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# About Kerr's fringes formation

**Abstract:** the Kerr effect is widely used to study the characteristics of transparent media and the processes occurring in them, along with a variety of optical methods of experimental investigation, in which an isotropic substance placed in an electric field acquires the property of a uniaxial crystal with an optical axis directed along the applied field. As a result, birefringence occurs and a fringe pattern is formed at the exit from the Kerr cell, which is very similar to the interference pattern.

These stripes are lines of the equal phase shift between ordinary and extraordinary rays. However, another explanation of the reason for their occurrence is possible. The article considers two options for explaining the formation of Kerr bands such as from the point of view of polarization and interference. The conditions for the occurrence of both types of bands are considered. It is shown that kerrograms can be converted into interferograms in bands of infinite width by simply inverting the resulting pattern. The article considers features of the implementation of experimental methods of classical and holographic interferometry. From a practical point of view, they are quite complex and costly. Therefore, it is concluded that for optically active media, in several cases, the experimental methods for obtaining interferograms can be replaced by a simpler electro-optical method, and well-developed methods for processing interferograms can be used for processing kerrograms.

**Keywords:** polarization, interference, holography, optical path difference, Kerr effect, kerrograms, phase shift.

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**Introduction.** Methods of classical and holographic interferometry stand out among the most widespread methods of visualizing transparent phase objects.

However, if the medium in question is nonlinear and optically active, electro-optics based on the Kerr effect can be of great help.

Each of these methods has its pros, cons, and its field of application.

Interferometric methods [1, 2] are realized by creating at least two interfering beams, one of which passes through the object, the other through free space. The resulting interference pattern is determined by the phase profile of the $\Delta\Phi$ field after the investigated inhomogeneity and can serve to determine the required parameters. These methods have several disadvantages — they require alignment of the optical paths of light beams and many optical elements of very good quality. Because here the wavefronts of beams that have passed along different paths at the same time interfere, all additional phase distortions reduce the measurement accuracy.

Interferometry, which was discovered back in the 19th century, and now occupies a worthy place in the arsenal of experimental research methods. Figure 1 shows a setup designed to study laser breakdown of liquids in the nanosecond range [2, 3]. The advent of lasers and computer technology greatly facilitated the work of experimenters, but the shortcomings inherent in the method did not go away. This is the need for very high-quality, and therefore very expensive, optics and a high degree of vibration protection of research facilities.

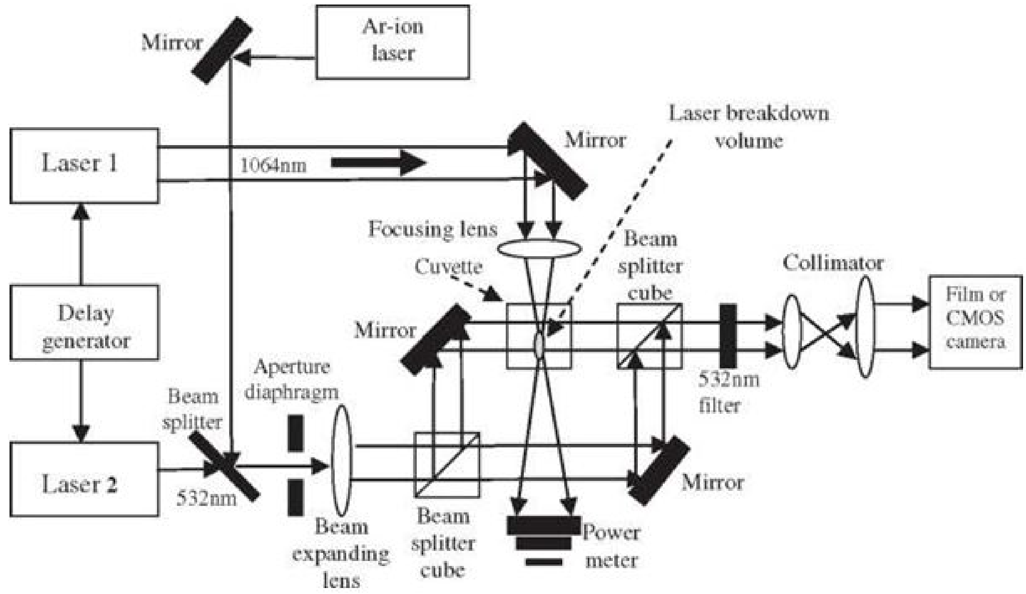


FIGURE 1 – Experimental setup with a Mach-Zehnder interferometer [2]

Figure 2 shows the fragments of the interferograms obtained on the installation.

