Manufacturing problem contest [invited]

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Publisher's version / Version de l'éditeur:
https://doi.org/10.1364/AO.56.0000C1
Applied Optics, 56, 4, p. C1, 2016-10-21

2016 Topical Meeting on Optical Interference Coatings: Manufacturing Problem Contest [invited]

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

For the Manufacturing Problem contest, participants were asked to fabricate on provided blank substrates a challenging filter with specific reflectance and transmittance targets covering a wavelength range from 400 nm to 1100 nm. The problem was selected such that in order to achieve a performance close to the targets, a submitted filter had to include at least one thin absorbing layer. Nine teams from six countries participated in the contest using different deposition techniques. The teams' designs had a number of layers varying from 36 to 235, and a total thickness from 2.0 µm to 14.6 µm. The performances of all submitted filters were measured by two independent laboratories and the results were presented at the Optical Interference Coating meeting in June 2016.

OCIS codes: *(310.1620) Interference coatings; (310.1860) Deposition and Fabrication; (120.2440) Filters.*

http://dx.doi.org/10.1364/AO.99.099999

1. Introduction

Optical thin film coatings have played an important role in the advancement of many fields, including telecommunication, displays, lasers, optical sensing, scientific discoveries such as the detection of gravitation waves, etc. The field of optical thin film coatings is in constant evolution in order to meet new demands from different applications. The main purpose of the Manufacturing Problem contest is to test and expose the state of the art in optical thin film manufacturing capabilities, so that the whole thin film community can learn and benefit from this exercise. In each contest, the participants are challenged to manufacture a complex optical filter with specific requirements and the results are presented at the OSA's Topic Meeting on Optical Interference Coatings (OIC) held every three years. Five Manufacturing Problem contests had been held to date [1-5], since the first edition organized by J.A. (George) Dobrowolski and Steve Browning in 2001 [1].

The OIC 2016 Manufacturing Problem contest consisted in the fabrication of a very challenging filter with specific reflectance and transmittance targets from 400 nm to 1100 nm, as described in the contest description document [6]. To achieve a performance close to the targets, a filter design had to include at least one thin absorbing layer. Teams wishing to participate needed to notify the organizers first and were then provided with a maximum of three NBK7 blank substrates (donated by Edmund Optics) on which they could deposit their filters. The participation in the contest involved designing the filter, characterizing the coating materials and processes, manufacturing the filter, measuring its performance, and finally submitting the filter to the organizers with the mandatory and optional information (and before the deadline). The performance of the submitted filters was measured by two independent labs: Optical Data Associates (ODA) and National Institute of Standard Technology (NIST). The results were analyzed and the final ranking of the samples was presented at the OIC 2016 conference.

The present paper gives the details of the 2016 OIC Manufacturing Problem Contest, with measurements and ranking of the nine samples submitted from seven different institutions around the world.

2. Formulation of the problem

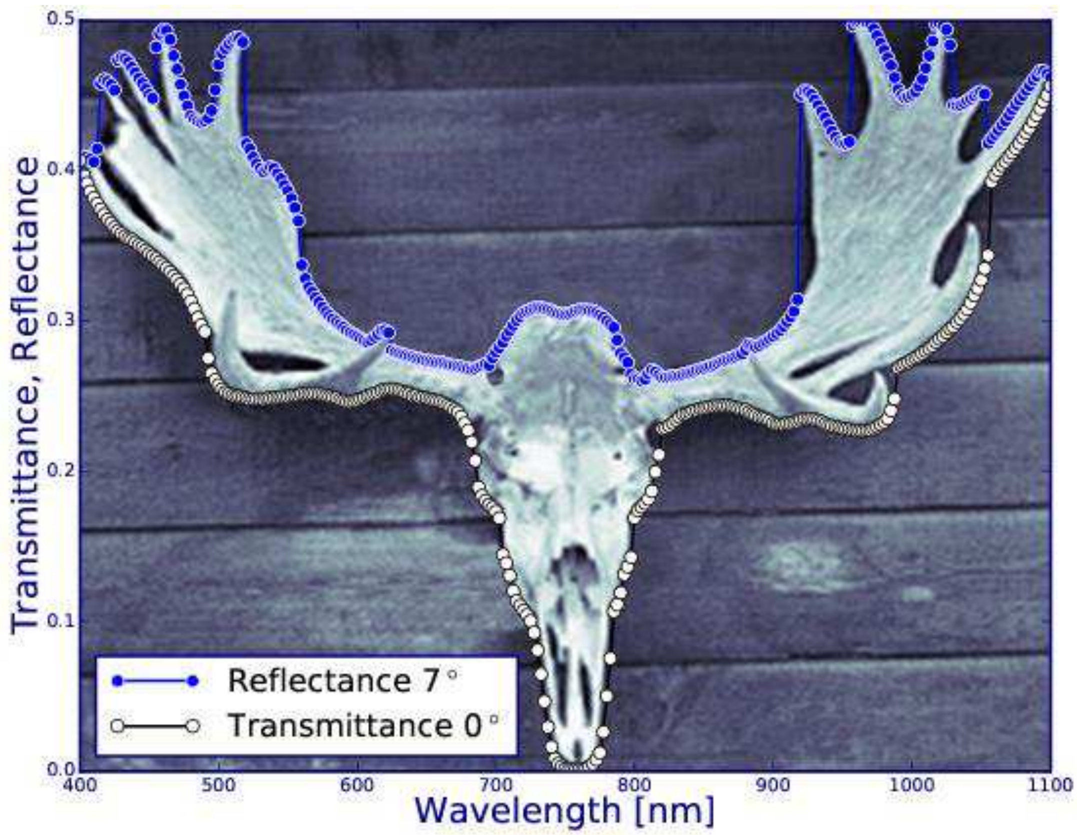

Figure 1 - The transmittance and reflectance targets for 2016 OIC Manufacturing Problem Contest *(2 columns wide)*

