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Supper-Gaussian TiO_2 laser mirror made by RF-sputtering of pure titanium target

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The aim of this report is the elaboration of TiO_2 thin film coatings with Super-Gaussian reflectivity profile designed to be used as mirror in laser unstable resonators. RF reactive sputtering of pure titanium target was selected as technological method. The gas flow and Ar to O_2 ratio of gas mixture optimization were set as result of optical transmission spectra measurements. Secondary collisions that take place behind the selected stainless steel mask give the possibility to obtain the required reflectivity profile. The central reflectivity of 29 %, the waist of 1.42 mm and the super Gaussian order of 3.5 were obtained. The fitting method and procedure is developed.

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1. Introduction

Many applications such as ophthalmic surgical microscopes, industrial cutting or drilling, rangefinders, systems with high far-field brightness and so on require lasers with low diffraction beams. Minimal diffraction limited value corresponds to the fundamental mode TE_{00} Gaussian profile beam. Lasers with high quality of the beam can be obtained by using smooth mirrors whose reflectivity gradual decreases to zero at the edge. Such mirrors were used in unstable resonator schemes [1-3]. Other important advantage of lasers with unstable resonators is the large mode volume that permits the elaboration of small and miniaturized lasers. But only a limited number of devices have been demonstrated experimentally [4, 5]. More than that, in many cases a flat profile and a small divergence is needed, that is a laser beam with super-Gaussian profile [6].

To make dielectric mirrors with a variable reflectivity profile, several thin film vacuum deposition techniques with a proper setup have been used. Two different experimental setups can be imagined: the rotating mask [7, 8] and the fixed mask method. In the first, the mask with a shaped aperture rotates on the mirror axis to produce a radial variable thickness layer. The second, on the contrary, is essentially based on the shadowing effect of a fixed noncontact mask with a circular aperture. Multilayer TiO films with constant thickness were extensively used as mirror for YAG:Nd lasers. Electron-beam evaporation of TiO_2, SiO_2 synterized pieces is frequently used for films deposition. However TiO_2 films prepared by conventional electron beam evaporation exhibit considerable absorption [9, 10]. Studies have been made on TiO_2 films to relate optical as well as structural properties with deposition techniques, as well as deposition parameter [11-13]. TiO_2-layers for self-cleaning applications were deposited on glass and silicon wafer [14] by reactive DC-sputtering at various oxygen and argon pressures.

A technique having the possibilities of film deposition into sufficiently high vacuum pressure to perform particle collisions is needed for the realization of films with variable thickness. RF sputtering method of pure titanium disc in reactive O_2/Ar gases is described in paper. Variable-reflectivity mirror with super-Gaussian profile was obtained and characterized.

2. Experimental details

Titanium dioxide (TiO_2) thin films were deposited by RF magnetron reactive sputtering using a conventional magnetron sputtering system (Fig. 1). The base pressure of the vacuum chamber was 5×10^{-4} Pa and was measured by a wide range gauge (Edwards WRG-S). The reactive and sputtering gasses were O_2 (5N) and Ar (6N). Total pressure was measured by a capacitive gauge (MKS Baratron 626A) and was kept constant at 8×10^{-1} Pa during the depositions. Sputtering was performed using an one inch diameter magnetron gun (AJA International Stiletto).The sputtering target was a titanium (99,99% pure) disc. The distance between target and substrate consists 55 mm, - reasonable small to keep sufficiently high energy of sputtered particles. Multiple scattering of such particles with gas atoms/ions is required for the realization of film thickness profiling. Gases flows were controlled by two mass flow controllers (Bronkhorst MFC 0-15 sccm) and were kept constant. All the depositions were made at 100 watts RF power using a RF- 13.5 MHz generator and associated matching box (Advanced Energy Integro 133). The films were deposited on polished λ/4 flatness BK7 glass substrates. Prior to deposition all the samples were ultrasonically cleaned using isopropyl alcohol.

