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3D INSPECTION BY CONICAL WAVEFRONTS

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INTRODUCTION

For observation of the point-like objects and some other objects we use an optical microscope, which comprises objective plus ocular pair, micrometric movement system along depth coordinate and x, y – stage. To get "in focus" image of the point-like object we change the position of the objective plus ocular pair by means of micrometric movement system. The position of the latter defines z – coordinate of our point-like object. After placing the image in the center of the field of view, we may estimate its x, y – coordinates. This is an ABC – approach that is as old as optical microscope.

In the case of N point-like objects in 3D space we must repeat the above described operation N times. However, the point-like elements of the **straight-line object** are liying along the straight line and their positions in 3D space are extremely correlative. Therefore instead of 3N coordinates we must estimate only 5 parameters: x_0, y_0, z_0 coordinates of the center of the straight-line object and two angles, projected oriented angle Θ_{xy} and meridional orientation (dip) angle Θ_z. The information compression factor is equal to 3N/5. And how to get in the experiment the equivalent rising of productivity?

The solution of this problem gives **meso-optics**, a part of optics, in which we study conical wavefronts and their physical and informational property [1]. The fundamental feature of the meso-optics is that straight-line is accepted by the meso-optical lens as a **whole unit**. The output data of straight-line object in the meso-optical microscope have the structure of **two** point-like signals. The position coordinates of these two signals contain total information on position in 3D space of our straight-line object. The information compression occurs in the meso-optical microscope instantly without any calculations.

The first device, which perceives "horizontal" straight-line object as a single object and which does not subdivide this object into many separate elements on the detection stage, has been built in the Joint Institute for Nuclear Research (JINR), Dubna, in 1986 [2, 3, 4] and has been termed Meso-optical Fourier Transform Microscope (MFTM). This microscope detects selectively only straight-line objects and performs an information compression about each such object "on-line", that is in the frame of the illumination stage. Any other objects are converted by MTFM into an uniformly distributed background.

To detect selectively "vertical" straight-line object as a whole unit without depth scanning, there was constructed Caustical Meso-optical Microscope [5, 6]. In the illuminating part of this confocal device we use a cylindrical meso-optical condensor, which restricts the illuminating region to the narrow 1D "fens" oriented parallel to the optical axis of this microscope.

In conclusion we explain principle of a new optical microscope which produces an **image** of the straight-line object inclined at the angle ~45° with respect to the optical axis. This microscope [7] is provided with meso-optical illuminating condensor, two traditional imaging lenses and special image transformer. The first test model of this optical microscope has been built [8].

CONICAL WAVES

A point-like object, illuminated by light beam, generates a secondary spherical wave (fig. 1). To estimate the position coordinates of such an object O, we perform a depth scanning by means of the optical lens L, which produces a magnified image of our object. Thus we may estimate z – coordinate of the point-like object. To find its x, y – coordinates, we use x, y – stage of the optical microscope, to put the image in the center of the field of view. For N point-like objects these operations must be repeated N times.

However, the measurement program can be changed drastically in the case, if many point-like objects are mutually correlative in 3D space, for example, they produce an object in the form of the straight-like segment. For this object the secondary wave has the form of a **cone**. In contract to the continuous spherical wave, the generating line of the conical wave has a **kink**, and, due to this, a cone has a definite orientation in space, and the generating line of a cone can be subdivided into two parts, left and right.

In fig. 2 the straight-line segment AB is illuminated by plane wave PW. The secondary wave is a **cone**. We see that ouverture angle of this cone is equal to $2\alpha_z$, where α_z is the orientation angle of the segment AB.

MESO-OPTICAL FOURIER TRANSFORM MICROSCOPE (MTFM)

A principal scheme of the MTFM [2] is shown in fig. 3. A convergent light beam illuminates "horizontal" straight-line objects. The crossover of this light beam is in the vicinity of the meso-optical mirror with ring response.

Each "horizontal" straight-line object generates a far-field diffraction pattern in the form of a narrow bright strip, which crosses the optical axis of the MFTM. The width of this strip is equal to the diameter of the convergent beam crossover (~60μm).

