Thin Film Dielectric Gradient Optical Structures for Space Photonics

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Abstract— Characteristics, technological aspects and test results of thin film dielectric gradient optical structures for space and aviation photonics are considered. The perspectives of pulse magnetron sputtering for manufacturing optical structures are shown. The gradient and nanogradient refraction index profiles provide wide-band and wide-angle working spectral characteristics of the systems and their stability against power laser radiation and space environmental factors.

1. INTRODUCTION

Photonics plays an important role in space and aviation technology. It includes devices for optical and laser navigation, detection of objects by their emission, reflection, transmission, or absorption and then their location, tracking, and recognition, etc.. The basis for many devices is interference structures (IS). They typically present themselves as dielectric optical coatings from alternating layers of materials with high n_h and low n_l refractive indexes n. The high level of complexity of tasks solved with space and aviation photonics brings new higher requirements to IS; as an example of such requirements one can point out requirements to spectral characteristics of IS: superwide working wavelength band (e.g., $\lambda = 0.5 \ldots 5.0\,\mu\text{m}$), simultaneous operation on multiple wavelengths, wide viewing angle, deep modulation of amplitude characteristics (e.g., $R_1 > 99.9\%$, $R_2 < 0.1\%$, and so on, here R is reflectance), high spectral resolution (e.g., $\Delta\lambda_{0.5} < 2\,\text{nm}$ at transmission $T_{0.5} > 0.8$), low optical losses ($1 - T - R < 5 \cdot 10^{-5}$).

The huge challenge is to ensure resistance and spectral characteristics stability of IS over a long time period (up to tens years) against action of space environment factors, including intermittent high-intensity heating and deep cooling, UV radiation, and against factors related to the functioning of spacecraft, in particular, laser radiation with high power density ($W > 10^9\,\text{W/cm}^2$) and plasma. Authors' experience in the design and manufacture of precision optical coatings and lasers assumes that these problems can be solved by use of thin film dielectric optical structures with gradient profiles of refractive indexes n instead of the conventional multilayer IS with an abrupt stepwise changes of the refractive index n_h/n_l and n_l/n_h at the layer boundaries in going from one layer to another [1, 2]. The latter negatively affects mechanical and thermal stability and laser damage resistance. The gradient optical structures have been shown to satisfy the above mentioned requirements to spectral characteristics and provide obtaining different kinds of filters, mirrors, high-contrast polarizers, phase converters and antireflection coatings. However we should know what is resistance of these structure to action of space environmental factors and laser radiation. Therefore, design, technological aspects and test results of thin film dielectric gradient and nanogradient optical structures for space and aviation photonics are considered in the paper.

2. DESIGN OF GRADIENT OPTICAL STRUCTURES

If the permittivity $\varepsilon = \varepsilon(z)$ and, accordingly, the refractive index $n = n(z)$ continuously, gradually distributed by a certain law along the normal axis (thickness) $\mathbf{z}$ of a thin film dielectric optical structure, the latter is called as gradient one with longitudinal 1D_z gradient [1], while optics comprising such structure is called as gradient optics. If change of ε or n occurs on the thickness less than 100 nm, such structure is called as nanogradient one. The use of various refractive index profiles $n(z)$ (linear, quadratic, sinusoidal-like, polynomial of fifth degree and others) can improve the amplitude-spectre, angle, polarization, phase characteristics; in particularly, very wide working spectrum band and wide operation angle may be provided. For example, Figure 1 depicts the gradient profile $n(z)$, leading to excellent characteristics of hyperwide-band (0.5–5 μm) gradient antireflection coating for sapphire optical elements at incident angles of 0°, 10° and 25°. Note, the given profile $n(z)$ has not very complex shape.

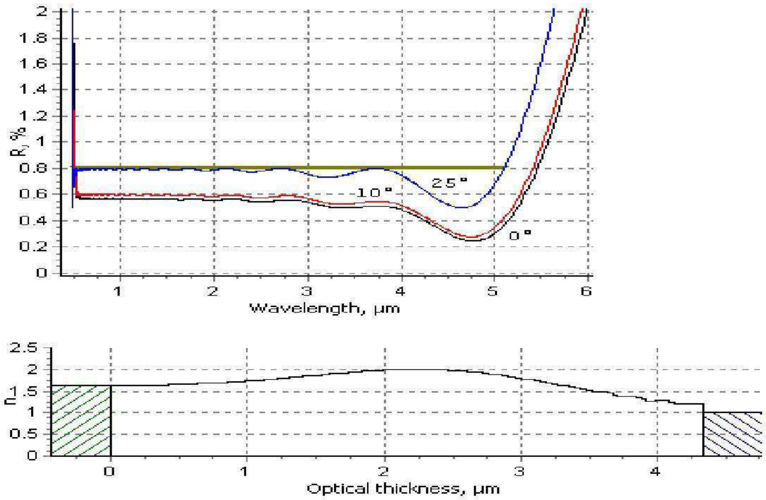

Figure 1: Antireflection feature of the gradient coating at three values of incident angles (upper plot) and its refractive index profile $n(z)$ (lower plot).

