Printed and Embroidered Electronic Passive Components

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Abstract

Wearable electronics and smart textiles is rapidly developing area currently. An integration of electronic components and systems directly on/into textile substrates leads to the development of promising new technologies among which it is possible to include printing of passive electronic components and/or embroidering of passive electronic components directly onto textile substrates using conductive threads. The paper deals with comparing of the electrical parameters of printed and embroidered planar passive electronic components. Different types of planar inductors and interdigital capacitors were designed and realized. Their basic electrical parameters such as nominal values and resonance frequencies were measured and compared each other. Presented results can be used for the realisation of functional printed or embroidered components and systems designed not only for smart textiles.

Introduction

Nowadays, development of electronic systems is focused on flexible printed electronics that are easily integrated into smart systems such as smart textiles, RFID, smart cities, internet of things, etc. [1], [3] [4]. Important part of these systems are passive electronic components that have to meet requirements such as low price, simple, smaller size, lighter, flexible, planar and robust for the harsh environment. These requirements have led to development of planar passive electronic components created by the screen printing technology and embroidery/knitting technology. The rules for design of planar passive components on printed circuits boards are know very well but electrical properties of screen printed and embroidered/knitted passive planar components can be different. Based on this, behaviour of planar passive electrical components created by the screen printing and embroidery technology is necessary to observe and compare.

The screen printing technology allow to print silver, gold and copper pastes on flexible substrates but their electrical conductivity is lower than bulk copper on the printed circuit boards. Embroidery/knitting technology can use electrical conductive threads that allow to create conductive patterns on the textile substrates (Fig. 1). Electrical conductivity of these threads is also lower than bulk copper. However electrical conductivity of pastes and threads is sufficient for realisation of planar passive electrical components [2]. In order to design an electronic system composed of these components, first it is necessary to know their electrical parameters and behaviour in the frequency domain. For this purpose the different types of passive components such as inductors and capacitors were created by screen printing and embroidery technologies.

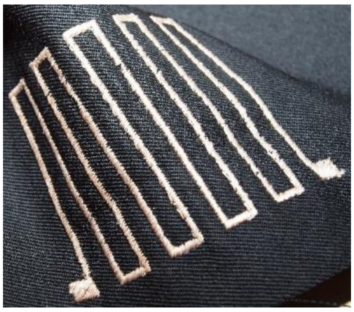
Fig. 1: Embroidered conductive pattern on the textile substrate.

Test Samples Design

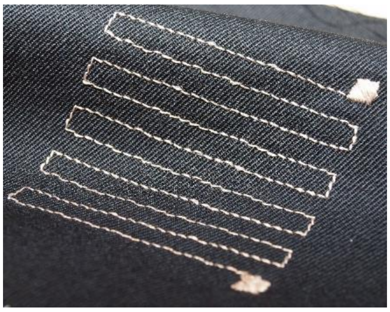
Test samples of the planar passive electronic components such as the square-shape spiral and meander inductors and capacitors with the interdigital structure were designed and realized. For each type of these passive component three pieces were realized and measured because of the statistical evaluation. Nominal values of the capacitance and inductance for designed components were also calculated and compared with the measured values.

All printed passive planar components were created by the screen printing technology on the PET foils by silver paste (DuPont 5029). All test samples were not covered a protective layer.

The hybrid thread was used for embroidered test samples of the passive planar components. The core of this thread consists of polyester fibers that are spun with 8 brass wires. The diameter of each wire is 30 µm. The thread consists of 69 % brass and 31 % polyester. The thread fineness is 72 tex and its electrical resistance is 7.7 Ω/m. Conductive patterns of planar components were created by embroidery machine Bernina 750 QE on woollen textile substrate. Two types of embroidered components were designed and created. The first type consists of conductive pattern filled with many conductive threads (Fig. 2a). The second type consists of conductive pattern created with only one conductive thread (Fig. 2b).



A



B

Fig. 2: Embroidered passive components, A) conductive pattern filled with many conductive threads, B) conductive pattern created with only one conductive thread.

For electrical parameters comparison the test samples (PCB) were also created by using photolithography technology on a copper-coated glass-epoxy laminate substrate (FR4) of 0.6 mm thickness with a copper thickness of 18 µm.

Square-shaped spiral inductors

The inductance of the square-shaped spiral inductor is possible to determine from equation 1. The value of the inductance is dependent on geometric dimensions and on the number of spirals. The inductance is in *nH* and dimensions are in *mm*.

$$L = 6 \cdot \frac{(D+d)^2 \cdot n^2}{15D - 7d} \quad (1)$$

Where $D = d + 2n(w + s) + w - s$ and n is the number of spirals [5, 6].

