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STRATEGY OF DESIGN OF SOPHISTICATED OPTICAL MULTILAYERS

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The demand for very special optical coatings, having unusual optical characteristics that have no similarities with the traditional coatings, steadily increases. Typical examples are colour temperature converters, some types of narrow band reflectors, etc. A thin-film designer often encounters the very well known problem of the starting design. In this paper, a strategy of multilayer design is described. Taking an example, the target function is defined and then the complete design procedure is illustrated. The use of only two popular optical multilayer materials, namely SiO_2 and TiO_2 is assumed. BK7 glass and air are assumed as surrounding media. In all analysed cases, only a certain number of alternating layers can be assumed as the starting point of the design procedure. The method of global multilayer design is used in the first step, it is followed by the Tikhonravov's design method, and finally by the gradient refinement. Other possible ways and methods are discussed, and some hints are given.

1. *Introduction*

Designers of optical thin films multilayers are faced with increasing demands for the tailored optical multilayer components. At present, the situation is much better than about 30 years ago when pioneers of the computer-aided optical-thin-film design made the initial development, because the new computers made this work much easier and increased the design capabilities very much. Comparing the original papers of Baumeister [1], Seeley [2], Macleod [3], Thelen [4] and Dobrowolski [5] with the presently available computer software and hardware, we can hardly believe that all that progress has been made in only a few decades. Regardless of the excellent tools in their hands, thin films designers encounter the situations when they have no idea how to start a design procedure and attain the required optical characteristics of a thin film multilayer. The aim of this paper is to present a way how to start, proceed and complete the multilayer design procedure by using the existing well-known design procedures with the accent on the new Tikhonravov's design method [6].

2. Design strategy

We consider the design process with the following assumptions: We use only two optical multilayer materials, with known optical properties like refractive index, dispersion and absorption, and two surrounding media, the BK7 glass and air.

The first step is the generation of the target function. It can be generated in very fine or in larger increments, depending on the complexity of the target curve. Of course, if we design a broadband coating, like a neutral attenuator or antireflective coating, larger increments are suitable. We must keep in mind that with larger increments, we only roughly define the shape of the target function. There are always many points (wavelengths) between two points of the target function, so the spectral characteristics of the designed filter may be very different.

In the second step, we choose a relatively small number of alternating layers, depending again on the complexity of the design target. For the antireflective coating, 3 – 5 layers are applied, and for more demanding designs, 20 – 30 layers are necessary. We select the design wavelength and assume for all layers equal optical thickness of $\lambda/2$ for the selected design wavelength. Other thicknesses can also be chosen such as λ or some other multiple of $\lambda/2$.

Next, we start the global search. During this procedure, computer generates automatically designs with the given materials, changing only the thickness of the layers. In this way, we can obtain thousands of randomly or systematically generated multilayers. Their optical thicknesses vary from 0 to λ (0 to 2λ in the case of the starting layers of thickness λ). In this way, we overcome the problem of the selection of the starting design. At the same time, computer calculates the deviation of any generated design from the target design, and then we can select some of the generated ones.

After having generated a number of designs, we can continue with their optimization. Any kind of a local-type optimization like gradient, variable metric or damped least squares are used. At this step, we can choose the number of iterations, depending on the method applied.

Now, we have a certain number of multilayers that have the same or smaller number of layers than the starting design. The differences between the obtained designs characteristics and the target design can be analysed at this step. We can determine the deviation that can be allowed, and have some of the designs that are quite close to the wanted characteristics.

