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Implementation of long-wavelength cut-off filters based on critical angle

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Our first attempts at the fabrication of long-wavelength infrared cut-off filters with extended transmission and rejection regions that are based on the use of the critical angle, the dispersion of refractive indices, and on thin-film interference were not very successful. The design of the filter consisted of layers placed at the interface between two high-index prisms. Using the available deposition equipment, the layers produced were porous and very rough. The pores adsorbed water vapor, which resulted in absorption. The roughness made the process of optical contacting very difficult. In this paper we describe the adjustments in the design and deposition processes that allowed us to obtain filters with a better and more stable performance.

OCIS codes: 120.2440, 260.2030, 310.6860, 260.6970, 310.1860, 240.1485.

1. Introduction

In 1999 we described a new type of long-wavelength cut-off filter that was based on thin film interference and critical angles as well as on the use of at least one material with a rapid variation of the refractive index with wavelength [1]. Examples of materials with such behavior are, for example, some transparent conducting coatings and Reststrahlen materials. Layers of these materials need to be embedded between two high-refractive-index prisms, together with layers made of a second material whose purpose is to suppress reflection within the pass band of the filter. The rejection region is caused by a combination of reflection, absorption, and critical angle effects. Because of the high-refractive index of the prisms, the best method for combining the two prisms is through optical contacting. A detailed description of the theory of such filters and some numerical results for devices based on indium tin oxide (ITO) and magnesium oxide layers can be found in [1,2].

A tolerance analysis of our original ITO-based system indicated that the performance of the designs based on this principle would be very insensitive to film thickness variations but quite sensitive to variations in the optical constants [1]. Published data showed that the optical constants of ITO layers depend critically on the doping level and on the process used for their production. We therefore felt that it would be easier to verify experimentally our numerical results by constructing a device based on MgO, a material with a simple stoichiometry and a Reststrahlen reflection peak in the 22 μm spectral region and a refractive index that increases significantly at shorter wavelengths.

In Section 2 of this paper we describe our first attempt at producing such a filter. In Section 3, the results of our second attempt are presented. This is followed by some conclusions in Section 4.

2. First Deposition Attempt

The refractive index profile of the long-wavelength cut-off filter that we decided to produce is shown in Fig. 1(a). As already mentioned in the Introduction, the material in which the critical angle occurs is MgO. The high-refractive index layers are made of

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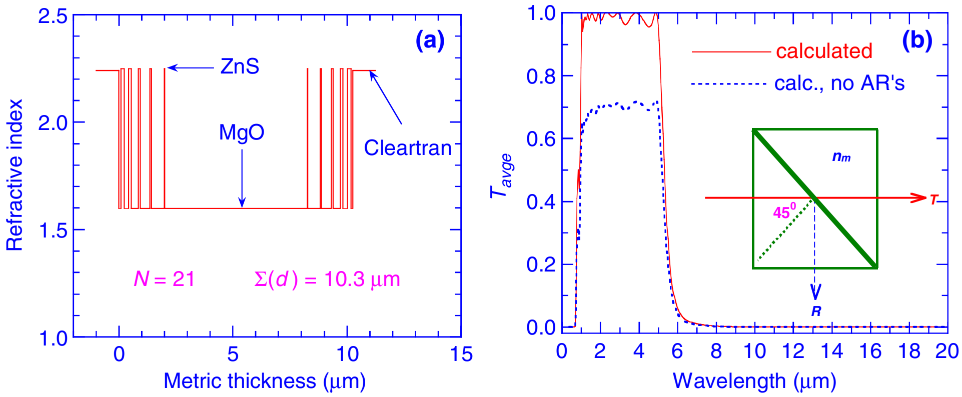

Fig. 1. (Color online) Long-wavelength infrared cut-off filter based on 21 layers of MgO and ZnS placed between two Cleartran prisms. (a) Refractive index profile, (b) calculated transmittance for light of average polarization. Also shown is the effect of non-antireflection- (AR-) coated prism surfaces on the transmittance.