The thin film community is constantly facing challenges to meet difficult coating requirements from a large number of applications. One example is the coating of solar cells, for which both the reflectance and the absorption need to be specified; to enhance the efficiency of the device, the reflectance must be as low as possible and the absorption as high as possible so that more photons can be converted to electrons and holes. To reflect such realities and other practical applications, we have selected for the OIC 2016 Manufacturing Problem Contest a problem with both transmittance and reflectance specified from 400 nm to 1100 nm as shown in Fig. 1 (the "Moose-Head Problem"). A noticeable feature of the filter specification is that the values of the transmittance T and reflectance R at any wavelength do not add up to unity, implying that an absorbing material must be introduced in the coating design in order to match target spectra as much as possible. This particularity, with the peculiar profile of the target spectra, contributes to make this manufacturing contest one of the most difficult so far, undoubtedly requiring a significant effort from the participants.

For the filter design and evaluation, the performance of the filter is assessed using a merit function (*MF*) defined below:

$$MF = \left\{ \frac{1}{2N} \left[\sum_{i=1}^{N} \left(\frac{T_i - T_i^D}{\Delta T_i} \right)^2 + \sum_{i=1}^{N} \left(\frac{R_i - R_i^D}{\Delta R_i} \right)^2 \right] \right\}^{1/2}, \qquad \textbf{(1)}$$

where T_i, T_i^D and ΔT_i are the measured transmittance, target transmittance and transmittance tolerance, respectively, and R_i, R_i^D and ΔR_i are the measured reflectance, target reflectance and reflectance tolerance, at the specified wavelength λ_i. N is the total number of wavelengths and the tolerance ΔT_i and ΔR_i are set to 0.01 at all wavelengths. A list of numerical values for the targets is available online with the description of the 2016 OIC Manufacturing Problem and as a supplement to this article [7].

3. Discussion of the problem

To confirm that the problem can be solved using commonly available coating materials and deposition techniques, we have investigated a number of filter designs based on different coating materials and having various numbers of layers and overall layer thicknesses. In the designs, the low index material was SiO_2 and the high index material is selected from TiO_2, Al_2O_3, Nb_2O_3, or Ta_2O_5 and most optical constants are taken from Palik [8]. We found that every filter design investigated had to include at least one thin absorbing metal layer, Ti, Al, Nb, Cr, In or Inconel™, in order to reproduce, even roughly, the shape of the target curves (optical constants of the metals were taken from Palik [8] and Dobrowolski et al. [9]). This is not surprising, as mentioned above, since $T + R < 1$. The implication of the presence of thin metal layers in the designs is significant for the fabrication of the filters since thin metal layers require accurate optical characterization and a tight layer thickness control during their fabrication.

