The development of the bistable micromechanical actuator for optical relay

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Abstract. In this work is presented the results of the development of the bistable micromechanical actuator for optical MEMS switch, whereby the mentioned actuator is fabricated on the bulk technique of the microsystems engineering. The influence of local profile stiffening on the dynamic behavior of the arch-shaped suspension was experimentally and theoretically researched. This paper is described theoretical and experimental results, obtained during numerical simulation and measuring of the optical switch amplitude-frequency dependence for AC and DC control voltage. Using dynamic methods gives an option of reducing control voltage level.

1. Introduction
In recent decade, microelectromechanical systems (MEMS) became widely used as switching equipment components, specifically, electrical and optical relays and switches. The differential feature of such components consists in the absence of optoelectronic conversion of the switching signal, low input power, miniature overall size, low weight and fabrication cost. The switching of the optical signal is performed by the electromechanical system, which enables micromirror motion in the optical channel. The key component of such systems is flexible beam suspension. The vast majority of flexible suspensions of micromechanical structure are linear elements, wherein linearity provides easy energy conversion. More interest is generated in nonlinear stiffening elements. The reason of the interest in nonlinear suspensions is the opportunity to build multistable systems. Special attention is given to arch-shaped suspensions, which profile is determined by the shape of the mechanical stability loss. Nonlinearity of such suspensions is conditioned by the spur increase of the axial load under lateral beam load [1]. Such structure has two mechanical power minimums, in other words, has two stable states. The presence of two power minimums is determined by stability loss. However, there is bifurcation irregularity in such systems, in other words, significant difference between potential well depths of the first and the second stable states [2]. The method of the local stiffening of arms of the arch-shaped suspension is used to increase the state stability [3]. To ensure effective switching performance between stable states, dynamic methods with AC and DC control voltage are used. The resonance frequency of the control voltage has amplitude-dependent characteristic.

2. Development of design and fabrication method
The bistable actuator of the optical relay is the microelectromechanical system (Fig. 1), designed to perform the optical switching through optical fiber channels. The signal switching process is realized by stopping or passing the optical signal by the micromirror displacement (Fig. 2). The micromirror displaces by 38 μm, which allows arranging the optical signal transmission. The distance between the
optical fibers is 40 μm. In order to reduce the losses the collimating microlens is formed at the optical fiber end using wet etching method [4], herewith, the optical losses amounts 0.7 dB.

The micromechanical system of the actuator is fabricated on the bulk technique of the microsystems engineering using deep reactive-ion etching (DRIE). Furthermore, DRIE provides one-cycle formation of the micromechanical system as well as the channel for optical fiber, which significantly simplifies the positioning of the optical system. As a structural layer the single-crystal silicon is used, fixed on the glass substrate using the anode merging method. The structural layer thickness is chosen based on the optical fiber diameter (125 μm) and equals 90 μm. The mechanical structure is released by the etching of the glass substrate, herewith, forming the cavity for the deep mounting of the optical fiber.

The main element of the bistable micromechanical actuator is the nonlinear flexible suspension (arched beam), where the availability of two stable states is conditioned by the mechanical stability loss. The heavy increase of the axial load on the beam under the lateral load leads to the formation of two mechanical energy miniumms. The lateral load is forming at the central section of the arched beam by joining the comb actuator. To eliminate non-symmetrical (rotational) buckling mode the flexible suspension is made of two arched beams attached in parallel. For said arched flexible elements the small depth of the second potential hole and asymmetrical load values of bifurcation points are common [2]. In order to increase the mechanical stability of the second stable state, method of the local stiffness increase of the arched beam was applied, the beam profile has irregular longwise thickness (Fig. 1). This method allows significantly increasing the ratio between the upper and the lower levels of the mechanical energy near the second stable state (Fig. 3). Herewith, the absolute value of the upper mechanical energy level depends less on the element thickness [3].
Figure 3. The dependence of the potential energy from the actuator displacements.

The electrode system of the actuator comprises two opposite systems of comb actuators and has nonlinear behavior. The profile of the comb electrodes is also formed having irregular thickness, which provides the gap changing between electrodes surfaces when the actuator moves. The changeable gap allows reducing the load level after abrupt switching, which reduces the probability of the rebound motion when the voltage rapidly releases, and simplifies the electrical control system. Furthermore, the changeable gap provides the better penetration of the etching components and DRIE reaction wastes ejection, which simplifies the etching of narrow cavities at the small deviation of the specific capacity of the actuator [5].

3. Experimental studies

3.1. Studies of the static behavior

To perform the experimental study on the bistable actuator the prototypes were fabricated. To measure the displacements optical and electrical methods were used involving capacity-voltage converter, which allows recording changes of the capacity of the comb structure of the actuator when moving. Herewith, the DC voltage was applied to one of the arrays of the comb actuator, and the capacity was measured at the opposite one. The actuator displacement and action forces of the flexible suspension are shown in Figs. 4–5. The experimental results show effective conformance with the analytical dependence and computational model of the flexible arched suspensions [3].

