Bending Influence on the Flexible Interdigital Structures

Boyanka M. Nikolova, Georgi T. Nikolov and Ralica T. Krumova
Department of Technological Management of Communication Systems, Faculty of Telecommunications
Department of Electronics, Faculty of Electronic Engineering and Technologies
Technical University of Sofia
8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria
Electricity system operator, 201 Tsar Boris III blvd., 1618 Sofia, Bulgaria
{bnikol, gnikolov}@tu-sofia.bg; ralicakrumovaa@gmail.com

Abstract – **In recent years, there has been a significant increase in interest in the use of flexible sensor structures for various applications. These structures are relatively inexpensive and can be fabricated in different shapes and sizes. The present article investigates three types of flexible capacitive sensor structures with different forms. The influence of bending on their capacitance, impedance, and dielectric losses in the frequency domain has been studied. Some of the obtained results are presented graphically, and an analysis of the properties of the structures has been conducted.**

Keywords – **bending sensor; flexible substrate; inkjet printing; interdigital structure; silver nanoparticle ink.**

I. Introduction

Conventional electronics are based on the use of rigid and brittle inorganic materials, which require specific technologies and cleanroom environments for their fabrication. This makes the production and handling of these materials a costly process. The emergence of flexible sensor structures removes significant limitations for this type of electronics. It needs to meet the requirements imposed by new applications that demand mechanical flexibility of the materials used. Printed and organic electronics fill this existing gap in technologies, which is why they have gained considerable interest in the production of circuits, sensors, bioelectronics, photovoltaics, displays, and lighting [1, 2, 3].

Organic and polymer electronics rely on the use of organic materials as substrates or active materials in electronic circuits and systems. Some organic electronic devices have reached a level of technological maturity that is high enough for market deployment. This is the case with well-established devices such as organic thin-film transistors (OTFTs) or particularly organic light-emitting diodes (OLEDs), which are already used in most displays and televisions [3, 4].

The development of inexpensive flexible sensors, biomedical devices, or intelligent systems is currently gaining significant interest. These devices require the full utilization of polymers as substrates. Polymers can make electronics very cost-effective, environmentally friendly, biocompatible, or biodegradable. Some polymers can also stretch or deform into arbitrary shapes without losing their properties. The fact that they are inexpensive and compatible with printing technologies, rather than standard cleanroom techniques like photolithography, allows for the use of plastic or paper substrates [1, 4].

To maximize the interaction between the sensing layer and its environment, the most commonly used capacitive structure consists of a substrate and combined or interdigital electrodes (IDE). Unlike capacitors with parallel plates, where the electric field lines are constrained by the dielectric material placed between the two electrodes, IDE capacitors generate an electric field between the two interdigitated electrodes positioned at a specific distance from each other. IDEs are among the most widely used transducers, especially in the field of biological and chemical sensors, due to their inexpensive and straightforward manufacturing process, as well as their high sensitivity. To detect and analyze a biochemical molecule or analyte, impedance and capacitance need to be investigated. These two parameters strongly depend on the geometry of the structure and the distance between the electrodes.

The goal of this article is to investigate the electrical parameters of flexible interdigital capacitive structures implemented using inkjet printing technology on Polyethylene terephthalate (PET) substrates and subjected to deformation or bending.

II. Capacitance of Flexible Interdigital Structure and Influence of Bending

The interdigital capacitor is a passive component realized by two interdigitated structures deposited on a substrate. The shape of the conducting layers is presented in Figure 1 [5, 6, 7, 8]. At the core of these structures are long conducting strips, also called fingers, which provide a connection between the two interdigital electrodes and control it by varying the distance between them. Usually, the distances (d) between the conductors and at their end (d_E) are the same. The length (L) and width (W) of the fingers are also important and depend on the applications for which the sensors will be used. When the IDE structure is printed on a substrate, the main characteristics to be considered are the substrate thickness (h) and its dielectric constant or dielectric permeability (ε). Additionally, the thickness of the fingers (t) and their resistance (ρ) will also affect the electrical characteristics.

There is an analytical model for calculating the capacitance of planar, multilayered, and planar IDE structures, which is based on an appropriate approximation

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and specific mathematical methods for capacitance determination. The total capacitance of a multilayer IDE structure is obtained by adding up the capacitance of each layer [5, 7].

