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Micro-bending sensor made from polydimethylsiloxane

***Abstract**. The article describes the process of manufacturing micro-bending sensors from polydimethylsiloxane and the checking of their function on the basis of damping behaviour. We tested three manufactured alternatives and from the results we determined coefficients for the calculation of the mass of weight on the assumption that the level of damping is known. We also tested the micro-bending sensors in practice as a walking detector, we can imagine similar uses for the sensor because it is compact, reliable, simple to produce, resistant to unfavorable conditions and cheap.*

Streszczenie.** W artykule opisano konstrukcję czujnika ugięcia wykonanego z polydimethylsiloxanu. Zbadano trzy alternatywne konstrukcje i określono masę obliczeniowoą przy założeniu że poziom tłumienia jest znany. Zbadano też praktyczne zastosowanie czujnika jako detektora kroków. **Mikroczujnik ugięcia wykonany z polydimethylsiloxanu

Keywords: Polydimethylsiloxane (PDMS), sensor, micro-bending, weight, pressure
Słowa kluczowe: Polydimethylsiloxane (PDMS), czujnik kroków, miokroczujnik ugięcia.

Introduction

Polydimethylsiloxane (PDMS) is a polymeric material on the basis of silicone, which is used in many scientific fields for various applications. One of the key characteristics is the excellent heat resistance of the material, under long term heat exposure PDMS resists temperatures of 200 °C and for short term exposure temperatures up to 350 °C. This is why it is very often used in electronics for pouring plates of wide connectors, transformers, power sources and so on.

The authors of publication [1] concentrate on one concrete type of polydimethylsiloxane identified as Sylgard 184 and check its mechanical characteristics at various hardening temperatures (25 - 200 °C). The results show that the hardening temperature can change certain mechanical characteristics of PDMS. Samples prepared at a hardening temperature of 25 °C showed a hardness value of 43.8 Shore A, whereas samples prepared at a temperature of 200 °C showed a hardness value of 54 Shore A. In the construction of sensors (particularly pressure sensors) this information is very important because the hardness of the material undoubtedly affects the resulting behaviour of the sensor. Publication [2] describes a magnetic pole sensor which is constructed from two types of PDMS and a multimodal optical fibre with iron nano-particles. The cover of the sensor is formed by hard polydimethylsiloxane and the internal part of the sensor is filled with a soft silicon gel based on PDMS, so that it is possible using a magnetic field to deflect the first optical fibre with the iron nano-particles. The deviation of the optical fibre has an output of lowering the optical performance. A sensor set up like this can detect a magnetic field up to 0.3 T. A slightly altered sensor can also for instance detect vibrations up to 100 Hz, as is shown in publication [3]. A simple form of pressure sensor made from PDMS is shown in publication [4]. When manufacturing the sensor it is very important to maintain the same hardening temperatures and periods so that the results are not distorted. At the point of action of pressure forces on the wave roller the condition of total rebound is not met, which results in a lowering of the output performance. The accuracy of measurement of this type of sensor is around 2 %. Another physical quantity which can be measured by sensors is heat. Polydimethylsiloxane is a heat sensitive material and this is why the authors of publication [5] decided to fill the void in a single modular optical fibre with this material for the purpose of raising the sensitivity of the heat sensor working on the principle of modal interference. The experimental results showed that the sensitivity of the sensor was -384 pm/°C in the temperature range 25 – 80 °C, if the diameter of the optical fibre with a hollow core was 30 µm. The sensor can be used for the exact checking of temperatures in real time in for instance, the biological, chemical and pharmaceutical industry fields. An interesting application of the use of PDMS is shown by the authors of publication [6]. In the article they describe an optical sensor based on double PDMS type C micro cavities, where the first cavity is formed by a Fabry-Perot interferometer (FPI) and a second cavity is filled with W03/SiO_2 powder. If the sensor is exposed to air mixed with hydrogen, they have a redox reaction as a result of raised surrounding temperatures, which leads to a change in the length of the micro-cavities caused by the expansion of PDMS. The sensitivity of the hydrogen sensor is -15.14 nm/% for a hydrogen concentration range of 0 – 1 %.

