Band filters: two-material technology versus rugate

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We demonstrate theoretically and experimentally a band filter with two reflection and broadband transmission ranges, which was obtained with standard two-material technology. The fabricated filter has transmission and reflectivity characteristics better than those achievable with rugate technology. © 2007 Optical Society of America

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1. Introduction and Formulation of the Problem

Band filters with ranges of reflectivity at ~100% and broad ranges of high transmission have practical importance in scientific and technological applications. For clarity, let us consider a band filter, which suppresses the third-, fourth-, and fifth-harmonic orders and reflects the first-harmonic order. Rugate technology (RT),[1–4] even in the presence of well-developed standard two-material technology (S2MT), is now considered to be a way of producing filters of such a type.[5–7] RT relies, in principle, on an infinite number of materials with continuously varying refractive indices.[8] The main advantage of RT is the fact that such a refractive index profile provides fewer parasitic reflections from interfaces between low-refractive index material and high-refractive index material layers. Disadvantages of RT consist of difficulties in controlling the properties of slowly varying materials during the coating procedure,[6] whereas in S2MT, the material properties are well defined and can be controlled with high precision.[9] RT, among other technologies, has hitherto demonstrated the best capabilities in producing band filters,[6] though agreement between realization and design is not entirely satisfactory. The authors of Ref. 6 reported a 20% thickness error between design and realization. They started from rugate design and approximated it with 244 layers, of which 160 were thin.

On the other hand, the maximum principle[10] predicts that S2MT design can provide better agreement with the target spectral characteristics than RT design with both the same total optical thickness and the same given maximal and minimal refractive indices of materials. Discussions on comparison of S2MT and RT can be found in Refs. 6, 8, 11, and 12. It is critical that the S2MT band filter inevitably contains many thin layers down to several nanometers, which are quite difficult to manufacture with the necessary precision.

The numbers of layers in designs are comparable for S2MT and RT multilayer approximations, and the total optical thicknesses are similar. As shown in Section 2, the designs can consist of up to 200 layers.

Old coating techniques and types of control did not allow manufacture of such complex error-sensitive designs. As shown in Ref. 9 optical control of thin layers is practically impossible with one-wavelength monitoring systems and is quite difficult in the case of broadband monitoring.[6] The reason for this is the high ratio of the monitoring wavelength to the thin layer thickness, which can be of the order of 100. Variations of the optical signal on the scale of the layer thickness are therefore small, and the deposition error is large. For the magnetron sputtering deposition technique used in this work to produce the band filter, we proposed to use time control. This relies on a stable deposition rate of the process in the Helios coating machine (Leybold Optics, Alzenau, Germany).

The goal of this work was to combine the best presently available properties of S2MT in terms of design and manufacturing and demonstrate its capability in producing complex band filters with high accuracy.

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As a result, in this paper, we demonstrate the first, to the best of our knowledge, realization of a S2MT design of the band filter, which has similar optical characteristics to those demonstrated by the RT design. We would nevertheless like to emphasize that (i) no comparable RT realization has been demonstrated so far, and (ii) RT still has the potential to realize a more complex band filter than that shown in this paper.

2. Design

To compare the RT and S2MT approaches, we chose the next spectral target of a band filter (see Fig. 1): high reflectivity in the ranges of 1000–1080 and 1900–2350 nm, and high transmission in the ranges of 370–1000 and 1080–1900 nm. This target suppresses the third-, fourth-, and fifth-harmonic orders and reflects the first-harmonic order. Suppression of high-reflection bands is discussed in Refs. 13 and 14.

There are many different analytic methods of extending the transmission band by suppressing the high-reflection band (or stop band) of the structure,[13–15] but all of them show that for symmetrical structures the number of materials necessary increases as that of high-reflection band order to be suppressed. Experimental rules are found in Ref. 14 and show that the maximum number of suppressed high-reflection-band orders cannot be higher than $2m - 3$, where m is the number of different materials. For suppression of third-, fourth-, and fifth-harmonic orders at least three materials are needed. To reduce, then, the number of materials necessary to two, which is tolerable for standard coating technologies, we replaced a layer of one material with an intermediate refractive index by a combination of layers with high- and low-refractive indices. Usually the total optical thickness of these layers is equal to that of the layer with an intermediate refractive index. Unfortunately, because of this procedure, thin layers appear. Qualitatively, the appearance of new thin layers can be understood in terms of the optical thickness of an intermediate layer being divided by n, where n is the number of new layers with high- and low-refractive indices. These new thin layers are difficult to control with known old coating machines, but it becomes possible to control them with the new technique and machine described in Section 3.