For the investigated structures, where the electrodes are deposited on a substrate with finite thickness and no additional deposited layers, the total capacitance of the structure is obtained from [5]:

$$C = 2C_{air} + (\varepsilon_{sub} - 1)C_{sub}, \tag{1}$$

where C_{air} is the capacitance of practically infinitely thick air layers above and below the IDE structure with a dielectric permeability equal to 1, and C_{sub} is the capacitance of the substrate with a dielectric permeability ε_{sub}.

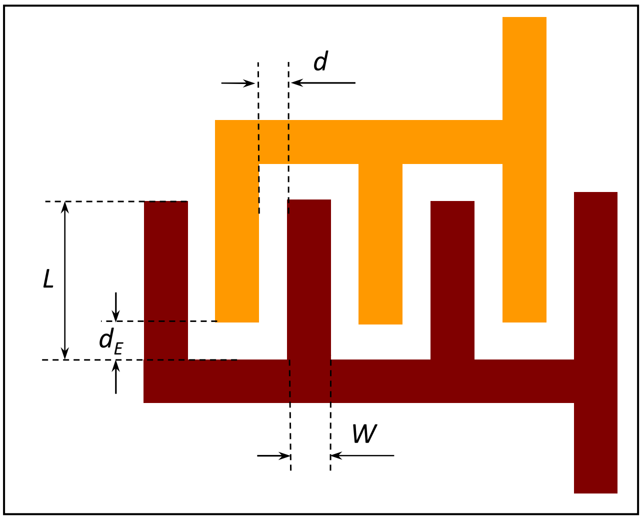


Fig. 1. Typical interdigital capacitive structure

The capacitance provided by each layer, C_x (where x represents air or substrate), depends on its dielectric constant, thickness, and electrode shape. It also linearly depends on the length of the electrodes (L) as well as their number (N), and can be expressed as:

$$C_x = (N-3)\frac{C_I}{2} + 2\frac{C_I C_E}{C_I + C_E} \quad (\mathrm{N} > 3). \tag{2}$$

In the above equation, C_I is the capacitance of the electrodes located in the middle of the IDE structure, and C_E is the capacitance of the two outermost electrodes located at the ends of the structure. The calculation of C_I and C_E is performed using mathematical methods of conformal mapping technique. Thus, the capacitance C_I is determined by the formula:

$$C_I = \varepsilon_0 \varepsilon_r L \frac{K(k_I)}{K(k_I')}, \tag{3}$$

where $K(k)$ is the complete elliptic integral of the first kind with modulus k. On the other hand,

$$k_I = t_2\sqrt{\left(t_4^2 - 1\right)/\left(t_4^2 - t_2^2\right)} \text{ and } k_I' = \sqrt{1 - k_I^2}, \tag{4}$$

where the variables t_i are the Jacobi elliptic functions of modulus k.

On the other hand, the capacitance C_E is determined as:

$$C_E = \varepsilon_0 \varepsilon_r L \frac{K(k_E)}{K(k_E')}, \tag{5}$$

where

$$k_E = 1/t_3\sqrt{\left(t_4^2 - t_3^2\right)/\left(t_4^2 - 1\right)} \text{ and } k_E' = \sqrt{1 - k_E^2}. \tag{6}$$

In engineering mechanics, the process of bending describes the behavior of a structural element subjected to external loading applied perpendicular to the longitudinal axis of the element. It is assumed that the structural element has at least one characteristic, such as length, width, or thickness, that is a smaller fraction, usually 1/10 or less, than the other two.

When IDE structures are subjected to circular bending, either outward or inward, two effects need to be considered in calculating their capacitance: the redistribution of the electric field due to the change in electrode shape from coplanar to cylindrical, and the change in the ratio between the electrode width and the gap between the electrodes due to mechanical loading on the substrate surface.

Taking into account the equations (3) and (5) presented above, it is possible to determine the effect of bending on the electrical field redistribution in IDEs and consequently on the capacitance value. For this purpose, a transformation is used in the first L-space, where the plane is bent, and the second X-space, where the plane is flat [5, 7, 8]. The bending effect is primarily assessed through the change in the Jacobi elliptic functions t_i.

It is important to note that capacitance and resistance of flexible structures are challenging to calculate theoretically, especially under bending, as complex physical models need to be employed. Additionally, the dielectric permeability of all materials strongly depends on various external factors such as the frequency of the electric field, temperature, relative humidity, and others. This necessitates the measurement of these parameters.

