Long-wavelength polarizing cutoff filters for the 275–550-nm spectral region

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The design and manufacture of a multiple-reflection-type multilayer element is described that efficiently removes all wavelengths higher than 550 nm from the incident radiation and that at the same time acts as a polarizer in the 275–550-nm spectral transmission region. © 2002 Optical Society of America

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1. Introduction

The Atmospheric Environment Service, Downsview, Canada, is constructing an instrument that consists of an ultraviolet (275–550-nm) and a visible (500–1000-nm) spectrograph. In this instrument there is a need for a cutoff filter that transmits in the 275–550-nm spectral range and that removes light of longer wavelengths. There is also a need for a polarizer for the transmitted radiation.

Thin-film long-wavelength cutoff filters that transmit the 275–550-nm spectral region are difficult to design by conventional means. First, there are not many coating materials with high refractive indices that transmit in this region. Coating materials that were used for this purpose in the past include Sc_2O_3 ($n = 1.88$ at $\lambda = 385$ nm), Ta_2O_5 ($n = 2.22$), and Al_2O_3 ($n = 1.67$). Second, if contiguous quarter-wave reflector stacks are used to produce the rejection, secondary reflection maxima will occur in the intended transmission region. This is so because the ratio of the wavelengths of the high and low rejection limits is high. Thelen[1] has shown that higher-order reflection bands can be suppressed through the use of three or more different materials. However, such solutions consist of more layers and are difficult to implement for the ultraviolet spectral region.

MacNeille-type polarizers[2,3] for the 275–550-nm spectral region can be readily designed. They are composed of a number of contiguous quarter-wave stacks sandwiched between two right-angled quartz prisms. The number of contiguous stacks, the total number of layers, and the angle at which the incident radiation falls onto the hypotenuse bearing the films all depend on the refractive indices of the coating and prism materials, and, for this spectral region, the total number of layers required will also be high. For example, a solution based on Sc_2O_3 and SiO_2 between quartz prisms may consist of three contiguous quarter-wave stacks with a total of 52 layers, and the incident radiation will fall onto the films at an angle of 51.57°. When the expensive Sc_2O_3 material is replaced by the lower-refractive-index Al_2O_3, the total number of layers required for a similar performance will be even larger. The solution requires the use of an ultraviolet-transmitting optical cement.

2. Multiple-Reflection Filters

An unconventional but highly effective approach to the solution of the cutoff filter problem can be based on multiple reflections (see, for example, Ref. 4). In Fig. 1 are shown two four-reflection arrangements in which the emergent beam is collinear with the incident beam. (Of course, arrangements with a different number of reflections are also possible). In Fig. 1a identical multilayer coatings are embedded between quartz prisms, whereas in Fig. 1b the multilayers are deposited onto the front surfaces of flat plates. The throughput of such devices is equal to R^4, where R is the reflectance of a single coating, so the attenuation of the incident light will be low wherever the reflection is high, and, conversely, it will be quite high at wavelengths where the reflection is low. For best results the light that is transmitted by the multilayer coatings should be removed in some way so it will not return into the propagating beam on

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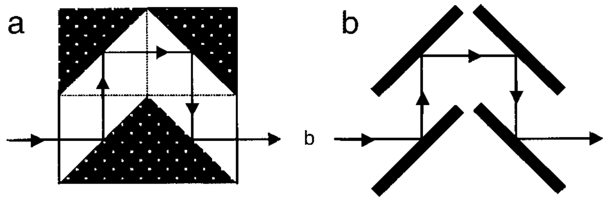

Fig. 1. Four-reflection arrangements based on (a) 45° prisms and (b) plates.

reflection from any other surface. One can do this in one of several ways:

(a) By departing from right-angled prisms or parallel plates, such that there is an angular separation between the transmitted and the backreflected beams,
(b) By painting the outside surfaces of the shaded prisms with a black paint or by applying black layer coatings to those surfaces;
(c) By making the shaded prisms or the plates from black glass;
(d) By incorporating a black layer coating into the special multilayer.

This technique was used previously for the extraction of relatively narrow bands of wavelengths in spectral regions where the same goal cannot be achieved by more-conventional means because of a lack of suitable coating materials.[5] It is not commonly used because it requires more space than a conventional transmission filter.

Multiple reflection filters appear to be well suited for the construction of long-wavelength cutoff filters because, if a coating design is found with high reflectance in the desired transmission region and low reflectance at higher wavelengths, the long-wavelength rejection will extend throughout the spectral region for which the coating materials are substantially transparent.

