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# Monochromatic monitoring of optical coatings production using multiple witness chips

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**Abstract:** The paper discusses the most important computational aspects for using multiple witness chips in the optical coating production with monochromatic monitoring. The application of monochromatic monitoring in the production of a complex narrow band pass filter is considered as an example. The selection of the number of witness chips, the division of filter layers into groups for monitoring by different chips, and the selection of monitoring wavelengths for each chip are discussed. Results from simulation experiments on filter production demonstrate the practical advantages of the proposed approach, in particular, the possibility of using an error self-compensation mechanism in monochromatic monitoring with on-line corrections of monitoring signal levels for terminating layer depositions.

**Keywords:** optical coatings, monitoring algorithms, monochromatic monitoring.

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# Монохроматический контроль производства оптических покрытий с использованием нескольких контрольных чипов

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**Аннотация:** Рассматриваются наиболее важные вычислительные аспекты использования нескольких контрольных чипов при производстве оптических покрытий с монохроматическим контролем процесса напыления. В качестве примера исследуется применение монохроматического контроля при изготовлении сложного узкополосного фильтра. Обсуждаются выбор количества контрольных чипов, распределение слоев фильтра по группам для контроля различными чипами, а также выбор контрольных длин волн для каждого чипа. Результаты модельных вычислительных экспериментов по производству фильтров демонстрируют практические преимущества предлагаемого подхода, в частности, возможность использования механизма самокомпенсации ошибок при монохроматическом контроле с оперативной коррекцией уровня сигнала в конце напыления слоя.

**Ключевые слова:** оптические покрытия, алгоритмы контроля, монохроматический контроль.

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**1. Introduction.** Over more than forty years, monochromatic monitoring of optical coatings with non-quarter-wave layer optical thicknesses has evolved from its original form called level monitoring [1, 2] to a variety of monitoring techniques using different strategies and algorithms [3]. By strategy, we mean choosing between direct and indirect forms of monitoring, using one or more monitoring chips, and choosing monitoring wavelengths to control the deposition of different coating layers. Monitoring algorithms differ in the way they predict the termination time of layer deposition. In this paper, we will consider two main types of such algorithms.

In the original form of level monitoring, layer depositions are terminated upon reaching specified monitoring signal termination levels, which are pre-calculated based on known thicknesses of the theoretical coating design. Unfortunately, this type of monitoring leads to a strong cumulative effect of growing layer thickness errors. To minimize this negative effect, it has been proposed to use monitoring algorithms with active corrections of termination levels based on accumulated information about the actual monitoring signal [4–6] and to employ

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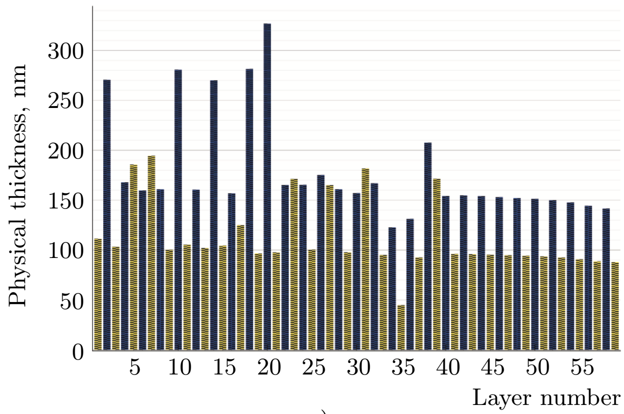
monitoring strategies with multiple monitoring chips [6]. The use of multiple chips is particularly useful when depositing coatings with a large number of layers [7].

The cumulative effect of thickness error growth is a consequence of the correlation of layer thickness errors in optical monitoring [3]. Along with this negative effect, the correlation of errors can also produce a positive effect of error self-compensation, which was discovered many years ago for a very specific form of monochromatic monitoring called turning point monitoring [8, 9]. The presence of this positive effect in monitoring with termination level corrections was first noted in [5]. The existence of this effect can also be expected in the case of monitoring using multiple witness chips [7].

