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Optimization of the parameters of the layer system on the example of the optical structure

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***Abstract* — Optimal parameters of the layer system have been investigated and described the most effective constructions of multidimensional search methods for the given problem have been defined. Features of realization of multidimensional search methods are also described.**

***Keywords* — modeling, optimization, multidimensional search methods, light transmission, multilayer interference coating, the layer system**

I. INTRODUCTION

An optical coating is one or more thin layers of material deposited on an optical component such as a lens or mirror, which alters the way in which the optic reflects and transmits light. One type of optical coating is an antireflection coating, which reduces unwanted reflections from surfaces, and is commonly used on spectacle and photographic lenses. Another type is the high-reflector coating which can be used to produce mirrors which reflect greater than 99.99% of the light which falls on them. More complex optical coatings exhibit high reflection over some range of wavelengths, and anti-reflection over another range, allowing the production of dichroic thin-film optical filters. An antireflective or anti-reflection (AR) coating is a type of optical coating applied to the surface of lenses and other optical elements to reduce reflection. In typical imaging systems, this improves the efficiency since less light is lost. In complex systems such as a telescope, the reduction in reflections also improves the contrast of the image by elimination of stray light. This is especially important in planetary astronomy. In other applications, the primary benefit is the elimination of the reflection itself, such as a coating on eyeglass lenses that makes the eyes of the wearer more visible to others, or a coating to reduce the glint from a covert viewer's binoculars or telescopic sight. Interference-based coatings were invented and developed in 1935 by Ukrainian physicist Oleksandr Smakula, who was working for the Carl Zeiss optics company.

Anti-reflective coatings are used in a wide variety of applications where light passes through an optical surface, and low loss or low reflection is desired. Examples include anti-glare coatings on corrective lenses and camera lens elements, and antireflective coatings on solar cells. In this work will be considered anti-reflective coatings.

The mathematical problem of the synthesis of layered optical coatings similar to the synthesis of different tasks in other areas of physics: electromagnetism, radiophysics, acoustics, etc.

II. MODELING AND OPTIMIZATION

To estimate the influence of changing interference systems parameters on the resulting transmission the matrix method was used. It based on the determination of a characteristic matrix [2]. The matrix method for calculating spectral coefficients of the layered media was first suggested by F. Abeles (1950) and has been widely employed ever since. The results of the previous section allow to provide here its very simple presentation. Let us assume a multilayer coating consisting of a finite number of homogeneous and isotropic layers.

If the geometrical thickness of a layer is equal to d, and refraction coefficient is equal to n, the characteristic matrixes of the homogeneous dielectric film have the appearance:

$$M_s(n,d,\lambda)=\begin{Vmatrix}\cos\delta(n,d,\lambda) & -\frac{i}{p}\sin\delta(n,d,\lambda)\\ -ip\sin\delta(n,d,\lambda) & \cos\delta(n,d,\lambda)\end{Vmatrix}, \quad (1)$$

where $\delta(n,d,\lambda)=\dfrac{2\pi\cdot n\cdot d\cdot\cos\theta}{\lambda}$ – is the phase thickness of a layer, p=√ε/μ cosδ. In the case when the direction of propagation of radiation coincides with a perpendicular to the interface, δ = 0 and correspondingly $p = n$.

Knowing a characteristic matrix of one layer (1), we can determine a characteristic matrix of k-th layer of multilayer systems, as a product of matrixes of each layer:

$$M(\bar{n},\bar{d},\lambda)=M_k(n_k,d_k,\lambda)\cdot M_{k-1}(n_{k-1},d_{k-1},\lambda)\cdots M_2(n_2,d_2,\lambda)\cdot M_1(n_1,d_1,\lambda), \quad (2)$$

where M_j – is a characteristic matrix of j-th layer; $\bar{n} = (n_1, n_2, ..., n_{k-1}, n_k)$ – is a vector of the values of refraction indices of layers; $\bar{d} = (d_1, d_2, ..., d_{k-1}, d_k)$ – is a vector of geometrical thicknesses of layers.