Fig. 4 depicts the dependence of the force for the arched beam with regular profile thickness; the non-symmetry with respect to the zero of the displacement force is clearly seen. The use of the irregular profile beam allows increasing the symmetry of the characteristic points of the displacement and stability of the second stable state (Fig. 5).

In the process of this research the switching rate of the actuator was defined: 1.5 ms to block the optical channel (Up) and 2 ms to open the optical channel (Down). Herewith, the local increase of the stiffness of the flexible suspension brings switching time closer as well: 1.25 ms to block the optical channel (Up) and 1.3 ms to open the optical channel (Down). The transient processes are shown in the Figs. 4–5 as well.
3.2. Studies of the dynamic behavior

The method of the local increase of the stiffness of the arched suspension leads to the increase of the actuator switching load and control voltage. Dynamic switching methods can be used to decrease the control voltage [6]. Herewith, to control the actuator we use resonant signal step-up, excited by the AC voltage with addition of the DC bias voltage. The system of the arched flexible suspension has quadratic and cubic nonlinearities, in other words amplitude dependent resonance frequency [7].

To define the frequency characteristic the prototypes of the optical relay actuator were tested under variable load. The oscillation excitation performed by the AC voltage without DC bias allows achieving the separation of the mechanical oscillations from electrical actuating signal. The frequency of the electrical actuating signal equals to the half of the self-resonant frequency of the actuator.

To provide the quality oscillations the resonator was placed in the vacuum chamber. The quality was defined based on the bandwidth amplitude-frequency response of the resonator under different pressure and small actuating voltage (from 1–0.05 V) (Fig. 6). The actuating voltage value was chosen based on the limits of the linear response range of the resonator. At the high amplitude of the AC voltage (5–10 V) the frequency dependence has clearly nonlinear dependence (softing) (Fig. 7). The characteristics available from experiments correspond to the theoretical dependencies.

Figure 4. The dependence between the force and displacement, and the transient process of the arched beam with the regular profile thickness.

Figure 5. The dependence between the force and displacement, and the transient process of the arched beam with the irregular profile thickness.

Figure 6. Quality – pressure dependence of the resonator oscillations.

Figure 7. The frequency response of the bistable actuator with the arched suspension $U_{ac} = 5 \, \text{V}$.
The amplitude and phase characteristic of the actuator of the optical relay under different load at decreasing frequency is shown in Fig. 8. Herewith, the failure of high-quality oscillations occurs at the phase change much lesser than 90°, and doesn’t depend on the oscillation amplitude. It can be explained by the increase of the oscillation sensitivity to the frequency slew rate of the AC signal.

When measuring the frequency response of the resonator with AC actuating voltage with DC bias, a disturbance on the measuring electrodes can be observed from the electrical actuation signal. The obtained amplitude-frequency characteristics are shown in Fig. 9. Herewith, the resonance frequency bias is observed within 1.35 kHz range at the bias voltage $U_{dc} = 45$ V.

**Figure 8.** The amplitude and phase characteristic of the actuator of the optical relay under different load, and voltage $U_{ac} = 5$ V; Sweep down by frequency

**Figure 9.** The amplitude and phase characteristic of the actuator of the optical relay at voltage $U_{ac} = 5$ V and different bias voltages.

By using the obtained frequency dependences we can provide significant reduce of the control voltage when exciting the oscillations by the AC voltage with the DC bias. The nonlinear behavior of the resonator oscillations allows exciting the oscillations with the frequency, which significantly differs from the self-resonant frequency within the linear response range. The AC voltage frequency is defined by the frequency at which the jump of the amplitude frequency dependence occurs for the correspondent bias voltage. When the bias voltage is absent, the forced oscillations don’t lead to the significant increase of the oscillations of the micromirror, as well as the bias voltage doesn’t lead to its switching. After the abrupt switching to the second stable state, the resonance oscillations decay due to the resonance frequency change.

In the process of the testing the micromechanical resonator was excited under atmospheric pressure by the voltage at the frequency of 4.6 kHz and amplitude of $U_{ac} = 10$ V. The quality of the mechanical resonator in this case amounts 40. The supplying of the bias voltage of 50 V leads to the abrupt switching and displacement of the micromirror to the second stable state. In order to decrease the pressure the resonance system was placed in the vacuum. As it is seen in the Fig. 8, the quality increase for the nonlinear oscillations doesn’t lead to the significant increase of the amplitude, as it is for the linear systems. At the quality factor of 8000 the switching between the stable states is provided at 35 V of the DC bias and 5 V of the AC voltage.
4. Conclusion
In the process of this research, the dynamic characteristics of the bistable electromechanical optical switch were studied. Experimental and numerical results demonstrate that the system of the arch-shaped suspension has quadratic and cubic nonlinearity. Herewith, the initial profile of the arch-shaped beams and external and internal axial loads are overriding factors, which determine the behavior and nonlinear features of the arch-shaped beams. The use of the dynamic methods to perform switching makes it possible to reduce control voltage level.

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