Contributed paper

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Study on the possibilities of controlling the laser output beam properties by an intracavity deformable mirror

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The possibilities of controlling the laser beam properties by a deformable mirror introduced into the laser optical cavity were studied theoretically and experimentally. The experiments were performed under conditions of an industrial high power transverse flow cw CO_2 laser operating with a stable resonator of a folded configuration. A deformable bimorph mirror of a surface profile controlled by the voltage applied to the mirror electrodes is implemented to the laser system as a back cavity mirror or as a one of the inner folding mirrors. The near- and far- field characteristics of the laser beam versus the resonator configuration controlled by the changes of the focal length of the deformable mirror are discussed in the paper. The analysis reveals that the resonator with an inner deformable mirror is much more sensitive to the mirror curvature variations than the resonator in which the deformable mirror is used as a back cavity mirror. The presented results show that dynamic and controllable changes in the resonator properties result in the controlled modification and optimisation of the laser output power and spatial parameters of the laser radiation.

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

1. Introduction

Increasing use of high power lasers in industry has led to the increasing demands concerning the effective methods for optimisation and control of the laser beam parameters, which are responsible for the results of the laser radiation – materials interaction. Improvements in the laser beam characteristics and adjustment of the beam intensity profile to the process result in better coupling of the laser beam energy to the target material and thus in more efficient processing.

Solutions to the problem of the reliable and flexible control of the laser beam properties are offered by adaptive optics (AO) methods. Adaptive optics systems measure the aberrations in an optical system with a wavefront sensor, generate correction signals with a control system, and correct aberrations through active control of a deformable mirror (DM) geometry. The better quality of the wavefront enables better performance of a system.

Significant progress obtained over past decades in the development and design of compact and cost effective deformable mirrors [1–3] has resulted in the moving of adaptive optics technology beyond its traditional applications in astronomy and military observations. Nowadays, AO systems have found numerous applications in scientific research, technology, and engineering. Application examples in scientific fields include uranium enrichment and nuclear fusion where the DM used for distortions compensation in the laser beam allows the high intensity condensation in the target chamber. Examples of technological applications of AO systems include free-space laser communication where DMs have been found to be efficient solution for coupling light into optical fibers, microelectronics industry including laser etching and photolithography, biomedical imaging – especially ophthalmology, and industrial laser processing like cutting, welding, soldering, surface hardening, etc.

Deformable mirrors implemented in the industrial laser systems are mainly used for intra- and extra-cavity laser beam control, and shaping of the laser beam intensity profiles. It has been proved in many experimental reports that the adaptive optics implemented in the high power laser system allow active correction of the laser beam wavefront aberrations, e.g., due to the thermal induced distortions in the laser active medium or/and thermal deformation of the laser optics as well as the spatial mode control and dynamic and controlled adjustment of the focal parameters of the laser beam in the region of a laser processing [4–7].

In this paper, we focus on the intracavity use of adaptive optics to enhance the performance of a high power industrial laser by an active control of the laser output power and spatial parameters of the laser radiation. The use of the controllable curvature mirror within the laser resonator allows the dynamic changes in the resonator configuration that can result in the modification and optimisation of the laser output characteristics decisive for the laser material processing.

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The paper presents the results of theoretical and experimental analysis of the near- and far-field characteristics of the laser beam versus the resonator configuration controlled by changes in the focal length of the adaptive mirror introduced into the laser optical cavity.

2. Laser resonator configuration

The modal performance of a laser system with an intracavity deformable mirror (DM) is investigated for a high power, transverse-flow, cw CO_2 industrial laser designed to operate with a stable multipass resonator of configuration given schematically in Fig. 1. The resonator comprises a total reflector (1) and an output coupler (2) and two flat mirrors (3,4) folding the beam path through the laser active zone between the end cavity mirrors. In a standard configuration, the end mirrors (1,2) of the cavity are spherical with radii of curvature of $R_1 = R_2 = 30$ m. The ZnSe meniscus output coupler (2) of reflectivity 50% collimates the beam leaving the resonator. The resonator is closed in the laser chamber sealed off with the ZnSe output window (5). An effective diameter of the mirrors is $D = 20$ mm and the resonator length measures $L = 4.3$ m. The Fresnel number of the cavity and the stability parameter are equal to $N_F = D^2/4L\lambda \approx 2.2$ and $G = (1 - L/R_1)(1 - L/R_2) \approx 0.7339$, respectively. At nominal conditions of the laser operation, the output power measures $P = 1.5$ kW for the beam quality factor of $M^2 \approx 2.8$.