zinc sulfide, and in combination with the low index layers they acted as antireflection coatings for the pass band region. The multilayer consists of 21 layers with a total metric thickness of 10.3 μm and is sandwiched between two right-angled Cleartran prisms. Cleartran is a chemically vapor-deposited ZnS material that is transparent throughout the visible and near-infrared parts of the spectrum [3]. To reduce the deposition time, the thin-film design was intentionally symmetrical, so that half the system could be deposited in one run onto two identical prisms that were later contacted to each other. The optical constants of the coating materials used in the calculations are given in Fig. 2(a). They were obtained from measurements with visible and infrared spectrophotometic ellipsometers of single layer samples.

The calculated average transmittance of this filter for both polarizations is shown in Fig. 1(b). It was shown in our previous paper that there is very little polarization dependence of these curves in the cut-off and rejection regions [1]. Also indicated in this diagram is the expected transmittance of the system when the outer surfaces of the prisms are not provided with antireflection coatings. Figure 3 shows the calculated error corridors resulting from 10% relative and 10 nm absolute random thickness variations in all the layers [Figs. 3(a) and 3(b)] and for 0.1% and 0.01% absolute random variations in the refractive indices of the ZnS and MgO materials [Figs. 3(c) and 3(d)]. These corridors were calculated from 50 randomly generated layer systems with the above errors and indicated that with such random errors, one would expect the transmittance curves of 66% of the experimentally produced coatings to fall within the corridors. These results confirm for the MgO case once again the conclusions we drew in [1] concerning the sensitivity of the designs to thickness and optical constant variations.

In Fig. 4(a) we show the dependence of the design depicted in Fig. 1(a) on the angle of incidence. As can be seen from this diagram, a limited tuning of the cut-off wavelength is achieved by adjusting the angle of incidence of the light on the coatings. However, this also results in the deterioration in the performance of the filter if convergent light is used [see Fig. 4(b)].

Because of the use of ZnS layers, magnetron sputtering, which usually results in very accurate and dense layers, could not be used for this project because our sputtering systems cannot deposit ZnS layers. The only equipment available in our laboratory in which MgO and ZnS could be deposited in one run was an electron beam evaporation system

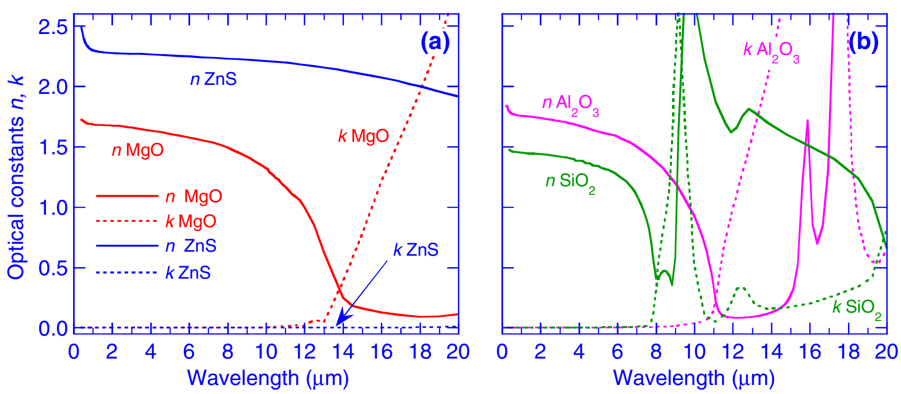

Fig. 2. (Color online) Optical constants of the coating materials used in the calculations in this paper. (a) Experimentally determined optical constants of MgO and ZnS, (b) optical constants of Al_2O_3 and SiO_2 taken from Palik's books [10,11].

