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Diffractive optical components for high power laser beam sampling

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Abstract
We investigate the use of low frequency diffraction gratings to extract good quality, low power copies of a high power laser beam. Low frequency gratings are expected to be rugged and to produce few perturbations of the beam under measurement. In order to obtain beam samplers that allow an easy integration in the beam delivery of high power industrial lasers we designed and constructed them as reflective components. In this work we report experimental tests that characterize their performance in the measure of beam parameters such as beam size, waist location and divergence.

Keywords: High power laser beams, CO_2 lasers, diffraction optics, laser optics

1. Introduction

Most laser–material interactions are sensibly affected by laser beam parameters such as power density distribution, beam collimation or field polarization state [1]. For this reason it turns out to be extremely important to be able to measure these parameters on the high power beams usually involved in industrial applications [2, 3]. Moreover, it appears preferable to have this measure being performed in real time and this is for several reasons a rather complicated task. Direct measurements on a high power beam are in general hard to perform and, if installed on-line, necessarily interfere with the laser–material interaction process.

A much easier approach is based on using a beam sampler, that is an optical device extracting a low power copy of the high power beam under measurement [4]. This procedure enables us to perform all the desired tests on the low power sampled beam provided that the following hold. (i) The low power beam is an exact copy of the high power one. (ii) The extraction process does not affect the properties of the principal beam too much. (iii) The extraction process is not dependent on the high power beam properties. These conditions appear trivial and it also seems that they can be easily overcome. In actual fact they limit even the use of common systems such as partial reflecting mirrors when combined with high power beams. It is well known that if one adopts a reflected low power beam scheme, the high power beam has to be transmitted through the sampler. This eventually causes the bulk sampler material to deform and the transmitted beam wavefront to be distorted. In contrast partial reflectors with very high reflection coatings transmit only the low power copy of the main beam. Unfortunately in this case a perfectly uniform transmission coefficient producing an exact copy of the beam under test is hard to obtain.

For these reasons our work investigates the properties of diffraction samplers based on high power reflector technology. In particular we focus our attention on low frequency gratings.

The use of reflective components is preferred for the ruggedness and thermal properties of the commonly used substrate materials and for the better cooling geometry they allow us to adopt. The low frequency grating scheme is adopted as it is expected to produce the lowest effect on the beam under test, also in terms of field polarization state [5]. This property has been experimentally verified and is reported in a different paper [6]. Moreover, a reduced number of sharp edges in the grating structure is expected to enhance the damage threshold of the component [6].

In this paper we describe some numerical analysis and experiments that show how these low frequency gratings enable a low power level, good quality, sample extraction from high power laser beams. We show that beam parameters measured on the low power copy consistently compare to those measured on the main beam. Our numerical and experimental studies refer to parameters and materials typical of CO_2 lasers but can easily be scaled to the case of solid state lasers.

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2. Numerical simulations

In this section we will approach the problem of designing a simple diffractive optical component suitable to extract a low power good quality copy from a high power laser beam, introducing the smallest change in the beam under test. As anticipated in section 1 such a device should act preferably as a reflective optic. This also makes it easily integrated in the beam delivery chain typical of industrial laser systems. In spite of that, the recent introduction of high power resistant optical materials, such as CVD-Diamond [7], makes transmitting components possible as well [8]. The design procedures described in this section also hold for the implementation of low level, low frequency, transmission samplers.

The basic idea is to refer to diffraction gratings, and in particular to a surface engraved with a sequence of steps, with period Δ and depth d. In traditional gratings, used for example in spectrophotometers to spread different wavelengths, the ratio λ/Δ is of the order of unity, due to the fact that a large angular resolution is usually desired. In the case of industrial laser applications, typical flying-optic beam delivery set-ups involve distances of some metres between the laser head and the first folding mirror. This implies that ratios λ/Δ of the order of 1/100 can be accepted, the smaller angular resolution being compensated by the long beam path before any beam handling. In our case, where applications in the field of CO_2 lasers are concerned, $\lambda = 10.6$ μm and it turns out to be reasonable to investigate the effect of grating periods Δ of the order of 1 mm.