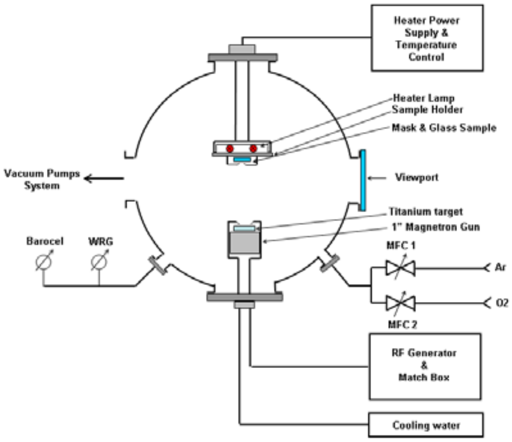

Fig.1. Experimental setup of RF sputtering of graded-index TiO_2 films

3. Deposition of thin TiO_2 films with constant thickness

Many other deposition parameters as gas pressure, Ar/O_2 ratio, substrate temperature influence the optical quality of deposited films such as refractive index, absorption coefficient or light scattering value. The distance between target and substrate consists 55 mm, - reasonable small to keep sufficiently high energy of sputtered particles as multiple scattering of such particles with gas atoms/ions is required for the realization of film thickness profiling. In the prime stage of experiments the mask before substrate is missing in order to establish optimal deposition conditions. In such conditions the thickness of films is quite constant over the surface. Such films were used for optical characterization. The optical transmission was measured by a Lambda 1050 Perkin Elmer spectrometer in the spectral range 300 -1800 nm. Transmission of TiO_2 films spectra are given in Fig. 2, were pure substrate transmission is also shown.

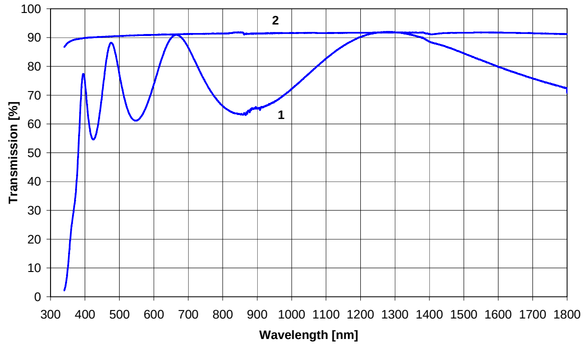

Fig. 2. Transmission spectra of thin TiO_2 films: interference spectrum (1) and pure substrate (2)

As we can see, films have the transmission values in maxima close to transmission value of pure substrate. That means good quality of films without absorption or scattering. Lower transmission level occurs when oxygen pressure or substrate temperature haven't optimal values. From the minima values we can calculate the refractive index of film, using the formula for optical transmission [15]:

$$T = \frac{4n_f^2 n_s}{2n_f^2(n_s+1)+(n_f^2-1)(n_f^2-n_s^2)\sin^2(\delta)} \qquad (1)$$

When sin (δ) = 1 we obtain from (1) value of film's refractive index:

$$n_f = \sqrt{N \pm \sqrt{N^2 - n_s^2}} \qquad (2)$$

$$\text{where} \quad N = \frac{2n_s}{T_{\min}} - \frac{n_s^2+1}{2} \qquad (3)$$

Sign plus must be taken in (2), because the refractive index of film is higher than that of the substrate. The value of TiO_2 film's refractive index calculated from interference spectra is n = 2.2.

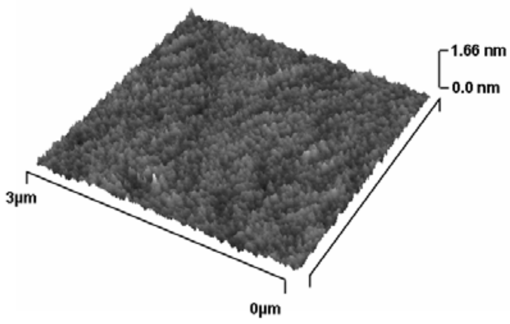

Fig.3. AFM image of TiO_2 film surface.

Morphology of film surface was determined by AFM microscope model Veeco Di Innova (Fig. 3). The film roughness is 0.11 nm. Optimal values of gas flow are 8 sccm for Ar and 2 sccm for O_2. Optimal surface temperature was found to be 150 °C.

4. Making of TiO_2 films with graded-reflectivity for YAG:Nd lasers

Even since the first years of the development of the laser techniques unstable resonators were proposed to enhance the laser radiation features (increasing the brightness, attainment of small diffraction beams and a better use of the volume of the active medium). Because the constant radial reflectivity mirrors induce large diffraction losses, the solution is to use graded-reflectivity mirrors, having a soft edge. However, the use of this technique became possible far later, when technologies to produce variable reflectivity radial profile laser mirrors were developed. Mainly the method was applied to high volume active medium lasers (excimer lasers, CO_2 lasers, etc.). Other applications, even rarely used, are such as miniaturized solid state lasers, which at a resonator length of 10 cm generate in the fundamental mode. The advantage of this solution is the possibility to achieve laser radiation having Gaussian or Super Gaussian profile. In this paper we develop a method to produce a laser mirror having designed parameters. The production of such mirrors is not serialized because of the specific requirements of each laser.

The mirror must be made of thin lasting dielectric layers (high melting temperature oxides) that ensure the necessary resistance to the laser radiation and an appropriate refractive index. The Super Gaussian reflectivity profile mirror has the next analytical form of the reflectivity:

$$R = R_0 \exp\left[-2\left(r/\omega_m\right)^n\right] \qquad (4)$$

where R_0 is the peak reflectivity in the center of the mirror, r is the radial coordinate, ω_m is defined as the radius at which the reflectivity diminishes by e^2 times, and n is the Super Gaussianity order.