The parameters from equation 1 are explained in Figure 3. Realized screen printed and embroidered square-shape spiral inductors with 5 spirals are presented in Figure 4.

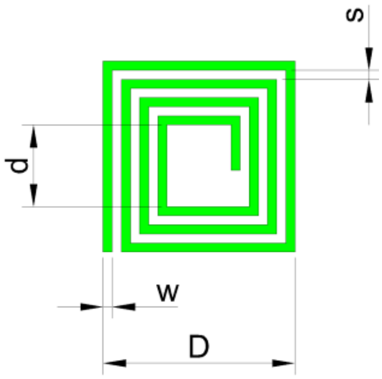


Fig. 3. Design of the square-shaped spiral inductor.

A B C

Fig. 4. Square-shaped spiral inductors, A) screen printed on the PET foil, B) embroidered on the textile substrate, C) embroidered on the textile substrate with one conductive thread.

<u>Meander inductors</u>

The inductance of the meander inductor is possible to determine from equation 2. The value of the inductance is dependent on geometric dimensions and on the number of meanders. The inductance is in *nH* and dimensions are in *mm*.

$$L = 0.1 \cdot d \cdot \left[4 \cdot n \cdot \ln \frac{2(a+w)}{w} - K_n \right] \tag{2}$$

Where the parameter of K_n depends on the number of meanders n [5, 6].

The parameters from equation 2 are explained in Figure 5. Realized meander inductors on the PET foil and textile substrates with 10 meanders are presented in Figure 6.

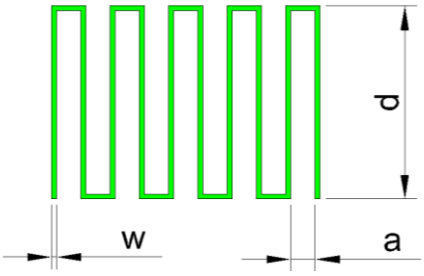
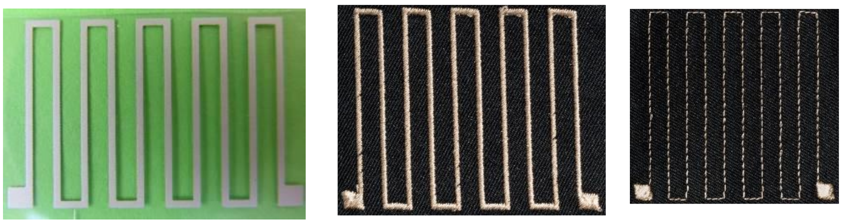


Fig. 5. Design of the meander inductor.



A B C

Fig. 6. Meander inductors, A) screen printed on the PET foil, B) embroidered on the textile substrate, C) embroidered on the textile substrate with one conductive thread.

<u>Interdigital capacitors</u>

The capacitance of the interdigital capacitor is possible to determine from equation 3. The value of the capacitance is dependent on the geometric dimensions. The capacitance is in *pF* and dimensions are in *mm*.

$$C = \frac{\pi \cdot \varepsilon_0 \cdot \frac{\varepsilon_r + 1}{2}}{\ln\left(\frac{\pi \cdot s}{w_p + t} + 1\right)} \cdot l \cdot \frac{n}{2} \tag{3}$$

Where n is the number of interdigital pairs [5, 6].

The parameters from equations 3 are explained in Figure 7. Realized screen printed and embroidered interdigital capacitor with 20 interdigital pairs are presented in Figure 8.

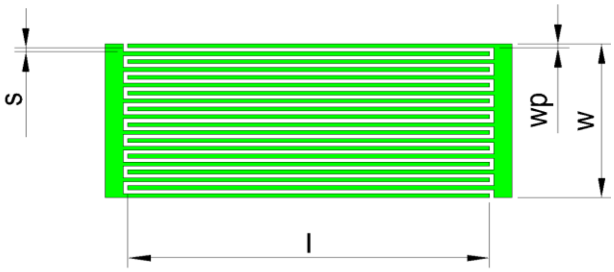


Fig. 7. Design of the interdigital capacitor.

