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A SYSTEM FOR PRECISE LASER BEAM ANGULAR STEERING

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Abstract

A system for precise angular laser beam deflection by using a plane mirror is presented. The mirror was fixed to two supports attached to its edges. This article details the theoretical basis of how this deflector works. The spring deflection of a flat circular metal plate under a uniform axial buckling was used and the mechanical stress was generated by a piezoelectric layer. The characteristics of the deformation of the plate versus the voltage control of the piezoelectrics were examined and the value of the change resolution possible to obtain was estimated. An experimental system is presented and an experiment performed to examine this system. As a result, a resolution of displacement of 10^{-8} rad and a range of 10^{-5} rad were obtained.

Keywords: laser beam angular drifts, beam deflector, laser beam scanning.

1. Introduction

The spatial stability of the propagation direction of a laser beam is vital for measurement and production techniques. In the field of metrology, this concerns a number of systems, including those where the axis of the beam is the reference, e.g., measurements of straightness. The beam's propagation direction also influences the precision of length and displacement measurements, e.g., for interference devices (laser interferometers), for time of flight methods (laser trackers, laser distance meter) and for devices that use spatial scanning with a laser beam, such as laser triangulation methods with scanned line technique and scanning microscopes (atomic force microscopes) where the measurement basis is the measurement of the angular deviation of the laser beam reflected by the measurement probe (a cantilever).

The angular stability of a laser system and the active beam displacement compensation is often the main limiting factor in achieving application precision. The axis instability of an angular laser beam can reach up to 20 µrad per hour in laser interferometer systems. The normalized method [1] of determining the angular changes in the position of the beam axis uses the measurement of the centroid of the beam. The information about this displacement may be used to compensate the angular displacement of the beam [2].

There are numerous methods used for the angular control of the beam: a wedge [3] and window [4], a tilt mirror [5–10] a mirror matrix [11,12] and a diffraction grating generated by liquid crystals [13]. Only those systems that do not cause distortion of the beam wavefront, such as tilt mirrors [5, 8–10] or wedges [3] can be applied in interference displacement measuring systems. Systems based on a mirror stilted by piezoelectric elements are usually used owing to the possibility of controlling them with a voltage. They are also highly precise [5, 10]. Their angular positioning resolutions are no higher than a few microradians. In Micro-Electro-Mechanical-Systems (MEMS) applications there is a number of solutions, by which a lateral strain in a piezoelectric material film is converted to a vertical deflection through membrane deformation [6, 7, 12].

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It is particularly difficult to obtain small deflections – smaller than a tenth of a microradian – in angular control of a laser beam. In this article, a system is proposed that allows control of the direction of the laser beam with a degree of precision never before obtained; a precision of nanoradians for a small range of deflection. The change of direction of the beam is obtained by a deflection of the mirror which reflects the beam. To control the mirror, the deflection of a metal plate occurs under strain in the piezoelectric layer.

2. The concept of the laser beaming system structure

The system described below is intended to deflect the laser beam in order to compensate its unwanted angular fluctuations. The task of this work was to assure the deflection range of the beam reached 10^{-5} rad and that the resolution approached 10^{-8} rad.

It was proposed to use a piezoelectric actuator in the form of a round metal plate with a thin (0.2–0.3 mm) piezoelectric layer. This actuator operates as the active element which deflects the mirror. One of the electrodes that biases the element is the metal base and the other is the metallic coating applied to the top of the piezoelectric layer. The applied voltage creates an electric field normal to the element's surface. Because of an inverse piezoelectric effect, the piezoelectric layer extends towards the direction of the electric field's action and its dimensions are reduced in the other directions. The stress that occurs in the base plate because of the deformation of the active layer may be divided into two components. The longitudinal component of the stress causes axial deformation of the metal plate. The transversal component of the stress vector does not influence the geometry of the system (Fig. 1a).

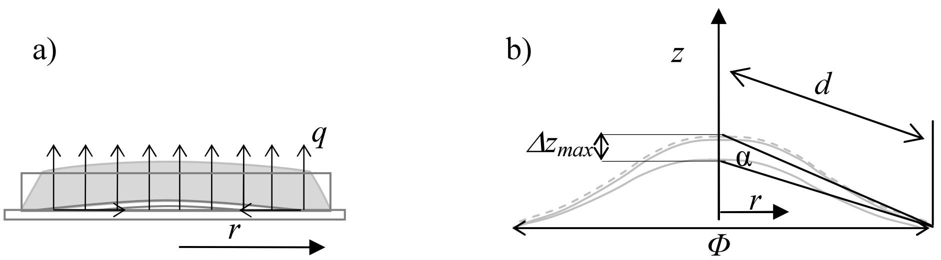

Fig. 1. a) Active component of the stress, b) deformation of the piezoelectric element.

