Optica Applicata, Vol. XIV, No. 1, 1984

Two-mirror focusing system with spherical surface for 10.6 μm high-power laser radiation*

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In mirror focusing systems usually one or two aspheric mirrors are applied which are expensive and difficult to perform. The standard designs of mirror objectives are not suitable to focus the high-power laser radiation emerging from an unstable resonator.

In this paper a simple system of two spherical mirrors, being a modification of the Schwarzschild telescope, is suggested. This system is of corrected spherical aberration of third order. For the sake of comparison the spherical aberration has been determined also from the real ray tracing. The system considered fulfils also the Marechal criterion. The systems of uncorrected IIIrd order aberration better than a single mirror and having other advantages like long frontal focal length have been also considered.

1. Introduction

Technological applications of high-power CO_2 lasers impose restrictions on the laser light focusing system. The requirements concerning resistance of the optical elements to high power levels, to admissible thermal deformations and to the exploitation conditions in the industry, eliminate from the considerations the lens systems based on transmitting materials. The mirror optics makes it possible to adjust the system by using the visible light, to exploit the elements of large diameter and to assure a compact construction. The relatively low usage of mirror optics is, above all, due to the central obscuring of the radiation beam (appearing usually in such a system) which results in high losses. This difficulty may be overcome if an out-off axis ray-tracing is used, which requires the application of aspheric optics or, at least, four-mirror elements with spherical surfaces [1]. The other possibility is to transform the incident beam by using special input systems containing the flat or conic surfaces [2]. A ring-form radiation beam of internal (d_i) and external (d_e) diameters may be also obtained from an unstable resonator of magnification $M = d_e/d_i$. Since such resonators are employed in CO_2 high power lasers then for these lasers there exist mirror optical systems which do not introduce any additional losses caused by the

* This paper has been presented at the European Optical Conference (EOC'83), May 30–June 4, 1983, in Rydzyna, Poland.

central obscuring of the laser radiation beam. The parameters of these focusing systems are determined uniquely by the transversal dimensions of the beam and its magnification M.

In this paper different configurations of focusing system are analysed. In the system of Cassegrain, Ritchey-Chretien, and Dall-Kirham types, the expensive aspheric mirrors were replaced by spherical ones providing that the application of aspheric mirrors was unnecessary. A new configuration of the focusing system that has been proposed, is a modification of the Schwarzschild aplanat [3].

Due to the axial symmetry of both the analysed beam and the telescope only the spherical aberration was considered, providing that a focusing system completely compensated in third-order aberration, may be performed for a limited class of radiation beams. The systems uncompletely corrected, but better than the single mirrors, admitting a larger range of beam magnifications M, as well as offering additional advantage (as long object distance, for instance) were also discussed. The system configurations being the subject of considerations are shown in Fig. 1. The laser radiation beam characterized by the external diameter d_e, and the magnification M hits the mirror 1 and then the mirror 2, being next focused at a distance s from the mirror 2 (Fig. 2). This system is described by two parameters, if dimensionless variables (normalized to the total

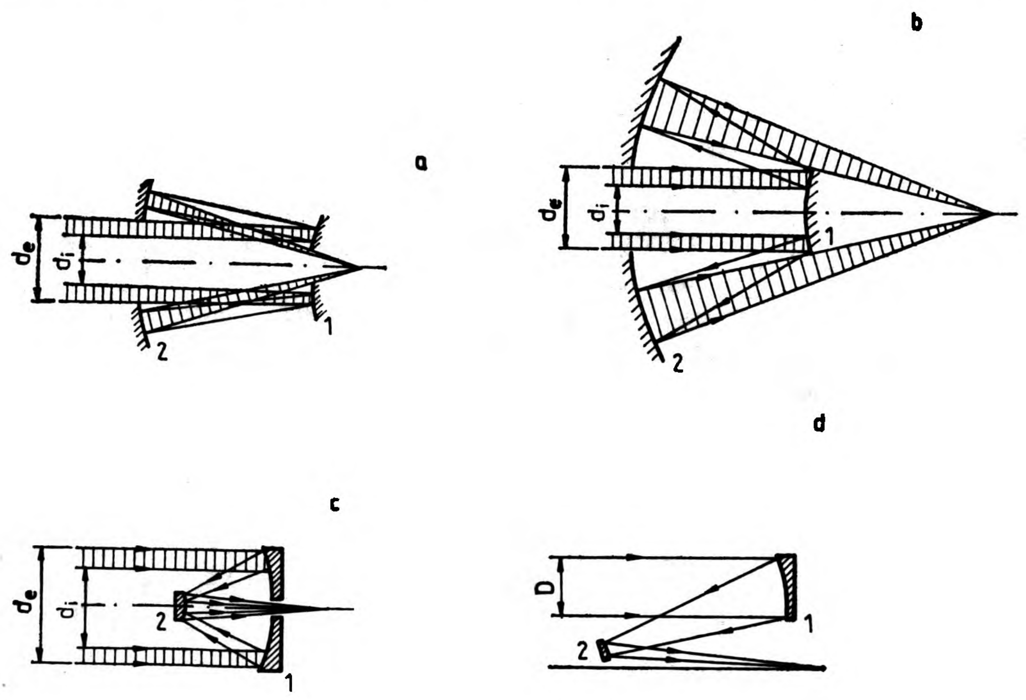

Fig. 1. Configurations of focusing systems with two mirrors: internal focusing system (a), outer focusing system (b), Cassegrain system (c), and Dall-Kirham system (d)

focal distance f of the system) are used. The configurations of the systems from Fig. 1a and 1b are described by the parameters M_+ and f_-, where M_+ is the beam magnification in the plane of the focusing mirror and $f_- = -r_-/2$ is the focal length of the diverging mirror.