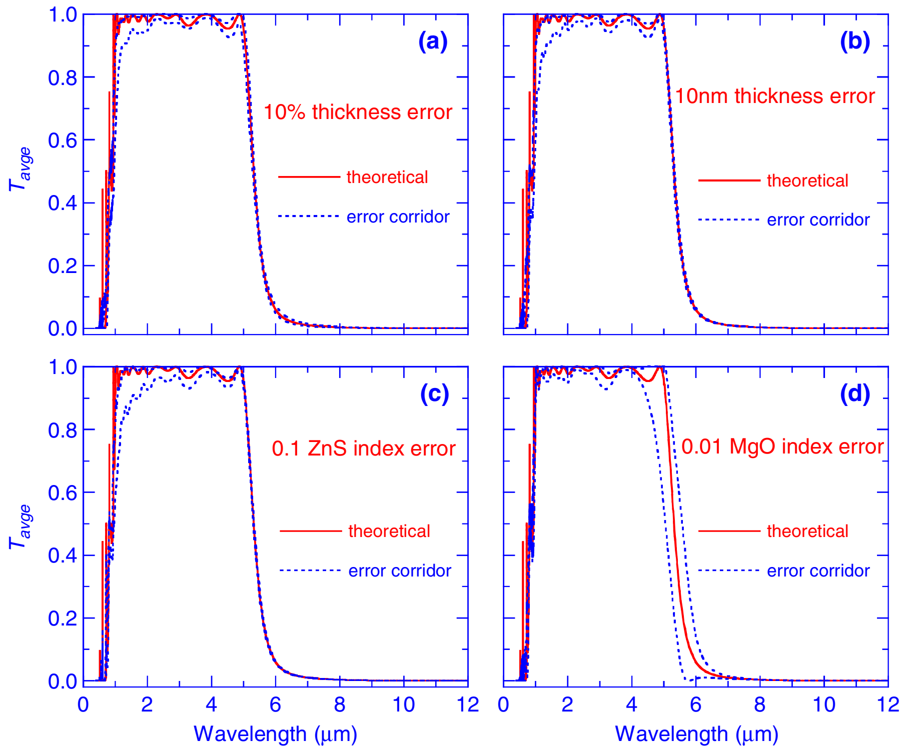

Fig. 3. (Color online) Error corridors resulting from 10% and 10 nm random variations in the thicknesses of all the layers (a), (b) and for 0.1 and 0.01 random variations in the refractive indices of ZnS and MgO, respectively (c), (d).

equipped with an ion source (Balzers BAK 760 box coater with a 980 cm diffusion pump). ZnS is quite dense when evaporated at room temperature but MgO is not [4]. Raising the substrate temperature to 250° was not very effective in reducing the porosity of the MgO layers and, in addition, it reduced the sticking coefficient for the ZnS layers [5]. To obtain nonabsorbing MgO films, a residual atmosphere of 6×10^{-5} Torr of O_2 was required. Unfortunately, the lifetime of the ion gun filaments under these conditions was shorter than the time required for the deposition of this thick-layer system, and so the MgO layers had to be evaporated without ion-assist.

Our first experimental results presented at the 2007 Optical Interference Coatings conference were rather disappointing [6]. One reason was that the rough surfaces of the resulting multilayer made it difficult to optically contact the two coated prisms afterwards. Figures 5(a) and 5(b) show the rms surface roughness measured for the surfaces of BK7 witness glasses without and with the multilayer that was deposited onto the Cleartran prisms during the first attempt. The witness glass was placed next to the prisms, so that it received the same coating. One can see that after the coating the RMS roughness increased from 14.8 nm to a value of 28.6 nm. Even after some light polishing the two coated prisms could not be contacted without the use of a few drops of liquid acetone.