The deformable mirror used in our experiments was developed and manufactured at Turn Ltd, Russia [8]. It is a molybdenum water-cooled mirror of a bimorph type with seven control channels. The total diameter of the mirror aperture is 60 mm and the diameter of the active controlled region is 25 mm. The reflecting surface of the mirror is provided with a high reflectivity coating for the wavelength of 10.6 µm. The mirror surface is deformed by applying the voltages to the control channels from the range of –150 V up to +250 V. The voltage is supplied to the mirror from the electronic unit via a personal computer. The convex profiles of the deformable mirror surface are obtained when the same positive voltages are applied to all mirror actuators. The concave profiles of the mirror are obtained for the negative voltages.

The deformation characteristics of the mirror specified by the manufacturer were verified in the independent interferometric tests. The mirror was tested in the interferometer based on the Twyman-Green configuration, with using He-Ne laser operating at 633 nm as an illumination source and CCD camera as a detector. Interferograms for the deformed mirror surface were recorded and analysed in terms of the Zernike polynomials coefficients [9] for different combination of voltages applied to the active channels. Different combinations of the active channels and their voltage form different shapes of the deformable mirror reflective surface.

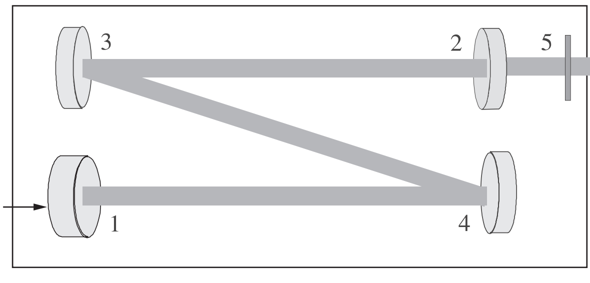

Fig. 1. Diagram of three-pass folded resonator of the transverse flow cw CO_2 laser.

For the purpose of the analysis presented in the paper only deformations corresponding to the defocus mode, i.e. all electrodes actuated to the same voltage, are considered. Typical interference patterns of the reflective surface of the mirror recorded under the same control voltage at all control channels are shown in Fig. 2. The measurements prove that the surface of DM then takes approximately a parabolic shape, especially over the central active region of the mirror. Figure 2 shows also the deformation of the mirror surface, measured as a vertical deflection from the initially flat profile (at $U = 0$ V) and respective radius of curvature. The maximum central displacement of the mirror surface measured at the aperture of 25 mm is approximately +2.84 µm at 150 V and –4.4 µm at 250 V. The limiting values for radii of curvature for concave and convex reflective surface of the deformable mirror are $R \approx +24$ m and $R \approx -17$ m, respectively.

The detailed measurements of the mirror shape response to the sequence of the voltage changes (–150 V→0 V→+250 V and +250 V→0 V→–150 V) show hysteresis of less than 14%. This intrinsic property of a bimorph mirror should be taken into account in the procedure of the dynamic control of the mirror surface.

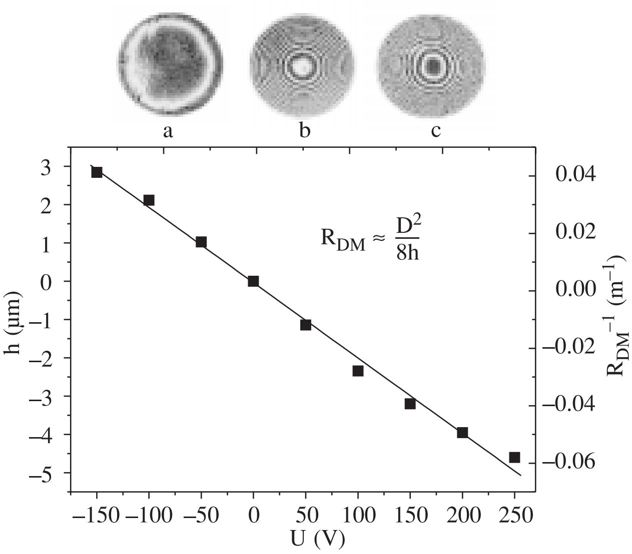

Fig. 2. The average values of the mirror surface deflection measured versus the voltage applied to the mirror actuators and examples of the interference patterns of the deformable mirror recorded for all actuators set to zero (a), all actuators set to U = –150V (b) and all actuators were set to U = +150V (c).