The choice of the above parameters proved to be convenient from both the physical and numerical points of view.

For the system from Figs. 1c, d beam magnification in the diverging mirror plane M_- and focal distance of the converging mirror $f_+ = r_+/2$ were assumed as convenient parameters describing the variables normalized to the focal distance. The system in Fig. 1a seems to be the most interesting solution of the focusing system. In this system the mirrors can be easily protected from the influence of the vapours of the processed material by applying the blowing of the protective gas via a hole in the mirror r_-, through which the radiation emerges. It is, therefore, this solution to which the greatest attention is paid.

2. Internally focusing systems

The general geometrical relations for the system derived on the base of paraxial optics are the following (Fig. 2):

$$\begin{aligned} &r_+ = 2f_-M_+/(f_-+1), \quad r_- = -2f_-, \\ &l = (M_+-1)f_-, \quad M_- = f_- - (f_- -1)M_+, \\ &s = M_+. \end{aligned} \tag{1}$$

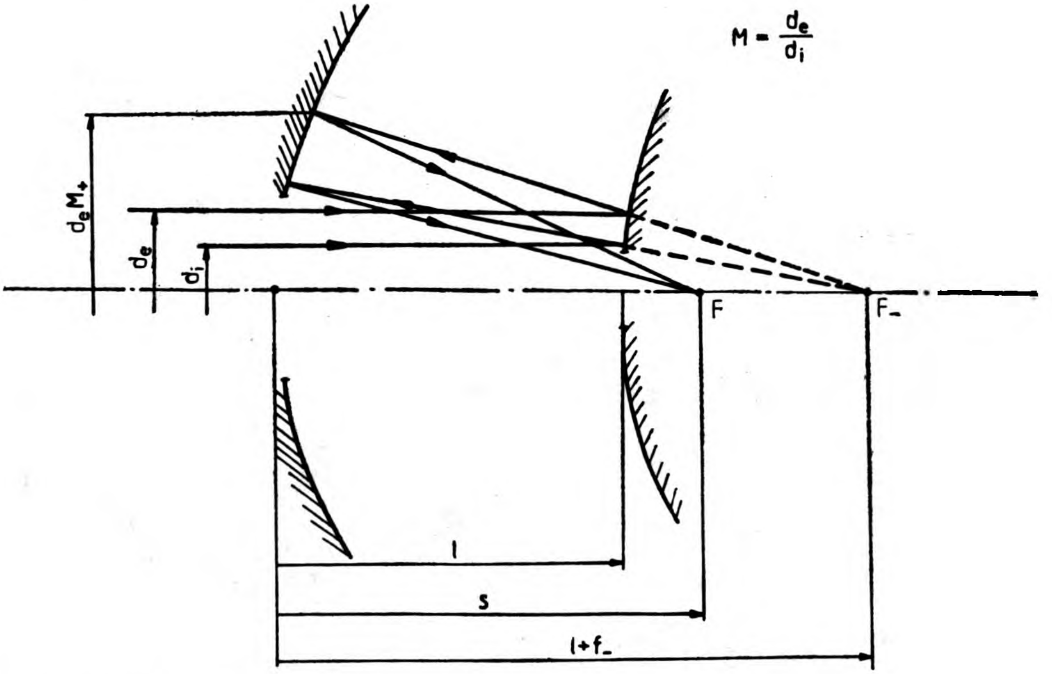

Fig. 2. Two-mirror internal focusing system

For the said configuration of the system, M_+ must be positive, and greater than unity, while in order to avoid the diaphragming $M_+ \geqslant M$ and $M_-^{-1} \geqslant M$. Besides the unequality $f_- > 1$ must hold. This configuration is considered in two variants: (1) the system with corrected third-order spherical aberration, and (2) the system of maximal front focal length.

2.1. The system with corrected third-order spherical aberration

Wave spherical aberration of third order may be presented in the form

$$\Delta = \sum_{i=1}^{\infty} S_i = \sum_{i=1} a_i d^{2i+2} \tag{2}$$

where S_i is spherical aberration of $(i+2)$-order. The wave spherical aberration of third order is equal to

$$S_1 = a_1 d^4 = -2^{-9} f_-^{-3} [M_+(f_-^2-1)(f_--1)-1] d^4, \tag{3a}$$

while the transversal spherical aberration equals

$$\delta_t = 2\frac{\partial S}{\partial d}, \tag{3b}$$

and the longitudinal spherical aberration is given by

$$\delta_l = 4d^{-1}\frac{\partial S}{\partial d}. \tag{3c}$$

For the sake of comparison the longitudinal spherical aberration was also determined immediately from the ray-tracing in the system

$$\delta_l = \{[2f_- M_+/(f_-+1)][1-\sin i_2/\sin 2(i_1+i_2)]\} - M_+ \tag{4a}$$

where

$$\sin i_1 = d/f_-, \tag{4b}$$

$$\sin i_2 = [\sin 2i_1 (f_-+1)/2M_+][2(1-\sin i_1/\sin 2i_1) + M_+ - 1 - 2M_+/(f_-+1)]. \tag{4c}$$