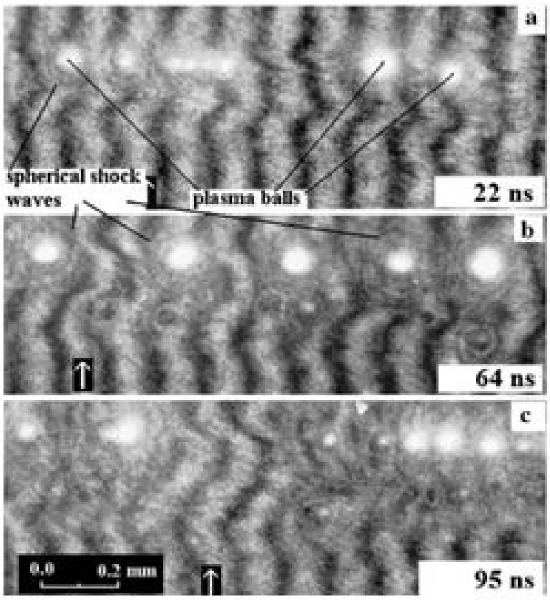


FIGURE 2 – Fragments of interferograms measured at different time delays, illustrating the dynamics of a warmed channel in ethanol. The output of the laser pulse was 65 mJ. The radiation goes from right to left. The arrows indicate the planes where the radial distributions of the refraction index were calculated

Holographic interferometry [4-8] lacks some classical disadvantages. Requirements for the quality of optics are significantly lower since during registration in real-time and by the method of two exposures, the wave fronts of beams that have passed along the same path at different times interfere. All distortions that exist in the optical paths at both exposures are mutually compensated, and only the appeared difference in the phase distribution is recorded. But the number of optical elements is quite large in this case. In addition, it is necessary to ensure the high mechanical stability of the circuit during the entire measurement process.

Holographic interferometers sometimes require even more optical elements than classical ones (Figure 3).

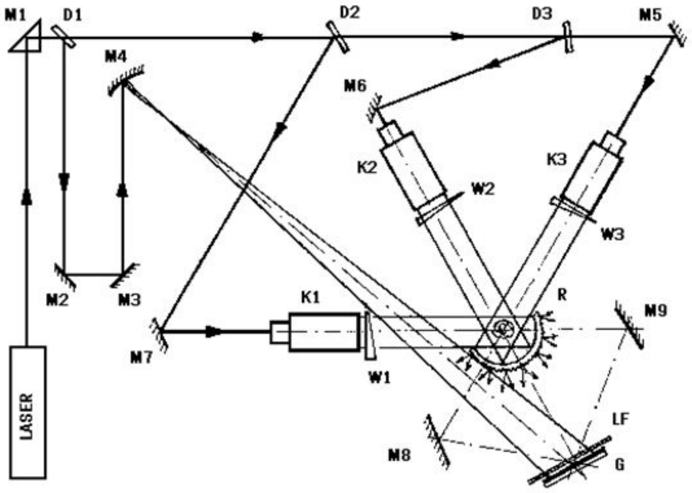


FIGURE 3 – Optical scheme of a 3-angle holographic interferometer [3]

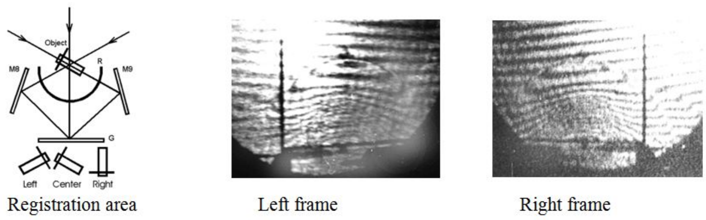


FIGURE 4 – Plasma torch interferograms obtained on the experimental setup with Fig.3

The electro-optical method based on the Kerr effect [9-11] is distinguished by the simplicity of the optical scheme (Figure 5) and does not require vibration protection and high-quality optics. In addition, since the Kerr effect manifests itself under the action of an external electric field (the optical axis is induced in the medium), it becomes possible to relate the optical characteristics of the resulting pattern with the electrical parameters in the investigated region of the object.

