourth curve exhibits the smallest losses. It is mainly because the larger amount of ink printed in a defined area implies a thicker metal layer. The DC sheet resistance of the fourth '470 dpi and 2 layers' sample was measured to be 0.44 Ω per square while that of the '360 dpi and 2 layers' one was 0.64 Ω per square. It can be assumed that the very first printed layer on paper works more like a planarization process which is usually not sufficient for high frequency electronics, while the following printings make the active conductive layer.

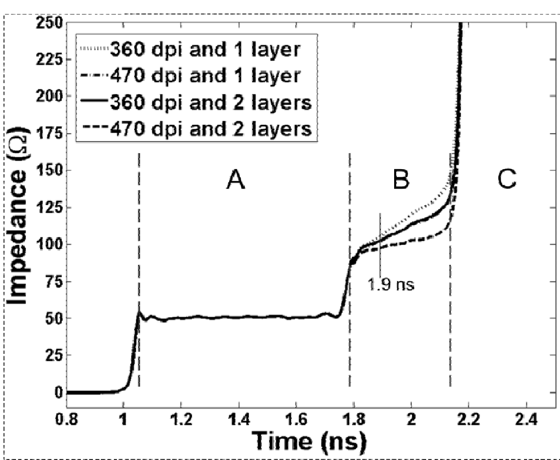

Figure 2. TDR measurement of inkjet-printed CPWs on paper substrate with different printing resolutions in the printing direction and number of layers, all the samples have the same pattern

Although additional layers would further reduce the losses as it can be predicted for the curve tendency in Figure 2, the layer number needs to be kept as small as possible considering the cost for applications.

The characteristic impedances of the printed CPW samples under the setting of 470 dpi in the printing direction with two layers are shown in Figure 3 to 5. The impedances were measured at the time around 1.9 ns as indicated in Figure 2 to avoid the measurement error induced by the manual attachment of the SMA. Figure 3(a) shows the measured impedances of two series of CPWs as a function of the gap size from 100 µm to 500 µm. One series has the geometric parameters of s = 1.6 mm and g = 10 mm, and another series has s = 4.8 mm and g = 20 mm. It has also been observed that the width of the ground conductors has negligible effect on the CPW's characteristics if it is at least twice as wide as the signal conductor. As shown in Figure 3(b), an obvious variation in impedance data occurs when the width of the ground conductors drops below 10 mm.

The impedance of a device under test is usually preferred to be close to 50 Ω to obtain the best measurement accuracy in the high frequency characterization. As can be seen in Figure 3 the CPW with the geometric parameters of s = 4.8 mm, w = 100 µm and g = 20 mm yields the impedance value about 51.2 Ω.

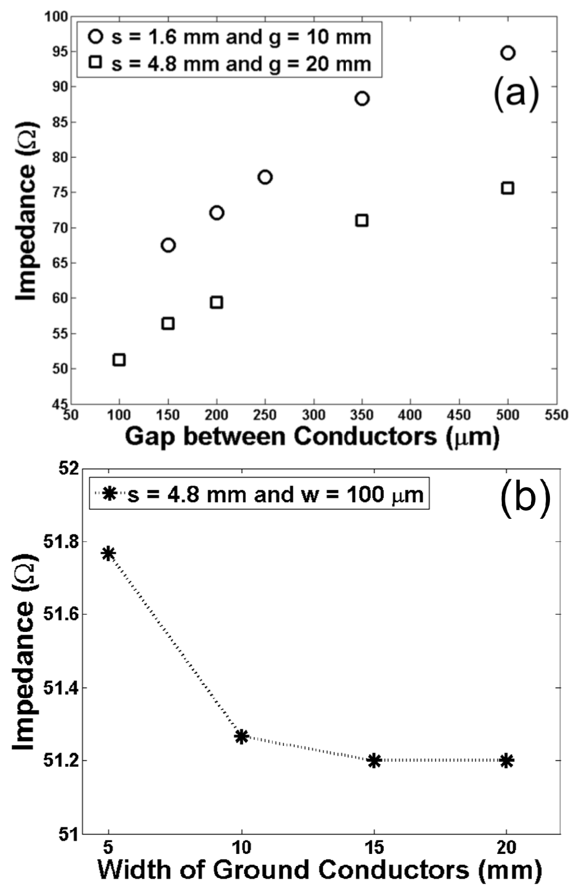

Figure 3. The measured characteristic impedances of the CPWs inkjet-printed with 470 dpi in the printing direction and 2 layers on paper substrate as a function of (a) the gap size between the conductors and (b) the width of the ground conductors

Figure 4 shows the measured impedances of the CPW samples with w = 500 μm and g = 10 mm as a function of the width of the signal conductor being swept from 1.6 mm to 4.8 mm in steps of 0.8 mm. The measurement was repeated on three different dates for the samples with s = 1.6 mm, 2.4 mm and 3.2 mm. It can be seen that the impedance of the same sample might vary day to day.