The main feature of the MFTM is that the diameter of the focal circle, produced by the meso-optical mirror with ring response, depends on z – coordinate of the "horizontal" straight-line object. The diffracted light is reflected from the meso-optical mirror with ring response and produces **two** meso-optical images in the vicinity of the focal circle 5. Thus, each straight-line object is mapped by MFTM into itself and is twice multiplexed.

In the MFTM with one common CCD-matrix [4] these two meso-optical images, L and R, are projected into **one** CCD (charge-coupled device)-matrix of the TV-pick up photoelectric system. There are four linear combinations of the mutual correlative moving modes of two meso-optical images in the frame of the CCD-matrix (fig. 4). Each moving mode corresponds to one of four parameters of our object: transverse coordinate x, depth coordinate z, orientation angle Θ_{xy} and dip angle Θ_z.

We have:

$$\left.\begin{array}{ll} \Theta_{xy} = C_1(x_L - x_R); & z = C_2(x_L + x_R); \\ \Theta_z = C_1(y_L - y_R); & x = C_2(y_L + y_R); \end{array}\right\} \quad (1)$$

where C_1 and C_2 are constants.

Now we show an example of the event with two straight-line objects, A and B, which have small kink angle. In fig. 5 we present meso-optical signals observed in the MFTM [4] at three longitudinal coordinates y. At y=4,413 mm we see only two meso-optical images, L_A and L_R of the first object A. At y=4,593 mm we see two pairs of meso-optical images, one pair, generated by the first object A, and another pair, generated by the second object B. At y=4,843 mm we see again only one pair of the meso-optical images of the second object B. The standard measurement errors of our MFTM were estimated as $\Delta\Theta_{xy}=1,8'$ and $\Delta\Theta_z=2,7'$ [9].

MFTM was indeed the first optical device, which perceives the straight-line as a whole unit without any subdividing it into independent point-like elements on the measurement stage.

CAUSTICAL MESO-OPTICAL CONFOCAL MICROSCOPE FOR "VERTICAL" STRAIGHT-LINE OBJECTS

This class of confocal meso-optical microscopes is based on the caustic phenomenon in optics, which can be detected by means of a simple experimental set up (fig. 6) [5]. A cylindrical **half-lens** L is illuminated by collimated light beam from a laser. The monochromatic pattern of cylindrical caustic is detected by means of the photoplate Hph of very high spatial resolution (~1000 lines per mm), which is inclined at small angle with respect to the light beam axis. The microstructures of the caustic edge for several position of the observation plane with respect to the focus are given in fig. 7.

The principle of the confocal caustic meso-optical microscope for selective observation of the "vertical" straight-line objects is presented in fig. 8. The **illuminating** cylindrical half-lens L_1 produces a caustic interference pattern. The objects are in the vicinity of the focus of the half-lens L_1 and are oriented parallel to the external light rays of the caustic pattern. The stop S rejects all internal light rays. The **imaging** cylindrical half-lens L_2 focuses the light rays of the external part of the caustic interference fringes. The position of the region, where two systems of interference fringes, one from the half-lens L_1, and another from the lens L_2, are overlapped, is controlled by transversal moving of these two half-lenses along x – axes.

IMAGING OF THE STRAIGHT-LINE OBJECTS ORIENTED AT ~45° WITH OPTICAL AXIS

Now we explain the principle of the new optical microscope [7, 8], which enable us to get the **image** of the whole straight-line objects oriented at ~45° with respect to the optical axis without any depth scanning. The problem of the imaging of such objects by means of the traditional optical microscope is the direct corollary of the fact, that the magnified image of such object is located on the focal plane which is inclined at very small angle with respect to the optical axis (fig. 9). The ratio of the angles β_1 and β_2 is defined by the relation

$$\sin \beta_1 / \sin \beta_2 \approx M, \quad (2)$$

where M is the linear magnification of the imaging lens L. For $\beta_1 \approx 45°$, $M \approx 90$, we have $\beta_2 \approx 1°$. Due to this the light rays are going at very grazing angles with respect to the photodetector plane.

It is interesting to mention the Scheimpflug condition [10], for construction of the light sectioning device, containing a scanning mirror [11, 12]. Namely, the plain of the object and the plain of the magnified image must cross each other on the line, lying in the plain of the imaging lens L.

