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Transmission fibre-optic transducer used for a silicon structure's displacement measurement

***Abstract**. The study shows a construction and experimental results of a beam-through fibre-optic transducer used for a silicon beam displacement measurement. The transducer consisted of two plastic optical fibres (POF) placed opposite each other – one transmitting light and the other one receiving it. The first one was connected to light source equipped with a LED, the second one to a photodiode of an optical power meter. Displacement of the thick structure placed between them resulted in a change of optical power collected by the receiving fibre.*

Streszczenie.** Artykuł przedstawia konstrukcję oraz wyniki doświadczalne dla transmisyjnego przetwornika światłowodowego do pomiaru przemieszczenia belki krzemowej. Umieszczenie struktury krzemowej pomiędzy powierzchniami czołowymi światłowodów powodowało zmianę mocy optycznej na wyjściu przetwornika.(**Transmisyjny przetwornik światłowodowy przeznaczony do pomiaru przemieszczenia struktury krzemowej)

Keywords: optoelectronic transducer, optoelectronics, optical fibres, MEMS
Słowa kluczowe: przetwornik optoelektroniczny, optoelektronika, światłowody, MEMS

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Introduction

There are many types of fibre-optic transducers used for industrial purposes. Their advantages are small size and weight, non-contact measurement, resistance to electromagnetic noise, non-electric transmission providing ability of operation in environments characterized by a high risk of explosion or fire. Production lines are often equipped with intensity, retro-reflective, interferometric, transmission and other sensors [1, 2]. Beam-through optic sensors are commonly applied as a barriers detecting an intrusion of an object. On the other hand they can be a good solution for small structures' displacement measurements.

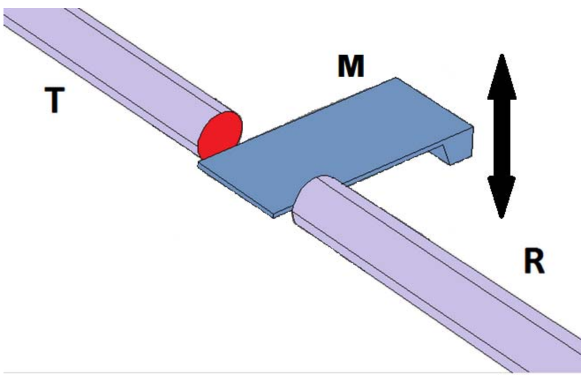

Fig.1. Construction of the beam-through fibre-optic transducer

The study shows a construction of a transmission fibre-optic transducer consisting of two plastic fibres placed opposite each other. The transducer operates on a 660 nm wavelength. Optical light source was equipped with a red-light emitting diode. Received optical power was measured by a compatible optical power meter. A silicon structure (M) was placed between precisely cut fronts of the fibres (T – transmitting, R – receiving) (figure 1.). A change in displacement of the structure effected in a change of received optical power. The output power characteristic is symmetrical due to a circular shape of the cross-section of the fibres. Effective measurement range can be described as a half of a diameter of the fibre's core. Distance between the fronts of the fibres was limited by an optical power density. The study shows both analytical analyses for different types of fibres and experimental results for 1000 μm plastic optical fibres. The study proves that the sensor can measure a displacement of a small MEMS structure (a silicon beam) with high sensitivity and resolution.

Analytical results

Analytical calculations were prepared for different, commonly used types of fibres: single-mode fibres, 50/125 μm multi-mode fibres, 62.5/125 μm multi-mode fibres, 980/1000 μm plastic optical fibres. The basic properties of fibres taken into account during the calculation were the core's diameter and the fibre's numerical aperture. A numerical aperture for a fibre surrounded by air is described by the equation:

(1) $$NA = n sin\,\theta$$

Where: NA – numerical aperture, n – refractive index of air, Θ – acceptance angle for the used fibre

Absorption in the fibre's core was omitted due to very short fibres length in the experimental case. The calculations assume cone light distribution on an output of the emitting fibre. Having regard to the fibre's core diameter d and the numerical aperture NA, received optical power in the distance s from the emitting fibre (without beam-barrier) was calculated using basic trigonometric dependencies and the equation (2):