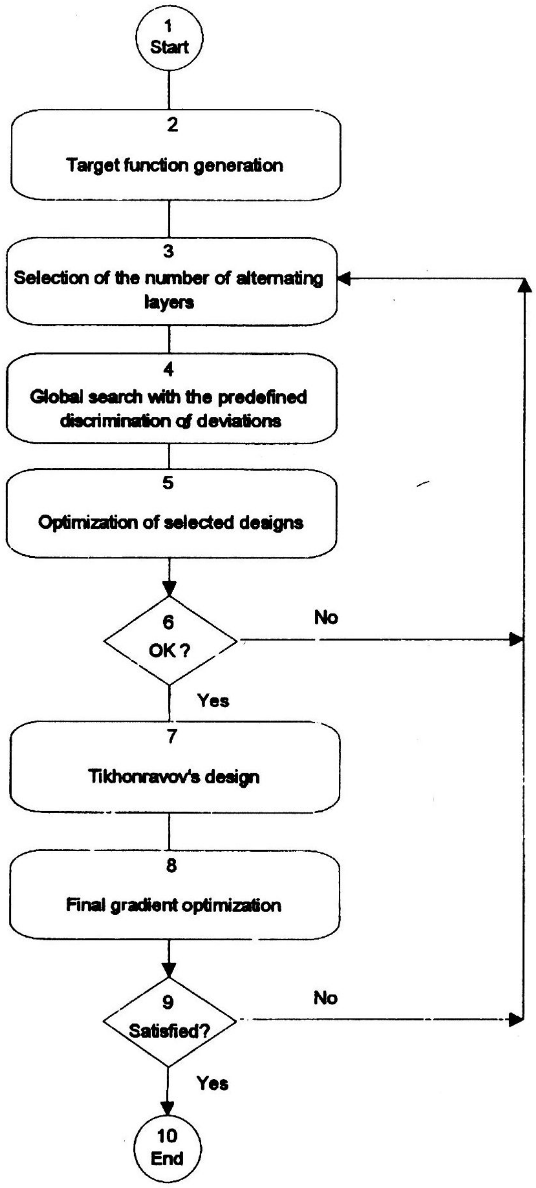

Fig. 1. Flow diagram of the presented design procedure.

Subsequently, we apply a relatively new method of the "needle design" introduced by Tikhonravov. In this new optimization method, new zero-thickness layers are introduced into the coating design. After the new layer has been added, one of the local optimization methods is used to improve the new design. If the zero-thickness layer has been placed in the correct position, the local optimization method will force the new layer to grow. This procedure lasts until the wanted deviation has been obtained.

Finally, we conclude the whole design process with a fine gradient optimization. The described design process is shown schematically in the flow diagram in Fig. 1.

3. *Evolution of an example design*

The target function is sometimes defined by the outline of an object in a photograph [7]. For the illustration of the above described process, we have chosen the contour of the Zagreb Cathedral. For this presentation, it has been assumed that we want to design a filter with the transmittance that has the shape of the Cathedral in a wavelength range between 400 nm and 800 nm.

Following the step 2 in the flow diagram, we generate the target function in certain wavelength increments which we found to be appropriate and optimal. For shorter wavelengths, a smaller increment is necessary, but this strongly depends on the given shape. In the presented example, the target function consisted of 80 points, i. e., approximately one point at every 5 nm. If one would double the number of target points, it would result in a significant increase of the design time. That is why we speak about an optimum selection of the target function.

In the step 3, we must decide how many initial layers we want to choose and what are their average optical thicknesses. This step is not a critical one, because we can always set a new layer number or thickness in the case that the final design is not up to the requirements. We started our design with 14 layers, then with 29 layers, but finally increased the starting number of layers to 39 alternating layers. They all had the same optical thickness of $\lambda/2$. This is schematically shown in the flow diagram in Fig. 1.

Next, we start with the step 4 that runs automatically after we decide how many multilayers we will generate and search. At the end of this step, we selected only the multilayers that had the deviation less of than 30. Thicknesses have been generated randomly round the starting thicknesses of $\lambda/2$. This step yielded 9 possible solutions. We selected 4 of them whose deviations were less than 15. In Fig. 2a, spectra of these 4 designs are shown together with the target values.

After this step, we started the Tikhonravov's design procedure with 400 iterations on each of the four designs. Then we obtained 4 designs that are shown in Fig. 2b. The number of their layers varied from 47 and 57.

Finally, we have chosen two of the obtained designs for the final gradient optimization (step 7 in Fig. 1). At this step, we continued with the 500 iterations for each of the two chosen multilayers designs.

