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Optical systems of a very large chromatism*

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A method of calculations of optical systems of a large chromatism has been elaborated. In this method, a possibly great displacement of the focal plane can occur when the wavelength of the light beam coming from the tunable laser is changed. Three such systems have been designed, and their properties numerically estimated and compared with the results of examinations carried out for the light beams from the argon and dye lasers, respectively. The relative chromatism of order of a few per cent has been achieved. Such systems may find their applications in laser technology, microsurgery and the like.

1. Introduction

One of the very quick methods of changing the focus position of the laser beam in an optical system is to change the wavelength of the generated radiation. In the case of tunable lasers the wavelength may be changed within 10–200 nm [1]. The width $d\lambda$ of the generated line remains practically unchanged and may amount to 10^{-12}–10^{-9} m depending on the resonator construction. The change of the wavelength of the laser beam generated in a dispersive resonator may occur in very short periods of time [2], [3]. The caustics of localization changeable in time may be exploited in the laser processing of material or in the microsurgery [4], and the like. Let us examine the practical possibilities of changing the position of the focal planes of optical systems as a function of the light wavelength. The purpose of this analysis is to elaborate the concept of a focusing system of the highest possible monochromatism, the other geometric aberrations being well correlated. Note that we are looking for optical systems the properties of which would be quite opposite to those of classical systems where the chromatism is usually subject to minimizing procedure.

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2. Analysis of the optical systems aiming at the enlargement of chromatism

Let us first consider the dispersive properties of the optical materials. The glasses of SF, STF, and crystals, such as TiO_2, $SrTiO_3$ and the like, belong to the optical materials of the highest dispersion. A very high dispersion is also characteristic of the elements produced by holographic techniques.

The present work is limited to examination of the possibilities of applying the optical elements produced from the highly dispersive glasses. A convenient measure of the optical dispersive material is the Abbe number defined, in a given wavelength interval, by the following formula [5], [6]:

$$\nu_{12} = \frac{n_{12}-1}{n_1-n_2} \tag{1}$$

where n_1 and n_2 denote the refractive indices for the edges of the given wavelength interval, while n_{12} is the average value of the refractive index. For a thin lens it may be shown [6] that the relative change in the focal length $\Delta f/f$ is inversely proportional to the Abbe's number determined for the given wavelength interval $\Delta\lambda$

$$\frac{\Delta f}{f} = \frac{-1}{\nu} = \frac{-1}{n''-1}\frac{\Delta n}{\Delta\lambda}\Delta\lambda \tag{2}$$

where Δn denotes the change of the refractive index in the given range of the wavelengths, while n'' represents the average value of the latter. As can be seen, the relative displacement of the focus for a single lens depends exclusively on the dispersive properties of the material of the lens and not on its geometry. Thus, the relative change of the focal length is directly proportional to the product of the change of the generated wavelength $\Delta\lambda$ and the differential dispersion of the material.

As shown in Figure 1, the differential dispersion $\Delta n/\Delta\lambda$ diminishes rapidly with the increase of the wavelength. Therefore, materials should be chosen so that the spectrum of generation of the radiation be close to the short-wave absorption edge.

In the case of a single dimensions optical element the correction possibilities are very limited and the of the caustics exceed, as a rule, the change of the focal length Δf for small $\Delta\lambda$. Let us analyse the dispersive properties of a two-element optical system. The preliminary analysis shows that the most advantageous is the system composed of two elements the optical powers of which are of opposite signs, and with the dispersion of one of them being distinctly dominant. Such a system may occur in two variants interesting from our point of view; their schemes are shown in Figs. 2**a**, **b**. The displacement of the focal plane ΔS, determined on the basis of the formalism of the matrix transformations of the optical ray in the optical system, is described for both variants by the same formulae (the sign "+" corresponds to the variant from Fig. 3**b**, while the sign "−" – to that from Fig. 2**a**) if $\Delta f_2 \gg \Delta f_1$

$$\frac{\Delta S}{S} = \pm\frac{S}{f_2\nu}; \quad \Delta S = \pm\left(\frac{S}{f_2}\right)\Delta f_2 \tag{3}$$

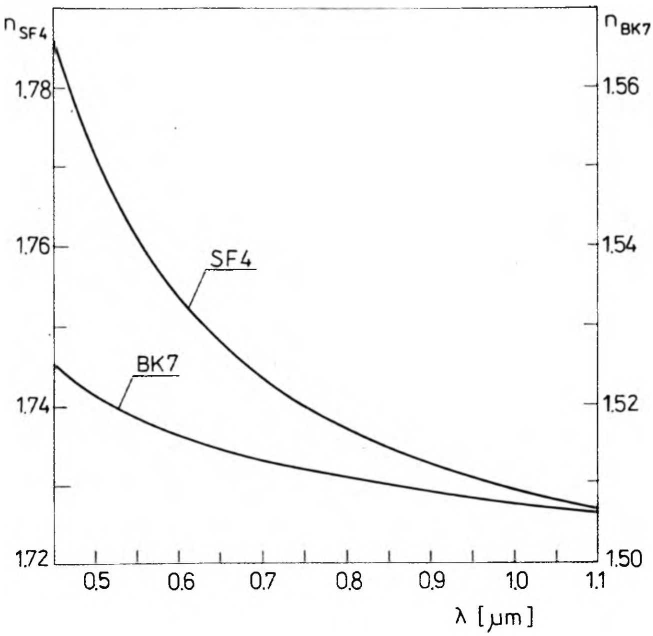

Fig. 1. Dependence of the refractive index n on the wavelength λ for two chosen materials — SF4 and BK7