(2) $$P_r = PD \cdot S_r = \frac{P_e}{S_c} \cdot S_r = \frac{P_e}{R_r^2} \cdot r_r^2$$

where: PD – optical power density, S_r – cross-section area of a core of a receiving fibre, P_e - power emitted by a transmitting fibre, S_c – area of a light-circle in the distance s from the emitting fibre, r_r – radius of a core of a receiving fibre, R_r – radius of a light-circle

For the investigated types of fibres, the plastic one (referred as POF 1000 μm on the graph), having 980 μm core diameter and NA = 0.5, had the highest calculated received optical power. It is mainly due to the fact that it has the biggest cross-section core's area, which enables it to collect much of optical power, even though the numerical aperture for the combined emitting plastic optical fibre is much bigger then for the glass fibres.

Area of a segment of a circle S_{SG} corresponding to a fibre's core can be described by the equation (3) [3].

(3) $$S_{SG} = r^2 cos^{-1}\left(\frac{r-h}{r}\right) - (r-h)\sqrt{2rh - h^2}$$

Where: S_{SG} – area of a segment of a circle, r – radius of a circle of which segment is a part (in case of cross-section of the fibre's core $r = r_r$), h – height of the segment

Placing a thin beam-barrier (thickness h_B = 50 µm) between the front surfaces of the fibres cause a loss of optical power collected by the receiving fibre. An area of the receiving fibre's core overridden by the object was calculated from the difference of the two segments of the circle (representing the fibre's core) determined by a lower and upper edge of the barrier (4) (figure 2.).

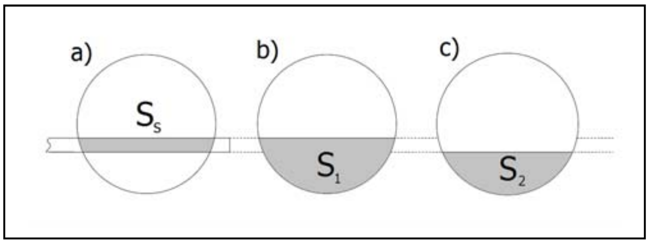

Fig.2. Segments S_1, S_2 of the fibre's core marked by the beam-barrier (a)

(4) $$S_s = S_1 - S_2$$

where: S_s – shuttered area of the fibre's core cross-section, S_1 – area of a segment of the fibre's core cross-section marked by an upper edge of the beam-barrier, S_2 – area of a segment of the fibre's core cross-section marked by a lower edge of the beam-barrier

The received optical power in such case should take into account decreased area of receiving fibre's core collecting optical power (5, 6).

(5) $$S_{NS} = S_c - S_s$$

where: S_{SN} - area of the fibre's core cross-section not shutter by the beam-barrier, S_C – area of the fibre's core cross-section, S_S – shuttered area of the fibre's core cross-section

(6) $$P_r = PD \cdot S_{NS}$$

where: P_r – received optical power, PD – optical power density in the distance l from the emitting fibre, S_{NS} – area of the fibre's core cross-section not shuttered by the beam-barrier

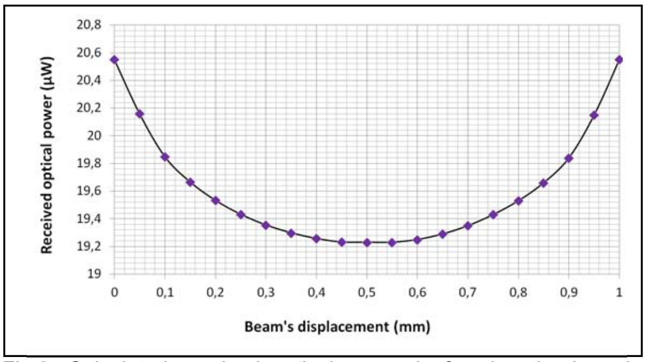

Fig.3. Calculated received optical power in function the beam's displacement for the distance between the fibres s = 2.5 mm

Figures 3. and 4. show calculated output characteristic for the case where the thin beam-barrier is placed between the front surface of the fibres, for two different distances between the fibres: s = 2.5 mm and s = 3.5 mm (according to beams' widths w = 2 mm and w = 3mm), for power emitted by the transmitting fibre P_e = 0.3 mW.

