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PRE-DESIGNMENT of a highly sensitive nanophotonic pressure sensor

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ABSTRACT

The paper considers the constructive implementation of the nanophotonic sensor of comprehensive application, proposed by the authors earlier and investigated using computer simulation. Here we investigate one of the constructive solutions of a supersensitive pressure sensor based on nanostructures, providing miniaturization of sensors and their application in various technical products. Based on the previously conducted mathematical simulation of the process of high-frequency electromagnetic radiation propagation through a nanocones array, which is the essential element of the proposed design, justified decisions about the overall dimensions of the structure, its internal structure, and the optimal frequency of the field excitation source are made. This work solves, in particular, the problem of protecting the sensor's internal structure from external electromagnetic fields. Employing solid-state modeling, the linearly reciprocating motion of the sensor plates under external loading in the proposed device design is confirmed.

Keywords: nanophotonic devices, microsensor, computer simulation, finite element method, miniaturization

1. INTRODUCTION

The next step in the technical device's miniaturization is the move from the currently used microsensors to nanosensors, which typically do not exceed 100-200 nm. The need for nanosensors arises in a wide range of technical products in various application areas. Inertial nanosensors are being actively developed for navigation devices[1-3]. Nanothermometers are in demand in medicine, biology and chemistry. They allow one, for example, to measure the intracellular temperature noninvasively and precisely[4-6]. Also, nanosensors are represented by highly sensitive gas analyzers[7] and nanoscales[8]. In geophysics, nanoelectromechanical systems can be used for oil production monitoring, during well drilling procedures, and oil recovery enhancement[9,10].

The paper[11] published by the authors earlier provides a background on the prospects of using nanophotonic units in modern control and monitoring systems for technical devices which need miniaturization. A theoretical justification and mathematical modeling of the electromagnetic wave propagation through a dynamically changing nanostructure array of conical elements are given (Fig. 1).

The sensor operating principle is based on the electromagnetic field strength alteration when passing through a nanostructure ща truncated cones. When clamping due to externally applied pressure the nanostructure changes the cone diameter in central cross-section and cone density which influences the logged electromagnetic field signal. Thus, the pressure P (Pa) is a function of the electric field $\mathbf{E}'$ (V/m) at the sensor output:

$$P = p(\mathbf{E}'),$$

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here $\mathbf{E}' = g(\mathbf{E}, \mathrm{R}, \varepsilon, \mu, \sigma)$, $\mathbf{E}$ – the electric field at the sensor input (V/m); ε – dielectric permeability (F/m); μ – magnetic permeability (H/m); σ – conductivity (S/m); R – cone's radius in the section passing through the sensor center (m).

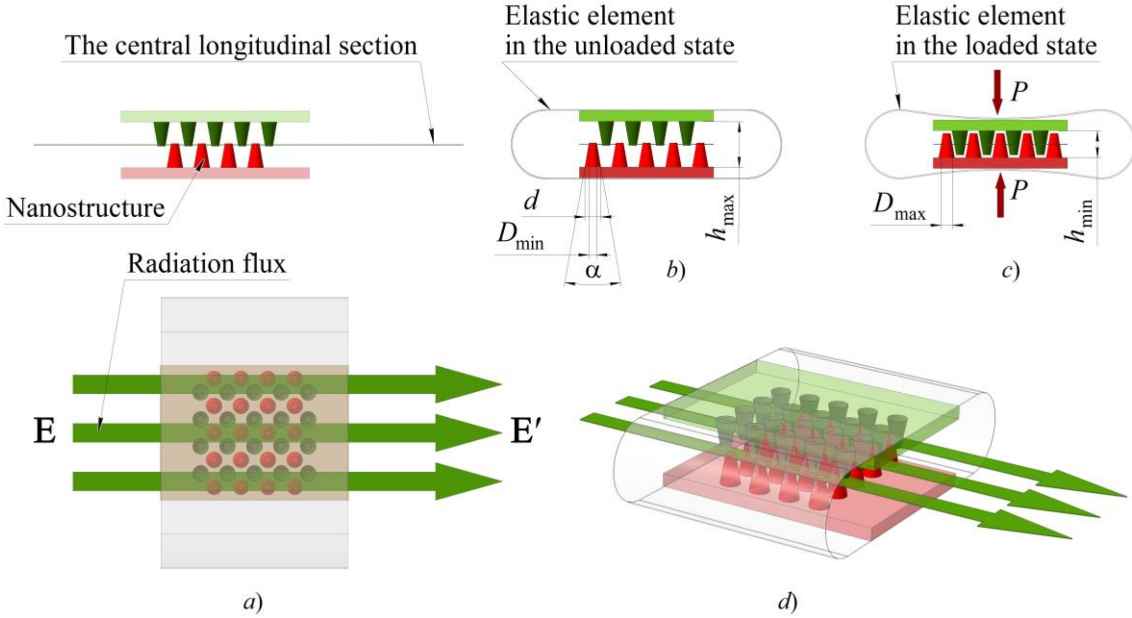

Figure 1. The sensor operating principle: a), d) principal scheme of the pressure sensor; b) unloaded state; c) loaded state. Here D_{min} – the diameter of the smaller truncated cone base, D_{max} – the diameter of the bigger truncated cone base, d - the diameter of truncated cone in the cross-section, α – cone angle, h_{max} - the maximum clamping height of the structures, h_{min} - the minimum clamping height of the structures