The second important characteristic of polydimethylsiloxane is that it does not react with human skin. The authors of publication [7] describe a non-invasive measuring probe with a Braggs grill encased in polydimethylsiloxane. The probe is intended to measure respiration and heart frequency. The measurement is based on the movement of the rib cage where this movement is transferred to the FBG with the aid of a contact band. The experimental measurement carried out in the laboratory proved the functionality of the sensor system proposed. A similar issue is resolved in publications [8-11]. Work [12] introduces flexible bio-sensors localized surface plasma resonance (LSPR) with MIM nano-disks, which are integrated in a PDMS substrate through an adhesive SiNx layer. The structure of the three layered MIM sensor LSPR showed a high sensitivity thanks to the space overlap of the LSPR waves with the surroundings. This MIM LSPR flexible bio-sensor can be used in the future to detect various illnesses such as, for instance, cancer.

The final significant characteristic of polydimethylsiloxane is its optical permeability. The authors of publication [13] tested various phosphorous nano-particles YAG:Ce for lighting and communication. Phosphorous powder was mixed with PDMS and toughened in a parabolic reflector. The chromatic temperature (CCT) was measured for various flows from laser diodes and also the time characteristics of the impulses. It was found that a change in the LD current does not have an effect on the spectral characteristics of the white light created. The CCT varied based on the concentration of YAG powder but a change in the concentration of the powder does not affect its communicative characteristics in any way. Study [14] deals with a flexibile LED structure with high effectivity. A copper film is applied to a polyimide (PI) substrate onto which blue LED diodes are glued. A thin layer of PDMS is applied to the LED diodes, which contains yellow and red phosphor with particle sizes of 25 μm. Through changes in the mass ratios of yellow and red phosphor in PDMS it is possible to achieve different shades of white light. Improving the lighting qualities of LED diodes is also studied by the authors of publications [15-20].

In certain applications it is not possible to use certain materials, such as metals, wood or hard plastics due to the effect of unfavourable infuences. Polydimethylsiloxane is resistant to most chemicals, acids, corrosion, UV rays and radiation. Other reasons why we chose PDMS in particular, are its mechanical properties, low price for small dimensional sensors and of course, its simple preparation.

Methods

Micro-bending sensors belong to the amplituidinal fibre sensor group. With the aid of these sensors it is possible to measure various physical quantities such as pressure or temperature. The influence of the physical quantities measured results in the breaking of an important condition for spreading light in optic fibre and energy losses occur. The main cause of energy loss is the breaking of the condition of total rebound at the core/cover interface because during the change of geometry (bending) of the optic fibre the light (ray) falls on the interface of the core/cover at a different angle. It is known from the behaviour of light at the interface of two dielectrics that a total rebound will occur when the angle of approach is equal to or greater than the limiting angle. For two environments with a refractive index of n_1 and n_2 this condition applies.

(1) $$\Theta_d \geq \sin\frac{n_2}{n_1}$$

Figure 1 shows a typical layout of a micro-bending sensor with an optic fibre. In practice in most cases a multimodal optical fibre with a core diameter of 50 μm or 62.5 μm is used. The micro-bending sensor is is formed of two adjacent deforming boards on which deformation spikes are placed, between these two deformation boards two deformation elements are placed. If a measured physical quantity acts on the boards, then the deformation elements are compressed and the spikes will deform the optic fibre.

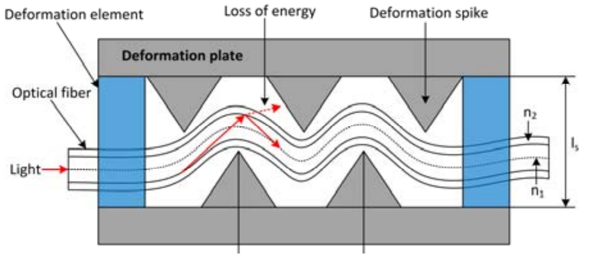

Fig.1. Typical layout of micro-bending sensor

The maximum losses in an optic cable occur if the wave number is equal to the difference in the wave numbers of the conducted modes and radiated modes.