For the proposed solution, the plate is fixed in a circumferential way and can be considered as an evenly loaded circular symmetrical plate according to the Kirchhoff's plate theory. Assuming a uniform distribution of stress q in the direction normal to the surface of the piezoelement, the equation of the deflection line z (Fig. 1b) is described by a fourth degree polynomial function [14]:

$$z = \frac{q}{64D}\left(\Phi^2 - r^2\right)^2, \tag{1}$$

where q represents the stress on the active part (force on surface), D − the plate stiffness of the element, r − the distance from the element's centre, Φ − the diameter of the plate and the support. The elongation of the piezoelectric layer in the direction normal to the surface is related to the proprieties of the material's piezoelectric layer.

Micro−deflection of the mirror is achieved by the difference between displacements of its edges along the axis transverse to the piezoelectric element plane. One of the two edges is supported in the piezoelectric element centre and the other is fixed to its edge. The outer mirror's support is placed outside the active area of the element, at a distance of $\Phi/2$ from its centre. The angle of change can be described as:

$$\alpha = \frac{2\Delta z_{\max}}{\Phi}, \tag{2}$$

where Δz_{max} is the total deformation resulting from the surface's deflection and the lengthening of the piezoelectric structure in the centre of the element.

If supports of a sufficient height are used, then the angle of change can be described by the coefficient difference of the directional lines connecting the mirror's support points.

3. Examination of the piezoelectric element with regard to the possibility of controlling the beam

A piezoelectric element FT-35T-2.6A1 produced by Kepo Electronic Co. Ltd. was used for the construction of the experimental beam-bending device. It is produced as a round brass plate with a diameter of Φ = 35 mm. The plate was covered with a 0.2 mm thick piezoelectric layer with a diameter of 25 mm. The piezoelectric active layer is covered with a conductive metal of 23 mm diameter on its surface. The voltage supply range of the element is up to 30 V. The metal base is also the bias electrode.

3.1. The estimation of the range of angular displacements of the centre of the plate, based on the piezoelectric element shape deformation

In order to estimate theoretically the predicted range of the angular displacement, a registration of profiles of the piezoelectric element surface for supply voltages of 5 and 15 V was performed. The examples of the experimental results are presented in Fig. 2. Note that the observed deformations are 10 times smaller than the element's dimensional inaccuracy, which is why the element deformations have been analysed statistically.

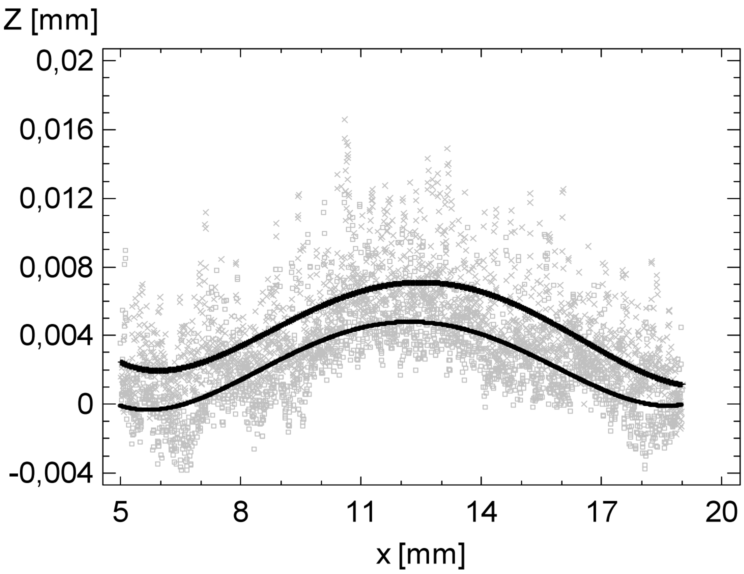

Fig. 2. The deformation of the piezoelement for voltages of 5 and 15V.