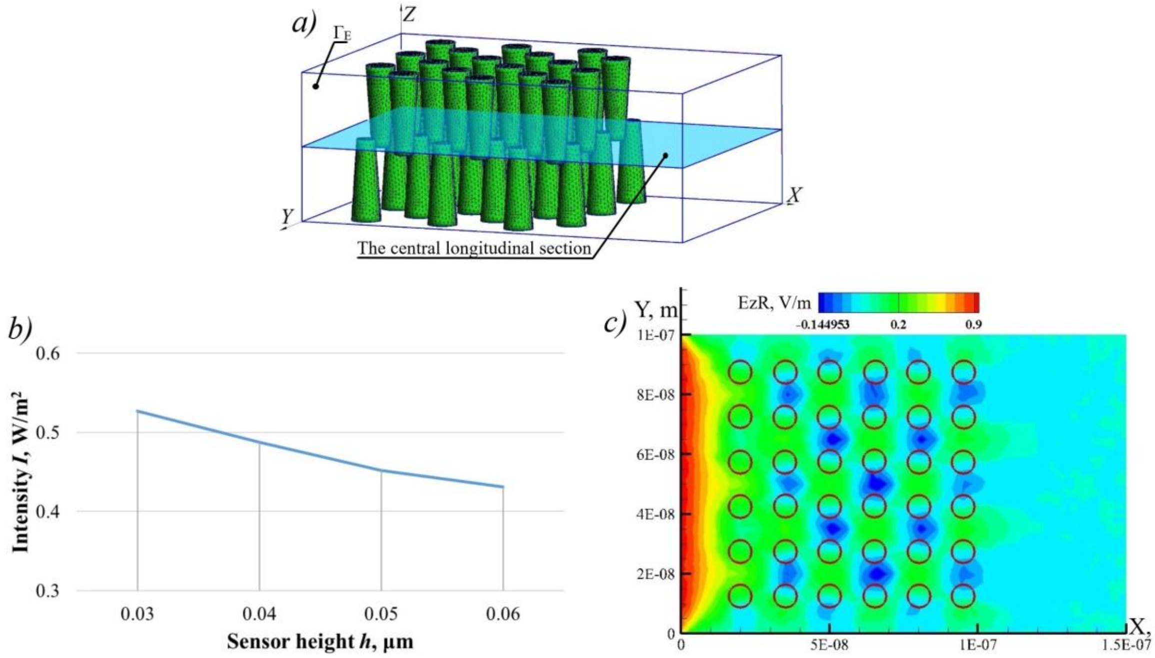

Figure 2. a) the nanostructure of cones array, b) the intensity I at the reference point p_0 depending on the sensor's clamping height, c) the real component Ez in the central cross-section of the sensor (actual height is h = 0.05 μm)

Numerical three-dimensional modeling of the considered system gave results (Fig. 2) that can be implemented in technical items of various applications: pressure sensors, vibration sensors, temperature sensors, sensors controlling geometric parameters of the surface, etc11. Using mathematical modeling, we have selected the optimal sensor external sizes and cone materials and calibrated the radiation source frequency, which made it possible to achieve a monotonic decrease of the intensity function I (Fig. 2.b). Authors proposed the following configuration: 1) the nanoarray consists of two arrays of cone inclusions; 2) the source frequency is f = 580 THz; 3) the non-magnetic and dielectric materials are used; 4) the internal nanostructure size is 1.E-7 m.

2. PRELIMINARY DESIGN OF THE PRESSURE SENSOR

The high degree of sensor noise immunity from the influence of electromagnetic radiation is determined by its design, which excludes microelectronic elements. According to Fig. 3, the pyramidal nanostructures 1 and 2 are placed on base 3 and the elastic element of the sensor 4. An applied external force F (N) leads to mutual displacement of the nanostructures. The magnitude of their displacement is functionally related to the variation of the radiation flux in the optical fiber 5. The radiation flux is fed into the sensor and read from it through the connector 6.