(2) $$\beta - \beta' = \pm\frac{2\pi}{\Lambda}$$

where: *Λ* - period of micro-bending.

In case of a change of conduction through an optical cable in relation to a change in the thickness *ΔF* acting on the deformation plates the relationship applies

(3) $$\Delta T = \left(\frac{\Delta T}{\Delta X}\right)\Delta F\left(K_f + \frac{A_s Y_s}{l_s}\right)^{-1}$$

where: *ΔX* – change in the seperation of the deformation boards, *ΔT/ΔX* - sensitivity, *ΔF* - thickness, A_s – area of section, l_s - length of deformation element, Y_s – Youngs module of elasticity, K_f – the effective constant of elasticity of an optic cable. The effective constant of elasticity K_f is expressed

(4) $$K_f^{-1} = \frac{\Lambda^3}{3\pi Y d^4 \eta}$$

where: *Y* – the effective Youngs module of electricity, *d* – the diameter of the optic fibre, *η* – number of diffractions.

Experimental setup and measurement

We defined the dimensions of the micro-bending sensors and chose a suitable method of manufacture (the casting method). We printed out the proposed casting form on a 3D printer made from heat resistant material (PETG) so that it was possible to speed up the manufacturing process (hardening). Figure 2 shows the construction and dimensions of the sensor with 5 steel wires.

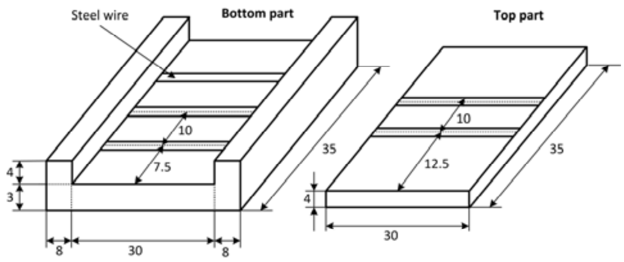

Fig.2. Dimensions of a micro-bending sensor with five steel wires

The surface of the casting form was porous so we covered the form with a thin layer of oil so that the sensor wouldn‘t be damaged when it was turned over. We put steel wires with a diameter of 2mm in the grooves of the casting form and filled the form with a mix of PDMS and a hardening agent. We vulcanized all the prepared samples in a heating box at a constant temperature of 70 °C. Figure 3 shows the deformation part of the PDMS sensor and a printed casting form

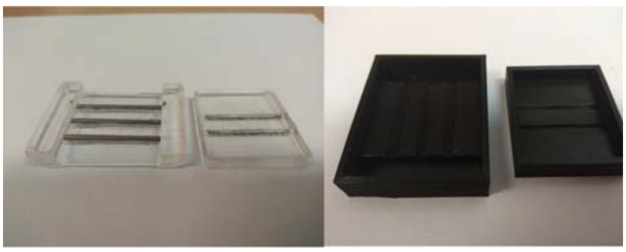

Fig.3. A micro-bending sensor made from PDMS and a casting form

In order to measure we used a multimodal optic fibre with a core diameter of 62.5 μm and a OLTS EXFO AXS 200/350 unit. We placed the optic fiber, with its secondary protection removed, between the PDMS deformation parts such that it went through the centre of the sensor. We gradually added weight of 945g into the container placed on the PDMS micro-bending sensor and read off the damping values for a wave of 850 nm in length. The complete layout of the measuring workspace is shown on figure 4.

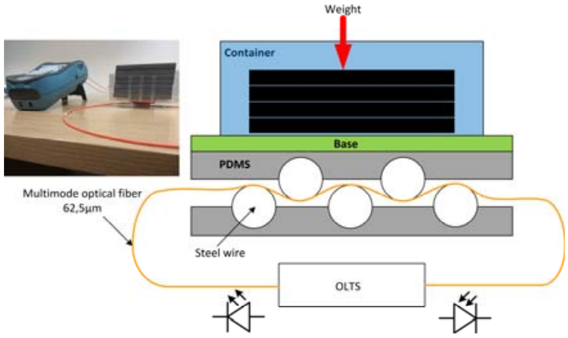

Fig.4. Layout of the measuring work space

Results

We made three variations of the sensor (with 5, 11 and 15 steel wires) and investigated the damping behaviour up to a weight of 19845 g. A uniform spacing of the steel wires of 10 mm was maintained for all samples, only the length of the sensor changed in relation to the number of steel wires. All other parameters remained the same. We measured each sample five times and averaged the values. Figure 5 shows the results of the measurement for three micro-bending sensors with five cables.