The requirement of zeroing the third-order spherical aberration may be satisfied by choosing the single parameter family of the system described by relations

$$\begin{aligned} M_+ &= (f_-^2-1)^{-1}(f_--1)^{-1} = s, \\ r_+/r_- &= (f_-+1)^{-2}(f_--1)^{-2}, \\ s-l &= s_F = (f_-^{-3}-f_--1)(f_-^2-1)^{-1} = M_-. \end{aligned} \tag{5}$$

Additionally, obvious requirements $M_+ > 1$ and $s > l$ are valid which leads to the following restrictions:

$$f_{-\min} < f_- < (\sqrt{5}+1)/2 = f_{-\max} \tag{6}$$

where

$$f_{-\min} = \left(\sqrt[3]{1+\sqrt{23/27}} + \sqrt[3]{1-\sqrt{23/27}}\right)/\sqrt[3]{2} = 1.324718$$

is a solution of the equation $f_-^3 - f_- - 1 = 0$.

For $f_- < f_{-\min}$ the focus of the system lies in its inside, while for f_- greater than $f_{-\max}$, M_+ becomes less than 1. For the above range of variability of f_- the magnification M_+ varies from 1 to about 4.08 (for $f_- = f_{-\min}$). This means, that for the beams of laser radiation of high magnification M no focusing system of corrected spherical aberration may be designed. This is practically of no greater significance, since high magnification M appears in unstable resonators of very high effective transmission, moreover, for great M the beam radiation may be transformed at the expense of relatively low power loss into a beam of M belonging to the interval, in which the compensation of spherical aberration is possible by applying a central diaphragm, provided that M is high enough. For example, the beam of radiation of steady intensity within the circle of diameter d may be transformed into ring beam of magnification $M = 4$ with the loss of about 6%. It is not necessary that the maximum magnification M of the beams concentrated by system be always equal to M_+ of this system. The requirement that the losses due to diaphragming of the beam by the mirrors of the system be equal to zero gives the conditions: $M \leqslant M_+$ and $M \leqslant M_-^{-1}$ (Fig. 3).

For the discussed configuration of the focusing system and for the magnifications less than $M = 1+\sqrt{2}/f_-$ (f_- greater than $\sqrt{2}$) the second condition results in an additional diminishing of maximal values of M

$$M_{\max} = (f_-^2 - 1)(f_-^3 - f_- - 1)^{-1} < M_+, \tag{7}$$

while for $M > 1+\sqrt{2}$ ($f_{-\min} \leqslant f_- \leqslant \sqrt{2}$), $M_{\max} = M_+$ may be assumed. Therefore, the application of beams of $M > 1+\sqrt{2}$ is advantageous. The geometrical dependences concerning the system are illustrated in Fig. 4. The results of calculations of wave aberration of the next order are presented in the graph (Fig. 5).

The analysis of the results of calculations for real behaviour of rays in the system of considered configuration allows us to state that the proper correction of the system is insufficient to make the third-order aberration equal to zero. Much better corrected system is obtained by encountering the third and fifth orders of aberrations. From the analysis given in [5] it follows that the optical correction of spherical aberration encountering the third- and fifth-order aberrations is realized when the longitudinal spherical aberration of the rim aperture ray is equal to zero.

For $S_1 = 0$ from the Marechal criterion [4] it follows that the influence of aberration is small (the decrease of intensity at the focus centre by no more than $20^0/_0$), if the following condition is fulfilled

$$S_2 = a_2 d^6 \leqslant 0.66\lambda, \tag{8}$$

which in dimensional variables leads to the limitation concerning the admissible aperture number N of the system

$$N = f/d \geqslant \sqrt[5]{1.5 a_2 10^4}\, \sqrt[5]{d\,[\mathrm{cm}]/\lambda\,[\mu\mathrm{m}]}. \tag{9}$$

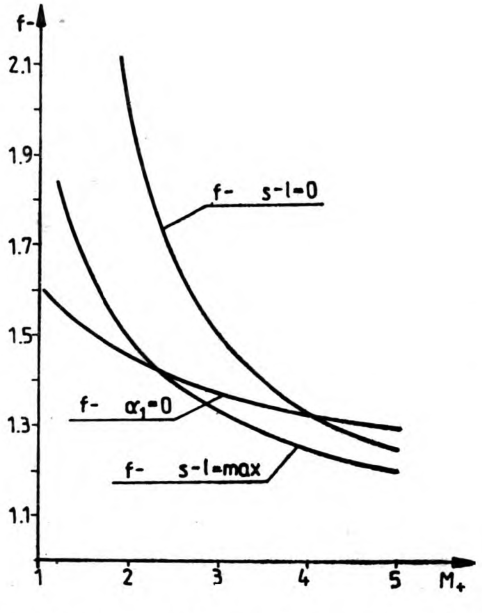

Fig. 3. Focus of divergent mirror as a function of beam magnification at the focusing mirror: III-order corrected system, $a_1 = 0$ (a), maximal frontal focus length of the system, $s_F = \max$ (b), and frontal focus length of the system equal to zero, $s_F = 0$ (c)