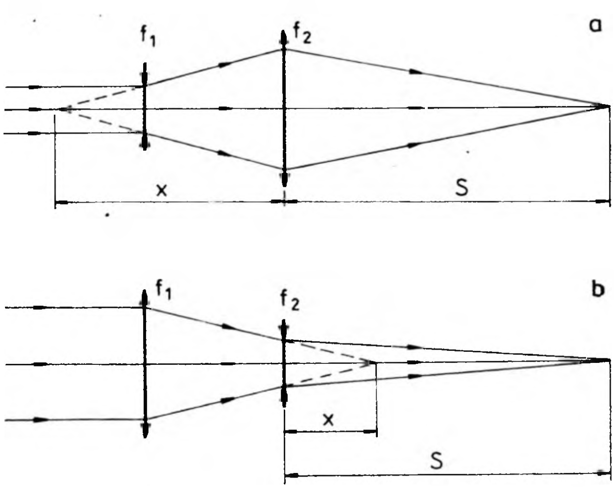

Fig. 2. System with a high-dispersive lens: **a** — positive, **b** — negative

where ν denotes the Abbe number defined in (1), S — the average image distance for the given interval $\Delta\lambda$, while ΔS is the change of the image distance within the $\Delta\lambda$ interval.

As may be seen, both variants show the same properties differing only in sign. The relative chromatism $\Delta S/S$ is linearly proportional to the image distance S and may achieve the values much higher than v^{-1}. These are in reality some modifications of the disadjusted Galileo telescope of the image point located in the finite distance.

In the system presented in Fig. 2**b**, a well-corrected photographic objective may be used as an element of positive power, while the dispersive element may be designed as an aplanatic negative lens [6]. Further analysis has been carried out for the STF3 material characterized by the highest Abbe number [7], see table. The

Dispersion properties of selected optical materials [7], [8]

Material	n_e	n_D	ν_e	ν_D
SF4	1.7617	1.755	27.32	27.52
SF6	1.8318	1.806	25.17	25.36
STF3	2.1683	2.1696	16.89	17.02
STF11	2.0711	2.0557	16.5	16.62
BK7	1.5187	1.5167	63.96	64.17

$\nu_e = \dfrac{n_e - 1}{n_{F'} - n_{C'}}$, $\nu_D = \dfrac{n_D - 1}{n_F - n_C}$ – Abbe numbers,

n_e, n_D, n_F, n_C, $n_{F'}$, $n_{C'}$, – refractive indices for e, D, F, C, F′, C′ lines

calculations have been performed for the range of the argon laser spectrum (476.5–514.5 nm), i.e., for the change $\Delta\lambda = 38$ nm. The assumed linear approximation of the dispersive dependence of the refractive index of this material [7] gives the Abbe numbers $\nu = 75.02$ within this region. The programme KOSO used by us enabled both the determination of the ray trace through the optical system according to the rigorous laws of refraction and the calculation of the wave aberrations. The results of calculations are presented in Fig. 3. The value S of this figure corresponds to an arithmetic mean of the image distance calculated for the extreme values of the refractive index within the $\Delta\lambda$ interval. The angular resolution, being the measure of the imaging quality, is defined as the ratio of the aberration spot diameter Δq to the image distance S.

Both the resolution and the chromatism grow up with the increase of X. At the same time, however, the image distance S becomes greater. As it follows from the preliminary calculations there exists such a configuration of the optical system in which a good correction of the geometric aberrations may be achieved, while the chromatism is kept at a very high value. In the particular cases, it is possible to achieve $\Delta S/S$ equal even to several per cent. The relative chromatism $\Delta S/S$ is linearly proportional to the image distance S. In the up-to-now calculations, it was obviously assumed that the first element of the system was free from aberrations. In such a case, a well-corrected photographic objective of sufficiently great image distance (greater than the focal length of the negative lens) may be employed. Taking advantage of the results of the numerical analysis we have elaborated the concept of the whole optical