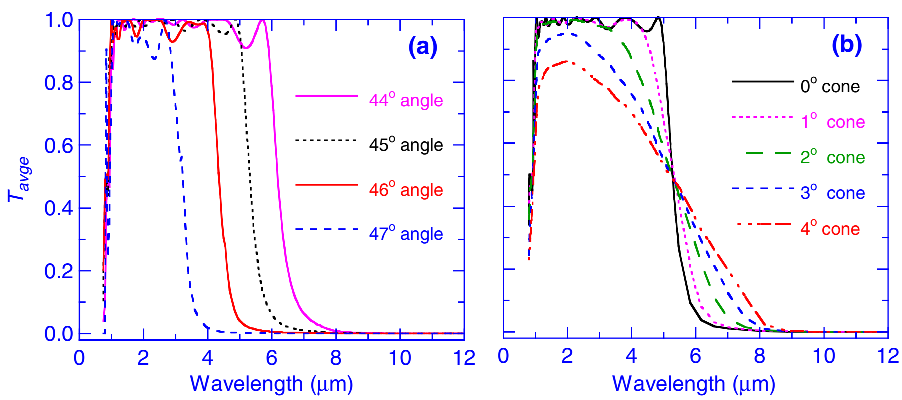

Fig. 4. (Color online) Angular performance of the design of Fig. 1. (a) Variation of cut-off wavelength with angle of incidence, (b) effect of convergent light.

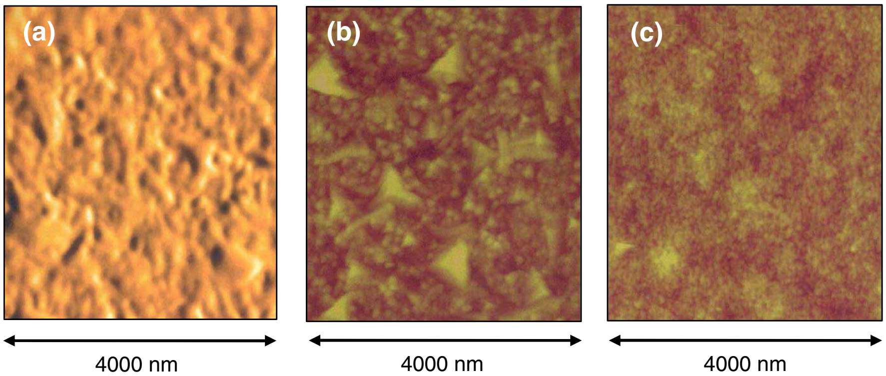

Fig. 5. (Color online) Surface roughnesses of multilayer coatings. (a) Witness glass without any coatings (RMS roughness 14.8 nm), (b, c) witness glasses with the coatings deposited during first and second manufacturing attempts had RMS roughnesses of 28.6 and 2.96 nm, respectively.

In addition, the MgO layers that made up most of the layer system were porous and adsorbed water vapor. This gave rise to a significant absorption in the near infrared spectral region. The average transmittances for *s*- and *p*-polarized light of the filter produced under these conditions were measured for several angles of incidence both on a Nicolet FTIR Magna IR 550 series II spectrophotometer with a divergent beam and on a Woollam IR variable angle spectrophotometric ellipsometer with a collimated beam. However, here we only present the ellipsometer data because they are more accurate for our angle sensitive filters (see Fig. 4). In Fig. 6 we compare the expected performance (a) at the design angle with the ellipsometric measurement (b). As mentioned before, this performance was less than satisfactory.

3. Second Deposition Attempt

It followed from the above that the two problems to overcome were the absorption of the water vapor in the MgO films and the excessive roughness that prevented an easy optical contacting of the coated prisms. Ritter in 1976 reported that Al_2O_3 forms dense, amorphous coatings even when evaporated onto room temperature substrates [7]. In the past, Al_2O_3 has been used for enhancing the adhesion of evaporated films to substrates, as well as smoothing layers and, more recently, to prevent the breakup of thick MgF_2 layers [8]. We found that when Al_2O_3 layers of approximately 80 nm thicknesses were deposited on porous coatings in the presence of an ion beam, they sealed the pores against moisture penetration as well as smoothed the surface of the coating and thereby interrupted the conical growth within the MgO layer. This resulted in much smoother surfaces. Such thin thicknesses of Al_2O_3 layers were relatively small compared to the total thickness of the MgO layer so that their absorption in the long-wavelength region did not seriously impact the performance of the system.