The main formulae describing grating diffraction are easily deduced considering a plane wave incident on the structured surface [9, 10]. The diffraction angle θ_m corresponding to the mth diffraction order is given by

$$\sin\theta_i - \sin\theta_m = m\frac{\lambda}{\Delta} \tag{1}$$

where θ_i denotes the incidence angle of the incoming beam; both θ_i and θ_m are measured from the normal to the grating surface. Equation (1) shows that, as the reflection angle of the zero order θ_0 is equal to the angle of incidence (as in a normal mirror), the angle between the main reflected beam and its low power first-order replica, namely $\theta_0 - \theta_1$, is independent from the angle of incidence, as long as small values of θ_i ($\sin\theta \approx \theta$) and λ/Δ are concerned. For incidence angles up to 20° and $\Delta = 1$ mm, the above approximation leads to a relative error within 6% in the calculation of $\theta_0 - \theta_1$. With this approximation, we can calculate the separation K between the centres of the two beams measured on a transverse plane at a distance z from the grating as given by

$$K = z\frac{\lambda}{\Delta}. \tag{2}$$

As an example this means that the zeroth-order and first-order beams are optically resolved at a distance of 59 cm in the case of 1/2 inch diameter incident beam and $\Delta = 0.5$ mm.

Moreover in the case of long period gratings ($\lambda/\Delta < 0.1$) and small incidence angles, the first-order efficiency η, that is the fractional amount of the total intensity diffracted into the first order, can be calculated as [10]

$$\eta = \left(\frac{4}{\pi^2}\right)\sin^2\left[\frac{\pi d}{\lambda}(\cos\theta_i + \cos\theta_m)\right]. \tag{3}$$

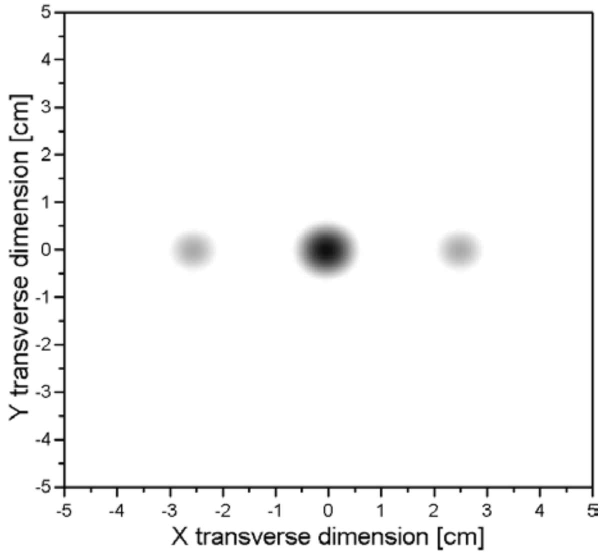


Figure 1. Transverse pattern (grey level log scale) of the laser intensity calculated for normal incidence at a propagation distance of 2.5 m from the grating surface.

This simple equation allows us to estimate suitable values of the groove depth d. Considering again small angles, with $d = 1$ μm we find $\eta \approx 12.65\%$, for $d = 0.4$ μm $\eta \approx 2.24\%$, and for $d = 0.1$ μm $\eta \approx 0.14\%$. The above values correspond to the maximum transfer efficiency typical of the normal incidence condition. Equation (3) clearly indicates that at larger incidence angles larger depths are needed to maintain the desired η value.

In order to extend these results to arbitrary grating profiles and field distributions different from plane waves, we wrote a numerical code based on Fourier optics, which performs the propagation of electromagnetic fields in the Fresnel approximation. Tranverse field distributions are managed in terms of intensity (I) and phase (φ) matrices. In this way, the effect of the structured surface of the beam sampler is simply performed introducing shifts proportional to the surface profile in the phase matrix. This approach also allows a quantitative comparison with real experiments, where Gaussian beams are involved, and enables parametric investigations such as that of varying the duty cycle (i.e. the ratio between high level width and period Δ) of a two-level grating as well as analysing multi-level surface profiles.

For the incident beam we firstly consider a fundamental Gaussian profile, normally incident on the grating, with initial uniform phase (beam waist on the sampler) characterized by an intensity distribution

$$I = I_p e^{-2r^2/w^2} \tag{4}$$

with $w = 5$ mm. The wavelength is fixed to $\lambda = 10.6$ μm. Figure 1 shows the principal beam and the diffracted beams (in log scale) at a propagation distance of 2.5 m, obtained with $\Delta = 1$ mm, $d = 0.5$ μm and duty cycle 50%. Figure 2(a) represents the intensity profile corresponding to the case of figure 1. Figure 2(b) reports the energy integrated along the transverse coordinate, starting from the optical axis. Naturally the presence of each diffracted order translates into a step in the energy curve.

