Diffractive optical elements for CO_2 laser beam diagnostics

C. HEMBD, H. J. TIZIANI

In laser machining great interest has been shown in diagnostic tools for on-line testing and correcting. We present here beam sampling mirrors, which are basically shallow gratings, and which can be applied to give an accurate sample of the original beam without deteriorating it. The method compares favourably with other techniques for beam diagnostics. First results using these elements are presented.

KEYWORDS: laser diagnostics, high-power lasers, diffractive elements, gratings, beam sampling, wavefront-sensing

Introduction

These days, CO_2 lasers are well developed, but the diagnostics of laser machining are becoming very important. Recent research work concentrates on measuring process parameters as well as on investigations of laser beam properties[1–4]. On-line measuring of beam direction and position may improve cutting quality, while controlling the wavefront quality may help in achieving a high Q-factor[5,6]. For beam profiling, circulating needles[7–10] are very powerful, where the beam is sampled along a line. The needle is then moved across the beam. The drawbacks are the mechanically limited sampling rates and the lack of information about the wavefront. Other workers have used ZnSe beam-splitters[11], or partly transmitting mirrors, which couple out only a small fraction of the beam. Recently, holographic beam-splitters on ZnSe substrates have become available[12]. These elements are known to introduce thermal defocusing of the laser beam at high powers[13–15]. Measurements on the wavefront of CO_2 lasers have been carried out by indirect methods, for example using a HeNe laser[16–18]. To overcome some of these problems there is a need for beam-splitters that work:

- for high powers (up to many kW laser power)
- with negligible losses
- without polarization dependence and
- without deterioration of laser beam quality

The use of gratings as beam-splitters was proposed some years ago[19]. Recently photolithographic fabrication of low diffraction efficiency gratings has been mentioned[20], but nothing was said about absorption and thermal properties.

Here, we report on the design, fabrication and properties of beam sampling mirrors meeting the above mentioned requirements. These elements diffract a small fraction of the beam power into the first order. For the diagnostic system, usually pyroelectric detectors are used. Examples of the application of grating mirrors to measure beam position, beam direction and wavefront quality are given. Finally, the advantages of using general diffractive elements for laser beam diagnostics will be pointed out.

Fabrication

The most flexible production method for diffractive elements is achieved by photolithographic methods[21]. It is, however, difficult to produce elements in this way which are thermally stable in a multi-kW beam. Two approaches, which have been described elsewhere[22,23], seem possible. The first is to use high reflection coatings on etched silicon. The second possibility is to use a galvanic copy process from photoresist structures, leading to a diffractive structure directly in a metal foil, for example copper.

In our case, ruled gratings were fabricated. Since copper mirrors show very high performance in the high-power domain, when cooling and mounting are optimized[24], they have been used as substrates. The gratings are coarse and have a typical groove-spacing of 70 μm. This separates the first order of a CO_2 laser beam by about 10° from the main beam. The accuracy of 1 μm, as achieved by a simple motor-positioning system, is sufficient for

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The authors are at the Institut für Technische Optik, Pfaffenwaldring 9, D-70511 Stuttgart, Germany. Received 17 February 1993. Revised 11 July 1993. Accepted 20 July 1993.

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fabrication—no interferometric control was needed. Groove depth in the range of 200 nm was controlled by the electrodynamic force on a diamond, mounted on a balance.

If the grooves are not equidistant, a phase modulation is introduced in the wavefront of the first-order beam. In this way, diffractive structures have been fabricated, such as a focusing mirror, where the first order has a focal length of 200 mm.

In certain cases, when no information about the wavefront is needed, as in the case of beam power measurement, diamond milled mirrors may be used. Here, the final polish is made by a spherical diamond of radius about 2 mm, resulting in a parabolic groove profile. However, the grooves, instead of being linear, are circular with a radius of 300 mm due to the technique of milling. We have also investigated such gratings with respect to industrial applications. They introduce wavefront aberrations in the first-order diagnostic beam, as will be shown below.