For the obtained profile (Fig. 2), the points marked by squares for the voltage of 5 V and by a star for 10 V were fitted with fourth degree polynomials, according to the dependence (1):

$$z = c_0 + c_1 \cdot x + c_2 \cdot x^2 + c_3 \cdot x^3 + c_4 \cdot x^4 \tag{3}$$

The parameters of the polynomials for the voltages of 5 and 10 V are presented in Table 1.

Table 1. Parameters of the regression model for the voltages of 5and 10V.

Voltage	Parameter of model	Estimate	Standard Error
5 V	c_0	0.0441	0.0033
	c_1	-0.0192	0.0012
	c_2	0.00287	0.00016
	c_3	-0.000169	0.000009
	c_4	0.0000034	0.0000002
	c_0	0.0371	0.0035
15 V	c_1	-0.0154	0.0013
	c_2	0.0023	0.00017
	c_3	-0.00014	0.00001
	c_4	0.0000027	0.0000002

The fitting was made for the 15 mm central part of the range that had the smallest shape deviations (smaller than 10 µm).

Taking into consideration the difference between the coordinate Δz_{max} of the maximum of the fourth degree polynomials, the change of the deformation of the element in its centre was estimated to be 0.0023 mm. The uncertainty (for the 95 % confidence level) of the estimation of the coordinate difference in the maximum curve adjustment is estimated approximately to be 0.1 µm. The change of the coordinate for the second support, placed 15 mm from the plate's centre and 2.5 mm from its edge was of the order of 0 ± 0.5 µm. Therefore, the change of the slope angle of the mirror's surface for the distance of its supports was determined as 15 ± 0.1 mm. For the voltage difference of 10 V, according to dependence (1), it will be of $(1.5 \pm 0.3)\cdot 10^{-4}$ rad. The displacement of the surface resulting from the piezoelectric material in the Z-axis is negligible. For typical piezoelectric materials, the d_{33} constant varies within the range of (300 ÷ 700) pC/N. For the element and the voltage range used, the resulting increase of length is three orders of magnitude smaller than the plate's deformation.

A similar result was obtained when the estimation of the angle assumption was made based on the difference of the directional coefficient of the straight lines fitted to the coordinates x on the section 12.5 to 25 mm. This section is assumed for the range where the piezoelectric layer is present. Outside of it, the Z coordinates are on the level of the brass base (approximately -0.25 mm).

For the voltage of 5V, the slope of the line was 0.00016 rad and for 15 V it was − 0.00033 rad. The change of the slope angle calculated on this basis was $(1.7 \pm 0.2)\cdot 10^{-4}$ rad.

The above estimations, based on the examination of the plate, allow the conclusion that the deformation of the used element is sufficient to ensure angular displacements of the mirror for the scope of roughly one-half angular minute.

3.2. Direct measurement of the deflection element as a function of biasing voltage

Direct measurement of the voltage characteristics was performed on a cylindrical support glued to the element's surface. A mirror was later mounted on this support.

The measurement objective was to determine the dependence between the deformation caused by the voltage for the real placement of the support. The element was supplied with voltages ranging from 2.5 to 20 V with steps of 0.5 V.

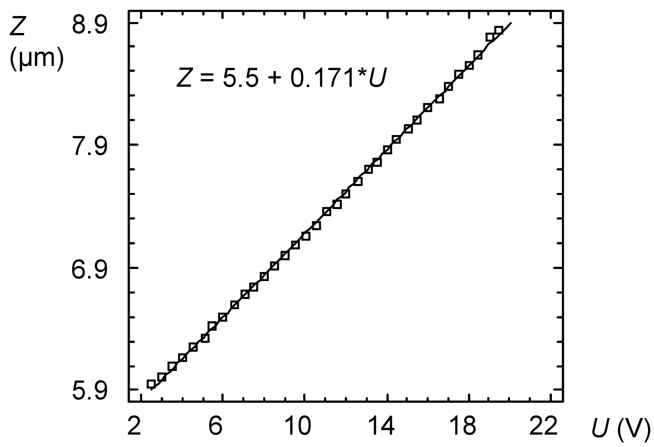

Fig. 3. Dependence of the slope along the element's axis as a function of applied voltage.

The obtained characteristic (Fig. 3) is linear with a slope coefficient of $\beta = 0.171$ µm/V and an R-squared coefficient equal to 99.94 %.