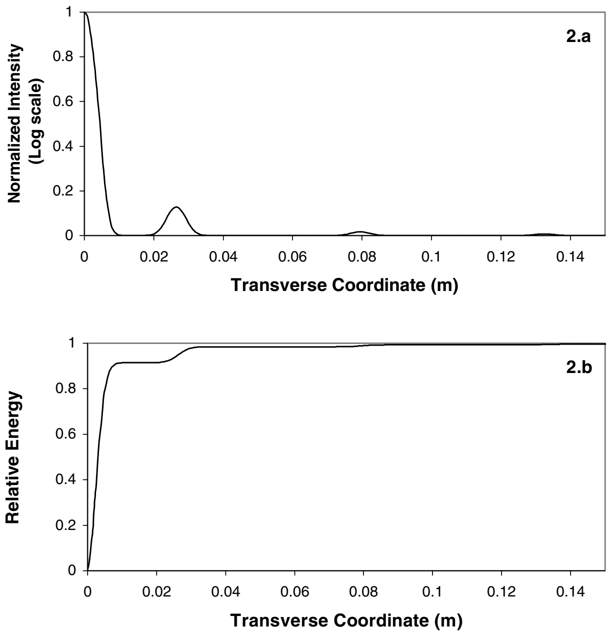


Figure 2. (a) Beam profile (log scale) and (b) relative integrated energy as functions of the transverse distance from the optical axis. Grating parameters and propagation distance are the same as for figure 1.

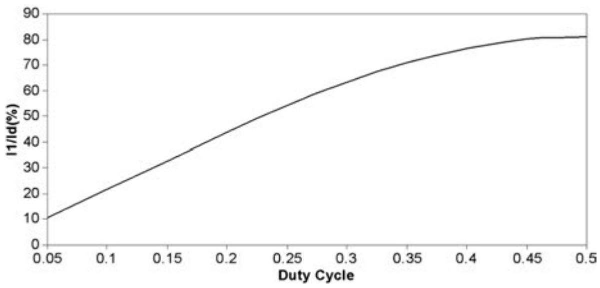


Figure 3. Relative first-order efficiency I_1/I_d versus grating duty cycle. The curve is symmetric for duty cycles larger than 0.5.

The effect of varying the grating duty cycle has been investigated considering the parameter I_1/I_d, where I_1 represents the intensity diffracted into the first order, while I_d represents the overall intensity diffracted out of the principal beam ($I_d = \sum_{m\geqslant 1} I_m$). This quantity turns out to be independent from d. We will consider conditions approaching the ideal sampler, that is the one for which $I_1/I_d = 1$. In this ideal case no energy is subtracted to the main beam I_0 except that directed on the sampled beam I_1.

In figure 3 I_1/I_d is plotted as a function of the duty cycle, with other parameters maintained equal to those of figures 1 and 2. The maximum achievable value of I_1/I_d is 81%, with a two-level surface profile. This result is obtained with a duty cycle of 0.5. This condition corresponds to the zeroing of all even orders ($m = 2k;\ k = 1, 2, 3\ldots$). Similarly, the order n and all its multiples ($2n, 3n\ldots$) are cancelled in the diffraction pattern if a duty cycle equal to $1/n$ is chosen.

We thus can try to design a grating with improved I_1/I_d ratio by exploiting a three-level geometry. Maintaining $\Delta = 1$ mm and superimposing a step of width 0.33 mm and depth $\lambda/16$ on a step of width 0.5 mm and depth $\lambda/24$ we obtain the amplitude reduction of diffraction orders multiples of two and three, thus reaching $I_1/I_d \approx 88\%$.

Table 1. Construction parameters for two-level gratings suitable for laboratory testing and high power beam sampling.

Parameter	Laboratory test version	High power laser sampler
Δ (mm)	1	1
d (μm)	1	0.1
Duty cycle	0.5	0.5
Incident power (W)	50	3000
λ (μm)	10.6	10.6
$\theta_0 - \theta_1$ (mrad)	10.6	10.6
I_0 (W)	34.5	2995
η (%)	12.6	0.14
I_1 (W)	6.3	4.2

For the sake of completeness, we have verified all the above results in the case of higher order Gaussian beams (TEM_{01}, TEM_{10} and TEM^*_{01}) incident on the grating, getting results consistent with those of the fundamental beam.

