Graded reflectivity mirrors with high reflectivity for 1.06 μm lasers

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Abstract. Multilayer dielectric (23 layers of ZrO2/SiO2) graded reflectivity mirrors (GRM) for 1.06 μm lasers with reflectivity in the centre of the order of 98.5% have been fabricated with the use of fixed 3D mask techniques. A 3D mask unlike the 2D one can prevent the appearance of side-lobes in the beam reflectivity profile in the case when the thickness of each of the 23 layers of the multilayer mirror is profiled. The results of investigation of deposited GRMs in Nd:YAG and Nd:YAlO3 lasers are presented.

1. Introduction

Multilayer dielectric (23 layers of ZrO2/SiO2) graded reflectivity mirrors (GRM) [1–5] for 1.06 μm lasers with reflectivity in the centre of the order of 98.5% have been fabricated with the use of fixed 3D mask techniques [5–10]. A 3D mask unlike a 2D one can prevent the appearance of side-lobes in beam reflectivity profile of a multilayer mirror with profiling of the thickness of each layer [5, 9, 10]. The results of investigation of deposited GRMs in Nd:YAG and Nd:YAlO3 lasers are presented.

In most papers on laser resonators with graded reflectivity mirrors (GRM) such mirrors for 1.06 μm have been used with about 50% maximum reflectivity in the centre [11–22], but in many cases, for example in special schemes of resonators or in amplifier laser fusion systems, a high reflectivity is needed of up to 100%, e.g. GR diaphragm has been used in Nd:glass laser systems [23–26] and in the 5 TW 1.3 μm Asterix IY iodine laser for beam shaping [27].

To fabricate dielectric mirrors with ~100% reflectivity multilayer coatings (unlike the 2–3 layers in the case of a low value of reflectivity) are needed. In this case instead of only one layer with variable thickness each layer has a variable thickness from a maximum value to zero to obtain the variable reflectivity profile with the desired peak value.

The main problem in the case of fabrication of GRM with high reflectivity is the appearance of lateral ripples in the reflectivity profile owing to the profiled thickness variations of many layers. To overcome this difficulty a method of using a 3D mask [5–10] instead of an ordinary 2D one has been used in [5, 9, 10] for the case of fixed mask techniques [3, 6–8, 28–32]. The simplest thick 3D mask has one conical or cylindrical hole with the smaller diameter contacting with the substrate.

In the present paper we consider our results on deposition of GRMs with approximately
Figure 1. (a) The scheme of deposition. (b) The simplified scheme of deposition. (c) Profiles of deposited layer without rotation and with planetary driving of substrates. (d) 3D mask with conical hole.

98.5% reflectivity in the centre without lateral ripples owing to the use of 3D masks with conical holes.

The results of investigation of fabricated GRMS in the plane-parallel resonator of a Nd:YAG laser showed a small increase of brightness in comparison with a hard-edge aperture (Fresnel number \( \sim 3.4 \)).

2. Apparalus for fabrication of GRMS

The deposition of GRMS having 23 layers of ZrO₂/SiO₂ with \( \lambda/4n \) maximum thickness of each layer on glass substrate was carried out in Balzers BAK-640 electron beam gun chamber with a universal planetary drive of substrate rotation, by similar techniques as for deposition of an aspherical surface for a frustrated total internal reflection apodized aperture [28–32].

The scheme of deposition is presented in figure 1(a). A number of flat plates (planets) with substrates rotate around the substrate holder axis, and also each of these planets rotates around its own axis. We designate the following distances: \( l \), between the source and the holder rotation axis; \( S \), between the planet centre and the holder rotation axis; \( s \), between the planet centre and the substrate centre. \( \psi \) is the angle of inclination of the planet plane to the holder axis.

