Broadband transmission filters from the 2013 Optical Interference Coatings manufacturing problem contest [Invited]

Li Li,[1,*] J. A. Dobrowolski,[1] Michael Jacobson,[2] and Catherine Cooksey[3]

[1]National Research Council, 1200 Montreal Road, Ottawa, Ontario K1A 0R6, Canada

[2]Optical Data Associates, 5237 E. Seventh Street, Tucson, Arizona 85711, USA

[3]National Institute of Standards and Technology, 100 Bureau Drive Stop 8442, Gaithersburg, Maryland 20899, USA

*Corresponding author: Li.Li@nrc.ca

Received 11 September 2013; accepted 24 September 2013;
posted 22 November 2013 (Doc. ID 197465); published 10 January 2014

A broadband transmission filter from 400 to 1100 nm was selected for the manufacturing problem contest. The purpose of the contest is to test the state of the art of current optical thin film manufacturing capabilities. A total of 37 people from 15 teams participated in the contest and submitted 17 samples. Diverse approaches were taken by participants to tackle the problem. A range of different solutions was obtained where the number of layers varied from 22 to 608, and the total layer thickness ranged from 1.859 to 23.099 μm. Two independent laboratories performed sample evaluation measurements. Three teams shared the best result with the lowest average measured merit function. © 2013 Optical Society of America

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

http://dx.doi.org/10.1364/AO.53.00A248

1. Introduction

The results of the Fifth Manufacturing Problem Contest were announced at the Optical Interference Coatings (OIC) conference in June 2013 in Whistler, BC, Canada. The contest has become a tradition at the OIC conferences and the reports of previous contests can be found in the OIC special issues of Applied Optics [1–4]. The purpose of the contest is to test the state of the art of current optical thin film manufacturing capabilities. We hope that through this challenging problem, the thin film community can learn more about the issues involved in manufacturing complex thin film optical filters.

For each contest, the organizers strive to select a difficult filter as the problem. Teams around the world can participate in the contest by submitting their filter samples manufactured according to the contest specification. Participants usually have four to five months to prepare their samples. The submitted samples are evaluated by two independent laboratories. The results are reported at the OIC conference and the samples are then returned to participants at the conference.

For the 2013 OIC Manufacturing Problem Contest, a broadband transmission filter was selected that covers both the visible and near-infrared spectral region from 400 to 1100 nm. This wavelength bandwidth is twice that of filters in the previous contests. For the contest, only the filter target performance and substrate were specified, and the rest was completely up to the participants. Entrants have complete freedom in their filter design and can use any combination of materials, number of layers, and overall thickness. They can choose the deposition

1559-128X/14/04A248-11$15.00/0

and monitoring processes that they feel would permit them to obtain the closest fit to the specified performance of the filter. There is no requirement to disclose the materials that they use, but sufficient information must be provided for the plotting of the refractive index profile of their filter design.

To attract more participants and to encourage people to take diverse approaches to solve the problem, an anonymity rule, first enacted for the 2007 contest, was followed where the names and organizations of all teams are listed in the presentation without linking them to specific results. This rule was effective and did indeed increase the number of entries in 2007 and 2010. For the 2013 contest, the rule was slightly modified to reveal the name(s) and organization(s) of the sample(s) with the best result. This change was a result of a survey taken from previous participants and consultations with people at OIC conferences. This year, we received a record number of entries from teams around the world.

In this work, the detailed results of the 2013 OIC Manufacturing Problem Contest are reported. In Section 2, the problem is described and followed by the problem discussions in Section 3. Participation, evaluation, and results are presented in Sections 4, 5, and 6, respectively. The conclusion is given in Section 7.

2. Problem Description

In the previous contests, the selected filters were all specified within the visible spectrum from 400 to 700 nm. For the 2013 contest, we decided to extend the wavelength region to cover both the visible and the near-infrared region from 400 to 1100 nm. This extension reflects a growing reality for practical optical coatings today: the need to operate in more than one wavelength region. It also provides additional challenges to participants in filter design, coating characterization, process control, and measurements. Detailed information about the 2013 Manufacturing Problem Contest can be found in [5].

