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OPTICAL INFORMATION TECHNOLOGIES

Simple Positioner with Nanometer Reproducibility of the Focused Light Beam Position on an Object

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Abstract—A simple positioner, which allows one to ensure the position of a focused light beam on an object with nanometer precision and reproducibility, is proposed and studied. It can be used for positioning of focused beams (in particular, laser beams) on surfaces of optical fibers, biological objects, optical disks, thin film modulators, and holographic memory systems in the micrometer and nanometer ranges.

Keywords: positioner, adjustment, reproducibility.

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INTRODUCTION

The efficiency of radiation insertion, e.g., into optical light guides is the fundamental characteristic of the system consisting of the source of radiation and the fiber; the value of this parameter determines the optical power that can be imparted to the light guide. Moreover, high-accuracy positioning of a focused light beam on the surface of optical disks or holographic memory systems is extremely important for accurate and noise-immune readout of information from optical carriers [1].

Accurate positioning of a focused beam at the input end of the wave guide with a size of the order of several micrometers or, e.g., at a chosen place inside a biological cell is quite a challenge. This task is usually performed by using various adjustment devices for matching the light source with the object. There are many domestic and foreign publications and inventions that describe investigations of devices capable of positioning a focused light beam on various objects, in particular, at the input end of the light guide [2]. The problem is solved by using a three-dimensional parallelogram mechanism with elastically connected arms, where the section with a movable base is located relative to the section with a motionless base in a position that allows translational motion in two mutually perpendicular planes. The authors believe that the accuracy of positioning of the focusing lens in this device is provided by eliminating movable connections in the mechanical transmission between the adjusted elements and by replacing sliding friction in optical tables by elastic molecular friction in the parallelogram mechanism.

This solution only partly eliminates the drawbacks of mechanical positioners. In the above-described device, the motion of the lens with respect to the light guide (or vice versa, of the light guide with respect to the lens) is ensured by micrometer screw-type mechanisms where uncontrolled deformations of the oil film used for lubrication of the rubbing surfaces of the microscrews and inevitable backplay effects do not

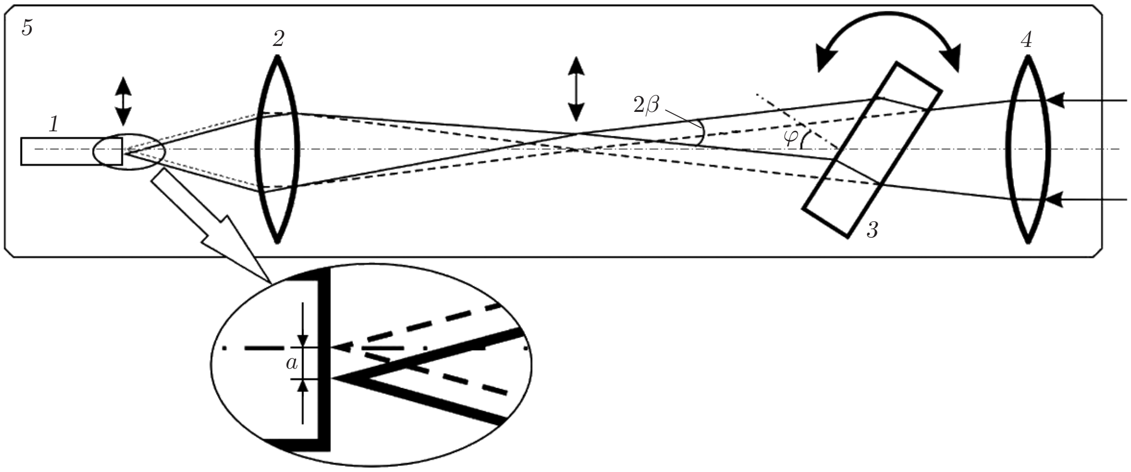

Fig. 1. Optical scheme of the positioner.

allow positioning of the focused laser beam at the end face of the wave guide within 10 nm. Moreover, the hysteresis phenomenon of the microscrews prevents reproducibility of positioning.