III. Measurement Setup

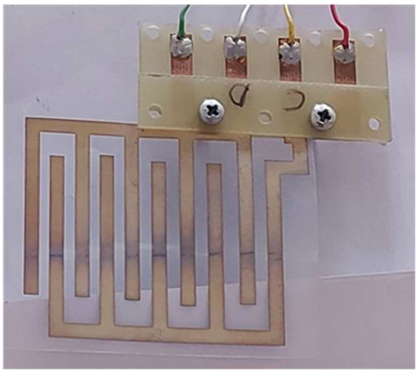
For the purposes of the measurements, three capacitive structures were used. They were implemented using the inkjet printing technology and printed on a flexible polymer substrate PET. The structures were printed using an Epson® Stylus C88+ printer and special conductive inks: Metalon® JS-B25P with silver nanoparticles and Carbon Ink JR-700LV. Ink with silver nanoparticles Metalon® JS-B25P was used, deposited in three layers, and sintered at 100°C for 60 minutes, with the following main dimensions [9, 10, 11]:

Structure 1: $d = 2.4$ mm; $d_E = 5.8$ mm; $L = 40$ mm; $W = 3$ mm

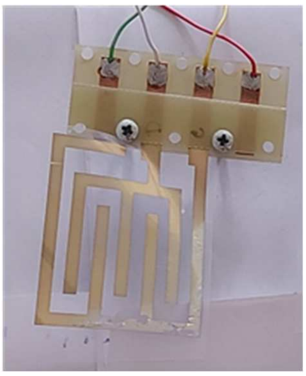
Structure 2: $d = 3$ mm; $d_E = 5$ mm; $L = 30$ mm; $W = 3$ mm

Structure 3: $d_1 = 3$ mm; $d_2 = 7.8$ mm; $d_E = 5.6$ mm; $W = 3$ mm

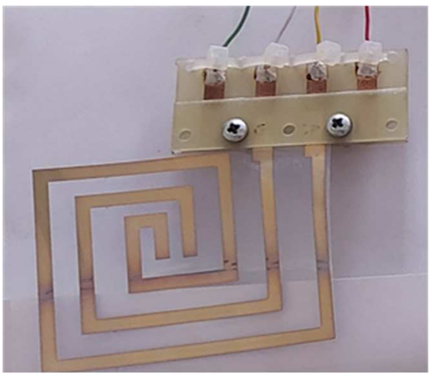
Figure 2 shows photos of the printed and measured structures. It can be observed that Structure 1 has a classical ID shape, while the shapes of the other two structures are slightly modified. One of the tasks in this article is to investigate the influence of the shape of the capacitive structures on their electrical parameters.



a) Structure 1



b) Structure 2



c) Structure 3

Fig. 2. The patterns of printed structures

Figure 3 shows the implemented setup of the experiment, which includes a tested structure that remains stationary, thanks to a test fixture, and is attached with rubber bands to a tube to achieve a bending effect. It is then connected to an impedance analyzer HM8118 for capacitance/resistance measurements, from which the data is recorded.

The LCR analyzer HM8118 has a frequency measurement range from 20 Hz to 200 kHz (in 69 steps) with a basic accuracy of 100 ppm. The device generates sinusoidal AC voltage for measurements ranging from 50 mVrms to 1.5 Vrms with a resolution of 10 mVrms.

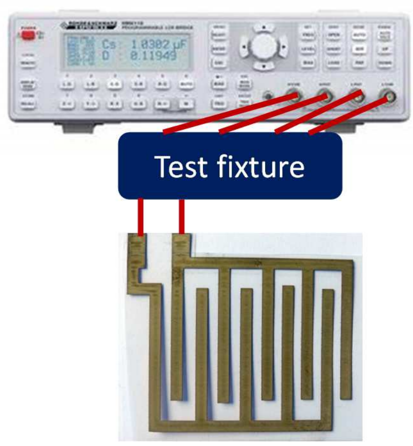


Fig. 3. Experimental set-up

To achieve bending, two tubes with different diameters were used – one with a diameter of 5 cm and the other with a diameter of 11 cm. The structures are attached to the tubes using rubber bands.

Knowing the diameter of the tube, the bending angle of the structure can be determined by applying the Cosine theorem (see Figure 4):

$$\cos\gamma = \frac{a^2 + b^2 - c}{2.a.b} \tag{7}$$

where a = AO, b = BO and c = AB.

Therefore, the bending angle for the tube with a diameter of 5 cm is 62°, while for the tube with a diameter of 11 cm, it is 27°.