A suitable structure is a glass substrate having an antireflection layer on which is deposed a thin film with the appropriate radial variable thickness. Because the mirror is used as an extraction mirror, the antireflection coating must be done on both sides of the substrate (Fig. 4).

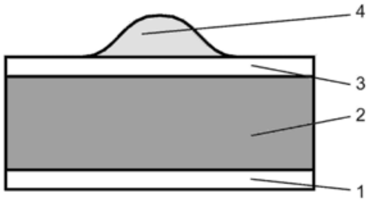

Fig. 4. The structure of the radial variable reflection mirror. 1,3 – antireflecting layer, 2 – substrate, 4 – radial variable thickness layer

The necessary profile for the thickness δ may be deduced from the interference theory of light in thin layers, giving:

$$\delta(r) = \frac{\lambda_0}{4\cdot\pi\cdot n_2}\cdot \arccos\left\{\frac{1}{2\cdot r_{12}\cdot r_{eq}}\cdot\left[\frac{(1-r_{12})^2\cdot(1-r_{eq}^2)}{1-R(r)} - r_{12}^2\cdot r_{eq}^2 - 1\right]\right\} \qquad (5)$$

where r_{ij} are the Fresnel coefficients of reflection at the boundary of two media:

$$r_{ij} = \frac{r_i - r_j}{r_i + r_j} \qquad (5a)$$

while r_{eq} is:

$$r_{eq} = \frac{r_{23} + r_{34}\cdot\exp(-j\cdot\frac{4\pi\cdot n_3\cdot\varepsilon_3}{\lambda_0})}{1 + r_{23}\cdot r_{34}\cdot\exp(-j\cdot\frac{4\pi\cdot n_3\cdot\varepsilon_3}{\lambda_0})} \qquad (6)$$

For an antireflection layer that is adjusted at the thickness $\varepsilon_3 = \frac{\lambda_0}{4\cdot n_3}$ the above equation becomes:

$$r_{eq} = \frac{r_{23} - r_{34}}{1 - r_{23}\cdot r_{34}} \qquad (7)$$

Using this equation and appropriate substitutions in equation (3.2) the profile of the film thickness δ can be deduced as a function of the necessary distribution of the reflectivity (Super Gauss analytical form).

The maximum value of the reflectivity that it can be obtained using this material is derived from equation (3.2) for cos φ = 1 and $\delta = \lambda/4n_2$, resulting

$$R_{0\max} = \left(\frac{2\cdot r_{12}}{1 + r_{12}}\right)^2 \qquad (8)$$

Titanium oxide is a promising material due to its large refraction index ($n_2 = 2{,}2$) and resistance to high intensity 1064 nm laser radiation.

For this material $r_{12} = \frac{1-2.2}{1+2.2} = -0.37$, that corresponds to $R_{0max} = 0.43$ (or 43 %). This value is sufficient for a laser mirror, because usually a Q-switched solid state laser needs a mirror with a reflectivity in center of 25 % - 35 %.

A smaller film thickness leads to a smaller reflectivity. Variable thickness layers were obtained using a mask having a certain calculated diameter and placed at a certain distance from the target. These parameters are experimentally determined as a result of many technological experiments and then numerically fitted to the above mentioned analytical curves. Due to the relative high gas pressure in the enclosure, the atom collisions appear also in the space behind the mask. This process leads to a scattering of the sputtered particles. The designed profile was selected from the technological nomogram built as a dependence between the distance from mask to substrate and the diameter of the orifice in the mask for selected optimized gas composition.

The film depositions with variable thickness were done according to the schematic presented in Fig. 1, using an orifice mask in front of the substrate. A measurement of the mirror reflectivity was done in order to determine the mirrors parameters (R_0, ω, n) using a simple layout. The Nd:YAG (1064 nm) laser beam is focused close to the tested mirror by a 200 mm - focal length objective lens. The mirror is placed on a micrometric X-Y translation table. Behind the mirror, at an appropriate distance, it was placed a powermeter measuring head. The experimental reflectivity curve for a mirror designed for R_0 = 30 % is presented in Fig. 5.

The parametric nomogram was built after several technological experiments for a orifice diameter in the mask of 1.65 mm and a distance from substrate to mask of 4.5 mm. The gas flow and the distance till magnetron were mentioned afore. The deviation of the radial profile from the specified form is caused by the circular indentation formed in the Titanium target following repeated depositions. Such deviations don't appear at plane surface targets.

