Multi-GHz Microstrip Transmission Lines Realised by Screen Printing on Flexible Substrates

Yizhi Shi, Zhenzhen Jiang, Sang Lam #, Mark Leach, Jingchen Wang, and Eng Gee Lim
Department of Electrical and Electronic Engineering, Xi'an Jiaotong-Liverpool University
Suzhou, Jiangsu Province, 215123, China
Email: *s.lam@xjtlu.edu.cn*

***Abstract*— This paper reports experimental work on 50 Ω microstrip transmission lines implemented by screen-printing low-cost silver paste onto thin flexible polyethylene terephthalate (PET) substrates of varying thickness. The microstrip line designs are based on PET substrates with thicknesses of 1.4 mm, 0.7 mm and 0.5 mm, leading to conductive track widths of 3.8 mm, 1.7 mm and 1.2 mm respectively for a 50 Ω line; these designs were then realised. The S-parameter measurements show that the insertion loss of the microstrip transmission lines on each substrate can be as low as 0.2 dB/cm, 0.17 dB/cm, and 0.14 dB/cm up to a frequency of 5 GHz in spite of the average quality of the silver paste used. The experimental results also show that the screen-printed transmission lines still work quite well in bent condition and wearable electronics application at GHz is possible.**

Keywords—microstrip transmission line, screen printing, polyethylene terephthalate, insertion loss, S-parameter, radio frequency (RF)

I. INTRODUCTION

The microstrip line is a popular planar transmission line structure commonly used in radio-frequency (RF) or microwave circuits built on printed circuit boards (PCBs). The microstrip line configuration is useful for realisation of microwave filters and other passive components such as couplers and power combiners or dividers [1]. Typically, rigid PCBs are used as they offer stable RF performance even above 10 GHz. However, current technology trends in for example wearable devices means that there is a desire for low-cost implementations of microstrip transmission lines through the printing of conductive tracks and ground planes on flexible substrates. Such structures would allow for the rapid prototyping of bendable/stretchable microwave devices [2]. The material properties of these flexible substrates as well as their thicknesses will be different in comparison to standard PCB specifications. The implementation of microstrip lines by printing techniques can also allow the experimental determination of properties of the dielectric substrate as a microwave material [3]-[4]. Some work on microwave transmission lines and antennas fabricated on flexible substrates using printing techniques have already been published [5]-[10]. However, so far, little experimental work has been reported on microwave microstrip lines made by screen-printing on thin flexible substrates using low-cost silver paste instead of expensive conductive ink.

In this work, microstrip transmission lines on thin flexible polyethylene terephthalate (PET) substrates of different thicknesses are investigated as an extension of the previously published theoretical work [11]. The microstrip designs with different conductive track widths corresponding to different PET substrate thicknesses have been verified by electromagnetic simulations using the COMSOL software. Fabrication was carried out by using a simple screen-printing method with low-cost apparatus and ordinary lab equipment. DC measurements were performed using a digital multimeter while S-parameters were obtained using a vector network analyser (VNA).

II. MICROSTRIP TRANSMISSION LINE

The structure of the microstrip transmission line is shown in Fig. 1. The top conducting strip is the signal-carrying track with a width w_{cond} and a thickness t_{cond}. A dielectric substrate of thickness t_{PET} and dielectric constant ε_r separates the conductive track and conductive ground plane such that the strip and ground plane form a parallel-plate capacitor structure.

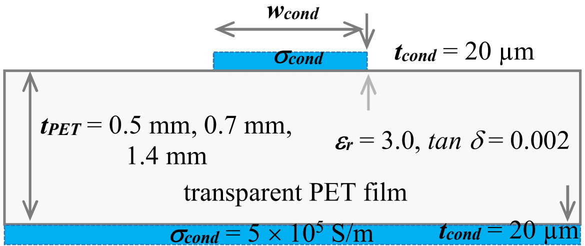

Fig. 1: Cross-sectional structure of a microstrip line printed using silver paste on a flexible PET film

In this work, the material of the conductive strip and ground plane is printed silver paste after thermal curing and the material of dielectric substrate is PET. According to the resolution of the screen-printing method, the track width of the microstrip lines should be >0.1 mm. In this work, three thicknesses of the PET substrate material are investigated, namely 1.4 mm, 0.7 mm and 0.5 mm, which respectively lead to conductive strip widths of 3.5 mm, 1.7 mm and 1.2 mm, to obtain a 50 Ω characteristic impedance in each case.