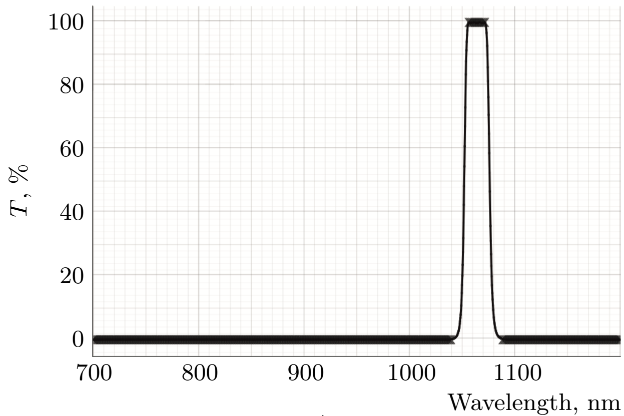
This paper discusses the choice of a monochromatic monitoring strategy with multiple witness chips for the production of a complex narrow band pass filter with non-quarter-wave layer optical thicknesses. In Section 2, the selection of witness chips for monitoring different groups of layers and the choice of monitoring wavelengths are discussed. In Section 3, simulation experiments on filter production are used to compare two basically different monitoring algorithms and to demonstrate the importance of taking into account the error self-compensation effect for selecting the optimal monitoring algorithm. The main conclusions are presented in Section 4.

**2. Considerations regarding the use of multiple witness chips.** In this paper, we use a complex 59-layer narrow band pass filter as an example to discuss the most important considerations for utilizing multiple witness chips in the optical coating production with monochromatic monitoring. We consider a direct form of such monitoring, in which replaceable monitoring chips are located on a rotating substrate holder [6]. The structure of the filter and its spectral transmittance are shown in Figure 1. In the filter design, the odd- and even-numbered layers are assigned model refractive indices of 2.35 and 1.46 respectively. The refractive index of the substrate is 1.52.

Typically, narrow band filters with steep transmittance slopes, as shown in Figure 1 b, are designed as multi-cavity Chebyshev-type filters with quarter-wave and multiple quarter-wave layer optical thicknesses [3]. However, in contrast to Figure 1 b, Chebyshev-type filters provide much narrower high-reflection regions. For this reason, the designed filter has non-quarter-wave layer optical thicknesses, which precludes the use of turning point monitoring. Therefore, we need to consider the possibility of using monochromatic monitoring with active correction of the layer deposition termination levels. The specific form of this correction will be discussed in Section 3.




a)




b)

Figure 1. Filter characteristics: a) layer thicknesses starting from the substrate; b) filter transmittance (solid curve) and target spectral requirements (closely spaced crosses perceived as continuous lines)

The first issue to consider is the number of chips to be used and the assignment of filter layers for monitoring on each chip. To address this issue, we use physical considerations. The discussed filter is a resonant structure, which is confirmed by the analysis of the distribution of the square of the modulus of the electric field strength in its layers at the central wavelength of its passband region (see Figure 2).

The resonances of the electric field in the filter structure are not as pronounced as in the case of quarter-wave narrow band pass filters [3, p. 46]. Nevertheless, four resonances are observed in Figure 2. As indicated in [7], when using several monitoring chips, the error self-compensation effect cannot be observed in all filter layers, but only in groups of layers monitored by individual chips. It is known that for classical quarter-wave narrow band pass filters, the error self-compensation effect works locally for the groups of layers forming each filter cavity [3, pp. 188–190].