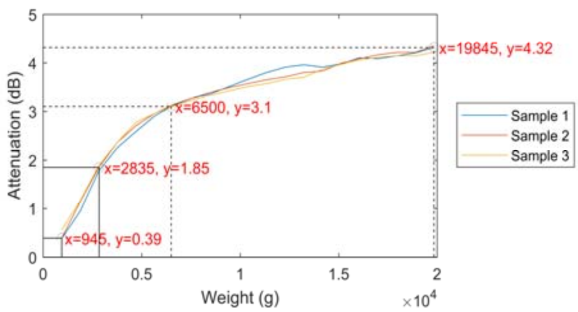

Fig.5. Damping characteristics of micro-bending sensors with 5 steel wires

The measured characteristics are very similar, which indicates a good reproductibility of measurement. If we concentrate on the linear part of the characteristic, we can say that the measurement ranges of all the sensors created are the same, 945-2835 g and 6500 – 19845 g. A loss of half of performance of the optic fibre occurs at a weight of 5842 g.

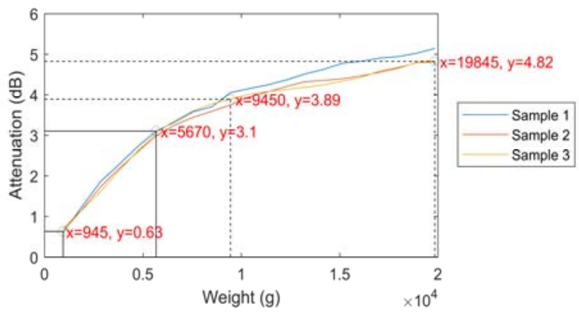

Fig.6. The damping characteristics of micro-bending sensors with 11 steel wires

Figure 6 shows the damping effect for micro-bending sensors with eleven steel wires. In comparison with the first variation of the sensor a doubled growth of the measurement range occurs in the first measurement range. On the other hand in the second measurement the range falls by 2950 g. The loss of half of the performance tied to the optic fibre occurs at a weight of 5481 g.

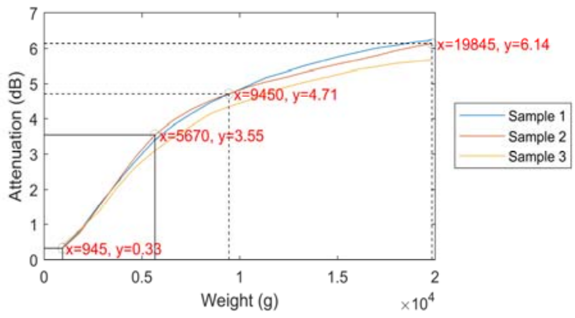

Fig.7. The damping characteristics of micro-bending sensors with 15 steel wires

Figure 7 shows the damping characteristics of sensors with 15 steel wires. In this variation of the sensors no increase of the measured range occurs, only the slope of the characteristic occurs. The loss of half of its performance occurs at a weight of 4965 g.

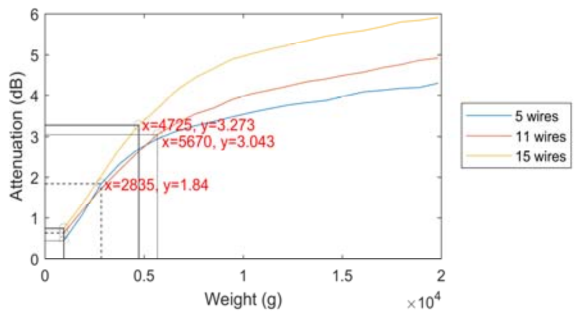

Fig.8. Comparing the damping characteristics of micro-bending sensors

Figure 8 shows a comparison of the individual sensor types. The data was obtained by averaging all of the measured values for each type of sensor. For clarity only the first measuring range of the sensors are shown in the graph. If we generate an inverse function and use a 4th series polynomial, we can state an equation for calculating weight.

$$y = c_1 \cdot z^4 + c_2 \cdot z^3 + c_3 \cdot z^2 + c_4 \cdot z + c_5 \quad (5)$$

$$z = \frac{x - mu}{\sigma} \quad (6)$$

where: *x* – the damping value measured.