The variable moisture content in the environment could be one cause of the impedance variation. The effect of the relative humidity (RH) level on the impedance was tested additionally. Under 50% RH, the impedance of one CPW sample was measured to be 93 Ω. After being put under 90% RH and 25 ºC for 15 minutes in an environmental chamber WK11-180 from Weiss Technik, its impedance dropped to 85 Ω. The reason is probably that the dielectric constant of the paper increases when the paper absorbs more water which has a large dielectric constant of 80 at 20 ºC [9]. Barrier films could be added to protect such paper-based electronics from the harsh environment [10]. From another perspective, paper's sensitivity towards moisture could be utilized for making humidity sensors.

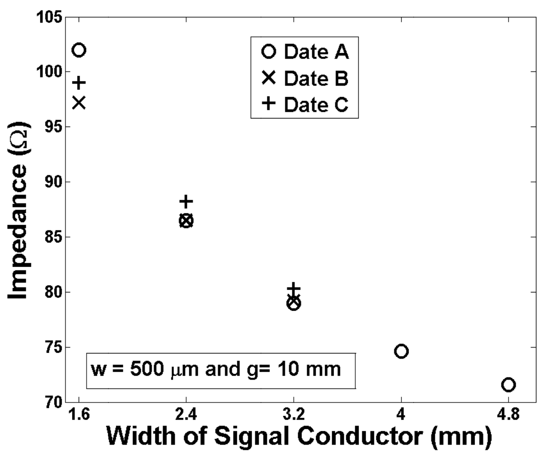

Figure 4. The measured characteristic impedances of the CPWs inkjet-printed with 470 dpi in the printing direction and 2 layers on paper substrate as a function of the width of the signal conductor, and the samples with s = 1.6 mm, 2.4 mm and 3.2 mm were measured repeatedly in three different days as indicated as Data A, B and C

While CPW samples printed with the same pattern at the same time on the same sheet of paper produced essentially identical impedance data, this was not the case when the samples were printed on different dates and on different sheets of paper. As shown in Figure 5, the three CPW samples investigated provided differences in impedance data that were significantly larger than the data scatter from repeated measurements. One potential explanation is evaporation of volatile organic acid from the paper coating, which depends on time, temperature, ventilation etc. The concentration of volatile organic acid in the paper presumably influences the dielectric behavior of the microporous layer both underneath the silver conductors as well as in the gap area, thus causing different impedances. The volatile organic acid might also play a role in the impedance variation of the same sample measured on different dates as shown in Figure 4. For practical applications the paper samples thus might have to be modified to enable more constant dielectric performance.

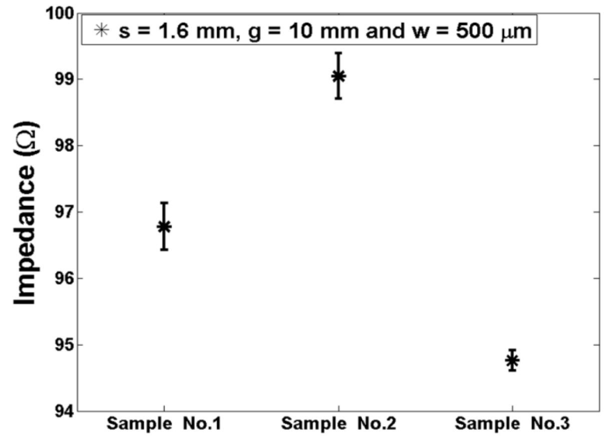

Figure 5. The characteristics impedances of three CPWs inkjet-printed with 470 dpi in the printing direction and 2 layers on paper substrate, all of samples have the same pattern

As shown in Figure 2, the optimal setting (470 dpi in the printing direction and two layers) gives decent conductor losses for short CPWs. However, for applications where longer conductors are necessary, the losses need to be reduced further. The most common method is to increase the metal layer thickness by overprinting the patterns for many times [2-4]. It is a straightforward method but the ink cost and processing time will rise significantly. Moreover, for some patterns like CPWs, a large amount of ink will overflow the gaps between the conductors. Authors of [5] employed a linearly-tapered microstrip line to compensate the increased resistance of inkjet-printed silver conductors. But this tapering technique is not practical for the CPW structure. In [11] a variable ink-layer thickness approach was studied to improve the printed antenna performance. In this approach, the antenna pattern areas with highest current density were printed with thicker ink layers. However, their investigation showed that the printed antenna's radiation efficiency mainly depends on the total amount of ink used and not how it is distributed throughout the structures. This approach was applied in the printing of one CPW sample as illustrated in Figure 6 in this work. The grey area was printed with 470 dpi in the printing area for twice, while the dark rim with 1.4 mm in width was printed for four times.