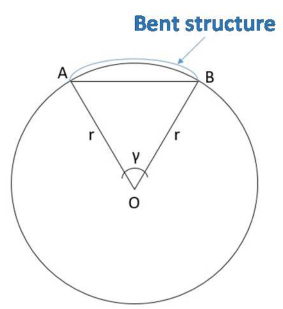


Fig. 4. Finding the bend angle

IV. Results and Discussion

And for all three structures, the parameters of capacitance (*C*), impedance (*Z*), and dielectric losses (*D*) were measured at 10 fixed frequencies. The measurement was performed three times – without bending the structure, and with bending at angles of 62° (or the pipe with a diameter of 5 cm) and 27° (or the pipe with a diameter of 11 cm), respectively.

Figure 5 shows the results of the capacitance measurement for the three unbent structures. In Structure 1, the capacitance is the highest (around 10 pF) compared to the other two structures (5 pF for Structure 3 and 2 pF for Structure 2). This difference is due to the shape of the structures since they were printed in the same manner and used the same materials (ink and substrate).

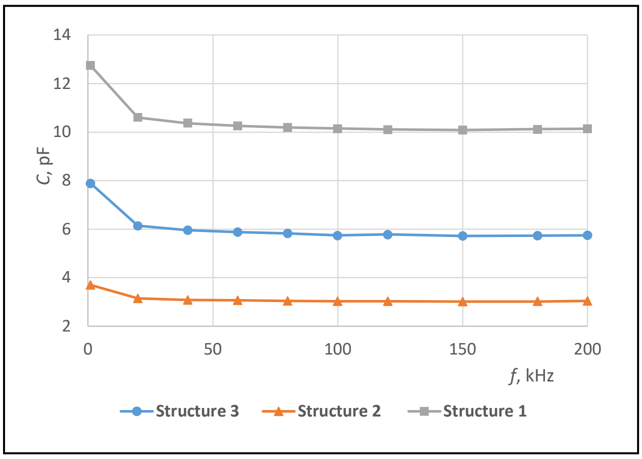


Fig. 5. The frequency dependence of capacitance for the three structures without bending

Figures 6, 7 and 8 show the results of measuring the capacitance *C*, impedance *Z*, and losses *D* for the classical IDE Structure 1. It can be observed that when the structure is not bent, higher capacitance values are obtained (around 10 pF), especially at low frequencies. The impedance of the structure does not change significantly, while the losses vary, particularly at higher frequencies.

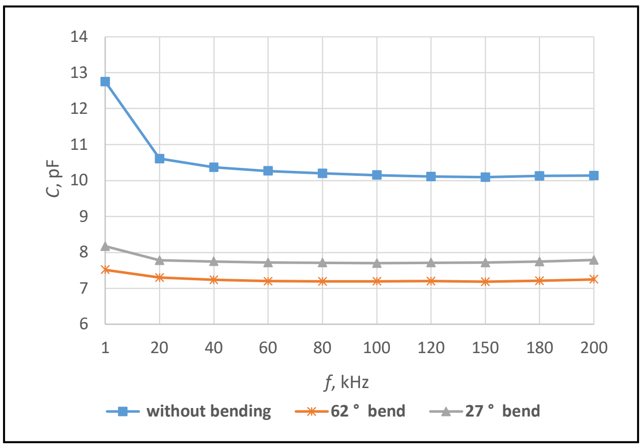


Fig. 6. The frequency dependence of capacitance for the Structure 1 at different bending

To provide a more precise assessment of the bending effect, graphs illustrating the differences in parameter values (capacitance, impedance, and losses) between bending and non-bending conditions are presented – Figures 9, 10 and 11. The differences are calculated by subtracting the value of a given parameter obtained without bending from the value of the same parameter obtained with bending. The resulting difference is divided by the value of the parameter without bending. The result is expressed as a percentage or:

$$\Delta X / X = \frac{X - X_0}{X_0} \tag{8}$$

where *X* is the value of measured parameter (capacitance, impedance or losses) with bending and X_0 - without bending.