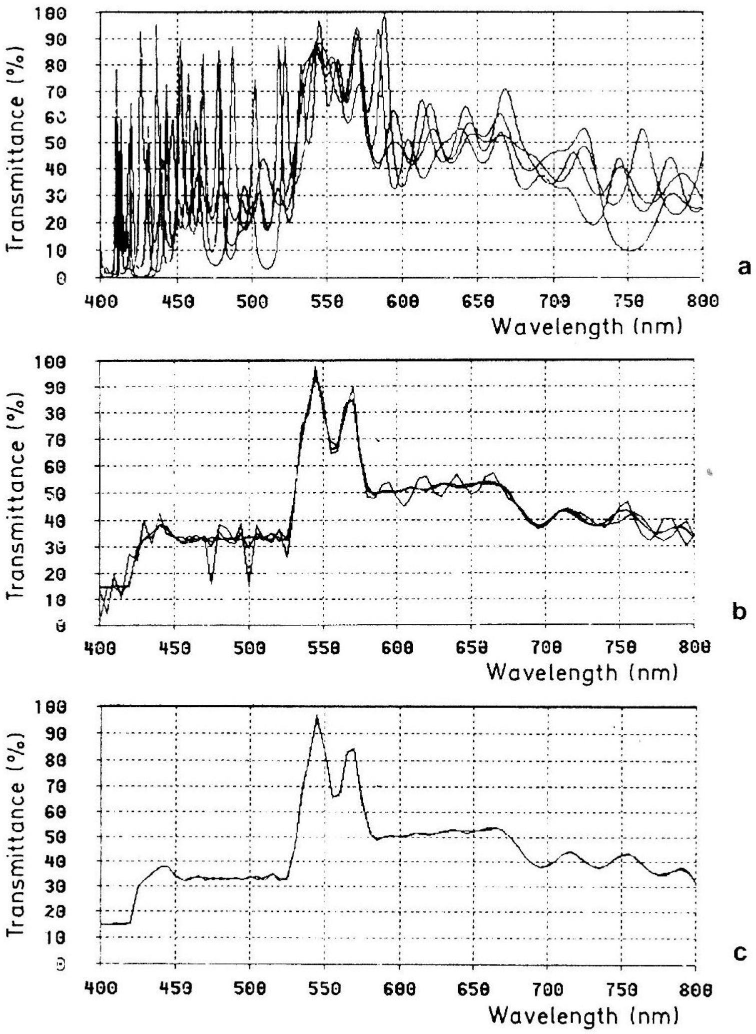

Fig. 2. Evolution of the spectra during the design process (a -corresponds to the step 4 in Fig. 1, b - to the step 5 in Fig. 1 and c - to the two final designs, respectively).

At the end, we ended up with two multilayers. Their deviations were less than 1.5, but their numbers of layers are different. One of them has 63 layers, and the other one 53 layers. It would have been quite reasonable to choose the system containing fewer layers for the production purposes, but both systems are interesting for academic considerations. In Fig. 2c, both final designs are shown. Practicaly, there is no difference between the last two designs, in the sense of their optical properties.

4. Discussion

In the presented procedure, following the flow diagram shown in Fig. 1, a way of the design process of an optical multilayer with predefined optical properties has been presented. It is only one of many possible procedures. However, it very directly leads to the final solution. Assuming only two materials and a certain number of layers, the whole process runs almost automatically with very few but important interventions by the designer. This enables the designer to be fully concentrated on the physical problems during the design process and to avoid dealing with the time consuming jobs like programming, data typing, etc. It certainly requires some experience in defining the target function, in deciding what kind of global optimization will be applied, what increment in the analysis will be used, etc. The same holds for the selection of materials. Regardless of the improvement of the design tools, knowledge and experience are always required.

The time spent for the whole process was about 20 hours, on an IBM PC compatible computer with a 80386 processor, running at 33 MHz. With faster computer, we reach the situation when the computation time is shorter than the time needed for decision making. This allows placing harder tasks on the computer, like more complicated target functions, etc.

5. Conclusions

In the present paper, evolution of design of a thin film multilayer with the predefined optical properties has been presented. One design strategy has beeen thoroughly analysed and illustrated. The desing procedure has been shown on a flow diagram. It has been shown that the presented design strategy, using Tikhonavrov's design method, is highly efficient and fast even for the most complicated target functions. The time needed for the complete design process is very short even if calculation is done on a personal computer.

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STRATEGIJA PRORAČUNA SLOŽENIH OPTIČKIH VIŠESLOJEVA

Zahtjevi za višeslojnim optičkim prekrivima posebnih, netradicionalnih značajki u stalnom je porastu. Primjeri su pretvarači temperature boje, uskopojasni reflektori, itd. Često smo suočeni s problemom početne strukture višesloja. Ovdje se opisuje strategija proračuna višesloja. Izabrana je proizvoljna ciljna funkcija i opisan cijeli postupak oblikovanja višesloja uz pretpostavku dvaju optičkih materijala, SiO_2 i TiO_2. Podloga je BK7 staklo a upadno sredstvo zrak. U prvom koraku primijenjena je metoda globalnog oblikovanja, zatim je upotrebljena Tikhonravova metoda i na kraju fina gradijentna metoda.