The selected filter for the 2013 contest is a broadband transmission filter and its transmittance at normal incidence was specified as the target shown in Fig. 1. The transmittance was defined as the total transmission, including both the first and second surfaces of the substrate. The filter substrates were N-BK7 optical glass and the sizes were 50 mm × 50 mm × 4 mm. The substrates were donated by Edmund Optics.

A merit function (MF), defined below, served to evaluate both the calculated and measured filter performance:

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

where T_i^D, T_i, and ΔT_i are the target transmittance, the measured or calculated transmittance, and the transmittance tolerance at the specified wavelength λ_i, N is the total number of wavelengths (350) and ΔT_i is the tolerance and is equal to 0.01 at all wavelengths.

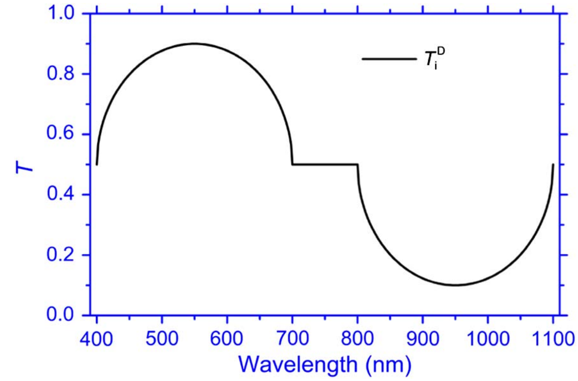


Fig. 1. Filter transmittance target for the 2013 OIC Manufacturing Problem Contest.

To manufacture the filter, the participants needed to carry out several critical tasks: (a) select coating materials; (b) measure the optical constants of these materials from 400 to 1100 nm; (c) determine a suitable filter design with a series of layers and layer thicknesses; (d) select a suitable coating deposition process, such as e-beam evaporation, ion-assisted deposition, or sputtering and deposit the multilayer filter coating; (e) control layer thicknesses during deposition using timing, crystal monitoring, or single or wideband optical monitoring methods; and (f) measure the transmittance at the specified wavelengths and evaluate the performance. Some of the abovementioned tasks may have to be repeated in order to obtain better or more accurate results. They are not trivial and require significant effort from the participants and support from their organizations.

Similar to producing practical optical filters for real applications, the participants also had to consider many factors in the selection of the filter designs and deposition processes and had to make many compromises. These selections are normally made not only to satisfy coating optical characteristics but also to meet many other nonoptical criteria such as mechanical performance. Most importantly, the filter has to be manufactured within the available time and budget. For the contest filter, or any other real filter, there always exist many good solutions depending on the evaluation criteria. Although the only evaluation criterion in the contest is the measured performance, due to the nature of the contest, we encouraged participants to try diverse approaches (different filter designs and deposition processes) to tackle the problem so that we would have a spectrum of possible solutions for the filter. As a result, the thin film community can learn from this exercise. We hope participants would be generous in providing any additional information about the thin film design and the materials used, as well as any other nonproprietary information about the process parameters.

When submitting their filter sample(s), participants provided the mandatory information: the measured transmittance at the given wavelengths, the calculated MF and measured MF, and the index profile of the filter design (layer thickness and refractive index at 550 nm).

As noted, the only basis for the evaluation of submitted samples was the average MF based on the transmittance measured by two independent laboratories: Optical Data Associates, LLC (ODA) and National Institute of Standards and Technology (NIST). Other than the transmittance measurements, the submitted samples were not subjected to any other analytical measurements, such as Auger or TEM. All samples were returned to the participants at the conference after the presentation of the results.

3. Discussion of the Problem

During the selection of the manufacturing problem filter, the organizers have to investigate many issues: the type of filter that should be chosen, available coating materials that could be used, possible design solutions to the filter, the difficulty of manufacturing the filter, what kind of equipment is needed to deposit the coatings, and how to measure the filter performance.

In the following section, we will present some of the organizers' filter designs. The discussion will be mostly focused on the manufacturability of these filters. Although the filter designs are not the same as those of the participants, they do provide some insights into the issues faced in manufacturing complex filters, which may help readers to understand the contest results.

The design of the broadband transmission filter in the contest is relatively straightforward. There are two approaches to making the filter: deposit the filter coating on one side of the filter substrate, leaving the other side uncoated, or deposit the coatings on both sides of the substrate. In the latter case, the coating on the second side can be a simple antireflection coating or a complex multilayer filter coating just like on the first side. In our filter designs, we took the first approach, as did most of the participants (14 out of 17).

