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Simulation analysis and preparation of a high optical density laser protection filter

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Abstract: High optical density (OD) filters have been widely used in space observation, optical detection, and laser protection. However, the lack of high OD value filters is restricting their application. This paper reports the formulation of a three-dimensional mesh model that can help predict the effects of pinhole defects, thickness error, and uniformity on the transmittance and OD value of optical filters. A laser protection filter (LPF) with a high OD value was prepared on fused silica using a microwave plasma-assisted pulsed DC reactive sputtering technique. The transmittance and OD value of the LPF were measured. Comparing the designed, measured, and simulated results, we found that the thickness error and uniformity of the layers mainly affected the passband transmittance of the LPF and had little effect on the OD value of the blocking band. In contrast, the pinhole defects were the main factor that decreased the OD value of the blocking band. The average OD values of the prepared LPF in the blocking bands of 527–532 and 755–833 nm were 8.832 and 10.191, respectively. By comparing the transmittance and OD value of the simulated and measured results, we found that the LPF has ±1% uniformity error and 0.5% pinhole ratio. Suggestions for preparing high OD optical filters are provided and further improvements are summarized.

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1. Introduction

In the field of optical thin films, the optical density (OD) characterizes the depression ability of the blocking band of multilayer optical filters. The higher the OD value, the deeper the depression depth. Numerically, the OD is the logarithmic ratio of the intensity of the transmitted (I_t) light to that of the incident light (I_i). High OD optical filters, such as notch filters [1], bandpass filters, and long-wave/short-wave blocking filters, have been widely used in space observation [2,3], study of biomedicine at the cellular scale [4], Raman and fluorescence spectroscopy [5], protecting sensitive electro-optical sensors from laser radiation damage [6], and interferometric detection of gravitational waves [7,8]. With the development of optical detection systems, the demand for OD filters is increasing. The OD value is a key parameter determining the performance of optical filters.

The design of high OD optical filters can be facilitated by modeling using thin-film design software such as TFCalc, Essential Macleod, and OptiLayer, which are based on ideal layer assumptions [9–11]. Optical thin-film preparation techniques based on energetic processes, such as ion beam assistance, ion beam sputtering, and magnetron sputtering [12–14], have made it possible to manufacture high-performance optical interference thin films comprising
several layers, ranging from one hundred [15] up to a few thousand [16,17]. However, it is difficult to obtain filters with an OD value greater than 6.

According to the growth theory on coatings, the stress relaxation during thin-film preparation can result in some open pores [18,19]; therefore, the density of a coating is lower than the theoretical density. The pore structure shifts the refractive index and extinction coefficient of optical thin films [20]. The system error of the monitoring and coating machine leads to thickness error and nonuniformity of thin films. This implies that pinholes are formed inside the coatings [19]. Defects, such as voids and imbedded particles, are inevitable during the deposition process, resulting in pinholes [21,22] and thereby affecting the optical properties. Moreover, the density and refractive index decrease, which reduces the transmittance of the bandpass and OD value of the rejection bands. Many researchers have found that the OD value is affected by pinhole defects and nonuniformity of the thin films [19,22]. However, to what extent the OD value is affected by these factors remains unclear. Therefore, to improve the OD value of optical thin films, it is necessary to study the effects of pinhole defects and nonuniformity on the transmittance and OD value of optical filters.

In this study, a high OD laser protection filter (LPF) with rejection bands of 527–532 and 755–833 nm and an average OD value greater than 7 was successfully fabricated. The optical thin-film system of the LPF was designed using the TFCalc software. By establishing a three-dimensional mesh model of the LPF using MATLAB, we studied the effects of pinhole defects, thickness error, and uniformity on its OD value. The LPF was deposited using a microwave plasma-assisted DC reactive sputtering technique, and the refractive indices, extinction coefficients, transmittances, and OD values of the deposited films were analyzed. In comparison with the simulated results, we discussed the influences of these factors on the transmittance and OD properties of the LPF.

