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sensors MDPI

Impact of Conductive Yarns on Embroidery Textile Moisture Sensor

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Abstract: In this work, two embroidered textile moisture sensors are characterized with three different conductive yarns. The sensors are based on a capacitive interdigitated structure embroidered on a cotton substrate with an embroidered conductor yarn. The performance comparison of 3 different type of conductive yarns has been addressed. In order to evaluate the sensor sensitivity, the impedance of the sensor has been measured by means of a LCR meter from 20 Hz to 20 kHz on a climatic chamber with a sweep of the relative humidity from 30% to 65% at 20 ºC. The experimental results show a clear and controllable dependence of the sensor impedance with the relative humidity and the used conductor yarns. This dependence points out the optimum conductive yarn to be used to develop wearable applications for moisture measurement.

Keywords: sensor; e-textile, embroidery, moisture, capacitive.

1. Introduction

Embroidery has been revealed as the most effective technique to implement wearable sensors. This fact is due to the availability of the manufacturing technology (industrial embroidery machines), the efficient exploitation of the expensive specialized conductive threads and the repeatability of the involved geometries and layouts [1]. These wearable sensors are suitable for application fields such as health monitoring[2,3], physical training[4], emergency rescue service and law-enforcement [5]. In particular, the integration of flexible, lightweight, low-profile and comfortable designs allows the deployment of wearable solutions [6]. In the last years, a great effort has been focused in designing new sensors included in garments for healthcare applications [7].

This work is an extended version of the previous paper published by the authors at EUROSENSOR conference 2018 [8]. In [8] an embroidered textile sensor in order to measure the moisture was presented. In this extended version, a comparison of the electrical properties of the electrical sensor with several types of conductive yarns are analysed and assessed. In addition, the full characterization and electrical modelling has been carried out.

The remainder of the paper is organized as follows. Section 2 describes the Material and methods including the used conductive yarns, the textile sensor layout and implementation as well as the measurement set-up. In Section 3 the experimental results are shown and discussed. Finally, in Section 4 the conclusions are summarized.

2. Materials and Methods

The proposed moisture sensor is based on a capacitive embroidered interdigitated structure whose dimensions are depicted in Figure 1. Three different conductive yarns are used to see the behaviour of each yarn. Firstly a commercial Shieldex 117/17 dtex 2-ply has been chosen, this yarn is made of polyamide (PA) coated with pure silver. Secondly, two commercial Bekaert yarn has been chosen, this yarns are made of stainless steel (SS) in mix with polyester (PES) or cotton (CO). One of the Bekaert yarns is made by polyester (80%) and stainless steel (20%). The other Bekaert yarn is made

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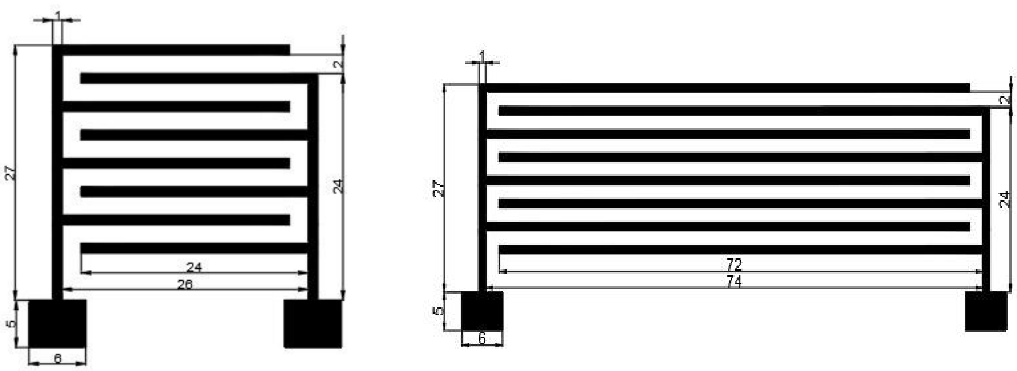
by a mix of cotton (80%) and stainless steel (20%)[9]. Furthermore these yarns, Shieldex and Bekaert, are made by different techniques. Shieldex yarn is made by a coating of pure silver in the surface of the PA filament (Figure 2a). The Bekaert yarns are made by mixing fibbers of different materials (cotton and polyester with stainless steel) at the beginning of the process to manufacture the yarn (Figure 2b). The most important properties for the used yarns are summarized in Table 1.

