Some features of the interaction of electromagnetic radiation with complex fractal objects

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Abstract. The effects and phenomena arising from the interaction of both coherent structured and scattered electromagnetic radiation with complex fractal objects are considered. Attention is paid to such fractal objects as complex diffraction gratings. The questions of their practical application and further researches are discussed.

1. Introduction

In the synthesis of nanoscale films, the important thing is not only the purity or structural perfection of the synthesized materials but also the possibility of creating a nanoscale pattern on the surface of a nanoscale film. Since creating this pattern in nanotechnology is done by using individual methods, it is not very promising from a practical point of view. Nowadays it is necessary to design group methods for the synthesis of nanoscale films to create a regular ordered structure on the entire area of the sample simultaneously.

From a practical and technological point of view, it is promising to create a transitional thin film layer free from impurities and inhomogeneities on the substrate surface and grow a nanoscale film on its surface. On the surface of the substrate, impurities and structural inhomogeneities are ideally absent, and atom migration over the surface exists, therefore, a physical agent is needed that would create a corresponding inhomogeneity on the surface of the substrate.

A promising objective is to obtain graphics on the surface of the substrate, which is a fractal self-similar structure. Then the atoms deposited on the substrate would be embedded in its structure in accordance with the principles of self-organization. For this, it is necessary to create a resonator triggering self-organizing processes. In order to achieve this, we used a volumetric interference structure of the hologram type consisting of the local, regularly alternating regions of maxima and minima similar to the future structure. The problem is that it is possible to create a diffraction grating that transforms the electromagnetic field propagating in space.

In our opinion, new perspectives in materials science open up new opportunities in materials science. The use of coherent radiation, not only in time but also in space with the transformation of the
The positions of atoms and molecules of the synthesized film, will provide control over nanotechnological processes.

2. The electromagnetic field as a universal structuring physical agent

A distinctive feature of fractal structures is the presence of a hierarchy as the formation of the initial fractal structures of atoms, molecules or clusters of matter. Then there is the formation of a higher level of these fractal aggregates. There is an analogy with the principle of the formation of artificial holograms carrying information load. There was an interest in the possibility of using fractal structures in nanotechnology and nanoelectronics to obtain ordered structures with a wide range of applications [1].

The fractal structure of waves in a random environment can lead to fractal structures resulting from the effects of waves on the medium, so fractal analysis of the resulting fields can lead to completely new results [2].

The universal physical agent is the electromagnetic field, which covers a range from hundreds of meters (radio waves) to angstrom fractions (hard gamma - quanta). The resonant frequency of the interaction is easily determined by the absorption peaks. On the surface of the substrate, the electromagnetic field can have the required distribution of its characteristics such as amplitude and phase, which will create conditions for the formation of microcrystals and stimulate the synthesis of nanostructures at the molecular level [3].

An interesting aspect is the use of various diffraction gratings for the conversion of electromagnetic radiation. The more complex the structure of such lattice is, the more interesting results can be obtained. The priority in the conversion of electromagnetic fields using diffraction gratings with a complex shape for the implementation of a certain structure with the maxima and minima of the interference pattern (light field) arising due to the diffraction of the primary electromagnetic radiation belongs to the V.A. Soifer's scientific school. He laid the foundations of a new science: computer optics [4]. One of the objectives of computer optics is the creation of a diffractive optical element (DOE) for converting electromagnetic field falling on the DOE plane into a specific configuration of maxima and minima. There are various types of DOEs like axicons, modans, focusators, etc. that have been developed and created by Soifer's colleagues. Another, more practical interest is the inverse problem: image analysis and reconfiguration of the DOE for the available distribution of the electromagnetic field. This problem is solved with respect to the phase function of the DOE, which performs the required conversion of the light beam [5].

The simplest DOE is a zone plate, where a binary or halftone relief is created using the methods of precision lithography, including electron lithography. This relief converts incident electromagnetic radiation (IER) into an image of the required configuration. Such zone plates are called “focusators”. The DOEs whose Fresnel zones are displayed as a system of black and white binary rings of the same width are called diffraction axicons. To obtain more complex distributions of the light field, calculation methods that are determined by the range of tasks to be solved are used. Figure 1 shows the binary phase DOE (focusator) for focusing the light flux in the letter "R" [4]. The more complex is the required distribution of the light field, the more complex is the DOE topology.

