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WHAT DOES THE TERM «LIGHT BEAM» MEAN?

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Сороко Л.М. E13-99-226
Что означает термин «пучок света»?

За последние десять лет наиболее тривиальный и наиболее прозрачный научный термин «пучок света» подвергся изменениям, вызванным недифрагированными пучками света в оптике. Степень этих изменений была настолько велика, что, опираясь на новое значение термина «пучок света», некоторые исследователи допускали существование тахионов или сверхсветовых тахионных волн внутри указанных специфических пучков света.

Тенденция использовать научный термин «пучок света», наполненный новым физическим содержанием, появляется в статьях по недифрагированным бесселевым пучкам света, по пучкам света на большую глубину с пространственной и временной локализацией энергии, а также по нерасплывающимся волновым пакетам как решениям волнового уравнения. Все эти широкополосные композиции дают предельную пространственно-временную локализацию полей в ходе процесса распространения в свободном пространстве.

Между тем, никто не обсуждал главной особенности указанных световых пучков, а именно то, что пучки света не образуют теней или тенеподобной интерференционной картины вниз по пучку. Если вы установите непрозрачный экран в этот «пучок света», то вы не увидите никакого явления тени вдоль оптической оси этого «пучка света». Вместо этого вы обнаружите на некотором расстоянии за непрозрачным экраном, что пучок Бесселя восстановился снова, как если бы это была птица феникс.

Чтобы исправить эту ложную ситуацию, мы должны ввести новый физический термин с чистым смыслом. Автор статьи объясняет, как можно это сделать.

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Soroko L.M. E13-99-226
What Does the Term «Light Beam» Mean?

During the last ten years the most trivial and the most lucid scientific term «light beam» has been subjected to the transformations induced by the family of the non-diffracting light beam in optics. The degree of these transformations was so high that due to the new meaning of the term «light beam» some authors admitted the existence of tachyons or superluminal tachyonic waves inside of these specific light beams.

This tendency of using the scientific term «light beam» filled with new physical content we observe in the papers of the non-diffracting Bessel light beams, the large-depth light beams with spatially and temporally localized energy and also on the non-spreading wave-packet solutions to the wave equation. All these wide-band compositions give the extremely high spatio-temporal localization in the course of the propagation in free space.

Meanwhile nobody discussed the main feature of such light beams, namely, that these light beams do not produce a shadow or a shadow-like interference pattern down to the beam stream. If you put an opaque stop into this «light beam», you do not see any shadow phenomenon along the optical axis of this «light beam». Instead you find out that some distance behind the stop, the Bessel beam will be regenerated over again as if it were a phenix bird.

To correct this false situation, we must introduce a new physical term with a pure meaning. The author of this paper explains how we can do this.

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

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1 INTRODUCTION

During the last ten years or so, the most trivial and the most lucid scientific term "light beam" has been transformated and has been filled with new physical content. The starting point of this process was the experimental investigations of the so-called non-diffracting Bessel beam [1]. This beam was generated from a cw laser light by an annular slit and a collimating lens. This Bessel beam had sharply picked radial profile over large distance outclassing the Rayleigh range. For example, an axiconic laser string [2], having the form of thin light pencil beam, had the focal range of 50 meters, and the effective diameter of the string of $\sim 70\ \mu$m. The measurement error of this axiconic laser string is of the order of 15 μm and is restricted practically by the air turbulence. The focal range of the traditional lens of diameter D=100 mm with focal length f_0=25 m is equal only 500 mm, that is, the factor of merits of this axiconic laser string in this example is equal to 100:1 and can be made higher.

If Refs [1,2] and in many others a conical wavefronts are used. All such phenomena can be covered by one general term MESO-OPTICS where we study and we use conical convergent light beams with their extraordinary properties [3].

There have been treated some classes of non-spreading wide-band "focus wave modes" [4], "Bessel-Gauss pulses [5], and "X waves" [6]. An optical version of the X waves, named the "Bessel–X pulse" with special localization of the order of 10^{-3} mm and with time duration of 3 f sec ($3 \cdot 10^{-15}$ sec) have been treated by computer simulation and the cross-correlation interference patterns of these femtosecond Bessel–X pulses have been estimated experimentally [7].

The degree of transformation of the scientific term "light beam" was such that on the basis of the new meaning of the term "light beam", several authors [8] admitted the existence of hypothetically tachyons or superluminal tachyonic waves inside of these light beams.

Meanwhile the main feature of all these light beams is that they do not produce a shadow or a shadow-like interference pattern down to the beam stream. To prove this it is sufficient to put an opaque stop into the center of this "light beam". You will see that along the optical axis of this "light beam" there is no shadow phenomenon. Instead of this you will find that some distance behind the stop, the Bessel beam will be regenerated over again as if it were a phenix bird.

It is obvious that we must correct this false situation. We must introduce a new physical term with a pure physical meaning. The author of this paper explains how to do this.

In Sec. II we give the analysis of the properties of the light beam having plane wave-front and a wave vector, which is perpendicular to the wave front. We describe the structure of the interference pattern in the region of the overlapping of such two plane beams. It is shown that the superluminal phase velocity along the interference planes of extremum light intensity is observed inside the interference pattern exactly in the same fashion as the analogous phenomenon taking place on the axis of the Bessel light beam.

In Sec. III we consider the shadow phenomenon in the case of the classical conical beam (meso-optics). In Sec. IV we explain the mechanism of the longitudinal interference of two coaxial conical wave fields. It is shown that this phenomenon is equivalent to the shadow cone spreading in the case of only single conical convergent wave.