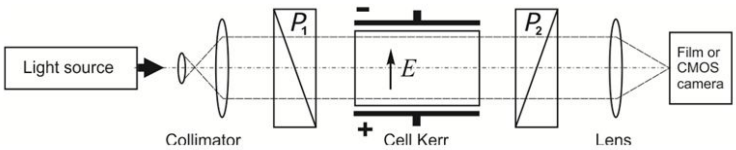


FIGURE 5 – Optical scheme of obtaining Kerr bands

Moreover, the fringe patterns (kerrograms) obtained in this case are very similar to the interference patterns (Figure 6).

FIGURE 6 – Kerrograms — bands of equal phase shift $\Delta\Phi$ between ordinary and extraordinary rays

The commonly obtained Kerr band diagrams are explained in terms of polarization. However, the generality of the form of kerrograms and interferograms suggests a connection in this case between polarization and interference phenomena. In addition, the simplicity of the optical design is captivating. For these reasons, it makes sense to try to understand when and how interference methods can be replaced by electro-optical ones.

**The main results.**

**Kerr effect.** If nitrobenzene is placed in an electric field, it will become a nonlinear uniaxial medium with an induced optical axis oriented in the direction of the field.

When a plane-polarized light beam hits perpendicular to the optical axis, it is divided into two beams (ordinary and extraordinary), which move at different speeds and are polarized orthogonally to each other. As light passes through the induced optical axis nitrobenzene, its initial state of polarization undergoes a series of changes.

Depending on the angle at which the plane of polarization of the normally incident light is oriented to the optical axis, the ratio of the intensities of the o- and e-rays is different. If this angle is $45\,^\circ$, then the intensities of both rays are the same. A decrease in the angle (towards $0\,^\circ$) leads to a decrease in the intensity of the e-beam, and an increase in the angle (towards $90\,^\circ$) leads to a decrease in the intensity of the o-beam.

If the velocities of the o- and e-rays are different, the refractive indices will also be different, which depends on the strength of the electric field.

$$n_e = n + \frac{2}{3}\lambda B E^2 \qquad \text{and} \qquad n_0 = n - \frac{1}{3}\lambda B E^2, \tag{1}$$

where $n_e$ is the refractive index of the extraordinary ray; $n$ is the refractive index of an ordinary ray; $n$ is the refractive index in the absence of a field; $\lambda$ is the wavelength of light; $B$ is Kerr constant, $E$ is electric field strength.

Due to their different velocities ($\nu_e = c/n_e$, and $\nu_0 = c/n_o$), a phase shift $\Delta\Phi$ arises between the ordinary and extraordinary rays, which after passing the distance $l$ in the medium is equal to

$$\Delta\Phi = \frac{2\pi}{\lambda}(n_e - n_0) \cdot l. \tag{2}$$

Taking into account expressions (1), we obtain for the phase shift

$$\Delta\Phi = 2\pi \cdot B \cdot l \cdot E^2. \tag{3}$$

The light beam (most often it is a laser) at the entrance to the Kerr cell (Fig. 5) is converted by polarizer $P_1$ into a linearly polarized one with a polarization plane oriented at an angle of 45 ° to the direction of the induced optical axis. When passing through the Kerr cell, initially linearly polarized light propagates in the form of elliptically polarized light, which is a superposition of two orthogonally polarized waves with a phase shift (3).

As it propagates through the Kerr cell, the form of beam polarization undergoes changes (Figure 7) — linear, elliptical, circular, elliptical, again linear, and so on. As a result, this leads to the fact that the intensity of the light passing through the analyzer $P_2$ of the Kerr cell crossed with the polarizer $P_1$ changes.