The ease with which flat surfaces can be optically contacted also depends to a certain extent on the materials of the surfaces that are to be joined. We therefore also investigated numerically the effect on the performance of the layer system with three different thin layers of different materials placed at the center of the MgO layer. The materials chosen for these calculations were ZnS, air, and SiO_2. In each case, it was assumed that the total metric thickness of the layers in the contacted systems was 60 nm. In the case of the air gap, the optical contacting would take place on special small contact areas made of silica layers and placed at the edges of the prisms (see [9]). The refractive index profiles and the calculated

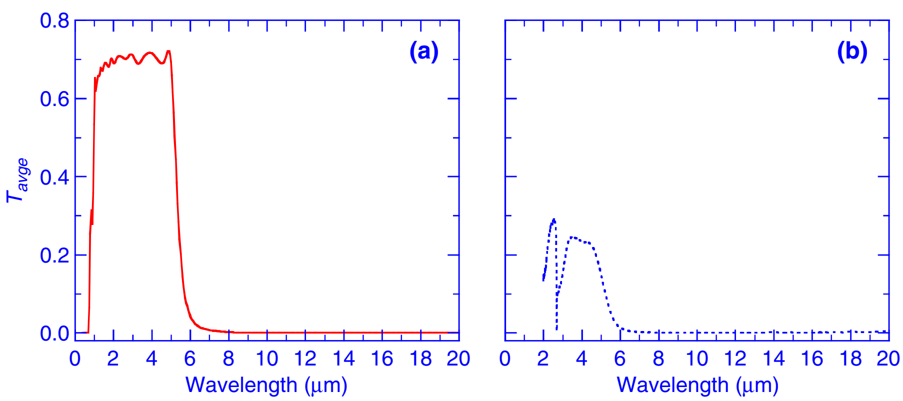

Fig. 6. (Color online) Comparison of (a) the calculated expected and (b) the ellipsometrically measured performances of the first attempt of the manufacture of the IR long-wavelength cut-off filter.

