Dielectric films deposition with cross-section variable thickness for amplitude filters on the basis of frustrated total internal reflection

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ABSTRACT

Various optical elements with Gaussian and super-Gaussian transmission or reflection characteristics are used both inside the laser cavities to create a good mode discrimination, and outside them to avoid Fresnel diffraction ripples in beam cross-section, e.g.\(^1,^2\) (review papers). The frustrated total internal reflection amplitude filter or so-called apodized aperture (FTIR AA) is one of these devices.

In this paper we describe the FTIR AA which is a glass cube consisting of two right-angle prisms with their hypothenuse faces near the optical contact, separated by the single dielectric film with smooth monotonous variable thickness along the cross-section.

Close to spherical and different smooth flat-top shape surfaces which are SiO\(_2\), SiO or MgF\(_2\) single profiled films with \(\sim 0.5\text{-}1.5\mu m\) maximum value of thickness were deposited on glass or quartz substrates by electron beam, reactive heating or sputtering techniques. The comparative analysis of rotating mask and noncontacting mask methods for preparation of profiled films has been carried out.

The results of testing of such filters in lasers and laser radiation damage thresholds of films in optical contact conditions are presented herein.

1. INTRODUCTION

The FTIR AA are used in laser physics for many years. It should be mentioned that principle of work of such type of AA was studied already by I. Newton (see \(^3,p.1\)), the drawing of this unit is also presented in the book\(^3\) (p.33), the experimental fabrication of one-dimentional flat-top profile FTIR AA was carried out in \(^4\), two-dimentional flat-top and near-Gaussian one - in \(^2,^5,^6\). The authors of \(^7\) investigated FTIR AA with spherical surface on one of two prisms inside the eximer laser cavity. Such AA can be successfully used inside the cavity of a copper-vapor laser. They are also used in the primary standard of relative energy density profile in beam cross-
section 8.

In most cases the profiled surface of one of two prisms was a surface of an ordinary spherical lens and the output beam had only near-Gaussian intensity profile with the elliptical cross-section. We know only papers 2,3,6 in which the surface divided two prisms had the special shape for formation in two-dimensions both near-Gaussian and smooth flat-top profiles with circular cross-section of the output beam without using cylindrical lens.

In this paper we develope the vacuum deposition techniques for preparation of single dielectric profiled films which has been carried out in our papers 2,3,6. It should be mentioned that similar problems are also solved in papers 9-23 to fabricate the dielectric multilayer or metal mirrors and filters with variable optical characteristics along the cross-section.

2. DESIGN OF THE FTIR AA

The photograph of the FTIR AA device is presented at Fig.1. This AA consists of two total internal reflection 90° or Brewster prisms with their working faces near the optical contact conditions separated by a single dielectric film (∼1-2λ maximum thickness, λ is the laser wavelength) which has smooth changing of thickness along two coordinates. It results in smooth changing of transmittance along the cross-section due to the gradual layer thickness variation under the conditions of total internal light reflection on the contact surfaces of two prisms. In most cases we used two right-angle isosceles glass prisms and deposited the profiled film on the hypotenuse face of one of them or on the plane substrate optically contacted with its face. There are two types of FTIR AA - with convexity or concavity on the hypotenuse face of the prism (Fig.2 a,b). In the first case the FTIR AA works in the transmitted beam, in the second case - in the reflected one.

Fig.1. The photograph of the FTIR AA device.

Fig.2. Transmitted beam FTIR AA (a) and reflected beam one (b).

