Micro-Opto-Electro-Mechanical Transducers for Measurement and Control Systems

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Abstract

In this article operating principle and determination method of design parameters of micro-opto-electro-mechanical (MOEM) – transducers based on optical tunnelling effect (OTE), which is supported to its operating process within specified range of high sensitivity. Possibility of adjustable measurement range of those transducers by using feedback circuit is considered. Transducers of mechanical (pressure and acceleration) parameters with quasi-linear transfer function are developed.

Keywords: *Transducers, pressure, acceleration, high sensitivity, optical tunnelling effect, quasi-linear.*

I. INTRODUCTION

In recent years most of the MEMS transducers are developed by mean of capacitive measurement. Since operating range of these transducers' capacitive gap is set around tens micrometre, it becomes increasing excitation voltage. Main disadvantages of capacitive MEMS transducers are possibility of electric discharge, occurred at maximum deflection of sensing element (SE) and it leads to the failure of such devices, and non-linearity transfer function, which depends significantly on the modulation depth of the capacitive gap [1-4].

To overcome these drawbacks and to ensure effective use of measurement and control systems, it is suggested to use MOEM-transducers based on OTE. In this paper, generalized models of transducers with various types of SE, which possess quasi-linear transfer function for measuring some mechanical parameters, is considered.

II. OPERATING PRINCIPLE OF MOEM-TRANSDUCERS BASED ON OTE

OTE can be placed on the base of the transducers with boundary modulation of radiation. For the electromagnetic wave propagating in some kinds of medium, the presence of homogenous medium, while not only mechanical contact, but also approached medium distance (order of wavelength) between each other, can handle.

A transducer based on OTE, described in fig. 1, consists of optical radiation source (OS), primary transducer (PT), photodetector (PD) and the electronic block (EB).

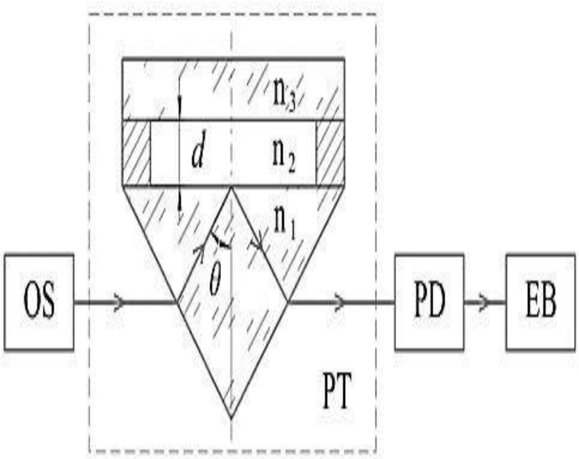

Fig.1. Typical MOEM-transducer based on OTE

PT represents as total internal deflection prism (refractive index – n_1) and SE (refractive index – n_3), impacted by mechanical parameters (ψ) (including pressure, angular velocity and acceleration). In this case, the differences between these transducers are the different structural solutions and deflection of SE. The initial gap d_0 between SE and the prism is set smaller than the wavelength of radiation. The material of SE with reflective index n_3 is chosen in such a way that its relative to the prism n_1 at the condition of total internal reflection (TIF) is occurred earlier than relative of medium n_2 between prism and SE, i.e. $n_3 > n_2$. The incident angle θ to the modulated surface is chosen in such a way that TIF condition is only occurred at the optical contact of prism to SE. It means that θ must execute the following condition

$$\arcsin(n_2/n_1) < \theta < \arcsin(n_3/n_1). \qquad (1)$$

Mechanical parameters ψ may lead to change of gap d between SE and the base of prism, and consequently to the modulation of optical radiation reflected part, which gives information. While decreasing the gap large amount of optical energy pass through SE and absorb that leads to reduce output signal of PD. For non-polarized optical wave reflectivity of structure with one reflection from the modulated boundary is defined as [5-6]:

$$R[d(\psi)] = 0.5 \cdot \left\{R_{\perp}[d(\psi)] + R_{||}[d(\psi)]\right\}, \qquad (2)$$

where $R_{\perp}[d(\psi)]$, $R_{|}[d(\psi)]$ − reflectivity of mediums boundaries for perpendicular and parallel polarized wave, respectively, under the influence of ψ (fig. 2).