The laser output characteristics are studied and compared for two options of the deformable mirror location in the laser resonator (Fig. 1): I – the DM replaces the back mirror (1) of the cavity and II – the DM is implemented to the laser cavity as the folding mirror (3).

3. Fundamental mode properties – theoretical considerations

The laser mode behaviour in a resonator with an intracavity deformable mirror can be approached theoretically by applying the ABCD matrix formalism for a Gaussian beam [10–12].

The fundamental mode parameters can be found from the self-consistency condition that a stable mode of the resonator reproduces itself after each round trip through the resonator. Then, the complex gaussian beam parameter q can be written as a function of the ABCD matrix elements [10]

$$\frac{1}{q_i} = \frac{1}{R_i} - j\frac{\lambda}{\pi\omega_i^2} = \frac{D_i - A_i}{2B_i} \pm j\frac{\sqrt{4-(A_i+D_i)^2}}{2B_i}, \quad (1)$$

where R_i and ω_i are the measures of the wavefront radius of curvature and the radius of the Gaussian beam in the reference plane i, respectively. Consequently, the gaussian mode radii ω_i (i = 1,2) on the end mirrors of the cavity and the respective curvature radii R_i are given by

$$\omega_i^2 = \frac{\lambda}{\pi}\frac{2B_i}{\sqrt{4-(A_i+D_i)^2}}, \quad R_i = \frac{2B_i}{D_i - A_i}. \quad (2)$$

Having ω_i and R_i, the radius of the beam waist ω_{0i} can be found as [11]

$$\omega_{0i}^2 = \frac{\lambda}{2\pi}\frac{1 - B_i\sqrt{4-(A_i+D_i)^2}}{1 - A_i D_i}. \quad (3)$$

The far-field full divergence angle of the Gaussian beam is $\theta_i = 2\lambda/\pi\omega_{0i}$. The above equations, describing the gaussian mode parameters in a resonator system characterized by the matrix ABCD, are used in this paper to study the influence of the internal deformable mirror on the output beam properties for the laser cavities under consideration.

The elements of the transformation matrix ABCD describing a complete round trip of the beam through the cavity with an internal mirror are given by the elements of the product matrix [12]

$$\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = M_{R_i} M_{L_i} M_{R_{DM}} M_{L_j} M_{R_j} M_{L_j} M_{R_{DM}} M_{L_i}, \quad (4)$$

where i, j = 1,2 and $j \neq i$. An internal mirror is spaced a distance L_i from the respective reference plane located before the back resonator mirror (i = 1) or just before the output one (i = 2). M_{L_i} (M_{L_j}) is the transfer matrix that accounts for free-space propagation through the distance equal to L_i or $L_j = L - L_i$; and L is the length of the beam path in the resonator. M_{R_i}, M_{R_j} describe the reflection at the end cavity mirrors of radius of curvature R_i, R_j, and M_{DM} is the matrix for reflection at the inner deformable mirror of curvature R_{DM}

$$M_{L_i} = \begin{pmatrix} 1 & L_i \\ 0 & 1 \end{pmatrix}$$
$$M_{Ri} = \begin{pmatrix} 1 & 0 \\ -1/R_i & 1 \end{pmatrix} \quad . \quad (5)$$
$$M_{DM} = \begin{pmatrix} 1 & 0 \\ -1/R_{DM} & 1 \end{pmatrix}$$

The matrices M_{L_j} and M_{R_j} in Eq. (4) are given respectively, by replacing the index i with j. For the case when the deformable mirror of a variable curvature replaces the back mirror ($R_2 = R_{DM}$) of the resonator and the inner folding mirrors are flat, the Eq. (4) simplifies to

$$\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = M_{R_i} M_L M_{R_j} M_L. \quad (6)$$

For the given ABCD elements, the standard form of the condition describing the stable cavities $0 < G = g_1 g_2 < 1$ can be written as $0 < G = (A_i + D_i + 2)/4 < 1$ [12].