The principle scheme of our microscope for imaging of the strong inclined, ≈45°, straight-line object without depth scanning is given in fig. 10 [7]. To turn the light rays falling on the observation screen A′B′ at small grazing angles we use special image transformer provided with many (~300) mirror lamelar elements, located in the plane of the primary image A′B′ of our object AB. The reflected light rays are directed into the second imaging lens L_2, which produces the secondary image B"A" of our object AB on the plane, perpendicular to the optical axis of the secondary imaging lens L_2.

The real scheme of our microscope is given in fig. 11, where AB is our straight-line object, L_1 – the first imaging lens, A′B′ – the primage image, where the image transformer of many mirror lamelar elements is located, L_2 – the second imaging lens, and B"A" is the final (secondary) image of our object on the plane perpendicular to the optical axis of the lens L_2.

The variation of the linear magnification of the linear magnification M along the primary image induces the geometrical scale distortions, which can be corrected by the simple computer program. The image transformer R has small convex sagging induced by the variation of the real linear magnification along our object AB. For AB=0,58 mm and focal length of the primary lens L_1 equal to 3,4 mm, the length of the magnified image A′B′=48,8 mm, and the sagitta $\Delta \approx 0{,}58$ mm.

The top view of the first model of the optical microscope, which enables us to produce the magnified image of the inclined object at the angle ≈45°, is shown is fig. 12 [8].

The model consists of the light source LS, object O, the first imaging lens L_1, image transformer IC, plane mirror M, the second imaging lens L_2 and the image detector ID.

The object O is the linear aray of the point like elements, inclined at the angle $\approx 45°$ with respect to the optical axis. The primary image, produced by the first imaging lens L_1, cannot be detected by any plane detector due to very small grazing angles of the light rays. Therefore we use the image transformer IC, which consists of 10 separated mirror elements of the width 3mm. Each mirror element has been oriented in such a manner, that the reflected rays were directed into the aperture of the second imaging lens L_2, which produced the second image on the plane image detector ID.

The "in focus" image of our object O is given in fig. 13. The "out of focus" primary image of the same object O, produced by the first imaging lens L_1 on the photofilm, oriented perpendicular to the optical axis of the first imaging lens L_1, is shown in fig.14 at three different objective stops of the lens L_1.

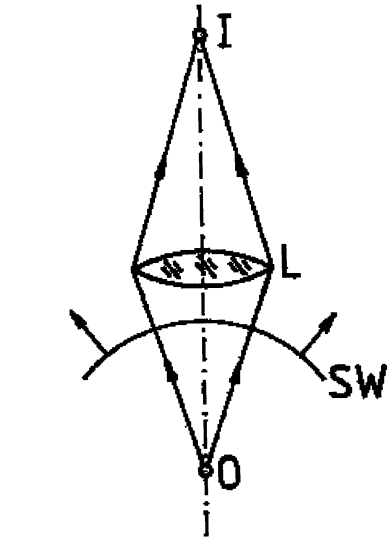

Figure 1. A point-like object O is imaging by the lens L into its image I. SW – spherical wave.

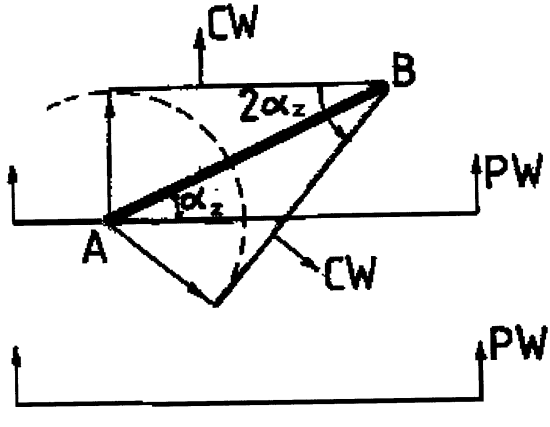

Figure 2. A straight-line segment AB, illuminated by the plane wave PW, generates a secondary conical wave CW, where α_z is the orientation angle of the straight-line segment AB.