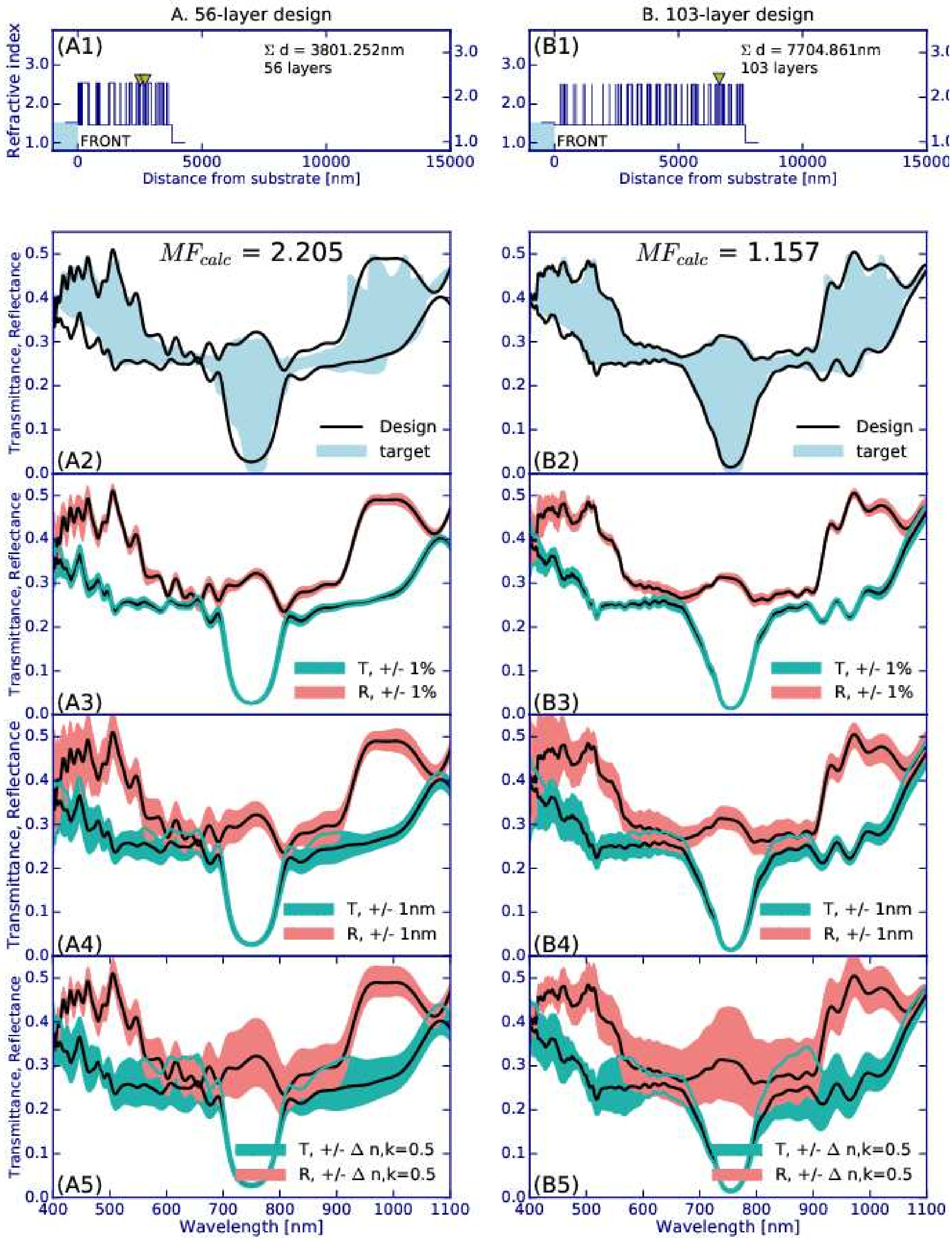

Figure 2 – Two examples of possible designs for the Manufacturing Problem: (A) a thinner 56-layer and (B) a thicker 103-layer solutions. (row 1) Refractive index profiles, (row 2) Calculated reflectance and transmittance spectra, compared to the target curves (blue silhouette). (row 3) Variance envelopes for RMS error of 1 % on all layer thicknesses. (row 4) Variance envelopes for RMS error of 1 nm on all layer thicknesses. (row 5) Variance envelopes for RMS error of 0.5 on *n* and *k* of the metal layers only. (All the envelope curves were calculated from a sampling of 1000 calculated spectra with different RMS distributed errors. The envelopes defines areas within which 68 % of the calculated error-spectra are contained.) *(2-col wide)*

Table 1 (extracted from Ref. 9). Variation of the refractive index and extinction coefficient of Inconel600 with thickness.

λ (nm)	Inconel 5.1 nm		Inconel 9.9 nm		Inconel 19.1 nm	
	n	*k*	*n*	*k*	*n*	*k*
400	1.554	1.905	1.518	2.623	1.531	2.812
450	1.863	1.848	2.183	2.509	2.219	2.797
500	2.164	1.815	2.479	2.379	2.563	2.735
550	2.434	1.758	2.784	2.428	2.935	2.858
600	2.671	1.708	3.184	2.444	3.448	2.904
650	2.874	1.673	3.576	2.348	3.941	2.760
700	3.050	1.652	3.879	2.181	4.280	2.504
750	3.205	1.650	4.083	2.004	4.463	2.251
800	3.344	1.661	4.212	1.855	4.547	2.057

Figure 2 shows two examples of designs based on SiO_2, TiO_2 and Inconel™: (A) a 56-layer solution with two thin metal layers, with thickness values of 5.0 nm and 7.4 nm, and (B) a thicker 103-layer solution, with a single 11.3 nm thick metal layer. Figures 2(A2) and (B2) compare the calculated *R* and *T* spectra for these designs with the target spectra (shown as a blue silhouette). We can see that increasing the number of layers in the design and its total thickness by a factor 2 roughly leads to a decrease of the calculated merit function by half.

To gauge how difficult these filters would be to fabricate, the sensitivity of the designs to thickness errors was evaluated by generating 1000 spectra with different RMS thickness errors, and looking at the variance of the calculated results at each wavelength (within a distribution width containing 68 % of all results). Figures 2 (A3) and (B3) show the sensitivity of the designs with 1 % relative RMS thickness errors, while Figs. (A4) and (B4) show the results with 1 nm absolute RMS thickness errors. The observation of a larger sensitivity to 1 nm RMS errors indicates that the filters would be difficult to fabricate because they require precise layer thickness controls, especially for the thin metal layers.

Another added complication for the fabrication of the filters with metal layers is that the optical constants of the thin metal films must be controlled precisely. It is well-known that the optical constants of thin metal layers can vary significantly with thickness, as reported by Dobrowolski, Ho and Waldorf [9] and Goodell, Coulter and Johnson [10] for layers of Inconel 600 with different thicknesses. Table I shows that individual variations of *n* and *k* as large as 1.0 can occur for Inconel 600 with thicknesses between 5 nm and 20 nm, and our experience indicates that the similar phenomenon could occur with other metals. The effect of such a fluctuation in the performance of the contest filters were demonstrated by running a sensitivity evaluation similar to above, but with RMS variations of 0.5 both on *n* and *k* of the metal layers only, assuming no thickness errors for all the layers. Figures 2 (A5) and (B5) show that the sensitivity to the optical constants variation of the metal is significant, suggesting that one of the main challenges in fabricating the filters is the control of these thin metal films (thicknesses and optical constants).

A last difficulty for the fabrication of these filters is the partial oxidation of the metal layer during the deposition of subsequent oxide materials. This problem has been documented in the past, and one possible way to avoid it is to deposit a thin protective layer on top of the metal, a protective layer that would oxidize during the deposition of the next oxide layer (i.e. a thin *a*-Si layer would protect the metal layer, and be part of a thicker SiO_2 layer once oxidized) [11].

4. Participation

The description of the 2016 Manufacturing Problem was posted on the OSA website (OIC dedicated section) in October 2015. A total of 12 teams requested blank substrates to participate in the contest. Amongst them, 9 teams were able to submit samples on time, for a total of 9 samples. The teams, listed in Table 2 (in alphabetic order of affiliation), are from six different countries and three continents and represent governmental research laboratories and industries.

For the contest, the same anonymity rule as in the previous contest is adopted: all participants and their affiliations are disclosed at the OIC 2016 conference, however, their names are not linked to a particular sample, except for the winning team whose identify is announced at the conference. It was noted in the past that this anonymity rule encourages participation. In the next sections, the samples are referred to by number only.