2. Design and simulation

2.1 Optical design of a laser protection filter

The two rejection bands selected for the optical notch filter were 527–532 and 755–833 nm. The OD in these bands is more than 7 on average under normal incidence. To achieve this, two different multilayer optical films were deposited onto the opposite surfaces of a fused silica substrate: a notch filter with rejection over both the 527–532 and 755–810 nm bands was deposited on the first substrate surface and an edge filter with rejection over the 755–833 nm band was deposited onto the second substrate surface. To ensure sufficient rejection band quality, the multilayer films were designed with a \((\alpha H \beta L) = \alpha H \text{ periodic structure by employing alternating high (H) and low (L) refractive index materials, where } \alpha \text{ and } \beta \text{ are the adjustment constants for forming an adaptive notch filter structure with desired rejection band position and width [23], and } s \text{ represents the number of periods.}

2.2 Simulation of pinhole defects and uniformity effects on OD

The multilayer LPF structures were used in the simulation and experimental sample fabrication for a direct comparison. The simulation was done by building a model of the multilayer films, focusing on the influence of pinholes and thickness uniformity on the transmittance/OD value of the LPF. In practice, the actual density of such deposited films is lower than the theoretical material density, due to the presence of defects such as pinholes. In addition, a physical thickness error is induced by the deposition system during the deposition process (such as thickness monitoring/control error). These deviations affect the uniformity of the films and the period of the multilayer structures. The pinholes and layer uniformity are considered dominating factors in the simulation of the OD value and spectral transmittance.

To model pinhole distributions, a single layer was used as a starting point. The layer is divided into an \(N \times N\) 2D mesh. The pinhole ratio, assuming that it is known, is used to calculate the number of mesh elements that have pinholes in the 2D mesh. For example, in a
100 × 100 mesh with a pinhole ratio of 1%, there should be 100 mesh elements corresponding to pinholes. For simplicity, the pinholes are assumed to be voids (refractive index = 1), and the geometry of the pinholes is the same as that of each individual mesh element. In practice, the geometry is random and may not contain simple voids.

To simulate the thickness error and uniformity, two steps were taken. First, a thickness control error for each layer was randomly generated within ranges of 0 (no thickness error), ±0.5, ±1.0, ±2.0, and ±5.0%. Second, in addition to the thickness control error, the uniformity of the layer was considered. The thickness variation within a layer due to nonuniformity was randomly generated within the same ranges.

To model the multilayer LPF, the described method was applied to every layer of the filter; thus, a 3D mesh structural model was constructed. For convenience, normal incidence was used for the measurement and simulation; this means that each columnar mesh element is a small LPF. Therefore, the OD value of the entire LPF can be obtained by averaging the results of each small filter. Figure 1 shows the schematic of the mesh setup.

Figure 2 shows the simulation calculation flowchart. To study the influence of pinhole ratios and thickness uniformity on the transmittance and OD value of the films, five steps are involved in the simulation. First, the environmental parameters of the films are set: optical thin-film system, mesh number, variations in the refractive indices of the materials, and substrate as a function of the wavelength. Second, the simulation parameters are set: pinhole ratios (0, 0.1, 0.5, 1, 2, and 5%), thickness uniformity error with a random distribution (0, ±0.5, ±1, ±2, and ±5%), and both the factors. Third, the transmittance and OD value of one columnar mesh element are calculated (by setting the mesh number as 1 × 1) using the eigenmatrix method [23], and the results are verified using the TFCalc software (each columnar mesh element can be seen as an optical thin-film system). Fourth, if the results are correct, the mesh number is set as 100 × 100 to calculate the transmittance and OD values of the notch filter (substrate side 1), edge filter (substrate side 2), and LPF under different conditions. Otherwise, the model is modified, and these steps are repeated. Finally, we export and plot the calculated data and analyze and discuss the influence of these factors on the transmittance and OD value.
2.2.1 Effects of pinhole ratios on the OD value

A 100 × 100 mesh model was used for the simulation. The pinhole ratios used were 0 (no pinholes), 0.1, 0.5, 1, 2, and 5%. The transmittance and OD value for the given pinhole ratios were calculated under three different configurations: notch filter only, edge filter only, and notch plus edge filter (desired LPF, to be fabricated on two surfaces of the substrate). Figures 3(a), (b), and (c) show the OD value and transmittance of the notch filter, edge filter, and LPF, respectively.