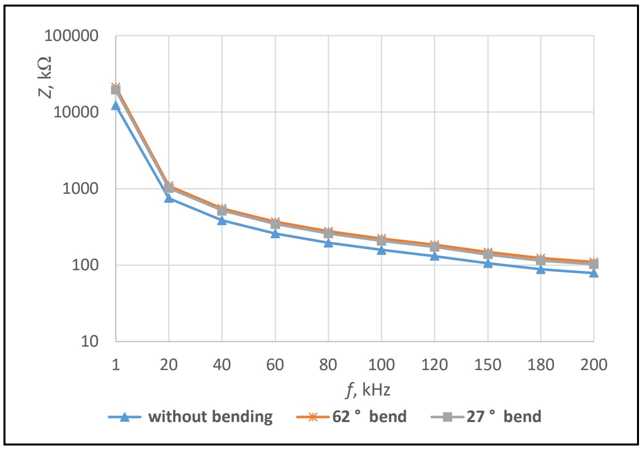


Fig. 7. The frequency dependence of impedance for the Structure 1 at different bending

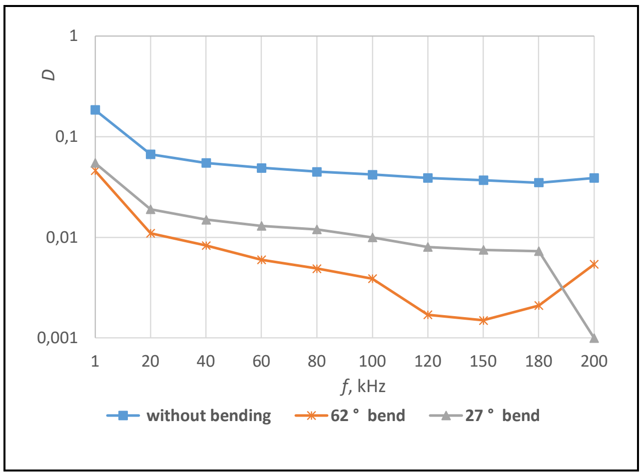


Fig. 8. The frequency dependence of dielectric losses for the Structure 1 at different bending

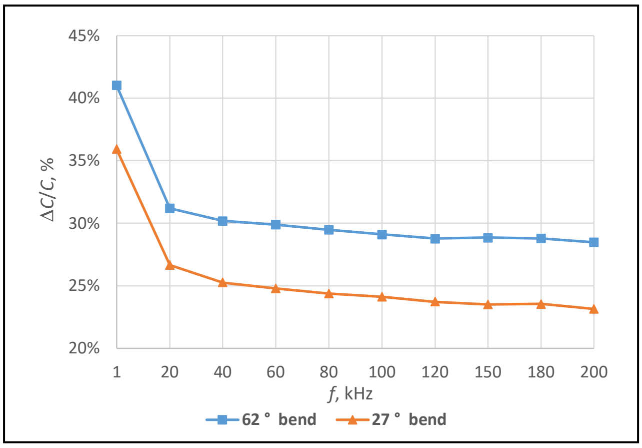


Fig. 9. The frequency dependence of relative bending change of capacitance for the Structure 1

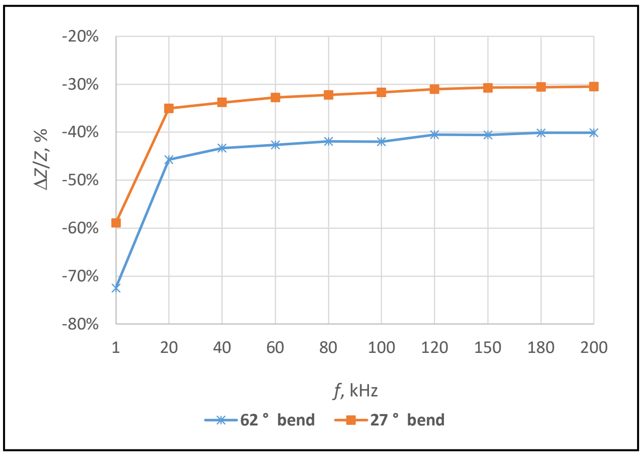


Fig. 10. The frequency dependence of relative bending change of impedance for the Structure 1

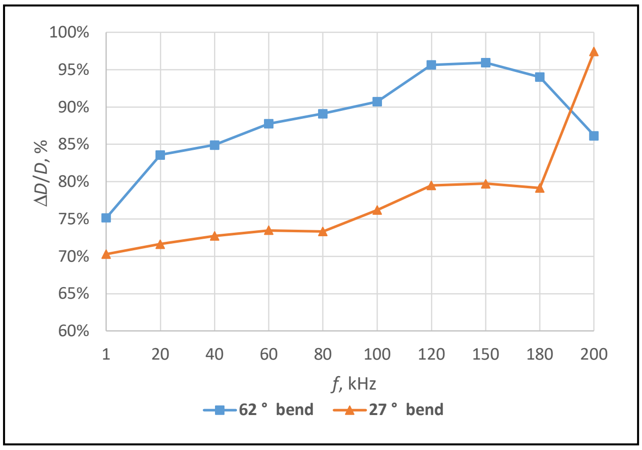


Fig. 11. The frequency dependence of relative bending change of dissipation factor for the Structure 1

Figures 12 and 13 show the differences in capacitance ($\Delta C/C$) between bending and non-bending conditions for Structures 2 and 3, respectively. The obtained results are expressed in percentages.

