Conditions for the dynamic control of the focusing properties of the high power cw CO_2 laser beam in a system with an adaptive mirror

G. Rabczuk[1], M. Sawczak
Institute of Fluid Flow Machinery, Polish Academy of Sciences
Fiszera 14, PL 80-952, Gdańsk, Poland

ABSTRACT

A mirror with a controllable focal length designed for the high power cw CO_2 industrial laser was integrated into the laser beam guiding system in order to verify conditions for the dynamic control of the laser beam focusing properties. The ability of the mirror to correct the thermal distortions in the laser output window was investigated by measuring the beam characteristics versus the mirror shape at different conditions of the laser operation defined by the output power level. The experimental tests prove that the mirror enables dynamic adjustments of the laser beam diameters at the focusing optics and in consequence the control of the focused beam parameters.

Keywords: variable curvature mirror, laser resonator, output beam characteristics

1. INTRODUCTION

There is a growing need in the industrial laser applications for the optical systems allowing active and flexible control of the laser beam properties in the processing region. The possibly simple and cost effective procedures for the adjustment of the laser beam parameters according to the requirements of the specific technological processes are highly required. It concerns not only the power density in the processing zone but also the density distribution across the beam as well as the spatial and temporal stability of the near and far field properties of the laser radiation.

It is commonly recognised that the full control of the focusing properties of the beam in the processing region requires taking into consideration the thermal distortion of the optical elements which are exposed to the laser radiation of high power density. Inevitable absorption of the laser radiation in the laser optical elements[1-2] especially in the transmissive optics like output coupling mirrors, windows and lenses lead to physical changes in their optical properties what next can result in the unacceptable changes of the laser beam characteristics in the processing region. Therefore, the efficient control of the processes accomplished by the laser device, at the whole range of the laser operation parameters, requires also the control and compensation of these effects.

Some solutions to these problems are offered by adaptive optic methods[3-5], which are frequently applied in the modern laser technology for dynamic modulation and controlled adjustment of the laser radiation characteristics as well as for active compensation of various distortions in the laser systems. Due to very high cost and technological complexity of the adaptive systems, the access to them is still limited.

The power dependent behaviour of the laser beam properties was studied experimentally for the industrial system based on the transverse flow DC cw CO_2 laser with the output power controlled in the range from 0.5 to 2kW.

In order to verify conditions for a dynamic control of focusing properties in the processing zone of the laser a mirror with a controllable focal length was integrated into the beam guiding system. The shape of the mirror was controlled by the hydrostatic pressure variations generated in the cooling medium behind the mirror plate.

The influence of the thermal distortions induced in the laser output optics on the beam properties and ability of the deformable mirror to correct them was a subject of the performed investigations.

Correspondence: e-mail: rabczuk@imp.gda.pl

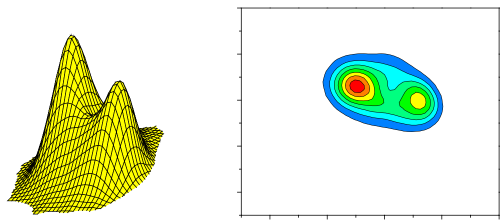
2. INFLUENCE OF THE THERMAL LENSING EFFECT ON THE PROPERTIES OF A HIGH POWER LASER BEAM

The power dependent behaviour of the laser beam properties was studied experimentally for the conventional transverse flow DC cw CO_2 laser with the output power controlled in the range from 0.5 to 2kW. The laser optical cavity characterised by a Fresnel number of 2.4 is a stable, symmetrical resonator of a multipass configuration comprising spherical mirrors with radii of curvature R_1=R_2 =30m. The output coupler is a ZnSe meniscus mirror with 50% reflectivity. The beam is taken out from the laser through the ZnSe window sealing off the vacuum chamber. The laser output beam is directed by a flat reflector to the processing head with a focusing lens located at the distance of 2.2m from the laser enclosure.

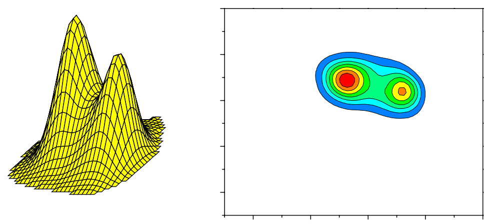
Taking into account the Fresnel number as well as the ratio of the mirror aperture and the fundamental mode size (1.94) in the considered resonator the beam intensity profile corresponding to the mixture of the lower order modes (TEM_{00}, TEM_{01}, TEM_{02}) can be anticipated. The real beam characteristics are influenced not only by a resonator configuration but also by active medium properties including the small signal gain profile, saturation intensity and the medium optical homogeneity.