The angular deflection of the mirror can be represented as:

$$\alpha = \frac{\beta \cdot U}{d}, \tag{4}$$

where U stands for the controlling voltage and d represents the distance between the supports of the mirror.

The value of 1.7 µm/10 V differs from the value obtained during the plate deformation analysis (2.3 µm/10V). The cause of the difference might be the registration of the voltage characteristics at a point other than the element's axis. The value of $\beta = 0.171$ µm/V was adopted for further calculations because the characteristics measurement was performed in the mirror's support. The uncertainty of the β coefficient determination was estimated to be $u_\beta = 0.001$ µm /V.

3.3. Hysteresis of the piezoelectric actuator

In further research on the possibility of using a piezoelectric plate for the proposed application, an attempt to register its hysteresis, typical for piezoelectric elements [15], was made. A deflection along the element axis was observed three times. Measurements were taken for voltages ranging from 5 to 9 V using ascending and descending deformations marked in Fig. 4 by × and ▫, respectively.

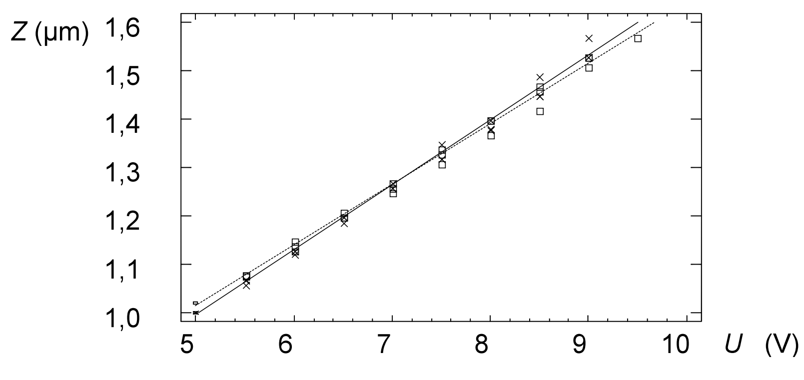

Fig. 4. Deflection of the plate's axis versus voltage for both directions of the deformation.

The statistical analysis of regression did not show any significant coefficient differences of linear regression for either direction. Therefore, the random variability in this case is larger than the value of hysteresis that is possible to be observed.

3.4. Estimation of the possible positioning resolution

In order to determine the possible positioning resolution of the angular mirror, it was determined with what resolution it might be possible to change the location of the surface in the centre of the piezoelectric element as a function of the given voltage.

The displacement of the centre of the plate was measured by a TH-PGI 830 profilometer with a resolution of 0.8 nm and with the level of environmental oscillation in the range of 20 nm. An example of the results is shown in Fig. 5.

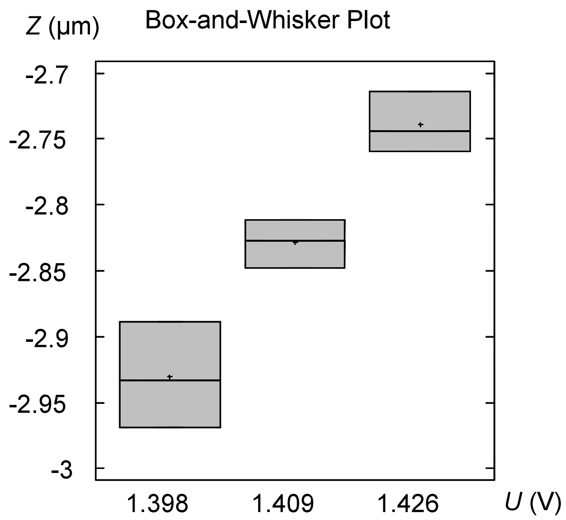

Fig. 5. Excitability threshold of the piezoelectric element for a given voltage.

For the abscissa, the central line is a median of three coordinate results of the axis placement, the scope marked in grey refers to the dispersion of the results and the cross mark shows their average values. The voltage values marked on the ordinate axis were given approximately every 10 mV; the real set value being read directly from the device. The obtained results differ statistically, which allows us to assume that the change of the element's surface position is greater than the random effects of oscillations and voltage instability. The smallest displacement possible to be observed was 8 nm for the given voltage difference of 10 mV.