The difficulties arise when we make the optical contact between the deposited film and the face of another prism. At first we must remove the dust particles from the surfaces by the air stream and after that we must translate one surface to another very accurately without distortion. For this purpose we used a system of stress adjusting screws in the mount of the device with the hand control and also the stress deposited circles or strips on the face with profiled film. The best way to translate the faces with high precision near the optical contact conditions is the use of high precision positioning system with computer control.
The calculations of the FTIR elements have been made in papers 25,24,25. For the glass substrate with refractive index $n=1.52$ and angle of incidence on the film $\theta=45^\circ$ for $I_{\text{min}}/I_{\text{max}}=1:100$ (I$_{\text{min}}$ and I$_{\text{max}}$ - the intensity of the output beam at the edges and at the center of FTIR AA in the case of uniform input beam) the film thickness in the maximum thickness place $d$ must be approximately $d_\perp \sim 1.03\lambda$ for $E_\perp$ and $d_\parallel \sim 1.20\lambda$ for $E_\parallel$ ($E_\perp$ and $E_\parallel$ - the electric field vector component perpendicular and parallel to the plane of incidence). For $I_{\text{min}}/I_{\text{max}}=1:1000$ $d_\perp \sim 1.50\lambda$ and $d_\parallel \sim 1.67\lambda$.

Fig.3 presents the calculated profiles of internal dielectric film for the transmitted beam FTIR AA which makes from the uniform beam the super-Gaussian one, namely:

$$I(r)/I_{\text{max}} = \exp\left[-\left(r/r_0\right)^N\right],$$ (1)

for $N=2$ (curves 1), 5 (curves 2), 10 (curves 3). In this Figure solid lines present the film profiles for $E_\perp$, dotted lines - for $E_\parallel$; $r$ is the distance from the beam center; $I(r_0)/I_{\text{max}} = 1/\exp$ (in this case $d_\perp \sim 0.31\lambda$, $d_\parallel \sim 0.43\lambda$); $I(r_1)/I_{\text{max}} = 10^{-3}$.

![Fig.3.Profiles of internal dielectric films for the transmitted beam FTIR AA.](image)

3. DEPOSITION OF SINGLE PROFILED FILMS FOR THE FTIR AA

Two methods of deposition of profiled thin films are well known. They are: 1) rotating mask technique, e.g. 9,11,14,15,20 and 26 for the photographic AA; 2) noncontacting or fixed mask technique (the use of a shadow effect of the mask on substrate), e.g. 5,12,16,18,19,21 and 27 for the photographic AA.

We used both methods in the different evaporation units to produce single dielectric profiled films of SiO$_2$, SiO and MgF$_2$.

The masks have been made by the photolithography method.

3.1. Rotating mask technique

3.1.1. Deposition equipment

The film profile in the rotating mask technique is prepared by the deposition of dielectric through a mask which is rotated with respect to substrate. The mask has a calculated opening angle $\varphi$ as a function of radius $r$: $\varphi = \varphi(r)$.

This technique was carried out in Balzers BAK-510 and BAK-550 units with resistive heating.

Fig.4 shows the masks for this type of technique: a - for production the transmitted beam FTIR AA (see Fig.2a), b,c - for production the reflected beam one (see Fig.2b).

We have been used motor with polyethylene bearing ($\sim 3.10^3$ R.P.M., 50V) to rotate the chuck with mask relatively the substrate. The belt-drive reduced the rotation.
down to 30 R.P.M. (see Fig.5). The deposition time was 20 minutes to deposite \( \approx 1.2 \mu m \) film. The mask chuck was placed at the distance of 50cm over the evaporation source with the size \( 1 \times 4 \text{cm}^2 \). The working pressure inside the chamber was \( \approx 4 \times 10^{-6} \text{mbar} \).

Fig.4. Masks for fabrication the profiled films by rotating mask technique.

Fig.5. The design of rotation system for rotating mask technique.

3.1.2. The profiles of deposited films

The quality of the profile of deposited film depends on the good alignment between the center of mask and its rotation axis and also of the uniformity of mask rotations.

We investigated deposited films in the Mach-Zehnder interferometer. Fig.6a shows the interferogram of SiO film for the transmitted beam FTIR AA (mask Fig.4a). We can see some ripples on the deposited surface. The pattern is similar to Fig.6 of paper 2b on the fabrication of photographic AA by rotating mask technique in which a radial striation pattern has been created by vibration in motor shaft and/or motor mechanism. The problem was eliminated in paper 2b by using a special turntable and a stroboscopic light for speed control.