The dependence of the stability factor G on the deformable intracavity mirror curvature (R_{DM}^{-1}) is shown in Fig. 3. For the resonator I with the DM integrated to the system as a rear mirror, the stability limit (G = 1) is attained for the radius of curvature $R_{DM} \approx -25.7$ m while the resonator II with the DM replacing the inner folding mirror is stable up to $R_{DM} \approx -27.9$ m. A significant difference in the slope of curves $G = f(R_{DM}^{-1})$ implies that the latter resonator is much more sensitive to the DM curvature variations than the former one and respectively the stronger influence of the DM curvature changes on the laser output characteristics can be anticipated.

Fundamental mode parameters of the resonators under investigation following the model calculations are depicted in Fig. 4. The calculations show that in the cavity containing an inner concave or convex mirror, there are two beams characterized by the different values of the far-field divergence θ_i (and thus by the different waist size ω_{0i}). These beams are transformed into each other by the reflection on the inner folding mirror that divides the cavity space into two respective regions. In the resonator with the DM serving as a rear mirror and with flat folding mirrors there is one beam of the divergence angle defined completely by the radii of curvature of the end resonator mirrors and their distance.

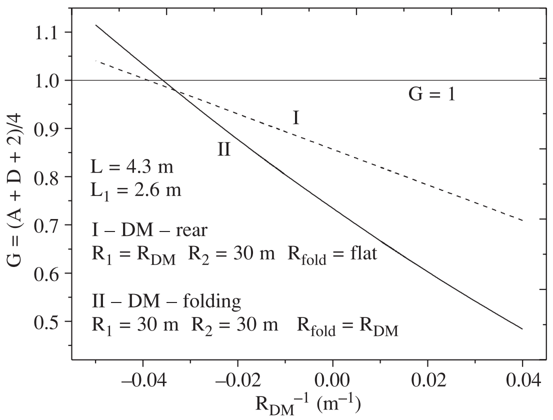

Fig. 3. G – stability parameters of the resonators; *I* – the DM replaces a rear cavity mirror, *II* – the DM is an inner folding mirror.

As it follows from Fig. 4(a), in the considered range of the DM curvature variations, the divergence of the TEM_{00} increases and the beam waist decreases respectively with an increasing of the DM curvature in the direction from the convex to the concave profiles. The beam in the resonator with DM rear mirror is characterized by the lower divergence (the larger waist size) and the larger beam size on the end cavity mirror than the beam in the resonator with the DM implemented as an inner folding mirror.

The laser beam quality decisive for the beam propagation and focusing conditions is related to the number of transverse modes oscillating in the real laser cavity. It can be roughly estimated by the ratio of the mirrors limiting aperture and the fundamental mode size measured at the plane of the aperture. For a fixed value of the cavity mirrors aperture, with an increase of the fundamental mode size on the respective mirror the number or contribution of higher order modes to the beam decreases and the output beam of a better quality can be expected. As it follows from the data given in Fig. 4(b), the beam of the lower quality will be formed in the resonator with the DM serving as a folding mirror.

Conclusions concerning the TEM_{00} properties in the resonators under consideration are supported by the diffraction type analysis implemented by means of a computer code based on the Fox and Li approach [13]. In order to study the influence of the aperture and curvature of the inner cavity mirrors the round trip of radiation inside the three-pass resonator, with two inner folding mirrors, is broken into six steps of mirror- to mirror propagation [14,15] described by the respective Fresnel-Kirchhoff integrals. The calculated loss factors describing the fundamental mode related to the changes of the radius of the curvature of the DM are shown in Fig. 4(b).

The strong increase in the diffraction losses for the DM curvature approaching the stability limit responds to the strong aperturing of the fundamental mode on the resonator mirrors in the region of their convex profiles. In the case of the resonator with an inner deformable mirror, the losses are evidently lower compared to ones calculated for a resonator with a rear DM, what has been already predicted by the G-parameter behaviour versus the resonator configuration.