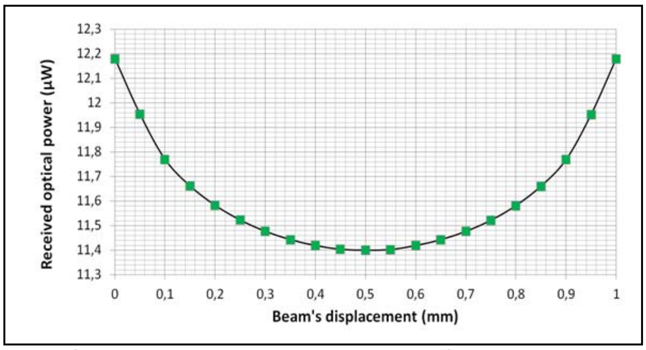

Fig.4. Calculated received optical power in function the beam's displacement for the distance between the fibres s = 3.5 mm

Practical research

The practical research was prepared for 980/1000 µm plastic optical fibres, NA = 0.5, which were previously analytically proven to be most effective in the case of the beam-through fibre-optic transducer. The emitting fibre was connected to the AFL NOYES OLS-1C light source of P_e = 0.3 mW. The chosen operating wavelength was 660 nm (standard for plastic optical fibres' single transmission). The optical power from the receiving fibre was measured by the compatible AFL NOYES CSM1-1 optical power meter.

Two different construction of the sensor were made. In the first one the distance between the fibres was s = 2.5 mm, in the second on it was s = 3.5 mm. The fibres were mounted in a holder made of duralumin. Tooling of the holder was carried by cheap traditional mechanical methods (drilling and cutting). The fibres were precisely aligned both in a longitudinal axis and the distance between the front surfaces.

A thin beam (thickness h_B = 50 µm) was placed between the front surfaces of the fibres. A width of the beam was 0,5 mm smaller than the gap between the fibres. In the case of construction of the s = 2.5 mm its width was w = 2 mm, in the case of s = 3.5 mm width w = 3 mm. A length l of the beam was equal 4 mm in both cases. The beam was precisely cut by laser cutting methods [4, 5].

The displacement of the beam was controlled by a micrometric linear table type MX-40SC equipped with the BAKER electronic displacement transducer. Beam was moved in one axis with step equal its thickness h_B = 50 µm in the measuring range equal diameter of the fibre d = 1 mm.

Figures 5. and 6. show experimental output characteristics for the two different transducer's constructions of s = 2.5 mm and s = 3.5 mm. The maximum reached collected optical power for the construction having smaller distance between the fibres was P_c = 17 µW.

Linear ranges were determined for the both experimental characteristics. Table 1. shows the slope factors of the linear ranges.

Table 1. Linear ranges for the experimental characteristics

Distance between the fronts of the fibres	Edge	Range [mm; mm]	Slope factor
s = 2,5 mm	falling	(0.05; 0.30)	-17.71
	rising	(0.70; 0.95)	17.13
s = 3,5 mm	falling	(0.05; 0.35)	-11.49
	rising	(0.65 ; 0.95)	11.19

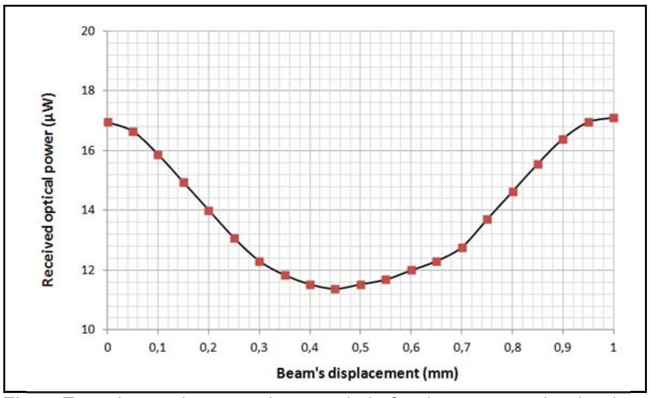

Fig.5. Experimental output characteristic for the construction having distance between the fibres s = 2.5 mm