III. SILVER PASTE PRINTED ON PET SUBSTRATES

With the microstrip designs verified by electromagnetic simulations [11], the transmission lines are implemented by screen-printing the silver paste onto the PET films. Afterwards,

---

This work was supported in part by research development fund (RDF-14-02-36) from Xi'an Jiaotong-Liverpool University.

thermal curing needs to be performed. This process leads to a change in the conductivity of the printed silver paste for different curing temperatures and durations. To determine the conductivity of the printed silver paste, the DC resistance and the thickness of the printed microstrip lines should be measured and then the sheet resistance, the resistivity and hence the conductivity can be calculated. The measurements of the DC resistance of the conductive tracks can help find the practical relationship between the conductivity of printed silver paste and the loss of the microstrip transmission lines. To a certain extent, the measured DC properties can be used to infer the RF performance of the printed microstrip transmission lines.

Several samples of microstrip line printed using silver paste underwent varying thermal curing conditions. The conductivity of the printed silver paste of different conductive track widths as a function of curing temperature is shown in Fig. 2.

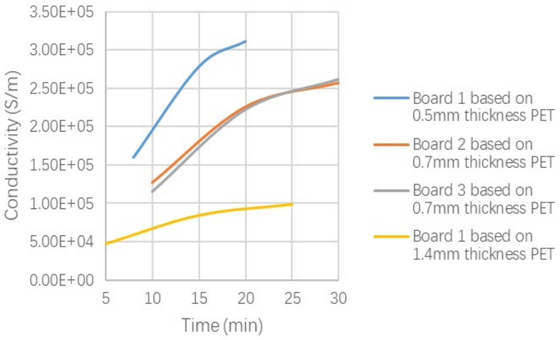

Fig. 2: Experimentally determined conductivity of printed silver paste with different curing time

It is apparent that for a longer thermal curing duration, higher conductivity can be obtained from the printed silver paste. The improvement in conductivity can be more than 200%. For this reason, following the printing of the silver paste onto the PET substrates, a longer thermal curing duration is preferred to obtain better RF performance of the printed microstrip transmission lines. Fig. 2 also shows that after a curing time of around 30 minutes, the improvement in the conductivity of the printed silver paste dwindles. As a result, a thermal curing temperature of 150°C for 30 minutes is considered sufficient to obtain a conductivity that will provide good RF performance as a microstrip line. Comparing with the typical value of the conductivity of silver, $\sigma_{Ag}=6.2\times10^7$ S/m, the measured conductivity values of the printed silver paste are about two orders of magnitude lower. According to the previously published theoretical study [11], this silver paste is considered useable despite the lower conductivity.

IV. S-PARAMETERS MEASUREMENT RESULTS

In addition to the DC resistance measurements, two-port *S*-parameter measurements of the printed microstrip lines were performed using a VNA. Microstrip lines printed on PET of different substrate thicknesses were measured under flat as well as bent conditions. Fig. 3 shows the measurement set-up of the microstrip line bent at 30 degrees. The measurement results for the microstrip line under both conditions are shown in Fig. 4.

S_{11} and S_{22} represent reflection coefficients at port 1 and port 2 respectively. As shown in Fig 4, the reflected signals in both normal and bent conditions only account for a small fraction of the incident signals. For a microwave transmission line, such *S*-parameter results are considered reasonably good performance. A transmission line is close to a matched network system when $S_{11} = 0$ or $S_{22} = 0$ as the reflection coefficient $\Gamma = (Z_0\text{-}Z_L)/(Z_0+Z_L)$. At 1 GHz, $S_{11} = -19$ dB in the normal and bent conditions while $S_{22} = -22$ dB and -16 dB in the respective conditions. The difference in the curves of S_{11} and S_{22} is probably because the transmission line is not completely symmetrical due to the minor defects in the screen printing and the connections of the SMA connectors.

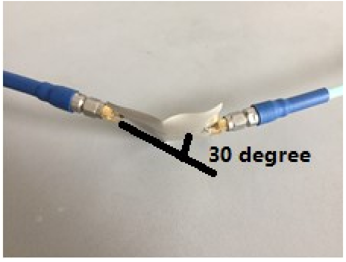

Fig. 3 Two-port *S*-parameter measurements with the microstrip line bent at 30 degrees

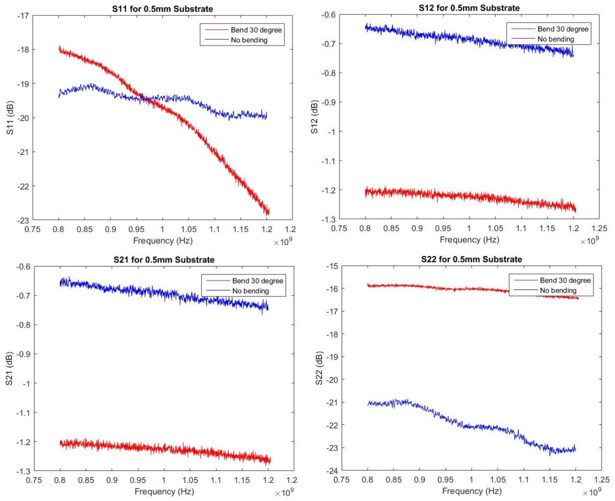

Fig. 4: Measured S-parameters of the microstrip transmission line printed on a 0.5 mm PET substrate in the normal condition and when bent at 30 degrees