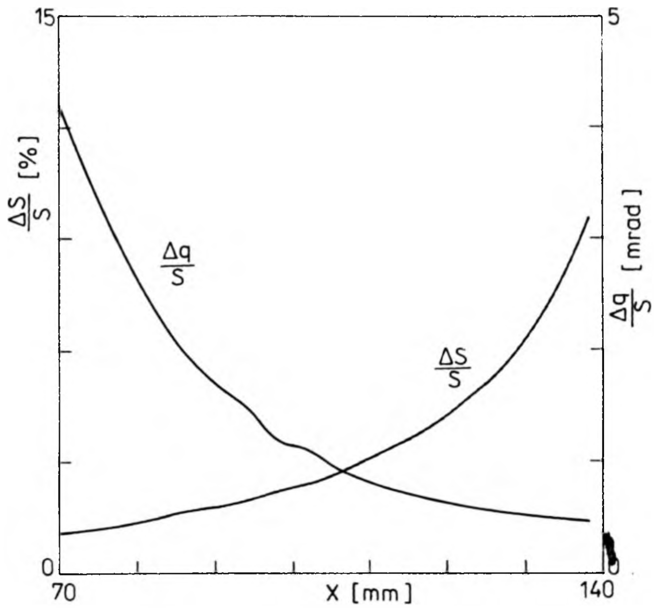

Fig. 3. Dependence of the relative chromatism $\Delta S/S$ and the angular resolution $\Delta q/S$ of the system from Fig. 2**b** on the distance X

trajectory which would realize an essential displacement of the focal plane for a possibly small aberration spot and suitably high aperture angle. The system consists of an axicone employed as a beam expander. Burch mirror objective as a focusing element and a negative lens of focal length $f = -155$ mm as a dispersive element (Fig. 4).

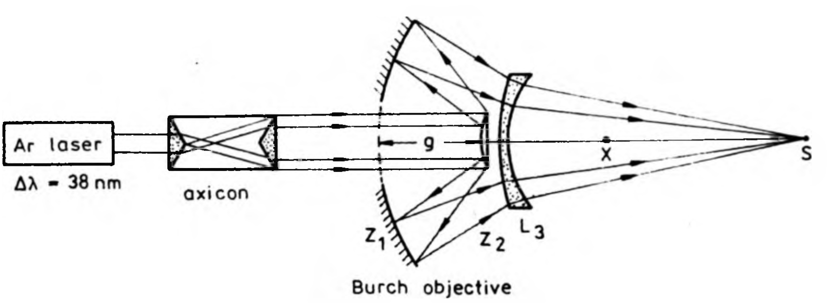

Fig. 4. Scheme of the optical trajectory of the system of tunable caustics and an annular entrance beam

In this system, there exists a possibility of changing the focal length by displacing the mirror Z_2 changing a distance g between mirrors. The fundamental advantage of this solution is that some parameters of the optical system, such as the focal length, aperture angle, and the focus displacement range, can be adjusted according to the needs, while a relatively good resolution is preserved. As a shortcoming, a significant difficulty in the adjustment of the whole unit should be mentioned. Particularly critical is the alignment of the axis of cones in the axicone. Small decentration of any of the objective mirrors worsens essentially the imaging quality. The wave aberrations of such a system may be reduced to some fractions of the wavelength λ (Fig. 5).

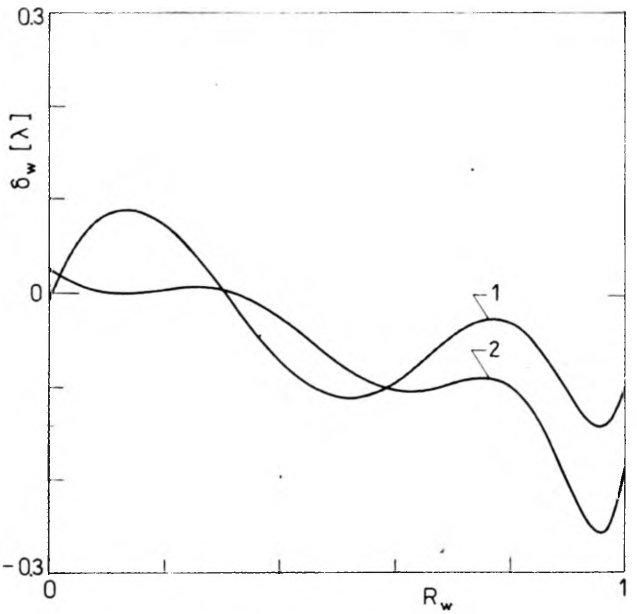

Fig. 5. Wave aberration δ_w as a function of relative radius R_w in the exit pupil of the system for two wavelengths: 1 — for $\lambda = 476.5$ nm, $S = 458.2$ mm, $n = 2.1973$; 2 — $\lambda = 514.5$ nm, $S = 440.7$ mm, $n = 2.815$

In order to examine the properties of the variant *I* (Fig. 2**a**), we have selected the scheme (Fig. 6) which gives the possibility of both good correction and high chromatism. The negative lens is proposed to be made of BK7 glass while the dispersive collective of the SF4 glass. This system is characterized by a high relative chromatism, similarly to the previous one, but by slightly greater spherical aberrations (Fig. 7).