For the design of gradient optical structures a new method of analytical and numerical synthesis for given spectrum characteristics has been developed. It is based on a combination of two algorithms: analytical one, using Fourier analysis to determine the gradient construction, and a heuristic algorithm of its searching to solve the problem of optimization. On the basis of the new synthesis method an engineering program for computer simulation of thin film gradient optical structures has been developed.

3. TECHNOLOGICAL ASPECTS OF MANUFACTURING GRADIENT COATINGS

There are different approaches to deposition of thin film dielectric gradient structures. Among them one can point out some known methods: glancing-angle deposition with electron beam evaporation of source materials and plasma-enhanced chemical vapor deposition from gas precursors [3]. The more prefarable technique, to our best knowledge, is based on ion sputtering of source materials (targets), especially, ion sputtering in a magnetron discharge allowing deposition of precision optical structures [1–5]. The magnetron discharge is a low pressure gas discharge in crossed electric and magnetic fields where cathode serves as a sputtered target.

Therefore, an automatic two-magnetron sputtering system with computer control and monitoring *in situ* has been developed [1] and successfully employed for obtaining various thin film gradient optical structures with filtering, reflection or antireflection properties. Figure 2 depicts the diagram of magnetron set-up for deposition of longitudinal $1D_z$ gradient coatings. Magnetrons sputter different materials (M1 — Si; M2 — metals: Nb, Ta, Ti) in atmosphere of reactive gas mixture $Ar + O_2$. Coordinates X_1, X_2 and X_3, algorithm of substrate movement over the magnetrons, and sputtering power of each magnetron determine composition of material deposited on the substrate. The deposited material composition in turn determines the current value of $n(z)$. Ar is used as a sputtering gas. O_2 is used for oxide synthesis from deposited Si and metal on the substrate surface. Oxygen is chemically activated in magnetron discharge plasma as well as in activator A and due to UV laser radiation directed towards the substrate. The mid-frequency pulse mode of magnetron operation is used [1]. The monitoring *in situ* system (spectrovisor) allows to test optically the deposit directly during the fabrication process and to make corrections of operation parameters if it is necessary.

4. TESTING GRADIENT OPTICAL STRUCTURES

Testing the fabricated thin film optical structures was carried out to confirm their comprehensive long time period resistance to intense laser and other kinds of radiation, thermomechanical action (cyclic temperature changes) and other aerospace factors (including vacuum). It was accepted the quick and cheapest way to evaluate the properties of optical structures is acceleration of testing by forcing degradation processes. The accelerated testing was carried out in laboratory conditions simulating the real space situation with use of the method of planning multifactor experiments and

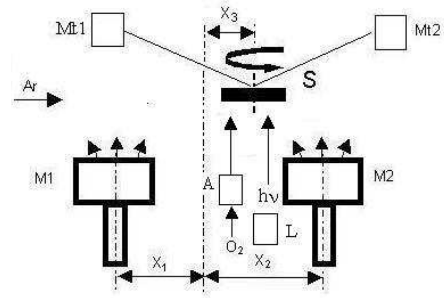

Figure 2: Two-magnetron sputtering system for deposition of thin film gradient structures. A — gas activator (O_2); Ar — sputtering gas; L — UV laser; M1, M2 — magnetron sputters; Mt1, Mt2 — optical parts for monitoring the structures *in situ*; S — rotating the substrate; arrows indicate the direction of sputtered atoms movement.

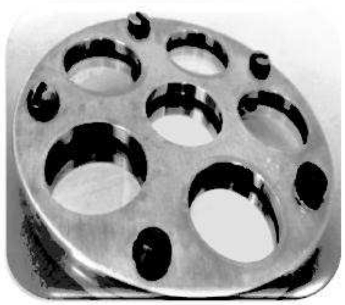

Figure 3: Photograph of specimens with gradient thin film optical structures (disposed on the holder) after thermocycling test.

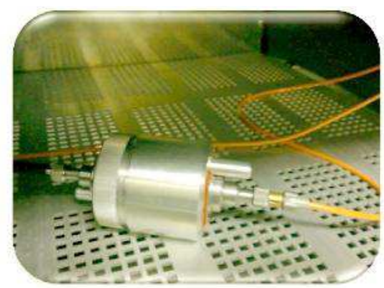

Figure 4: The fiber optic device with the capsule for fixing the tested specimen inside of the heating-cooling chamber.

models describing the resource dependency on influencing factors.