For Structure 2, the capacitance ranges from 2 pF to 4 pF, with the highest value occurring at a large bending angle and the lowest value during small bending angle. The difference, expressed in percentages, ranges between 20% and 40%, with a tendency towards 40% for larger bending angles and a 30% difference for smaller bending angles.

For Structure 3, the capacitance remains around 5 pF for all three measurements, and in percentage terms, the difference in capacitance between bending and non-bending conditions is approximately 30% at 1 kHz and between 10% - 15% for the other frequencies. This indicates that at higher frequencies, the electrical parameters of this structure do not change significantly under deformation.

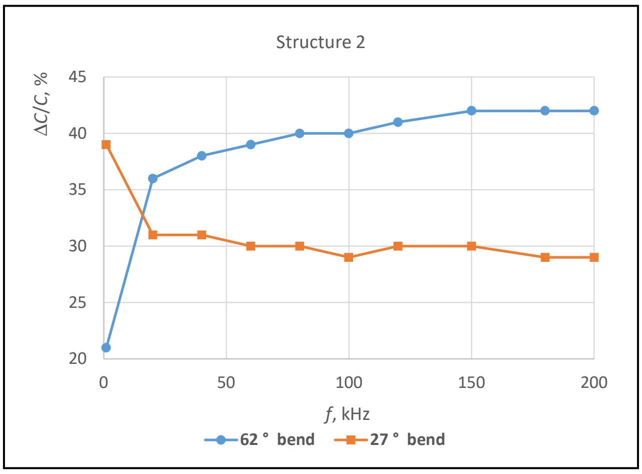


Fig. 12. The frequency dependence of relative bending change of capacitance for the Structure 2

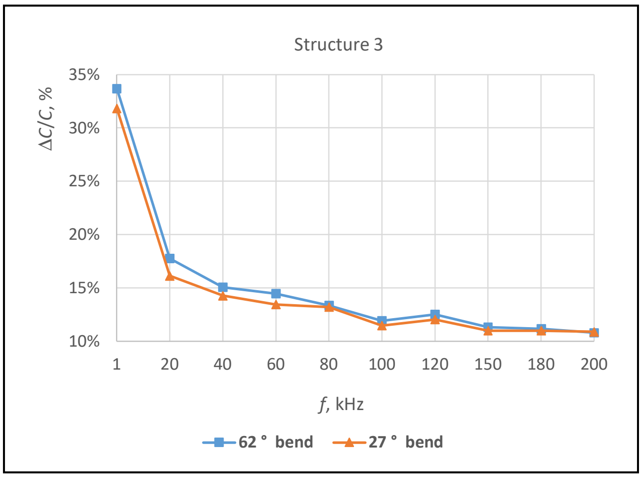


Fig. 13. The frequency dependence of relative bending change of capacitance for the Structure 3

V. Conclusion

The investigation of the electrical parameters of impedance, resistance, capacitance, and losses of realized capacitive structures subjected to deformation are presented in the paper. In general, the capacitance values of the different structures decrease during bending, with the highest values observed in Structure 1 (10 pF) and the lowest in Structure 2 (2 pF). The impedance values are highest for both bending (70.52 MΩ) and non-bending (42.17 MΩ) conditions in Structure 2, while they are lowest in Structure 1 (ranging from 20 MΩ to 78 MΩ). Higher losses are observed in Structure 3 when it is not subjected to deformation (0.29), while lower losses (0.0054) are observed in Structure 1 with a large bending angle. Overall, the losses are highest when the structures are not subjected to bending.

From the obtained results, it can be seen that the classical IDE structure exhibits the highest capacitance and lowest losses. This structure also shows the largest change in capacitance during bending (around 40% at low frequencies), indicating its potential use as a deformation sensor.

Although the capacitance values for all three structures are not very high, they exhibit sufficient changes during bending. Therefore, in order for the structure to be used as a deformation sensor (for pressure, displacement, gauge, force, distance and other factors), their capacitance should be increased, and their measurement should be facilitated, possibly by increasing their surface area.

Acknowledgment

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