Resonant tunneling of light in nanostructures: gradient dielectric *vs* metallic foils?

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Abstract

The physical fundamentals and mathematical basis for analysis of propagation and tunneling of light through nanogradient photonic barriers, formed by thin film dielectrics without free carriers, with continuous distributions of refraction index $n(z)$ / dielectric permittivity $\varepsilon(z)$ across the film, are developed. The decisive influence of giant artificial heterogeneity-induced non-local dispersion, both normal and abnormal, stipulated by the subwavelength gradient and curvature of distribution $\varepsilon(z)$, is shown to provide the controlled formation of reflectance/transmittance spectra for any spectral range in need. Formation of cut-off frequency, separating the traveling and tunneling regimes of waves propagation through nanogradient barriers in the transparent dielectric with $\varepsilon > 0$, but grad$\varepsilon < 0$, is visualized by means of new exact analytical solutions of Maxwell equations for gradient nanooptics. A technology of ion sputter deposition of nanogradient dielectric films is developed, and the parameters of fabricated films are measured. The perspectives of replacement of metallic foils (thin films) by nanogradient dielectric thin films in optoelectronic systems are discussed.

1. Introduction

Tunneling is one of the fundamental phenomena in the dynamics of waves of different physical nature. It attracted attention after the prominent research of G. Gamov (1928), devoted to the nuclear alpha-decay, where the probability of percolation of alpha-particles with energy E through the potential barrier with the maximum U_0 ($> E$) was determined namely by the tunneling. The synthesis of tunneling structures forms nowadays a rapidly shaping trend in nanooptics. One can emphasize the perspectives of using of wave tunneling effects in the elaboration of gradient nanooptics devices – subwavelength filters, reflectors, large angle polarizers and reflectionless coatings, as well as in the problems of principle, connected with the optimization of processes of energy transfer by waves of different spectral ranges. The nanostructured materials with wave tunneling may be considered as a kind of metamaterials. The paper presents new insights on linked problems in physics, technology and perspectives of optimization of parameters of gradient dielectric nanostructures.

2. Physical aspects

So, take as a base for our consideration the results of exact analytical solutions of Maxwell equations for subwavelength gradient dielectric structures [1-3]. Fig. 1 depicts one example of such a structure.

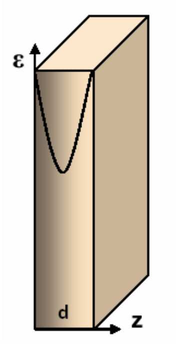

Fig. 1: Dielectric film with subwavelength gradient of refraction index (dielectric permittivity ε); d ~ 100 nm for visible and IR ranges

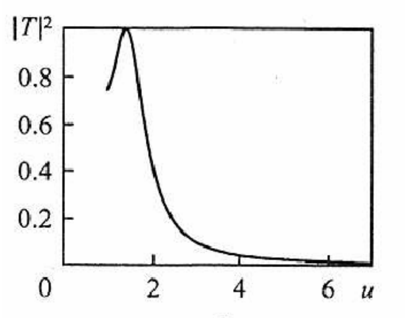

Fig. 2: Transmission spectrum for waves, tunneling through the nanogradient film: $|T|^2$ – transmission coefficient, u – normalized frequency

The obtained results may be shortly presented as:

A. Non-local, heterogeneity-induced dispersion, determined by technologically controlled shape and spatial scales of profiles $n(z)$ / $\varepsilon(z)$ within the nanofilm, proves to be much stronger, than the natural material dispersion, especially in the visible and IR ranges. Having nothing in common with local material dispersion, this artificial non-local effect results in formation of both normal and abnormal dispersion of the film, subject to the shape of spatial profile $\varepsilon(z)$, the host material being the same.

B. This non-local effect also results in drastic changes of film's reflection / refraction spectra and formation in the layer of non-dispersive transparent medium with $\text{grad}\varepsilon < 0$ of the controlled cut-off frequency Ω, dependent upon the heterogeneity scales, providing, in it's turn, the formation of tunneling regime for frequencies $\omega < \Omega$ [1,2]. Owing to interference of waves, reflected in each point of profile $\varepsilon(z)$ within the nanogradient film, the resulting wave, reflected from the film's interface in the tunneling regime, can be vanished, which means the reflectionless (resonant) tunneling through the gradient barrier and its complete transparency (Fig. 2).

