Application of optical narrow-band mirrors in sensor of concentration of dust in coal mines

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Abstract. The article presents a new design of the sensor for measuring dust, which is based on the effect of absorption of optical radiation passing through the dust layer. Fundamentally new is the use of a powerful low-cost LED, the spectral part of the radiation range required for measurement of which is formed by the structure of auxiliary reflective optical interference filters. A technique based on the introduced stability criterion of the synthesized interference coating is developed, which makes it possible to study the transformation of the spectra with real errors in the film thicknesses.

1. Introduction
In modern optical instrumentation, optical interference narrow-band mirrors (NBM) are used to isolate sections of the spectrum. In the scheme for measuring the dust concentration in coal mines with an LED as a radiation source (RS), shown in figure 1. It is required to allocate for the photodetector (PD) only the band of the spectrum that is intended for measurement in the processing and registration unit, while the LED emits a wide spectral range, as shown in figure 2.

The selection of the necessary spectral region is achieved by introducing mirrors that reflect only the spectral band of a given width. This article describes the basics for the development of an interferential mirror with the control of its characteristics, presents the results of the synthesis, and also develops a
technique that allows us to evaluate the introduced stability criterion of the synthesized coating to study the transformation of the spectra with real errors in the film thicknesses.

2. Methodology for evaluating the quality of synthesis and manufacturing of an interference filter

There are two ways to solve the problem of selecting the required frequency range from a wide spectrum of optical radiation. The first of them involves the installation of a bandpass filter in front of the radiation receiver, and the second-the formation of a special path of propagation of optical radiation using blocking filters (reflectors) for a given wavelength and angle of incidence $\beta$, as shown in figure 3.

![Figure 3](image)

**Figure 3.** A method of separating optical radiation with the use of narrow-band reflecting mirrors.

The production and synthesis of optical coatings for reflecting or transmitting optical radiation in a given frequency range is based on interference from numerous layers of the film structure, each layer of which differs in thickness $d$, equal to

$$d_k = 0.25\lambda_0 / n_k,$$

$\lambda_0$ – the central frequency, which corresponds to either the minimum or maximum transparency; $n_k$ – the refractive index of the $k$-th layer of the film. In the case of the synthesis of a narrow-band coating, the maximum reflection of which must be achieved when the filter is installed at an angle of $\beta$, it can be recommended to increase the layer thickness to the value

$$d_k = 0.25\lambda_0 (n_k)^{-1} / \cos \left( \arcsin \left( (n_k)^{-1} \sin \beta \right) \right).$$

For the implementation of optical transmission or band-pass filters in the infrared range, materials such as magnesium fluoride (MgF$_2$), calcium fluoride (CaF$_2$), barium fluoride (BaF$_2$), quartz glass, zinc sulfide (ZnS), cadmium telluride (CdTe), silicon (Si) and germanium (Ge) should be used, and for the visible range – silicon oxide (SiO$_2$), quartz and borosilicate glasses, zirconium dioxide (ZrO$_2$) [1].

The quality of achieving the goal of obtaining an optical filter with a given dependence of the transmission coefficient on the wavelength can be evaluated using the following method. At the first stage, the approximation to the implementation of the optical filter is estimated by the ratio

$$\Delta T = \frac{1}{M} \sum_{m=1}^{M} \sqrt{(T_{\text{calc}}(\lambda_m) - T(\lambda_m))^2} \leq \delta T,$$

where $\Delta T$ is the quality criterion for approximating the theoretically calculated dependence of the transmission coefficient on the wavelength $T_{\text{calc}}(\lambda)$ to the transmission spectrum of the manufactured filter $T(\lambda)$, which is determined by the required accuracy of the technical implementation of $\delta T$. This quality is estimated for a reflecting narrow-band mirror in a given frequency range of transparency by the ratio.
10 \log \left( \frac{T(\lambda)}{T_{\text{min}}} \right) \leq -TdB,

where \( TdB \) – magnitude level, which is determined by the width of the frequency interval of transparency or blocking of optical radiation, \( T_{\text{min}} \) is the minimum value of the transmittance. Next, check for the level of the transparency coefficient outside the specified frequency band using the formula

\[
T^* = \left( \sum_{n=1}^{N} T(\lambda_n) \right) / N \leq T_{\text{thresh}},
\]

\( T_{\text{thresh}} \) – set threshold level for the side lobes of the spectral characteristic of the mirror outside the reflection band.

3. Narrow band mirror. Technique, that allows to study the transformation of the spectra with real errors in the film thicknesses

Narrow-band reflecting mirrors are synthesized on the basis of a system of layers

\[
D_0 (0.5BH0.5B)mD; \ m = 0.5(N-1),
\]

where \( D_0 \) is air, \( D \) is a substrate, \( B \) is a layer with a high refractive index and an optical thickness equal to \( \lambda / 4 \), corresponding to the center of the reflection spectrum, and \( H \) is a layer with a low refractive index. The numerical factor before the layer symbol means that the optical thickness of the layer is changed in proportion to this factor; \( m \) is determined from the number of layers \( N \) [2]. Figure 4 shows the dependence of the transmission coefficient \( T \) on the wavelength \( NBM \) from layers of zirconium dioxide and silicon with \( m=8 \) at \( \lambda=580 \) nm narrowband.