From (2) it is easy to find a value of a MLS transmission at the fixed values of $\bar{n}$, $\bar{d}$ and λ:

$$T(\lambda) = 1 - \left[\left| \frac{n_0(M_{11}(\lambda) + n_S \cdot M_{12}(\lambda)) - (n_S \cdot M_{22}(\lambda) + M_{21}(\lambda))}{n_0(M_{11}(\lambda) + n_S \cdot M_{12}(\lambda)) + (n_S \cdot M_{22}(\lambda) + M_{21}(\lambda))} \right| \right]^2, \quad (3)$$

where n_0, n_S – are the refraction indices of external environment and substrate accordingly, M_{11}, M_{12}, M_{21}, M_{22} – are the elements of a characteristic matrix M_j.

For the numerical calculation of the transmittance spectra of MLS the objective function is represented as [3]:

$$\max_{\bar{n}, \bar{d}} F(\bar{n}, \bar{d}) = \left(\frac{1}{L} \sum_{i=1}^{L} T^2(\bar{n}, \bar{d}, \lambda_{(i)}) \right)^{1/2}, \quad (4)$$

where L – is a number of a grid points for a spectral interval from λ_1 to λ_2. At the it's uniform distribution with a step $\Delta\lambda$

$$L = \frac{\lambda_2 - \lambda_1}{\Delta\lambda} + 1, \quad (5)$$

where λ_1 and λ_2 – are the short-wave and the long-wave boundary accordingly of researched wave spectral region.

In our experience various gradient methods are efficient for a search of the merit function minimum. All the methods of the type imply re-iterated calculations of the merit function and its gradient, i.e., the vector comprised by partial derivatives of the merit function with respect to the layers sought for parameters. These two operations are essential, and so the rate and precision of their fulfillment determine to a considerable degree the calculation potentials of the method [6].

Very often multilayer optics synthesis problems are solved success-fully through reiterated optimization of the merit function with series of random starting designs. As a quasioptimal solution, a vector of the coating parameters is taken, which corresponds to the deepest of the obtained minima. Sometimes, it is worthwhile to pick out several quasioptimal solutions, especially, if the minima are about the same depths. The final selection of the best solution can be done on the basis of the results of their practical implementation.

It is difficult to give all-embracing recommendations concerning the starting design choice and algorithm peculiarities for different types of synthesis problems. Let us only note here that good starting designs can be also set in case of wide-band mirrors and polarizer's synthesis [6-7].

Usually, the steepest descent method predetermines a fast de-crease of the function along the first few directions of one-dimension, minimizations. Then the speed of the decrease slows radically. This is especially evident when the function isolines have a "ravine-like" structure. Experience shows that the merit function isolines in the synthesis problems look exactly like the former. The "ravine-like" pattern of the merit function grows fast as the number of the F-function variables, i.e., the number of the layers increases. The conjugate gradients method allows to manage the ravine-like pattern of the minimized function in a simple and reliable way. The conjugate gradients method differs from the steepest descent one in the fact that a one-dimension minimization is not implemented along the antigradient but rather along some "adjusted" direction obtained with the previous descent direction taken into account [1, 3, 6].

Let us now discuss synthesis problems where the starting design choice is vague, as a rule. Such are the problems of synthesis of antirefrection coatings, neutral beam splitters, multilayer systems featuring non-standard spectral properties. Let us make another remark concerning optimization of multiextremal functions. In principle, there are mathematical methods of their global minimum search. However, a strict employment of these methods which would ensure determining the global minimum is not feasible practically when the number of variables exceeds 1 or 2 because it implies the necessity of tremendous amounts of computer time. Due to this fact, methods are mostly used which, speaking strictly mathematically, cannot guarantee unconditional determining of the global minimum, but they are completely justifiable in solving practical problems. The considerations above, related to a search of quasioptimal solution of the synthesis problems accord with this approach [3].