Considering S_{21} and S_{12} which represent the ratio of the transmitted signal to the incident signal at port 1 and port 2 respectively. As shown in Fig. 4, the values of S_{21} and S_{12} when there is no bending are both around -0.7 dB. On a linear scale, this means that the ratio of the transmitted signal to the incident signal is about 0.92. So the insertion loss of this microstrip transmission line is small when there is no bending. Since the design frequency is 1 GHz, the insertion loss at 1 GHz can be determined to be 0.14 dB/cm for the 5 cm microstrip transmission line. When bending the transmission line to 30 degrees, the insertion loss increases to about 0.24 dB/cm. It is understandable that there will be a higher signal loss when bending the microstrip transmission line. If the silver paste is of better quality, the conductivity of the printed conductive tracks can be higher and the loss will be lower.

Fig. 5 shows the measured *S*-parameters of the microstrip transmission line printed on a 0.7 mm PET substrate. The reflection coefficients S_{11} and S_{22} are more or less the same as those of the microstrip line printed on the 0.5 mm PET substrate. The values of S_{21} and S_{12} are both around -0.84 dB at 1 GHz. So the insertion loss is about 0.17 dB/cm in the normal condition without bending. Fig. 6 shows the measured *S*-parameters of the microstrip transmission lines printed on a 1.4 mm PET substrate but with different curing times (30 min and 20 min) of the printed silver paste. Comparing the two situations, the values of S_{11} and S_{22} for a longer curing time tend to be more desirable.

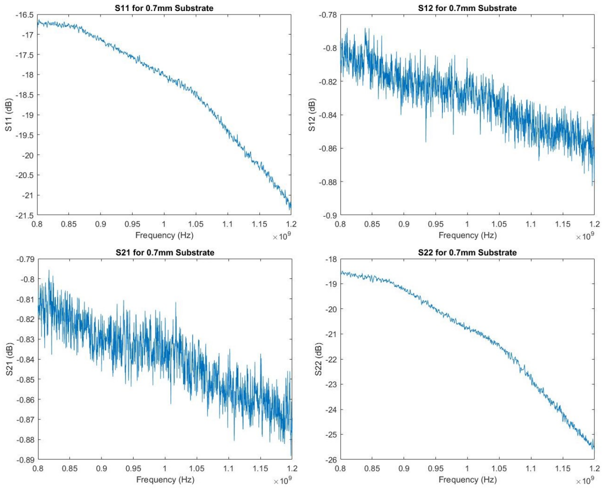

Fig. 5: Measured S-parameters of the microstrip transmission line printed on a 0.7-mm PET substrate

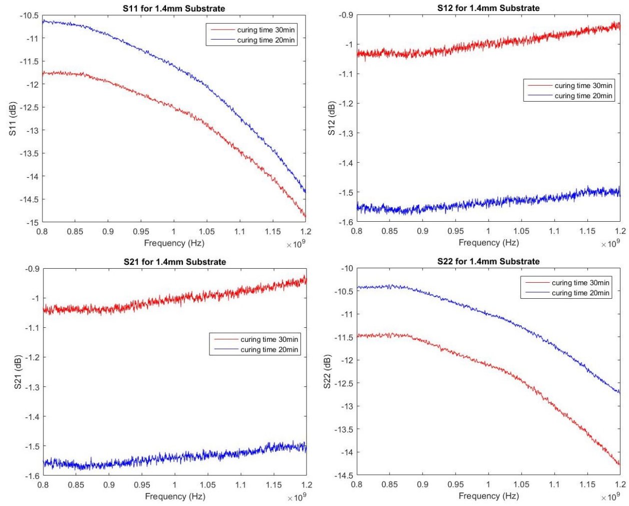

Fig. 6: Measured S-parameters of the microstrip transmission lines printed on 1.4-mm PET substrate

As for the insertion losses, the values of S_{21} and S_{12} for 30 min curing are about -1 dB and the values corresponding to 20 min curing are about 1.5 dB at the design frequency 1 GHz. So the insertion loss for the 30 min curing time is 0.2 dB/cm and for the 20 min curing time 0.3 dB/cm. These results confirm that with a longer curing time, the conductivity of the printed conductive tracks is higher (Fig. 2) thus giving better RF performance in terms of the reflection coefficients.