Grating properties

Diffraction efficiency

Diffraction efficiency η_n of a grating in the nth order is defined by the ratio of the diffracted power P_n in that order and the total incident power P_0 (see Ref. 25).

$$\eta_n = P_n/P_0 \tag{1}$$

Theoretical calculations for grating profiles giving the desired diffraction efficiency independent of polarization have been carried out some years ago[19,25]. For grating periods in the range of a wavelength, groove profiles with tolerances well below 100 nm are required. Therefore, it is easier to remain in the region where scalar theory is valid, that is when grating periods are of the order of 5 wavelengths and diffraction efficiency is approximately polarization independent. Our gratings have periods of more than 50 μm and scalar approximation should hold. An analytical expression for binary gratings, taking into account polarization effects, as well as measurements for binary gratings have been reported recently[20].

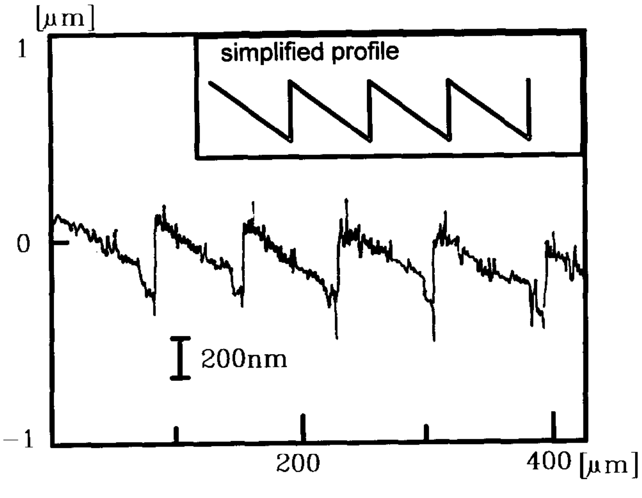


Fig. 1 Profile of ruled grating with blaze

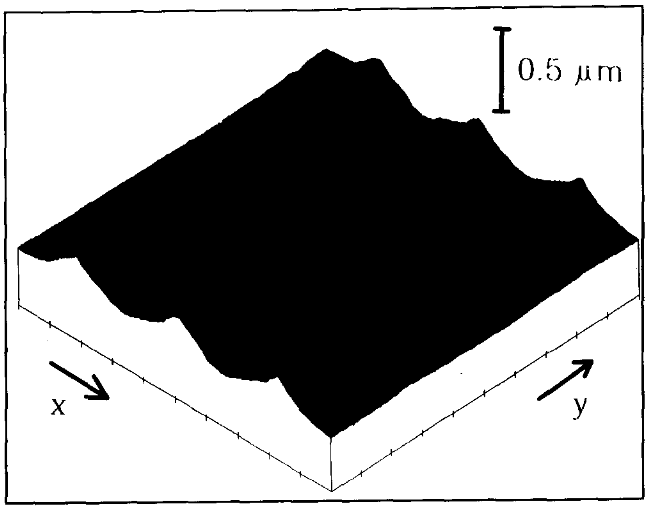


Fig. 2 Profile of diamond milled grating, field of view: 200 × 200 μm²

The diffraction efficiency varies to a first approximation by the square of the groove depth.
Direct calculations were carried out numerically on the basis of electromagnetic theory[25]. We compared these with experimental results for diamond milled and ruled gratings. Groove-profiles were measured by optical profilometry (Figs 1 and 2). Figures 3 and 4 show diffraction efficiencies depending on polarization and the angle of incidence. The relative deviation of the diffraction efficiency between s and p-polarization does not exceed 20% and seems acceptable for practical applications.