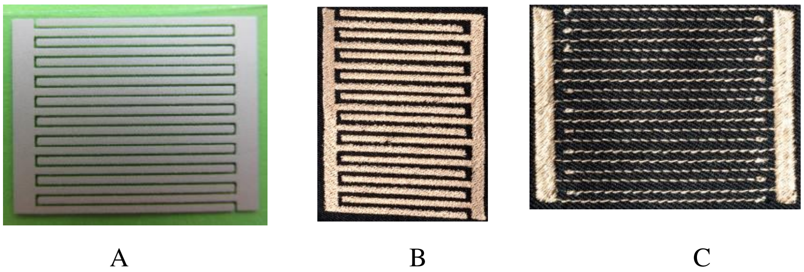


Fig. 8. Interdigital capacitor, A) screen printed on the PET foil, B) embroidered on the textile substrate, C) embroidered on the textile substrate with one conductive thread.

Testing and Measurement

Every real passive electronic component has its parasitic resistance, inductance and capacity. The parasitic capacitance of the inductor and the parasitic inductance of the capacitor are an undesirable parameters. The values of these parasitic parameters depend on the design and construction of the passive components. The electrical parameters of real passive electronic components are frequency dependent. Thus for real passive electronic component self-resonant frequency can be determined. This is the state when the inductive and capacitive reactance of the component is equal and impedance has a maximum or minimum value. The self-resonant frequency of passive components is important parameter for high frequency systems because correct functionality of the passive component is guaranteed to this self-frequency. The next important parameter of inductor and capacitor is quality factor that directly depends on conductive pattern resistance. For all test samples the nominal values of inductance and capacitance were measured and impedance to frequency characteristics were measured as well. The Keysight E4980A Precision LCR Meter was used for measurement of the nominal values of particular planar passive components. This measurement was carried out for frequency of 1 kHz and voltage level of 1 V. The Agilent 4287A RLC meter was used for impedance to frequency characteristic measurement. This measurement was carried out in the frequency range of 1 MHz to 1 GHz.

Results

The main aim was to compare electrical parameters of screen printed and embroidered planar passive components with electrical parameters of planar components created by photolithography technology. The measured nominal value of the inductance or capacitance was also compared with calculated theoretical values. The impedance to frequency characteristics are the next important results where the self-resonance frequency of tested passive components can be determined. Obtained results can show electrical parameters differences that are dependent on used manufacturing technology. Measured nominal values of screen printed planar passive components are different against embroidered components. These differences were caused by different geometric sizes because of spill of silver paste after screen printing.

Square-shaped spiral inductors

Calculated inductance value for the inductor with 5 spirals and dimensions of *D =50 mm*, *d = 21 mm* is 1.25 µH. Measured nominal value of the inductance is approximately 1.6 µH for embroidered inductor and 1.4 µH for inductor created by photolithography on the printed circuit boards.

For test samples created by embroidery technology with one thread the calculated inductance value is 2.7 µH and measured nominal value of 3.4 µH for inductor with 7 spirals and dimensions of *D =50 mm*, *d = 24 mm.* Measured nominal value of inductance for inductor created on the PCB is 3.5 µH. This small deviation of inductance nominal values can be caused by a change of inductor dimensions during embroidery process.

In figure 9 the self-resonance frequencies of square-shape spiral inductors created by embroidery and photolithography technology are presented. The self-resonance frequency is around 60 MHz for embroidered inductors, 95 MHz for inductors on the PCB. For embroidered inductors there are visible changes in impedance value for resonance frequency. This differences are caused by different quality factor for embroidered inductor and embroidered inductor pattern based on one thread.