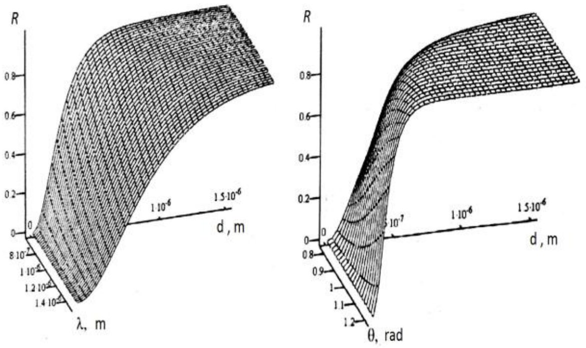

Fig. 2. Reflectivity dependence of mediums boundaries $R(\lambda,\theta,d)$ to magnitude of gap d

The variations of output power radiation can be evaluated by reflectivity of modulated boundary medium - power ratio of reflected radiation to the incident power. Since ψ may cause changes the gap d, the transfer function of PT is defined as that the output optical power is depend on changing of gap $P_{out}= f\{R[d(\psi)]\}$.

Transfer function is generally determined by dependence of reflectivity $R[d(\psi)]$ of interface "prism - air - SE" (P-A-S) to gap $d(\psi)$. By using an op-amp based transducer "current-to-voltage", the output voltage PU $U_{out}(\psi)$ can be represented as: $U_{out}(\psi)=(I_D+S_{PD}\cdot P_{OS}\cdot k\cdot\{R[d(\psi)]\})\cdot R_{I\text{-}U}$, where k – coefficient of optical losses; P_{OS} – optical power of OS, I_D – dark current of PD; S_{PD} – sensitivity of PD; $R_{I\text{-}U}$ – resistance in feedback loop of op-amp based transducer "current-to-voltage".

III. DESIGN PARAMETERS DETERMINATION OF TRANSDUCER BASED ON OTE

Methods of determining the design parameters of transducers are based on providing required range of sensitivity and, ensure the implementation of required measurement range of mechanical parameters ψ. At the same time it is necessary to select the range of gap variation depends on geometrical parameters of SE according to nominal value for supporting the quasi-linearity of transfer function and the range of gap d is determined by analysing the changes of transducers' sensitivity, which can describe as:

$$S(d)=\frac{R[d(\psi)+\Delta d(\psi)]-R[d(\psi)]}{\Delta d(\psi)}\ . \qquad (3)$$

Note that the sensitivity of transducers is not constant in the range of measurement and also varies due to design parameters. To provide high sensitivity and nano-range displacement while measuring mechanical parameters ψ, determined by design parameters, the region, where the sensitivity decreases more than n times of the maximum value, i.e. till $S=S_{max}/n$, for example, 3-times (fig. 3).

Reflectivity depends on incident angle θ, wavelength of radiation λ and distance. Deflective sensitivity becomes increase while increasing incident angle value. To maximize the range of deflection $w(\psi)$ of SE (about 1μm), it is necessary that the incident angle must be a few degrees greater than the minimum value θ_{min}, which can be defined as: $\theta_{min}= arcsin(n_2/n_1)$.

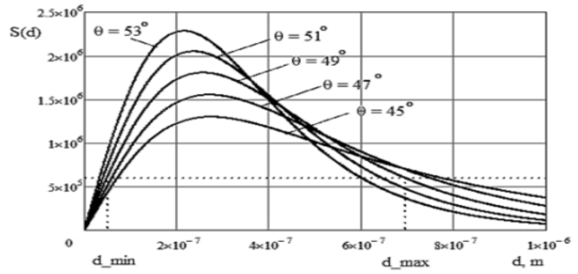

Fig. 3. Dependence of sensitivity to magnitude of gap

While developing the transducers based on OTE, by using fused quartz as the material of SE with air medium between SE and prism, the possible operating ranges of gap between the prism and SE d, the axial angle of incident radiation θ and wavelength of incident radiation λ, for example, around $d \approx 40...70$ nm, $\theta \approx 47^o...53^o$ and $\lambda \approx 0.7...1.4$ μm, respectively, can be selected.

IV. MODEL OF PRESSURE TRANSDUCER BASED ON OTE

For measuring pressure a transducer is possibly developed based on OTE with P-A-S system by using fused quartz. In this transducer SE may be constructed as membrane, which deforms under specific pressure p (fig. 4).