Bykov et al. [3] described a three-coordinate piezoelectric positioner. In this device, the object is positioned owing to application of electric voltage. A significant drawback of this device is the fact that its operation requires continuous control voltage and at least three high-voltage power sources. The hysteresis of the piezoelectric elements makes the required reproducibilities of positioning rather problematic.

There is also a device for mating a fiber light guide with a transmitter, which ensures positioning of a focused beam at the input end of the wave guide [4]. In that work, the focusing problem was solved by organizing small displacements of the focusing lens (or wave guide end face) in two directions across the laser beam ensured by precision microscrews.

The drawback of that engineering solution is the fact that such a level of accuracy is hardly reachable for mechanical positioners because of inevitable backplay effects in directing optical tables where the focusing lens or the fiber is fixed. The relative positions of the adjusted optical elements are affected by friction, wear, and errors of fabrication of movable parts involved into transfer of motion between the elements. Moreover, the presence of a hysteresis of microscrews makes multiple incidence of focused light onto a preliminary chosen point almost impossible.

In all devices considered above, uncontrolled changes in positioning are comparable with the error of device operation.

The goal of the present work is to determine the possible accuracy and reproducibility of radiation positioning by the proposed device both experimentally and theoretically.

OPERATION PRINCIPLES OF THE POSITIONER

The posed problem is solved by choosing an appropriate optical scheme of the device (Fig. 1). The main elements responsible for the accuracy, reproducibility, and wide range of positioning are the complementary (to the main short-focal-length lens *2*) long-focal-length *4* and the plane-parallel plate *3* placed between them. The distance between the lenses is much greater than the focal length of the lens *2*. The plane-parallel plate can rotate around two mutually perpendicular axes.

The motionless platform *5* accommodates the section with the positioning object, which has a moving base *1* in three mutually perpendicular directions. Accurate parallel shifting of the focus of the electromagnetic radiation beam is performed by rotating the plane-parallel plate, which is made transparent for electromagnetic radiation. The positioning process begins from preliminary matching of the object with the use of the moving base to the axis of the electromagnetic radiation beam. After that, all elements of the device are fixed. Subsequent rotation of the plate provides final and accurate adjustment of the electromagnetic radiation beam position. When the plane-parallel plate is rotated around one of the axes, parallel displacement of the beam occurs, and the first Airy disk formed by the lens *4* is shifted across the beam propagation direction. This, in turn, induces small displacements of the second disk on the optical

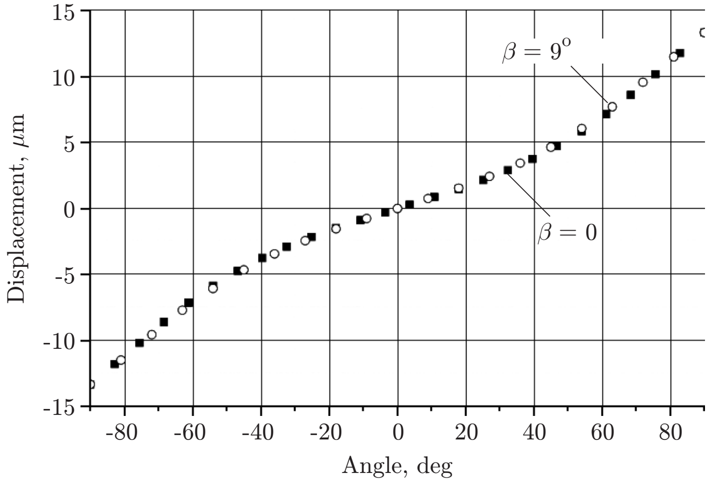

Fig. 2. Displacement a of the focused beam versus the angle φ of rotation of the plane-parallel plate.

object surface if the distance between the lenses is much greater than the focal length of the lens *2*. The displacement a of the focused beam is determined as a function of the plate rotation angle φ by the formula

$$a = d\Big\{\sin\varphi - \frac{1}{4\cos\beta}\Big[\frac{\sin 2(\varphi-\beta)}{\sqrt{n^2-\sin^2(\varphi-\beta)}} + \frac{\sin 2(\varphi+\beta)}{\sqrt{n^2-\sin^2(\varphi+\beta)}}\Big]\Big\}K, \tag{1}$$

where d, φ, and n are the thickness, rotation angle, and refractive index of the plane-parallel plate, respectively, 2β is the angle of beam convergence behind the focusing lens *4*, and K is the transverse demagnification of the lens *2*. The dependence $a(\varphi)$ is plotted in Fig. 2.