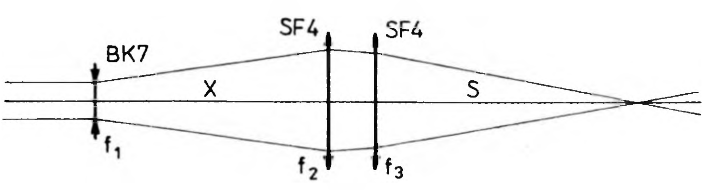

Fig. 6. Optical scheme with a highly dispersive exit collective

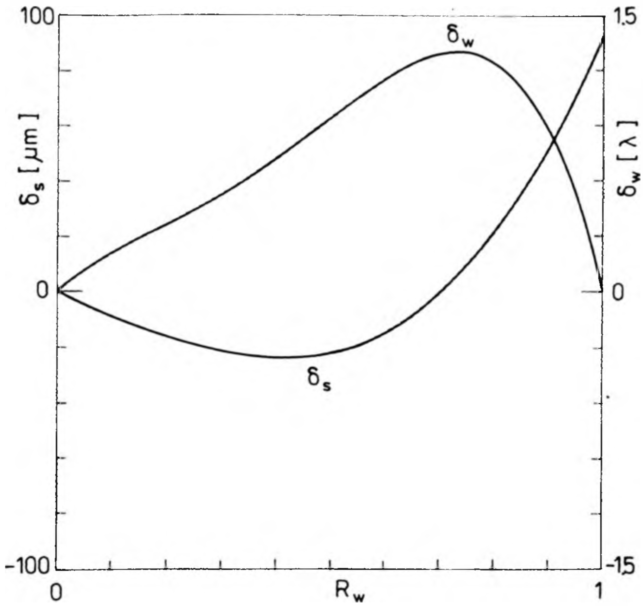

Fig. 7. Spherical aberration δ_s and wave aberration δ_w as functions of the radius R_w in the exit pupil of the system from Fig. 6

3. Examination of the chromatism in the above-mentioned systems

The examination of the chromatism has been carried out by using the beams of an argon laser and a dye laser. Different methods of chromatism measurement have been tested, i.e.:

1. Photographic recording of caustics in a cuvette filled with a smoke.
2. Measurement of focus displacement by using a focusing screen.
3. Scanning of caustics along the optical axis with the help of a detector with a pinhole of diameter comparable with the foreseen diameter of the focus.

The first and second methods are charged with a significant subjective error and are used only to visualization and qualitative estimation of the phenomenon, while the third one offers a much more accurate quantitative estimation of chromatism.

3.1. Examination of chromatism of the system with exit high-dispersive collector

The photographic method of recording the caustics was used in preliminary examinations of the optical system from Fig. 6 (see also Figs. 8**a**, **b**, **c**). Thereupon, the intensity distribution along the optical axis has been measured for several selected

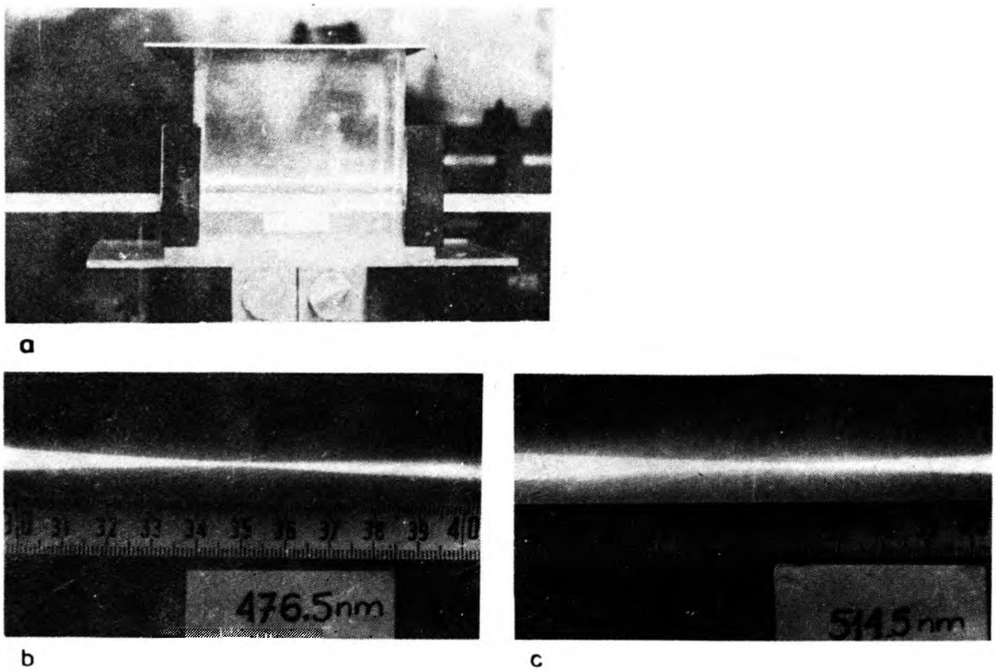

Fig. 8. Set-up for photometric caustics: **a** — photography of the caustics for the laser beam of the wavelength: b — $\lambda = 476.5$ nm, **c** — $\lambda = 514.4$ nm