In Sec. V we present our proposal concerning the elimination of the false situation with term "Bessel light beam". It will be proved that the light structure observed on the axis of the conical light beam must be called CENTRAL INTERFERENCE LOBE. We present arguments for this proposal, which take into account the length of the central interference lobe, its radial profile, the evident generalization on the wide-band short Bessel pulses, the superluminal phase velocity as a general feature of any interference picture, azimuthal variation of the X-waves and the absence of tachyons in the central interference lobe.

2 PLANE WAVE FRONTS

In fig. 1 we present a 3D-scheme of the plane wave of light, with wave fronts, oriented perpendicular to Z-axis, where λ is the wave length and $\vec{k}\,(0,0,k)$ is the wave vector oriented along Z-axis. The planes marked by the full lines correspond to positive maximum of the electric field, and the planes marked by the dashed lines correspond to negative maximum of the electric field.

The interference picture produced by two plane waves in the region of its mutual overlapping is stable in space (fig. 2), if $\lambda_1 = \lambda_2$. The interference fringes are oriented along the bisectrix of the angle between two wave vectors $\vec{k}_1$ and $\vec{k}_2$. If we fix our attention only on one interference plane then we find out that the phase velocity of light along this interference plane is equal to $\sqrt{2}\,c$, where c is the velocity of light in vacuum, that is, this is a superluminal moving.

If two plane beams have different wave lengths, $\lambda_1 \neq \lambda_2$, and $\Delta\lambda = \lambda_1 - \lambda_2$, then the interference fringes are oriented at the angle $\varphi = tn^{-1}\lambda_2/\lambda_1$ and the interference pattern is moving as a whole in space with velocity $v_\perp$, oriented perpendicular to the interference planes, where $v_\perp = \Delta\lambda/\lambda_0 \cdot c/\sqrt{2}$, and $2\lambda_0 = \lambda_1 + \lambda_2$ (fig. 3).

3 CONICAL WAVE FRONTS

A 3D-scheme of the convergent monochromatic conical wave, produced by the conical transducer, is given in fig. 4. In the region of the overlapping of all components approaching the optical axis Z from various azimuthal directions we observe so-called monochromatic Bessel light beam, which is none other than an azimuthal symmetric interference picture with radial profile described by the Bessel-function:

$$A(\rho, Z, \varphi, t) = C_1 \cdot J_0(k\rho)\exp[i(z - \zeta t)], \tag{3.1}$$

where $k_Z = k \cdot \cos\theta$, θ is the angle between the wave vector $\vec{k}$ and Z-axis, and

$$\zeta = c/\cos\theta, \quad (\zeta > c), \tag{3.2}$$

is the phase velocity of light along Z-axis.

The interference picture in this overlapping region is produced by two groups of the conical wave fronts. The first group is the conical wave fronts before the crossing of Z-axis, and the second group consists of the conical wave fronts after the crossing of Z-axis. And the convergent conical waves after the crossing of Z-axis became the divergent ones. So the length of the "Bessel light beam", which exists only in the region of the overlapping of all components of the initially convergent conical light beam, is restricted.

In fig. 4 we present also the cross section of the "Bessel light beam" in its central part with typical radial interference profile.

From fig. 5 we may conclude that at some point A on the axial symmetric conical wave there is a set of wave vectors $\vec{k}_\varphi$ laying on the conical surface with apex angle $\theta = tn^{-1}\,k_\rho/k_Z$. Therefore Z-axis can be considered only as a symmetry axis. This feature is typical for any interference picture, in particular, shown in fig.2 for the case of two plane waves, where the number of wave vectors is equal to two.

In fig. 6 we show the shadow phenomenon for plane wave (a) and for convergent conical wave (b). In fig. 6.a the shadow, produced by ball of the diameter d, is oriented along the wave vector $\vec{k}$, that is, parallel to Z-axis. The depth distance B, at which the shadow does practically disappear, is equal to

$$B \approx d^2/2\lambda. \tag{3.3}$$

The same depth distance B defines the length of the shadow phenomenon also for conical light beam, which must be count out along each wave vector $\vec{k}$.

The structure of the shadow at different Z coordinates is shown schematically in fig. 7 for the case of the conical light beam, at Z = 0.23 and 48 mm. From fig. 7 we see also that the light intensity on the symmetry axis after ball is influenced by this ball only at small distances after ball. At very large Z-coordinates the influence of the ball on the zero intensity light region is practically absent.

4 LONGITUDINAL INTERFERENCE OF THE COAXIAL CONICAL WAVES

The experimental setup with two narrow coaxial transmitting rings (annular slits), which has been used for experimental investigation of the longitudinal interference of the coaxial conical waves, is shown in fig. 8 [9,10,11]. A collimated light beam from laser 1 is converted by the objective lens 2 into a convergent light beam which goes through the pinhole in the opaque screen 3. The second objective lens 4 produces the single mode light beam which illuminates the screen 5 with narrow coaxial transmitting rings. The second opaque screen with annular transmitting zone 6 restricts the number of the narrow coaxial transmitting rings, which contribute to the observed interference pattern. Narrow coaxial transmitting rings of width 20 μm each on the opaque screen 5 were fabricated by the laser photosynthezator [2]. The diameter of the focused laser spot was equal to 1 μm. The grooves on the glass backing of the opaque screen 5 are working as a circular diffraction grating, and the observer seas the rainbow spectra by placing the opaque screen 5 between the glow lamp and the eye. The system of 10 narrow coaxial transmitting rings with spacing 200 μm has been fabricated.