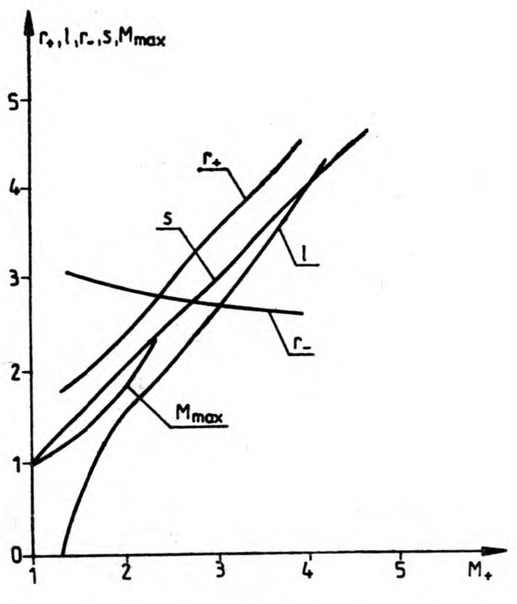

Fig. 4. Geometrical dependences for the internal focusing system with the correction of III-order spherical aberration

For example, let us put $a_2 = 3.6 \cdot 10^{-5}$ and $d = 3$ cm. Then for $\lambda = 0.55$ μm and $\lambda = 10.6$ μm N is greater than 1.24 and 0.69, respectively, i.e., the focal length must be respectively greater than 3.72 cm and 2.07 cm. For minimal admissible focal lengths of the system this corresponds to the spot magnitude at the focus of about 1.7 μm and 17.8 μm. Usually, such a sharp focusing is not used in technological applications of laser beams. Therefore, with approximation justified by the practice it may be assumed that the system is completely corrected. The basic error of the system corrected in third order (especially, for magnifications M from the neighbourhood of the upper limit) is connected with small value of frontal focus length $s_F = s-l$, which for the upper limit ($M = 4.08$) is equal to zero. Therefore, it is reasonable to apply sometimes the system uncorrected with respect to third-order spherical aberration but characterized by a greater value of frontal focus length.

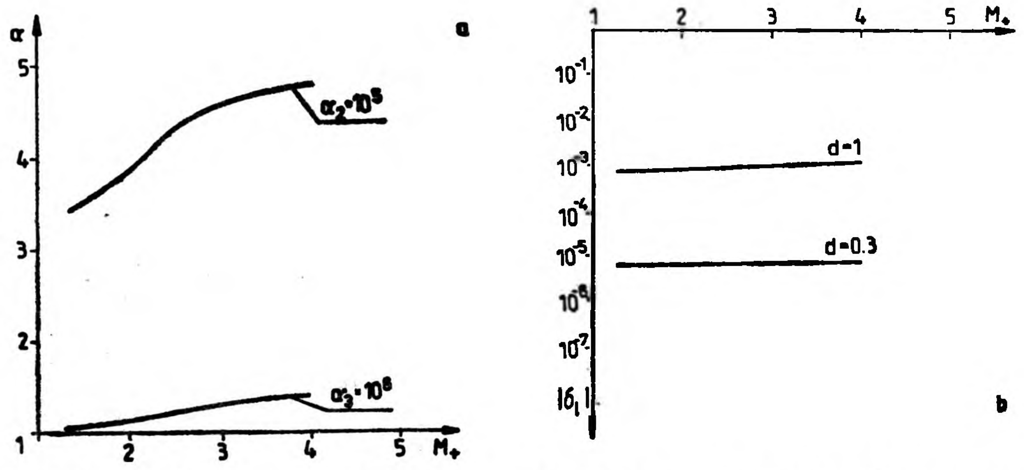

Fig. 5. V- and VII-order spherical aberration coefficients as a function of beam magnification on focusing mirror (a), total spherical aberration computed from ray tracing through the system (b)

2.2. System of maximum frontal focus length

The frontal focus length of the focusing system is maximal if the external ray of the beam passes in the immediate vicinity of the rims of the internal aperture of the mirrors r_+ and r_-. This condition means that a single parameter family of systems characterized by

$$M_+ = M \quad \text{and} \quad f_- = 1+M_+^{-1} \tag{10}$$

is considered.

The basic relations of such systems (Fig. 6) are the following:

$$r_+ = (1+M)(1+0.5\,M^{-1})^{-1}, \quad r_- = -2(1+M^{-1}),$$
$$l = M-M^{-1}, \quad s_F = s-l = M_- = M^{-1}. \tag{11}$$

Simultaneous correction of third order aberration and maximization of the frontal focus length may be obtained only for the beams of magnification $M = 1+\sqrt{2}$. The wave aberration of third-order is equal to

$$S_1 = a_1 d^4 = 2^{-9}[2-(1+M^{-1})^2](1+M^{-1})^{-3} d^4. \tag{12}$$

For the optimally chosen focus position and for coherent illumination the Marechal criterion yields

$$S_1 = |a_1| d^4 < 0.9\lambda, \tag{12a}$$

which restricts the admissible aperture number N of the focusing system

$$N \geqslant 22.3 \sqrt[3]{a_1} \sqrt[3]{d\,[\mathrm{cm}]/\lambda\,[\mu\mathrm{m}]}. \tag{12b}$$