The use of binary or halftone DOE allows us to create a light field with a quite complex configuration and its structural complexity is determined by the capabilities of the precision

Figure 1. The topology of the focus of the light field in the letter "R".
lithography technology on the one hand, and computer and software engineering for solving the direct and inverse diffraction problems on the other hand.

There is great interest in the use of DOE for the creation of a fundamentally new elemental base of computer engineering [6] and other unconventional applications of diffractive optical elements [7].

The use of such techniques in micro and nanotechnology will enable creating the light field of a complex structure in the space above the substrate. This field creates a non-equilibrium region at the interface between the substrate and the external environment. At this boundary, the processes of material deposition and the formation and subsequent growth of nuclei occur under different conditions than under the classical theory of condensation. Experimental research has been conducted [8] to obtain thin nanoscale films with a fractal structure.

A curvilinear diffraction grating made by a special algorithm was used as a converter of electromagnetic radiation. It is a semiconductor or glass substrate on which a self-affine topology is formed in the form of a slit structure consisting of a complex set of intersecting circles. This structure is a planar device for converting scattered electromagnetic radiation into coherent form [9].

These slits play the role of waveguides that propagate electromagnetic waves. In such slit structures, interference of several undamped electromagnetic waves occurs. Resonance phenomena affect the interference pattern both in the far zone and in the near zone. This phenomenon can be interpreted as the expansion of the near zone to the far. The minimum size of the diffracting element will be determined by the minimum size of the taper angle formed when the arcs of circles intersect, and the maximum size by the size of the entire grate. Then there will be a continuous set of diffracting elements, characterized by various geometric features, ranging from the submicron range (the minimum possible values of the wavelengths of the diffraction spectrum lie in the optical range and ultraviolet) and to the largest, determined by the grating boundaries and already in the millimeter range of wavelengths. It should be taken into account that the grating, even with not very dense graphics, with a slit of several microns size, will contain about 400,000 ordered diffracting elements, which will give a diverse, ordered, intense diffraction pattern [11].

A micrograph of a similar slit structure, taken with a JSM-35 electron microscope, is shown in figure 2.

**Figure 2.** Micrographs of slit structures.

Comparison of two devices with the same graphics but made by different technologies, one of which is made with the help of slits, and the other with the help of strokes forming a thin film on the surface of the substrates, shows a higher efficiency of the slit structures. The minimum slit width, 0.1 μm, is associated with the band of the covered spectrum of electromagnetic radiation (0.1 μm - the wavelength of the ultraviolet range). But, as the experiment shows, even with a slit width of 7 μm, the entire spectrum of the optical range is structured. This can be explained by the fact that the minimum covered wavelength will be determined not only by the parameters of the slit but also by the dimensions of the taper angle in the fractal graph.
The minimum slit depth equal to 0.1 µm is chosen empirically based on general physical considerations: the height of the step as a diffracting element cannot be less than the wavelength of electromagnetic radiation. At this depth, the structured area reaches several centimeters.

When using such diffraction gratings, a number of very interesting effects can occur. It is known that at the interface between two media or phases surface electromagnetic waves may appear and propagate along the surface. In the case of a curved diffraction grating, these must be completely new phenomena. Prerequisites for their use were discussed in detail in [11]. A fragment of one of the topologies is shown in figure 3.

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** A fragment of one of the topologies.  **Figure 4.** Light field appearing in space.

The calculation of the light field resulting from the interaction of the fractal-matrix topology of the grating with electromagnetic radiation is a difficult challenge requiring powerful computing equipment and appropriate software.

Therefore, at present the problems of calculating the light field can be solved only for fragments of the gratings with electromagnetic radiation in the optical range showed that when irradiated by reflection from light from a non-point non-monochromatic radiation source, a complex light field is formed in the space above the surface of the grating. It is an ordered system of interference maxima and minima located in a volume of space several mm above the surface of the substrate. Such a light field has a complex internal structure, as shown in figure 4. This figure shows a photograph of the light field that occurs when a halogen lamp is irradiated with scattered light. A similar light field appears when irradiated by diffused sunlight.