If, in addition, it could be arranged that the reflectance were high in the required transmission band for only one of the two principal polarizations of the incident radiation, the same device would also act as a polarizer for the transmitted light, thus satisfying both requirements for the problem at hand.

3. Design of Polarizing Long-Wavelength Cutoff Filters

To act as a long-wavelength polarizing cutoff filter for the current problem, a multilayer coating must, for an angle of incidence of 45°, have high reflectance in the 275–550-nm spectral region, fairly low reflectance in the 550–1000-nm wavelength band for one of the polarizations, and low reflectance throughout the 275–1000-nm spectral region for light of the other polarization. With currently available substrate and coating materials it has been found easier to find a solution to this problem with the embedded multilayer geometry depicted in Fig. 1a.

A. Solution Based on Sc_2O_3 and SiO_2 Coating Materials

Because of its low absorption and relatively high refractive index in the UV region, Sc_2O_3 is the ideal material for use in the filters described above. The calculated reflectance for *s*-and *p*-polarized light and the refractive-index profile of a coating based on this material are shown in Fig. 2a. The layer system consists of 52 Sc_2O_3 and SiO_2 layers of appropriate thicknesses. In the calculations it was assumed that both coating materials do not absorb in the spectral region of interest, in accordance with published data for Sc_2O_3.[6] If such a coating were applied to the hypotenuse sides of four right-angled prisms, arranged as shown in Fig. 1a, the intensity of the light that propagates through the device would be equal to the fourth power of the reflectance (dotted curves in Fig. 2). As a result, more than 90% of the *s*-polarized light in the 275–550-nm spectral region should be transmitted, whereas less than 1% of the light in the 550–1000-nm range of wavelengths should emerge from the device. The transmittance for *p*-polarized light is less than 1% throughout the 275–1000-nm spectral range. In this and in all subsequent similar calculations it has been assumed that perfect antireflection coatings for the 275–550-nm spectral region are applied to the incident and emergent air–quartz interfaces.

B. Solution Based on Ta_2O_3, SiO_xN_y, and SiO_2 Layers

The calculated reflectance for *s*- and *p*-polarized light and the refractive-index profile of a layer system that consists of 38 layers made from Ta_2O_3, SiO_xN_y, and SiO_2 are shown in Fig. 2b. Our rationale for using three materials in this design was to take advantage of the high refractive index of Ta_2O_3 and thus to reduce the number of layers and the overall thickness of the solution. However, because the extinction coefficient of this material starts to increase at the shorter wavelengths of interest in this problem, SiO_xN_y was also used to reduce the amount of Ta_2O_3 used. The performance of this system is somewhat worse than that of the system described in Subsection 2.B, but it does consist of fewer layers and does not use the highly expensive Sc_2O_3 coating material.

C. Solution Based on SiO_xN_y and SiO_2 Layers Only

The corresponding calculated performance of a 43-layer system based on the use of SiO_xN_y and SiO_2 coating materials only is shown Fig. 2c. Although the transmittance in the passband is lower, the maximum reflectance of the radiation to be rejected is significantly lower. This should result in a significantly higher attenuation of the unwanted radiation.

D. Solution Based on Al_2O_3 and SiO_2 Layers

The final solution presented here is based on Al_2O_3 and SiO_2, and it consists of 90 layers. The refractive index of Al_2O_3 is considerably lower than those of Sc_2O_3 and SiO_xN_y, and this is why many more layers are required for high reflectance to be achieved in the 275–550-nm spectral region. The extinction coefficient of Al_2O_3 is much lower than that of SiO_xN_y, and more layers could have been used to increase the R_s reflectance in the 275–550 spectral region. However, the resultant system would have been even more complicated.