It is interesting for the entire optical thin film community to see the high performance that can be attained for the Manufacturing Problem when using different deposition processes. The organizers always hope for groups equipped with different types of deposition

Table 2 List of participating teams and their affiliations

Team Leaders	Organizations
Zach Gerig	Advanced Thin Films, Boulder CO , USA
Oleg Prosovsky, Alexandr Gvozdey, Isamov Andrey	FSUE ORPE Technologiya, Obninsk, Russia
Liao Bo-Hei, Hsiao Chien-Nan, Chiu Po-Kai, Lee Chao-Te, Huang Po-Han	Instrument Technology Research Center, NARlabs, Hsinchu, Taiwan
Penghui Ma	NRC of Canada, Ottawa ON, Canada
Marc Lappschies, Jan Brossmann, Stefan Jakobs	Optics Balzers, Jena, Germany
Masahiro Akiba and Makoto Seta	TOPCON Corporation, Tokyo, Japan
Karen Hendrix	Viavi Solutions, Santa Rosa CA, USA
Tim Gustafson	Viavi Solutions, Santa Rosa CA, USA
Lucas Alves	Viavi Solutions, Santa Rosa CA, USA

Table 3 Summary of the Measurement Equipments

	ODA	NIST
Instrument	Cary 5000	Perkin Elmer Lambda 1050
Beams	Double-grating and double-beam	Double-beam
Wavelength range	400 nm to 1100 nm, 1.0 nm steps (interpolated to 2.5 nm steps)	400 nm to 1100 nm, 2.5 nm steps
Light-source	Tungsten-halogen / deuterium	Tungsten-halogen / deuterium
Detectors	Photomultiplier / PbS	Photomultiplier / InGaAs (noise in 850-950nm range)
Reflectance Accessory	Standard V-W 7° specular reflectance accessory (Agilent)	150 mm integrating sphere
Transmittance accuracy	±0.1 % in visible, ±0.2 % in NIR	±0.1 % in visible, ±0.2 % in NIR
Reflectance accuracy	±0.2 % in visible, ±0.2 % in NIR	±0.2 % in visible, ±0.5 % in NIR

equipment to take part in this exercise and to be generous in providing auxiliary information about their thin film design and the materials used, as well as any other pertinent non-propriety information about the process parameters. To learn as much as possible from this exercise, the organizers made it mandatory that the participants provide the refractive index profile of each sample submitted.

5. Samples Evaluations

Once the submitted samples were received by the organizers, they were randomly marked with a number tag from S01 to S09, and any references to the submitting team (package, tags) were removed. The samples were then re-packaged in identical boxes and sent for evaluation to two independent laboratories: ODA and NIST. The transmittance and reflectance at the specified wavelengths were measured with double-beam spectrophotometers. The detailed specifications of the instruments are listed in Table 3.

When performing the evaluation at NIST, it became clear that there was an issue with some of the reflectance data provided by their instrument: a large random noisy signal was observed in the near-infrared (NIR), around the detector change of the instrument (highlighted in Fig. 3). Pressed by time, it was agreed that NIST reflectance data from 850 nm to 925 nm would be removed from their spectra, and replaced with ODA values (we did not want to leave this part of the spectra blank, as it would have penalized the submitted samples with reflectance curves matching well the target at these wavelengths).

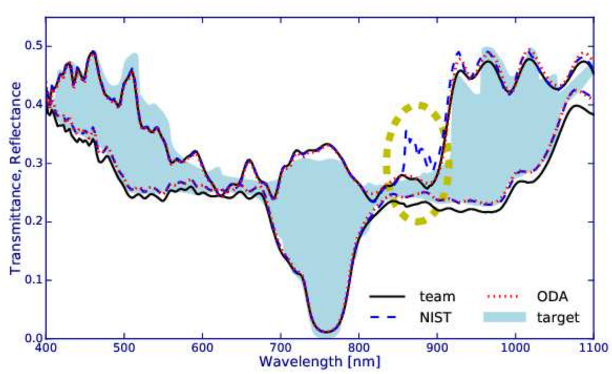

Figure 3 Example of typical measured spectra showing some noisy reflectance data from NIST between 850 nm and 925 nm. Also note the good agreement of transmittance spectra, and some discrepancies for reflectance spectra in the NIR; these two observations were made for measurements on most samples.

Apart from this noise problem, the spectrophotometric spectra evaluated at ODA and NIST were in good agreement, with an almost perfect match of the transmittance (visible and NIR) and reflectance (visible) spectra, and small but noticeable discrepancies in the NIR part of the reflectance curves.

All the measured spectra were compared to the targets by mean of merit function *MF* values calculated from Eq. (1). The average of the *MF* values measured from the two evaluation labs were used to rate and rank the submitted samples.

6. Results and Discussion

The information provided by each participating team and the evaluation results obtained for the 9 submitted samples are presented in Table 4. The table lists detailed information about the designs: the number of layers and total thickness on the front and back sides of the substrate, refractive indices and thicknesses of the metal layers), as well as the *MF* values calculated by the participants from their designs, the *MF* values measured by the participants on their fabricated filters, and the *MF* values evaluated by ODA and NIST. Note that RMS error estimations were added on certain values of *MF*, based on known measurement uncertainties provided by the evaluation labs (from Table 3) [12]. In addition to numerical values, Table 4 also includes some additional experimental details voluntarily provided by participants. From these, one can see that sputtering was used by many participants for manufacturing the coatings, which is not a surprise given the known stability and quality of films produced with this method. We also see that at least two participants used evaporation, one of which using it for depositing the metal layer only.