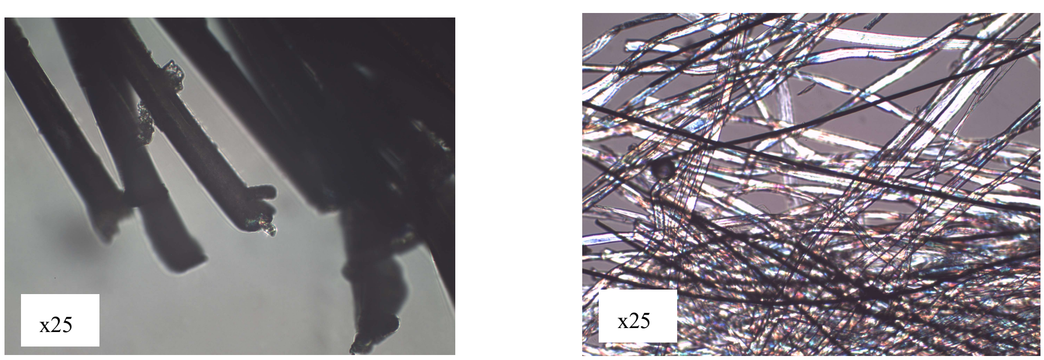
These conductive yarns are used in order to embroider the interdigitated structures on a high hygroscope substrate. Specifically, a cotton substrate with a thickness (h) of 0.43 mm has been chosen. A Singer Futura XL-550 embroidery machine with a satin fill stitch pattern has been selected in order to achieve a homogeneous yarn distribution over the sensor surface.



a)

(**b**)

Figure 1. Layout and dimension detail of the proposed moisture sensor (in mm): (a) short sensor; (b) long sensor. The bottom squares correspond to the characterization pads.



a)

b)

Figure 2. Microscope image of the used conductive yarns (a) Shieldex: this yarn is made of polyamide (PA) coated with pure silver; (b) Bekaert: This yarns are made by mixing fibbers of cotton with stainless steel.

Table 1. Most important properties about the yarns

Properties	Shieldex	Bekaert(PES-SS)	Bekaert(CO-SS)
Density(tex)	11.7/2	20/2	20/2
Linear resistance (Ω/cm)	<30	50	35-70
Thread type	Twisted Multifilament	Ring yarn	Ring yarn

In order to compare experimentally the sensors behaviour, the implemented devices have been tested in a *CCK-25/48 Dycometal* climatic chamber and the sensors impedance have been measured

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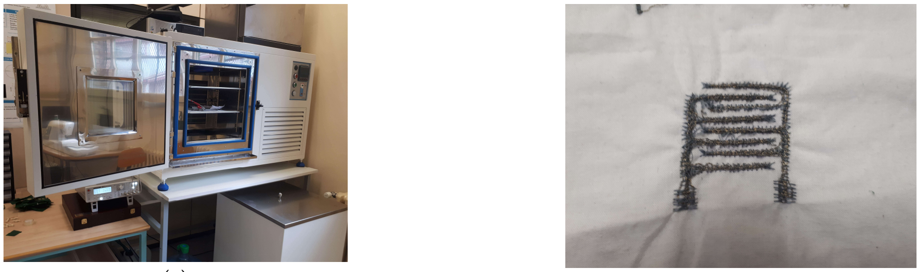
by means of an external Rohde & Schwarz HM8118 LCR meter. An image of the experimental setup and the embroidered short sensor are shown in Figure 3.



(**a**) b)

Figure 3. Image of the experimental setup.

The sensors impedances have been measured from 20 Hz to 20 kHz in a 30% to 65% range of relative humidity environment, whereas the temperature has remained constant at 20 ºC.