Absorption and thermal deformation

Absorption measurements have been carried out by a calorimetric method[13,24]. Both diamond milled and ruled gratings were tested at 45° angle of incidence,

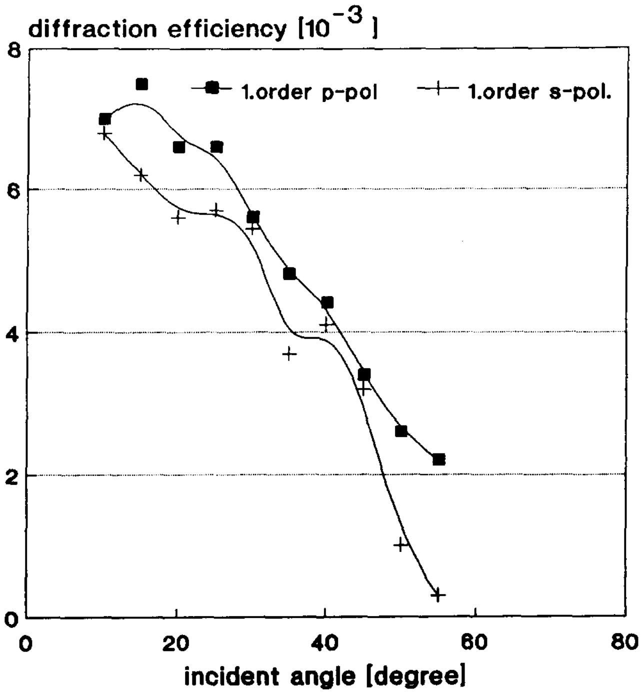


Fig. 3 Dependence of the diffraction efficiency versus incident angle for a ruled grating

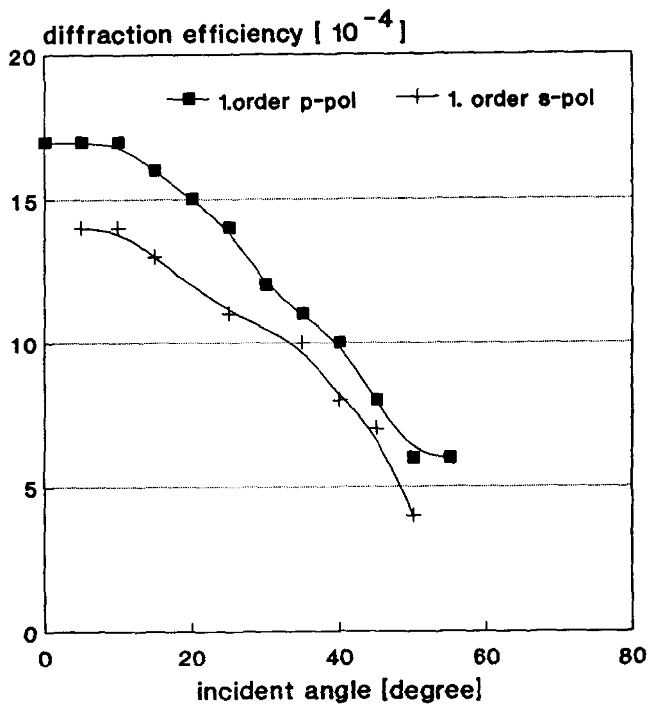


Fig. 4 Dependence of the diffraction efficiency versus incident angle for a milled grating

which is typical of high-power laser applications. First-order diffracted beams (± 1st order) propagate at 37° and 59° angles respectively. Results are shown in Table 1 where each sample was measured with grooves parallel (first value) and perpendicular to the plane of incidence. Values for plane mirrors of uncoated copper are given for comparison. From these values we can expect that thermal deformations of water-cooled diffractive elements, especially defocusing ones, will be on the same scale as those values found for plane Cu-mirrors[26]. Measurements in a 1.5 kW beam of 12 mm diameter showed no influence of thermal defocusing due to the grating.

During the lifetime of our components (two years by now) and under normal laboratory conditions, small visible defects have appeared, which might be caused by burn-in of dust particles and surface oxidation. However, this fact did not change the integral optical behaviour of the gratings.

Additionally, the gratings were tested in focused beams at 1.4 kW laser power. Power densities up to 150 kW cm^{-2} of cw-radiation did not lead to destruction.