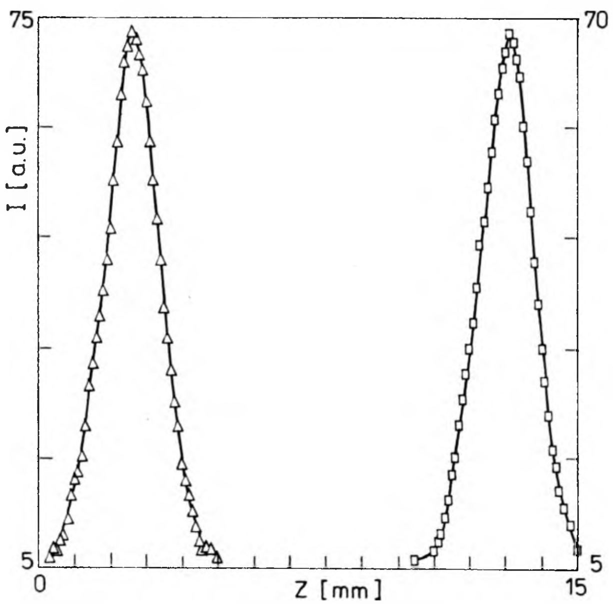

Fig. 9. Results of measurements of intensity distribution I along the optical axis Z for two wavelengths — 476.5 nm (△) and 514.5 nm (□)

values of the image distance S. Since the dispersion of the SF4 and BK7 glasses is well known, the examination of caustics displacement was reduced to the extreme spectral lines of the argon laser light (Fig. 9). As shown in Fig. 10, a good consistence of the experimental results with those foreseen theoretically has been observed.

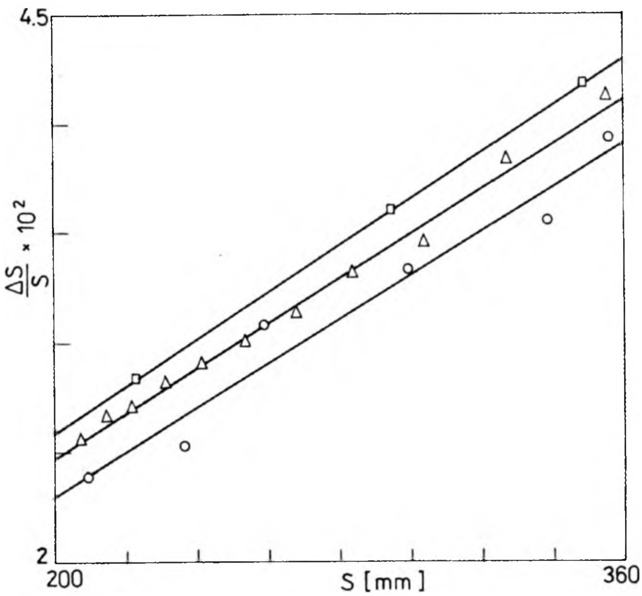

Fig. 10. Relative chromatism $\Delta S/S$ as a function of the image distance S of the system from Fig. 2**b** within 476.5–514.5 nm: △ – results of theoretical calculations, □ – results of scanning along the optical axis, ○ – results of photographic recording

3.2. Examination of chromatism of the system with the negative exit element

In the first part of examinations, a TAIR-33 (300/4.5) teleobjective has been applied as the first element in the scheme presented in Fig. 2**b**. The negative lens of focal length $f = -155$ mm has been produced from the STF3 material. Similarly as in the previous case, the chromatism of the system has been determined in the argon laser spectral range, by applying a focusing screen method of determining the focal plane position. The results of measurements have been compared with those of theoretical calculations (Fig. 11). The slope coefficient for the experimental points occurs to be 1.55 times higher than that calculated theoretically. This is probably due to the fact that the estimation of the STF3 material dispersion has been lowered. The values of the refractive index taken for calculations result from the linear extrapolation of the tabulated values [7], while in reality the dispersion of this material is much higher in this spectral range due to the close vicinity of the absorption edge. For two selected

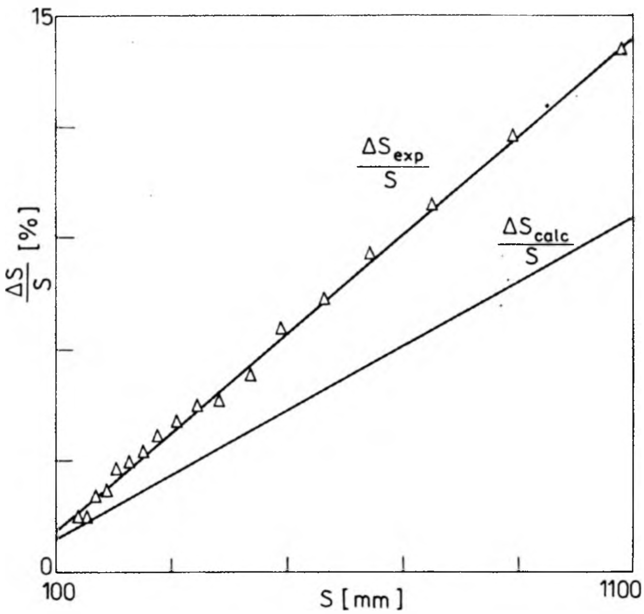

Fig. 11. Relative chromatism $\Delta S/S$ as a function of the image distance S of the system from Fig. **2b** within 476.5–514.5 nm: △ – experimental results, —— results of theoretical calculations

image distances $S = 342$ and 374 mm, the measurements of the intensity distributions have been carried out along the optical axis (Figs. 12, 13). In both cases, the diameter of the focus was comparable with the width of the pinhole and may be estimated as being less than 30 μm.