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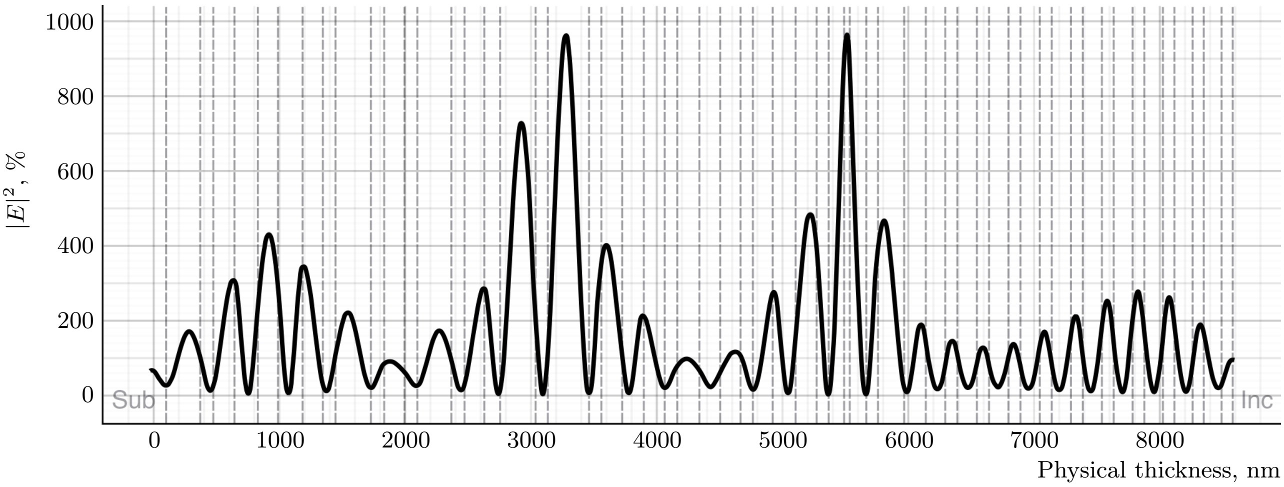


Figure 2. Electric field distribution inside the filter at its central wavelength of 1064 nm. The square of the electric field modulus is shown in percentage relative to the square of the amplitude of the incident field

We assume that a similar effect occurs in the case under consideration as well. For this reason, we choose the four monitoring chips and the following distribution of the groups of layers monitored by these chips: chip 1 — layers 1–12, chip 2 — layers 13–28, chip 3 — layers 29–44, chip 4 — layers 45–59.

An additional insight into the assignment of filter layers for monitoring by different chips is provided by analyzing the sensitivity of different layers to thickness errors of the same magnitude. The sensitivity of different layers to thickness errors is estimated using the standard deviations of the filter transmittance caused by these errors from the transmittance of the unperturbed filter design. The most sensitive layer is assigned 100% sensitivity, and the sensitivities of the other layers are determined relative to this value according to their standard deviations.

The results of the layer sensitivity analysis are presented in Figure 3. It is evident that the sensitivity of the filter layers to thickness variations is very low for layers at the boundaries of the above-selected layer groups. This means that only thickness variations in the central parts of these groups can significantly affect filter transmittance, i.e. contribute to the error self-compensation effect, if it indeed exists. Thus, the results presented in Figure 3 confirm the correctness of the layer distribution. Note that the existence of the error self-compensation effect will be studied in the next section.

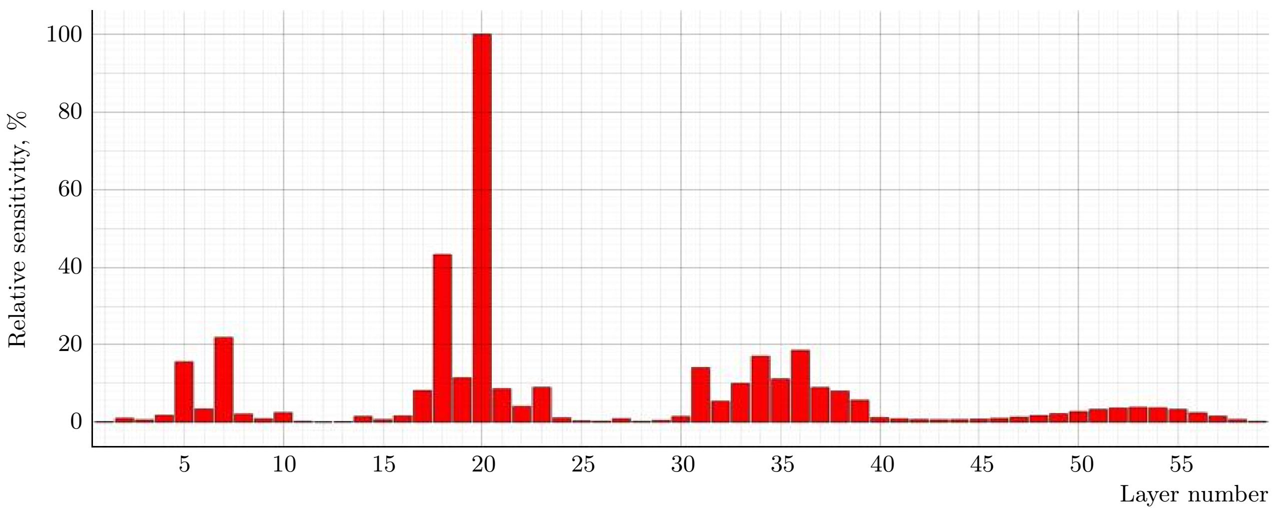


Figure 3. Relative layer sensitivity to thickness errors normalized to the most sensitive layer as a reference value (100%)