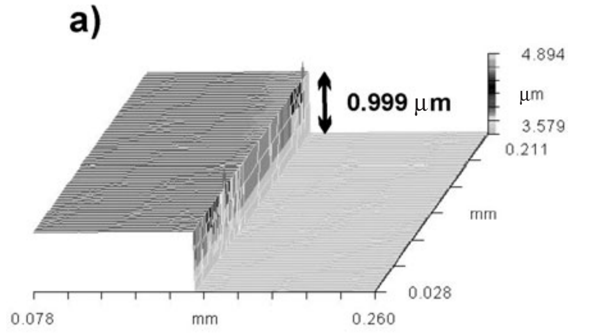
Table 1 summarizes two-level grating parameters we consider suitable to be experimentally tested in our laboratory, compared to parameters useful in the case of low level sampling of high power beams. For our laboratory tests we choose a relatively large extraction value as we plan to test the grating with a 50 W CO_2 laser and a first diffraction order of at least a few watts is needed to be detected with our beam analysis instruments.

3. Beam sampler fabrication

As discussed in the previous sections we focus our attention on the construction of a reflective sampler for high power CO_2 laser applications. The most common reflectors for this kind of laser are based on high reflection metallic coatings (usually silver or gold) on a high thermal-conductivity substrate (usually silicon or copper). A copper substrate presents the highest thermal conductivity but silicon is often preferred for its lower thermal expansion coefficient.

Two different strategies could be adopted to produce the desired mirror profile. The first is based on a masking process during the deposition of the metallic coating on to the substrate. The second is based on etching the substrate itself, either by a chemical process or by a reactive ion one. We tested both these technologies. The production of gratings with a two-step masked gold coating deposition turned out to be successful as long as step depths of the order of 100 nm are required. Deeper profiles present the risk of delamination of the successive metallic layers.

To attain the desired component for our laboratory tests, as detailed in the previous paragraph, we oriented our choice on chemically etching a silicon substrate. The chemical etching of silicon is a widespread technology thanks to its application in microelectronics, but the chemical processing of copper is also known to be viable and is widely described in the literature [11]. In figure 4 we show a portion of the surface profile obtained etching a long period grating on a silicon substrate. Profiles are obtained from the interferogram produced by a Zygo new-view interferometer. Both the precise square shape of the etched steps (of depth 1.0 μm) and the quite good surface quality are evidenced in the interferometric measurements.



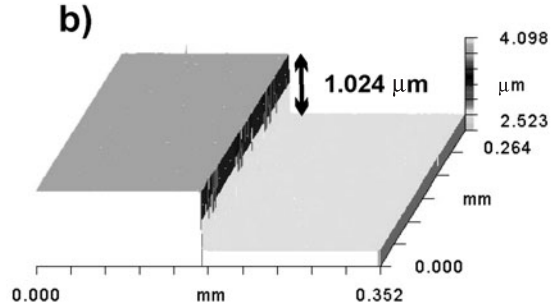


Figure 4. Profiles of the grating step measured with an interferometric technique. (a) Bare silicon substrate resulting from the chemical etching process. (b) Substrate of (a) covered with a layer stack to enhance the reflectivity: the stack is approximately 9 μm thick; the reflectivity is 99.8%.

Metallic mirrors are always overcoated with additional dielectric layers either to protect the metallic surface or to selectively enhance the mirror reflectance at the laser emission wavelength. In the first case a single thin layer is deposited of a low IR absorption dielectric (such as YF_3 or BaF_2). In the second case multiple alternating layers are deposited, of low and high refractive index materials such as BaF_2 and ZnSe. This technique produces at 10.6 μm relatively thick coatings (sometimes several micrometres). We investigated the effect of depositing such a kind of coating on the surface profile produced on the mirror substrate. Figure 4(a) shows the bare substrate profile while figure 4(b) shows the profile of the same grating with an enhanced silver coating (approximate coating thickness 9 μm). The surface quality and groove depth appear almost unaffected by the physical evaporation coating process. Only the step edges appear slightly rounded on a spatial scale of the order of tens of nanometres. We also tested the behaviour of a protected gold coated sample (not reported in the figure), obtaining the same good results.

