SYNTHESIS THE BROADBAND INTERFERENCE SYSTEMS BY JET INDUCTIVE COUPLED RF PLASMA TORCH IN DYNAMIC VACUUM

Abdullin I.Sh.\textsuperscript{1}, Galiaoutdinov R.T.\textsuperscript{2}, Kashapov N.F.\textsuperscript{2}

\textsuperscript{1}Kazan State Technology University 68, K.Marx str., Kazan 420015 – Russia
\textsuperscript{2}Scientific and Research Institute of Pumping Engineering Technology, apart. 20, house 42, Gavrilov str., Kazan 420137, Russia

Abstract

The problem of the thin film coatings synthesising with an adjusting absorption under the jet non-equilibrium high frequency induction (RF) plasma in dynamic vacuum conditions is considered. The method of the broadband interference systems designing based on the variation by a complex part of the high frequency permeability allows by one-layer coating to receive zero reflection from high reflecting surfaces for given wavelength of the electromagnetic spectrum. In case of suppressing the reflection from aluminium mirrors (reflectance $R \sim 90\%$) the given method justified its efficiency.

1. Introduction

The evaluation of the electromagnetic fields' distribution in stratified media has the theoretical and practical importance. The implementation of interference systems according to the thin film optics principles needs the presence of films with certain physical parameters. The need for stable coatings with predictable optical properties in terms of the quasiuniform film structures stimulates the development of thin film technologies with an adjusting absorption in them.

The problem of suppressing the reflected electromagnetic signal/ wave from the high reflecting surfaces in the given spectral range is of importance. It is known that the deposition of a nonabsorbing coating over a metal substrate reduces reflection [1,2]. For obtaining zero reflection at a given point of spectrum it is necessary that the refractive index of a dielectric coating would satisfy the following relation [3]:

\[
n_2 = \sqrt{n_1 + \frac{k_1^2}{n_1 - 1}},
\]

where $n_2$ is the refractive index of a nonabsorbing coating, $n_1$ and $k_1$ are the real and imaginary parts of the complex refractive index of metal ($n_1 - i \, k_1$), where $i$ is the imaginary unity. Hence, in order to receive zero reflection at the wavelength $\lambda = 0.55 \times 10^{-6}$ m for an aluminium mirror (complex refractive index of which is equal to $\tilde{n}_1 = 0.6 - i \, 5.01$ [4], the dielectric with the refractive index 7.95 is needed. It is not realisable because of the lack of the optical materials with such high refractive index in the visible spectrum range! The problem has its solution in case of coatings with the adjusting absorption coefficient.
Fig. 1. Operating diagram of the RF-plasma plant: 1 - RF generator; 2 - plasmatron; 3 - samples on which thin films are sputtered; 4 - vacuum chamber; 5 - pumping-out system; 6 - manipulator; 7 - system for gas delivery; 8 - measurer-controller of the gas-flow rate; 9 - transducers of mode; 10 - diagnostic equipment; 11 - base plate.

The purpose of this work is to synthesise and to embody the coatings with the adjusting absorption for reaching the given high frequency permeability in the visible spectrum range using jet non-equilibrium RF-plasma in dynamic vacuum conditions. It allows creating interference systems with the required spectral characteristics.

2. Experimental procedure

Thin film optical coatings were produced in plasma plant as presented in fig. 1. Its basic elements were as follows: high frequency generator [5], vacuum unit, system for working gas delivery, high frequency plasmatron [6], diagnostic and control equipment and device for details' pulse handling. The induction plasmatron intended for obtaining RF-discharge of low pressure is presented in fig. 2. It includes the Ruhmkorff coil 1 supplied with water cooling jacket, device of Ruhmkorff coil travel 2 and the flash chamber 3. The flash chamber and cooling jacket 4 represent all-welded constructions. The plasmatron was being fixed in the opening of the base plate 5 through the clamping flange 7.