The transmittance plots show that as the pinhole ratio increases, the transmittance at the passbands of the filters significantly decreases. When the pinhole ratio is 5%, the spectra over the bandpass of the filters are quite narrow, and the ripples gradually disappear. The influence of the pinhole ratios on the transmittance increased in the order of notch filter, edge filter, and LPF.
Comparing the OD values of the films, we find that with the increase in the pinhole ratio, the OD value in the blocking band decreases rapidly, whereas that in the passband reduces slightly. The OD value in the 527–532 nm band of the notch filter is more sensitive to the pinhole ratio under the same conditions (see Fig. 3(a)). The OD value in the blocking band of the LPF is mildly affected by the pinhole ratio; Table 1 lists the results. The influences of the pinhole ratios on the OD value increased in the order of LPF, edge filter, and notch filter.

Table 1. Difference in the OD Value of the LPF Affected by Varying Pinhole Ratios

<table>
<thead>
<tr>
<th>Pinhole ratios (%</th>
<th>LPF (527–532 nm)</th>
<th>LPF (755–833 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>Det-value (ratio)</td>
</tr>
<tr>
<td>0</td>
<td>9.906</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>0.1</td>
<td>9.829</td>
<td>0.077 (0.78%)</td>
</tr>
<tr>
<td>0.5</td>
<td>9.473</td>
<td>0.433 (4.37%)</td>
</tr>
<tr>
<td>1</td>
<td>8.300</td>
<td>1.606 (16.21%)</td>
</tr>
<tr>
<td>2</td>
<td>7.269</td>
<td>2.637 (26.61%)</td>
</tr>
<tr>
<td>5</td>
<td>5.698</td>
<td>4.208 (42.46%)</td>
</tr>
</tbody>
</table>

Legend: Det-value means the difference between the simulated and designed OD values.

2.2.2 Effects of uniformity on the OD value

In practical depositions, uniformity and thickness errors are unavoidable. As mentioned above, this deviation affects the OD value and is therefore included in our simulations. In this section, the model is assumed to have no pinholes under this condition. The thickness variations of 0, ±0.5, ±1.0, ±2.0, and ±5.0% were simulated. A 100 × 100 mesh model with a random thickness distribution was established. Figures 4(a), (b), and (c) show the transmittance and OD values of the notch filter, edge filter, and LPF under varying uniformity errors, respectively.
Figure 4 indicates that the transmittance at the bandpass of the thin films rapidly decreases with an increase in the uniformity error, with the spectra randomly shifting in the direction of long or short waves. When the uniformity error is greater than ±2.0%, the transmittance profiles at the passband of the notch filter and LPF become irregular. By contrast, the influence of the uniformity on the transmittance of the edge filter is relatively less. The effects of the uniformity on the OD value of the films are minor; Table 2 lists the results of the OD value deviation. Even when the uniformity error approaches ±2%, the OD values of the LPF in both the blocking bands are greater than 9. Further, when the thickness error is ±5%, the OD spectrum in the blocking band becomes narrower.

### Table 2. Difference in the OD value of the LPF affected by Varying Uniformity errors

<table>
<thead>
<tr>
<th>Uniformity (%)</th>
<th>LPF (527–532 nm) Average value</th>
<th>Det-value (ratio)</th>
<th>LPF (755–833 nm) Average value</th>
<th>Det-value (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.906</td>
<td>0 (0%)</td>
<td>10.486</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>±0.5</td>
<td>9.867</td>
<td>0.039 (0.39%)</td>
<td>10.464</td>
<td>0.022 (0.21%)</td>
</tr>
<tr>
<td>±1</td>
<td>9.777</td>
<td>0.129 (1.30%)</td>
<td>10.322</td>
<td>0.164 (1.56%)</td>
</tr>
<tr>
<td>±2</td>
<td>9.646</td>
<td>0.260 (2.62%)</td>
<td>10.257</td>
<td>0.229 (2.18%)</td>
</tr>
<tr>
<td>±5</td>
<td>6.186</td>
<td>3.720 (37.55%)</td>
<td>9.536</td>
<td>0.950 (9.06%)</td>
</tr>
</tbody>
</table>

Legend: Det-value means the difference between the simulated and designed OD values.