Since the distribution of filter layers among the monitoring chips has already been done, the choice of monitoring wavelengths for each chip (generating monitoring spreadsheets) should be discussed. Since we intend to use a monitoring algorithm with corrections of the layer deposition termination levels, this choice should be based on considerations that ensure the most reliable application of such algorithms. These considerations were discussed in detail previously in [7, 10].

To generate monitoring spreadsheets for the four monitoring chips, we use the criteria considered the most important in the aforementioned references. These requirements for the initial and final swing values should satisfy the following lower and upper constraints:

$$0 < a\% \leqslant Swing_{\text{in}} \leqslant b\% < 100\%,$$

$$0 < c\% \leqslant Swing_{\text{fin}} \leqslant d\% < 100\%.$$

Note that the concept of the *Swing* is discussed in detail both in [7, 10] and in the text [3].

We also introduce a quantity called Entry Variation ($EV$), which is either the absolute value of the difference between the transmittance level at the beginning of layer deposition and the first transmittance extremum, if such extremum exists, or the absolute value of the difference between the transmittance of the initial and final levels, if there is no transmittance extremum. The following requirement is applied for $EV$ values of all layers, except the first layers on chips:

$$EV \geqslant e\%.$$

In our experiments, we use $a = c = 10\%$, $b = d = 90\%$, and $e = 4\%$. To automatically generate monitoring spreadsheets that meet these requirements, we apply a new efficient method proposed in [10]. It allows creating spreadsheets with any specified number of acceptable monitoring wavelength switches. To determine the wavelengths at which the layers on the chips should be monitored, we sequentially increase the number of wavelength switches on each chip until the formulated requirements are met. As a result, we obtain four monitoring spreadsheets with 3, 4, 5, and 2 different monitoring wavelengths for chips 1–4. Table 1 shows the monitoring wavelengths selected for the chips. The monitoring wavelengths were chosen in the spectral range from 400 nm to 800 nm with a step of 5 nm.

Table 1. Monitoring wavelengths (MW) for layer groups on four chips used to monitor the deposition of layers 1–12 (chip 1), 13–28 (chip 2), 29–44 (chip 3), and 45–59 (chip 4)

| Chip 1 | | Chip 2 | | Chip 3 | | Chip 4 | |
|---|---|---|---|---|---|---|---|
| Layers | MW, nm | Layers | MW, nm | Layers | MW, nm | Layers | MW, nm |
| 1–3 | 665 | 13–15 | 635 | 29–31 | 600 | 45–46 | 585 |
| 4–8 | 450 | 16–18 | 555 | 32–35 | 475 | 47–59 | 730 |
| 9–12 | 400 | 19–24 | 465 | 36 | 795 | | |
| | | 25–28 | 500 | 37–38 | 445 | | |
| | | | | 39–44 | 435 | | |

Strictly speaking, the generated spreadsheets contain layers with violations of the stated requirements for two layers: layer 14, which is monitored on chip 2, and layer 34, which is monitored on chip 3. However, these violations are minor. The $Swing_{\text{in}}$ values for these layers are slightly below 10%, namely 9.9% — for layer 14 and 9.2% — for layer 34. Further compliance with the stated requirements could be improved by allowing more wavelength switches on chips 2 and 3, but it is hardly practical. Therefore, for the experiments discussed in the next section, we use the monitoring spreadsheets from Table 1.

**3. Simulation experiments on production with multiple witness chips.** In simulation experiments of this section, we model the instability of the deposition rates of high and low index materials. The mean deposition rates of these materials are assumed to be 0.2 nm/s and 0.4 nm/s, respectively. We consider random variations of rates from these values with standard deviations of 5% and 10% of these values. Shutter delays with a mean value of 0.5 s and a standard deviation of 0.1 s are also modeled. Monochromatic monitoring in transmittance mode with measurement intervals of 2 s is considered. Random noise of 0.1% is introduced into the transmittance data. It should be noted that this value is 5–10 times higher than the measurement noise of the best modern monitoring systems [4].