The commercial optimization program in Ref. 16 was used to design the band filter on the base of S2MT and RT.[4] The S2MT solution was found without any starting design using one of the versions of the needle optimization technique.[17] The design consists of 182 Ta_2O_5/SiO_2 alternating layers. The designed spectra of the filter for both technologies are shown in Fig. 1.

The merit function for the rugate filter is 1.58, and for the S2MT filter, it is 1.56. We define the merit function as

$$F = \frac{1}{L}\sum_{j=1}^{L}\left(\frac{R_p(\lambda_j) - R^{(j)}}{\Delta R^{(j)}}\right)^2, \qquad (1)$$

where $R_p(\lambda_j)$ is the theoretical reflection characteristic at wavelength λ_j, $R^{(j)}$ is the target reflection value, $\Delta R^{(j)}$ is the corresponding tolerances, and L is the number of selected wavelength points. The merit function shows how close to the target we are. A smaller value of the merit function shows that we are closer to the target, and so a design with a smaller merit function is better. From Fig. 1 and the merit function data, we concluded that the maximum principle works quite well, and for the same refractive index limits and the same optical thicknesses, the S2MT design demonstrates slightly better optical characteristics (namely, the reflectivity is closer to the target) than the RT design. It does not mean, of course, that there are no better designs than those realized. Here we would like to emphasize that comparison of the designs was made on the equivalent base (i.e., materials, total optical thickness, and optimization algorithm).

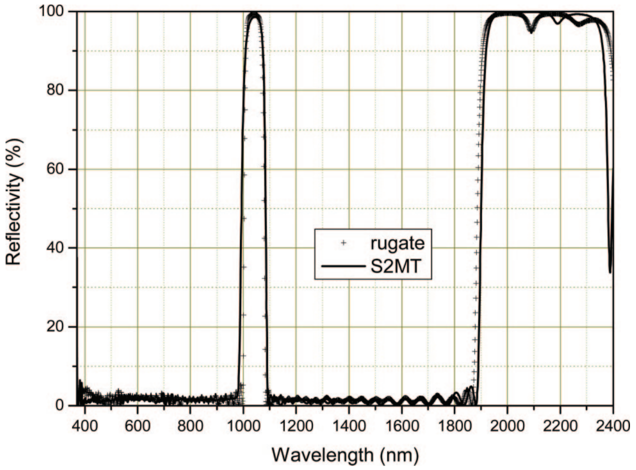
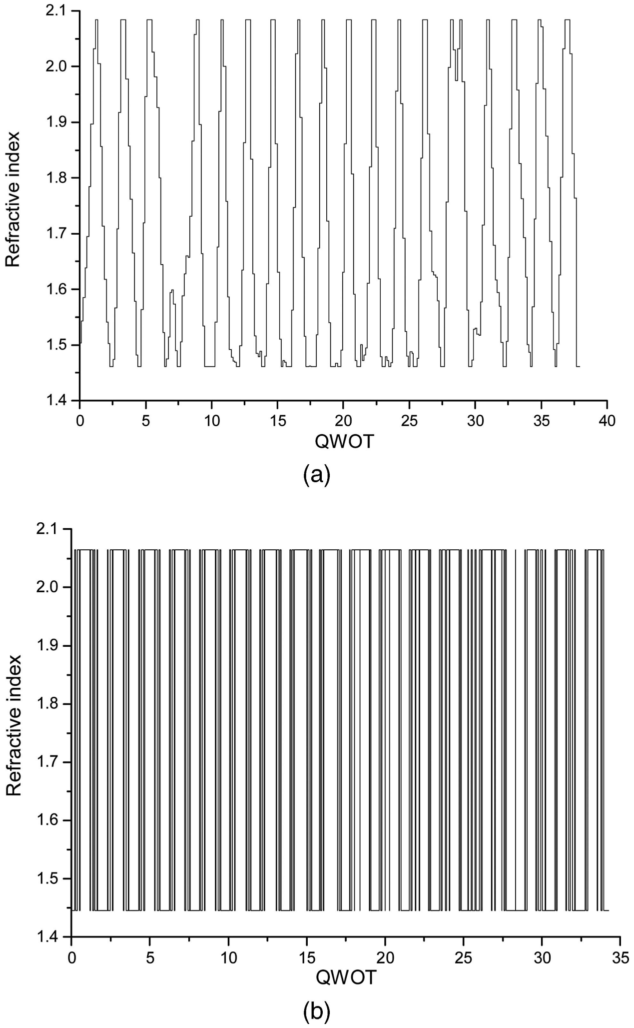