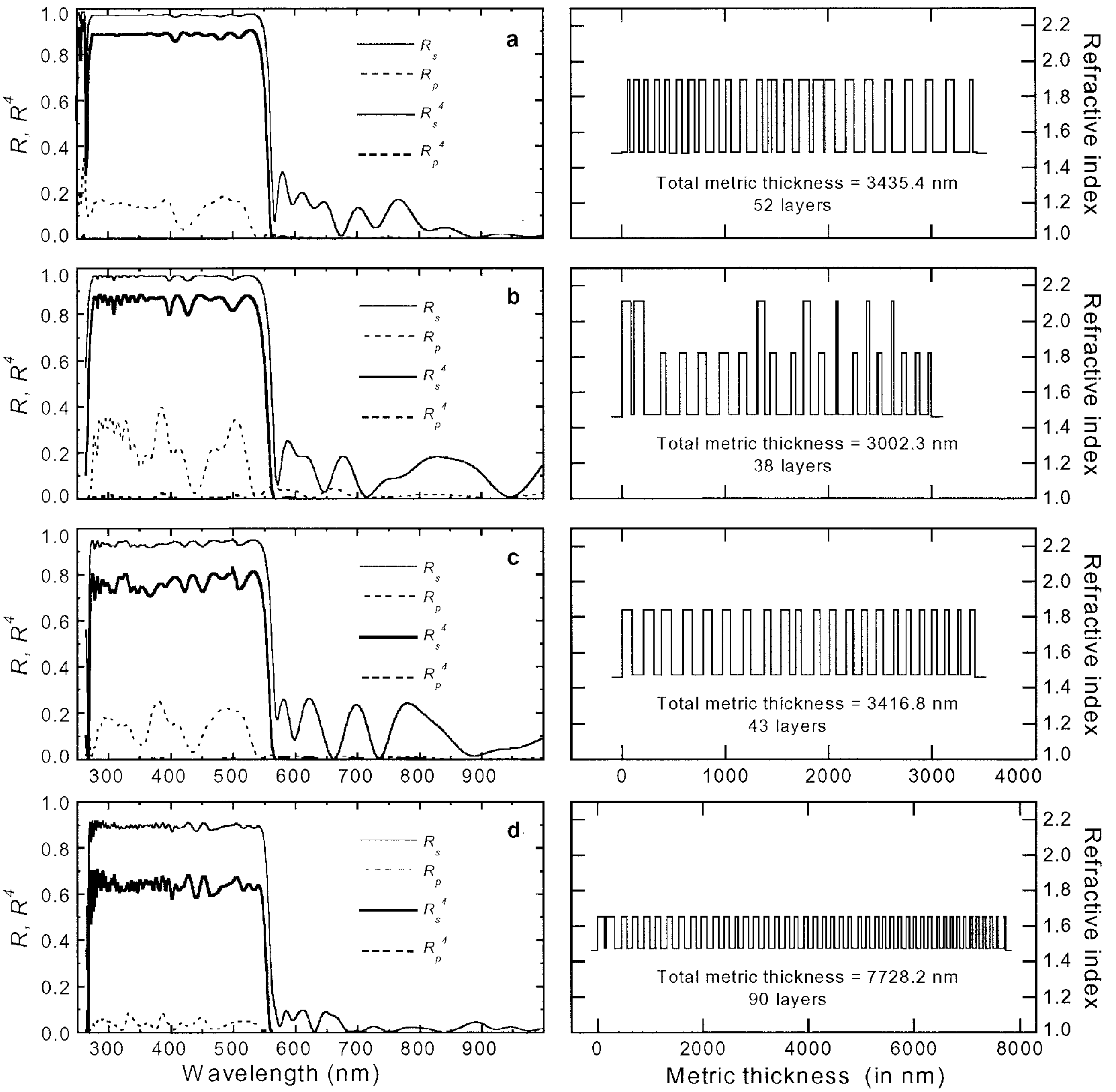

Fig. 2. Calculated reflectance and throughput ($T = R^4$) for *s*- and *p*-polarized light and the refractive-index profiles of a, a 52-layer system composed of Sc_2O_3 and SiO_2 layers; b, a 38-layer system of Ta_2O_3, SiO_xN_y, and SiO_2 layers; c, a 43-layer system of SiO_xN_y and SiO_2 layers; d, a 90-layer system of Al_2O_3 and SiO_2 layers.

4. Manufacture of a Prototype

For good results, the optical constants of all the materials used in the designs must be well known. The optical constants used in the four designs are listed in Table 1. The constants for all the materials were especially determined for this project from a combination of spectrophotometric transmission and spectrophotometric ellipsometer measurements. The exceptions are the constants for Sc_2O_3, which were determined earlier at the National Research Council of Canada from spectrophotometric transmission measurements. The layers of the multilayer systems must be deposited with higher accuracy of thickness than is possible by evaporation. The multilayers are therefore best prepared by processes such as magnetron or ion beam sputtering, which can be precisely controlled. However, targets made from scandium are excessively expensive. This is a reason why in our laboratory we decided against the implementation of the solution of Subsection 2.A.