In the second part of measurements, the optical trajectories have been put together, according to the scheme presented in Fig. 4, and the measurements were made similarly to those performed for the ideal system. However, in this case, the sizes of caustics were not so small due to both the aberrations introduced by the axicone and the errors of adjustments of the system. The axicone worsenes significantly the spatial structure of the beam increasing the sizes of caustics by the same means. The diameter of the focus in this system was about 80 μm. As it was shown in Fig. 14, the length of the focus was so great that the caustics for different lines partly covered one another; this situation was not observed in the case of the ideal system (Figs. 12, 13).

In both cases, the pinholes of diameter comparable with that of the caustics were employed. Thus, the diameter was estimated by assessment. One should expect that the real diameters of caustics were smaller, particularly in the case of an ideal system shown in Fig. **2b**. The geometry of the experiment and the low level of the power which reached the searcher did not allow us to apply a pinhole of a smaller diameter. However, such a method of measurement shows correctly the displacement of caustics for different wavelengths and renders some information about the length of the focus.

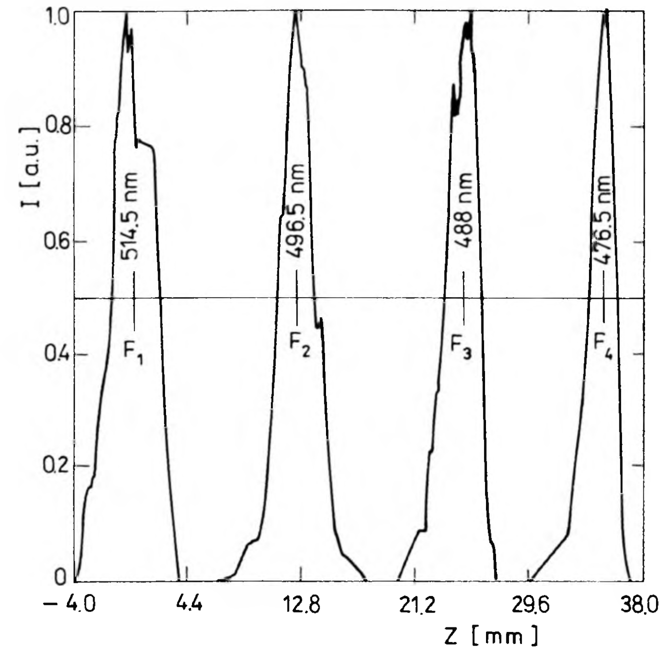

Fig. 12. Results of measurements of the intensity distribution I along the optical axis Z in the caustics of the system from Fig. 2**b** for $S = 474$ mm, for four lines of the argon laser spectrum