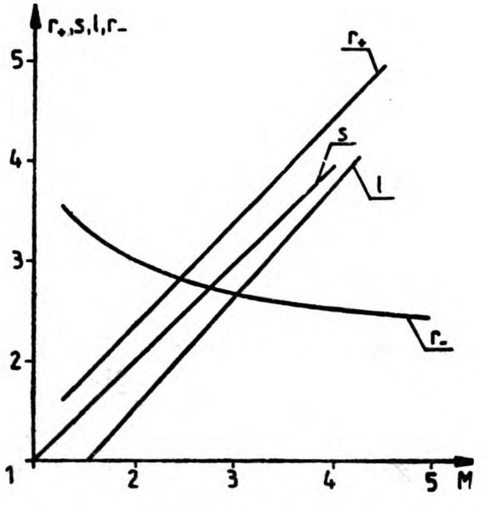

Fig. 6. Geometrical dependences for the internal focusing system with maximal frontal length

For example, for $a_1 = 3\cdot 10^{-1}$ and the other conditions unchanged N is greater than 2.63 and 0.98, the corresponding focal length f being no less than 7.9 cm and 2.94 cm, respectively. If compared with the compensated system, these restrictions did not increase too much, especially for the radiation of a CO_2 laser beam. The results of numerical calculations are presented in Figs. 6 and 7. In Fig. 7 the calculated coefficient of V-order aberration was shown additionally.

Another independent criterion of applicability of a given focusing system configuration is a comparison of its aberration with the aberrations of a single spherical mirror of the same focal length. The graph of the longitudinal spherical aberration for a single mirror is presented in Fig. 8.

The usage of a single mirror offers an advantage of system compactness. Since for a spherical wave aberration of a mirror the relation [4]

$$S_1 = -2^{-9} d^4 \tag{13}$$

holds, we have another condition

$$a_1 \leqslant 20\cdot 10^{-4}. \tag{13a}$$

This is fulfilled, at best, for the magnification close to $1+\sqrt{2}$, since for this value we obtain a system compensated for a spherical aberration of third order and of maximal frontal focus length. The value of the third-order spherical aberration increases with M and, for example, for $M = 5$ we obtain $a = 6.3\cdot 10^{-4}$ which does not satisfy the condition (13a).

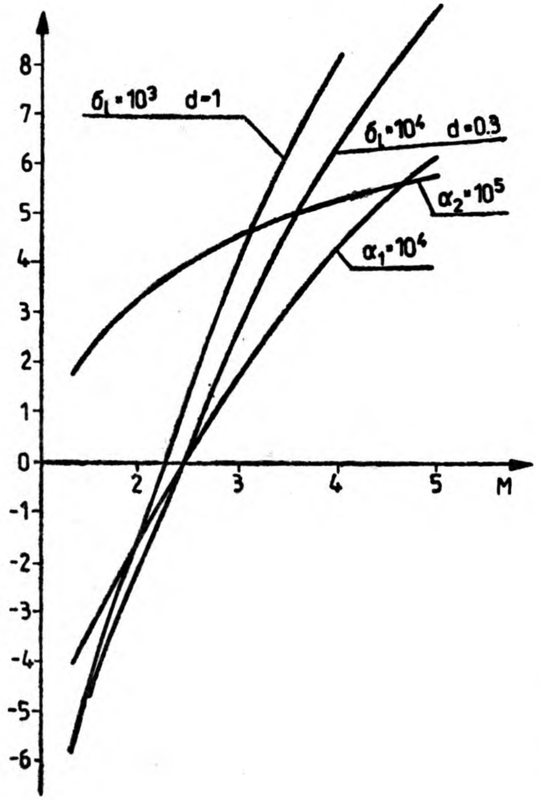

Fig. 7. III- and V-order spherical aberration coefficients as a function of beam magnification on focusing mirror, for maximal frontal focal length and total spherical aberration computed from ray tracing through the system

If the frontal focus length may not be shorter than 1 cm the focal length of the system f must fulfil the inequality

$$f\,[\mathrm{cm}] \geqslant M. \tag{14}$$

For the system compensated for third-order aberrations we obtain analogously

$$f\,[\mathrm{cm}] \geqslant (f_-^2-1)(f_-^3-f_--1)^{-1}. \tag{14a}$$

For example, for $M = 3$ it got $f \geqslant 4$ cm, while for $M = 3.5$ the focal length becomes $f \geqslant 7.5$ cm thus being more than two times greater than for the system of maximal frontal focal length.