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We consider two basically different monitoring algorithms for determining the instants of layer deposition termination. The first one, called the quasi-swing (QS) algorithm, is based solely on determining the transmittance level at which layer deposition should be terminated. The second one, called the thickness monitoring (TM) algorithm, determines the growing thickness of the deposited layer. Their detailed description can be found in [11].

The QS algorithm belongs to the same type as the algorithm of [4–6]. It uses the same termination level correction scheme described by the formula:

$$T^a_{\text{term level}} = T^a_{\text{last extr}} + \left(T^t_{\text{term level}} - T^t_{\text{last extr}}\right) \frac{T^a_{\text{prev extr}} - T^a_{\text{last extr}}}{T^t_{\text{prev extr}} - T^t_{\text{last extr}}},$$

where the superscripts $t$ and $a$ correspond to the theoretically predicted and actually measured transmittance values. The subscript “term level” stand for the theoretically predicted and corrected termination levels, the subscripts “last extr” and “prev extr” stand for the last two recorded transmittance extrema before the termination levels. For thick layers with two extrema recorded during layer deposition, the QS algorithm is identical to the algorithm of [4–6]. It includes a special procedure for calculating actual extrema in cases where only one extremum or none of them were recorded.

There is a fundamental difference between the QS and TM algorithms. The QS algorithm is based on the use of actual transmittance extrema extracted from the measured monitoring signal. This signal is affected by errors in determining the thicknesses of previously deposited layers, meaning these errors will contribute to the algorithm’s error in determining the thickness of the currently deposited layer. In other words, the thickness errors of all deposited layers will be correlated by the monitoring procedure. The TM algorithm directly determines the thickness of the currently deposited layer by solving a low-parameter inverse problem using only the measurement data accumulated during the deposition of this layer [11]. For this reason, it is expected to be less susceptible to the influence of previously made errors.

To compare the applicability of the QS and TM algorithms to monochromatic monitoring of the filter under consideration, 1000 simulation experiments were conducted with each algorithm. Since production and monitoring errors are random, a large number of experiments is required for reliable statistical analysis. The quality of the filter performances obtained in these experiments was assessed by variations of the merit function ($MF$) used to design the filter:

$$MF = \frac{1}{L} \sum_{\{j\}} \Big( T(\boldsymbol{X}, \lambda_j) - T(\lambda_j) \Big)^2 .$$

Here $T(\boldsymbol{X}, \lambda_j)$ is the spectral transmittance of the coating with the simulated layer-thickness vector $\boldsymbol{X}$ in $m$-dimensional space, $m$ is the number of coating layers (in our case $m = 59$), $T(\lambda_j)$ is the filter target transmittance indicated by crosses in Figure 1b, $j$ is the number of the wavelength point in the wavelength grid used to design the filter, and $L$ is the total number of wavelength grid points.

Let $\delta MF$ denote the variation of the merit function for the simulated vector $\boldsymbol{X}$ with thickness errors. Note that all $\delta MF$ values are positive. Figure 4 shows histograms of the number of experiments corresponding to different $\delta MF$ values in the series of experiments with the QS (Figure 4 a) and TM (Figure 4 b) algorithms. Note that the $x$-axis scales in Figure 4 a and Figure 4 b differ by a factor of 5. This is because the merit function variations in the case of the TM algorithm are several times higher than in the case of the QS algorithm.

It turns out that for the QS algorithm, the average value of merit function variations is 0.0547, while for the TM algorithm it is 0.327, which is about 6 times higher. However, the thickness errors in the experiments with the QS algorithm are generally higher than in the experiments with the TM algorithm. The average norm of thickness error vectors is 3.89 nm for the QS algorithm and 3.52 nm for the TM algorithm. This apparent contradiction is explained by the error self-compensation effect in monochromatic monitoring using the QS algorithm.