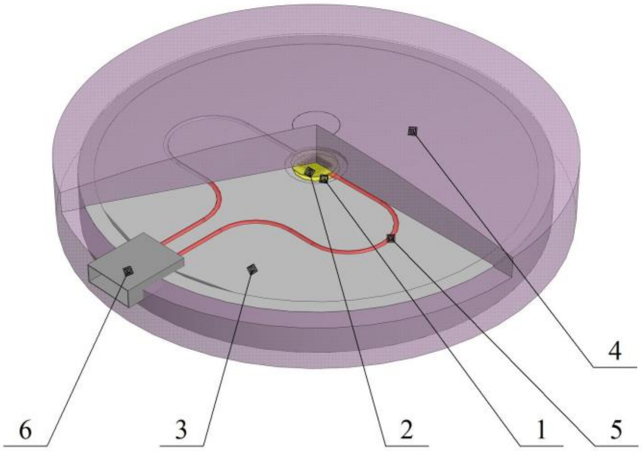

Figure 3. Pressure sensor concept scheme

Computer simulation of a sensor version (Fig. 4) with an elastic element of spherical shape and a flat area of 2 mm diameter for external force application confirmed linear dependence of deformation (displacement) of the area with nanostructure on the applied external force F (Fig. 5). It is possible to proceed from a given value of the applied external force F to the pressure P with the known surface area S of the force F application.

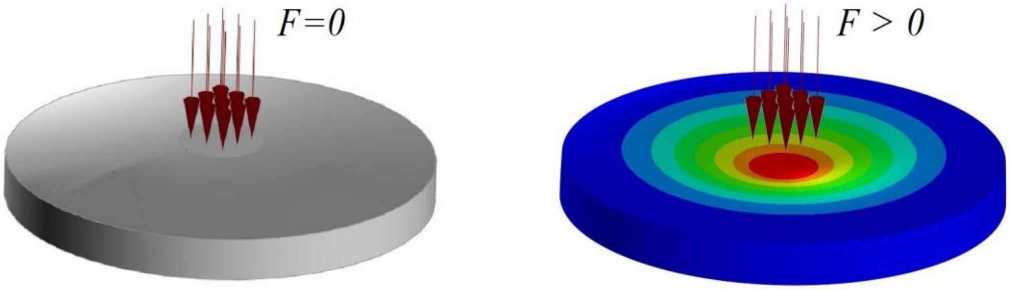

Figure 4. Deformation of the pressure sensor

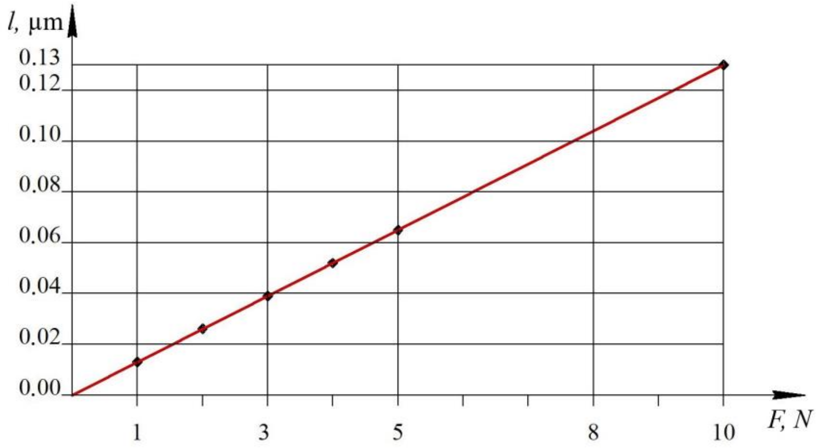

Figure 5. A relationship between the displacement *l* of the nanostructure and the external load *F* applied to a central flat area with a diameter of 2 mm, for the sensor in question

In this version of the pressure sensor with a measuring range of external loading force from 1 to 10 N, the elastic element is made of spring steel and has a thickness equal to 1 mm. In the range of external force F from 1 to 5 N, the linear displacements of the nanostructure elements correspond to the previously conducted simulation of electromagnetic field propagation in the sensor when changing the height of clamping of conical arrays of the nanostructure. The choice of the material, shape and thickness of the elastic element allows the characteristics of the sensor to vary over a wide range.

3. CONCLUSION

The paper proposes a preliminary design solution of a supersensitive pressure sensor based on nanostructures, protected from the influence of external electromagnetic fields. The design is presented based on previously conducted studies of electromagnetic wave propagation through the conic nanostructure of a sensor. The source frequency, cones material, and their spatial distribution were obtained by analysis of numerical simulation investigations. All the parameters were chosen to obtain the monotonic behavior of the electromagnetic wave intensity in the checkpoint behind the conic nanostructure (output point). Variants of constructive solutions can be expanded in the direction of measuring weak-acting forces, as well as increasing them. In this paper, we consider the pressure sensor, but the principle of its operation can be applied, for example, in sensors measuring temperature, vibration, acceleration, etc.

4. ACKNOWLEDGMENTS

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