The better results in our case were obtained with the mask of Fig.4c for the reflected beam FTIR AA, which is symmetrical with respect to the rotation axis. The interferogram of part of film surface deposited by this way is presented at Fig.6b.

Fig.6. Interferograms of profiled films deposited by rotating mask technique \((\lambda = 0.63 \mu m)\).

3.2. Noncontacting mask technique

3.2.1. Deposition equipment

Noncontacting or fixed mask technique produces monotonous profiled films owing to the shadow-effect of the mask which is placed between the source and the substrate at some distance from the substrate. This technique is more simple than previous one and we have been used it to produce the most of our profiled films.
To produce the smooth film profile we used both the effect of the rotation of the substrate with the mask as a whole along the source and the effect of the source with large size with immovable mask and substrate.

At first case we deposited films in resistive heating units (e.g., Balzers BAK-550 and UVN-71P-3 of Quartz Production Union, Kaliningrad town, USSR) and also in electron beam gun unit (Balzers BAK-640).

At second case we used A-700 Q Leybold-Heraeus planar magnetron rf sputtering unit and planar magnetron dc sputtering unit made in General Physics Institute on the basis of a chamber of ion-plasma deposition ORM-026 unit of Quartz Production Union.

The scheme of deposition in evaporation unit with an universal planetary drive of the substrate holder is presented at Fig.7a. A number of flat plates (planets) with substrates rotates along the whole substrate holder axis and also each of these planets rotates along its own axis.

We designate as \( L \) the distance between the evaporation source and the plane of planets centers, as \( l \) the distance between the source and the holder rotation axis, as \( S \) the planet center-holder axis distance, as \( s \) planet center-substrate center distance. The planet plane has an angle of inclination \( \psi \) to the holder axis.

For preparation of the necessary profile we placed the metal ring with thickness \( h \) between the substrate and the mask. The mask had a contour of the cross-section of desired surface of the film (circle or ellipse). To create the different film profiles we used a number of elliptical masks with the long axis of hole from 3 to 12mm and a number of metal rings with \( h = 0.5-3 \text{mm} \). The elliptical cross-section is made to compensate elliptical cross-section of output beam because of the oblique incidence of the beam on contact faces of the FTIR AA. Fig.8 shows two of such masks: a) for the transmitted beam AA, b) for the reflected beam one.

Let us suppose the simplest case: \( \psi = 90^\circ \), \( s = 0 \), see Fig.7b. When the substrate holder is immovable and the substrate rotates only along its axis the film profile deposited with the mask of radius \( R \) has two steps (Fig.7c). The radii of these steps are:

\[
R_{\text{min}} = R - h \tan \beta = R - h(S - l)/L, \tag{2}
\]

\[
R_{\text{max}} = R + h \tan \beta = R + h(S - l)/L, \tag{3}
\]

where \( \beta \) is the incidence angle and \( R, h < S, L \). When the holder rotates along its axis variations \( \beta \) produce the effect of smooth monotonous profile (Fig.7c), but in this case \( \tan \beta \) can be greater than \( R/h \) (there is not deposition in the center for such \( \beta \)). It results to a small pit in the center of film. Such effect was considered by the author of paper.

![Fig.7. Preparation of profiled film by noncontacting mask technique with the use of rotation (not to scale).](image)

![Fig.8. Masks for noncontacting mask technique.](image)
3.2.2. The profiles of deposited films

The deposited film profiles have been tested with the use both interferometer and profilometer. We have been used along with our own-made Mach-Zehnder interferometer such type of interferometer of Kristallprüfeinrichtung KP-74 (Berlin, Akademie der Zentrum für Wissenschaftlichen Geratebau). The all interferometric measurements have been carried out at $\lambda = 0.63\mu m$. The Talystep profilometer by Taylor-Hobson had 2mm translation.

The film profiles depend on the mask hole dimensions, metal ring thickness, evaporation time, possibility of rotation mask with substrate as a whole along the source, the size and the type of evaporation source.

Fig.9-11 present the profiles of deposited films which have been made by nonconducting mask technique with the use of two different effects: the substrate rotation(Fig. 9,11) and the large-size source(Fig.10).