3. Results and Discussion

Figure 4 shows the measured sensor impedance of the sensor embroidered with Shieldex when the moisture is swept from 30% to 65% for four different test frequencies. It is observed that the impedance module of sensor is reduced when the environmental moisture increases, which confirms the functionality of the proposed structure as a moisture sensor. The measured phase impedance of the sensor denotes that for low relative humidity the sensor has a capacitive behaviour, as expected. Moreover, for higher relative humidity concentration the sensor tends to be resistive. The reason of this behaviour is the hydrophilic property of the cotton. Indeed, when the relative humidity increases, the cotton substrate absorbs water and the electrical permittivity of the substrate increases. As a result, the impedance of the sensor is reduced.

Long and short sensors show similar behaviour with the relative moisture. However, as it is expected, the impedance of the longer sensor (Figure 4b) is lower than the impedance of the short device (Figure 4a). In particular, for the 20 Hz test signal, the short sensor impedance decreases from 0.7 GΩ to 20.4 MΩ when the moisture increases from 30% to 65%, whereas, for long sensor device it decreases from 0.57 GΩ to 12.5 MΩ for the same moisture range.

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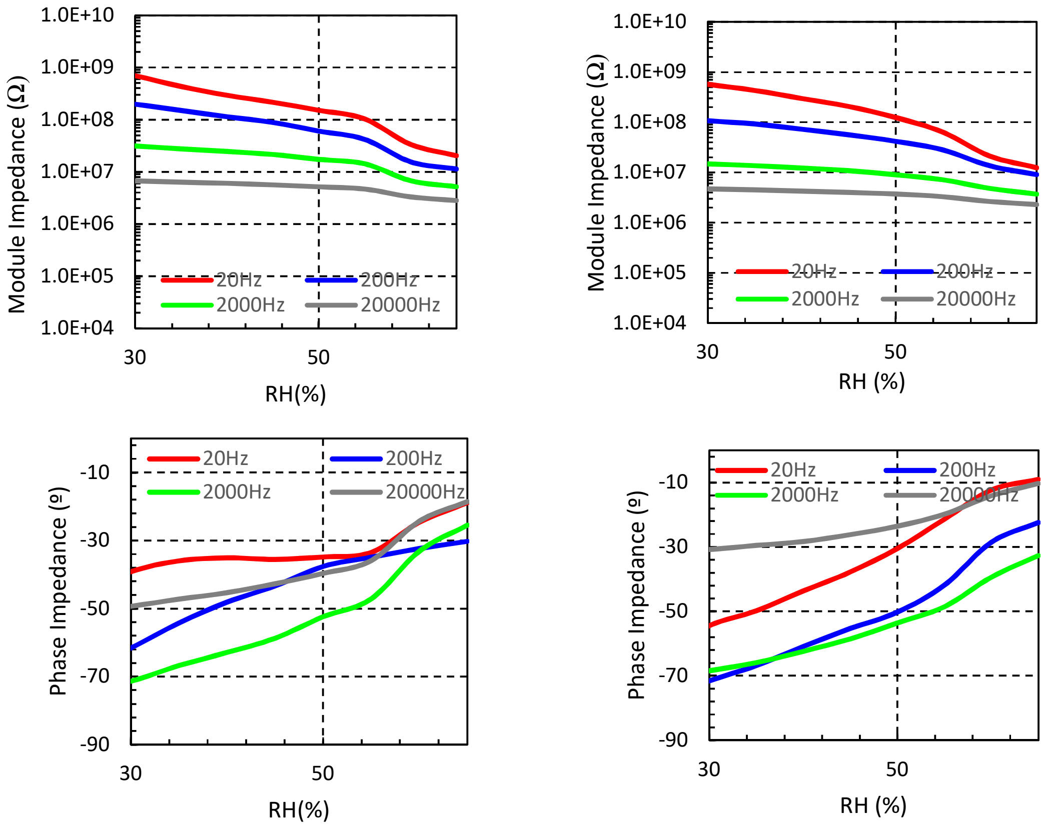

a) Short sensor impedance. b) Long sensor impedance.