To optimize very effectively use the Quasi-Newton methods. These methods used to either find zeroes or local maxima and minima of functions, as an alternative to Newton's method. They can be used if the Jacobian or Hessian is unavailable or is too expensive to compute at every iteration. The "full"Newton's method requires the Jacobian in order to search for zeros, or the Hessian for finding extrema. In optimization, quasi-Newton methods (a special case of variable metric methods) are algorithms for finding local maxima and minima of functions. Quasi-Newton methods are based on Newton's method to find the stationary point of a function, where thegradient is 0. Newton's method assumes that the function can be locally approximated as a quadratic in the region around the optimum, and uses the first and second derivatives to find the stationary point. In higher dimensions, Newton's method uses the gradient and the Hessian matrix of second derivatives of the function to be minimized. In quasi-Newton methods the Hessian matrix does not need to be computed. The Hessian is updated by analyzing successive gradient vectors instead. Quasi-Newton methods are a generalization of the secant method to find the root of the first derivative for multidimensional problems. In multiple dimensions the secant equation is under-determined, and quasi-Newton methods differ in how they constrain the solution, typically by adding a simple low-rank update to the current estimate of the Hessian [5]. Strictly, any method that replaces the exact Jacobian with an approximation is a quasi-Newton method. The methods given below for optimisation are other examples. Using methods developed to find extrema in order to find zeroes is not always a good idea as the majority of the methods used to find extrema require that the matrix that is used is symmetrical. While this holds in the context of the search for extrema, it rarely holds when searching for zeroes. Broyden's "good" method and Broyden's "bad" method are two methods commonly used to find extrema that can also be applied to find zeroes. Other methods that can be used are the Column Updating Method, the Inverse Column Updating Method, the Quasi-Newton Least Squares Method and the Quasi-Newton Inverse Least Squares Method. Such quasi-Newton methods are most often used Pearson's method, McCormick's Method, the Powell symmetric Broyden (PSB) method and Greenstadt's method.

Another effective method is an r-algorithm [3]. r-algorithm is for unconstrained minimization of (possibly) non-smooth functions, which has been somewhat popular despite an unknown convergence rate. It can be viewed as a Quasi-Newton method, although it does not satisfy the secant equation. Although the method involves subgradients, it is distinct from his so-called subgradient method. This method was developed academician Shore at the VM Glushkov Institute of Cybernetics of NAS of Ukraine.

III. RESULTS

Recently in [12] was proposed two components wide band interference filters for visible spectral range. Bat on spectral dependence of transmitivity there are some deviation from ideal curve (Fig. 1, curve 1). In order to improve level of transmitivity in the visible range up to 100% we applied different methods of multidimensional search. During optimization procedure we have found best parameters compare with [12] for antireflecting two component multinary optical coatings.

We used in parallel methods on p processors. In this case the acceleration in time range is possible compare to one processor computer. In linear approximation this acceleration is approximately is as integral part of q=[k/p+1]. On Figure 1 curve 2 is ease seen that optimization parameters which we got are improve spectral dependents of transmitivity compare with results, obtained in [12]. The same can be seen in Figure 2.

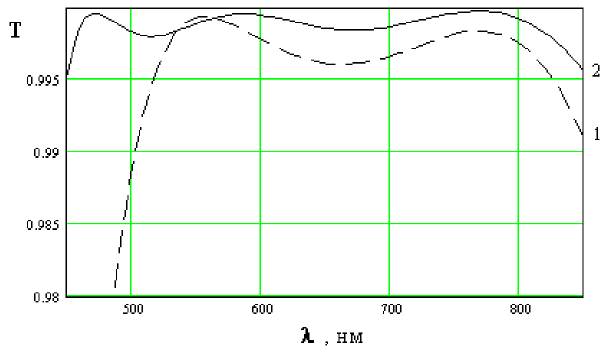

Figure 1. Coefficient of transmittivity for 7 layers two components filters with low (L) and high (H) refractive indexes n_L=1.35, n_H=2.1, substrate n_s=1.52: 1 − optical thicknesses for working wavelength λ_0 are equals 0.06 : 0.02 : 0.35 : 0.02 : 0.07 : 0.42 : 0.21 taken from [12]; 2 − optical thicknesses for working wavelength λ_0 are equals 0.038 : 0.035 : 0.047 : 0.126 : 0.014 : 0.059 : 0.155 after optimization, this work .