4. Experimental results

The experiments we carried out to test our beam sampler consist principally in the comparison of laser beam parameters measured directly on the laser output or using the beam sampler. The beam parameters taken into account in this work are beam waist diameter $d_0 = 2w_0$, waist location z_0, beam divergence θ and beam quality factor M^2 [12]. They have been measured on the beam emitted by a 50 W Universal UL-50 CO_2 laser by means of a coherent Mode Master MM-5 beam analyser. The two experimental layouts adopted for the beam

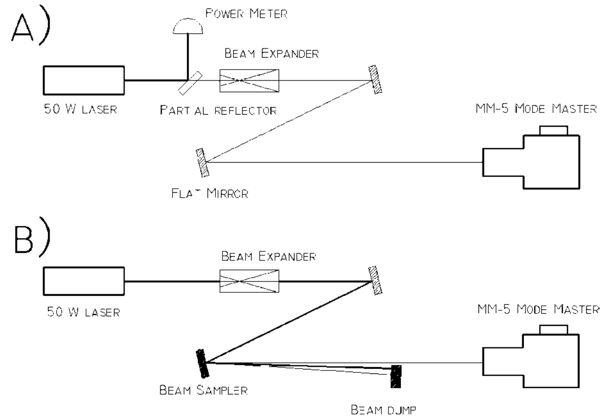


Figure 5. Schematic diagrams of the experimental set-ups: (a) configuration used to measure parameters of the test laser beam, and (b) configuration used to characterize the beam sampler behaviour. For clarity angles and distances are not in scale.

analysis are schematically shown in figure 5. Since the MM-5 accepts beam powers between 0.5 and 20 W we inserted a ZnSe partial reflector ($R = 90\%$) in the beam path when performing measurements directly on the main beam. The incident power being limited to 50 W during these tests, the deformation of the bulk ZnSe material due to light absorption is irrelevant and does not cause substantial changes in the parameters of the beam under test.

The use of a diffractive beam sampler with groove parameters as described in the first column of table 1 allows us to perform an equivalent analysis on one of the two first-order diffracted copies of the UL-50 beam, at a power level of about 3 W. As the laser beam transverse dimension is approximately 5 mm, we inserted in the optical path a beam expander (expansion ratio 3:1) which assures that a relatively large number of grating lines ($\approx$15) are affected by the radiation. The angle of incidence on the sampler was set to 15°. The sampler was placed in a mechanical mounting aimed at producing minimal grating distortions and allowing both air cooling on the component front surface or water cooling on its back surface. No substantial difference was observed by changing the cooling scheme. We have also studied the possible deformations of the sampler induced by the relatively small amount of absorbed laser energy involved in this set of experiments, using a commercial finite-elements software package (Cosmos/M 2.6). The result is always less than $\sim 10^{-8}$ m.

The comparison of data obtained from the MM-5 with the two different measurement set-ups is our main result and is summarized in table 2. The beam analyser was located for these measurements 2.4 m away from the beam sampler in order to resolve the diffracted secondary lobes, as detailed later.

Data reported in table 2 refer to averages over ten measures acquired every 5 min. The indicated error values are the standard deviations of these sets of measures. For comparison the accuracy of the MM-5 device as specified by the supplier (Coherent Photonics Division—Auburn, CA) is reported in the third column of table 2. The residual small discrepancies between the two sets of measures are within the accuracy of the instrument and are to be related to the thermal fluctuations typical of the air-cooled UL-50 laser. This confirms that the

Table 2. Beam parameters defined following the ISO Standard rule number 11146-1, measured directly on the UL-50 output beam and on the grating generated low power copy.

Beam parameter	Symbol (dimension)	Direct measure	On the sampled beam	Specified MM-5 accuracy (%)
x waist diameter	d_{ox} (mm)	11.8 ± 0.6	11.1 ± 0.3	± 2
y waist diameter	d_{oy} (mm)	12.8 ± 0.8	12.4 ± 0.5	± 2
x waist location	z_{ox} (m)	-7.3 ± 0.5	-8.2 ± 0.4	± 8
y waist location	z_{oy} (m)	-10.6 ± 0.8	-11.7 ± 0.4	± 8
x divergence angle	ϑ_x (mrad)	1.91 ± 0.03	1.98 ± 0.05	± 5
y divergence angle	ϑ_y (mrad)	1.49 ± 0.06	1.46 ± 0.04	± 5
x beam propagation ratio	M_x^2	1.68 ± 0.07	1.65 ± 0.04	± 5
y beam propagation ratio	M_y^2	1.53 ± 0.09	1.34 ± 0.03	± 5