### 2.2.3 Effects of pinhole ratios and uniformity on the OD value

During the preparation process, the optical properties of the thin films are simultaneously affected by various errors. Therefore, we simulated the combined effect of pinhole ratio and uniformity on the transmittance and OD value. According to a previous study on deposition uniformity, the thickness error (control error) of a coating machine is lower than ±1% [24].
Therefore, the simulation parameters were set as follows: 100 × 100 mesh number, ± 1% uniformity error, and 0.1, 0.5, 1, 2, and 5% pinhole ratios. Figures 5(a), (b), and (c) show the transmittance and OD value of the notch filter, edge filter, and LPF affected by the two factors, respectively.
The transmittance and OD value decreased due to these factors. Table 3 gives the deviation in the OD value in the blocking band, indicating that the decrease in the OD value in the blocking band is greater than that due to any single error factor. In other words, when there is a uniform film thickness error, the pinhole ratio of the films needs to be lower to obtain the required OD value.

Table 3. Difference in the OD Value of the LPF Affected by the Uniformity error (± 1%) and Varying Pinhole Ratios

<table>
<thead>
<tr>
<th>Pinhole &amp; Uniformity (±1%)</th>
<th>LPF (527–532 nm) Average value</th>
<th>Det-value (ratio)</th>
<th>LPF (755–833 nm) Average value</th>
<th>Det-value (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>9.906</td>
<td>0 (0%)</td>
<td>10.486</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>0.1</td>
<td>9.622</td>
<td>0.284 (2.87%)</td>
<td>10.370</td>
<td>0.116 (1.11%)</td>
</tr>
<tr>
<td>0.5</td>
<td>8.562</td>
<td>1.344 (13.57%)</td>
<td>10.050</td>
<td>0.436 (4.16%)</td>
</tr>
<tr>
<td>1</td>
<td>7.649</td>
<td>2.257 (22.78%)</td>
<td>9.728</td>
<td>0.758 (7.23%)</td>
</tr>
<tr>
<td>2</td>
<td>6.664</td>
<td>3.242 (32.73%)</td>
<td>9.044</td>
<td>1.442 (13.75%)</td>
</tr>
<tr>
<td>5</td>
<td>4.791</td>
<td>5.115 (51.64%)</td>
<td>7.585</td>
<td>2.90 (27.66%)</td>
</tr>
</tbody>
</table>

Legend: Det-value means the difference between the simulated and designed OD values.

We conclude that the pinhole defects and nonuniformity of the films reduce the transmittance in the passband and the OD value in the blocking band. The uniformity of the films has a significant influence on the passband transmittance, whereas the pinhole defects have a significant influence on the OD value in the blocking band. The combined effect of the two factors on the OD value is greater than that of any single factor. To obtain an optical filter with a high OD value, it is, therefore, necessary to apply an appropriate deposition process that results in thin films with a denser structure and a lower thickness error. It is also necessary to avoid contamination, such as by operating in a clean environment and cleaning the substrates using the energetic ion beam before deposition.
3. Experimental details

The samples were prepared using a high-power microwave plasma-assisted reactive sputtering system based on a rotating drum with the depositions done at room temperature. Figure 6 shows a schematic of the deposition system. The system consists of a drum, two targets with respective uniformity masks, a microwave source, and a film thickness crystal oscillator. In this system, the deposition and reaction processes are done separately (regions are labeled in Fig. 6). The rotating drum rotates clockwise about a horizontal coordinate axis at a rotational speed of 60 rpm; the rotational speed was optimized to allow sufficient oxidization of each deposited layer [25]. The target materials used were niobium (Nb) and silicon (Si). In the deposition region, only argon gas was introduced; oxygen gas was introduced only in the microwave plasma region (argon–oxygen mixture). The main function of the microwave is to generate oxygen plasma to produce highly reactive oxygen particles (O₂ molecules, O atoms, or O⁻), which enhance the oxidation of the deposited thin layers. It was also seen experimentally that this deposition process produced films of higher planarity and density. The deposition rate was monitored in-situ using a crystal sensor.