Table.1. Equation coefficients

Coefficients	5 wires	11 wires	15 wires
c_1	32.625	57.693	444.87
c_2	885.59	954.39	2381.5
c_3	3974.1	3431.2	4422.0
c_4	7427.9	6413.3	5730.6
c_5	7608.7	7882.3	7406.1
mu	3.2435	3.5829	4.4016
σ	1.0485	1.2495	1.5449

Figure 9 shows the damping characteristics for three sensors with five steel wires but this time we did not place the optic fibre in the middle of the sensor but 5 mm from both outer edges (laid out in a loop). In comparison with the original layout of the optic fibre a doubled growth occurs in the measuring range for the first measuring area. In the second measuring area the opposite occurs, a lowering of the range by 2005 g. The loss of half of the performance tied to the optic fibre occurs at a weight of 4795 g. A comparison with the original layout of the optical fibre can be seen in figure 10.

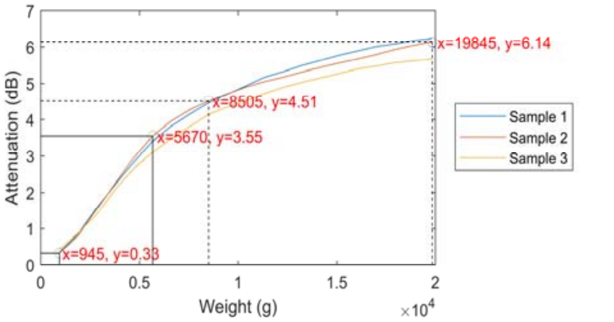

Fig.9. Damping characteristics of micro-bending sensors with 5 steel wires – layout of optic fibre in a loop

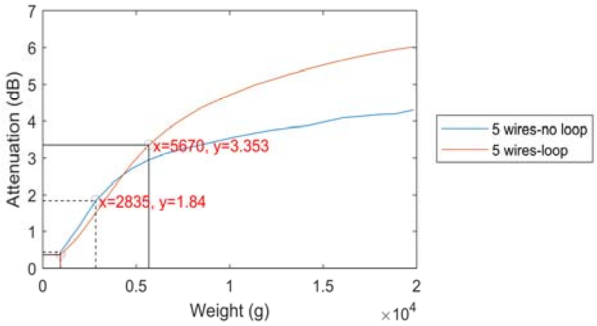

Fig.10. A comparison of the damping characteristics of micro-bending sensors with 5 steel wires – without a loop and with a loop

Conclusion

Functionality was tested on three differing types of micro-bending sensors. The sensors are functional over the whole range of the measured values and we assume that with a change of the spacing of the steel wires or the diameter of the steel wires it will be possible to achieve better parameters. From the testing of the sensors it can be concluded that the measurement ranges of the sensors can be controlled by the number of steel wires or the layout of the optical fibre in the sensor. The number of wires (diffractors) also affects the slope of the characteristic, a large difference is seen particularly between the variants with three and eleven steel wires. Polydimethylsiloxane proved to be a suitable material for this application because it ensures the necessary hardness and flexibility. After each measurement the PDMS returned to its original position after a few seconds, which is very important for reproducibility of results. The proposed sensor can be used in environments where there is a risk of magnetic interference, radiation and chemical threats. We also tested the sensor with five wires for detecting walking. With this sensor we achieved 100 % success in detecting the passage of persons weighing 70-95 kg, the damping measured varied between 5 – 7 dB. The sensor showed no signs of damage even during a larger numbers of repeats.

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