According to Fig. 1, the filter has high transmittance in most of the visible spectrum, and thus requires the use of transparent coating materials. Since the transmittance is only specified at normal incidence, two coating materials with high- and low-index would be sufficient. We therefore chose SiO_2 as the low-index material ($n_L = 1.46$) and Nb_2O_5 as the high-index material ($n_H = 2.30$). Both materials are commonly used in thin film filters and can be deposited by a variety of processes. All participants used two coating materials with low- and high-index materials.

We designed three filters with different numbers of total layers (L), total layer thicknesses (Σdi), and calculated MFs:

- Design 1: $L = 26$, Σdi = 2.050 μm, MF = 1.076,
- Design 2: $L = 68$, Σdi = 4.768 μm, MF = 0.475,
- Design 3: $L = 131$, Σdi = 8.230 μm, MF = 0.377.

The results of the three designs are shown in Fig. 2 in columns A, B, and C, respectively. The index profiles, the calculated transmittance (T), and the transmittance difference ($\Delta T = T - T^D$) are shown in rows 1, 2, and 3. The small total layer thickness in Design 1 is not sufficiently thick enough to obtain a filter that meets the target very well, especially in the wavelength region from 700 to 800 nm. This flat transmittance region between 700 and 800 nm was purposely introduced to make the problem more challenging. By roughly doubling the layer number L and the total thickness Σdi, we obtained a better Design 2 with a MF that is half of Design 1. Further doubling the layer number and the total thickness, however, did not reduce MF by half as seen in Design 3. As the number of layers and total thickness continues to increase, the improvement in MF becomes smaller and smaller. This observation is true for most of the filter designs, and thus thin film filter designers must make compromises in selecting an optimum range of L and Σdi according to filter specification.

During filter design and manufacturing, two types of errors could occur: refractive index errors and layer thickness errors. The former are caused by inaccurate refractive index measurements and the subsequent use of the inaccurate data in the filter design, or by the use of less stable deposition processes that cause refractive index variations from layer to layer. However, with more stable high-energy deposition processes such as ion-assisted deposition or sputtering, the index variations can be minimized. Our manufacturability study was thus limited only to thickness errors. These errors depend on the deposition process and the layer thickness monitoring method used. Three commonly used thickness monitoring methods in manufacturing thin film coatings are timing (for stable deposition processes), crystal monitoring, and optical monitoring with a single wavelength or a wideband. Crystal and optical monitoring are more complicated because their layer thickness errors could be accumulated and are both filter design and individual layer dependent. Therefore, we only considered the simpler case, the time monitoring process, in which the layer thickness errors are mostly independent of each layer and are much less correlated between layers than with optical monitoring, for example.

In the manufacturability simulations, we introduce a random layer thickness error in each layer of Designs 1, 2, and 3 and then calculate the transmittance differences for 20 simulations. The results are shown in Fig. 2 in rows 4 and 5. The root-mean-square (RMS) thickness error is 0.25 nm for row 4 and 1.00 nm for row 5. With a 0.25 nm RMS thickness error in row 4, a rather small value that is normally difficult to achieve, the calculated performances are very good in all three designs.