Prior to loading the samples onto the chamber, the substrates (fused silica, 20 mm diameter, 1 mm thickness) were cleaned using a four-stage ultrasonic bath to avoid contamination. The base pressure was $3 \times 10^{-6}$ Torr, the process pressure was $5 \times 10^{-3}$ Torr, and the substrate was pre-cleaned with an argon microwave plasma for 30 min. The deposition rate of the niobia (Nb₂O₅) and silica (SiO₂) films was controlled by adjusting the oxygen and argon partial pressures by optical emission monitoring. The niobia and silica deposition rates were optimized to 0.13 and 0.10 nm/s, respectively.

Various characterizations were done on the prepared samples. The transmittance of the film was measured using a Perkin Elmer PE40 spectrophotometer. The OD value of the LPF was measured using a SALSE 2 measurement system. The characterization of high OD films can be difficult: even small noise/background signals can cause significant errors in high OD measurements [26]; therefore, a high OD measurement system (developed by Fresnel Institute in France) with an accuracy of 1% and a measurement range of 400–1100 nm was used [27]. The system can consider and avoid measurement errors due to noise/background signals [28], and the highest optical density measurement that can be made using this system is currently 12 [29].

![Fig. 6. Schematic of a microwave plasma-assisted DC magnetron sputtering deposition system; target area is the deposition region, and the microwave area is the reactive region.](image-url)
4. Results and discussion

4.1 Experimental results

The optical thin-film design was introduced in Section 2.1. The high OD value LPF was prepared by depositing a notch filter (53 layers) on the substrate surface \textit{one} and an edge filter (36 layers) on substrate surface \textit{two}. Based on the analysis of the simulation results and the principles of the separated reaction sputtering, for improving the manufacturing accuracy, two steps of thickness calibration were employed to minimize the thickness control error (through the comparison of measurement and design transmittance): single layer calibration for each material and a multilayer structure test. Based on the Swanepoel method [30], we can easily obtain the refractive index and extinction coefficient of the two different materials based on their transmittance spectra. Figure 7 shows the optical constants of the alternating high (H) and low (L) refractive index materials, with (a) and (b) showing the refractive indices and extinction coefficients of Nb$_2$O$_5$ and SiO$_2$, respectively. The refractive indices and extinction coefficients at 532 nm of Nb$_2$O$_5$ and SiO$_2$ were 2.373/0.0002 and 1.476/0.0001, respectively.

Fig. 7. Refractive index and extinction coefficient of the alternating materials: (a) Nb$_2$O$_5$; (b) SiO$_2$.

Figures 8(a) and (b) show the transmittances of the notch filter (top of the LPF) and edge filter (bottom of the LPF), respectively. The results show that the transmittance of the notch filter shifts slightly in the direction of the long wave, and the transmittance in the passband around 480 nm decreases, indicating that the notch filter (53 layers) has a small accumulated thickness error. For the edge filter (36 layers), the designed and measured transmittances are largely identical.

Fig. 8. Transmittances of (a) notch filter (53 layers); (b) edge filter (36 layers).
Figure 9 shows the designed, measured, and simulated transmittance and OD values of the LPF. The selected simulation result was the one that most closely resembled the measured result, which was also affected by the pinhole ratios and uniformity. Notably, based on previous experimental experience, the thickness manufacturing error of the coating machine is approximately ±1%. Therefore, the parameters of the simulation model were set as follows: mesh number $100 \times 100$, uniformity error ±1%, and pinhole ratio 0.5%. The measured transmittance near 480 nm is lower than the designed one, and the position of the rejection band is slightly offset, consistent with the trends in the transmittance of the notch filter (Fig. 8(a)). This indicates that the accumulated thickness error of the notch filter affects the result of the LPF. The measured OD value decreases in the blocking bands of 527–532 and 755–833 nm. Notably, the measured OD value in the band 755–833 nm may approach the test limit, and the actual value may be greater than this tested value.

To further analyze the influence of the two factors on the OD value, the measured OD value in the range of 527–532 nm was compared with the simulated results. Table 4 lists the OD value deviation in the blocking band. According to the conclusion obtained in Section 2: the effect of pinhole ratios on the OD value in the range of 527–532 nm is greater than that in the range of 755–833 nm, and the transmittance in the passband decreased because of the pinhole ratios and nonuniformity. By comparing the simulated transmittance and OD value in the range of 527–532 with the measured results, we find that the simulation results are closest to the real situation, indicating that the pinhole ratio of 0.5% and a thickness error of ±1% were generated during the preparation process.