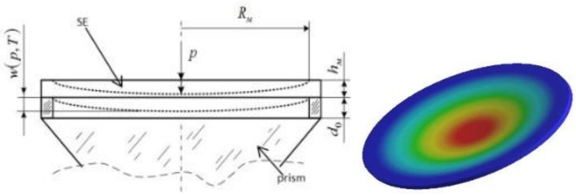

Fig. 4. Model of pressure transducer based on OTE

Under the influence of pressure (0…10MPa) the middle part of SE is deflected and, magnitude of this deflection also depend on temperature changes, which is taken into account by the Young's modulus $E_q(T)$ and Poisson's ratio $v(T)$ of material. Therefore, the deflection of membrane by pressure $w(p,T)$ is defined as [7-8]:

$$w(p,T)=\frac{3}{4}\cdot\frac{p\cdot\left[1-v(T)^2\right]}{E_q(T)\cdot h_M^3}R_M\,, \qquad (4)$$

where h_M, R_M – thickness and radius of SE.

This deflection $w(p,T)$ leads to variation of the distance d between the prism and SE, and thermal expansion of the material, which is ensuring the desired initial gap d_0. The distance d is defined as $d(p,T)=d_0+\Delta d_1(T)\text{-}w(p,T)$, where $\Delta d_1(T)=\alpha_L\cdot(T\text{-}T_0)\cdot d_0$ – the temperature variation of the distance d between the prism and the membrane; α_L – linear thermal expansion coefficient of the base, T_0 – room temperature (20°C).

Shape of transducer transfer function (dependence of output power of radiation to specific range of pressure, applied to SE) is determined based on two dependencies: reflectivity dependence $R(d)$ of medium (P–A–S) from the operating gap d, and dependence of the gap $d(p)$ to applied excessive pressure p.

To determine the total power of the reflected radiation P_{PD} it is necessary to consider the inequality of gap, occurred due to hemisphere shape of SE deflection. If the light source creates a circular optical spot of radius r_{opt} on perpendicular surface, however it can be an elliptical area on modulating media boundary in this type.

Output power radiation P_{PD} is determined by numerical integration of the equation:

$$P_{PD} = E_0 \cdot \cos\theta \int_0^{2\pi} \int_0^{\rho_{el}(\varphi)} R(d(r)) \cdot r \cdot dr \cdot d\varphi, \qquad (5)$$

where E_0 – illumination of conditional perpendicular surface, $\rho_{el}(\varphi)$ – boundary of elliptic area, $\rho_{el}(\varphi)=a\cdot b/(b^2\cos^2\varphi+a^2\sin^2\varphi)^{0.5}$;$r$, φ – polar coordinates of optical spot area, a, b – axis of the ellipse ($b=r_{opt}$, $a=r_{opt}/\cos\theta$).

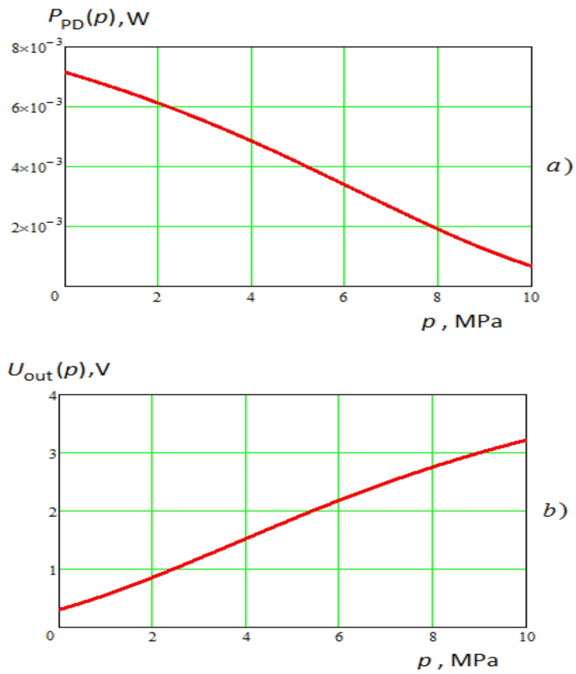

Fig 5. Dependence of optical radiation power (*a*) and the output voltage (*b*) on the pressure *p* = 0 ... 10 MPa.

To provide the required SE deflection during the applied pressure in the range of 0…10MPa the design parameters are selected. (e.g., R_M= 1.5 mm, h_M= 0.745 mm, θ=51°, λ=1.3 µm, P_{SO}=10mW, S_{PD}=0.4, R_f=1kOhm and d=0.05µm). Using the above parameter the output optical power P_{PD} (fig. 5a) and output voltage $U_{out}(p)$ (fig. 5b) are determined.

V. MODEL OF ACCELERATION TRANSDUCER BASED ON OTE

Several features of acceleration transducer based on OTE are considered. SE of this transducer may be made of quartz glass for reducing additional temperature error and, in most applications, and the operating range of the deflection sensing element transducer based on the OTE is only fraction of a micrometre.