Formula (1) is valid for electromagnetic radiation beams propagating in a thin cone with an apex angle 2β (see Fig. 1). The dependence of a on β leads to distortions of the shape of the first Airy disk. However, there are practically no distortions at $2\beta < 1$. For the laser beam diameter of 5 mm on the lens *4* and focal length $F_4 = 150$ mm, the angle β is smaller than 0.017 rad. In this case, formula (1) can be expanded into the Taylor series with respect to the small parameter β:

$$a = K\Big\{d\Big(\sin\varphi - \frac{1}{2}\,\frac{\sin 2\varphi}{\sqrt{n^2-\sin^2\varphi}}\Big) +$$

$$+\,d\beta^2\frac{3}{4}\,\frac{\sin 2\varphi}{\sqrt{n^2-\sin^2\varphi}}\Big[1 - \frac{\cos 2\varphi}{n^2-\sin^2\varphi} - \frac{1}{4}\,\frac{\sin^2 2\varphi}{(n^2-\sin^2\varphi)^2}\Big]\Big\}. \tag{2}$$

The second term in Eq. (2) determines the magnitude of distortions of the first Airy disk. The maximum distortions are observed at $\varphi \approx 0.84$ rad, and their magnitude is less than $1.5 \cdot 10^{-4}$ of the thickness of the plane-parallel plate *3* (for $n = 1.52$). For the plane-parallel plate thickness of 10 mm, the distortions are much smaller than the size of the first Airy disk; for this reason, they can be neglected.

It is seen from Eq. (1) that the domain of displacement of the focused spot is directly proportional to the thickness d of the plane-parallel plate. Therefore, it is easy to provide a wide range of displacements by using several independent plates of different thicknesses rather than one plate. In the proposed device, the focal length of the lens *2* is chosen to be 2 mm, and the lens *4* has a focal length of 150 mm. The lenses are located at a distance of 300 mm from each other. In this configuration, the lens *4* with allowance for the divergence of laser electromagnetic radiation forms the first Airy disk with a diameter of 60 μm, while the section with a moving base reflects this disk on the object surface with a demagnification factor of 75 ($K \approx 2$ mm/150 mm) to a focus with a smaller diameter (about 0.8 μm).

In the general case, rotation of the plate should also induce a displacement of the first Airy disk along the optical axis. Let us show that displacement can be neglected. The general expression for the displacement of the first Airy disk along the optical axis has the form

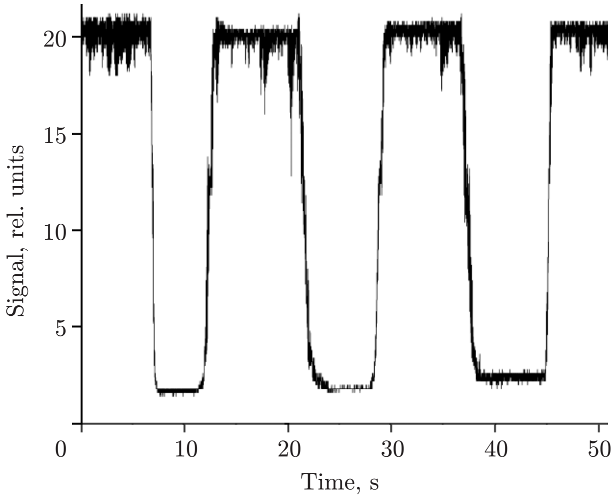

Fig. 3. Demonstration of positioner reproducibility on the basis of recording the intensity of light that passed through an orifice ∼1 μm in diameter. The minimums correspond to displacements of the focused beam outside the orifice due to plate rotation. The peaks correspond to positioning of the focused beam exactly on the orifice due to returning the plate to the initial position.

$$\Delta z = d\Big\{ -\cos\varphi + \frac{1}{4\cos\beta}\Big[\frac{\sin 2(\varphi-\beta)}{\sqrt{n^2-\sin^2(\varphi-\beta)}} - \frac{\sin 2(\varphi+\beta)}{\sqrt{n^2-\sin^2(\varphi+\beta)}}\Big]\Big\}. \tag{3}$$