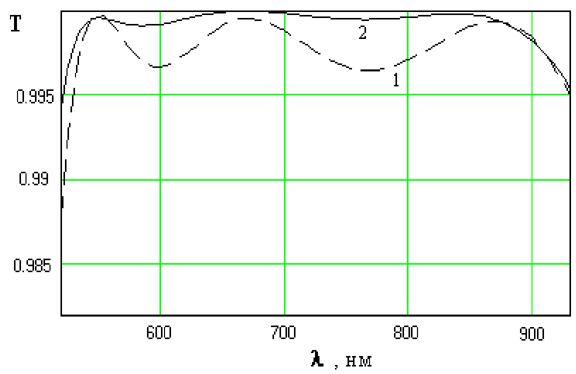

Figure 2. Coefficient of transmittivity for 7 layers two components filters with low (L) and high (H) refractive indexes n_L=1.35, n_H=2.1, substrate n_s=1.52: 1 − optical thicknesses for working wavelength λ_0 are equals .064 : 0.038 : 0.401 : 0.032 : 0.084 : 0.459 : 0.229 taken from [13]; 2 − optical thicknesses for working wavelength λ_0 are equals 0.063 : 0.012 : 0.229 : 0.02 : 0.082 : 0.224 : 0.167 after optimization, this work .

In solving any kind of the synthesis problems, it is necessary to" take into account a number of other non-quantitative aspects, including, firstly, the necessary costs of the solution in terms of computer time and labors costs. A waste of many hours in search of an optimal solution is evidently senseless if, on the other hand, we can find within several minutes "an acceptably adequate" solution satisfying all the requirements. All the above causes the following conclusion concerning the merit function optimization: a global optimization is frequently redundant and it is advisable to look for a sufficiently thorough local minimum ensuring the required accuracy of the pre-set spectral dependence approximation and good feasibility properties of the coating design. Such "quasioptimal" solution is frequently achieved due to a good selection of a starting design for the merit function optimization. The researcher's personal experience is undoubtedly of utmost importance, though a number of common rules can be recommended. This, firstly, concerns, edge filters of various type. It is advisable to use quarter-wave mirrors or some combinations of such mirrors as the first approximation to their design.

Let us consider the effect of technological errors on the final result. As a rule, the errors are small enough, so it is possible to estimate the influence of the changes in individual parameters by calculating the spectral coefficient derivatives with respect to the corresponding parameter. The first item of the section asserts there are sufficiently simple algorithms allowing to calculate spectral coefficient derivatives very precisely and of low calculation efforts. The significance of this result goes beyond the limits of this section. The possibility of an absolutely precise and fast calculation of spectral coefficients derivatives is of vital importance or design methods of synthesis of multilayer coatings. The major problem in estimating the impact of errors on multilayer coating properties lies in the fact that the concrete values of parameter variations are un known. Usually, we may suggest only some approximate mean values of errors.

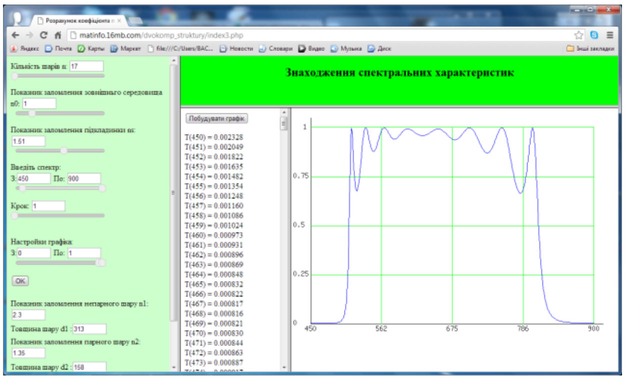

Figure 3. Software interface.

A question rises in this connection of how to estimate possible spectral coefficient variations. One of the ways is a multiple reiterated modelling of concrete values of the parameter errors and a subsequent calculation of corresponding spectral coefficients. However, the number of different options in modelling the errors is so great, that significant difficulties appear in interpreting the obtained results.

Developed a software that allows you to carry out the necessary calculations associated with optimization of the parameters of multilayer optical structures. Figure 3 shows the interface of this software. Software written in the Java programming language.

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