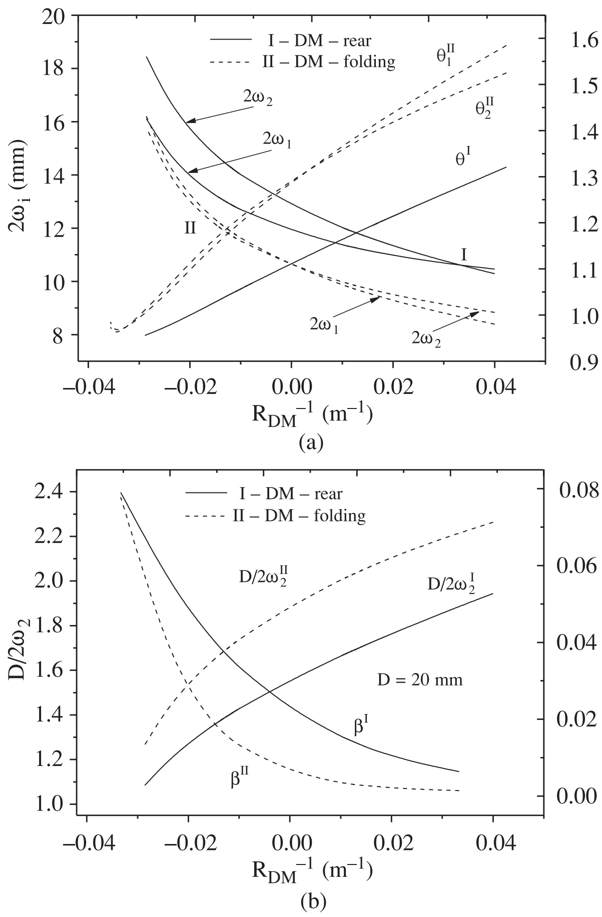

Fig. 4. Fundamental mode properties versus the curvature of a variable focal length mirror introduced to the stable laser cavity; (a) – the full angle of the beam divergence θ_i and the beam diameter $2\omega_i$ (i = 1,2) on the end cavity mirrors, (b) – the ratio $D/2\omega_i$ of the mirrors limiting aperture and size of the fundamental mode on the respective mirrors, β – the round trip intensity diffraction losses of the fundamental mode.

4. Experimental investigations

The theoretical predictions concerning the laser modal behaviour of a resonator with an intracavity mirror of a variable curvature were verified in the experimental tests performed under conditions of the industrial, high power cw CO_2 laser operation.

The beam intensity profiles and the output power from the laser were measured versus the voltage controlling the deformable mirror curvature for both considered locations of the DM in the laser resonator. Figure 5 shows the laser output power measured as a function of the voltage applied to the control channels of the deformable mirror. For the concave profiles of the DM, controlled by the voltages from –150 V up to 0 V, rather slight dependence of the output power on the DM curvature is observed for both con-

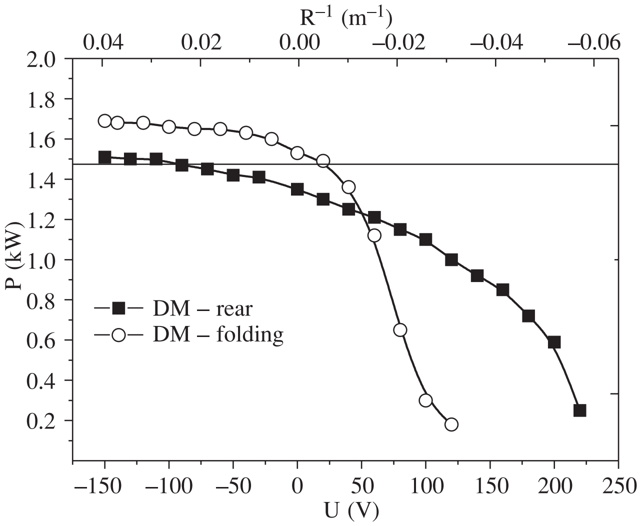

Fig. 5. The laser output power (P) measured versus the voltage controlling the deformable mirror curvature The solid horizontal line corresponds to the nominal output power measured for the laser with a standard mirrors.

sidered cavity configurations. The maximum value of the output power is measured for the minimum curvature of the concave surface of the DM which is attained at U = –150 V. In the system with the DM folding mirror, the fast decrease in the output power is observed for $U > 0$ when the deformable mirror attains its convex profiles. At $U \approx +120$ V ($R_D \approx -28$ m) when the cavity approaches the stability limit, the laser generation is practically extinct. In the case of the cavity with the DM serving as a rear mirror, the gradual decrease of the output power is observed. And even in the region of unstable convex-concave cavity configurations formed at the voltages of $U > +120$ V the relatively high values of the output power are still measured.