Table 1 Measured absorption values of gratings at 45° incident angle

Sample	Absorption s-polarization	Absorption p-polarization
Diamond milled	0.40%	1.08%
14 lines mm^{-1}	0.43%	1.03%
Ruled grating	0.51%	0.95%
14 lines mm^{-1}	0.51%	0.95%
Plane mirror copper	0.4%	1.0%

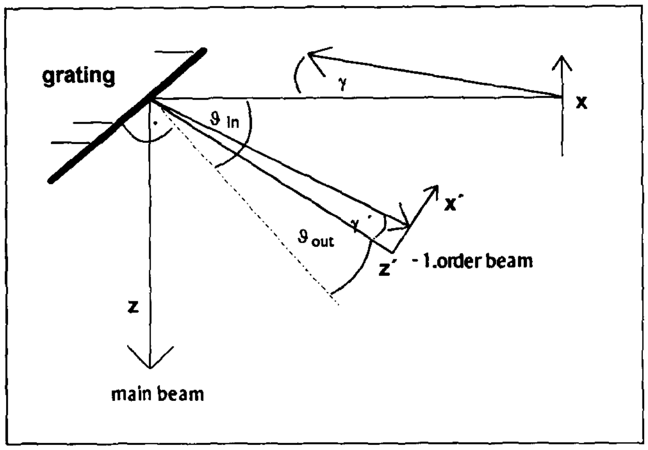


Fig. 5 Angles and coordinates at the grating

Wavefront quality

When using linear gratings for measuring the phase of a laser, one has to take into account the transformation of the ray angles (θ) in the plane of incidence at the grating, which follows from the grating equation[25]

$$\sin\theta_{\text{out}} = \sin\theta_{\text{in}} + m\,\lambda/p \tag{2}$$

where λ is the wavelength, m the diffraction order and p the grating period. This makes the inclination of rays towards the optical axis change in the plane of incidence. Using variables γ and γ' for the angles of the incoming and deflected rays relative to the optical axis z as shown in Fig. 5, we have, to a first approximation

$$\gamma' = \frac{\cos(\theta_{\text{in}})}{\cos(\theta_{\text{out}})}\gamma \tag{3}$$

Projection of the coordinates x,y to the new optical axis z' in the diagnostic beam leads to the following equation for the coordinates

$$x' = \frac{\cos(\theta_{\text{out}})}{\cos(\theta_{\text{in}})}x, \quad y' = y \tag{4}$$

Actually, a linear ruled grating will transform any spherical wave into an astigmatic wave. Reconstruction of the original wavefront can be achieved by (3) and (4). This is especially simple when the derivative of the wavefront is measured as in shearing interferometry or Hartmann sensing.

Diamond milled gratings with spherical grooves introduce additional wavefront aberrations. To test the quality of the grating we measured the first-order wavefront of a diamond milled grating with a Twyman Green interferometer (Fig. 6). The grating period was 70 μm, and the groove radius was 300 mm. The dominant errors are astigmatism and coma. Therefore, measurements of the beam direction are not independent of the beam position on the mirror.

Experimental results and applications

An application of our diffractive elements may be the monitoring of beam direction, position and wavefront quality. Depending on the application, different elements may show the best performance.