As the sensing element in the transducer of acceleration can be used quartz beam of small size, fixed at one end or quartz beam of small size, fixed at both ends but sensitivity to lateral acceleration these models could be effected the measuring process i.e., lateral acceleration effect at beam, fixed at one end is greater than 1/3 times greater than the beam, fixed at both ends.

In the acceleration transducer based on OTE as SE for reducing the sensitivity to lateral acceleration on the other axis become main disadvantage. Therefore, it is suggested to use four beams element SE, fixed at all ends, but the use of this SE without additional mass does not provide the required magnitude of the SE deflections, required to measure accelerations with high sensitivity in the selected measuring range ±10g. Therefore, in the schematics diagram of acceleration transducer is used a body with additional mass m_{add}, fixed in the central part of the SE. Diagram of MOEM acceleration transducer consists of prism, base, SE, air gap, additional mass (fig. 6). Under the influence of acceleration SE is deflected along OZ axis, and displacement magnitude of central part of SE of MOEM acceleration transducer with additional mass $w_4(a_z)$ is a function of parameters set [9-11]:

$$w_4(a_z) = \frac{12 \cdot \rho_q \cdot a_z \cdot l_4^4}{1536 \cdot E_q \cdot h_4^2} + \frac{12 \cdot m_{add} \cdot a_z \cdot l_4^3}{768 \cdot E_q \cdot b_4 \cdot h_4^3}, \qquad (6)$$

where E_q – Young's modulus of quartz, $J= b\cdot h^3/12$ – moment of inertia of a quartz beam, a_z – applied acceleration along axis OZ; m_{add} – additional mass; l_4, h_4, b_4 – length, thickness and width of four beam SE respectively.

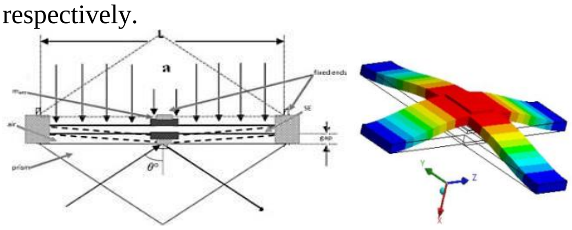

Fig. 6. Schematic and SE model 3D of MOEM acceleration transducer

The magnitude of the gap $d(a_z)$ depends on the displacement of the central part of the SE, and it is determined by taking into account the initial gap d_0: $d(a_z) = d_0 - w_4(a_z)$. Assume that the magnitude of the gap between the central part of a SE and the prism is constant along the modulation boundary of prism by mounting undeformable additional mass m_{add} at the centre of SE. The transfer function of accelerations transducer is the dependence of output voltage to acceleration magnitude, which have such form: $U_{out}(a_z)=[I_D+S_{PD}\cdot P_{PD}(R[d(a_z)])]\cdot R_{I\text{-}U}$.

Dependences of deflection of SE (a), reflectivity of transducer (b) and output power and output voltage (c) to acceleration a_z were determined at the following selected parameters: initial gap d_0 = 0.45 µm, length

l_4= 4 mm thickness h_4 = 0.28 mm, the refractive index of the prism n_1 = 1.46; the refractive index of SE n_3 = 1.46; separation medium - air ($n_2 \approx 1$); the incident angle $\theta = 49^0$ (fig. 7).