The laser beam profiles were measured versus the output power by means of a mechanical type beam scanner[7]. According to the ISO standards[8], the beam quality factor M^2 was concluded by a hyperbolic fit to the beam diameters measured along the beam propagation axis versus the distance from the focal plane of a focusing lens. The measurements were performed for the lens with a focal length of 127mm. Independently, the M^2 factor was estimated by measuring the beam diameters in the near field region.

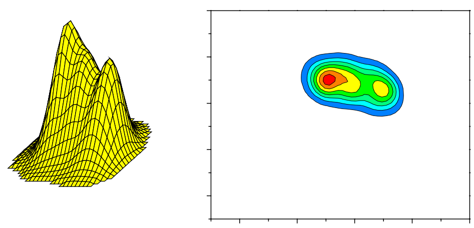
It follows from the measurements that in the linear range of the laser operational characteristics, $P_{out}=f(P_{in})$, the beam quality factor varies, on average, around the value of $M^2 \approx 2.5$. The differences in the spatial beam profiles measured for the output power in the range from 0.5kW up to 2kW are slightly detected. In spite of that, depending on the laser power the marked changes in the beam size on the focusing lens are recorded.



P=1kW



P=1.5kW



P=2.1kW

The examples of the unfocused beam profiles recorded at the distance of 2.6m from the laser enclosure, at the plane of the processing lens, are shown in Fig.1.

The power-dependent decrease of the beam size together with the related increase of the power density at the lens are responsible for the unacceptable changes in the focused beam characteristics including the focus size and its position in the processing region. These effects are ascribed to the thermal lensing at the laser output optics, especially at the ZnSe output window.

In order to verify this conclusion, we estimated the optical distortions in the transmissive optics used in the laser as an output window.

The interference pattern of a probe He-Ne laser beam (λ=632.8nm) was recorded by a CCD camera when the ZnSe window of 50mm in diameter and 6mm of thickness was irradiated by a cw CO_2 laser beam with the diameter of 16mm.

The changes in the interferometer fringe pattern were observed according to the temperature rise while the sample was exposed to the radiation. At the time of ~1min the steady state of the fringe pattern was obtained. After switching off the laser, approximately the same time was required for reaching the pattern corresponding to the initial state of an unheated sample.

By counting the number of interference fringes at the specific distance from the centre of the plate the local optical path difference between the beams reflected by two surfaces of the heated plate was found and the resulting focal length of thermal lensing was calculated.

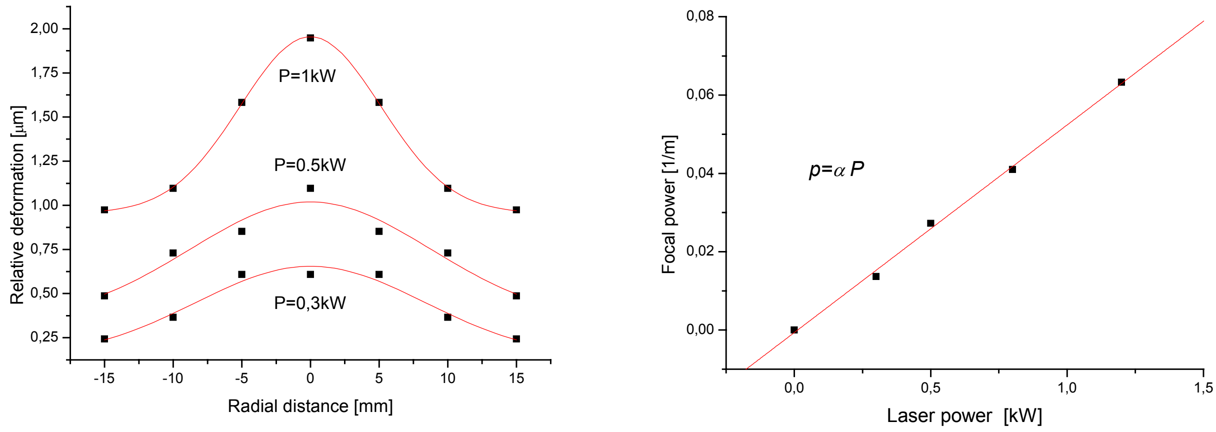


Fig.2 Relative distribution of the deformation of the ZnSe output window as a function of the irradiated power (a), the focal power of thermal lensing in the ZnSe plate as a function of the incident laser power (b)

The results given in Fig.2 show that the thermal deformations corresponding to the non-uniform heating of the ZnSe window follow the nonuniform, gaussian profile of the incident power density. The local deformation, of the ZnSe sample and the resulting focal power of an equivalent thin lens are measured to be linearly dependent on the incident laser radiation. It follows from the measurements that e.g. for P=1kW the effective focal length of the tested ZnSe window is ~19m while for P=1.5kW it is ~13m.