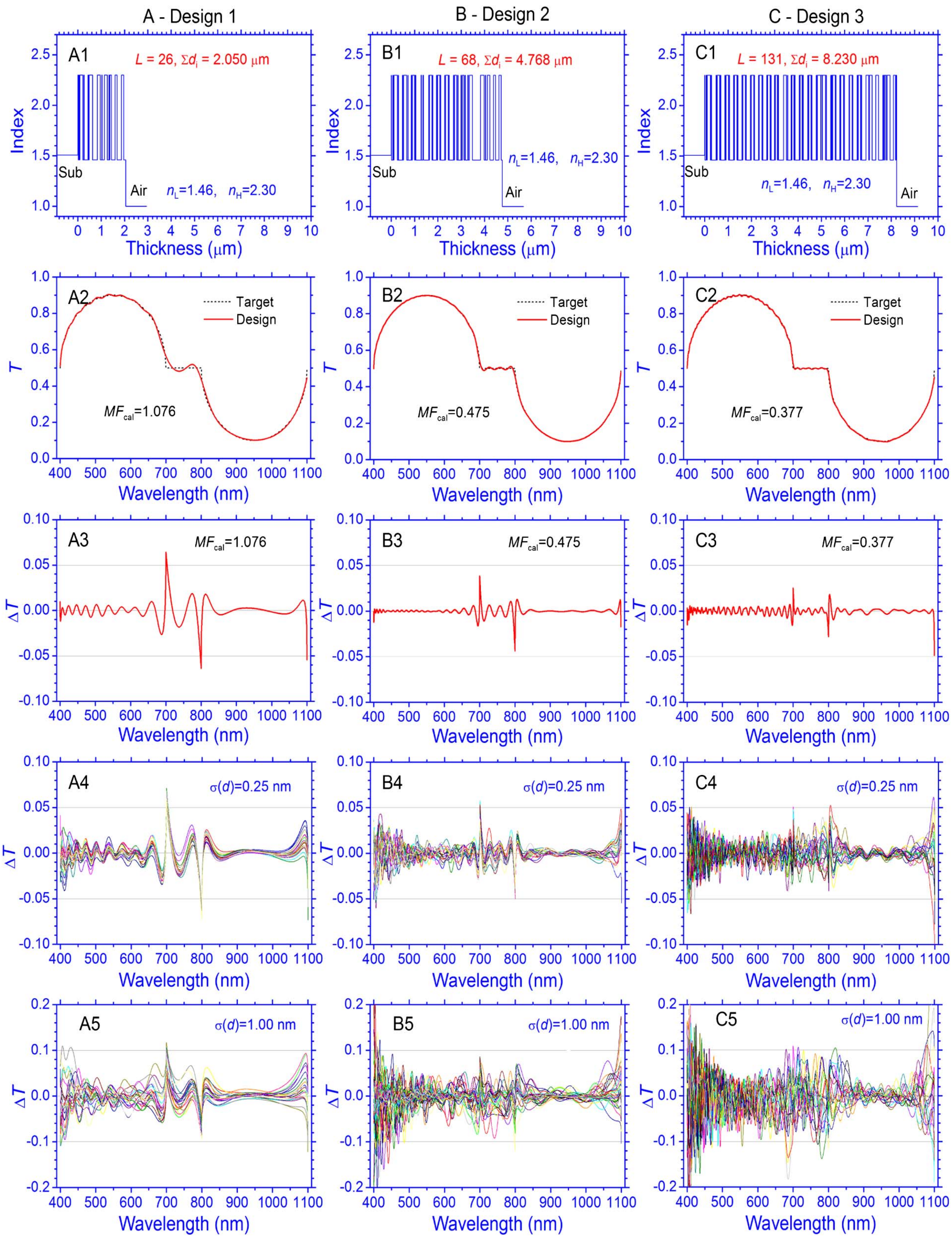


Fig. 2. Summary of the filter designs (rows 1–3) and error simulations (rows 4 and 5). Column A, Design 1; column B, Design 2; column C, Design 3. Row 1, refractive index profiles of the filter designs; row 2, calculated transmittance of filter design and targets; row 3, transmittance difference between the calculated transmittance and target; row 4, error simulation transmittance differences (RMS thickness error = 0.25 nm); row 5, error simulation transmittances (RMS layer thickness errors = 1.0 nm).

However, when a 1.0 nm RMS thickness error was introduced in row 5, the performance got much worse. Note that the vertical scale in row 5 is twice as that of row 4.

It is important to note that the influence of the thickness errors is different for the three designs (compare the diagrams in columns A, B, and C in the same row 4 or 5). The influence becomes more prominent with the increases in layer numbers and total layer thicknesses. This observation is generally true also for other thin film filters because the impact of layer thickness error usually adds up with the number of layers and total layer thicknesses. This influence becomes more visible when the errors increase from 0.25 to 1.00 nm (compare rows 4 and 5 in Fig. 2). The simulation results again demonstrate that filter designs with fewer layers or smaller total layer thicknesses are better choices if certain specifications can be met. The benefit of increasing the total layer thicknesses and the number of layers in order to reduce the MF and improve the filter performance often disappear when the errors are present.