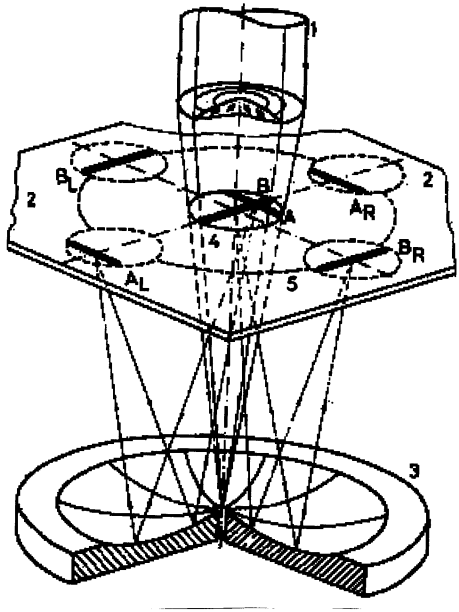

Figure 3. A principal scheme of the MFTM: 1 – Fourier transform lens of the illuminating system, 2 – working volume of thickness h, 3 – meso-optical mirror with ring response, 4 – field of view, 5 – focal circle, A and B – two straight-line objects, A_L and B_L are the left meso-optical images of the our objects A and B, A_R and B_R are their right meso-optical images.

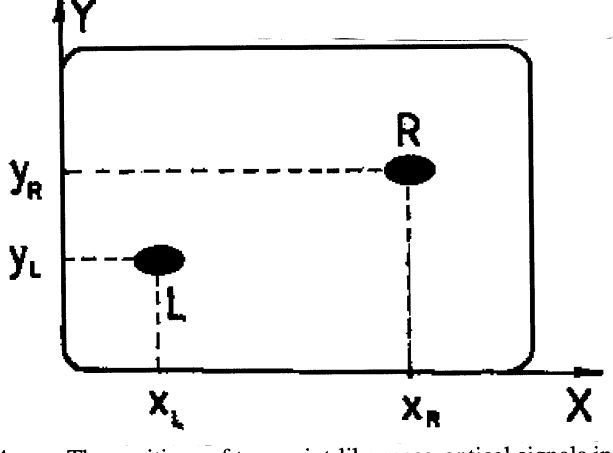

Figure 4. The positions of two point-like meso-optical signals in the xy-frame of the CCD matrix: L – the left signal, R – the right signal.

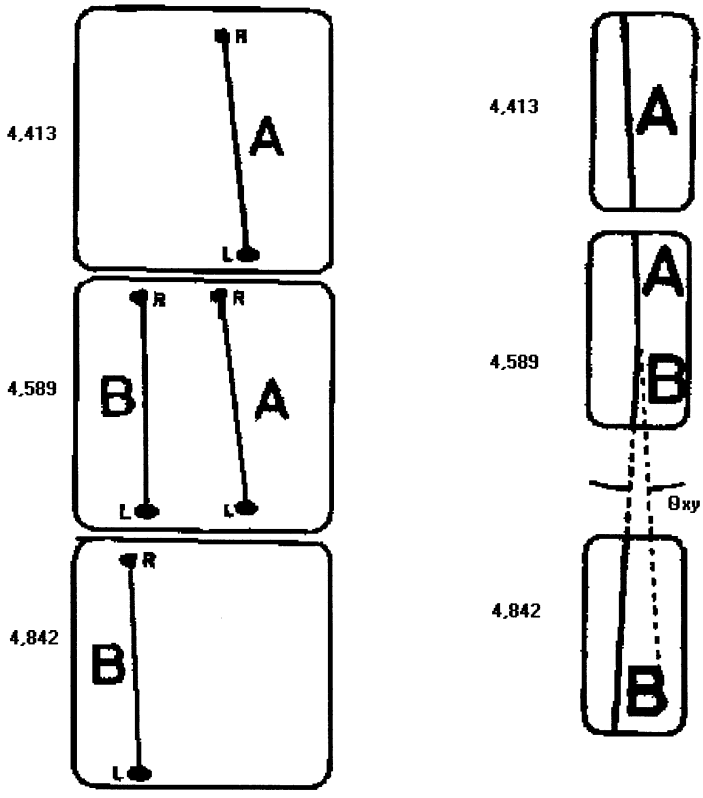

Figure 5. To the right:
Event with two straight-line objects A and B, having small kink angle, at three different y-coordinates.
To the left:
Three pictures observed on the CCD matrix of the MFTM at the same y coordinates.