Let us consider the simplest case: \( \psi = 90^\circ \), \( s = 0 \), and a 2D mask with radius \( a \) placed
at the distance $h$ from the substrate, see figure 1(b). When the substrate holder is immovable, and the substrate rotates only along its axis, the film profile deposited through the mask has two steps (figure 1(c)). The radii of these steps are (for a distance $L$ between a source and planet's centre in a parallel direction of a holder axis, and the scheme of figure 1(b)):  

$$
\begin{align*}
r_{\text{min}} &= a - h \tan \beta_1 = a - h(S - l - a)/L = a - h(S - l)/L = a - h \tan \beta \\
r_{\text{max}} &= a + h \tan \beta_2 = a + h(S - 1 + a)/L = a + h(S - l)/L = a + h \tan \beta
\end{align*}
$$

(1)

where $\beta_1 \approx \beta_2 \approx \beta$ is the incidence angle and $a, h \ll S, l, L$. When the holder rotates along its axis, variations of $\beta$ produce the effect of a smooth monotonic profile (figure 1(c)), but in this case $\tan \beta$ can be greater than $a/h$ (there is no deposition in the centre for such $\beta$). This results in a small pit in the centre of the film. Such an effect was considered in [10].

A 3D (extended) mask [5, 9, 10] with conical aperture is shown in figure 1(d). $D_1$ and $D_2$ are diameters, and $h$ is the thickness of the hole. The surface of the 3D mask with smaller diameter $D_1$ of the hole contacts with substrate, the surface with $D_2$ is nearer to the deposition source. This technique in many cases reduces undesirable side-lobes in the reflectivity profile of mirror with each layer having a variable thickness from a maximum value to zero. The same effect can be obtained by replacing the extended (3D) mask by two (or more) 2D (flat) ones with the hole diameters $D_1$ (contacting the substrate) and $D_2$ (at distance $h$) [5, 10]. Each of the variable layers is deposited on another variable one with the same 3D mask so that at diameter greater than $D_1$ there is no coating (because of contact of this side of the mask and substrate without any shadowing effect), and the side-lobes in the reflectivity profile are compressed [10]. The smooth profile of the central part is created by the shadowing effect of the hole with diameter $D_2$ (opposite side of the mask) at the distance $h$ from the substrate. It should be noted that we chose the relations between the dimensions of the 3D mask ($D_1, D_2, h$) that best reduced side-lobes in the reflectivity profile by the experimental way.

The chamber was pumped out to $2 \times 10^{-6}$ total pressure after heating of the substrates up to 300°C. and after the oxygen supply the total pressure became $2 \times 10^{-4}$ mbar. We used an automatic regime with a constant velocity of deposition with quartz control of layer thickness. The mean velocity of ZrO$_2$ deposition was 0.65 nm s$^{-1}$, SiO$_2$: 1.52 nm s$^{-1}$. We used K-8 glass substrates with $n = 1.52$. The refractive indexes of ZrO$_2$ and SiO$_2$ were 1.95–2.0 and 1.45 in our samples.

3. Characteristics of deposited GRMS

The transmission profiles of GRMS fabricated with the use of the 3D mask are presented in figures 2 and 3. If we approximate the central region of these curves by the super-Gaussian ones, for the reflectivity $R(r)$ we can obtain profiles $\sim R_0 \exp[-(r/r_0)^N]$ with $R_0 = 0.984; r_0 = 1.1$ mm; $N = 12$ (figure 2), and $R_0 = 0.985; r_0 = 1.5$ mm; $N = 15$ (figure 3). We used conical masks with 2 mm thickness and 3 and 5 mm diameters in the first case, and 4 and 6 mm diameters in the second case.

There are no ripples in the reflectivity profiles of GRMS which have been fabricated with the use of conical masks, in spite of the case when we used ordinary non-contacted 2D masks, side lobes in the reflectivity profile have been observed (figure 4) for $h = 2$ mm,
and 3 mm diameters of the hole. Figure 5 shows the transmission profile of the GRM with a pit in the centre.

The GRM transmission profiles in the beam of a 1.06 μm Nd:YAG laser have been recorded by computer processing of signals from two photodiodes PD1 and PD2 (a semitransparent mirror split the beam) [33]. PD1 was used as the reference. The lens formed the diminished image (0.2 mm) of the small diameter diaphragm on the surface of the GRM. PD2 was placed behind the GRM. The investigated GRM was placed on micrometric stages moving perpendicular to the direction of the laser beam. We used an integrating RC circuit as the load of the photodiodes. The output signal from it was fed into a digital voltmeter. The data of the experiment were collected and processed by a computer. At first the signal ratio was measured with the photodiodes without a GRM. Measurements of the transmission profile of the GRM were performed with the GRM displaced in steps of 0.1 mm perpendicular to the axis of the laser beam (and the small diameter diaphragm fixed). The measurements were averaged over 10 pulses. The laser was operated in the free-running regime.
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4. Investigation of GRMS in Nd:YAG and Nd:YAlO\(_3\) lasers