Cheaper materials, such as Ta_2O_5, SiO_xN_y, and Al_2O_3, either have higher extinction coefficients or have refractive indices that are lower than that of Sc_2O_3 in the 275–550-nm spectral region. We decided against implementing the three-material solution of Subsection 2.B because the absorption edge of

Table 1. Optical Constants of Coating Materials Used in the Four Multilayer Designs

	Al_2O_3				SiO_xN_y		Ta_2O_5	
Wavelength (nm)	n	k	Sc_2O_3[a]	SiO_2[a]	n	k	n	k
280	1.717	0.0012	1.935	1.509	1.951	0.0069	2.456	0.0441
300	1.704	0.0008	1.920	1.502	1.923	0.0044	2.386	0.0065
320	1.693	0.0006	1.911	1.496	1.903	0.0030	2.331	0.0012
340	1.685	0.0004	1.904	1.492	1.887	0.0022	2.288	0.0002
360	1.679	0.0003	1.896	1.489	1.876	0.0016	2.254	0.0001
380	1.673	0.0003	1.888	1.486	1.867	0.0012	2.226	0.0000
400	1.669	0.0002	1.880	1.484	1.860	0.0009	2.203	0.0000
450	1.660	0.0001	1.870	1.479	1.847	0.0006	2.160	0.0000
500	1.654	0.0001	1.860	1.475	1.840	0.0004	2.148	0.0000
550	1.650	0.0001	1.850	1.473	1.838	0.0005	2.137	0.0000
600	1.647	0.0001	1.840	1.471	1.834	0.0004	2.127	0.0000
650	1.644	0.0001	1.835	1.469	1.830	0.0003	2.119	0.0000
700	1.643	0.0000	1.830	1.468	1.827	0.0002	2.112	0.0000
750	1.641	0.0000	1.829	1.467	1.825	0.0002	2.105	0.0000
800	1.640	0.0000	1.830	1.466	1.823	0.0002	2.100	0.0000
850	1.639	0.0000	1.830	1.466	1.822	0.0002	2.094	0.0000
900	1.638	0.0000	1.830	1.465	1.821	0.0001	2.090	0.0000
950	1.637	0.0000	1.830	1.464	1.820	0.0001	2.086	0.0000
1000	1.637	0.0000	1.830	1.463	1.819	0.0001	2.082	0.0000

[a] Values of n; the value of k in all cases is 0.0000.

the Ta_2O_5 is too close to the 275-nm wavelength. It is difficult to reproduce experimentally the same value of the extinction coefficient from run to run close to the absorption edge. A change in the value of a significant extinction coefficient can give rise to sharp absorption bands in the region where high reflectance is required. This complicates the manufacture.

We also decided against manufacture of the Al_2O_3 and SiO_2 layer system of Subsection 2.D because of the large number of layers that would be required. This left the system of Subsection 2.C based on SiO_xN_y and SiO_2 layers.

The equipment used for the manufacture of the prototype was an AC magnetron sputtering system of the type described in Ref. 7. The automatic process control, the real-time parameter determination, and the reoptimization of the remaining layers proceeded in the manner described in the same paper. The process parameters for the deposition of the SiO_xN_y were as follows: The layers were deposited in an argon–nitrogen–oxygen gas mixture. The refractive index and the extinction of the SiO_xN_y layers were highly sensitive to the oxygen partial pressure. For the composition required in this multilayer, the following gas flow ratios were used: Ar flow:N_2 flow:O_2 flow::11.3:24.0:1.0. Multilayers were deposited simultaneously upon 2 cm × 2 cm quartz prisms and plates to facilitate the measurements.

5. Measurements of Experimentally Produced Coatings

All the normal transmittance measurements of the multilayer layer samples on plates were performed with a Perkin-Elmer Lambda 19 spectrophotometer. Measurements involving polarized light were made with a J. A. Woollam VASE 250-1800 variable-angle spectroscopic ellipsometer. The measurement geometries used during the evaluation of the coatings are shown in Fig. 3. First, the normal-incidence transmittance (Fig. 3a) of the coating upon a quartz plate was compared with the calculated transmittance. The results of this measurement are shown in Fig. 4a. The agreement throughout the spectrum of interest is excellent, which implies that the optical constants of the coating materials are well characterized and that the process control for the layer thicknesses was good.