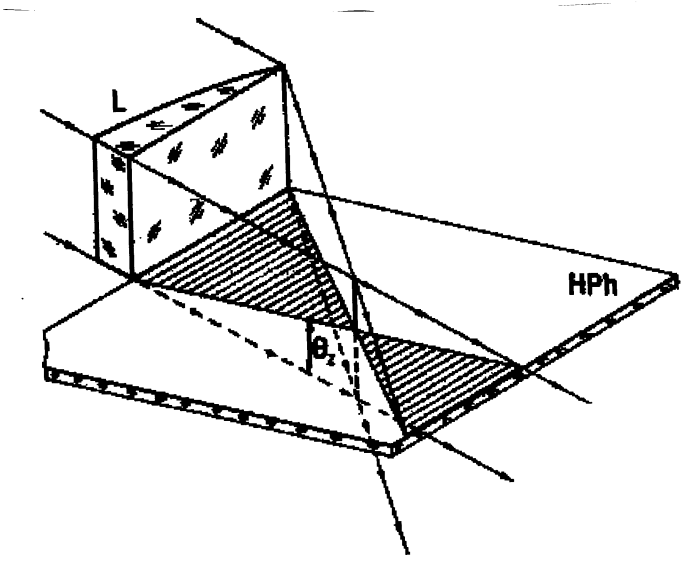

Figure 6. The geometry of the experiment for observation of the caustic phenomenon: L – cylindrical half-lens, HPh – photoplate, θ_z – inclination angle.

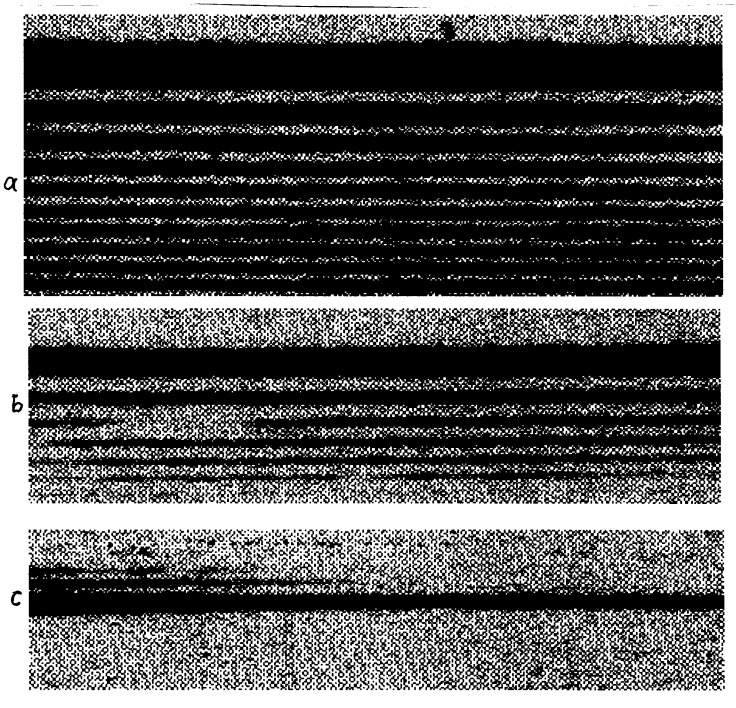

Figure 7. The microscopic structure of the edge of the caustic pattern at several positions of photoplate with respect to the focus region of the cylindrical half-lens L.