The obtained positioning resolution for the Z-axis allows the expectation that the angular control of the mirror supported on the length of d = 15 mm will allow displacements with a resolution equal to approximately 10^{-7} rad. This resolution can be better for the accomplished device, because the excitability threshold obtained experimentally was subjected to the uncertainty of changes of the applied voltage and to the influence of disturbing vibrations.

4. Setup and examination of an experimental system for steering the angular micro deflection of the laser beam

In Fig. 6, an outline of an experimental system for steering microdeflections of the laser beam is represented. A flat mirror (1) is subjected to an angular deflection. The element steering the deflection is a piezoelectric element (2). The mirror was glued to two steel cylindrical supports, which were earlier glued to the surface of this piezoelectric element. One of the supports is placed in its middle and the second near its edge, at a distance of d = 15 mm from the axis and 2.5 mm from the edge.

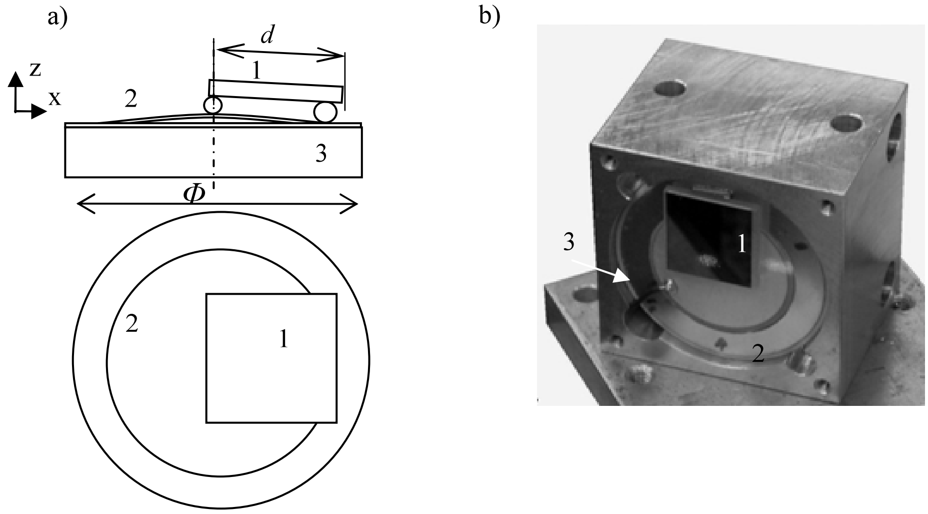

Fig. 6. a) The structure of the beam-deflecting device, b) the device without its front panel.

The piezoelectric element was mounted in a circumferential way to the front of a rigid ceramic ring (3). The diameter of the circle supporting the element is Φ = 35 mm. The system was located in a specially designed casing, which ensured a stiff mount of the ceramic ring and a power supply to the piezoelectric element. The system is bound to the exterior support such that the system can induce horizontal and vertical deflections.

5. Analysis of the device's proprieties

5.1. The deflector's sensitivity

To evaluate the metrological proprieties of the elaborated deflector, an analysis based on the measurements of angular microdeflection was performed. During the experiment, a sinusoidal voltage of given amplitude was used to control the piezoelectric element. At the same time, the change in the deflection angle was registered. A new interferential method, described in the patent application [16], was used for measuring the angular drift of the beam. The interferential device was calibrated initially with a laser interferometer in a configuration for angular deflection. The use of an innovative device for registering the beam deflection was necessary because such high resolution is not provided by any other methods. In Fig. 7, examples of the signals registered on the oscilloscope are represented: the piezoelectric controlling signal (channel 1, upper) and the output beam deflection measuring device signal (channel 2).

As the oscillogram shows, the amplitude of the voltage controlling the piezoelectric element is 4 V and the frequency is 4 Hz. The interferentially measured value (3 V) of the amplitude of the laser beam drift is $(4.0 \pm 0.3) \cdot 10^{-5}$ rad. For the control voltage of 4 V and the given construction data of the device, the theoretical value of the beam's deflection calculated based on dependence (4) should be $(4.6 \pm 0.3) \cdot 10^{-5}$ rad. Its uncertainty was estimated for the uncertainty of determining the slope coefficient u_{β} = 0.001 μm/V, the uncertainty of determining the voltage amplitude u_U = 0,1 V and the uncertainty of designing the supports distance u_d = 2 mm.