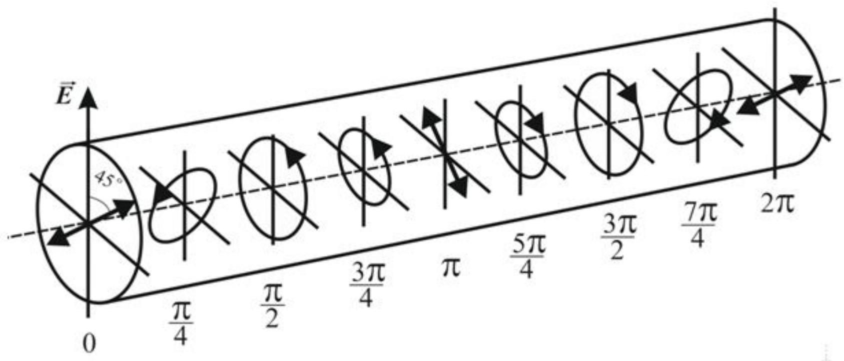


FIGURE 7 – Transformation of the type of polarization of light, depending on the phase incursion when it passes through nitrobenzene in the Kerr cell. E is the direction of the electric field strength vector

The result obtained at the exit from the Kerr cell will be considered from two positions: polarization and interference.

**Polarization.** Depending on the ratio of $E_o$ and $E_e$ , the angle $\alpha$ between the resulting vector $E$ and the transmission plane of the output polarizer $P_2$ changes the intensity of the light transmitted through it [9].

$$I = I_0 \cdot sin^2(\alpha) = I_0 \cdot sin^2\left(\frac{\Delta\Phi}{2}\right) = I_0 \cdot sin^2(\pi \cdot B \cdot l \cdot E^2).$$

As a result, we get a picture of Kerr bands, which are lines of equal phase shift. The maximum will be if:

$$sin^2\left(\frac{\Delta\Phi}{2}\right) = 1 \quad \Rightarrow \quad \frac{\Delta\Phi_{max}^{(k)}}{2} = \frac{\pi}{2} + m\pi = (2m+1)\frac{\pi}{2}$$

or

$$\Delta\Phi_{max}^{(k)} = (2m+1)\pi \qquad (light\ fringe).$$

The minimum will be if:

$$sin^2\left(\frac{\Delta\Phi}{2}\right) = 0 \quad \Rightarrow \quad \frac{\Delta\Phi_{min}^{(k)}}{2} = m\pi$$

or

$$\Delta\Phi_{min}^{(k)} = 2m\pi \qquad (light\ fringe).$$

Here m = 0, 1, 2, 3, ...

Figure 8 shows the kerrograms obtained near the tip of the tip-plane system at the pre-breakdown stage of the electrical breakdown of nitrobenzene [13].

FIGURE 8 – Kerrograms — bands of equal phase shift $\Delta\Phi$ between ordinary and extraordinary rays

**Interference.** Two conditions must be met for the interference of polarized rays.They must be coherent, and their polarization planes must coincide. Coherence is achieved by the fact that o- and e-rays are formed from one plane-polarized ray when it enters a nonlinear medium. And the condition of parallelism of the polarization planes is given by the analyzer $P_2$ (Fig. 5), passing from both beams only those components that coincide with its transmission plane (item 5 in § 79 [14]).

Thus, after passing through the polarizer $P_2$ , the oscillation planes of the vectorsof the E o- and e-rays coincide and there is an optical path difference between them

$$\Delta s = \frac{\Delta\Phi}{2\pi}\lambda, \tag{4}$$

therefore, they can interfere. In this case, the maxima will be observed if an even number of half-waves fits on this path difference

$$\Delta s_{max} = \tfrac{\Delta\Phi}{2\pi}\lambda = 2m\tfrac{\lambda}{2} \quad or \quad \Delta\Phi^{(in)}_{max} = 2m\pi \quad (lightfringe),$$

and the minima, if — an odd number of half-waves:

$$\Delta s_{min} = \tfrac{\Delta\Phi}{2\pi}\lambda = (2m+1)\tfrac{\lambda}{2} \quad or \quad \Delta\Phi^{(in)}_{min} = (2m+1)\pi \quad (dark\ \ streak).$$

**Comparison of interferograms and kerrograms.** Comparison of the conditions for the maxima and minima of interferograms and Kerr band patterns shows that they are reciprocal.