The presented results prove that the beam formed by the laser resonator is additionally modified at the laser output and in consequence, the power dependent changes of the beam diameter are recorded at some distance from the laser output.

3. DESCRIPTION OF THE VARIABLE FOCAL LENGTH MIRROR

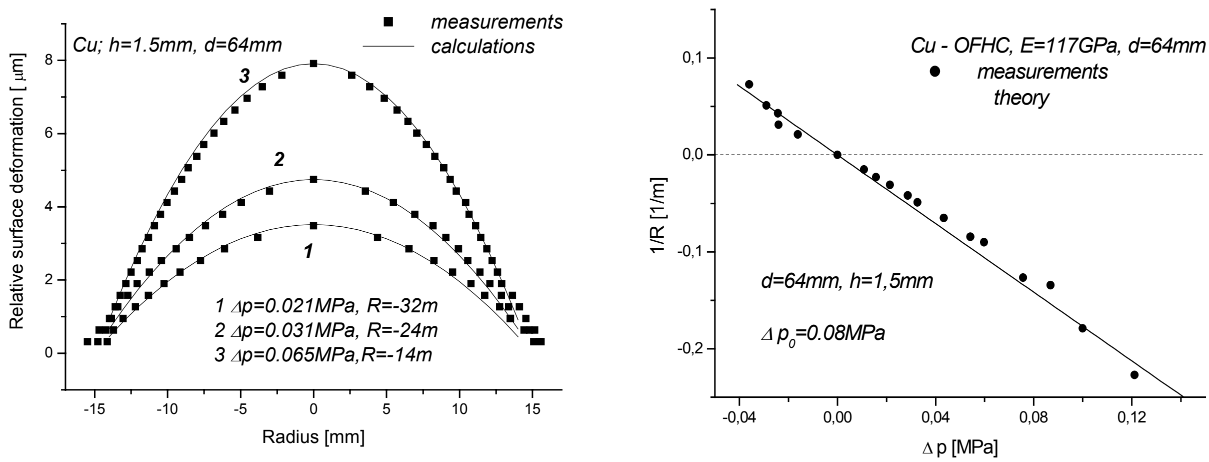
The design of a mirror with a variable focal length is based on the well known and often applied in adaptive optics principle[4-5] of the elastic deformations of a thin plate subjected to a rotationally symmetric and uniformly distributed load of the hydrostatic pressure. As the detailed description of the mirror design and its optical properties was reported in our previous reports[6] only some main features are summarised here.

A mirror surface which is a thin copper (OFHC), gold coated plate, undergoes deformation when the small changes of hydrostatic pressure are generated in a cooling liquid behind the plate. Depending on the thickness and the diameter of the mirror plate, different ranges of focal length are obtained for the same pressure loads. The deforming pressure is controlled by the movement of a piezo-driven piston. The system enables both concave and convex contours of the mirror.

The mirror surface was tested by the interference methods applying He-Ne laser and CCD camera. The examples of the 2D-contours, following the interferogram measurements of the mirror plate deformed by pressure changes are shown in Fig.3a. The analysis of the interferograms proves that in the applied range of pressure changes, the contours of the mirrors have a high level of the rotational symmetry. The results given in Fig.3 concern the mirror plate of the overall diameter 80mm and thickness of 1.5mm. The optical effective aperture is 60mm. Fig 3b presents the experimental dependence of the mirror curvature on the deforming pressure together with the data following the theoretical model for parabolic deformation of a circular plate, fixed at the edge and being under the action of a constant pressure[9].

Due to the mirror processing procedure the initial contour of the mirror (at $\Delta p=0$) is slightly convex and to obtain a flat surface of the mirror it is necessary to apply a small pressure Δp_0 (Fig.3b). Taking into account the value of Δp_0 necessary for a flat surface of the mirror a good agreement is observed between the experimental results and predictions of the theory for elastic deformations.

.