The positions of maxima and minima of the longitudinal modulation of the light intensity on the optical axis of the system is shown in fig. 9. As the angle between two wave vectors $\vec{k}_1$ and $\vec{k}_2$ is very small, $\sim 10^{-4}$rad., the fringe period A_Z of this modulation is of the order of 10 mm. The fringe period A_Z is also a slowly varying function of the order number of maximum N. This is a consequence of the fact that each narrow coaxial transmitting ring contributes to the interference picture as a point-like light source and the angle between the wave vectors $\vec{k}_1$ and $\vec{k}_2$ is varying inversely proportional to the distance from the opaque screen 5 to the observation point.

In fig.10 we explain the mechanism of creation of the on-axis longitudinal interference which can be produced by conical or helical light waves with mutual angle $(\theta_1 - \theta_2)$ between wave vectors $\vec{k}_1$ and $\vec{k}_2$ of two coaxial conical waves not equal to zero. The on-axis phase velocities of wavefronts, both above the light velocity c, are different. In the meridional cross section in the region of mutual overlapping of these two conical waves the interference fringes are oriented parallel to the bisectrix of the angle $(\theta_1 - \theta_2)$. The period of these fringes is equal to

$$a = \lambda / \sin(\theta_1 - \theta_2). \tag{4.1}$$

The orientation angle θ_0 of these interference fringes is equal to

$$\theta_0 = \frac{1}{2}(\theta_1 - \theta_2). \tag{4.2}$$

Each point of the meridional cross section shown in fig. 10, corresponds to a circle with center on the optical axis. Only the points lying on the optical axis of the system are indeed points. The period A_Z of the on-axis longitudinal interference of two coaxial conical waves is equal to

$$A_Z = a / \sin\frac{\theta_1 + \theta_2}{2}. \tag{4.3}$$

The length of the on-axis longitudinal interference picture is equal to CD.

In fig. 10 we show separately the conical waves going to the optical axis from the upper parts of these conical waves and the conical waves going to the optical axis from the lower parts of the same conical waves. Otherwise the picture would be very complex for explanation.

Thus the on-axis longitudinal interference of the light is the result of coherent superposition of two interference structures which propagate to Z-axis from two opposite directions, one from the upper side and another from the lower side of the meridional cross section. Each such interference structure is moving to the optical axis, then it crosses this axis and finally is propagating from the optical axis. To demonstrate this process visually in the experiment, we have chosen the experimental arrangement, in which the number of the narrow coaxial transmitting rings giving rise to the interference was equal to 10. The interference picture produced by overlapping of all 10 coaxial conical waves consists of one intense head maximum and 9 small secondary maxima. Thus we can see the evolution of each individual interference fringe.

The evolution of the interference picture in the planes perpendicular to the symmetry axis at various distances from the plane, where narrow coaxial transmitting rings are present, is given in fig.11. The sequence of six interference pictures observed in the planes perpendicular to the symmetry axis are shown in fig. 12 at $Z = Z_0 + k\Delta Z$, $k = 0, 1, 2, 3, 4, 5$. In fig. 12-a the maxima produced by the upper half coincide with maxima produced by the lower half of the interference pattern and are in phase. The radius of the first ring is equal to 39.5 mm. In the fig. 12-b we see the picture at $Z = Z_0 + \Delta Z$. The first ring is splitting into a doublet of two rings with radia 35.5 mm and 43.5 mm. In the plane with $Z = Z_0 + 2\Delta Z$ the corresponding radia are 31.5 mm and 47.5 mm. So the splitting gap is a linear function of Z-coordinate (fig. 13).

At some Z-coordinate the upper and the lower contributing interference components will be in antiphase, and the maximum disappears. The corresponding circle reappears again as we move along Z-axis. We see that in the experiments with longitudinal interference we may separate the upper and the lower components of the convergent conical waves.

The diffractive elements, proposed in [12] to control the structure of the non-diffracting beam over the given depth, consists of amplitude and phase parts, and the main variations in both parts of the diffractive elements are in the region of radial coordinates where our annular slits are present in the experiment, shown in fig. 8, for observation of the longitudinal interference of the coaxial conical waves. Thus the main contribution give the conical components in the initial aperture plane.

5 INTERFERENCE LOBES OR INTERFERENCE MODES

The shadow phenomenon, observed in the convergent conical wave, and the interference pattern, produced by two coaxial conical waves, demonstrate clearly that the term "Bessel light beam" is wrong and that the observed phenomenon is indeed of pure interference nature.Our attention is concentrated usually on the light field which is in the vicinity of Z-axis. So we deal with only central interference picture, which is termed a "lobe". The central lobe is surrounded by the lobes of higher orders. The light intensity in these lobes is decreasing with radial distance $\rho = \sqrt{x^2 + y^2}$ as ρ^{-1}.

However, the so-called X-waves has a complex azimuthal structure. In this case the azimuthal variation of the light intensity in the Z-waves can be termed as X-branches of the azimuthal structure of all interference lobes, or X-branches of the interference lobes. Everywhere the term "beam" is omitted.

In any case we must understand that the term "Bessel light beam" is uncorrect and that we have no scientific reasons to search for in the central interference lobe the mysterious tachyons or other imaginations.

However, we may use the term "wide-band femtosecond conical light".

An impression is evoked that the authors of Ref. [13] share, at least partially, the remarks on the term "Bessel light beam", presented here. The term "beam" is redefined more exactly several times in Ref. [13], and the term "mode" is used instead of the terms "beam". We find in Ref. [13] also the correct comparison of the "higher-order vector beams" with "higher-order concentric-circle-grating surface-emitting modes" in free space [14]. The term "vector Bessel-Gauss beam" is used also as "mode solutions of the vector wave equations". Each member of this family of beams is defined by azimuthal mode number, by radial polarization parameter and includes many solutions with zero intensity on the optical axis of the system.