C. Reflectionless tunneling through the subwavelength nanogradient films is possible in any spectral range, determined by technologically controlled film parameters. Fig. 3 demonstrates "Brewster effect" for inclined incidence of S-polarized wave on the gradient photonic nanobarrier that is a large angle polarizer.

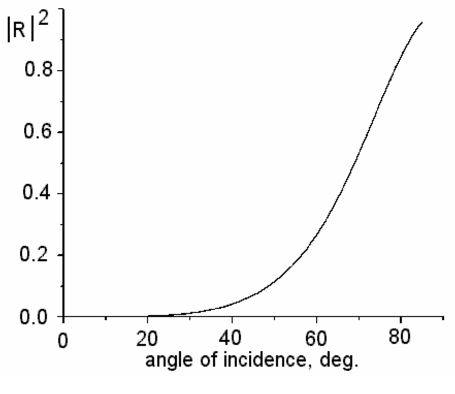

Fig. 3: "Brewster effect" for inclined incidence of S-polarized wave on the gradient photonic nanobarrier: reflection coefficient $|R|^2$ *vs* the angle of incidence

3. Technological aspects

Precision preparation of thin dielectric layers with nanogradient $n(z)/\varepsilon(z)$ is a very hard problem. We consider the best approach for obtaining high-quality optic dielectric thin films is the reactive pulse magnetron sputtering (RPMS) that is ion sputtering of target (a film material source) in reactive gas medium with synthesis of needed material composition on the substrate surface. RPMS provides energy activation of the growth process and obtaining stable dense solid solution of constituting components with low surface roughness and light scattering loss. RPMS ensures prevention of arcing on the target in very reactive gas medium, deposition process stability, as well as stability of deposited coatings against light radiation, environment and mechanics factors. A multitarget magnetron system with computer control and monitoring *in situ* has been developed and was successfully employed for obtaining 1D gradient multi-wave antireflection coating of subwavelength thickness (Fig. 4) [4]. Coordinates X_1, X_2 and X_3 and sputtering power of each target determine composition of the thin film deposited on the substrate. Accordingly, variation of $n(z)$ was received by regulation of the combined deposition of differently sputtered target materials (M1 – Si and M2 – Ti) in reactive gas mixture Ar + O_2. Apparatus for gradient coating testing was developed, too.

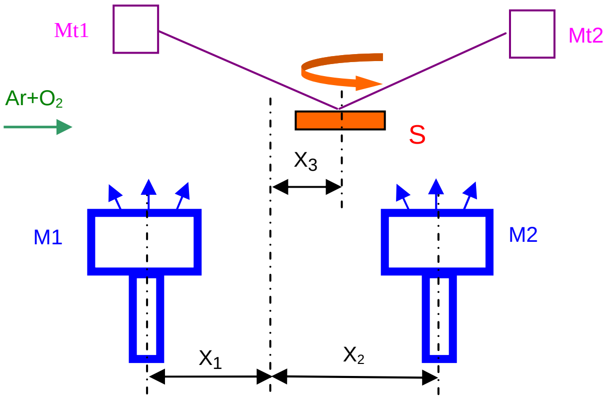

Fig. 4: Diagram of multitarget magnetron sputtering system (M1, M2 – magnetrons, Mt1, Mt2 – optical parts of monitoring system, S – rotating substrate)

4. Perspectives and Conclusion

The perspective alternative to metal-based plasmonics, formed by nanogradient dielectric films, can broaden essentially the list of low cost materials, used by optoelectronic devices, and solve the problem of lowering losses.

For each spectral range, the choose of host material and $n(z)$ / $\varepsilon(z)$ profiles can be optimized on such a way, that the effects of non-local dispersion under discussion will be located in the fixed spectral band, far from the absorption bands of the host material.

Subwavelength thickness of gradient srtuctures is perspective for the problems of miniaturization of optoelectronic devices and photonic crystals. This is preferable for lowering losses, too.

Thus, one can conclude the elaboration and employing of the resonant tunneling of light in gradient dielectric nanostructures is very promising for different applications.

References

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