4. Participation

For the 2013 contest, 17 samples were received from 15 teams composed of 37 people; these are the highest numbers among the contests held to date. The complete list of all the teams, team members, and their organizations are shown in Table 1, arranged in alphabetic order according to the last name of the first team member. The teams came from around the world: United States (7), Germany (2), Taiwan (2), Japan (2), China (1), and Canada (1). We hope teams from other countries will join the contest in the future.

We would like to remind future participants that information about the manufacturing problem contest is normally available on the OSA website the year before the OIC conference—this will be October 2015 for the 2016 contest. The deadline for submitting samples is around March 1.

5. Sample Evaluations

After the organizers received all the submitted samples, they were randomly assigned a sample number between S01 and S17. The original packages of the samples were removed and each sample marked with the assigned number for anonymous identification within the evaluation process. All samples were then placed in identical and numbered boxes and sent to the two evaluation labs, ODA and NIST. Both labs have provided evaluation services since the first contest in 2001; neither has any direct contact with the participants, and neither is allowed to submit samples to the contest.

The only measurements performed on the samples were the transmittance from 400 to 1100 nm at normal incidence. The measurement equipment used for the evaluations is listed in Table 2. The measurements were made as close to the center of the samples as possible. Great care was taken to achieve high accuracy. Overall, the measurements from the two labs were in good agreement for most of the samples. However, a few samples showed larger differences between the two measurements. These differences could be due to the use of different equipment or measurement conditions, or simply due to the nonuniformity in the filter coatings and slight discrepancy in the measured region. The average MFs calculated from the two labs' measurements were then used to rank the samples. The participants' measurements were used to identify potential problems.

6. Results and Discussion

The sample evaluation results are presented according the assigned sample numbers in Table 3. The table includes the filter designs (total number of layers and total layer thicknesses), the calculated and measured MF by participants, the measured

Table 1. Participating Teams in the 2013 OIC Manufacturing Problem Contest

Team No.[a]	Team Members	Organizations
1	R. Erz	JDSU, Santa Rosa, California, USA
2	E. Field, J. Bellum, and D. Kletecka	Sandia National Laboratories, Albuquerque, New Mexico, USA
3	R. Forgey	Hardin Optical Co., Bandon, Oregon, USA
4	Z. Gerig	Advanced Thin Films Inc., Boulder, Colorado, USA
5	K. Hendrix	JDSU, Santa Rosa, California, USA
6	J. Kao, D. Chiang, C. Hsiao, C. Lee, H. Chen, P. Chiu, W. Cho, B. Liao, and Y. Lin	Instrument Technology Research Institute, Hsinchu, Taiwan
7	M. Kato (submitted 2 samples)	Nikon Corporation, Tokyo, Japan
8	M. Lappschies and J. Brossmann	Optics Balzers Jena GmbH, Jena, Germany
9	C. Lee, K. Wu, and C. Kuo	National Central University, Chung-Li, Taiwan
10	P. Ma	National Research Council, Ottawa, Ontario, Canada
11	E. Nybank	JDSU, Santa Rosa, California, USA
12	G. Ockenfuss	JDSU, Santa Rosa, California, USA
13	M. Sugiura and K. Tamura	Tokai Optical Co., Ltd, Okazaki, Aichi, Japan
14	S. Wilbrandt, H. Haase, O. Stenzel, P. Munzert, U. Schulz, and N. Kaiser (submitted 2 samples)	Fraunhofer IOF, Jena, Germany
15	W. Yuan, W. Shen, Y. Zhang, and X. Liu	Zhejiang University, Hangzhou, Zhejiang, China

[a]There is no connection between team no. in this table and sample no. in the text.

Table 2. Summary of Measurement Equipment

	ODA	NIST
Equipment	Cary 5000 UV–VIS–NIR spectrophotometer	PerkinElmer Lambda 1050 UV–VIS–NIR spectrophotometer
Beams	Double-grating and double-beam	Double-beam
Wavelength range	180 to 3300 nm	175 nm to 3300 nm
Beam divergence	Horizontal, 3.2° half angle ($f/9$); vertical, 4.0° half angle ($f/7.2$); max. beam deviation from principal direction 0.8° (H) and 1.9° (V)	±5.0°
Light sources	Tungsten–halogen/deuterium lamps	Tungsten–halogen/deuterium lamps
Detectors	UV-extended photomultiplier/cooled lead sulfide detectors	UV-extended photomultiplier/ Peltier-cooled InGaAs detector
Transmittance accuracy	±0.1% in visible, ±0.2% in NIR	±0.1% in visible, ±0.2% in NIR
Wavelength accuracy	±0.08 nm in visible, ±0.4 nm in NIR	±0.08 nm in visible, ±0.30 nm in NIR