The results, with the evaluated spectra compared to the target curves and the participant spectra, are shown in Figs. 4 and 5. On these figures, each sample is represented by a refractive index profile corresponding to the submitted design (left-hand graphs in Figs. 4 and 5), and combined transmittance and reflectance spectra, from the participant and both evaluation labs (ODA and NIST), compared to the targets curves (right-hand graphs in Figs. 4 and 5). The results for the average evaluated *MF*s are also shown on the figure, along with the total thickness and the number of layers for each design.

Table 4. Summary of the submitted filter designs, MF values and final ranking

	Filter Design				MF from participants		MF from evaluation labs				
	Nb. layers (front+back coatings)	Total thickness (µm)	Nb. metal layers	Metal layers thick. (nm) [with nk]	MF Design	MF Meas	MF ODA	MF NIST	MF Ave.	Rank	Additional information
S01	160	11.4	1	8.5 [3.227 +i2.927]	0.989	2.904	2.701 ±0.008	2.673 ±0.012	2.687 ±0.007	4	Magnetron sputtering
S02	56+12	3.3+1.3=4.6	2	1.8, 9.4 [1.824 +i2.281]	1.385	1.724	**1.868 ±0.007**	**1.805 ±0.014**	**1.837 ±0.008**	**1**	**(winning sample)**
S03	129+43	9.4+3.1=12.5	1	9.9 [3.657 +i2.97]	1.624	2.002	1.907 ±0.008	1.887 ±0.013	1.897 ±0.008	2	Ion beam sputtering for dielectrics; evaporation for metal layers; observed delamination on back side
S04	34+13	1.4+0.6=2.0	1	6.27 [2.522 +i2.487]	2.900	4.842	4.398 ±0.008	4.485 ±0.011	4.442 ±0.007	8	
S05	36	2.5	3	1, 1.5, 1 [3.854 +i3.451]	2.395	--	10.609 ±0.008	10.838 ±0.010	10.724 ±0.006	9	Ion-assisted e-beam evaporation; Nb_2O_5, SiO_2, Cr
S06	111	6.8	1	6.667 [3.227 +i2.927]	1.273	2.091	2.220 ±0.008	2.157 ±0.013	2.188 ±0.007	3	Magnetron sputtering
S07	55	2.9	3	2.8, 0.9, 0.8 [3.379 +i3.665]	1.620	2.806	2.723 ±0.007	3.011 ±0.013	2.867 ±0.007	5	Magnetron sputtering
S08	108	7.5	1	6.2 [2.83 +i4.688]	1.957	3.338	3.836 ±0.008	3.900 ±0.013	3.868 ±0.008	7	Helios-PARMS-process (Nb_2O_5, SiO_2, Nb); broadband monitoring.
S09	235	14.6	3	2.1, 1.4, 4.3 [3.92 +i3.306]	0.716	3.826	3.694 ±0.007	3.601 ±0.010	3.648 ±0.006	6	Magnetron sputtering