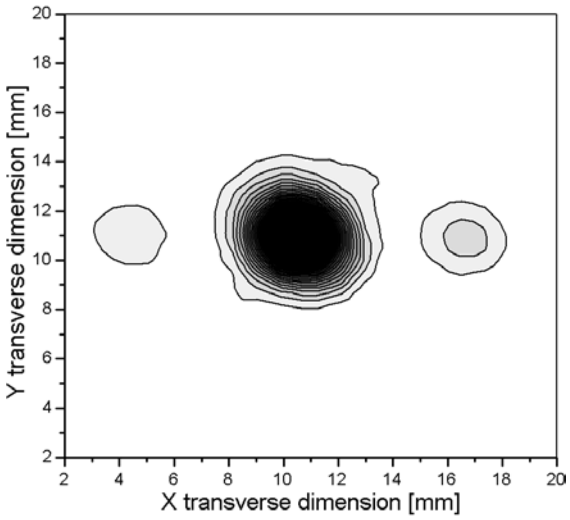


Figure 6. Transverse pattern of the laser intensity measured by placing the UFF 100 beam analyser at a distance of 55 cm from the grating. The angle of incidence on the grating is approximately 15°.

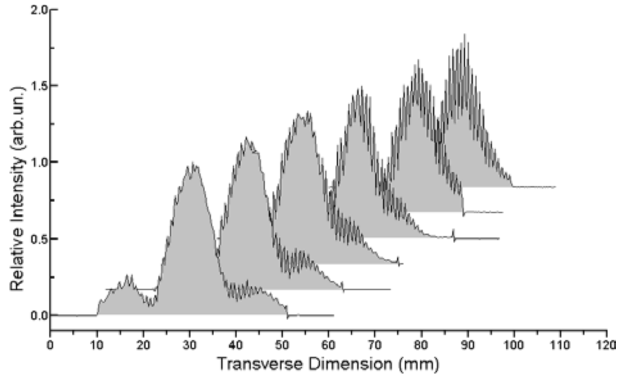


Figure 7. Laser beam shape measured with the 128-elements pyroelectric linear array, after the reflection on the beam sampler. The optical layout is that of figure 5(b) and the six profiles are recorded at 60 (highest line), 80, 100, 120, 140 and 160 cm (lowest line) from the sampler. The first-order diffracted lobes are resolved from the zeroth-order beam at a distance of 160 cm from the grating.

correct beam parameter values can be acquired on the diffracted copy of the beam under test.

The grating diffraction angle can be obtained from the diffracted beam patterns acquired by means of a Prometec UFF-100 two-dimensional beam scanner, as shown in figure 6. This pattern has been acquired at a distance of 55 cm from the sampler without a beam-expander. This optical set-up was necessarily adopted in order to have a power density sufficient for the UFF-100 scanner. From this intensity distribution we can estimate that diffracted beams propagate as expected at an angle of 10 mrad from the main beam direction. We have also verified with a power meter that the first order efficiency agrees with the value listed in table 1.

Finally, figure 7 shows how the diffracted beams develop during propagation after the reflection on the sampler. The beam profiles shown in the figure have been recorded using a 128-element Spiricon laser probe pyroelectric detector array at distances from the sampler regularly spaced between 60 and 160 cm; the detector was mounted on a precision translation stage and the laser was pulsed at a frequency of 100 Hz. In figure 7 it is clearly seen how the secondary lobes emerge from the interference pattern caused from their overlap. These profiles are obtained with the optical set-up shown in figure 5(b) and one can clearly see that almost 2 m of propagation are necessary to resolve diffracted beams with a diameter of 12–15 mm, such as those produced with the beam expander. For this reason a 2.4 m propagation distance was adopted to collect the MM-5 beam parameter data.

The beam sampler with the high-reflection coating has also been preliminarily tested with a 3 kW fast-axial-flow CO_2 laser (in this case a standard water-cooled mirror mounting has been used). Deformations of the order of 10^{-7} m are predicted by computer simulations when using a multimode 16 mm diameter beam. The beam quality factor measurements obtained with the sampler again appear consistent with direct measurements, so that the sampler behaviour compares well with the tests presented here. The detailed description of the high power experiments will be reported in the future.

5. Conclusions

We have verified the feasibility of low frequency, low extraction level, diffractive beam samplers based on the chemical etching of high reflectance silicon mirrors for high power CO_2 lasers. Laser beam parameters measured using these mirrors are experimentally proven to be consistent with those measured directly on the beam.

Acknowledgments

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