MFs calculated from the transmittance measurements by ODA and NIST, the average MF from the two labs, and the rank of the samples according to the average MF. Voluntary information provided by participants is also included in the table. The deposition processes used by some participants were sputtering or ion-assisted deposition, which was not a surprise since both processes are stable and produce good quality coatings.

Although the evaluation results are not linked to the participants, there are several ways that participants can identify their samples: by the number of layers, the total layer thicknesses, and their calculated and measured MFs. Here, we would like to remind participants to respect the anonymity rule for the benefit of all participants and future contests. We need to point out that there were slight differences between some participants' MFs and the ones presented in Table 3 due to the use of different total numbers of wavelengths; however, the small differences do not affect ranking. In the problem specification, only 350 wavelengths are selected (798 nm was not included). However, some participants used 351 wavelengths (including 798 nm) to calculate their MFs.

The evaluation results of all samples are also shown in Fig. 3 for samples S01 through S05, Fig. 4 for samples S06 through S10, Fig. 5 for samples S11 through S15, and Fig. 6 for samples S16 and S17. Each sample is represented by three diagrams in columns 1, 2, and 3 in the same row. The first

Table 3. Summary of Filter Designs, MFs, and Ranks

	Filter Design			MF by Participants		Measured MF by Two Labs				
Sample No.	No. of Sides Coated	L	Σd (μm)	Theory	Measured	NIST	ODA	Average	Rank	Additional Information Provided by Participants
S01	1	123	8.580	0.283	0.987	0.992	0.966	0.979	1	Magnetron sputtering
S02	1	22	1.859	1.960	2.314	2.234	2.342	2.288	9	Plasma-assisted deposition with rate 0.2 nm/s; all layers terminated using a wideband optical monitor
S03	1	100	8.693	0.360	11.687	14.483	14.941	14.712	13	
S04	1	116	6.366	0.700	2.278	2.095	1.939	2.017	7	
S05	1	22	2.154	1.500	18.482	18.257	18.015	18.136	14	
S06	1	142	7.932	0.401	1.031	0.984	1.121	1.052	2	Magnetron sputtering platform
S07	2	56 + 51	7.259	0.649	0.966	1.052	0.913	0.983	1	Coating materials SiO_2, Ta_2O_5
S08	1	30	2.208		2.772	3.041	3.094	3.067	11	High-index material Ta_2O_5
S09	1	76	4.036	0.530	0.959	1.001	1.010	1.005	1	
S10	1	83	5.243	0.380	2.027	1.543	1.592	1.568	4	Ion-assisted reactive sputtering; total deposition time 5.7 hrs; wideband optical monitoring
S11	1	55	4.169	0.492	1.600	1.520	1.591	1.555	4	
S12	1	136	9.222	0.359	2.561	2.453	2.547	2.500	10	Magnetron sputtering platform
S13	2	554 + 54	23.099	0.337	2.813	2.465	1.649	2.057	8	Magnetron sputtering platform
S14	1	38	2.500	0.420	1.850	1.953	1.813	1.883	6	
S15	2	24 + 4	2.733	1.160	1.674	1.727	1.949	1.838	5	Plasma-assisted deposition with rate 0.2 nm/s; all layers terminated using a wideband optical monitor
S16	1	36	2.585	0.816	3.240	3.334	3.113	3.224	12	
S17	1	76	4.036	0.530	1.062	1.095	1.120	1.107	3	

diagram (column 1) shows the target transmittance and the measured transmittance by the participants, and the measured transmittance by ODA and NIST with the calculated and average MFs. The second diagram (column 2) shows the transmittance differences measured by participants and the two labs. This diagram shows the same data as the first diagram; however, the transmittance difference is