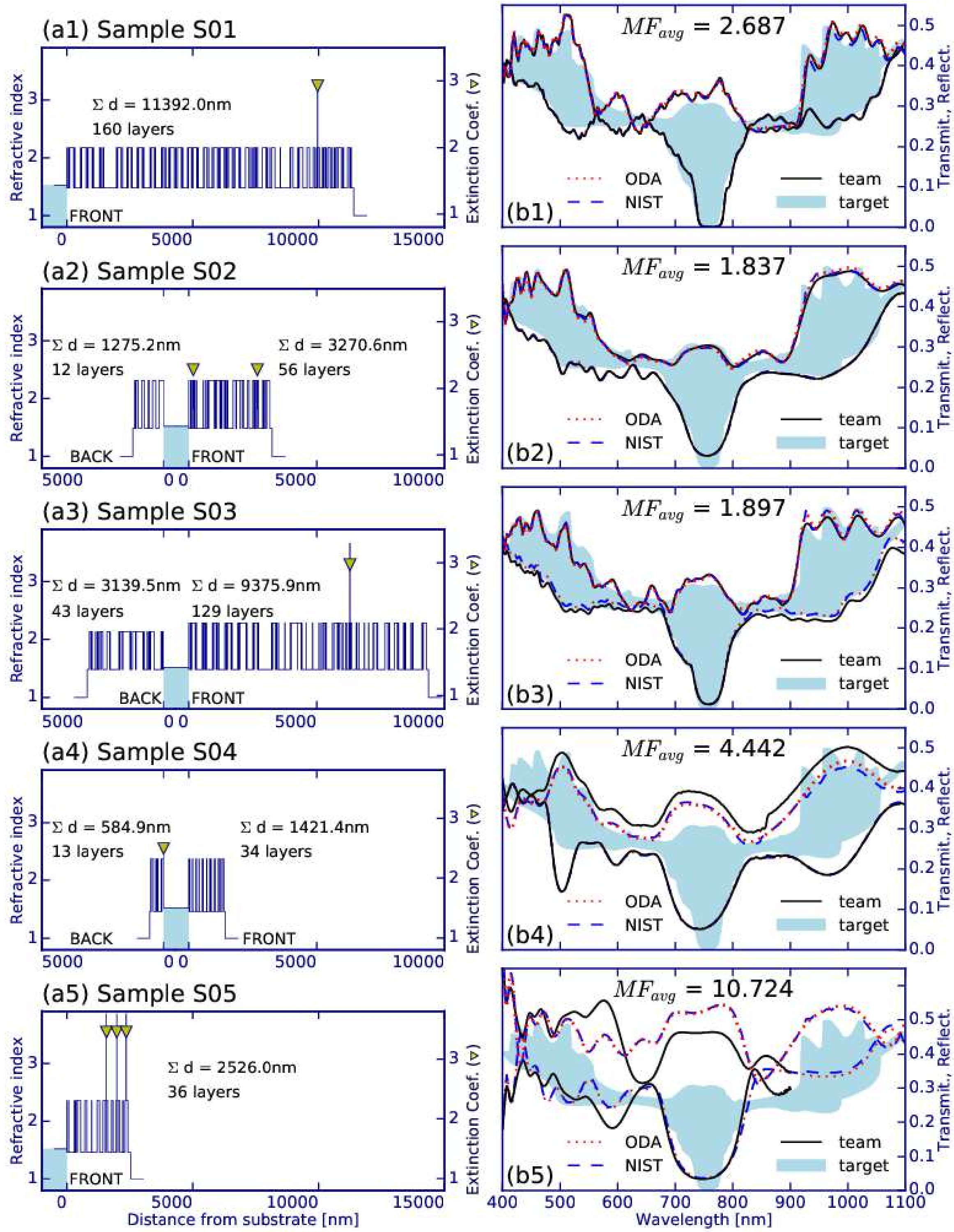

Figure 4 Evaluation results for the submitted samples. For each sample: left graph is the refractive index (and extinction coefficient) profile provided by the participant, and right graph shows the spectra measured by the participant and the two evaluation labs, ODA and NIST, compared with the target spectra (represented as a blue silhouette). The merit function MF_{avg} is an average of MFs calculated from ODA and NIST spectra (details are in the text). *(2-col wide)*

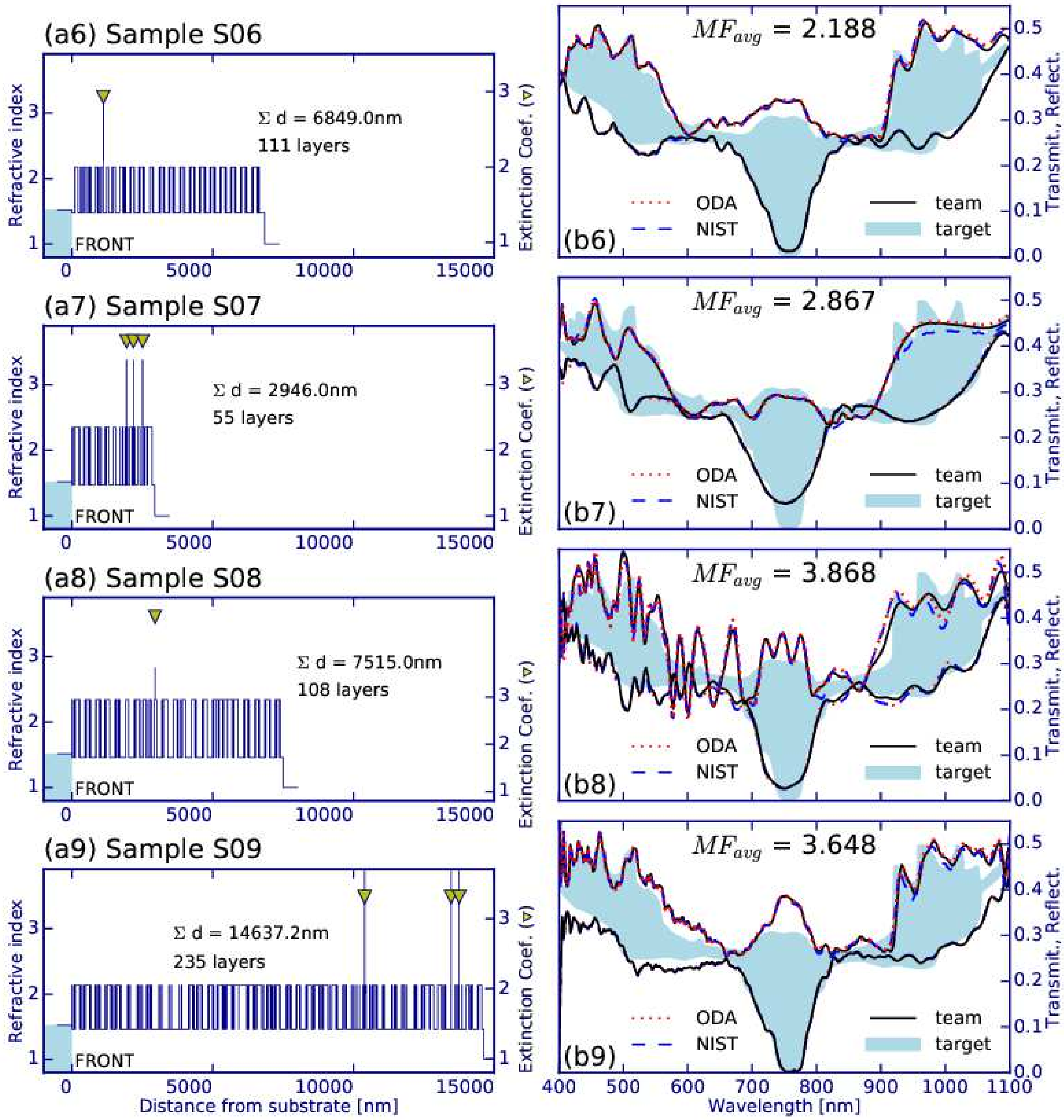

Figure 5 (Continuation of Figure 4) *(2-col wide)*

Although the sample identification numbers were random and not linked to particular participants as required by the anonymity rule, participants looking at the results presented in Table 4 and Figs. 4 and 5 should be able to recognize their own submitted sample, based on the information that they provided (design, measurement, calculated *MF*). We would like to remind the participants that they should keep this information for themselves to protect the anonymity of the results, and to facilitate future contest participation. The only exception to this anonymity rule is the identification of the winning team: **Masahiro Akiba** and **Makoto Seta**, from ***TOPCON Corporation,*** **Tokyo, Japan**. Their sample S02 has the lowest evaluated average *MF* value, 1.837, as shown on Table 4.