<table>
<thead>
<tr>
<th>Samples</th>
<th>LPF (527–532 nm)</th>
<th>LPF (755–833 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>Det-value (ratio)</td>
</tr>
<tr>
<td>Designed</td>
<td>9.906</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Measured</td>
<td>8.832</td>
<td>1.074 (10.84%)</td>
</tr>
<tr>
<td>Simulated</td>
<td>8.562</td>
<td>1.344 (13.57%)</td>
</tr>
</tbody>
</table>
4.2 Discussion

In this study, a simulation model of a high OD filter was established based on MATLAB, and the transmittance and OD value were calculated using a characteristic matrix method. The model has two advantages in simulating real manufacturing conditions: 1) An optical filter can be divided into any number of unit filters (10000 units in this study, mesh number 100 × 100). The more the units, the closer the result to the real situation; 2) Various ratios of pinhole defects and different magnitudes of thickness errors can be randomly inputted to analyze the influence of these factors on the film transmittance and OD value; in addition, the error factors can be further increased, and the model can be optimized. The existing commercial thin-film structure design software (such as TFCalc, OptiLayer, and Macleod) can only calculate one condition (which means that the mesh number is limited to 1 × 1) and cannot generate error factors quickly and randomly, which is another advantage of the proposed model.

The high OD value filters were deposited using a high-power microwave plasma-assisted reactive sputtering technique. The advantages of this coating system are as follows: 1) The surface of the substrate can be cleaned by bombarding with a high-power microwave source before deposition; 2) The Nb_2O_5 and SiO_2 films can be deposited more compactly by separating the deposition area (in front of the target) and the reaction area (in front of the microwave source) during the preparation process; 3) The film thickness error can be strictly controlled using a double-crystal in-situ monitoring technique.

By comparing the experimental and simulation results, we found that the pinhole defect and film thickness error can reduce the passband transmittance of the optical filter and change the width and position of the blocking band, thus affecting the OD value. The film thickness error has a significant influence on the transmittance value of the passband, because the accumulated physical thickness error leads to a change in the phase difference; however, the influence on the OD value is less. The pinhole defect reduces the deviation between the high and low refractive index values, thus shortening the width of the rejection band. Further, pinholes can reduce or even break down the periodic structure of the filters. This reduces the passband transmittance and decreases the OD value of the blocking band rapidly. Notably, defects (such as nodules and dust) introduced during the preparation process can be equivalent to the approximation of local nonuniformity and pinholes. Therefore, to deposit optical filters with a high OD value, it is necessary to obtain thin films with a dense structure and a stable thickness, also avoid contamination.

5. Conclusion and further works

A 3D mesh model of a high OD filter was established based on MATLAB, and the influence mechanism and degree of pinhole defects and uniformity on its transmittance and OD value were studied. The uniformity was found to mainly affect the passband transmittance of the multilayer films but had little effect on the OD value in the blocking band. In contrast, pinhole defects were the main factor that decreased the OD value in the blocking band. An LPF with a high OD value was prepared on fused silica using a high-power microwave plasma-assisted reactive sputtering technique. A denser structure was obtained by separating the reaction and deposition zones during the deposition, and the thickness was accurately controlled by using a double-crystal monitor system. The average OD values of the prepared LPF in the bands 527–532 and 755–833 nm were 8.832 and 10.191, respectively. The deviations from the designed data were 1.074 and 0.295, respectively. Compared with the experimental and simulation results, the prepared LPF exhibited a uniformity error of approximately ±1% and a pinhole ratio of 0.5%.
In conclusion, we believe that a clean operating environment is a prerequisite for preparing high OD filters. Moreover, it is important to improve the densification of the thin films. The nonuniformity of the layer and thickness error will decrease the transmittance over the passband. This study can serve as a basis for the preparation of high OD filters.

Further improvements will be made to modify the pinhole model with a random shape and introduce some new defects, such as nodules and dust, for a comprehensive analysis, so that we can obtain results closer to the actual situation.

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**References**