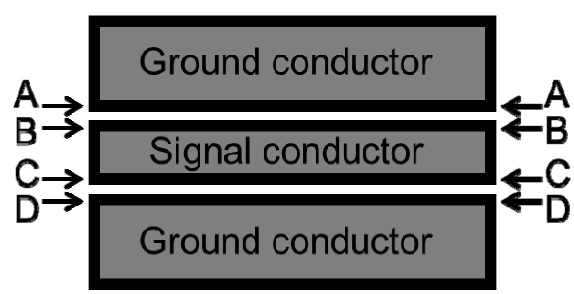

Figure 6. The top view of a coplanar waveguide with thicker ink layer in the 1.4 mm-wide rim, and the arrows with A-D letters indicate the edges where the highest current density is in the waveguide

This CPW sample was compared with those of the same pattern which were simply overprinted from one to four times respectively, and their enlarged TDR responses in the area B are shown in Figure 7. As stated above, it was found that the gap in the CPW would be overflowed if the pattern was overprinted beyond four times. The peaks in the beginning of the curves were caused by the imperfect electrical connection of the SMA by hand. It can be seen from the figure that the conductor losses decrease with the layer number going up till three. However, the '4 layers' sample shows no better performance than the '3 layers' one. The main reason might be that the ink was distributed quite uneven when the layer number reaches three, and more ink remained in the inner area for the '4 layers' sample than the '3 layers' one. The last sample shows the same magnitude of the curve slope as the '3 layers' one does, while it consumed 81.6 % of the ink that was printed for the latter one. The ink could be further saved if only the indicated A-D four edges, where most of the current is distributed, are thickened, and the rim width could be narrowed as well. It reveals that the variable ink-layer thickness approach is a cost-effective way to reduce the conductor losses in CPWs.

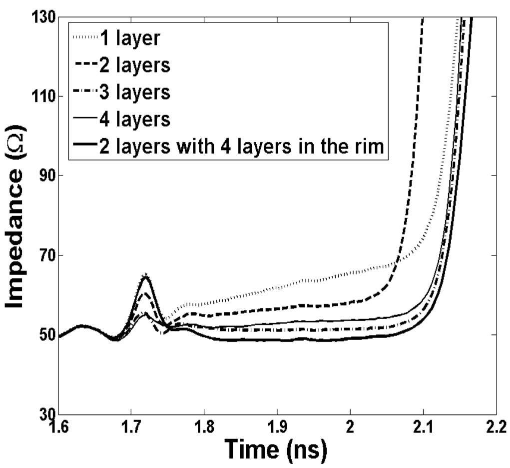

Figure 7. *TDR measurement of inkjet-printed CPWs on paper substrate overprinted for different times with 470 dpi in the printing direction, all the samples have the same pattern (s = 4.8 mm, w = 150 µm and g = 20 mm)*

Conclusion

The coplanar waveguides were inkjet-printed on single-side coated PE-photopaper with silver nano-particle ink. The printing resolution in the printing direction and the overprinting times were varied to compare the conductor losses in the waveguides at high frequency using the time domain reflectometry technique. The characteristic impedances of the waveguides printed under the optimal setting were measured with geometric variations. It was found that the width of the ground conductors has negligible effect on the CPW's characteristics if it is at least twice as wide as the signal conductor. One CPW sample with an impedance of 51.2 Ω was achieved, which would help to improve the measurement accuracy for the future characterization work.

The humidity test on the sample shows the dielectric constant of the paper changes with its water content, which might be one reason for the impedance variation of the same sample measured on different dates. Moreover the evaporation of volatile organic acid from the paper coating might influence the dielectric constant of the substrate too, which could explain the observed impedance difference in the samples with the same pattern printed on different paper sheets and on different dates.

Last, a coplanar waveguide sample was printed in a fashion that the pattern area with the highest current density is thickened. The measurement result has shown that this variable ink-layer thickness approach is a cost-effective way to reduce the conductor losses than simply overprinting the patterns.

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Author Biography

Yi Feng received the B.Sc. degree in microelectronics from Fudan University, Shanghai, China in 2005. She is currently pursuing the Ph.D degree within the iPack ViNN Excellence Center in the Royal Institute of Technology (KTH), Stockholm, Sweden. Her current research focuses on design and fabrication of low-cost printable wireless sensors and RFID sensors on flexible substrates.