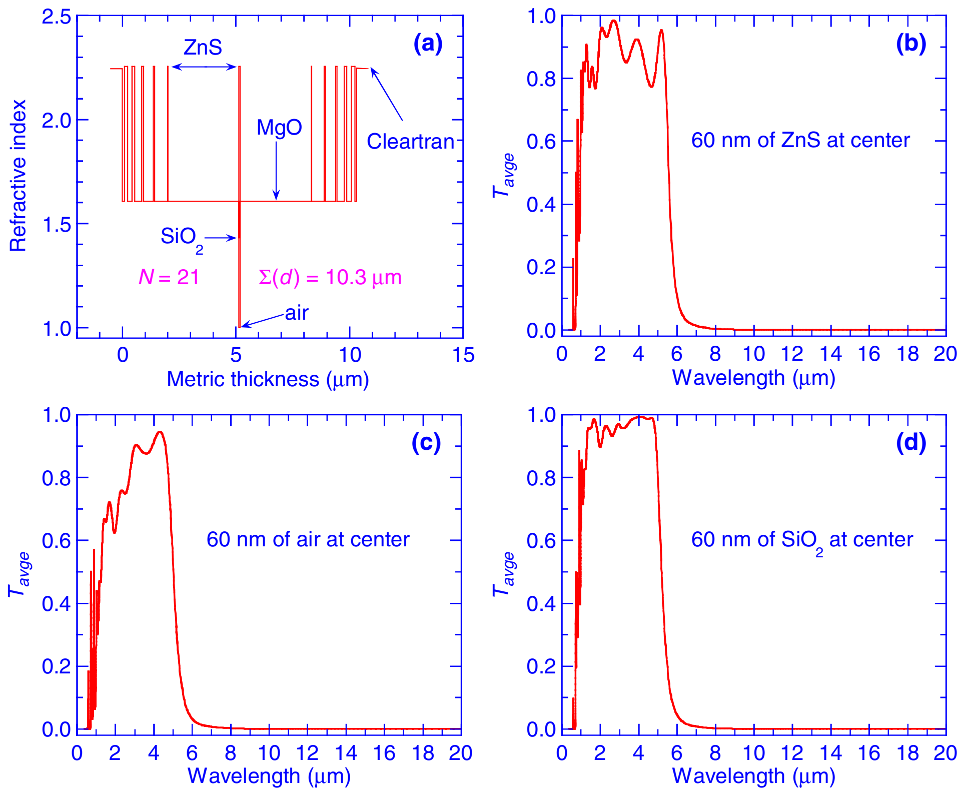

Fig. 7. (Color online) The effect on the calculated performance of the multilayer of Fig. 1 of placing thin layers of ZnS, air, and SiO_2 at the center of the 21-layer system. (a) Refractive index profiles, (b), (c), (d) calculated transmittances for light of average polarization for central layers made of ZnS, air, and SiO_2, respectively.

performances of a layer system containing the above three layers are shown in Fig. 7. It can be seen from this figure that the best performance is obtained when the central layer is made of SiO_2. Fortunately this is also a material that can be easily optically contacted. In these calculations, the optical constants for Al_2O_3 and SiO_2 [Fig. 2(b)] were taken from Palik's books [10,11]. Both of these materials have Reststrahlen peaks at shorter wavelengths than MgO but do not significantly absorb at wavelengths shorter than the cut-off wavelength of the filter to be constructed, and so they can be used in this application.

In view of the above experiments and calculations, we modified the 21-layer system shown in Fig. 1 accordingly, and the final design consisted of a total of 67 layers. With the exception of the central SiO_2 layer, all the other additional layers were made of Al_2O_3. The refractive index profile and the calculated performance of this new system are shown in Fig. 8; the overall thickness of the system increased from 10.3 to 12.3 μm, with a slight deterioration in the performance. Since the total thickness of the Al_2O_3 layers is only a small fraction of the total thickness of the MgO layer, it was possible to use the ion gun during their deposition.

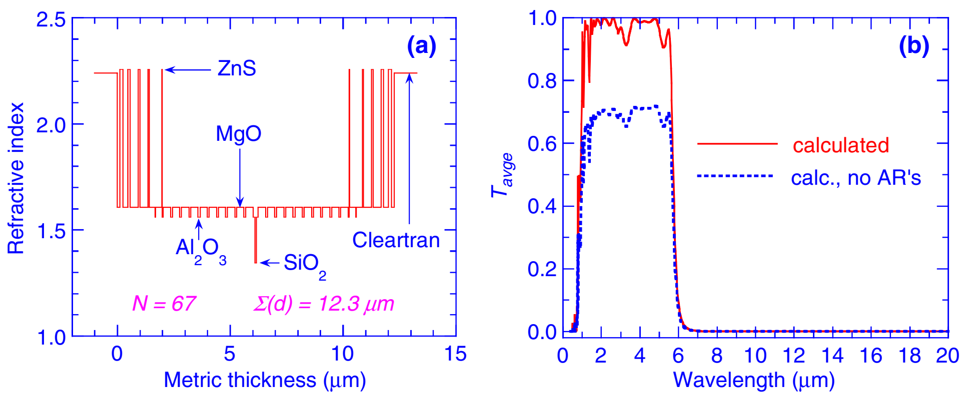

Fig. 8. (Color online) Long-wavelength infrared cut-off filter based on MgO with thin Al_2O_3 and SiO_2 layers. (a) Refractive index profile of the 67 -layer system, (b) calculated transmittance for light of average polarization. Also shown is the effect of non-AR coated prism surfaces on the transmittance.