![Figure 5](image3.png)

**Figure 5.** Various projections of the distribution of electric field strength.

The modeling of the interaction of scattered electromagnetic radiation with a complex curved diffraction grating was performed by professors G.N. Lukyanov and A.V. Kopyltsov. The modeling was done both for the stationary case, with consideration of the absorption and reflection of the
incident radiation, and the non-stationary case, in which the phenomenon of the semiconductor polarization and the distribution of electric charges over the surface of the resonator with regard to its topography. In the stationary case, the radiation frequency was changed with respect to the plate size, when the wavelength of the incident radiation and the frequency of the resonator surface pattern were compared taking into account its dimensions. The results show that the electric field strength after interacting with the self-affine surface is redistributed over its elements so that the graphs of the field distribution over the surface are not in random form, like the incident white radiation, but in regular form, which remains almost unchanged when the frequency of the incident radiation changes in a wide range [13,14].

The modeling has shown that regardless of the conditions at the surface boundary, after some time a stable and soliton-like distribution of the electric field strength is established over the surface of the resonator. The modeling results are shown in figure 5, where various projections of the electric field strength along the surface of the resonator are presented [13,14].

The formation of thin-film layers of copper, titanium, aluminum, and nickel were carried out on a magnetron sputtering unit which was developed on the basis of a converted and modified standard exhaust cart VUP-4. The experiments involved studying the effect of grating on the processes of obtaining new structures (deposition of thin and nanoscale films. These experiments used nucleation of crystal formation and growth, polymerization processes and etc.) or modification of the parameters of existing structures, various combinations of their arrangement, both under the surface of the substrate, on which the material was applied, and in the space of the working chamber.

Figure 6 shows a micrograph of the surface of a nanoscale copper film (optical microscopy, 400x magnification) grown by ionic magnetron sputtering on the surface of a K-8 optically polished glass substrate under standard conditions, in accordance with the generally accepted theory of condensation. This film completely repeats the structure of the substrate and therefore had no particular interest from the point of view of fractal physics. Obtaining films that have some kind of their own structure grown under the conditions for the implementation of self-similar processes has always been considered as a manufacturing defect. Therefore, despite the fact that most professional technologists are familiar with fractal films and films that have their own structure, almost no one has studied the methods of producing such films or studying their properties.

The fractal structures obtained in non-equilibrium conditions after the termination of the technological process tend to an equilibrium state, as a result of which their evolution continues. Their state can be compared, as it were, with a sharp freeze and a further slow evolutionary process of restructuring their structure. It is wrong to define these processes as degradation or aging since there is no deterioration in any characteristics or processes of decay.

The term maturation is more appropriate here but we suggest that the term “evolution” adequately describes these processes. The fractality of the film structures we obtained is confirmed and described in [15–17].
The films obtained have a distinct fractal structure over the entire surface of the sample, both in the central zone of the substrate and at the periphery. The disadvantages include the inability to influence in any way the processes of nucleation and growth of fractal structures. They are entirely self-organized, therefore, it is not possible to make any direct start. For this, it is necessary to establish an unambiguous correlation between the structural pattern of the diffraction grating, the method of its manufacture (slit or film matrix), the level of fractalization and the technology of film synthesis.

In the experiments the influence of the substrate material and the degree of its orientation on the structure was not found, and when a continuous film is formed, its structure and morphology become more complex. When moving to the center of the substrate, the complexes of ring-shaped and dome-shaped structures are observed. Dome-shaped elements are surrounded by the smaller ones on one side and have small dome-shaped "nucleus" formations under the dome, as shown in figure 7, scanning electron microscopy image.

Some conclusions can be drawn from the experimental material. It is necessary to ensure not only the force but also the information impact of the electromagnetic field. According to the data [18], information and structure are a single entity, and the formation process of any structure is a process of production and materialization of information, where the information is considered as a measure of order. In our case, the "information scheme" is a graphically expressed order construct in the form of a specific topological scheme [11]. By measuring the amount of information you can assess the level of structural organization of any system. At the same time, [19] suggests that as the corresponding structure is formed, information is transformed into substance, since there is simply no place for information to exist outside the substance of information. As a result of such transformation, information gives the substance a structure, shape, and complementarity, regarded as the ability to store and transmit information (for example, how and with what ingredients to combine this substance in chemical reactions). The only question is how and in what form to store and transmit information. I. R. Prigogine suggests [20] that in the interaction of any objects each of them undergoes certain changes, and the subsequent interaction of the changes will be even deeper, ensuring constant interaction and exchange of information between any structures (not excluding atoms and elementary particles), it is possible to achieve a gradual increase in the order of any structure.

3. Conclusion
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