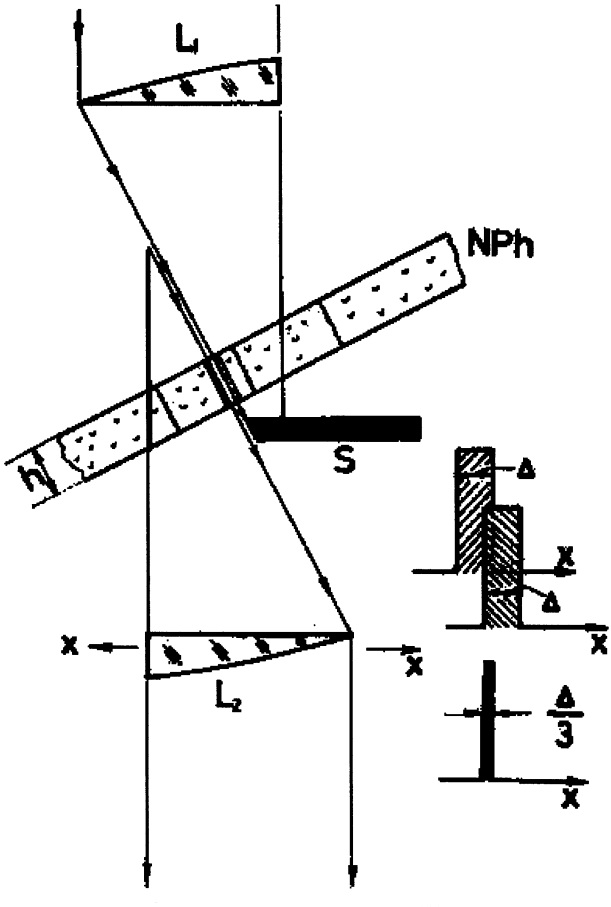

Figure 8. Confocal caustic meso-optical microscope for selective observation of the "vertical" straight-line objects: L_1 – illuminating cylindrical half-lens, NPh – working volume, S – stop, L_2 – imaging cylindrical half-lens. The moving of the L_2 half-lens is performed along x-axis.

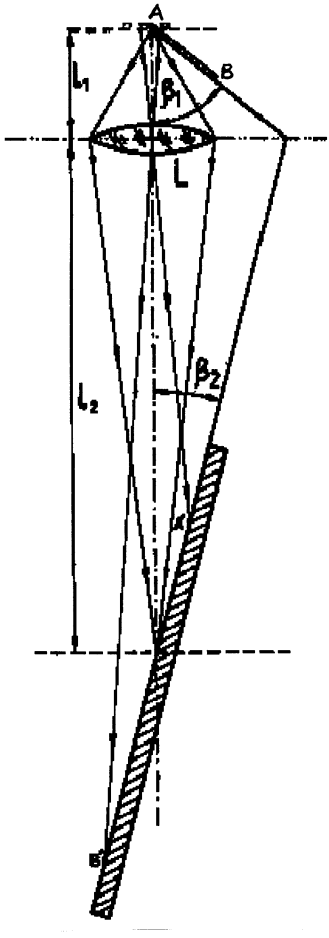

Figure 9. Position of the magnified image of our object AB, which is located on the plane inclined at very small angle with respect to the optical axis (see text).

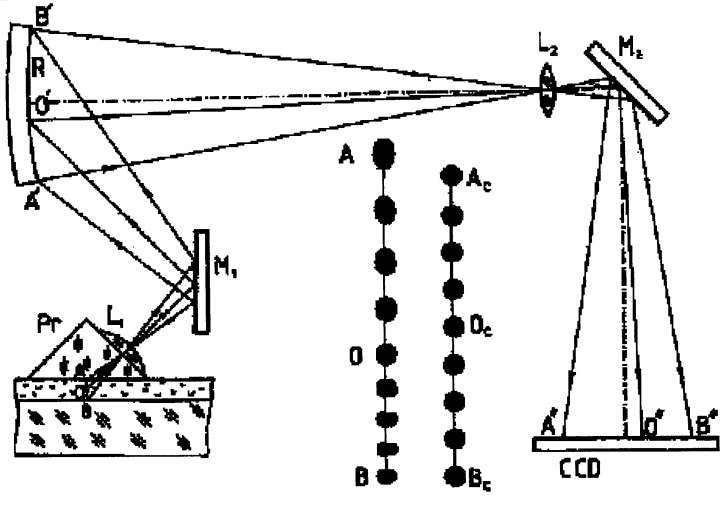

Figure 10. The principle scheme of the microscope for imaging of the strong inclined, ≈45°, straight-line object AB without depth scanning: Pr – immersion prism, L_1 – first imaging lens, M_1 and M_2 – plane mirrors, R – mirror image converter, L_2 – second imaging lens, A″B″ is the image of our object AB.