In order to produce the coatings, the plasma flows in stationary and pulse RF-discharge modes were used under variation of input parameters within the following limits: power consumption came from 2 up to 10 kW, working pressure came from 20 up to 250 Pa, flow rate of plasma-generating gas came from 0 up to 0.1 g s⁻¹; the generator frequency 1.76 MHz;
Fig. 2. The plasmatron for producing RF discharge in dynamic vacuum conditions: 1 - Ruhmkorff coil, 2 - device of travel of Ruhmkorff coil, 3 - flash chamber, 4 - cooling jacket, 5 - base plate, 6 - junk-ring, 7 - clamping flange, 8 - simplified diagram of system for plasma-generating gas and sputtered material delivery.

The optical coatings were deposited onto substrates from the optical glass (-8) 20 mm in diameter, 2-3 mm thick, which were set in a holder at the edge of plasmatron. The forpumping down to the pressure 0.1 Pa was effected from the vacuum system. Further, the plasma-generating gas, which in the area of an inductor was heated up to the plasma phase, was supplied and heated up the substrates. The needed temperature range was reached by permanent augmentation of power input to the discharge up to the certain value until amounted $T = 623 - 673$ K. The power input to the discharge amounted/ averaged at once $P_d = 2.4$ kW. The inductor by means of the device of travel was slowly going down and the stem end of the titanium oxide was found itself in the centre of the plasma clot. Owing to the low thermal conduction, the refractory TiO$_2$ was warmed up and sputtered at most at the stem end that enabled to continue the sputtering process for long. The heating by plasma allowed transforming the material into a vaporous phase. The plasma jet transported the vapour phase of material to substrates and assisted to condensing on them. The film
composition varied by changing the value of the flow rate of Ar and the sputtered material – substrate distance. After the sputtering being terminated, the sputtered material was brought out from a plasma clot.

3. Results and discussions

The vapour phase composition under TiO₂ sputtering is different depending on the path of transportation section. As a result of this, the composition of the obtained oxide coatings could be adjusted depending on the distance between the sputtered material and the base plate. At distances less than \( z = 0.05 - 0.07 \) m in the film composition in general pure Ti and lower oxides were present, as well. As moved off from the inductor area, the part of the oxidized phase was increasing and for the distance \( z = 0.18 - 0.25 \) m the film composition corresponded to the initial material composition.

If to neglect the thickness of a double electric layer at a surface of sputtering (\( t_D \sim 10^{-4} \) m), the distance \( L_D \), on which a dissociation takes place is possible to estimate as \( L_D \sim U / (n_e \rho v_e) \), where \( n_e \rho \) is the cross-section of the molecules dissociation by electronic shock, \( v_e \) is the velocity of the electron thermal motion, \( U \) is the gas velocity in a laminar stream. At an edge of the Ruhmkorff coil the length \( L_D \) at which dissociation takes place is \( L_D \sim 10^{-3} \) m (where \( n_e \sim 10^{18} \) m⁻³; \( U \sim 10^4 \) m/s; \( v_e \sim 10^6 \) m/s; \( \rho \sim 10^{-22} \) m⁻³).

Thus, on the initial section of vapour stream transportation path the process of molecules dissociation by an electronic shock is a determining factor. It establishes conditions for the occurrence of non-equilibrium concentration of atomic particles in vapour phase. As moved off from the inductor, the value of the dissociation rate was decreasing according to the law \( \exp (\lambda \sim k_B T_e) \), where \( k_B \) is the Boltzmann constant. As the electron concentration dramatically falls off along an axis as a result of their inelastic collisions with vapour particles, the role of dissociation process under removal from a Ruhmkorff coil is expected to weaken.

The presence of an extended transportation path at the jet RF-plasmatron allows precisely adjusting the value of TiO₂ coating absorption. Thus, the jet plasma-sputtering technology in dynamic vacuum enables to produce the coatings with the required optical performance in order to realise the multilayer interference systems.

One of the important problems of producing interference optical systems is the problem of broadband filters synthesis. When the required spectral characteristics of a coating should cover a wide range of low reflection, the use of absorbing materials allows considerably reducing the number of layers in synthesised systems in comparison with the all-dielectric systems. It essentially simplifies the technical embodiment of such systems. For suppressing the reflection from high reflecting metal surfaces the method of interference systems designing tied in a complex part of a high frequency permeability variation allows by an one-layer coating to meet the zero reflection from high reflecting surfaces for the given angle of incidence and fixed wavelength.