Acknowledgements

The main ideas of this paper has been expressed by the author at the lecture "Meso-optics and tachyons", which has been delivered at the seminar of the Institute of Physics, University of Tartu, Estonia, on 12.05.99. The author wish to thank Prof. Peeter Saari for invitation to come to Tartu and for very useful discussions.

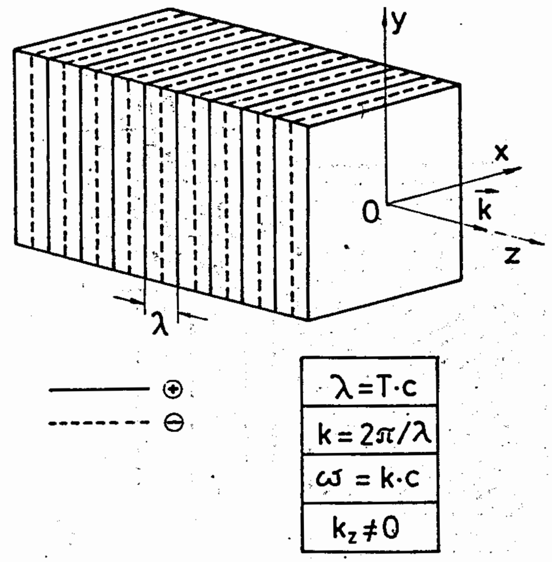


Fig. 1. Instantaneous presentation of the plane light beam of the wave length λ with wave vector $\vec{k}$ along Z-axis.

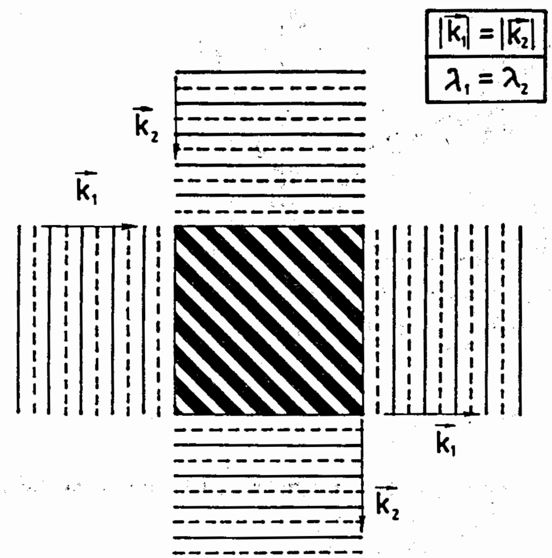


Fig. 2. Interference fringes of two mutually coherent plane light beams with $\lambda_1 = \lambda_2$.

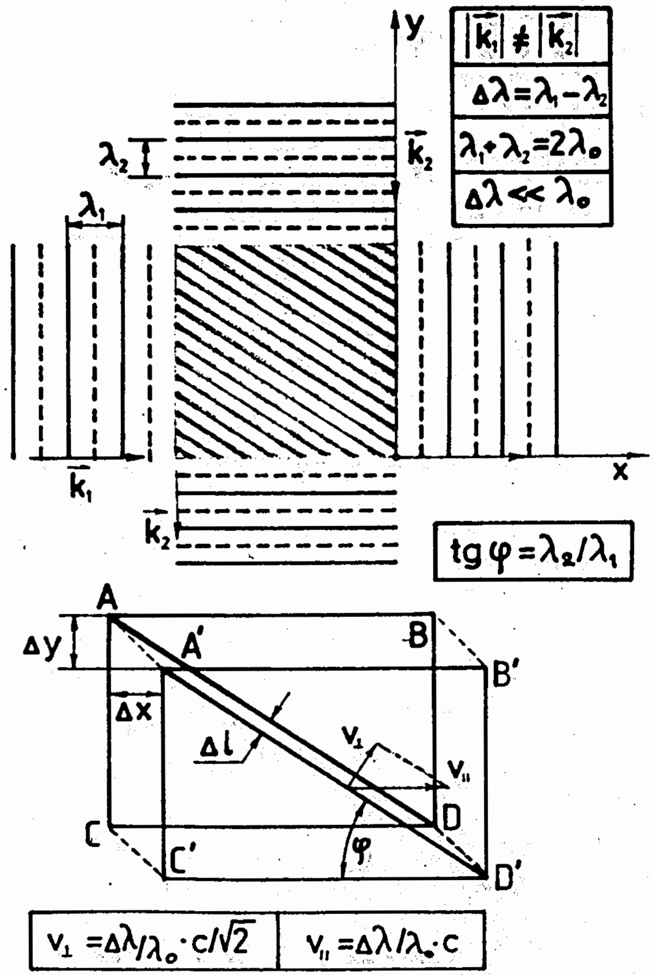


Fig. 3. The running interference picture of two plane light beams of the different wave lengths, $\lambda_1 \neq \lambda_2$.