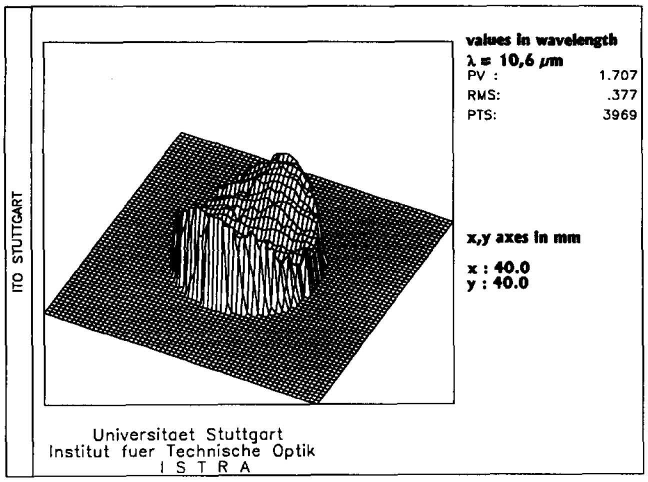


Fig. 6 Wavefront in the first-order diagnostic beam of a milled grating

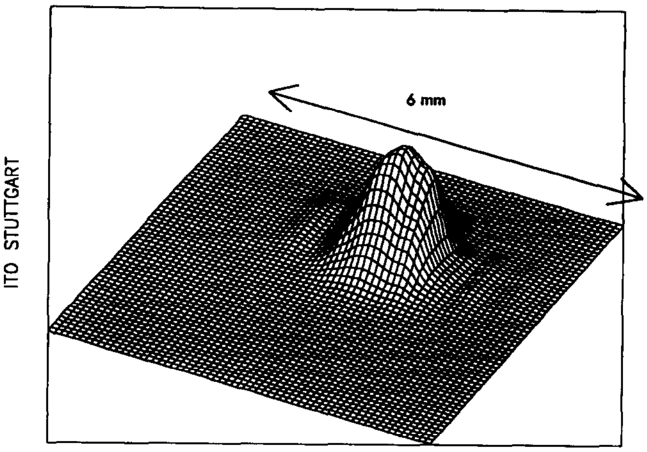


Fig. 8 Intensity distribution in the first-order focus of a focusing grating

Measuring the beam direction may be accomplished by focusing the first-order diffraction beam of a grating mirror on a position sensitive detector. Looking for a cheap solution for industrial applications, diamond milled gratings are appropriate. A diffraction efficiency of 10^{-5} leaving 10 mW from a 1 kW laser power beam is sufficient for a pyroelectric detector to work. This means our diagnostic beams still had to be attenuated when working with these detectors. A very compact design is achieved if the lens is omitted and a focusing mirror is used. Figure 7 shows the principal of the experimental set-up, while Fig. 8 gives the focus in the first order of the focusing grating as measured by a pyroelectric array. The focal length of the diagnostic element was 200 mm. Using the diagnostic element, measurements of beam direction were carried out. To demonstrate the capability of measuring mechanical vibrations the incoming beam was tilted by a piezoelectrical driven mirror. Using a pyroelectric quadrant detector, resolutions of 5 µrad have been achieved, with a bandwidth of 1 kHz (Fig. 9).

In the same way, beam position may be measured if the quadrant detector is placed in the image-plane of the lens.

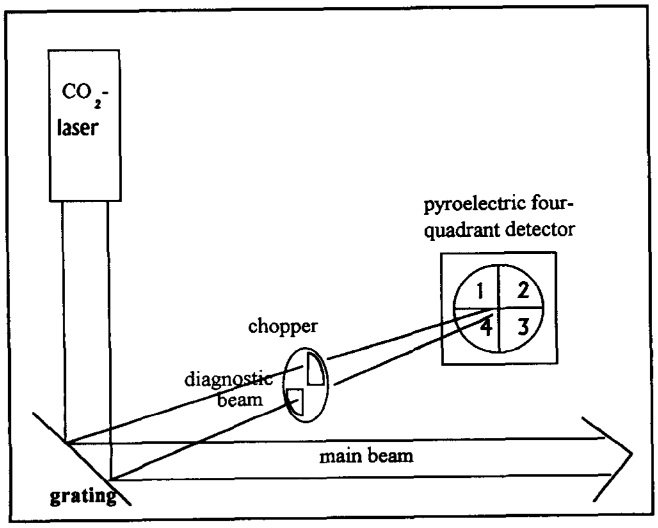


Fig. 7 Experimental set-up for measuring beam direction of a CO_2-laser

This arrangement still suffers from a sensitivity to detector misalignment and detector element cross talk. However, this may be overcome, using the structure shown in Fig. 10, where each quadrant of a mirror focuses a fraction of the main beam on a single detector.

Measurements of laser defocus have been carried out by the method of astigmatic focusing using a quadrant detector. If the diagnostic beam is astigmatic, the focus will have a sagittal and tangential focus line which results in a non-zero detector signal D as given by (3).

$$D = (u1 + u3) - (u2 + u4)/(u1 + u2 + u3 + u4) \quad (3)$$

In an astigmatic beam, D will depend on the focus position, as seen in Fig. 11.