As mentioned in the introduction, one of the main intentions of George Dobrowolski and Stephen Browning when organizing the first Manufacturing Problem contest in 2001 was that the whole optical coating community could learn and benefit from a challenging exercise. For this purpose, it is instructive to compare different design solutions to the problem, and gain insight about the importance of the manufacturability of individual design solutions to their final performance.

In terms of diversity of proposed solutions, Table 4 and Figs. 4 and 5 show that the submitted samples cover a large range of designs, with total thicknesses varying from 2 μm (S04) to 14.6 μm (S09), numbers of layers between 39 (S05) and 235 (S09), and numbers of metal layers varying from 1 (samples S01, S03, S04, S06, S08, S09) to 2 (samples S02, S07), to 3 (sample S05). Samples S02, S03 and S04 represent solutions with two coated surfaces, while the remaining samples are front-side coated solutions. From the design profiles in Figs. 4 and 5, we see a large variation in the extinction coefficients of the metal materials used, from 2.28 to 4.69, which confirms that many types of metals could solve the problem.

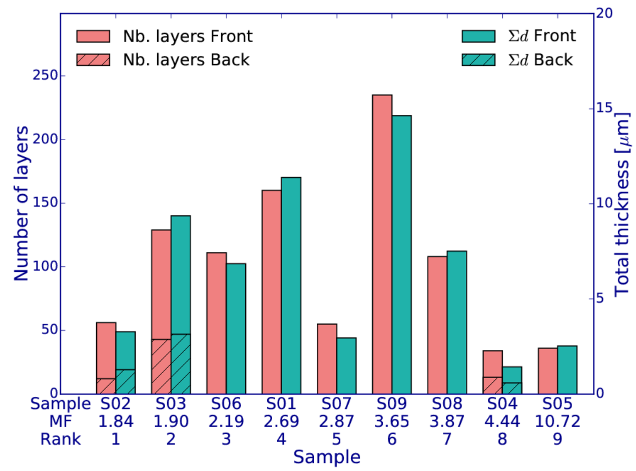

Figure 6 Comparison of the numbers of layers (red, left axis) and the total thicknesses (blue, right axis) for all the samples, ordered according to their measured *MF* (and rank).

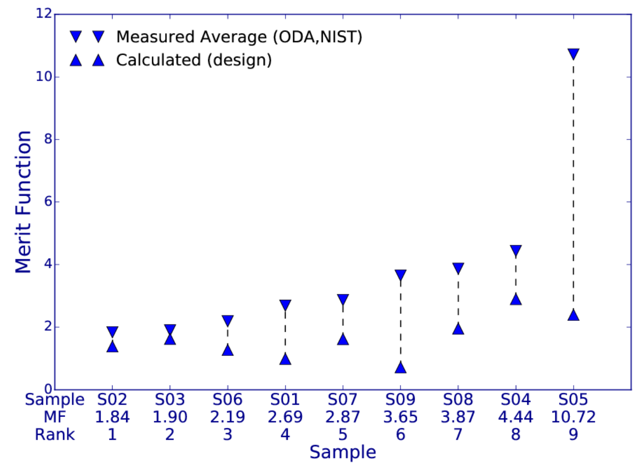

Figure 7 Comparison of the calculated *MF*s and the average measured *MF*s, for all the samples (ordered according to their rank).

Looking at the spectra shown in Figs. 4 and 5, we can see in a glance that the problem was not trivial and no team succeeded in reproducing the targets curves with fidelity. Conscious of the difficulty of the task, the teams seemingly took two distinct approaches to design a coating with a low *MF*, with differences most clearly seen on the long wavelength side of the reflectance spectra (top-right of the moose antler) and with the range of total thickness of the solutions; a first approach (seen with samples S01, S03, S06, S08 and S09) was to try reproducing the exact shape of the target as well as possible with the design, while a second approach consisted in just passing through the middle of that top-right antler shape (see samples S02, S04, S05 and S07). The former approach led to coatings much thicker than the latter approach. Samples S02 and S03 represent the best of each approaches; they both reached similar values of *MF*, but sample S02 did it with a simpler design (and slightly more success), and a reflectance spectrum 'just averaging' the shape of the target in the top-right antler area.

Other interesting observations from the spectra of Figs. 4 and 5 concern the accuracy of the measurements (useful information for the participants). Firstly, with a few exceptions, it can be seen that generally, the transmittance spectra measured by the participants matched well those measured by ODA and NIST. Secondly, we can see that the discrepancies in the reflectance spectra are more pronounced, particularly in the near-IR part of the spectra (including small differences between ODA and NIST data). This emphasizes that reflectance measurements are more difficult in general and many factors can introduce errors in the measurements; for example, sample thickness, probe-beam polarization, size and angular distribution, as well as visible and NIR detector size and response. Many of these factors are inherent in a particular instrument, which may lead to instrumental differences. Errors in the calibration and alignment of instruments and reflectance accessories may also result in measurement errors that can be quite large, e.g., backside reflection could be lost due to a bad alignment. Measurement accuracy is one of the key factors to achieve good results for the manufacturing problems, just like in manufacturing of any practical filters.

Figures 6, 7 and 8 compare the design properties for the submitted samples, and relate them to the calculated and measured *MF* values. Interesting observations can be made from looking at these graphs:

- The performance of the samples had no correlation with the total thickness of the coatings or the number of its layers once minimum requirements are met (an observation made in previous contests as well);
- The two samples with the lowest average measured *MF* values had coatings on both the front and back sides;
- The same two samples also had the smallest difference between design *MF* and measured *MF* values, suggesting a better knowledge and control of the fabrication process, and maybe the use of less sensitive designs;
- Some samples with complex designs and low design *MF* values resulted in relatively high measured *MF* values, suggesting unforeseen sensitivity issues.