The error self-compensation effect is a positive consequence of the correlation of thickness errors by an optical monitoring procedure. In optical monitoring using multiple witness chips, this correlation works within groups of layers monitored by individual chips. A general approach to assessing the strength of the error self-compensation effect was proposed in [12]. It is based on comparing the influence of correlated errors obtained in simulation experiments with optical monitoring with the influence of randomly generated uncorrelated thickness errors. To perform a comparison, a set of uncorrelated random error vectors is generated. These vectors are

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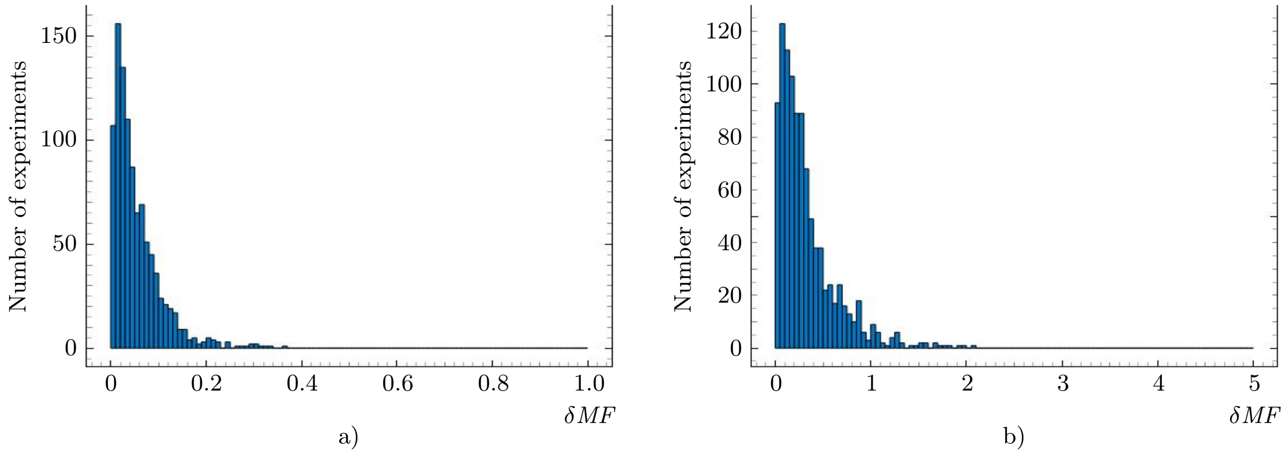


Figure 4. Histograms of the numbers of experiments with different $\delta MF$ values: a) QS algorithm; b) TM algorithm

uniformly distributed in $m$-dimensional space and are generated in such a way that their average norm coincides with the average norm of the correlated error vectors obtained in the simulation experiments.

Let $E\,(\delta MF)$ denote the mathematical expectation of $\delta MF$ values for uncorrelated error vectors. Consider a vector of correlated errors $\mathbf{\Delta}$ and denote by $\delta MF(\mathbf{\Delta})$ the corresponding deviation estimate. The following formula introduces a self-compensation coefficient:

$$c = \frac{\delta MF(\mathbf{\Delta})}{E\,(\delta MF)}.$$

It is reasonable to state that the error self-compensation effect is present in experiments where $c < 1$, and is absent when $c > 1$. The more experiments in the first group, the stronger the error self-compensation. It was proposed in [12] to estimate the strength of this effect using the mathematical expectation of the coefficient $c$ for all performed experiments. In experiments with the QS algorithm (Figure 4 a), the mathematical expectation of $c$ is equal to 0.111, which means a ninefold reduction of the average merit function variations in the case of correlated thickness errors compared to this value in the case of uncorrelated errors of the same level. For the TM algorithm (Figure 4 b), the mathematical expectation of $c$ is 1.07, which means that the error self-compensation effect is absent.

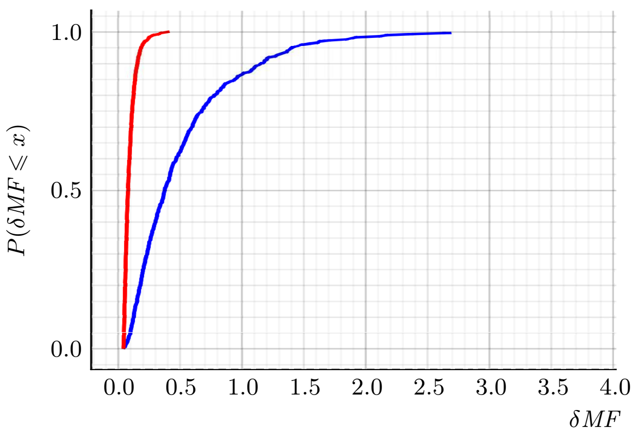


Figure 5. Cumulative distribution functions of $\delta MF$ values obtained in simulation experiments with the QS algorithm (red curve) and in experiments with uncorrelated thickness errors of the same level (blue curve)