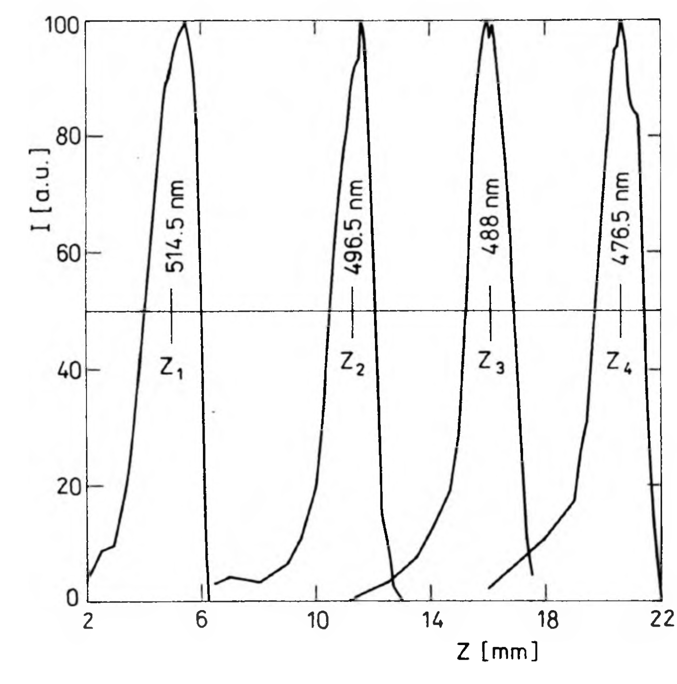

Fig. 13. The same as in Fig. 12, but for $S = 342$ nm

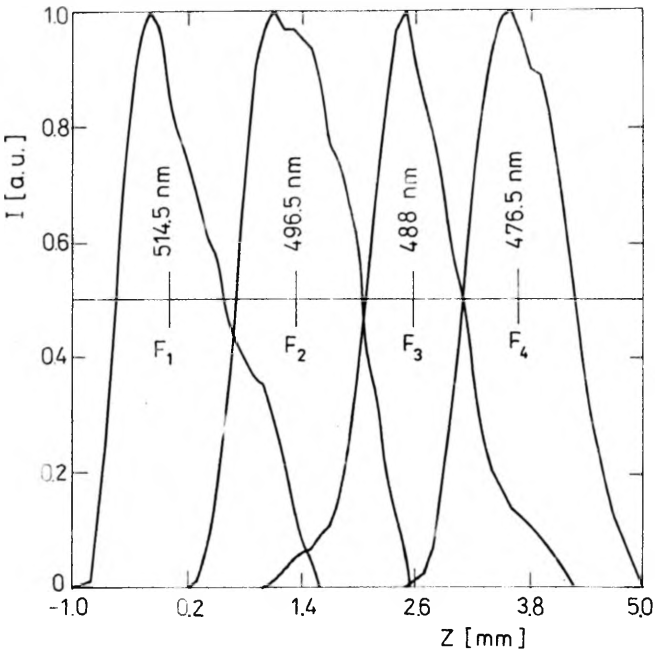

Fig. 14. The same as in Fig. 12, but for $S = 144$ nm

3.3. Examination of caustics displacement for a dye laser beam

When the differential dispersion as a function of wavelength is known, the results of examinations carried out for the argon laser spectrum may be extrapolated to other wavelength ranges. Therefore, a system with the negative lens (Fig. **2b**) has been examined within another range of wavelength changes, a little bit further from the absorption edge of the STF3 material. In the examinations carried out in the Quantum Electronics Section, Institute of Physics, Academy of Sciences, USSR, a pulse rhodamine 6G dye laser pumped by the second harmonics from the YAG pulse laser (Fig. 15) has been used.

The dye laser beam, after passing through a prism beam expander and the focusing system, was scanned in the plane transversal to the optical axis by a slit of 2–4 μm in width mounted to the photodetector window. The focusing system was an achromatic objective of $f = 250$ mm and the same diverging lens made of STF3 of the focal length $f = -155$ mm. The distance between the elements has been adjusted to make the image distance equal to 550 mm. It should be remembered that the geometry of the experiment was two-dimensional, which significantly simplified the adjustment of the optical trajectory and enabled the achievement of a sufficiently high signal level. The results of measurements of the photodetector signal were averaged for the series of 20 pulses, and represented graphically on a monitor and a plotter.

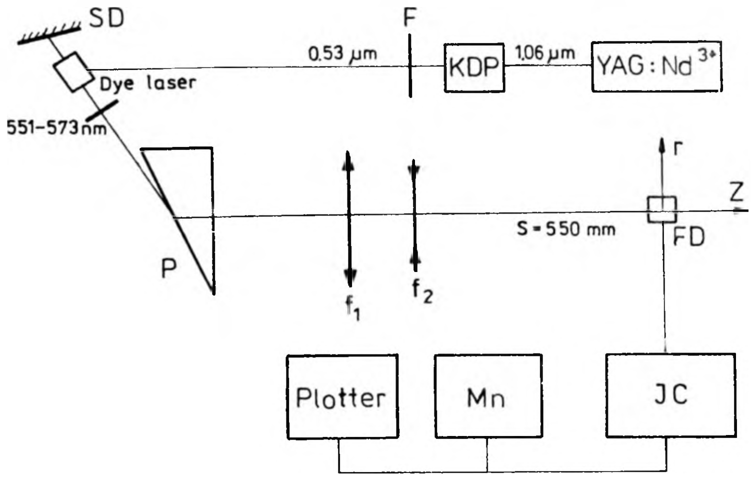

Fig. 15. Scheme of the set-up for examinations of caustic displacement for the dye laser beam: KDP – crystal KDP transducing the beam of the YAG: Nd^{3+} laser into a second harmonic, F – interference filter for $\lambda = 1.06$ µm, SD – reflexive diffraction grating of frequency 1500 lines/mm, P – prism, f_1, f_2 – elements of the focusing system, JC – central unit of the measurement system, Mn – system monitor, FD – photodetector with a measuring slit fastened to the stage assuring the shift along the optical axis Z, as well as in the perpendicular direction r

The examinations were carried out for three wavelengths. For each of them the caustics cross-section has been scanned for different z's. The caustics diameter, determined at the points where the signal dropped down to 50% of its maximum value, amounted to 45 µm. The measurements of intensity (Figs. 16, 17) refer to the maximal value at each cross-section. Hence, no immediate information about the intensity distribution is available along the optical axis. The caustics displacement read out from Fig. 16 in the wavelength range of 551–573 mm is equal to 16 mm. This result may be compared with the result extrapolated into this wavelength range and obtained for the argon laser beam. The caustics displacement read from Fig. 11 for the image distance $S = 550$ mm is 38 mm, while being multiplied by the ratio of the respective intervals of wavelength changes for the argon and dye lasers it amounts to 22 mm. The difference between the chromatism measured for the dye laser beam and the value calculated from the measurements for the argon laser beam is caused by both a significant error of measurement (about 2–3 mm) and a nonlinear dispersion of the STF3 material. As mentioned before, the beam diameter in the caustics is about 45 µm. The waist diameter of the Gaussian beam is about 12 µm for the beam convergence angle measured in the experiment. Hence, the multi-mode coefficient may be estimated as $K_m = 3.75$ in accordance with the definition presented in [9].