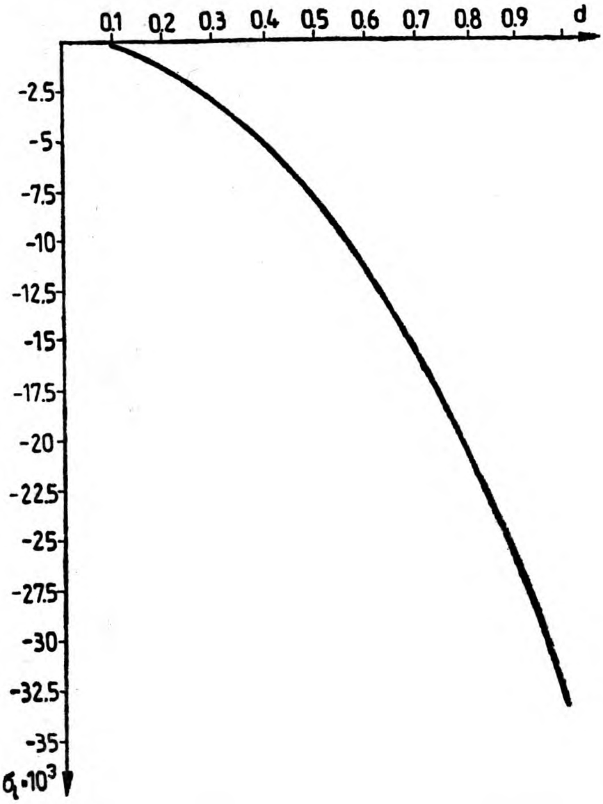

Fig. 8. Longitudinal spherical aberration for a single mirror as a function of beam diameter

3. System with external focusing. Modified Schwarzschild system of spherical mirrors

The geometrical relations derived from the laws of paraxial optics are the same as for the system with external focusing. Only the parameter f_- is contained within the limits $0 < f_- < 1$. A shortcoming of this system is that the maximal magnification of the beam $M_{\max}$ is always less than M_+, i.e., the necessary transversal dimensions of the focusing mirror for given M are much greater than the system discussed earlier

$$M_{\max} = M_- = M_+ - (M_+ - 1)f_-. \tag{15}$$

For the system of compensated third-order spherical aberration it holds

$$M_{\max} = (f_-^2 - 1)^{-1}(f_-^3 - f_- - 1), \tag{16}$$

$$M_+ = [(f_-^2 - 1)(f_- - 1)^{-1}. \tag{16a}$$

The transversal dimensions of the system connected with the magnification M_+ of the mirror r_+ depending on the solution are shown in Table 1.

Table 1

Type of system		Beam magnification, M					
		1.2	1.4	1.84	$1+\sqrt{2}$	3	4
Internal focusing	Corrected III-rd order aberration	1.3	1.6	2.02	$1+\sqrt{2}$	3	4
	Maximal frontal focus	1.2	1.4	1.84	$1+\sqrt{2}$	3	4
External focusing	Corrected III-rd order aberration	1.3	1.6	3.9	4.9	8	18

Theoretically, the system may be now corrected for any value of magnification M. However, this is impossible due to rapid increase of the magnification M_+. From the formulae (16) and (16a) it follows that for $M > 4$ ($(1-f_-) \ll 1$) it may be assumed with a good approximation that

$$M_+ \cong 2(M-1)^2. \tag{17}$$

For example, for $M = 4$ it is required that $M_+ \cong 18.5$ which means that for a beam of the external diameter 3 cm the focusing mirrors should have the diameter greater than 0.5 m.

From the consideration carried out by Bruch [3] it follows that for $f_- = (\sqrt{5}-1)/2$ the correction obtained concerns not only spherical aberration but also astigmatism. For the axial incidence of the laser radiation beam magnification must be greater than $\sqrt{5}$ while the magnification $M_+ = 2+\sqrt{5}$ is almost twice as high. Also in this case the focusing through the aperture in the mirror r_- is much more advantageous. Nevertheless, the Burch telescope may be used for non-axial incidence of the radiation beam when no effect of central obscuring occurs.

4. Spherical Cassegrain telescope

The system of mirrors and the ray tracing in the Cassegrain telescope (as well as in another telescope mentioned in the *Introduction*) are shown in Figs. 1c, d. In this case the following parameters describing the telescope variables normalized to the focal length are assumed: f_+ – focal length of the converging mirror r_+, M_- – magnification of the beam on the diverging mirror r_-. The above parameters change within the 0–1 limits, while it is requested that $s-l > 0$ and $M_- > f_+/(f_++1)$. Similarly as it was in the earlier case, the general geometrical relations are the following:

$$\begin{aligned} &r_+ = 2f_+, \quad r_- = 2f_+M_-(f_+-1)^{-1}, \\ &s = M_-, \quad M_+ = (f_++1)M_- - f_+, \\ &l = (1-M_-)f_+. \end{aligned} \tag{18}$$

Similarly again the spherical aberration of third order is expressed by the formula

$$S_1 = a_1 d^4 = -2^{-9} f_+^{-3} [1 - M_- (1+f_+)(1-f_+^2)] d^4. \tag{19}$$

The correction of the spherical aberration of third order is carried out for the family of systems described by the relation

$$M_- = (1-f_+^2)(1-f_+)^{-1} \tag{20}$$

where

$$M_{max} = M_-^{-1} = (1-f_+^2)(1+f_+). \tag{21}$$

It is easy to show that this case is of no interest, since the maximal admissible beam magnification M_{max} does not exceed the value $32/27 = 1.185$. Also for other single parameter families, such as, for instance, a concentric system of the front focal length equal to zero the obtained spherical aberration is greater than that for a single mirror of the same focal length (Fig. 9). Therefore, if the