The observed variations of the output beam power following the DM curvature changes accompany to the respective modifications of the output beam spatial structure. The characteristic examples of 3D and 2D laser beam intensity distributions, measured at different values of the control voltage are depicted in Fig. 6. The laser beam profiles were recorded by using the laser beam scanner of a rotating pinhole type [16].

As it has been predicted by the theory considerations, evidently more complex – multimode structure of the laser beam is recorded for the cavity with the DM serving as a folding mirror, especially for its concave profiles, compared to the corresponding profiles measured for the cavity with the DM as a rear mirror. In both cases, the DM curvature variations leading to the increase in the G parameter

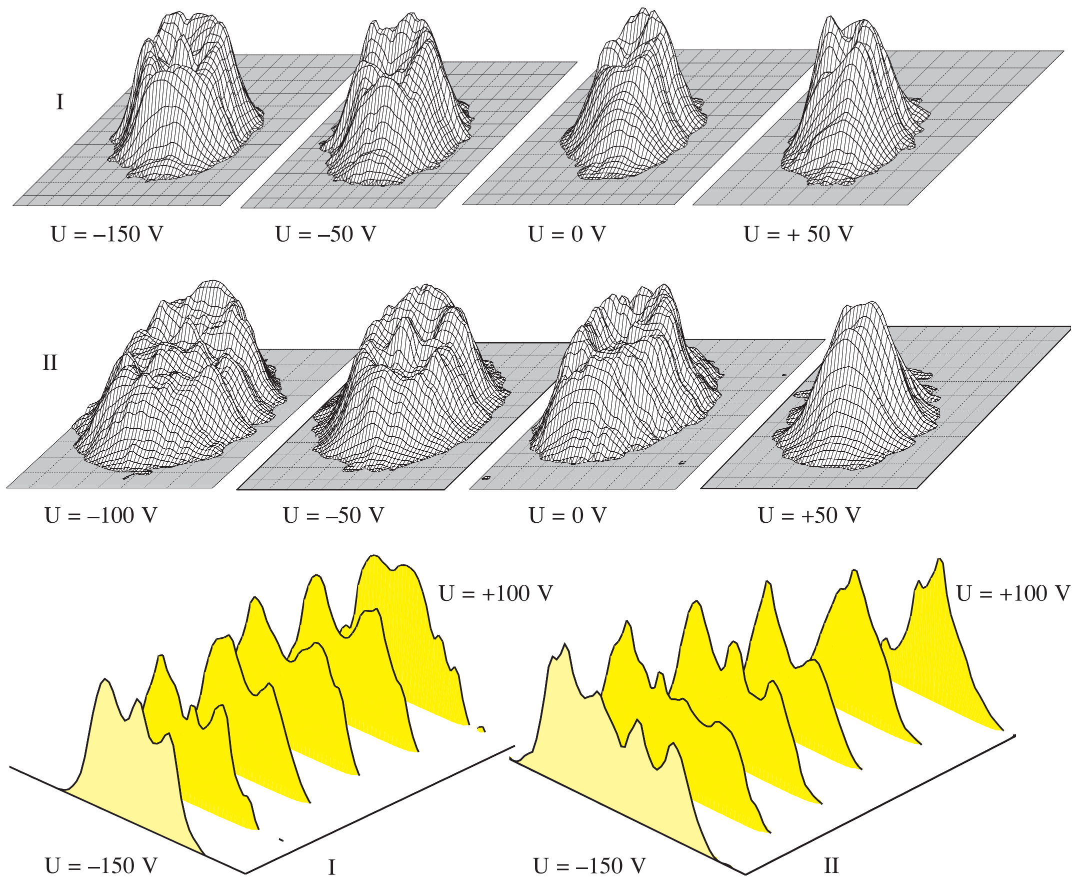

Fig. 6. *3D* – intensity distributions and *2D* – central intensity profiles measured at different voltages controlling the curvature of the intracavity deformable mirror; (*I*) – the DM is a rear mirror, (*II*) – the DM serves as a folding mirror.

result in the increase in the TEM_{00} size and in consequence in reducing the higher order modes contribution to the beam and in simplifying of its spatial mode structure.