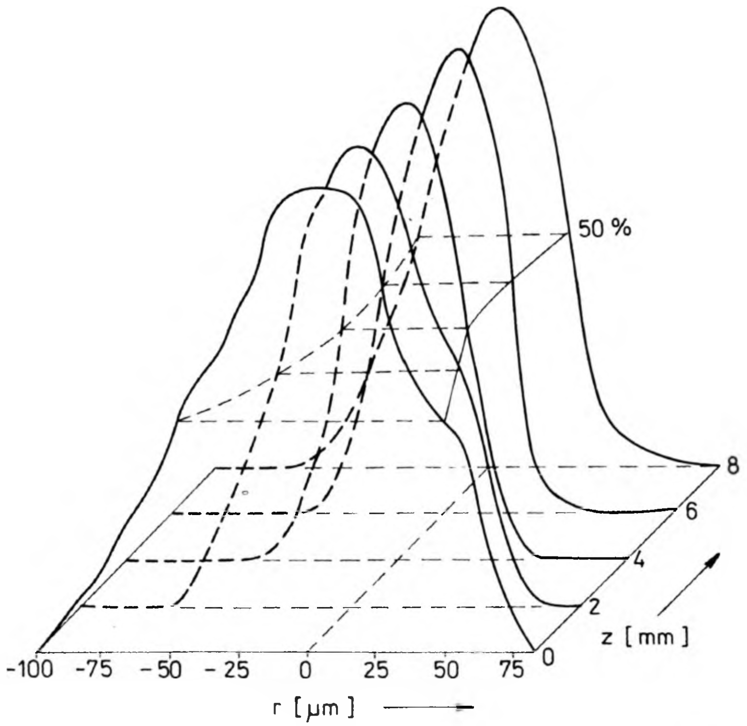

Fig. 16. Intensity distribution of the dye laser beam of the wavelength $\lambda = 551$ nm in the cross-sections in the vicinity of focus

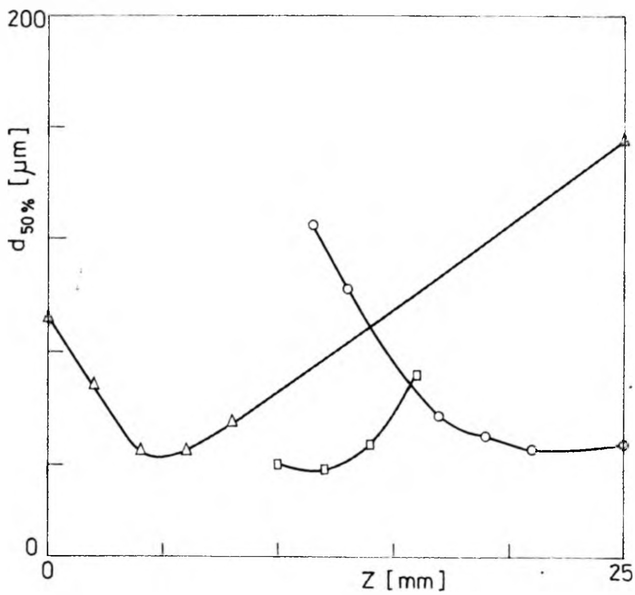

Fig. 17. Dependence of the beam diameter $d_{50\%}$ on the distance Z measured along the optical axis in the vicinity of the focus for different wavelengths: △ — for $\lambda = 551$ nm, ○ — for $\lambda = 560$ nm, □ — for $\lambda = 573$ nm

4. Conclusions

Both the theoretical analysis carried out and the experimental verification of the selected optical systems allow us to formulate the following conclusions:

i) In the wavelength range close to the aberration edge for the optical materials, i.e., when we have to do with a high differential dispersion, it is possible to obtain a very high chromatism exceeding significantly the length of the laser beam caustics even for radiation of low degree of spatial coherence.

ii) In the case when the spectrum range of the neodymium glass laser beam must be used dispersion of the known optical materials is not sufficiently high to obtain a significant chromatism. In this case a holographic lens should be applied, the differential dispersion of which is much more advantageous. The optical systems suggested in this paper may be easily adapted to the use of holographic elements, all the more because such elements may be produced in aplanatic versions.

iii) The methods of caustic displacement measurements applied in the present work yield reliable results. However, if the measurements of intensity distribution in the same caustics are necessary, a significant improvement of accuracy is indispensable. For the beams of divergence approaching the diffraction limit, the measurements should be performed with the accuracy of 2–5 μm and the size of the measurement element should be of the same order.

iv) The estimation of the influence of the system aberration as well as of the spatial coherence state on the caustics dimensions requires a deeper analysis. It seems, however, that in the case of small angles of the beam divergence it will be possible to design and produce a simple focusing system for which the aberration would be negligible and the sizes of caustics depend only on the divergence of the laser beam.

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Оптические системы с очень большим хроматизмом

Разработан метод расчетов оптических систем, в которых получается большое, по мере возможности, передвижение фокальной плоскости под влиянием изменения длины волны пучка перестраиваемого лазера. Изготовлены три такие системы, рассчитаны их свойства и сравнены с результатами исследований, проведенных для пучков аргонового лазера и лазера на красителях. Получен относительный хроматизм порядка нескольких процентов. Такие системы можно применить в лазерной технологии, микрохирургии и т.п.