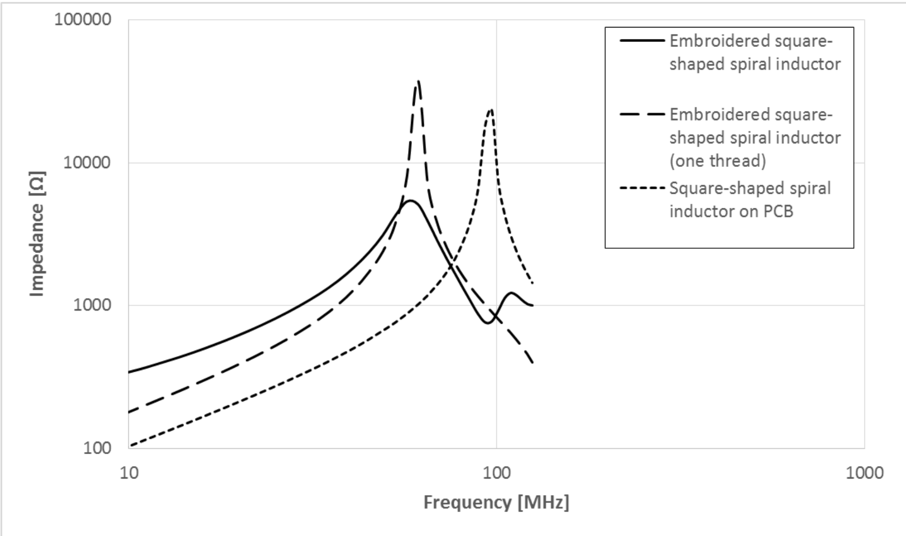


Fig. 9. The impedance to frequency characteristic for the square-shaped spiral inductors created by different technologies.

Meander inductors

Calculated inductance value for the inductor with 10 meanders and dimensions of *a = 5 mm*, *w = 1 mm,* K_n *= 16.86* is 0.41 µH. Measured nominal value of the inductance is approximately 0.46 µH for embroidered meander inductor and 0.43 µH for inductor created on the printed circuit boards.

For test samples created by embroidery technology with one thread the calculated inductance value is 0.67 µH and measured nominal value of 0.44 µH for inductor with 10 meanders and dimensions of *a = 5 mm*, *w = 0.24 mm,* K_n *= 16.86.* Measured nominal value of inductance for inductor created on the PCB is 0.62 µH. This deviation of inductance nominal values can be caused by a change of inductor dimensions during embroidery process.

In figure 10 the self-resonance frequencies of meander inductors created by embroidery, screen printing and photolithography technology are presented. The self-resonance frequency is approximately 180 MHz for embroidered inductors and inductor on the PCB, 200 MHz for inductors embroidered with one thread and 450 MHz for screen printed inductors. The inductor created by embroidery technology based on only one thread has higher resonance frequency than inductor with embroidered pattern. For embroidered inductors there are visible changes in impedance value for resonance frequency. This differences are caused by different quality factor for embroidered inductor and embroidered inductor created with one thread.

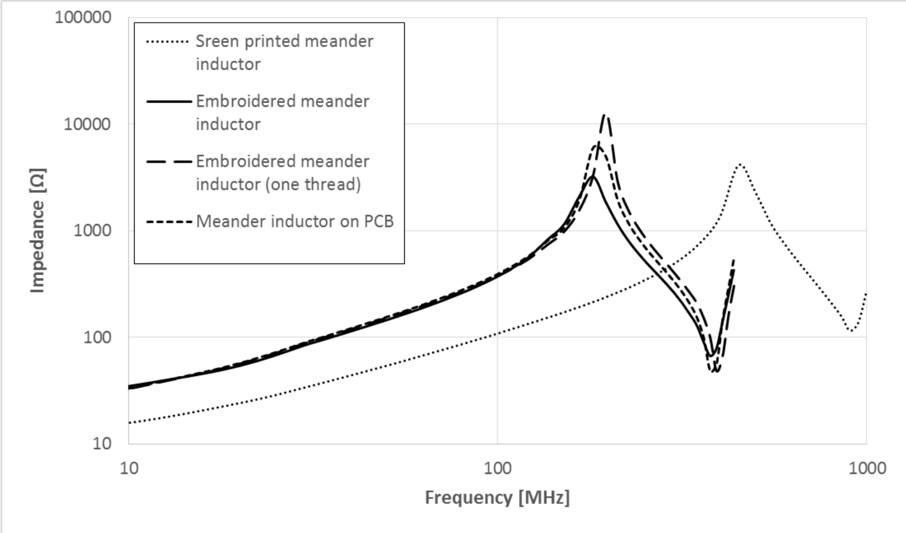


Fig. 10. The impedance to frequency characteristic for the meander inductors created by different technologies.

Interdigital capacitors

Calculated capacitance value for the embroidered interdigital capacitor with the number of interdigital pairs of 20 and dimensions of $w = s = 2\ mm,\ l = 20\ mm,\ \varepsilon_r = 4,\ t = 0.48\ mm$ is 22 pF. Measured nominal value of the embroidered capacitance is approximately 23.5 pF. Calculated capacitance value for test samples on the PCB is 20.5 pF for 20 interdigital pairs and dimensions of $w = s = 2\ mm,\ l = 20\ mm,\ \varepsilon_r = 4.2,\ t = 0.018\ mm$ and measured nominal value is 16 pF.