Its expansion into the Taylor series with respect to the small parameter β can be written as

$$\Delta z \approx d\Big\{ -\cos\varphi - \frac{1}{\sqrt{n^2-\sin^2\varphi}}\Big[\frac{\sin^2 2\varphi}{4(n^2-\sin^2\varphi)} + \cos 2\varphi\Big]\Big\}. \tag{4}$$

The value $-1.7d < \Delta z < 0.85d$ is the longitudinal displacement of the position of the first Airy disk formed by the lens *4* as the angle φ is changed from $\pi/2$ to $-\pi/2$. The focusing lens *2* operating with a demagnification factor of 75 yields the longitudinal displacement whose absolute value is equal to the squared transverse displacement; correspondingly, the value of Δz behind the lens *2* becomes smaller than a micrometer (for $d = 10$ mm).

The proposed device is insensitive to displacements of the plane-parallel plate parallel to itself. Moreover, the angular backplay effect is minimized. It is seen in Fig. 2. Indeed, to ensure a 9-μm displacement of the focused spot, the plate with the chosen parameters ($d = 1$ mm and $n = 1.52$) should be rotated by 76°. Even if the angular backplay values are rather large (0.1–1°), this backplay induces a shift of the beam focus on the positioning object only by ∼(0.01–0.1) μm. Therefore, the ultimate accuracy of the proposed device in positioning focused electromagnetic radiation on the optical fiber end face, which can be reached after elimination of the effects of air turbulence and vibrations of mechanical elements, is very high. By choosing an appropriate thickness of the plane-parallel plate, it is possible to reach a desired degree of accuracy of the laser focus displacement on the object surface. The use of additional plane-parallel plates of different thicknesses in the nanopositioner will ensure expansion of the positioning range with the nominal accuracy being retained.

EXPERIMENTAL RESULTS FOR POSITIONING ACCURACY

The measurements showed that the displacement of the first focused spot across the electromagnetic radiation beam is ±500 μm for the plane-parallel plate thickness of 7 mm and the maximum rotation angle of the order of ±15°, which, in turn, results in a small displacement of the second spot approximately by ±8 μm.

The accuracy and reproducibility of the position of the focused laser beam were verified in a model experiment aimed at measuring the amplitudes of slow and fast variations of the intensity of light that passed through a small orifice in a metal film with an inner diameter of 1.7 μm. The beam of a He-Ne laser with a wavelength of 0.63 μm was used in the experiment.

Figure 3 shows an example of the time evolution of the intensity of light that passed through the orifice. By turning the plate by an angle of 45°, the light was moved away from this orifice three times, which corresponds to three minimums in Fig. 3. When the plate was returned to the initial position, the photodetector signal recovered to the mean maximum value. According to our measurements, the uncertainty of the focus position on the orifice for this device (which corresponds to the signal noise at the peak stations) was approximately 10 nm. This estimate was obtained on the basis of the measured uncertainty of the angular position of the light beam owing to air turbulence, vibrations of mirrors in the laser, etc. The reproducibility of the focus position of the order of 10 nm was estimated on the basis of equality of the mean maximums of the light intensity. This value is much smaller than the diameter of the focused beam of electromagnetic radiation (∼1 μm) and is fairly sufficient for many applications of this device.

The advantage of the proposed wide-range nanopositioner of focused electromagnetic radiation is the possibility of reproducible spatial positioning in the range from micrometers to nanometers with the maximum possible elimination of various adverse backplay effects. The device can be used for scanning the beam of writing and reading of optical information and for returning the beam to a given point within several nanometers. It should be noted that this device is very simple in terms of its fabrication and convenient for applications in actual laboratory conditions.

CONCLUSIONS

A new optical scheme is proposed, which ensures the motion of the light beam in space. For the device based on this scheme, the possibility of reaching nanometer accuracy and reproducibility of positioning in a wide range of displacements (∼1 cm) with a negligibly small backplay effect is proved theoretically and experimentally. Operation of this device is demonstrated in experiments, and its practical relevance is validated.

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