Next, the reflectance of a single cube was measured. Because optical cements do not exist that are transparent throughout the spectral region of interest, it was necessary to use a contact liquid. One coated and one uncoated prism were held together with a few drops of glycerin, and we measured the

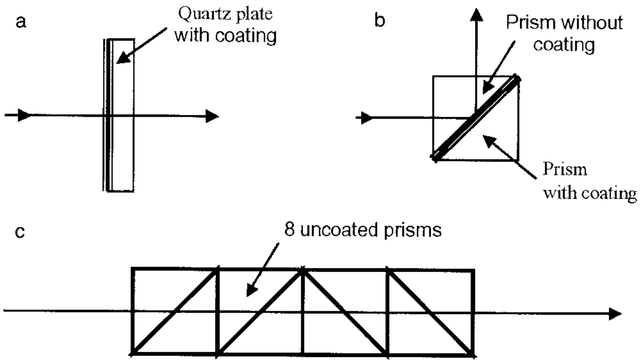

Fig. 3. Schematic diagrams of preliminary measurement setups for a, a single coating upon a quartz plate at normal incidence of light; b, a single coating embedded between two quartz prisms; and c, determination of the correction factor for eight uncoated prisms in series with thin glycerine layers between prism surfaces.

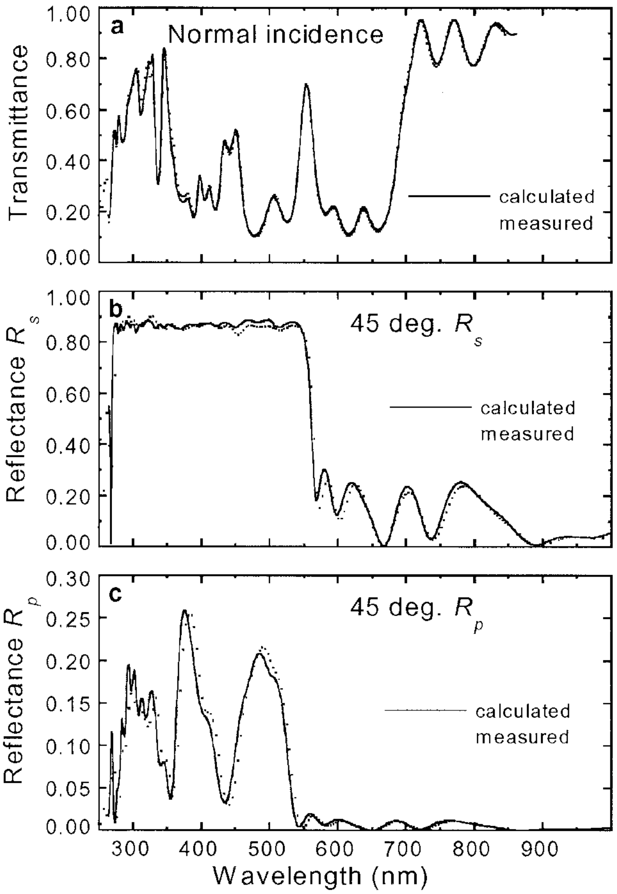

Fig. 4. Comparison of calculated and measured performances of a single coating of the type shown in Fig. 2c: a, deposited onto a quartz plate in air for normal incidence of light; b, c, embedded between two quartz prisms, with glycerin as a contact liquid, for light incident at 45° for *s*- and *p*-polarized light, respectively.

reflection for *s*- and *p*-polarized light by using the geometry of Fig. 3b. The results of these measurements are shown in Figs. 4b and 4c. The agreement between the calculated and the measured curves is still good, although there is a slight displacement of the measured curves toward longer wavelengths.

Before measurements were performed on a completely assembled device consisting of four cubes (Fig. 1a), a calibration transmission measurement was performed on a train of eight uncoated prisms contacted to one another with the aid of thin glycerin films (Fig. 3c). The measured transmittance for *p*- and *s*-polarized light is shown in Fig. 5. It can be seen that the glycerin–prism combination does absorb a finite amount of the UV radiation in the spectral range of interest and that the absorption is different for the *s*- and the *p*-polarized light. To compensate for the loss in the prisms and glycerin we multiplied the calculated curves for the final device by these curves before comparison with the measured throughputs shown in Figs. 6a and 6b for *s*- and *p*-polarized light, respectively. A correction based on the throughput of a train of eight uncoated prisms may not be strictly applicable to the folded configuration, but it was deemed to be better than no correction at all. The agreement between the calculated and measured data in Fig. 6 is reasonable. The main difference between the measured and the calculated curves in the 400–500-nm spectral region corresponds to a smaller departure in the same region for the single cube seen in Fig. 4b, and this illustrates well the amplification of small errors through the multiple reflections. The departure between the calculated and the measured throughput for *p*-polarized light at wavelengths lower than 375 nm is as much as 0.4% and is probably due to the to the difficulty of making accurate measurements at such short wavelengths.