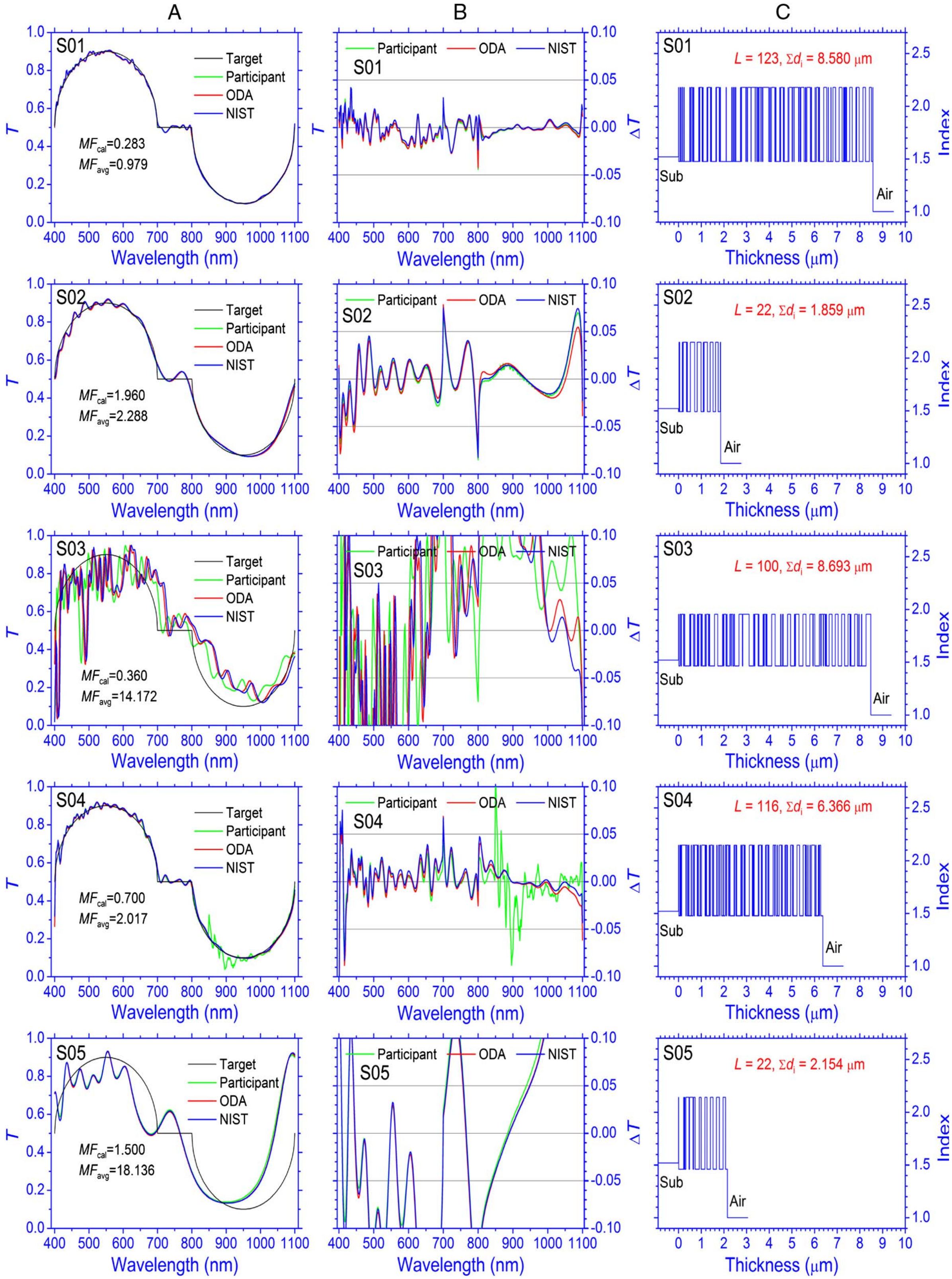


Fig. 3. Evaluation results of samples S01–S05. Column A, target and measured transmittance by participants, ODA, and NIST; column B, transmittance differences by participants, ODA, and NIST; column C, filter designs and index profiles of samples S01–S05.