Figure 4. Measured Shieldex sensors impedance from 30% to 65% RH at different frequencies (T=20ºC).

Figure 5 and Figure 6 shows the measured sensor impedance of the sensor embroidered with Bekaert PES-SS and Bekaert CO-SS, respectively.. In all cases it is observed that the sensor impedance module is reduced when the moisture increases, as we observed at the Shieldex yarn. However, both PES-SS and CO-SS show a significant impedance module reduction compared to Shieldex yarn, in all cases. In particular, for PES-SS at 20 Hz test single, the impedance module decreases from 0.12 GΩ to 0.92MΩ. In the case of the long sensor, the range decreases from 27MΩ to 0.47MΩ, whereas for CO-SS these values decrease from 0.13 GΩ to 4.2MΩ and from 23.7MΩ to 0.37MΩ for short and long sensor, respectively. The explanation for these differences between the Shieldex and Bekaert yarns is the electrical conductivity of the yarn, which depends on the conductive materials but also of the

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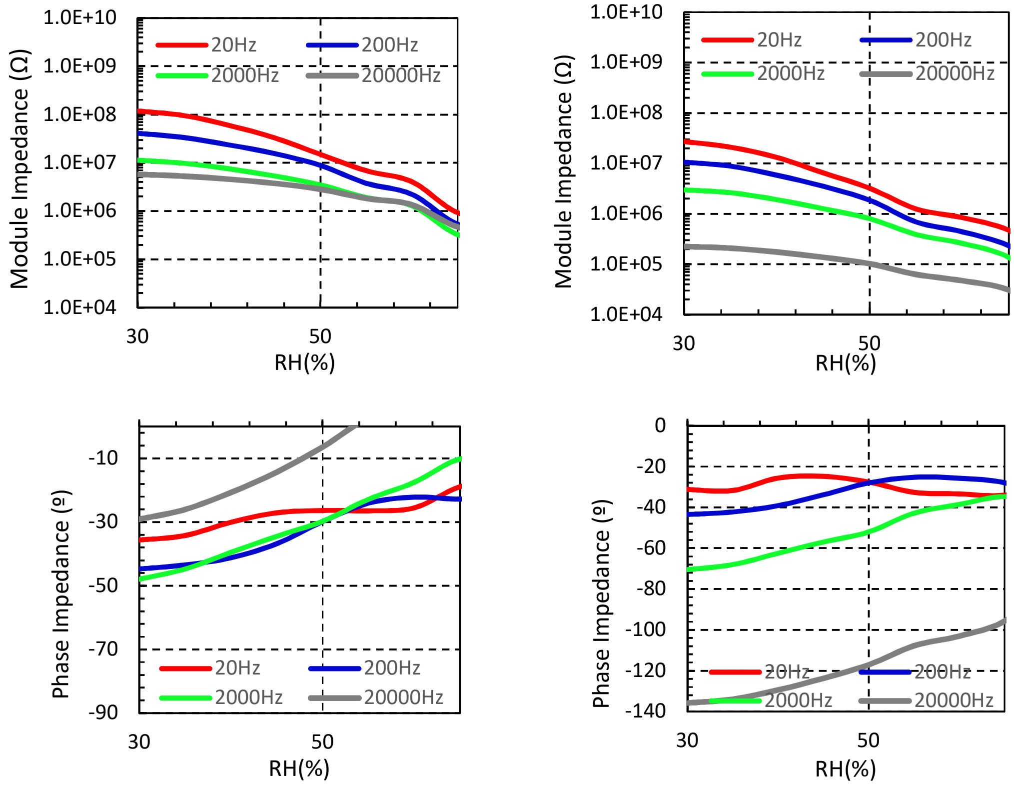
fabrication process. The non-conductive material of the yarn (i.e. polyester or cotton) does have any significant impact on this behaviour.



c) Short sensor impedance. d) Long sensor impedance.

Figure 5. Measured Bekaert(PES-SS) sensors impedance from 30% to 65% RH at different frequencies (T=20ºC).