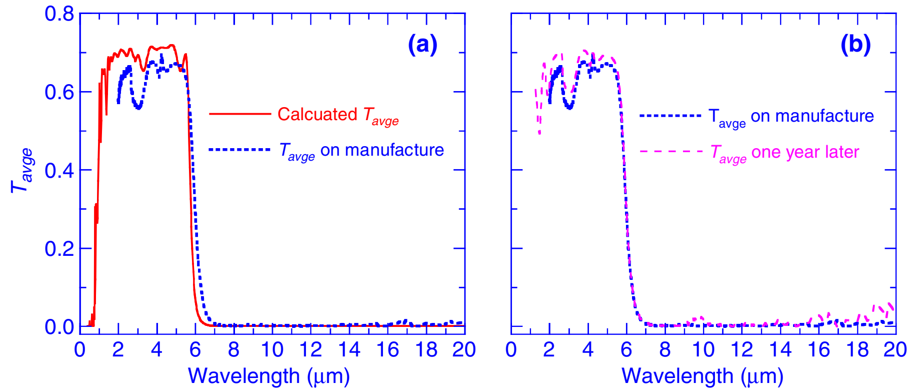

Fig. 9. (Color online) Comparison of (a) calculated and the measured average transmittances T_{avge} of the second attempt of the manufacture of the IR long-wavelength cut-off filter, and (b) transmittance spectra measured at J. A.Woollam Co. Inc. immediately after the manufacture and 1 year later at the NRC.

Coatings according to this design were produced on two Cleartran prisms and on a witness glass. The surface roughness of one-half of the layer system deposited in this way is shown in Fig. 5(c). It can be seen that the outermost surface now has an RMS roughness of only 2.96 nm, which is not only smoother than the surface of the coating produced at the first attempt but also is even smoother than the surface of the uncoated witness glass. The two coated prisms produced during this second deposition attempt could be readily optically contacted.

The transmittance of the modified cut-off filter was measured soon after its manufacture at J. A. Woollam Co. Ltd. on an IR variable angle spectrophotometric ellipsometer. The results of these measurements are compared to the calculated transmittance in Fig. 9(a). Clearly, the calculated and measured transmittances are now in much better agreement. One year later the cut-off filter was remeasured at the "National Research Council of Canada (NRC) on its newly acquired Woollam IR variable angle spectrophotometric ellipsometer. The agreement between these two measurements is very good (see Fig. 9(b)), especially if one considers that two different operators performed the measurements on two different instruments with different setups, likely on different parts of the filter.

4. Conclusions

Our first attempts at producing critical angle long-wavelength infrared cut-off filters made of MgO and ZnS layers were not very successful because the deposition process available to us resulted in porous layers with high RMS surface roughness. Because of the roughness, optical contacting of the two coated prisms was very difficult. In addition, the pores filled up with water vapor and the filters showed strong absorption in the transmission band. We modified the design and the deposition process and used thin Al_2O_3 layers to seal the pores in the MgO layer and to interrupt the growth of a columnar structure within the MgO and thus produced smooth interfaces. A thin SiO_2 layer was used to facilitate the optical contacting. This is a prime example of how frequently a designer needs to incorporate layers in a thin film design not for their optical effect but to meet other nonoptical requirements. We think that some of the techniques that we have used and described in this paper might be useful in other application areas such as, for example, broadband, wide-angle polarizers.

Measurements performed on the cut-off filter after 1 yr did not reveal any significant ageing of the transmittance curve. We conclude that it is possible to produce reasonable long-wavelength cut-off filters based on the above principle. However, filters of this type will be useful only when used with well-collimated light.

We believe this same principle could be used to produce cut-off filters operating at other wavelengths. On the basis of the behavior of the optical constants of Al_2O_3 and SiO_2 depicted in Fig. 2(b) it would appear that thick layers of these materials would also appear to be good candidates for cut-off filters effective at somewhat shorter wavelengths. Further tuning of the cut-off wavelength could probably be achieved by mixing MgO or one of the above compounds with other transparent materials.

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