Fig. 1. (Color online) Designed spectrum of the band filter for the RT (plus sign) and S2MT (curve) technologies. The calculations include only one surface of a BK7 substrate.

An important question is which design is more difficult to realize? A comparison of the designs in terms of their sensitivity to the manufacturing error is a critical point. The S2MT design [Fig. 2(b)] contains many thin layers sensitive to manufacturing errors. Nevertheless, the S2MT filter is less sensitive to deposition errors than a broadband chirped mirror that was successfully realized in Ref. 9. The refractive index profile of the RT filter, shown in Fig. 2(a), is sensitive to the period error, though it is rather insensitive to errors in the absolute values of the refractive indices.

3. Experiment

In the past 10 years, two coating technologies, magnetron sputtering[9] and ion-beam sputtering, capable of controlling thin layers (an example is chirped mirrors) have been successfully applied. Due to the stable deposition rate, the magnetron sputtering and ion-beam sputtering technologies enable one to control some or all layers by the time-control technique.



(a)

(b)

Fig. 2. Refractive index structures of the (a) RT (left) and (b) S2MT (right) filters. QWOT, quarter-wavelength optical thickness. The central wavelength is 2170 nm.

In this work, we used the magnetron sputtering Helios coating machine (Leybold Optics) for producing the band filter. This machine has a stable sputtering rate, which allowed time control to be used. The time-control procedure is described in detail in Refs. 9 and 18. Manufacture shows that the S2MT design can be realized with high precision so that the designed and measured spectral characteristics in Fig. 3 are close.

The design of the S2MT filter consists of many thin layers (5–20 nm thick), which may have optical properties other than those of thick films and bulk material. Nevertheless, the similarity of the two curves in Fig. 3 convinces us that the refractive indices of thin layers produced with magnetron sputtering technology are close to the theoretical data used in the design procedure. The deposition errors are small and have no influence on the final result even for the complex S2MT design. Analysis shows that the estimated total average error in the layer thickness relative to the design is 0.3% if we assume equal errors or 3% if we assume noncorrelated errors. The error analysis was made by using a standard procedure included in the OPTILAYER software.[16]

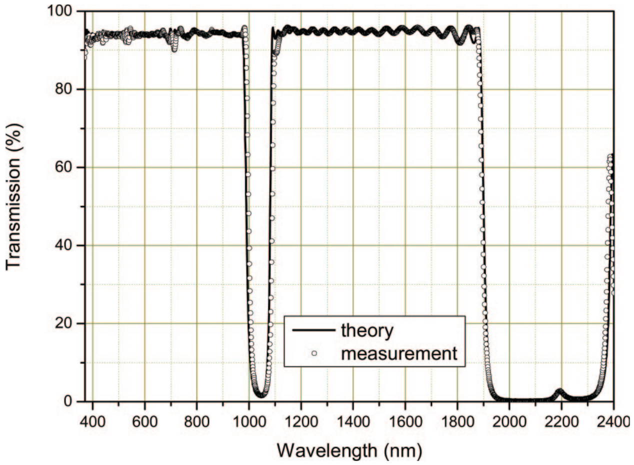


Fig. 3. (Color online) Design (curve) and measurement (circles) of the S2MT filter. The measurement and calculation include the backside of a BK7 substrate.

4. Conclusion

The S2MT band filter was designed by the needle optimization technique and manufactured with magnetron sputtering technology. Its properties are better than the design properties of the RT filter.[10] Experimental data show stability of the S2MT design and high manufacturing accuracy. Further realizations of the RT filter are needed to demonstrate its competitiveness in relation to the S2MT filter demonstrated in this paper.

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