To find out the operating frequency range of the printed microstrip transmission lines, *S*-parameter measurements were performed from 50 MHz to 8 GHz. In particular, the microstrip line printed on a 0.5 mm PET substrate was measured under both the normal and bent conditions. The measurement results are shown in Fig. 7. It can be seen that the difference in the measured results between the bent and normal situations are not significant which means that the microstrip transmission lines can be printed on the flexible PET substrates and used in bending situations. It can be assumed that below about 4.5 GHz, the microstrip transmission line printed on PET substrates can be used with an acceptable loss when there is no bending. When it is bent at 30 degrees, the maximum operating frequency is reduced to about 4 GHz. Therefore, these results imply that the microstrip transmission lines printed on the flexible PET substrate can be used in multi-GHz microwave circuits even when they are bent.

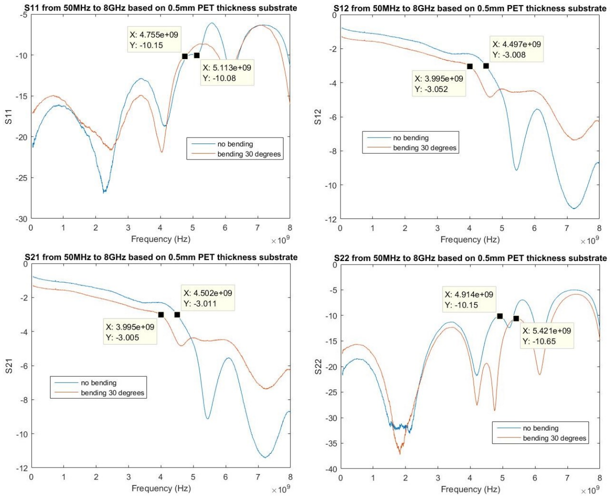

Fig. 7: Measured S-parameters from 50 MHz to 8 GHz of the microstrip line printed on a 0.5-mm thickness PET substrate

V. CONCLUSION

The experimental investigation of microstrip transmission lines printed on thin PET films has been presented. Microstrip lines implemented by the low-cost screen-printing method can achieve reasonably good results even under bent conditions. The printed microstrip lines can work up to about 4 GHz. These printed microstrip transmission lines can used to build RF circuits for applications such as 4G communication (≈ 1.8 GHz or 2.1 GHz) or Wi-Fi (2.4 GHz) for wearable electronics.

REFERENCES

[1] Terry C. Edward and Michael B. Steer, *Foundations for Microstrip Circuit Design*, 4th Edition, West Sussex, UK: Wiley (2016).

[2] S. Pacchini *et al.*, "Inkjet-printing of hybrid Ag/conductive polymer towards strechable microwave devices," *2015 European Microwave Conference* (*EuMC*), pp. 865-868, 2015.

[3] P. M. Narayanan, "Microstrip Transmission Line Method for Broadband Permittivity Measurement of Dielectric Substrates," *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 11, pp. 2784-2790, November 2014.

[4] Hong-Duc Nguyen *et al.*, "RF characterization of flexible substrates for new conformable antenna systems", *2016 10th European Conference on Antennas and Propagation* (*EuCAP*), pp. 1-5, 2016.

[5] S. M. Wentworth *et al.*, "Attenuation in silver-filled conductive epoxy interconnects," *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A*, vol. 20, no. 1, pp. 52-59, March 1997.

[6] D.-Y. Shin, Y. Lee, C. H. Kim, "Performance characterization of screen printed radio frequency identification antennas with silver nanopaste", *Thin Solid Films*, vol. 517, pp. 6112–6118, 2009.

[7] T. Bjorninen *et al.*, "Performance comparison of silver ink and copper conductors for microwave applications," *IET Microwaves, Antennas & Propagation*, vol. 4, no. 9, pp. 1224-1231, 2010.

[8] C.-M. Cheng and C.-F. Yang, "Develop Quad-Band (1.57/2.45/3.5/5.2 GHz) Bandpass Filters on the Ceramic Substrate," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 5, pp. 268-270, May 2010.

[9] K. Janeczek *et al.*, "Investigation of ultra-high-frequency antennas printed with polymer pastes on flexible substrates," *IET Microwaves, Antennas & Propagation*, vol. 6, no. 5, 549-554, 2012.

[10] G. A. Casula, G. Montisci, and G. Mazzarella, "A Wideband PET Inkjet-Printed Antenna for UHF RFID," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1400-1403, 2013.

[11] J. Wang, S. Lam, and E. G. Lim, "RF performance evaluation of microstrip lines printed on flexible polyethylene terephthalate (PET) films," *2015 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications* (*IMWS-AMP*), 2015.