Usually, a cylindrical lens is needed for such a set-up. Here, we can simplify the optical set-up if we use a plane diffraction grating, tilted by 45° with respect to the incident beam. This transforms any divergent wave into an astigmatic one in the first-order diagnostic beam. The experimental set-up is similar to that in Fig. 6. In addition, a plane parallel plate of ZnSe was put into the main beam. Figure 12 shows a

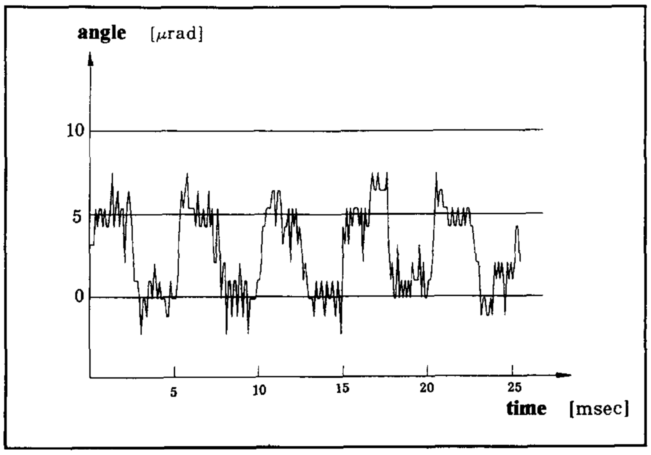


Fig. 9 Measured vibrations of a piezoelectrical driven mirror

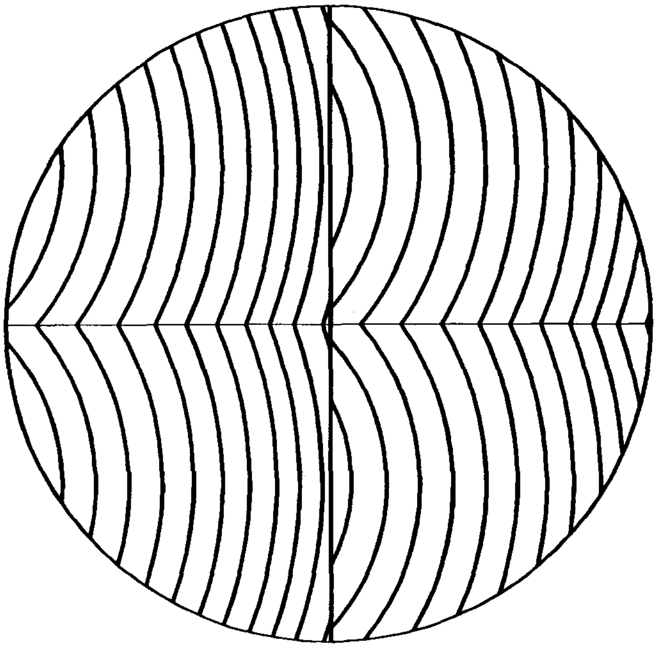


Fig. 10 Structure of diagnostic element for measuring beam position

measurement of defocusing caused by thermal lensing of the plane parallel plate at 1.5 kW laser power. No thermal influence from the grating itself could be observed.

Wavefronts were measured with a 1.5 kW CO_2 laser. Figure 13 shows an interferogram of the diagnostic beam of a high-power laser recorded by the pyroelectric vidicon. The tilt of the fringes indicates astigmatism, which is due to the grating and can be cancelled out numerically when the angles of the incoming and the deflected beam are known.

Conclusions

We have shown that gratings and diffractive elements on copper mirrors exhibit a high quality with respect to thermal behaviour and diffraction efficiency. They seem well suited for laser beam diagnostics. For integration into laser machining and on-line process diagnostics, a compact design may be achieved by using diffractive structures that help in signal preprocessing and substitute for additional optics. A very inexpensive design uses diamond milled gratings.