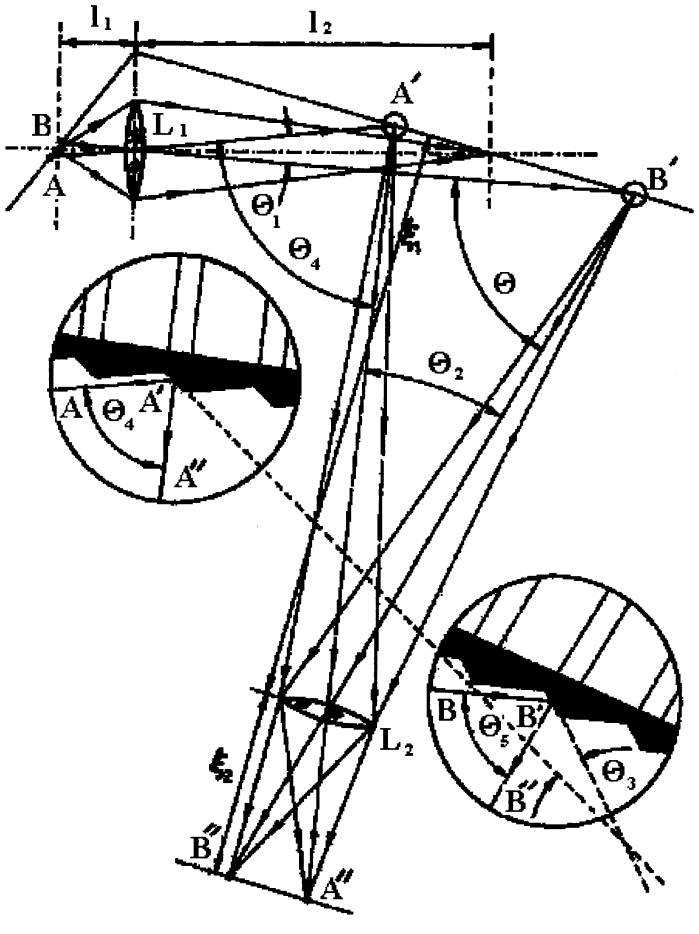

Figure 11. The real scheme of our microscope: AB – straight-line object, inclined at ≈45° with respect to the optical axis of the first imaging lens L_1, A′B′ - primary image where the special image transformer consisting of many mirror groves is located, L_2 – the second imaging lens, A″B″ is the final image of the whole object AB.

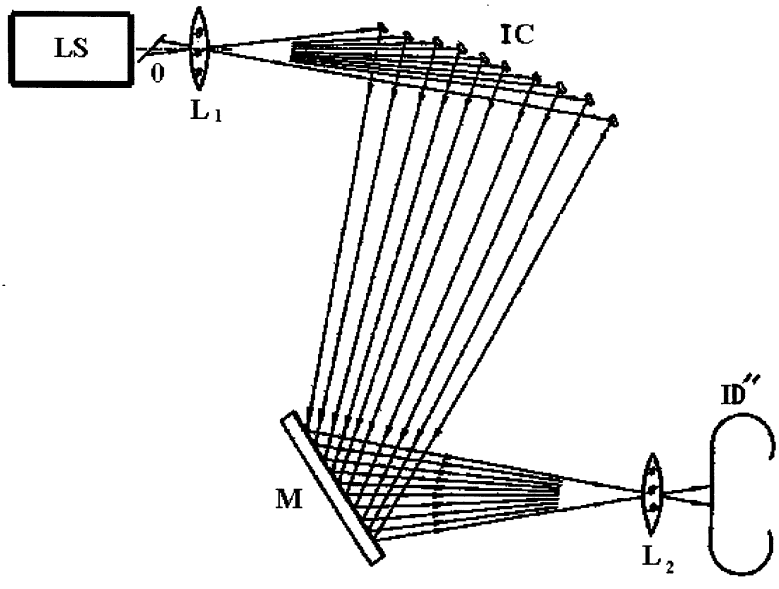

Figure 12. The top view of the first model of the optical microscope which produces the image of the inclined (≈45°) straight-line object without any depth scanning: LS – light source, O – inclined straight-line object, L_1 – the first imaging lens, IC – mirror image transformer, M – plane mirror, L_2 – the second imaging lens, ID – image detector.