Table 1 - Conditions of minimums and maximums

| **Interferograms** | **Kerrograms** |
|---|---|
| $\Delta\Phi^{(in)}_{max} = 2m\pi$ | $\Delta\Phi^{(k)}_{max} = (2m+1)\pi$ |
| $\Delta\Phi^{(in)}_{min} = (2m+1)\pi$ | $\Delta\Phi^{(k)}_{min} = 2m\pi$ |

Both classical and holographic interferograms are of two typessuch as in bands of finite and infinite width. Let's consider both types of customization.

**Tuning to strips of finite width.** When registering interferograms in bands of finite width, the circuit is first tuned to an infinitely wide strip (uniformly illuminated or darkened registration field), and then one of the beams is shifted (introducing an additional phase incursion in a known direction) to obtain a reference system of stripes. In this case, the inhomogeneities in the object appear in the form of curvature of the support system of stripes. A priori information is not needed to decipher such an interference pattern. The sign of the change in the phase incursion, that is, the direction of counting the bands, is set by the direction of the shift of the optical elements of the circuit when creating a system of these bands. In this case, the resulting phase incursion is considered simply as the shift of the band from the reference in fractions of the stripe pitch of the reference picture.

*a* *b*

Figure 9 – Holographic and classical interferograms when tuned to finite width bands: a — holographic interferogram of a plasma bunch output from the electric breakdown channel of a solid dielectric [15]; b — classical candle flame interferogram [16]

**Tuning to strips of finite width.** In case of interference of identical wavefronts propagating in the same direction and having a phase incursion constant at all points, the resulting interference pattern is one single strip — dark or light, depending on the phase ratio of the interfering waves. With this method of tuning, the changes made by the object will appear in the form of closed interference fringes, both outlining the inhomogeneity and located inside it. However, such an interference pattern can be deciphered only by a priori knowing the sign of the change in the phase incursion when passing from one band to another. This information is missing in the resulting picture.

*a* *b*

Figure 10 – Holographic and classical interferograms when tuned to an infinitely wide band: a — holographic interferogram of a plasma bunch output from the electric breakdown channel of a solid dielectric [15]; b — classical candle flame interferogram [16]

**Conclusion.** Thus, both kerrograms and interferograms, when tuned to an infinitely wide band, register the distribution of optical inhomogeneities in the observation area. But, if the interference fringes are lines of equal optical path difference is of the interfering waves, then the kerrogram is the lines of equal phase shift S between the ordinary and extraordinary beams that emerged from the Kerr cell.

The conditions for maxima and minima for interferograms and kerrograms are reciprocal (Table 1). Therefore, if we invert the kerrogram, we get an interferogram. In the process of registering a kerrogram, a picture of reference bands is not created, and when decoding kerrograms, a priori information about the sign (direction) of the phase shift change is also needed. Therefore, the resulting interferogram will correspond to an infinitely wide bandwidth setting.

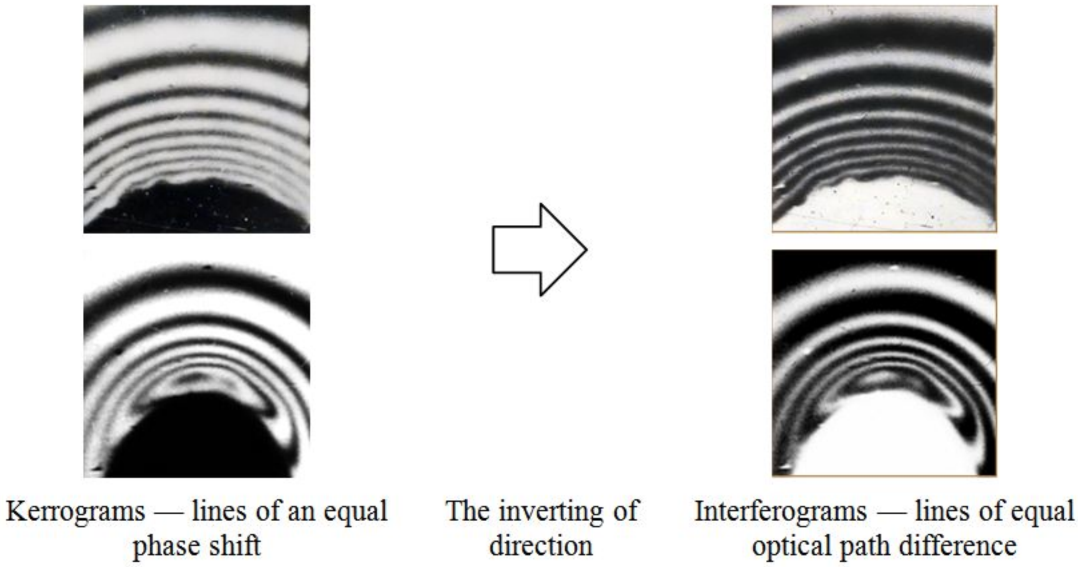


FIGURE 11 – Inverted kerrograms as an analogue of interferograms when tuned to an infinitely wide band