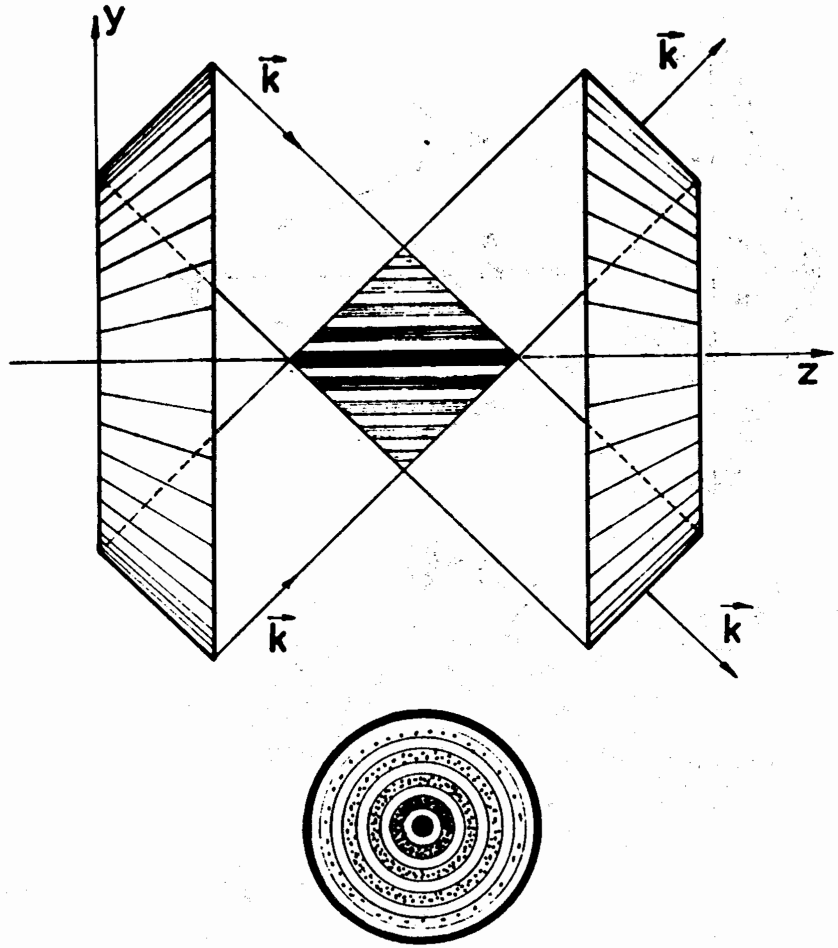


Fig. 4. 3D-scheme of the convergent conical light wave. The cross section of the "Bessel light beam" is shown below.

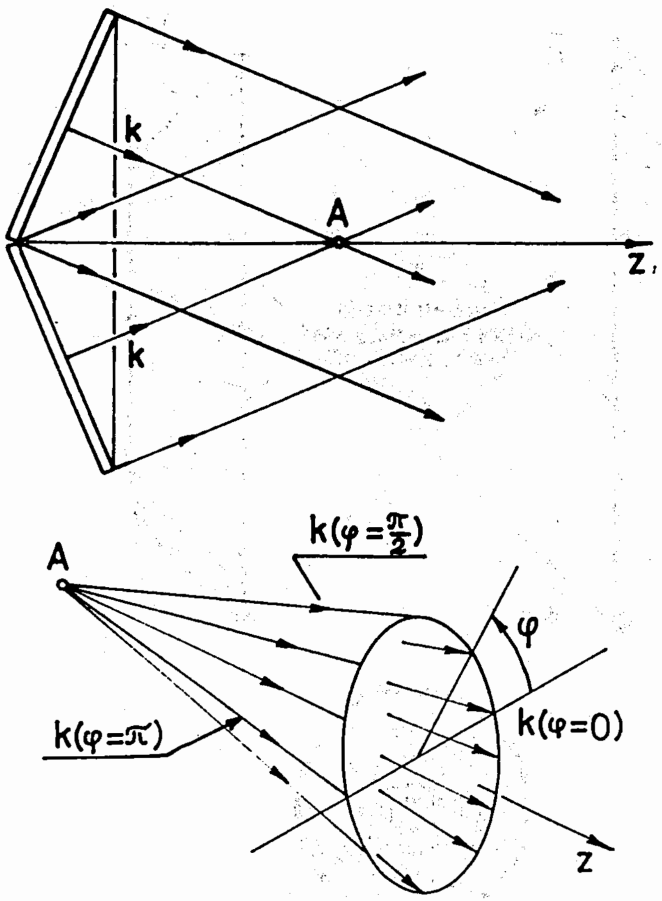


Fig. 5. The locus of the wave vector $\vec{k}_\varphi$ at the point A on the symmetry axis of the convergent conical light wave.