It should be noted that although GRMS give their best performance in unstable resonators [34] in many laser applications where the Gaussian and super-Gaussian profiles in the near field are required, the stable resonator is the only choice [34]. In [35] it was shown experimentally for the plane-parallel resonator with thermal lensing an increase of the axial candlepower of the Nd:YAlO\(_3\) laser with a GRM (without compensation of the thermal lens and with the use of a deformable mirror for its correction).

One of the fabricated GRMS (with transmission profile shown in figure 2) has also been used as a mirror of the plane-parallel resonators of Nd:YAG (figure 6(a)), and Nd:YAlO\(_3\) (figure 6(b)) lasers operating under free running conditions. The deposited surface of GRM was turned into the cavity [5]. The active element was placed inside a silvered monolithic enclosure made of quartz (the flashlamp was placed in one focus, the crystal in another focus). The first crystal had dimensions 6 cm \( \times \) 6 mm, the second one 8 cm \( \times \) 6 mm. The first crystal without antireflection coatings was turned at small angle to the resonator axis to prevent parasite generation of faces, the second one had antireflection coatings. The pumping energy was 75 J in both cases, the repetition rate was 10 pps (a), 3 pps (b).
To register the intensity distribution of the output beam we used a moving photodiode with a small diameter diaphragm (0.2 mm) in front of it. The power of the laser was measured by a pyroelectric power meter.

Figure 7 shows the spatial intensity profiles at 25 cm from the output of an Nd:YAG laser (curve 1) and at 7.5 m from it (curve 2). For comparison an ordinary hard mirror was placed instead of the GRM, and a 3 mm diameter hard-edge aperture was inserted inside the resonator. Figure 8 shows the spatial intensity profiles at 25 cm (curve 1) and at 7.5 m from this laser (curve 2).

The evaluation of full-angle beam divergence $\theta$ at the 1/e level gives $\theta = 0.74$ mr for the GRM case, and $\theta = 0.86$ mr for the hard-edge aperture. The output power was 0.160 W in the first case, and 0.170 W in the second case (approximately 30% of the energy with ordinary 99% mirror without hard-edge aperture inside the resonator).
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Figure 8. Spatial intensity profiles of beam at different distances from the output of Nd:YAG laser with hard-edge aperture.

Figure 9. Spatial intensity profiles of beam at different distances from the output of the Nd:YAlO₃ laser with GRM.

The comparison of the results of the experiments with GRM and hard-edge aperture shows, that if we compare brightness (W cm⁻² sr⁻¹) of the output radiation, the axial brightness in the case of using GRM is 1.4 times greater than with hard-edge aperture inside the resonator with almost the same output power. This difference is smaller than in [35], where for the case with uncorrected thermal lens the axial candlepower (W sr⁻¹) of laser radiation at the output resonator with GRM was more than two times greater than with an ordinary mirror (in our case the candlepower ratio is 1.3). We suppose that better improvement has been found in paper [35] because of the greater Fresnel number in their case (~19) in comparison with ~3.4 in our experiments. In the case of more modes in the resonator the introduction of a GRM improves the selectivity of modes.

Figure 9 shows the spatial intensity profiles at the same distances as in figures 7 and 8 for the Nd:YAlO₃ laser. The evaluation of θ from these data gives the value of θ = 0.36 mr.
The output power was 0.22 W, and the power of the laser with an ordinary 99% mirror instead of GRM was 0.59 W.

5. Conclusions

We have carried out the deposition of high-reflectivity GR multilayer dielectric mirrors for 1.06 μm lasers. The essential diminishing of side lobes in the reflective beam has been observed. These mirrors have been used as the high reflectivity mirrors of Nd:YAG and Nd:YAlO₃ lasers with plane resonators. For the Nd:YAG laser with the GRM we observed a small increase in brightness in comparison with a hard-edge aperture (Fresnel number ~3.4). Greater values of Fresnel numbers could give better performance of GRMs in plane-parallel resonators (more increase of brightness).

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