It should be noticed that the obtained impedance values at the low frequency range are too high in order to develop a portable device based on the proposed sensor. These wearable devices are typically based on a single integrated circuit, such as the *Texas Instrument AD5933 impedance converter* [10]. Nevertheless, using the proposed sensor in the range of kHz allows obtaining impedances in the range of a MΩ. In these cases, the impedance values can be measured with this integrated circuits.

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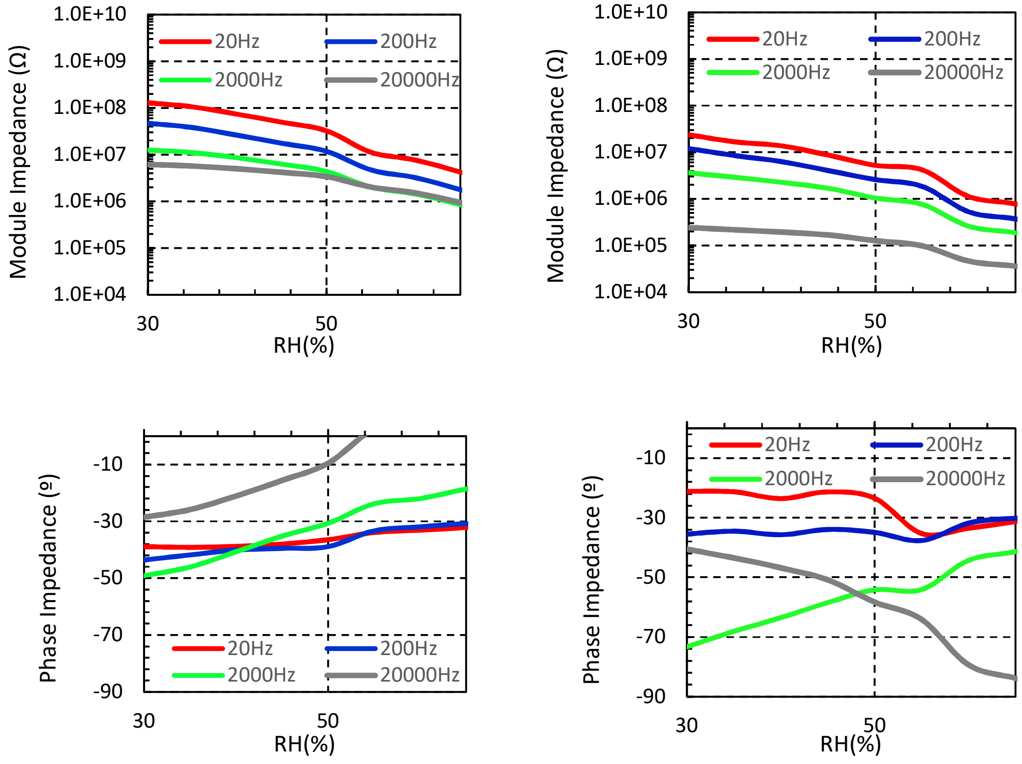

a) Short sensor impedance. b) Long sensor impedance.

Figure 6. Measured Bekaert(CO-SS) sensors impedance from 30% to 65% RH at different frequencies (T=20ºC).

For comparison, in Table 2, the impedance range values at 2 kHz are summarized. Again, it is observed that for the same parameters of size the sensors embroidered with Bekaert yarn had almost three times less module impedance than the Shieldex sensors. The difference should be due to the differences in the fabrication of each yarn. Bekaert yarns are made by fibres, meanwhile, Shieldex is made by coating a filament with silver. Other hypothesis consists of the fact that the Bekaert yarns can retain more moisture in their surface, and this moisture will decrease most effectively the values of impedance than in the other study case.

If we focus on the electrical model according to the measured behaviour of the proposed sensors at 2 kHz, they can be modelled as a RC parallel lumped model (Figure 7b), where the R and C values are moisture dependent. The C represents the capacitance and R the current leakage of the interdigitated structure.