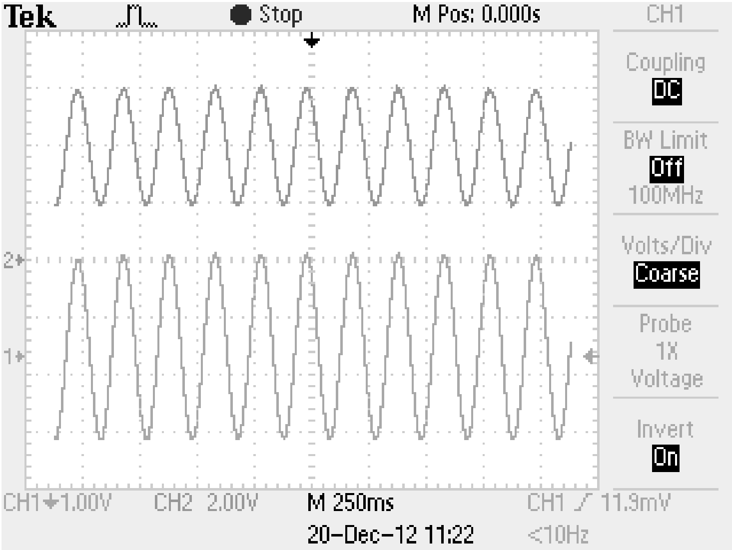

Fig. 7. Examples of registered signals: the device-controlling signal – channel CH2 and the interferometer's measuring signal [16] channel CH1.

A difference of over 10 % between these observations can be caused by many factors, deriving from the experimental characteristics of the test stand and in particular from the method of beam deflection measurement. At this stage of research, this difference is not significant.

The deflector is designed to compensate a slow deflection of the beam angle; therefore, the devices were tested at low frequencies up to 10 Hz. Preliminary tests have shown that the resonance frequency of this construction is 1.5 kHz, which is the upper limit of the bandwidth.

5.2. Resolution evaluation

As underlined at the beginning of this article, the purpose of the research described here was to develop a system that allows small angular deflections of the beam to be obtained. The results achieved in this area are illustrated by an experiment which determines how small the angular drifts generated in the constructed device may be. During an experiment similar to the one mentioned above, a sinusoidally changing voltage was given (Fig. 8; channel 2) and the output signal was observed (channel 3).

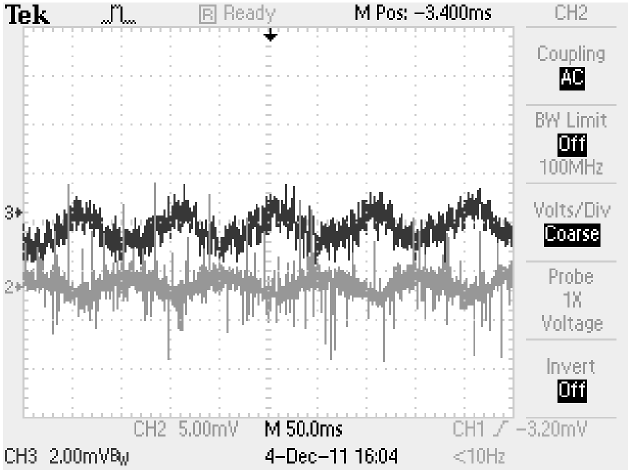

Fig. 8. Smallest interferometer measurement signal observed [16]- channel CH3- in response to the given changes – channel CH2.

The goal was to find the smallest value of the controlling signal amplitude that was visible in the interference device. Signals were identified by frequency (in this example 10Hz). For the 2 mV signal, a response of 2 mV amplitude was observed, which was calculated as a beam drift angle of $2.5\cdot10^{-8}$ rad.

6. Conclusion

A new solution for steering the angular laser beam deflection at high resolution is presented. The executive element in the transducer was a round metal plate with a piezoelectric layer. The plate was deformed transversally under the stress generated by the piezoelectric layer biased by the electric voltage. The plate's deformation caused a displacement of one of the two supports of the flat mirror and consequently, produced a change of the slope angle of its reflecting position. This solution allowed the control of the reflection angle of the light beam falling on the mirror's surface with a resolution of $2.5\cdot10^{-8}$ rad. The scope of the displacements it is possible to achieve in the example system is of the order of 10^{-5} rad.

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