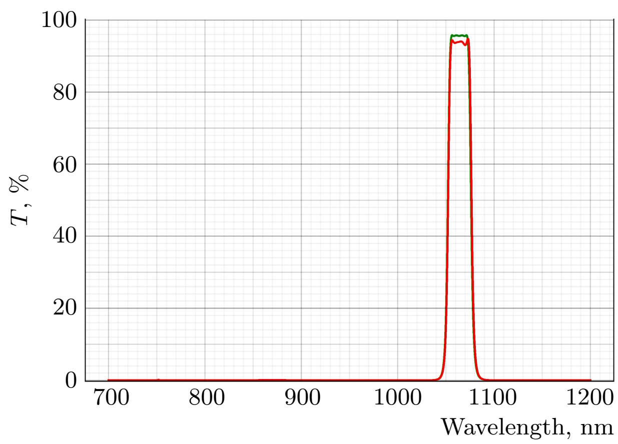


Figure 6. Transmittances of the worst-case design obtained in experiments using the QS algorithm (red curve) and of the unperturbed theoretical design (green curve)

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A clear illustration of the error self-compensation effect is provided by a comparison of the cumulative distribution functions of $\delta MF$ values for correlated and uncorrelated thickness errors in Figure 5. The cumulative distribution function shows the probability of obtaining $\delta MF$ values that are less than the value indicated on the $x$-axis. In experiments with the QS algorithm, the worst $\delta MF$ value is 0.366, and in more than 95% of these experiments, it is three time or more smaller than this value. At the same time, in more than 50% of experiments with uncorrelated thickness errors, $\delta MF$ values exceed 0.366.

It is known from theory [3] that thickness errors have a negligible effect on the filter spectral performance in high-reflection regions and lead to a deterioration in the passband transmittance. This is illustrated in Figure 6, which shows the transmittance of the worst-case design obtained in the experiments with the QS algorithm and the transmittance of the unperturbed theoretical filter design. A reduction in passband transmittance of approximately 2% corresponds to a $\delta MF$ value of 0.366, which may still be acceptable. In the vast majority of experiments with the QS algorithm, the results are significantly better.

Overall, the results presented in this section demonstrate the importance of taking into account the error self-compensation effect in monochromatic monitoring of the production of various types of optical coatings. For the filter under consideration, they undoubtedly support the use of the QS algorithm with the termination level on-line correction.

**4. Conclusions.** A complex narrow band pass filter is considered as an example of selecting a strategy of monochromatic optical monitoring with multiple witness chips. The paper discusses a direct form of such monitoring, in which replaceable monitoring chips are located on a dome with deposited samples. The monitoring strategy is determined by the number of the used witness chips, the selection of layer groups to be monitored by each chip, and the assignment of monitoring wavelengths to the layers monitored by these chips. Physical considerations are used to select the number of chips and assign groups of filter layers to each chip. A recently developed method is used to generate monitoring spreadsheets for these chips, taking into account a number of criteria that ensure the most reliable application of monitoring algorithms with on-line corrections of layer deposition termination levels. One of the two algorithms considered in the paper, namely the QS algorithm, belongs to this type, while the second TM algorithm is based on determining the thickness of the deposited layer.

Simulation experiments on the filter production with monochromatic monitoring using the QS algorithm reveal the presence of a strong error self-compensation effect, which demonstrates its superiority over the TM algorithm, despite the lower level of thickness errors achieved by this algorithm. However, this does not mean that the QS algorithm will always be preferable for monochromatic monitoring of optical coating production. The presence and strength of the error self-compensation depend significantly on the coating type and the employed monochromatic monitoring strategy. Therefore, it is entirely possible that, due to its lower error rate, the TM algorithm will be more advantageous in other situations. This issue is of practical importance and requires further research, as algorithms similar to the TM algorithm are used in modern monochromatic monitors.

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