Table 2. Measured sensors module impedances ranges at 2 kHz.

Sensor	**Shieldex**	**Bekaert(PES-SS)**	**Bekaert(CO-SS)**
Short	31.2-5.18MΩ	11.3-0.32MΩ	12.6-0.85MΩ
Long	14.8-3.71MΩ	2.98-0.14MΩ	3.62-0.19MΩ

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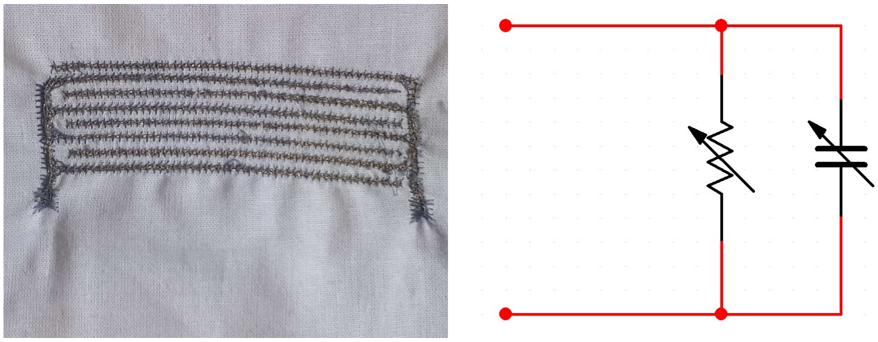

a) b)

Figure 7. Proposed long sensor a) physical implementation b) Electrical model

From Figure 8 to Figure 10, the R and C dependence from 30% to 65% RH at 2 kHz is shown for both short and long sensors with Shieldex, Bekaert PES-SS, Bekaert CO-SS yarn, respectively. It can be observed than when the moisture level increases the capacitance is increased, whereas the resistance is reduced in all cases. It should be pointed out that sensor based on Bekaert yarn shows higher sensitivity with the moisture than Shieldex yarn. This effect can be due to moisture impact of the electrical properties of the yarn. Table 2 and Table 3 summarize the resistance and capacitance values of the electrical model when the moisture is swept from 30% to 65. The Bekaert yarns have a larger range of resistance value than the Shieldex sensors. However, between the Bekaert sensors it is not observed a relevant difference. Specifically, the resistance of Shieldex short sensor is reduced about 39%, meanwhile for Bekaert PES-SS and Bekaert CO-SS the reduction achieves 95.7% and 90.2%, respectively when the moisture is swept from 30% to 65% (Table 2). For the same moisture range, the capacitance increases about one order of magnitude (x10) for Shieldex yarn and about two order of magnitude (x100) for Bekaert PES-SS and Bekaert CO-SS (Table 3). This key fact points out that Bekaert yarn are more sensitive to develop moisture sensors, increasing the overall sensor sensitivity. It should be pointed out that for all conductive yarns and sensor a clear sensitivity change is produced around 55 % RH.

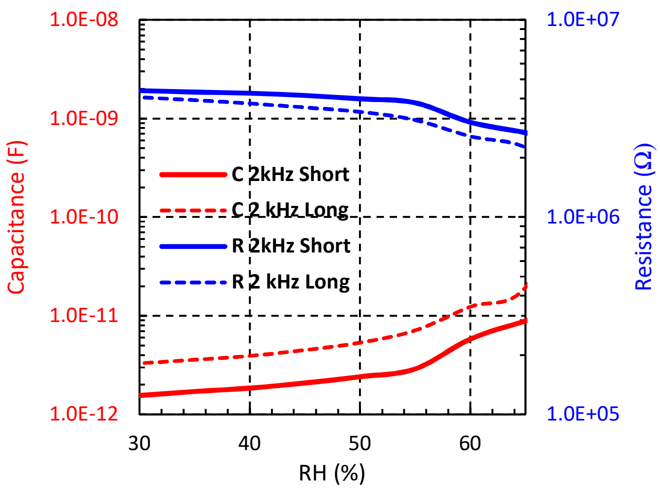

Figure 8. Measured Shieldex sensors impedance from 30% to 65% RH at different frequencies