Rys3 2D–contour of the mirror surface resulting from the interferometer measurement (a), *the dependence of the curvature radius on the deforming pressure measured in relation to the atmospheric pressure (b)*

4. FOCUSING CONDITIONS IN A SYSTEM WITH A VARIABLE FOCAL LENGTH MRROR

A developed mirror with a controllable focal length was tested under conditions of the cw CO_2 laser working at the output power of 1kW. The focusing conditions of the laser beam in the system equipped with the developed deformable mirror were tested experimentally for two mirror locations; close to the laser output and in the vicinity of the focusing lens of the processing head. For both cases, the focus diameter and its position were determined from the propagation caustics recorded by means of the laser beam scanner. The results concerning the focal properties of the beam measured versus the focal length of the deformable mirror are gathered in Fig.4.

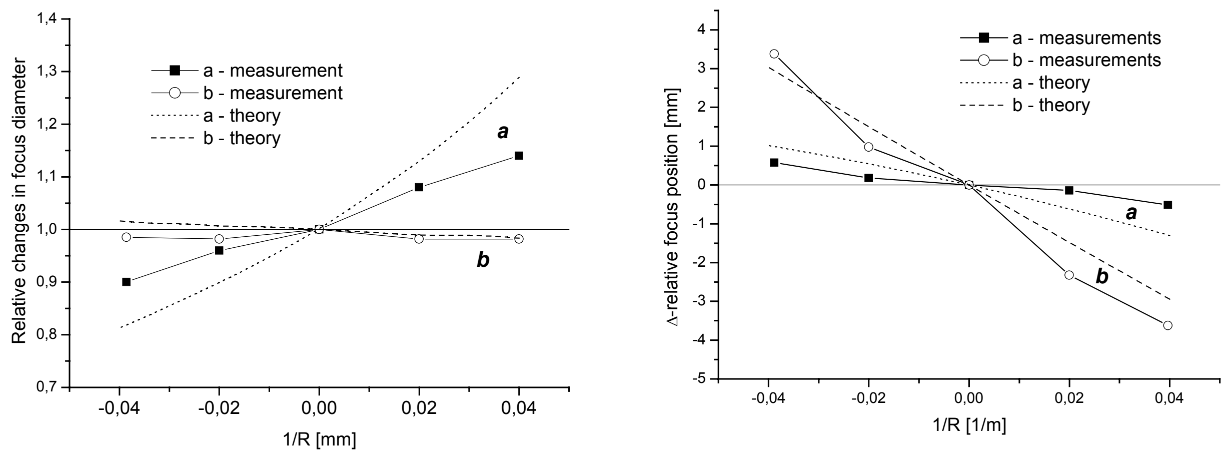
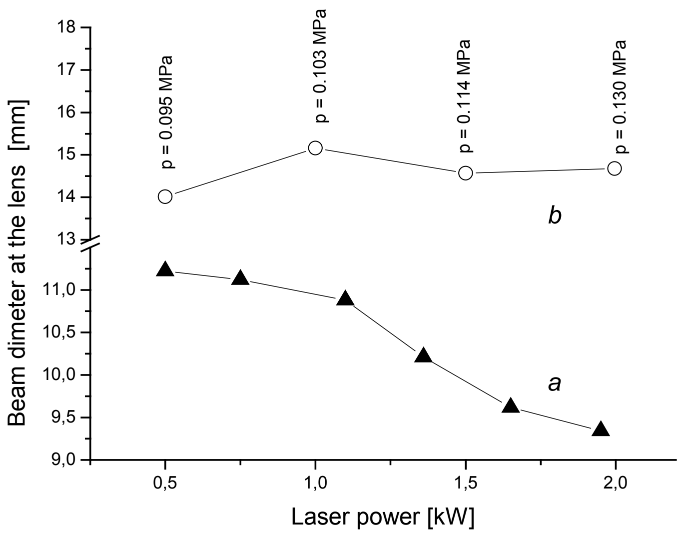


Fig.4 Focus shift and relative changes in the focus size vs radius of curvature of the variable focal length mirror. The measured values are given in relation to the focused beam waist position and its size for the flat mirror; a – the mirror located at the distance of 0.3m from the laser output window, b - the mirror located at the distance of 0.2m from the focusing lens and 4.2m from the laser output

Accordingly to the actual focal length, the deformable mirror located close to the laser enclosure transforms the laser output beam into the new one of the different waist size and the different waist position measured in relation to the focusing lens. It results in variations of the beam diameter at the lens and in respective changes of the focus diameter. For curvature varying from –0.04 [1/m] (convex profile of the mirror) to 0.04[1/m] (the concave one) the increase of abt. 30% in the focused beam size is measured. The focus location measured in relation to the focus position for the flat surface varies in the range of ±0.5mm.