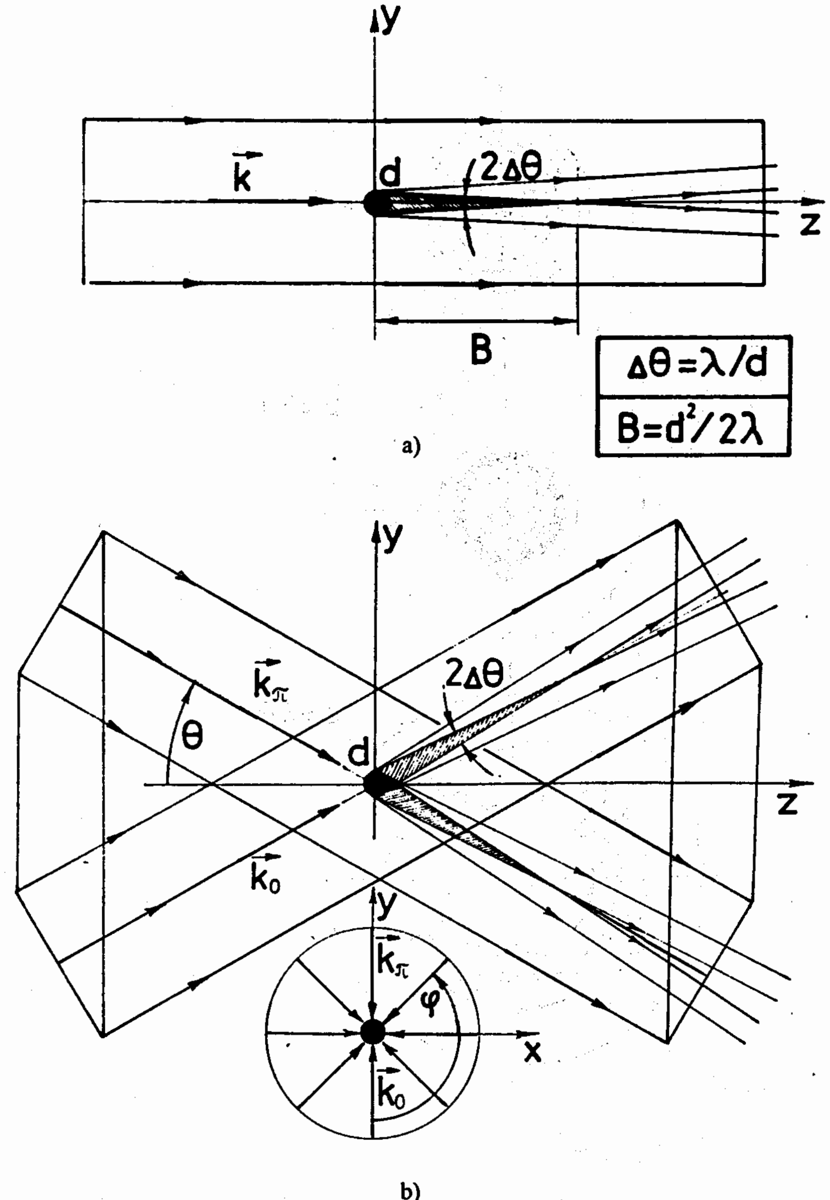


Fig. 6. Shadow phenomenon observed in the case of the plane wave (a) and in the case of the convergent conical wave (b).

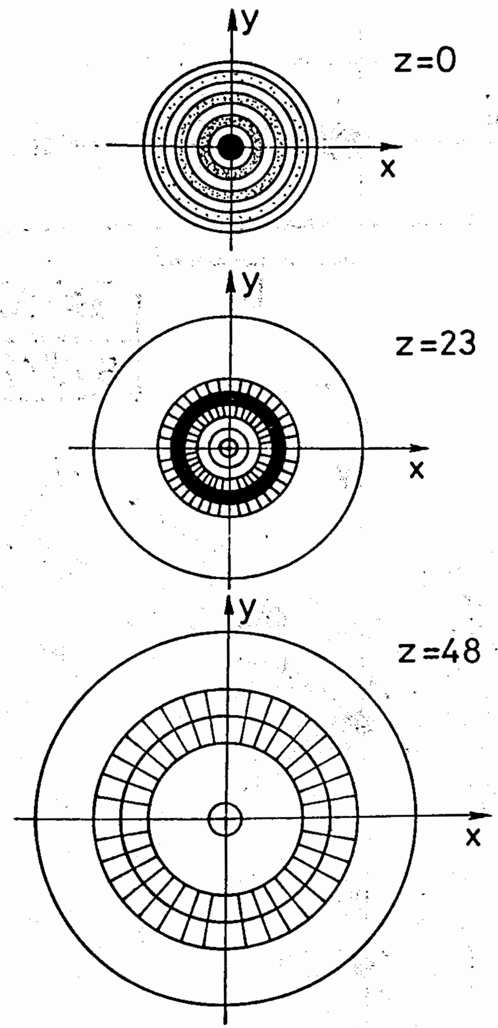


Fig. 7. The evolution of the shadow structure along Z-axis for convergent conical light wave.

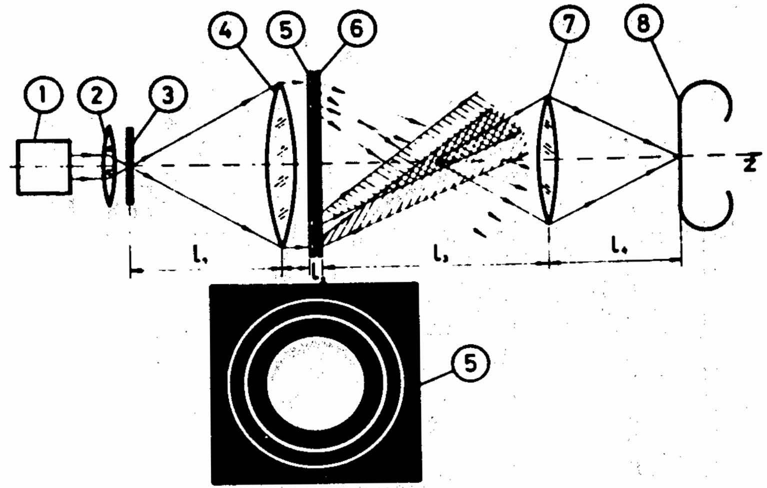


Fig. 8. The experimental setup used for experimental observation of the longitudinal interference of two coaxial conical waves.

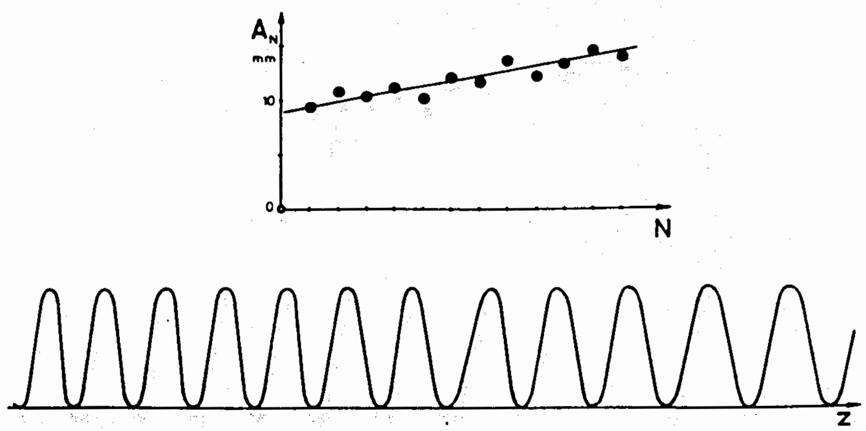


Fig. 9. The period of the longitudinal interference picture on the symmetry axis versus of the number of maxima, N. Below the on-axis light intensity along Z-axis.