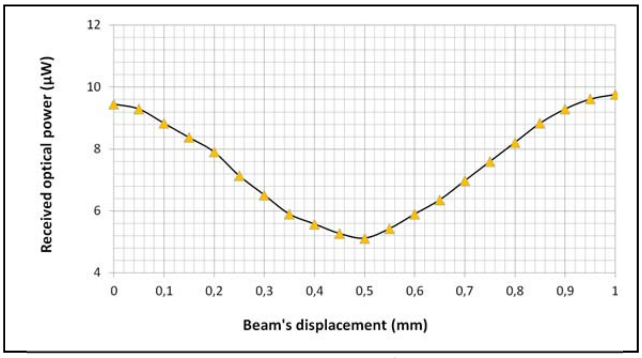

Fig.6. Experimental output characteristic for the construction having distance between the fibres s = 3.5 mm

Conclusions

The study shows the construction of the fibre-optic beam-through sensor consisting of two plastic optical fibres placed opposite each other. The type of the fibres was determined on the grounds of analytical calculations regarding parameters of the fibres and optical power density in a specific distance from the front surface of the emitting fibre. In both analytical and practical cases assumed emitted optical power was P_e = 0.3 mW. Maximum calculated received optical power for the smaller distance between the fibres s = 2.5 mm was 20.5 μW with no barrier between the fibres. In a real-life construction it was about 17 μW. The error of calculations is about 20 %. The reason of this is due to no consideration of ray tracing, only assuming all calculations on the grounds of optical power and simple trigonometric dependencies. Increasing the distance between the front of the emitting and the receiving optical fibres by 1 mm resulted in about 40 % maximum receiving optical power loss in both analytical and experimental case.

In the further research a 50 μm thick beam-barrier was placed between the fronts of the fibres. It resulted in the decrease of the receiving fibre's cross-section area collecting optical power. In analytical case the relative change of receiving optical power cause by displacing the beam between the fibres was less than 10 %. In the real life construction it was up to 50 %. Once again the calculations did not consider some phenomenoms like ray tracing, mirror reflection and dispersion of light on the edges of the beam.

Even though the error of the calculations was high, presented method can still be effective in determining whether designed construction is useful or not, especially in situations where the designing time is limited.

Slope factors of experimental characteristics were similar for falling and rising edges, which suggest that the transducer works properly for displacements to- and from- an axis of symmetry of the fibres' cores, which proves that mechanical methods of the constructions' tooling were proper and precise.

The construction designed in the study can be successfully used in a thin silicon structures small displacements measurements, ex. measurements of a deflection of a beam with ferromagnetic layer placed in a magnetic field [6].

REFERENCES

[1] Lee B., Review of the present status of optical fiber sensors, *Optical Fiber Technology 9 (2003)*, 57-79

[2] Annamdas V. G. M., Review on Developments in Fiber Optical Sensors and Applications, *International Journal of Materials Engineering 2011*; 1(1), 1-16

[3]<http://www.mathopenref.com/segmentareaht.html> [access: 18.06.2014 19:43]

[4] Pawlak R., Rosowski A., Tomczyk M., Walczak M., Laser microscale technologies - modeling assisted processes, *Proc. of SPIE Vol. 8703 87030N-10*

[5] Pawlak R., Tomczyk M., Walczak M., Domagalski P, . Semiconductor and ceramic microstructure made by single mode fiber laser, *J. Phys. Conf. Ser. 2014 Vol.494*, 1-8

[6] Golebiowski J., Milcarz S., Numerical models of magnetic field MEMS sensors used in optoelectronic Microsystems, *Proc. of SPIE 2013 Vol.8902 art. nr 890221*

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