Many factors contribute to the diversity in the submitted filter performance, such as: the initial designs, the use of different deposition techniques, thickness control, film characterizations, measurements, etc. Sample S05 was deposited using solely evaporation, which makes it hard to control precisely the thicknesses, and all the characterizations were performed on an instrument without near-IR capabilities [see Figs. 4(b5)], meaning that the participant had to extrapolate the optical constants in that wavelength range for the design and fabrication. Considering that, the performance of sample S05 seems fair and understandable.

As mentioned above, participants were asked to voluntarily share any information about their design and fabrication process. We saw for example that sputtering techniques were used by most teams and evaporation by two teams. Without details about the design techniques used, or the fabrication and thickness monitoring tricks employed during the manufacture of the samples, we cannot elaborate further on their merits and deficiencies. However, we can still reflect on the usefulness of some current techniques and methods available to the community for the problem in this paper. For the manufacture of multilayer systems involving thin metal layers, we have noticed in Section 3 that difficulty lies in the variability of the metals *n* and *k* values with thickness. This single factor leads to several challenges; let's look at some of them:

Design method. Even with modern techniques such as needle methods, global optimization, or gradual evolution, it is hard to design a filter with metal layers that have different *n* and *k* values depending on their thickness. Proper design might require fixing the thickness of these layers to known values, and going through cycles of filter design-fabrication-characterization. Recent design sensitivity studies and simulations of experiments [13] could certainly help selecting robust

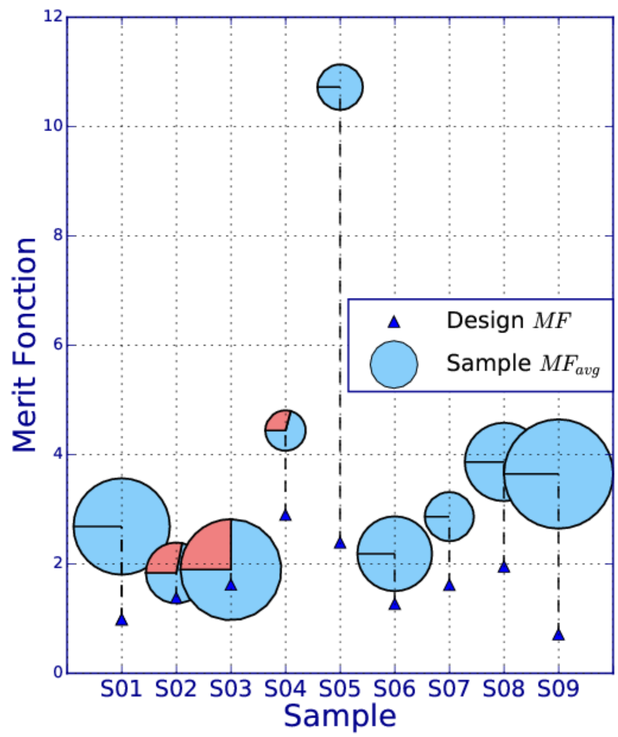

Figure 8 Comparison of the results for all the samples: The area of the pie symbols is proportional to the total thickness of the represented coating, with the red slice representing the back-side coating; their ordinates are the averaged *MF*s, and the triangle symbols represent the corresponding calculated design *MF*s (as provided by the participants).

designs, but they should ideally take into account this *n* and *k* variability factor.

Fabrication technique. Stability and reproducibility of the deposition technique is crucial for the exact control of the thickness of critical metal layers. For dielectric materials, sputtering has provided a stability shown by the increased complexity of the multilayer systems submitted to the latest Manufacturing Problem contests [14, 5]. However, for filters involving thin metal layers, extra cares must be taken to increase the accuracy of each metal thickness and protect it from subsequent oxidation [11, 15]. In-situ reoptimization, a powerful tool often used to reduce the effect of thickness errors on the performance of a manufactured filter, could be used in that situation [14, 16], but would be efficient only if the metal layers *n* and *k*, and thickness values are accurately monitored.

Monitoring technique. If a very stable deposition process can be achieved, timing could be used for the deposition of at least some of the layers. Modern techniques such as broadband monitoring, multi-wavelength quarterwave monitoring have proven to be efficient with dielectric multilayers, but they are still not ideal when it comes to evaluate *in-situ* the thickness and variable optical constants of thin metal films. In our view, a monitoring approach more suited for that task would involve both transmittance and reflectance (or ellipsometric) measurements, and could include a re-evaluation of the metal properties after deposition of subsequent layers, i.e. when the spectra become more sensitive to the metal properties. Another approach that may have been used by some participants is to interrupt the deposition, perform a thorough *ex-situ* characterization of the partial coating after deposition of the metal, reoptimize the remaining layers, and complete the fabrication.

7. Conclusion

A glance at Table 4 and Figs. 4 and 5 gives an idea of the difficulty of the 2016 Manufacturing Problem Contest, but it does not show everything. It does not reveal the long hours spent by the participants at searching a 'manufacturable' design, at characterizing the thin metal layers required and devising methods to make these layers as close as possible to the design, at revisiting the designs based on the finding about the thin metal layers, at looking at the best way to control the deposition, at carefully measuring the transmittance and reflectance of the coatings. It does not tell the negotiations and tight planning that some of the participants might have to do in order to be able to have enough machine time for fabricating the samples for this contest. All this time and work are not in vain as they provide useful information to the coatings community. Fifteen or thirty years from now, the same 'Moose Head' problem might show that this type of challenge will have been overcome, thanks to some novel technical progresses. Time will tell.

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Acknowledgment. We would like to thank Edmund Optics for their continuing support by donating blank substrates to the OIC Manufacturing Problem Contests.

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