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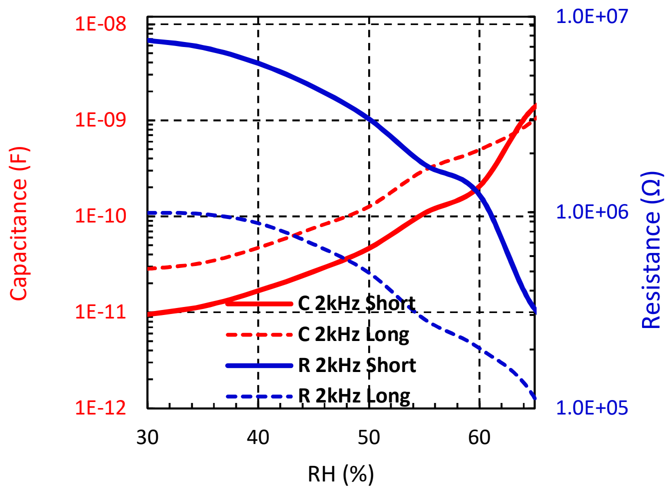

Figure 9. Measured Bekaert (PES-SS) sensors impedance from 30% to 65% RH at different frequencies

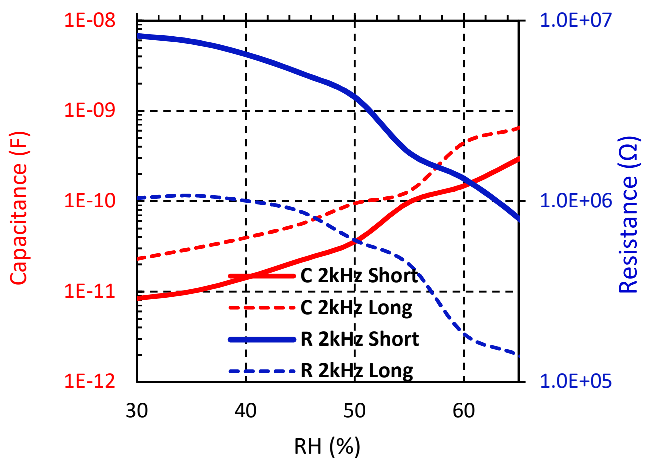

Figure 10. Measured Bekaert (CO-SS) sensors impedance from 30% to 65% RH at different frequencies

In the following tables the values of resistance and capacitance for the studied sensors.

Table 3. Measured sensors resistance ranges at 2 kHz.

Sensor	**Shieldex**	**Bekaert(PES-SS)**	**Bekaert(CO-SS)**
Short	4.42-2.68MΩ	7.57-0.32MΩ	8.22-0.8MΩ
Long	4.17-2.26MΩ	0.99-0.11MΩ	1.04-0.14MΩ

Table 4. Measured sensors capacitance ranges at 2 kHz.

Sensor	**Shieldex**	**Bekaert(PES-SS)**	**Bekaert(CO-SS)**
Short	1.56-8.84pF	9.48pF-1.37nF	8.37pF-0.29nF
Long	3.3-19.4pF	28.3pF-1.02nF	23pF-0.65nF

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4. Conclusions

In this work two interdigitated embroidered textile sensors have been proposed and characterized. The sensors have been embroidered over a cotton substrate with a commercial Shieldex 117/17 dtex 2 yarn, a commercial Bekaert (PES-SS) and Bekaert (CO-SS) 20/2 Tex. The measured results show that the proposed sensors can be used to measure moisture on textiles. In addition, the sensor under analysis can be modelled by means of a RC parallel lumped circuit, where the R and C value are moisture dependent. These results demonstrate experimentally the usefulness of the proposed sensors to develop wearable moisture sensors. With regard to sensor performance in terms of conductive threads, the Bekaert yarn shows a higher sensitivity than Shieldex yarn, to develop moisture sensor applications.

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Conflicts of Interest: The authors declare no conflict of interest.

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