The beam quality parameter M^2 was determined from the intensity distributions recorded in the far field region. The intensity distributions were recorded with the beam scanner at different locations from the focusing lens of a focal length of 190.5 mm. The lens was located in the processing zone of the laser at the distance of 2.6 m from the laser output.

The second moment definition [17] of the recorded intensity distributions was used to determine the beam diameters at respective locations. From a hyperbolic fit to the measured data the beam waist diameter $d_f = 2\omega_f$ and the full divergence angle θ_f of the focused beam and thus the beam quality parameter $M^2 = \pi d_f \theta_f / 4\lambda$ were concluded.

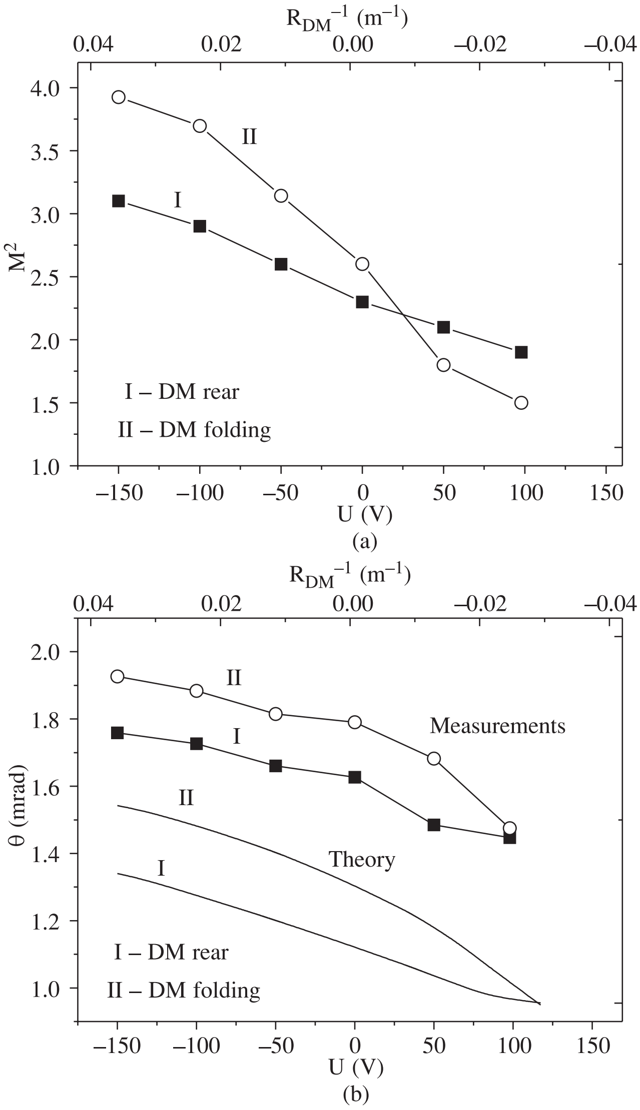

Fig. 7. The beam quality M^2 (a) and the experimental divergence angle (b) of the embedded single mode beam compared with the theoretical divergence of the fundamental gaussian mode.

The beam quality parameter M^2 determined by using the above procedure for different voltages controlling the deformable mirror shape is displayed in Fig. 7(a). At U = –150 V when the maximum of the output power is recorded and the beam structure corresponds to the largest contribution of the higher order modes the beam quality parameter measures $M^2 \approx 3$ in case of configuration *I* and $M^2 \approx 4$ in the case *II*. With the control voltage varying up to +100 V and with *G*-parameters approaching the stability limit the M^2 parameter of the beam is reduced to ~1.8 and ~1.5, respectively.