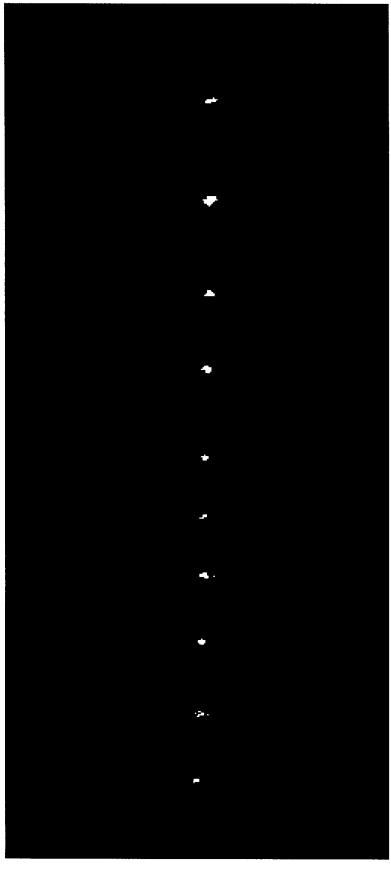

Figure 13. The "in focus" image of the inclined straight-line object which was produced by means of the first model (see figure 12).

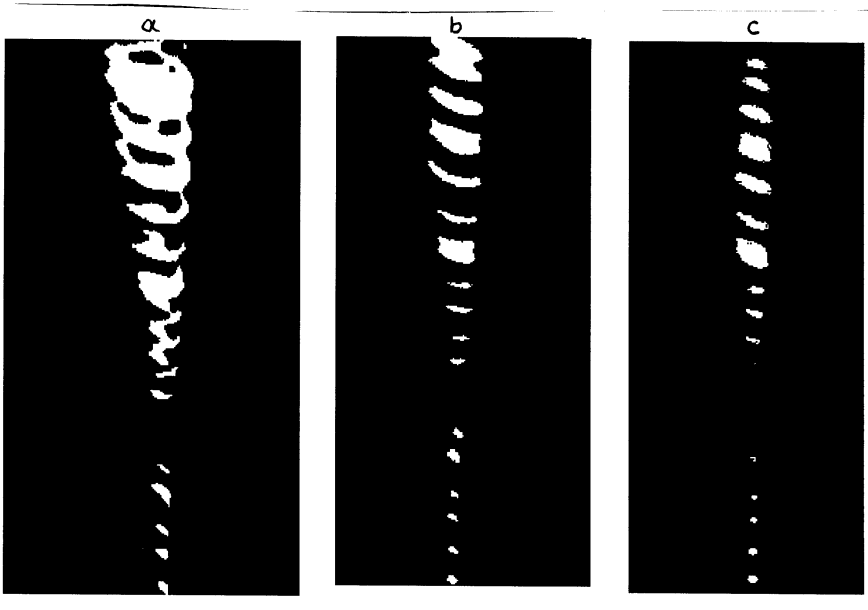

Figure 14. The primary "out of focus" images of the inclined straight-line object O, produced by the first imaging lens L_1 on the photofilm, oriented perpendicular to the optical axis of the first imaging lens L_1, at three different objective stops of this lens.

CONCLUSIONS

1. To observe straight-line objects in the course of 3D inspection, we must use an imaging lens that has a **kink** in its generating line.
2. The information compression about the straight-line objects occurs in the meso-optical devices **instantly** without any calculations.
3. The **caustic** phenomenon in optics has been firstly used in the **illuminating** as well as in the **imaging** parts of the confocal microscope.
4. Two cylindrical **half-lenses** used in the optical confocal microscopes can be considered as optical element with **kink** in its generating line.
5. The **image** of the whole straight-line object, inclined at the angle ~45° with respect to the optical axis has been firstly produced.

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Сороко Л. М. E13-2002-43
Трехмерная инспекция при помощи конических волновых полей

Показано, что проблема сканирования по глубине в оптической микроскопии может быть решена для класса прямолинейных объектов, если мы используем изображающую линзу, образующая которой имеет **излом**.

Описаны мезооптические устройства для селективного наблюдения прямолинейных объектов в пространстве без какого-либо сканирования по глубине, хотя информация о координате по глубине и угле погружения этого объекта не теряется.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2002

Soroko L. M. E13-2002-43
3D Inspection by Conical Wavefronts

It is shown that the depth scanning problem in optical microscopy can be resolved for the class of straight-line objects if we use an imaging lens, which has a **kink** in its generating line.

There are described the meso-optical devices for selective observation of straight-line objects in space without any depth scanning, though the information about depth coordinate and dip angle of this object is not lost.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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