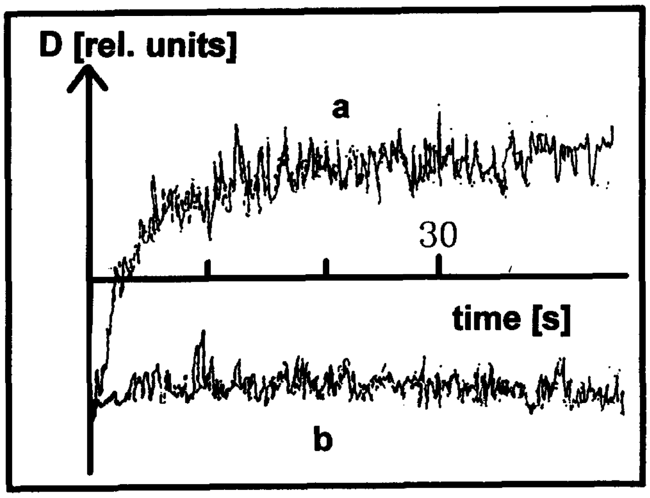


Fig. 12 Detector signal D in the beginning of laser action, (a) during heat-up of ZnSe plane parallel plate; (b) same without ZnSe plate

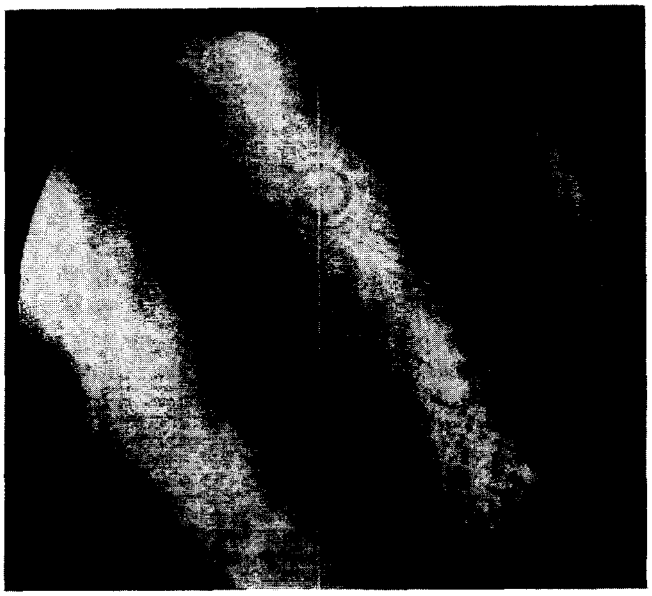
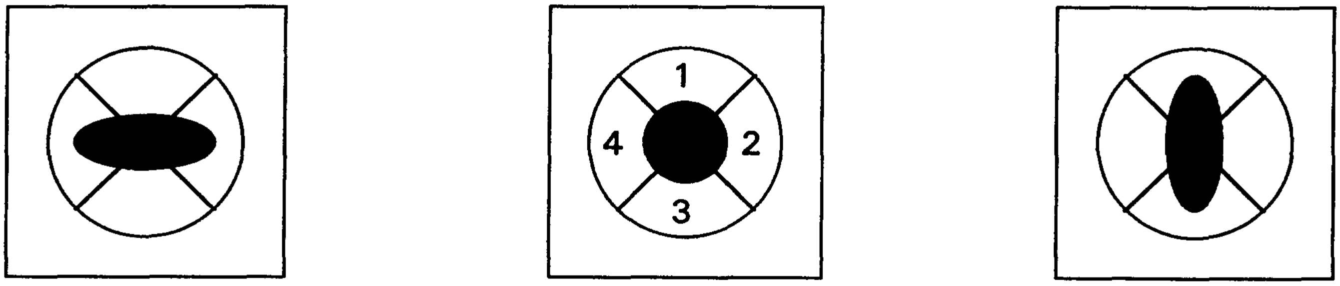


Fig. 13 Ronchigram of a 1.5 kW laser beam

We have carried out measurements using these elements yielding on-line information about divergence and beam misalignment. Reliable information about the wavefront of a high power laser can be achieved.



out of focus

in focus

out of focus

Fig. 11 Detector inside and outside focus

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