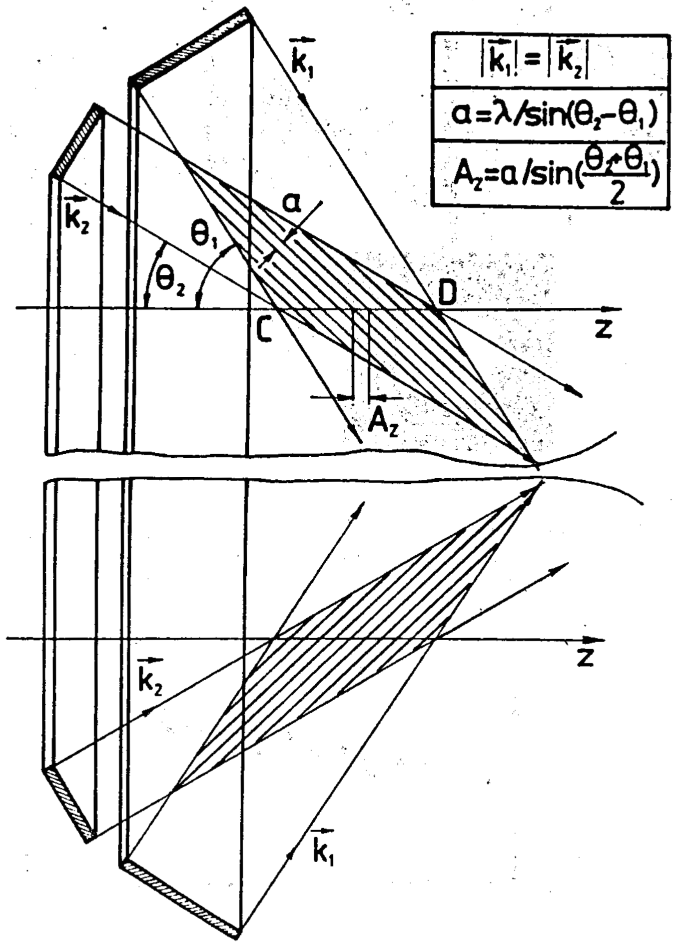


Fig. 10. The explanation of the mechanism of the longitudinal interference on the symmetry axis of the convergent conical light waves. CD is the length of the on-axis longitudinal interference picture.

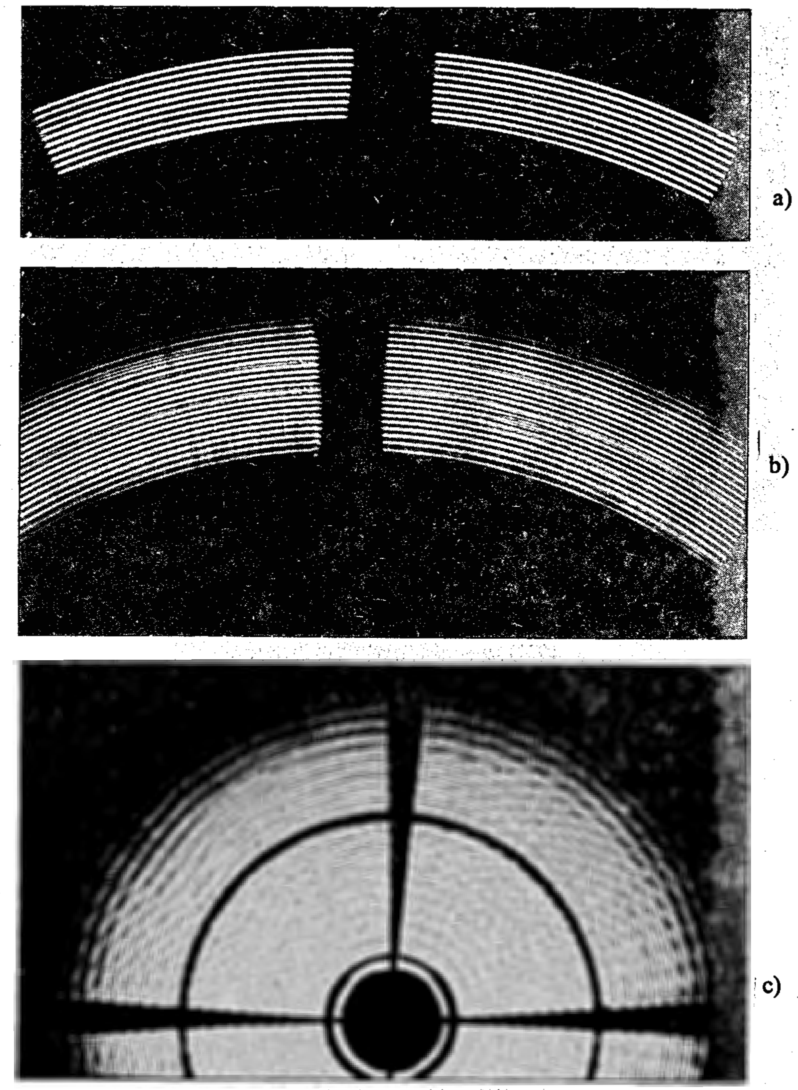
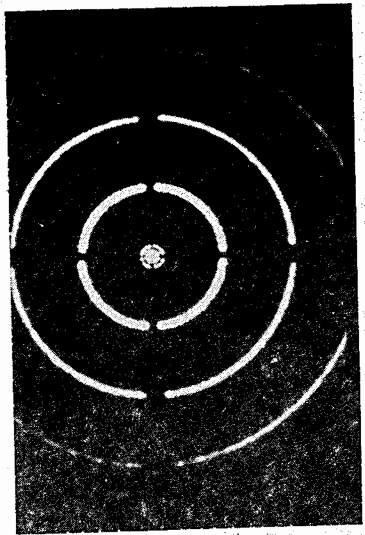
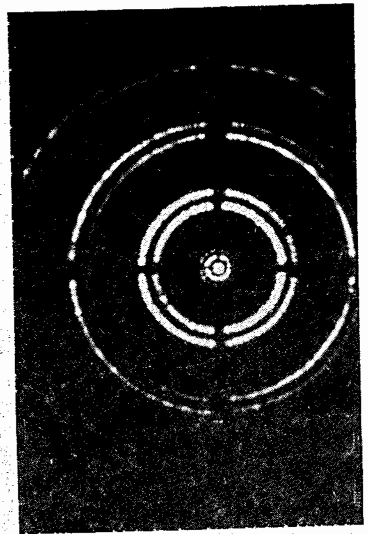