For the deformable mirror integrated into the beam guiding system close to the processing lens the focal length variations result in he focus shift from –4mm up to 4mm. At the same time, the focus size is practically unaffected. Observed variations of the focus size are lower than the measurement accuracy.

As it follows from Fig.6 the experimental results concerning the focused beam properties measured in dependence on the radius of curvature of the deformable mirror are generally in agreement with the theoretical predictions[10] following the gaussian beam propagation model. The discrepancies are ascribed to the fact that in the model the thermal distortions in the laser optics as well as some thermal deformation in the variable focal length mirror are not taken into account. All these effects can additionally modify the beam at the laser output and the real output beam propagation characteristics can differ from those predicted by the model of an undisturbed resonator beam.



In order to test the mirror ability to correct the thermal lens effects especially for the laser beam of the output power higher than 1kW the beam characteristics were compared for the system with and without adaptive mirror. The mirror was integrated into the beam delivery system of the laser at the position close to the laser output

In Fig. 5, the beam diameters at the lens without and with modifications introduced by applying the variable focal length mirror are compared.

The presented results confirm that the mirror of a variable focal length enables dynamic adjustment of the laser beam diameter at the focusing optics at the whole considered range of the laser power and in consequence the influence of the thermal lensing on the focal properties can be compensated.

5. CONCLUSIONS

The power dependent behaviour of the laser beam properties was studied experimentally for the industrial system based on the transverse flow DC cw CO_2 laser with the output power controlled in the range from 0.5 to 2kW.

The measurements reveal the marked influence of the thermal lensing effects in the laser ZnSe output window on the output beam characteristics defining the beam focusing conditions. In order to compensate the influence of these effects the mirror of a variable focal length was integrated into the laser beam delivery system

The mirror tests, performed for a specific output power, prove possibility for the controllable dynamic adjustment of the focus position as well as the focus size in the processing zone, depending on the mirror location in the beam path between the laser and the focusing optics.

The ability of the mirror to correct the thermal distortions in the laser output window was tested by measuring the unfocused beam characteristics versus the output power and the deformable mirror focal length. The performed analysis allows specifying conditions for the compensation of the thermal lensing effect.

ACKNOWLEDGEMENTS

Work was supported by the KBN through the Project PB 1495/T11/2002/22
The authors gratefully acknowledge the technical assistance of M. Piskulski.

REFERENCES

1. 1 H. Takahashi, M. Kimura, R. Sano, "Optical distortion of transmissive optics at high power CO_2 laser irradiation", Appl. Optics 28 (9), 1727 – 1730, 1989
2. E.W. Kreutz, B. Lang, R. Risters, " Investigations of transmitting optical components for CO_2 – laser radiation", Proc. 9. Int. Congress Laser , Optoelectronics in Engineering, Springer-Verlag, 452-457, 1990
3. Keming Du, P. Loosen, H. Kochmann, "Properties of a high-power CO_2-laser with an adaptive mirror", Optics Communications 106**,** 269-277 (1994)
4. M. Hounker, G. Waibel, A. Giesen, H. Hugel, "Fast and compact adaptive mirror", Proc. SPIE 3097, (1997) 310-319, Lasers in Material Processing , Leo H. Beckmann; Ed
5. H. J. Obramski, R. Mastle, A. Giesen, H. Hugel, "Optical measurement and control components for highly dynamic beam guiding and forming of CO_2 laser beams", Laser Opto, 32 (4), 36-42, (2000)
6. G. Rabczuk, M. Sawczak ," High power cw CO_2 laser beam properties in a system with a variable focal length mirror", Proc. SPIE, Laser Optics ' 2003 (in print)
7. G. Rabczuk, M. Sawczak, G. Śliwiński, " Diagnostic instrument for measurements of a high power CO_2 laser beam", Proc. SPIE, 4237, (2000), 212-217,. Laser Technology VI: Progress in Lasers*,* W. Woliński Ed.
8. ISO-norm. Document, "Test methods for laser beam parameters", ISO/TC 172/SC 9, 1995
9. R. Szilard, Theory and Analysis of Plates, Classical and Numerical Methods, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1974
10. H. Kogelnik, T. Li, "Laser beams and resonators", Proc. IEEE 54**,** 1312-1329, 1966