For test samples created by embroidery technology with one thread the calculated capacitance value is 10.5 pF and measured nominal value of 12.5 pF for capacitor with 20 interdigital pairs. Calculated capacitance for test samples on the PCB is 7.8 pF and measured nominal value is 8.8 pF. Small deviation between measured and calculated inductance nominal values can be caused by a change of inductor dimensions during embroidery process.

In figure 11 the self-resonance frequencies of interdigital capacitors created by embroidery, screen printing and photolithography technology are presented. The self-resonance frequency is approximately 80 MHz for embroidered capacitors, 150 MHz for capacitors on the PCB, 170 MHz for capacitors embroidered with one thread and 250 MHz for screen printed capacitors. The capacitor created by embroidery technology based on only one thread has higher resonance frequency than inductor with embroidered pattern. For embroidered capacitor there are visible changes in impedance value for resonance frequency. This differences are caused by different quality factor for embroidered capacitors and embroidered capacitors based on one thread.

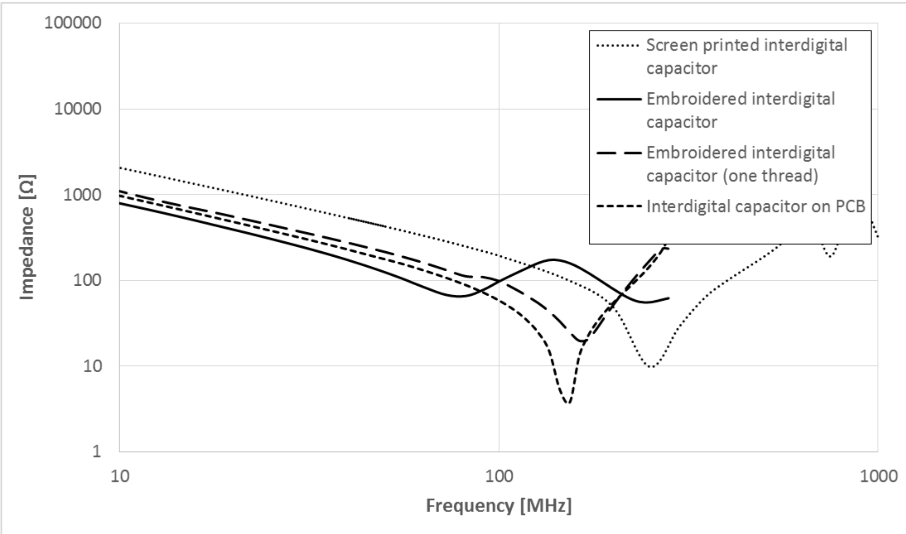


Fig. 11. The impedance to frequency characteristic for the interdigital capacitors created by different technologies.

Conclusions

Basic electrical parameters were measured and compared each other as well as with theoretical calculations of the planar electronic component parameters created by different technologies. The high frequency behaviour of the electronic components realized by the screen printing and embroidery techniques is very important and therefore measured frequency dependences of electrical parameters of these electronic passive components were presented.

Printed electronic components were created with silver paste on the flexible foil using screen printing technology. Embroidered electronic components were created with hybrid conductive threads on the textile substrates. Based on obtained results it is possible to declare that there are no significant differences between nominal values of passive planar components created by different technologies. Only measured nominal values of screen printed planar passive components are different against embroidered components because of different geometric sizes caused by spill of silver paste after screen printing. The self-resonance frequency for screen printed components is higher than for embroidered components even for components created by photolithography technology on the PCB. The self-resonance frequencies for embroidered components are similar to components created on the PCB. Electrical parameters of embroidered components with only one thread are better than electrical parameters of components created by embroidery of full conductive pattern. Measured differences in self-resonance frequency values are very important for the design of embroidered and screen printed system in the future.

Obtained results helped to determine and compare the electrical parameters of planar passive components created by embroidery, screen printing and photolithography technology. Obtained results can be useful for the design and realization of embroidered and screen printed planar electronics components and systems.

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Author Biography

Tomas Blecha received master degree in Electronic and Telecommunications at the University of West Bohemia in Pilsen in 2003 and Ph.D. degree in Electrical Engineering on the same university in 2007 and assoc. prof. in 2016 also at the University of West Bohemia in Pilsen. His main research interests are in the areas of design and characterization of microwave printed circuit boards and devices. In addition he is performing research in smart textiles, printed electronics, measurement, modelling and simulation for high frequency transmission lines and circuits.