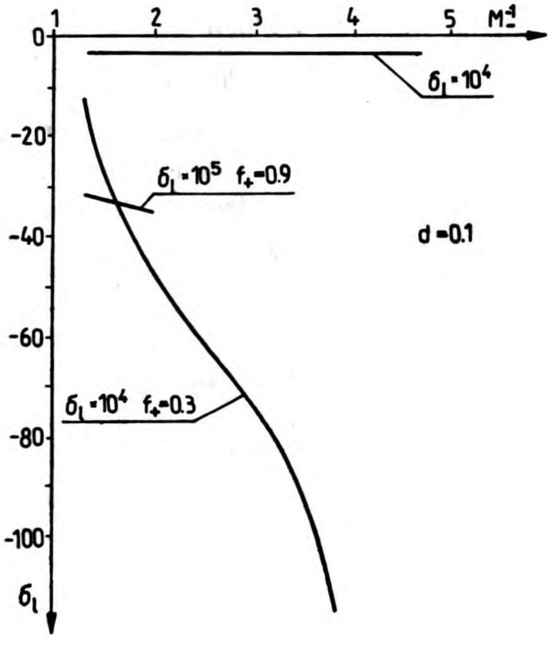

Fig. 9. Total spherical aberration computed from ray tracing through the Cassegraine system and for a single mirror

focusing system configurations described in Chapter 2 may not be applied, due to the external diameter of the beam and its magnification a single mirror with an additional plane mirror declining the converging beam should be used (Newton telescope). In some applications it is more advantageous to apply an oblique incidence of the beam on the single mirror. From the comparison of the Seidel coefficient and the Marechal criterion it follows that the highest limitation for the aperture number N is due to astigmatism

$$N \geqslant 9\sqrt[3]{d\,[\mathrm{cm}]}/\lambda\,[\mu\mathrm{m}], \tag{22}$$

assuming that the mirror deflects the beam in such a way that the focus in the focal plane is to be distant from the beam rim by a half of the beam diameter. If a weaker criterion for the coverage of focus with the beam rim is assumed then the factor 9 in the formula (22) should be replaced by 5.7.

5. The guiding line of the laser beam. Examples of focusing systems applied in praxis

In order to examine the effect of the high power laser radiation on the materials and to elaborate effective methods of interaction enhancement (beside a focusing system) a laser-beam guiding line and a stage moving in a horizontal plane (on which the subject processes will be positioned) must be built. To reduce the losses of the laser beam power in the transmission line the number of mirrors was reduced to the necessary minimum defined by the mutual position of the laser and the processing point and by the requirement concerning the admissible angle of beam incidence on the spherical mirrors as determined by the aberration. The latter may be presented acording to [6] in the form

$$\theta_A < \theta_d \tag{23}$$

where: $\theta_A = 0.5\beta^2/(f/d_e)$ – divergence angle of the beam caused by astigmatism,
$\theta_d = 2.44/d_e$ – diffraction divergence of the beam,

or

$$\beta < \sqrt{4.88\lambda f/d_e^2} \tag{23a}$$

where β is the angle between the incident and reflected beams.

The relative aperture of the system $1/N$ (where N is the aperture number), depends on its destination. For example, the systems of relative apertures equal to 1:18 are applied to hardening, the systems of relative aperture equal to 1 : 6 being used for cutting.

Scheme of the system is shown in Fig. 10. A divergent beam of magnification $M = d_e/d_i$ contained within the interval 1.4–2.0 emerges from the resonator. The beam falls on a spherical mirror 1 of focal length $f = 1.2$ m transforming the divergent beam into a collimated one. Next, after a reflection from two plane mirrors the beam falls onto a focusing system. Due to a rather long distance of the focusing system from the resonator, the diffraction effect changes the magnification of the incident beam on the focusing system to be contained within 3.5–5 interval.

The dimensions of the focusing systems with internal focusing are listed in Table 2. The calculations for the systems with compensation of third-order spherical aberration and for systems of maximal frontal focus length were carried out under the following assumptions:

– external diameters of the laser beam $d_e = 42$ mm,
– focal length of the system used for hardening $f = 750$ mm,
– focal length of the cutting system $f = 250$ mm.

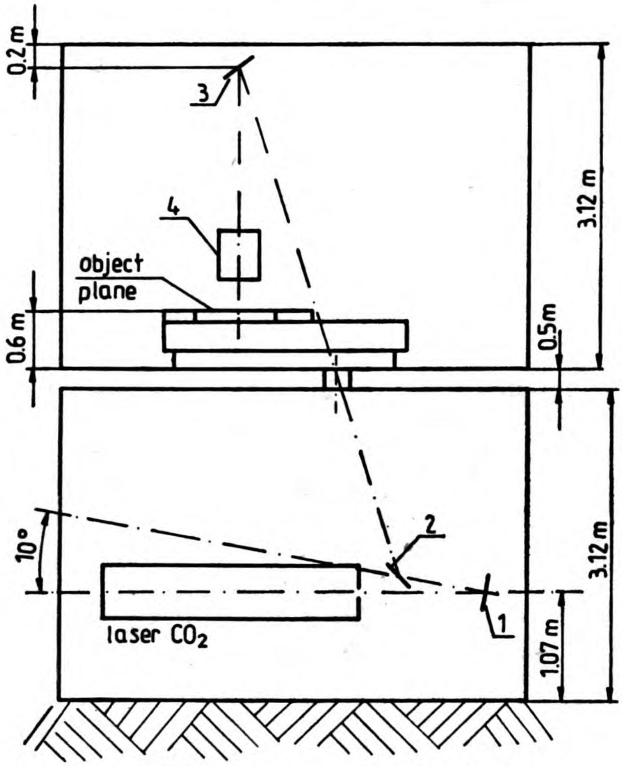

Fig. 10. Tracing of high power CO_2 laser beam: 1 – spherical mirror, 2, 3 – plane mirrors, 4 – focusing system