![Figure 4. Transmission spectrum of the synthesized narrow-band mirror.](image)

In the process of developing interference coatings, three tasks are solved: synthesis [1-5], analysis of the system's stability to errors in layer thicknesses [6-11], and the choice of technological aspects of manufacturing interference coatings [11-13]. The synthesis task consists of determining the coating design with a given accuracy that provides the required spectral characteristics. In general, the problem of coating synthesis belongs to the class of incorrectly posed problems [1-5]. Therefore, as a rule, several combinations satisfy the solution of such problems. Hence the task of analysis, which is to evaluate the solutions found in terms of their stability in relation to various errors that are inevitable in the implementation process.

Let us consider a technique based on the analysis of the transformation of the spectra at a finite value of errors in the layers. In the future, we will use the following notation. A multilayer film coating consists of \( m \) layers, on both sides of which semi-infinite media are applied. The layers are numbered in the direction of propagation of the light wave. Mathematically, multilayer optical systems are described as a \( m \) – layer system consisting of a finite number of layers with different complex refractive indices \( N_j = n_j - ik_j; \ i = \sqrt{-1} \) and optical thicknesses \( D = n_j d \) comparable to the wavelength of a light wave.
Here $n_j$ – the refractive index; $k_j$ – the absorption index of the $j$ layer. Usually, it is assumed that the optical layers are homogeneous, isotropic, and have strictly parallel boundaries and infinite extent. Fringing media are also considered homogeneous and isotropic. To illustrate the proposed technique, we consider the transmission spectra of an 8-layer interference filter, the spectrum of which is shown in Figure 4. In the manufacture of the coating, it is not possible to accurately obtain the calculated values of the refractive indices and layer thicknesses. Therefore, it is important to assess at what spread of these values the coating characteristics are insensitive or insensitive to deviations of the layer parameters from the nominal ones. To analyze the stability criteria according to the proposed method, a program for calculating functions $\Delta F_k$ was compiled, written in the language Wolfram Mathematica 8.0. Analytically, its value is expressed as [9]:

$$\Delta F_k = (\lambda_{n} - \lambda_{i}) N^{-1} \sum_{k} [T(\lambda_{i}, D_k) - T(\lambda_{i}, D_k + \Delta D_k)].$$

This method characterizes the transformation of the spectrum at arbitrary values of $\Delta D_k$. The introduced criterion can be used both to analyze the stability of the synthesized structure and to correct the spectral characteristics during the coating manufacturing process. To do this, it is convenient to use histograms of the stability of the entire structure. The histogram data allows you to determine what changes need to be made to the thickness of the films in order to obtain the desired structure or to perform a correction in the manufacture of coatings.

The calculations are based on the matrix method using the characteristic matrices of individual layers [4]. The program allows you to calculate the transmission and reflection spectra of given functions, find the stability of layers to error variations.

Figure 5 and Figure 6 show stability histograms for the coating layers, the first of which is constructed with an error in the layer thickness of 0.001$\lambda_0$, and the second with an error in the layer thickness of 0.075$\lambda_0$. The quality function is 0.98, which indicates that the coating is resistant to errors in the layers during the manufacture of the coating.

It follows from the analysis of histograms, that the greatest accuracy of manufacturing the layer thickness should be realized for the layer with the number $m=2$. All other mirror coating layers are resistant to errors in their optical thickness.

4. Conclusion

Thus, in this paper, an optical sensor scheme was proposed for measuring the dust concentration in coal mines using a low-power white LED as a radiation source. The proposed sensor design makes it possible to form narrow-band emission lines at wavelengths corresponding to the absorption maxima in the spectrum of dust. A narrow-band reflecting mirror made of 8-layers of zirconium dioxide and silicon. A technique based on the introduced stability criterion of the synthesized interference coating is developed.
The stability analysis of the synthesized narrow-band mirror was carried out, which showed that it is resistant to errors in the layers at the stages of pre-production control of samples and during production.

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Reference
[1] Voigt S, Orphal J, Bogumil K and Burrows J P 2001 J. Photochem and Photobiol 143(1) 1-9
[2] Orphal J, Dreher S, Voigt S, Burrows J P, Jost R and Delon A 1998 J. Chem. Phys. 109(23) 0217-21
[3] Bestugin A R, Krasyuk V N and Ryzhikov M B 2014 Radioelectr and Comm. Syst. 57(11) 495-501
[4] Bestugin A R, Ryzhikov M B, Svanidze V G and Novikova Y A 2019 Proc. of the 2019 Antennas Design and Measurement Int. Conf. (Saint-Petersburg: LETI) p 67-71
[5] Novikova Y A 2019 J. of Phys: Conf. Ser. 1399(2) 022042
[6] Kotlikov E N and Novikova Y A 2013 J. of Optic. Techn. (A Translation of Opticheskii Zhurnal) 80(9) 571-6
[7] Kryachko A F, Novikova Y A, Ryzhikov M B and Kucherova E V 2019 Research of perspective materials for thin optical films for the mid-IR Inter. Sem. on Electron Devices Design and Product. (Prague: IEEE) p 1-4
[8] Kotlikov E N and Novikova Y A 2016 Optics and Spectroscopy 120(5) 815-7
[9] Kotlikov E N and Novikova Y A 2013 J. of Optic. Techn. (A Translation of Opticheskii Zhurnal) 80(9) 571-6
[10] Kotlikov E N and Tereshchenko G V 1997 J. of Optic. Techn. (A Translation of Opticheskii Zhurnal) 64(3) 264-8
[11] Kotlikov E N, Novikova Y A and Tereshchenko G V 2020 IOP Conf. Ser.: Materials Science and Engineering 919(2) 022033
[12] Kotlikov E N and Tereshchenko G V 1998 Optics and Spectr. 84(1) 137-40
[13] Vaganov M A and Novikova Y A 2020 IOP Conf. Ser.: Materials Science and Engineering 862(2) 022028