Thus, the obtained kerrograms after inversion can be decoded using any of the currently developed methods for processing interferograms in bands of infinite width. Although the problem of determining the direction of the phase shift does not disappear.In addition, for optically active media the difficult experimental methods of obtaining interferograms can be replaced by a simpler electro-optical method.

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**Керр жолағының пайда болуы туралы**

**Аннотация.** Мөлдір орталардың сипаттамаларын және оларда болатын процестерді зерттеу үшін эксперименттік зерттеудің көптеген оптикалық әдістерімен қатар Керр эффектісі кең қолданылады, онда электр өрісіне орналастырылған изотропты зат оптика көмегімен бір осьті кристалдың қасиетін алады. Қолданылатын өріс бойымен бағытталған ось нәтижесінде екі сыну пайда болып, Керр ұяшығынан шыққан кезде жиек сызбасы қалыптасады, бұл интерференция үлгісіне өте ұқсас.

Бұл жолақтар қарапайым және кезектен тыс сәулелер арасындағы фазалық айырмашылықтың тең сызықтары. Сонымен қатар, олардың пайда болу себебін басқа әдіспен түсіндіруге болады. Бұл жұмыста біз Керр жолақтарының пайда болуын түсіндірудің екі нұсқасын қарастырамыз: поляризация мен интерференция тұрғысынан. Жолақтардың екі түрінің де пайда болу шарттары қарастырылады. Көрсетілгендей, керрограммаларды шексіз ені бар диапазондағы интерферограммаларға түрлендіруге болады. Классикалық және голографиялық интерферометрияның эксперименттік әдістерін енгізу ерекшеліктері қарастырылады. Практикалық тұрғыдан алғанда, олар өте күрделі және қымбат. Демек, оптикалық активті тасымалдаушылар үшін бірқатар жағдайларда интерферограмманы алудың эксперименттік әдістерін қарапайым электро-оптикалық әдіспен алмастыруға болады, ал керограммаларды өңдеу үшін интерферограмманы өңдеудің жақсы әзірленген әдістерін қолдануға болады деген қорытынды жасалады.

**Түйін сөздер:** поляризация, интерференция, голография, оптикалық жол айырмашылығы, Керр эффектісі, керрограммалар, фазалық ығысу.

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**О формировании полос Керра**

**Аннотация.** Для исследования характеристик прозрачных сред и происходящих в них процессов наряду с множеством оптических методов экспериментального исследования широко используется эффект Керра, при котором изотропное вещество, помещённое в электрическое поле, приобретает свойство одноосного кристалла с оптической осью, направленной вдоль приложенного поля. В результате возникает двойное лучепреломление и на выходе из ячейки Керра формируется картина полос, очень похожая на интерференционную.

Эти полосы представляют собой линии равной разности фаз между обыкновенными и необыкновенными лучами. Однако возможно и другое объяснение причины их возникновения. В данной работе рассматриваются два варианта объяснения формирования полос Керра: с точки зрения поляризации и интерференции. Рассмотрены условия возникновения обоих типов полос. Показано, что керрограммы можно преобразовать в интерферограммы в полосах бесконечной ширины простым инвертированием полученной картины. Рассмотрены особенности реализации экспериментальных методов классической и голографической интерферометрии. С практической точки зрения они достаточно сложны и требуют значительных затрат. Поэтому делается вывод, что для оптически активных сред в ряде случаев экспериментальные методы получения интерферограмм можно заменять более простым в исполнении электрооптическим методом, а для обработки керрограмм использовать хорошо разработанные методы обработки интерферограмм.

**Ключевые слова:** поляризация, интерференция, голография, оптическая разность хода, эффект Керра, керрограммы, фазовый сдвиг.

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