Consider an example of testing results. The fabricated optical structures are resistant to laser radiation with power density $W > 10^9\,\mathrm{W/cm^2}$ for $\lambda = 1.064\,\mathrm{nm}$, $\tau = 10\,\mathrm{ns}$ and physical thickness of thin film optical structures less than $2\,\mu\mathrm{m}$. When the thickness was up to $5\,\mu\mathrm{m}$, the structures were resistant to the combined effect of space factors — the combination of thermal cycling ($\Delta t^\circ = -60/+70^\circ\mathrm{C}$, 100 cycles) with UV exposure at power density $W > 100\,\mathrm{W/cm^2}$ for $\lambda = 300\,\mathrm{nm}$.

The quick test on thermomechanical stability of the gradient structures has been developed and performed. To determine the time resource, 3500 cycles of heating and cooling with the coefficient of load increasing $C_{in} =$ were carried out. One cycle included heating up to $+180^\circ\mathrm{C}$ with 5 minutes exposure and cooling down to $-190^\circ\mathrm{C}$ (by immersion into liquid nitrogen) with 1 minute exposure. Therefore every cycle created two thermal stocks ($-$ & $+$) for specimens. Thin film adhesion measurements were carried out after every 500 cycles of heating/cooling by the method of "Scotch tape". Figure 3 shows the appearance of the specimens with thin film structures after 3500 exposure cycles. The 7 years resource on thermomechanical stability of thin film gradient optical structures fabricated with magnetron sputtering has been confirmed. It should be noted that the confirmed resource meets world standards on reliability for optical devices. A number of the manufactured gradient structures showed the resource of 10–15 years that is above the world average.

It was also necessary to test the stability of optical structures during continuously varying operating conditions (*in situ*). For this, we developed a device with a separate specimen's capsule connected with optic fiber to a microspectrophotometer (Figure 4). The capsule is disposed in a heating-cooling chamber (Figure 4) then the device provides measuring spectral characteristics *in situ*. The tests were conducted with the developed nanogradient interference narrow-band filter with hyperwide barrier zone. Their procedure, for the instance, was as follows: the specimen was placed in the capsule. The microspectrophotometer was calibrated. At the beginning, the transmission spectrum was measured at $+20^\circ\mathrm{C}$. Then the capsule was cooled to temperature of $-30^\circ\mathrm{C}$, maintained 20 minutes for establishment of the temperature and the transmission spectrum was determined. After this, the capsule was heated up to $+45^\circ\mathrm{C}$, held-on for 20 minutes and the spectrum was measured. Then the capsule was heated up to $+70^\circ\mathrm{C}$, held-on for 20 minutes and the transmission spectrum was determined again.

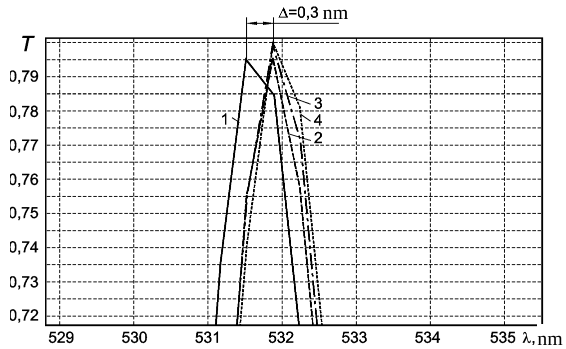

Figure 5: Transmission characteristics of the nanogradient filter when exposed to heat and cold; the sample temperature: 1 — +20°C, 2 — −30°C, 3 — +45°C, 4 — +70°C.

Figure 5 shows the measured *in situ* transmission spectra of a filter at the beginning (the left curve) and during the test. It is seen that the shift Δ of the developed nanogradient interference narrow-band filter characteristics is small ($\Delta \approx 0.3$ nm) in the given temperature range that provides stable work of optical structures, manufactured by pulse magnetron sputtering, in aviation and space photonic devices.

5. CONCLUSION

The gradient structures with different refraction index profiles (simple "one-periodical", multiperiodical, rugate-like, with apodization, etc.) with excellent properties, including gradient optical metamaterials [5] for devices based on transformation optics, have been produced. As an example of efficient applications of the developed and manufactured gradient optical structures one can point out their success application in laser ranging and location devices (the increase of energy efficiency by 30–40%). The experiments showed the gradient and nanogradient refraction index profiles provide wide-band or narrow-band and wide-angle working spectral characteristics (antireflective and others) in the visible and near IR field of the manufactured full-dielectric low-loss coatings and their stability against high-power laser radiation, thermal, mechanical and space environmental factors. The perspectives of mid-frequency pulse magnetron sputtering technology of thin film dielectric gradient optical structures for space photonics are confirmed.

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