Table 2

Parameter [mm]	Hardening system		Cutting system	
	s_F = max	$a_1 = 0$	s_F = max	$a_1 = 0$
r_-	1927.5	2025.0	642.5	675.0
r_+	2955.0	2992.5	985.0	997.5
l	2407.5	2505.0	802.5	835.0
s	2625.0	2602.5	875.0	867.5
s_F	217.5	120.0	72.5	32.5
M_+ [1]	3.5	3.5	3.5	3.5

The results contained in Table 2 indicate that hardening does not require the applications of the system of internal focusing since such a solution would

Table 3

Parameter [mm]	Cassegrain hardening system
r_+	450.0
r_-	183.67
l	160.71
s	214.28
s_F	53.57
M_- [1]	0.29

lengthen the setup to such an extent that its adjustment would be very difficult, each mirror being in a separate room. The reasonable sizes of the two-mirror system for hardening, at focal length of 750 mm, are obtained in the Cassegrain system (Tab. 3) or in the system shown in Fig. 11. For this purpose the simplest system is obtained by increasing significantly its focal length (for instance, to 2.5 m) and replacing the plane mirror 3 by a spherical one.

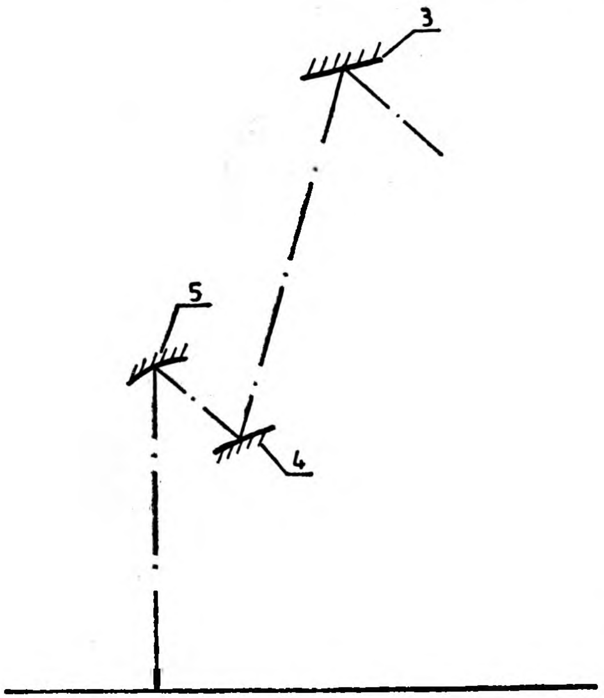

Fig. 11. Two-mirror focusing system for hardening with one spherical mirror: 3, 4 – plane mirrors, 5 – spherical mirror

6. Summary

From the analysis of the focusing system it follows that the spherical mirror optics may be exploited to focus the light power lens radiation. The light aberrations occur only in the Cassegrain system being greater for this system than for a single mirror. The criteria derived allow us to choose an optical construction of the focal system in each concrete case. For instance, if $\lambda = 10$ μm, $d = 4$ cm, and $M = 3 \pm 0.5$, then for $0 < N < 1$ the system of compensated third-order spherical aberration may be used, while for $1 < N < 3.75$ the best system would be that of maximal focal length. In particular, for $N > 3.75$ single mirror may be applied. However, the final option of the focusing system depends on the whole system designed, i.e., on the possibilities of guiding the radiation beam, the required depth of sharpness, the diameter of the laser beam, the maximal diameters of the mirrors and on the detailed requirements, e.g.: to assure protection against displacement of the system during the replacement of the telescope, or the independence of the work-piece distance from the first or the second mirror of the focal length of the system. The last requirement can be fulfilled only when a system with internal focusing is used for cutting and a Cassegrain systems for hardening.

The results obtained indicate that the application of aspheric mirrors is necessary for the majority of the cases met in practice.

References

[1] Shafer D. R., Appl. Opt. **17** (1978), 1072–1074.
[2] Czyż M., Borowicz L., Matczak M., Zgierski M., Cesarz T., Biuletyn WAT, No. 5 (1973), 125–133 (in Polish).
[3] Burch C. R., Proc. Phys. Soc. (London) **59** (1947), 41–46.
[4] Marechal A., Françon M., *Diffraction. Structure des images*, [Ed.] Revue d'Optique, Paris 1960 (in Russian).
[5] Jóźwicki R., *Optyka instrumentalna*, WNT, Warszawa 1970 (in Polish).
[6] *Metal mirror selection guide*, SPAWR Optical Research Report No. 70–004, Corona, CA, USA, 1976.

Received July 2, 1983