3.2.2.1. Deposition units using the substrate rotation

Fig.9a,b,c shows the interferograms and profilograms of films deposited in electron beam BAK-640 unit with universal planetary drive of the substrate holder system (Fig.7a). In this case $S = 21\ cm$, $s = 6.5\ cm$, $L = 51\ cm$, $I = 20\ cm$, $\Psi = 60^{\circ}$. The planet diameter was 20cm, substrate diameter - 4cm. The evaporation source has $\sim 1cm^2$ dimensions. The chamber is evacuated to $\sim 10^{-6}mbar$ base pressure and during the deposition the working pressure after the oxidation is $\sim 10^{-4}mbar$. The deposition time for $\sim 1.2\mu m$ SiO$_2$ film was $\sim 20min$. Fig.9 gives us profiles of $\sim 1\mu m$ thickness SiO$_2$ films deposited on optical glass substrate(K-8) with thickness 10mm :a - elliptical mask 3x2mm$^2$, 1.5mm ring; b - circle mask 3mm in dia, 1.5mm ring; c - elliptical mask 3x2mm$^2$, 2mm ring.

It should be noted that interferograms of films deposited by this way show the phase shift in the center of flat-top surface of the film (as a small pit in the center), see Fig.9a,b. In the case when film profile is close to spherical one there is not such phase shift on the interferogram, see Fig.8c.

We can't find any pits in the center of flat-top surfaces of the film Fig.9a,b on the profilograms of this films with resolution $\sim 500A^0$, see Fig.9a,for example.

The phase shift in the center was also observed when we produced flat-top profiled dielectric films in BAK-550 resistive heating unit with $S = 15\ cm$, $s = 4.5\ cm$, $L = 50\ cm$, $I = 20\ cm$, $\Psi = 70^\circ$, source dimensions 1x4cm$^2$ (also the universal planetary drive of substrate holder). We deposited $1.2\mu m$ films of SiO or MgF$_2$ on K-8 glass substrate in time interval $\sim 20min$. Working pressure was $\sim 4.10^{-6}mbar$.

At Fig.11 we can see the spherical top profile (mask dimensions 3x2mm$^2$, 2mm ring - a and three flat-top profiles: b - mask dimensions 3x2mm$^2$, 1.5mm ring; c - mask dimensions 3x2mm$^2$, 1.8mm ring; d - mask diameter 7mm, 0.55mm ring.

Oscillogram of Fig.11e shows the beam spatial profile ($\lambda = 0.63\mu m$) at output of the FTIR AA with Fig.11b deposited film. The input laser beam was uniform. We can see a small pit in the center of beam profile. This pit is convenient to transform Gaussian input beam into the flat-top one as in the case of paper28.
Fig. 9. Interferograms and profilograms of films deposited by electron beam with the use of universal planetary drive of the substrate holder system.

Fig. 10. Interferograms and profilogram of films deposited in different sputtering systems with the use effect of large-size source.
3.2.2.2. Deposition units with large size source

Fig. 10 presents the interferograms and the profilogram of SiO$_2$ films deposited:
- in A-700 Q rf sputtering unit (source diameter = 7.6 cm, distance between the source and substrate = 3 cm; b - in dc sputtering unit (the source had a ring shape with mean value of diameter 9 cm and 8 mm thickness along the diameter; distance between the source and substrate was 43 cm. Working pressure was $10^{-2}$ mbar(a) and $10^{-3}$ mbar(b).

The mask sizes were 3x2 cm$^2$. (Fig.10a on the right and Fig.10b) and 3 mm in diameter (Fig.10a on the left). The metal ring thickness in all cases was 1.5 mm.

Unlike flat-top profiles of the dielectric films fabricated with the use of substrate rotation along small-size source we have not seen any phase shift on the interferograms of films with flat-top profiles when we used large-size source $^a$.

4. INVESTIGATION OF THE FTIR AA IN LASER BEAMS

4.1. FTIR AA transmission profiles

Testing of the fabricated FTIR AA was carried out in the beam of He-Ne laser ($\lambda = 0.63 \mu$m) by photoelectric method with the use of the hole with 0.4 mm in diameter.