The experimental full divergence angle θ of the beam emitted from the laser source is $\theta = d_f / f$ where d_f is the measured diameter of the focal spot of the beam transformed by the lens with a focal length *f*. Figure 7(b) shows the comparison of the divergence angle of the embedded single mode beam measured as θ/M and the theoretical divergence of the fundamental gaussian mode [Fig. 4(a)]. The measured values of the divergence angles of the laser beam are generally higher than those predicted by the model. This is attributed to the influence of the diffraction on the cavity mirrors apertures and to the thermal distortions in the lasing medium and in the laser optics. All these effects, not taken into account in the model, influence the beam at the laser output and the real output beam propagation characteristics can differ from those predicted by the model of an undisturbed ideal resonator beam. Nevertheless, the above comparison confirms that the general functional dependency of the laser beam behaviour on the resonator configuration, determined by the curvature and location of the deformable mirror in a system, is in agreement with the theoretical predictions.

5. Conclusions

The results of the theoretical and experimental analysis concerning the output characteristics of the high power cw CO_2 laser with a deformable bimorph mirror introduced to the laser cavity are presented in the paper.

The measurements show that a resonator with the DM replacing one of the inner turning mirrors is much more sensitive to the DM curvature variations than the resonator with the DM serving as a back cavity mirror. The experimental tests confirm that the use of the deformable mirror with a controllable curvature in the laser resonator enables the dynamic and controllable changes in the resonator properties that result in controlled modification and optimisation of the laser output characteristics including the laser power, mode structure and respective M^2 factor. The presented results show the range in which the beam parameters of the laser under consideration can be varied by adjusting the voltage controlling the radius of curvature of the deformable mirror introduced to the laser cavity. The conclusions following the experimental analysis of the laser output characteristics are in agreement with the theoretical predictions concerning the laser mode behaviour in the system with the intracavity deformable mirror.

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Quantum Physics of Nanostructures

18th to 20th September, 2006

This is the second Nanoscale Physics and Technology Workshop organised by the Nanoscale Physics and Technology Group of the Institute of Physics, following the successful meeting in Daresbury, January 2005.

The theme of the second workshop is "Quantum Physics of Nanostructures". The two day meeting will feature 8 invited talks (see below), plus contributed talks and posters, on the distinctive quantum effects arising on the 1–100 nm length scale, e.g., in small particles and their assemblies, quantum dots, nanowires and at local sites on surfaces.

Confirmed Invited Speakers
STM-based spectroscopies of electronic states at surfaces, single atoms and molecules
Richard Berndt *Institute of Experimental and Applied Physics, University of Kiel, Germany*
Quantum physics of 2D and 0D systems
Walt de Heer *School of Physics,Georgia Institute of Technology Atlanta, USA*
Surface plasmon photonics
Thomas Ebbesen *Institut de Science et d'Ingénierie Supramoléculaires, Université Louis Pasteur, Strasbourg, France*
Quantum effects in size-selected clusters
Peter Lievens *Department of Physics and Astronomy, K.U. Leuven, Belgium*
Magnetism in Nano-Structured Materials
Ward Plummer *Department of Physics and Astronomy, The University of Tennesse, USA*
Vortex structures in quantum dots
Stephanie Reimann *Mathematical Physics, Lund Institute of Technology, Sweden*
Optical Properties and Optical Applications of Gold Nanoparticles
Vahid Sandoghdar *Nano-Optics, Swiss Federal Institute of Technology, Switzerland*
Effect of surface modification on the optical properties of semiconductor nanoclusters
Jess Wilcoxon *Nanostructures and Advanced Materials Chemistry Department, Sandia National Laboratories, USA*

Deadline for submission of abstracts is 20st June 2006. Abstracts should not exceed 1 page A4, should be prepared in Word or RTF format, and submitted by email attachment to the meeting secretary.

Registration is free as a result of financial support from the Group, but essential. Attendance is limited and the registration and accommodation booking procedures will be notified in the first instance to the authors of accepted abstracts by the end of June 2006.

The meeting will be held at the historic Falcon Hotel in Stratford upon Avon. A special single room rate for the duration of the conference beginning with dinner on Sept 18th and ending at 6pm on Sept 20th, inclusive of all meals will be £242, whilst a double room, also inclusive, will cost £352. Accommodation should be arranged directly with the hotel once registration has been accepted - booking details and reference code will be provided to you upon registration. Attendance on a "day only" basis is not possible.

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