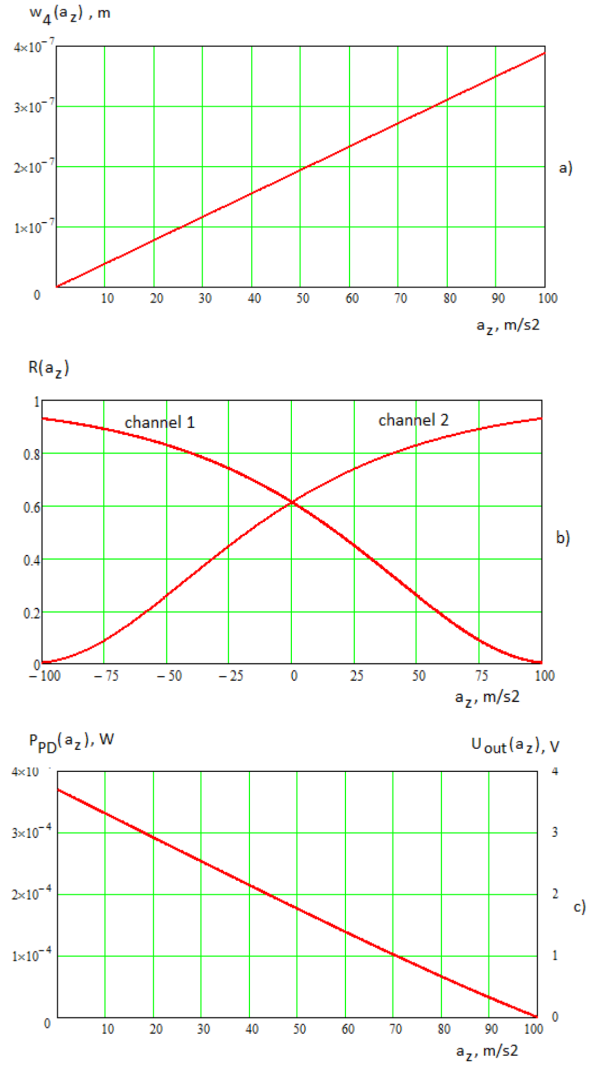

Fig. 7. Dependencies of SE deflection (*a*), the reflectivity of two channel transducer (*b*), optical power and output voltage (*c*) to acceleration a_z

According to the graph, the investigated model of MOEM acceleration transducer possesses transfer function, which provides quasi-linear characteristics within measuring range ±10g. In order to improve the linearity of the transfer function output optical signals with two readout channels by using additional prism, mounted symmetrically with respect to the central part of the SE, can be arranged.

VI. OPERATION OF TRANSDUCER BASED ON OTE WITH ADJUSTABLE MEASURING RANGE

In the transducers with adjustable measurement range SE restrains itself by the base, represented as piezo-ceramic actuator, which is feed controlled voltage with feedback circuit (fig. 8). Output signal, applied with feedback circuit to piezo-actuator at the expense of reverse piezoelectric effect changes the linear dimension of piezo-actuator, which leads to the change of gap in the contact region of optical radiation to the structure P-A-S. As a result of reflectivity this structure becomes function of output voltage. In case of feedback operating feedback leads to the expansion measurement range, which can be changed by adjusting the parameter of feedback circuit [12-16].

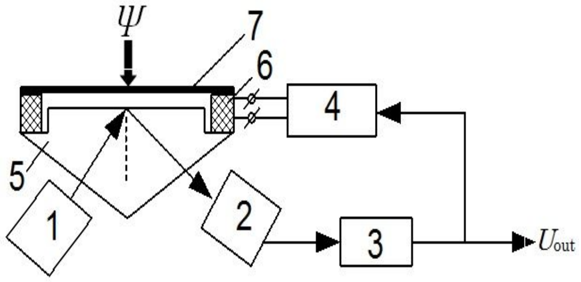

Fig. 8. Model of transducer with adjustable measurement: *1*– OS, *2* – PD, *3* – I-U, *4* – voltage amp, *5* – prism, *6* – piezo-ceramic element, *7* – SE

The gap magnitude of structure is determined by initial gap d_0, SE deflection $w(\psi)$ and variation of gap due to the effect of feedback $\Delta d_0(U)$:

$$d_{fed}(\psi, U) = d_0 - w(\psi) + \Delta d_0(U) \quad . \qquad (7)$$

Dependence of output voltage to measured parameters in account of total loss k can be presented as:

$$U_{out}(\psi) = \{ I_D + S_{PD} \cdot P_{OS} \cdot k \cdot (\mathrm{R}[d_{fed}(\psi, U)]) \} \cdot R_{I\text{-}U} \,. \qquad (8)$$

Dependence of U_{out} to d_{fed} can be calculated for several value of incident angle θ, which is significantly nonlinear. Since sensitivity to variation of gap, possessed extreme value, decrease at small and large gap on several orders of magnitude compared to maximum value, it can be increased the measurement range of transducers. By decreasing incident angle maximum sensitivity is reduced and observed at large gap value, but it is increased the range, in which variation of sensitivity is not exceed predetermined value. The sensitivity to variation gap is not decreased by more than two times compared with maximum value at the selected quasi-linear section, it can be calculated the measurement range and determined the transfer function of those transducers.

VII. CONCLUSIONS

The study on the operating principle and schematic diagram of MOEM transducers based on OTE is presented in the current paper. Mathematical models of transducers and analytical formula of transfer functions are formulated. By using negative feedback circuit with piezo-actuator as base of transducers measurement range can be extend significantly.

The several geometrical designs of pressure and acceleration transducer sensing element are investigated. To provide higher sensitivity, magnitude of initial gaps and geometrical design parameters for each transducer are defined. The transfer functions for measuring pressure and accelerations provide quasi-linear characteristics within the calculated region of measurement and such types of transducers can be used in measurement and control systems.

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