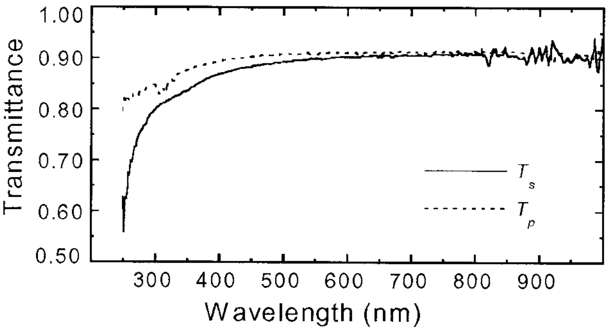

Fig. 5. Transmittance for *s*- and *p*-polarized light of a train of eight uncoated quartz prisms arranged as in Fig. 3c.

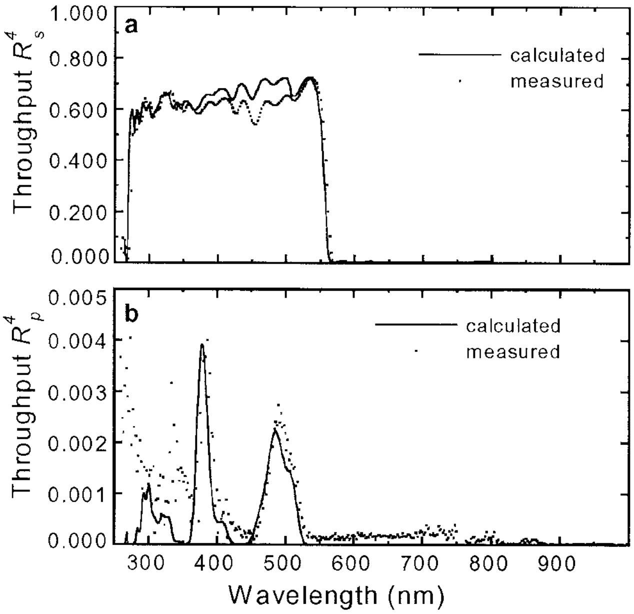

Fig. 6. Comparison of calculated and measured throughputs of an eight-prism device of the type shown in Fig. 1a for a, *s*- and b, *p*-polarized light.

6. Conclusion

Using multiple reflections is an efficient way of designing long-wavelength cutoff filters that are effective over a wide range of wavelengths and that consist of a moderate number of layers. If materials with suitable refractive indices are chosen, it is also possible to design a device that at the same time acts as a good polarizer. It has been demonstrated that the complex multilayers required for this purpose can be deposited with sufficient accuracy. However, there is a need for a careful determination of the optical constants of the coating materials and a well-controlled deposition process. The device was designed for a specific application, and this determined the 275–1000-nm spectral region of the device's operation. It is the use of this spectral region that has made the problem difficult. First, there is a lack of transparent cements for this spectral region. This is why, for the construction of the prototype, a contact liquid was used, but this liquid is not a practicable option for space equipment. One way to overcome this problem is to reduce the number of interfaces by constructing the device from two identical rhombs and to place them in optical contact after coating. Alternatively, if good antireflection coatings for the 275–550-nm spectral region can be designed, there is no need for optical contact of the two rhombs. A third option is to hold the two components mechanically in close proximity without the use of antireflection coatings: Air gaps of the order of 20 nm introduce a one-time loss in transmittance of less than 3%. A further advantage of the use of fewer components is that the not inconsiderable problem of proper alignment is also reduced.

Second, as stated above, there is a lack of high-refractive-index coating materials for this spectral region. There is no doubt that similar devices for the visible and infrared parts of the spectrum would be much easier to design and construct because the problems associated with the lack of optical cements and high-refractive-index coating materials would disappear.

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