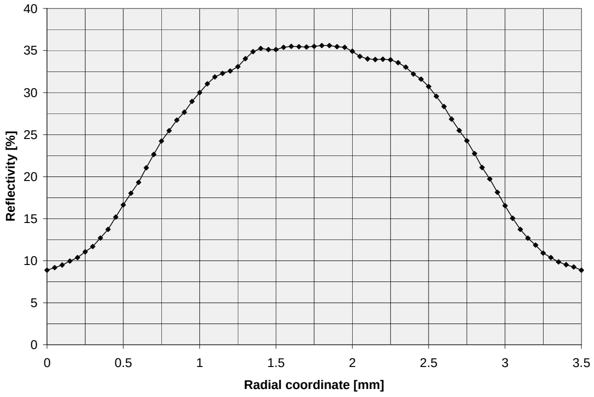

Fig. 5. Experimental reflectivity curve

5. Fitting procedure and determination of super-Gaussian parameters

The experimental curve must be fitted to an analytical Super-Gauss function:

$$y = 1 - R_0 \cdot e^{-2\left(\frac{x}{\omega}\right)^n} \qquad (9)$$

The problem consists in determining the parameters R_0, ω and n which satisfy the measured transmission profile best. The next approach was used to determine the analytical coefficients from the experimental data:

- for $x = 0$ the transmission y is $y = 1 - R_0$, so the value of R_0 remains that previously determined, when the regression was tried (29.7 %),
- for $x = \omega$ the transmission y is $y = 1 - R_0/e^2$, regardless n. This can be stated thus: all the super-Gaussian distributions, regardless their Gaussianity degree n, have at the waist $x = \omega$ the same normalized value ($1/e^2$)

This second remark enables us to determine the waist ω as equal that x for which $y = 1 - R_0/e^2 = 0.96$. From experimental data we deduced that this transmission was obtained for x = 1.60 mm, which is the waist ω of the super-Gauss distribution. The order of Gaussianity n was determined using a minimization method based on the least squares method. The merit function σ is:

$$\sigma = \sqrt{\sum_{i=1}^{m}\left(y_i - y_{Gi}\right)^2} = \sqrt{\sum_{i=1}^{m}\left(y_i - 1 + R_0 \cdot \exp\left(-2\cdot\left(\frac{x_i}{\omega}\right)^n\right)\right)^2} \qquad (10)$$

In equation (4.2) the only unknown term is n. For different values of n, laying between 2 and 5, σ is appropriately calculated. In Fig. 6 the merit function is presented.

It can be remarked that the minimum (the best fit) is attained for n = 3.65. Therefore the measured data are best described (with an error σ = 0.028) by a super-Gauss distribution having the next parameters: R_0 = 29.7 %, ω = 1.60 mm and n = 3.65.

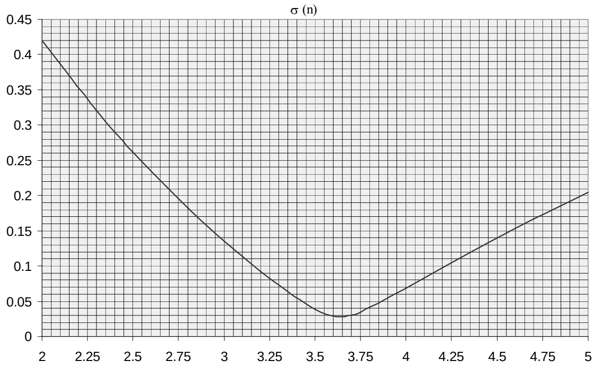

Fig.6. The merit function σ (n).

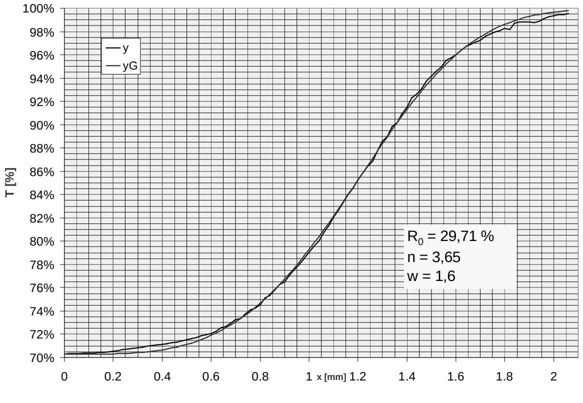

Fig. 7. The fit of the experimental data (y) with the fitting curve (yG)

The experimental data and the fitting curves are presented in Fig. 7. A good agreement between the experimental data and the fitting curve is remarkable.

6. Conclusions

Reactive RF reactive sputtering of pure titanium disc as target is a good technique for vacuum deposition of thin TiO_2 films. Maximum transmission for wavelengths more than 1 μm is quite close to the transmission of the substrate, proving the high quality of the film. This gives the possibility of making mirrors for YAG: Nd and other near IR active laser media. Films with variable super Gaussian profile reflectivity can be produced by using the shadowing effect of a fixed mask containing circular aperture. A fitting method for determining mirror's parameters was proposed.

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