Fig. 11. The evolution of the interference picture at different distances from the plane with narrow coaxial transmitting rings:
a) in the plane of the rings,
b) in the plane of selfimaging Talbot,
c) before the interference region.



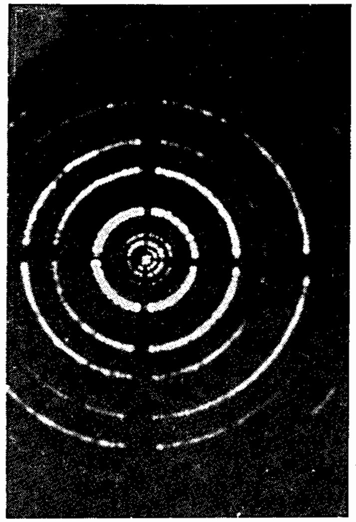
a)



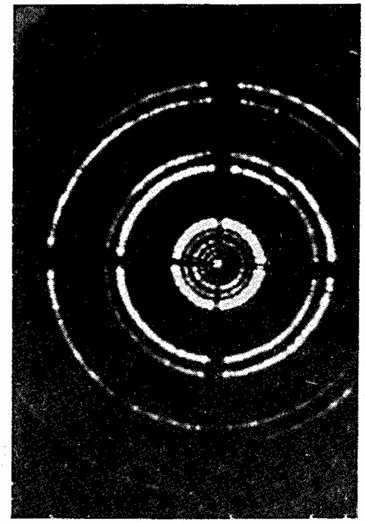
b)

c)

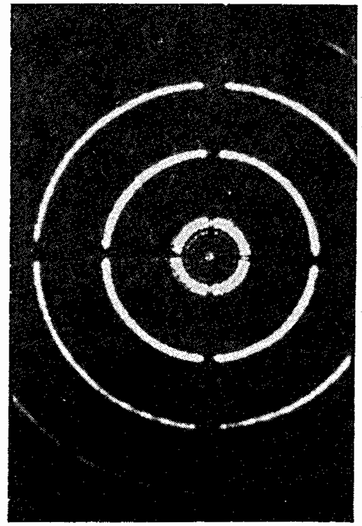
Fig. 12



d)



e)



f)

Fig. 12. Sequence of six interference pictures in the planes perpendicular to the symmetry axis of the convergent conical light wave in the case when the number of the narrow coaxial transmitting rings is equal to 10: a, b, c, d, e, f.

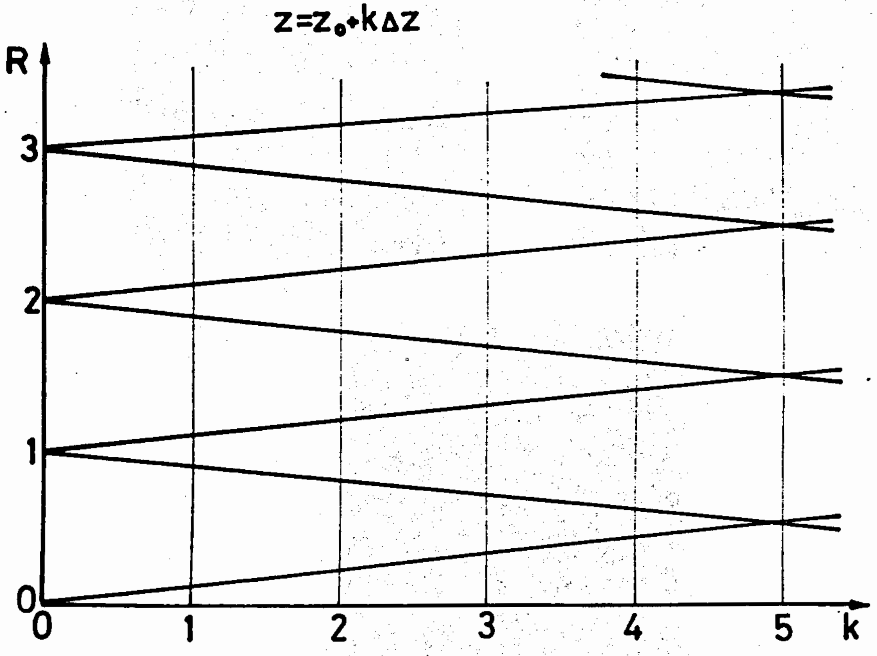


Fig. 13. The radius of the central bright rings at different Z-coordinates.

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