By solving the problem of suppressing the reflected electromagnetic signal from high reflecting Al surface in the visible spectrum range \( \lambda = 0.4 - 0.7 \) μm the method of the imaginary

\[
F = \int_{\lambda_1}^{\lambda_2} [R(\lambda) - R(\lambda)]^+ d\lambda.
\]

part variation in a complex refractive index was applied. To evaluate the fit of the produced coating spectral characteristics to the required performances the evaluative functional \( F \) was introduced.

where \([\lambda_1, \lambda_2]\) embrace the wavelength range in which the synthesis was yielded; \( R(\ast) \) is the calculated energy reflectance of the synthesised coating. In this case, \( \ast = 0.4 \) μm, \( \ast = 0.7 \) μm, and \( R(\ast) = 0 \). The problem of synthesis was considered in a variational approach and came to
minimisation of the functional both by layers thicknesses and by value of the complex refractive index of an absorbing upper layer. As an initial estimate, the solution $R(\tilde{n}_1, n_2) = 0$ in one central spectral point $\nu = 0.55 \cdot 10^7$ m was searched. And such thickness of an absorbing coating $h_2$ that in case of the calculated complex refractive index of an absorbing coating $\tilde{n}_1$ would satisfy to the given zero reflectance at this point was found. At that, the optical constants of layers TiO$_x$, depending on a degree of oxidisation and the composition of the required absorbing coating as well, defined through the filling factor $q$, were calculated within the framework of Garnett model [7]. Further, taking into account the dispersion properties of coatings, the solution was defined more precisely by means of minimising an evaluative functional (2).

The spectral reflectance for the found solution (where $n_2 = 2.6$; $k_2 = 0.544$; $h_2 = 0.04 \cdot 10^6$ m; and the evaluative functional $F$ is much less than $10^{-5}$) taking into account that the dispersion of the complex refractive index is presented in fig. 3.

![Graph](image)

Fig. 3. The spectral reflectance $R(\nu)$ of one-layer coating TiO$_x$ on Al surface in the visible spectrum range.

The synthesised coating reduces the integrated reflectance from high reflecting surface in the visible spectrum range down to value less than 2.5%. The found solution is ensured with such thickness $h_2$, which brings to that the phases of reflectances $r_{12}$ and $r_{21}$ from an interface air-absorbing film and absorbing film-metal coating are proved to be in an antiphase. At the same time, the complex refractive index $\tilde{n}_2$ of an absorbing coating of TiO$_x$ ensures equality of these amplitudes. So, the conditions of zero reflection are met. As well as the jet low pressure RF-plasmotron gives an opportunity to synthesise a film with the given complex refractive index.

The proposed technique of producing optical coatings using the jet RF-plasmotron in the dynamic vacuum conditions allows to realise the required spectral characteristics using coatings TiO$_x$ with the given absorption.

Conclusions

The technique for thin-film coatings production using the jet low pressure RF-plasmotron has the number of advantages over the techniques of thermic deposition employed in high vacuum technology. This technique allows overlapping operations of the material sputtering, ionisation and excitation of atoms, to shape a directional stream of particles and to transport them onto a surface, as well as to warm up substrates, to sputter clean and to sputter polish their surfaces. The presence of an extended transportation section enables to control the physical chemical processes and
composition of sputter-deposited material. It ensures, in turn, an opportunity to check the process parameters for the coating production with the aim of obtaining the required complex refractive index. The required value of absorption coefficient reproducibility appreciably simplifies the procedure of synthesising the interference coatings with the given spectral characteristics.

The information about the composition of absorbing layer depending upon the conditions of coatings producing allows to predict the optical performances of a layer and to choose the necessary parameters of process procedure.

The synthesised coatings of TiO$_x$ with the required absorption allow to reduce the integrated reflection of Al mirrors from 90 % down to 2.5 % in a wide spectral range (from $0.4 \cdot 10^{-6}$ m up to $0.7 \cdot 10^{-6}$ m).

References (in Rus.)