Fig. 12 shows oscillograms which characterize the spatial intensity profiles of the laser beam at the output of the FTIR AA with deposited film of Fig.11b (a), at the distance of 80 cm (b), and at a distance of 8 m from this AA (c). The input beam had a Gaussian spatial intensity profile with $r_0 = 2.6 \text{mm}$. The photograph of the beam cross-section at the distance of 8 m from the output of this AA is shown at Fig.12d.

The calculations of oscillogram of Fig.12a have been shown that we can approxima-

$^a$We are grateful to Angela Piegary from ENEA (Rome) who advised us to use sputtering technique to fabricate flat-top profiles of the films without inhomogeneities of films in the center.
te the output beam profile with the super-Gaussian curve (1) with N=6 and \( r_0 = 1.94 \text{mm} \).

Fig. 13a shows oscillogram of the output beam of the FTIR AA with deposited film of Fig.11a. In this case the input beam was uniform and the output beam had bell-like form. The photograph of the output beam cross-section at the distance of 2m from this AA is presented at Fig.13b.

**Fig. 12.** The oscillograms of flat-top beam profile at the output of the FTIR AA and several distances from it. The photograph of beam cross-section at 8m from this AA.

**Fig. 13.** The oscillogram of bell-like profile at the output of FTIR AA and the photograph of beam spot at 2m from it.

### 4.2. Damage thresholds in laser beams of deposited films

The measurements of damage thresholds of deposited films have been made with the use of 1.06\( \mu \)m laser with 10ns bell-pulse duration and the Gaussian spatial profile of the beam. The focal spot was \( \sim 150 \mu \text{m} \) in diameter at 1/exp level.

The damage threshold was defined on the spark appearance on the surface of the film which can be observed with the help of microscope.

We tested \( \sim 1.2 \mu \text{m} \) thickness profiled films with \( \sim 5 \text{mm} \) diameter fabricated by different deposition technique. Table 1 gives us these results for nonconducting films and for the films under the optical contact conditions with another glass substrate (K-8).

<table>
<thead>
<tr>
<th>nonconducting film conditions</th>
<th>film under the optical contact conditions</th>
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<tbody>
<tr>
<td>( \text{SiO}_2 ), deposited by electron beam</td>
<td>12J/cm(^2)</td>
</tr>
<tr>
<td>( \text{SiO}_2 ), deposited by dc sputtering</td>
<td>11J/cm(^2)</td>
</tr>
<tr>
<td>( \text{SiO}_2 ), deposited by rf sputtering</td>
<td>6J/cm(^2)</td>
</tr>
<tr>
<td>( \text{SiO} ), deposited by resistive heating</td>
<td>1.5J/cm(^2)</td>
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</table>

Table 1. Damage thresholds of deposited films
We explain a low damage threshold of rf sputtering film the more dirty conditions inside the deposition chamber. The cleaning of the substrate before the deposition was carried out with Balzers fluids and last step was plasma etching.

In the comparison with the results of paper in which the damage thresholds have been defined for the $\lambda/4$ thickness SiO$_2$ and SiO films at similar to our conditions of irradiation we obtained lower damage thresholds for SiO$_2$ films. We explain this fact greater thickness of the films in our case.

It should be mentioned that the results of paper show that damage thresholds of deposited films don't depend on the diameter of laser beam when it is greater than $\sim100\mu$m and we can approximate our results to the diameter of laser beam greater than $150\mu$m.

5. CONCLUSIONS

The investigations have been shown that both the rotating mask and noncontacting mask techniques may be used for creating the spherical and smooth monotonous flat-top profiles of dielectric films up to $\sim1.5\mu$m maximum thickness.

The noncontacting mask method is more simple that rotating mask one and gives the possibility to produce the films with different cross-sections.

The films deposited by the rotating mask method have only circular cross-section, but this method gives the possibility to make more wide number of film profiles (if we shall remove the vibrations in motor shaft).

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7. REFERENCES