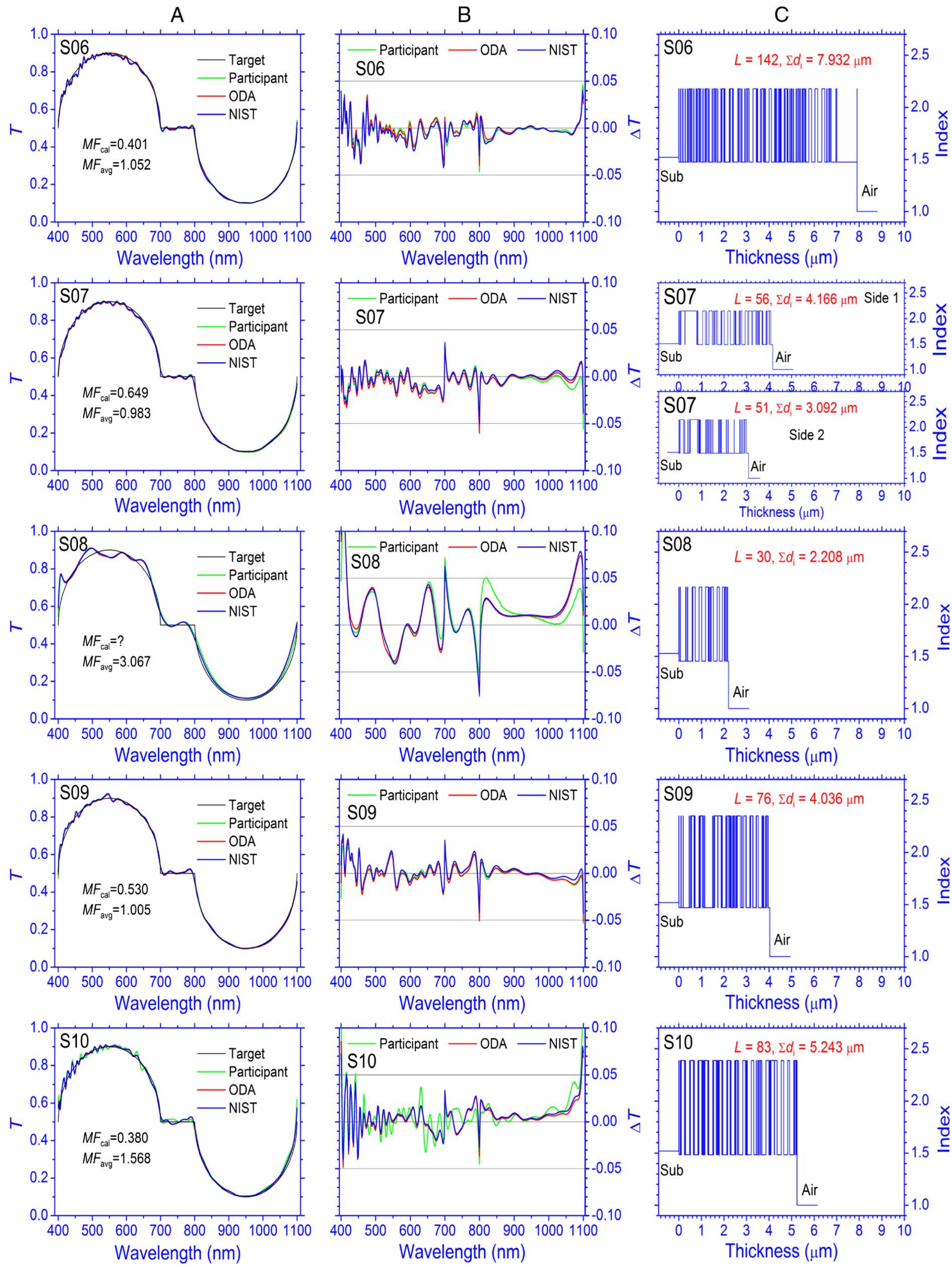


Fig. 4. Evaluation results of samples S06–S10. Column A, target and measured transmittance by participants, ODA, and NIST; column B, transmittance differences by participants, ODA, and NIST; column C, filter designs and index profiles of samples S06–S10.

more clearly shown. For comparison, all these diagrams in column 2 use the same scale even though some of the data points are off-scale and not plotted. The diagrams in column 2 enable participants to compare their measurements with those of the two labs and thus may help them to identify potential measurement issues in their own measurement equipment. The third diagram (column 3) shows

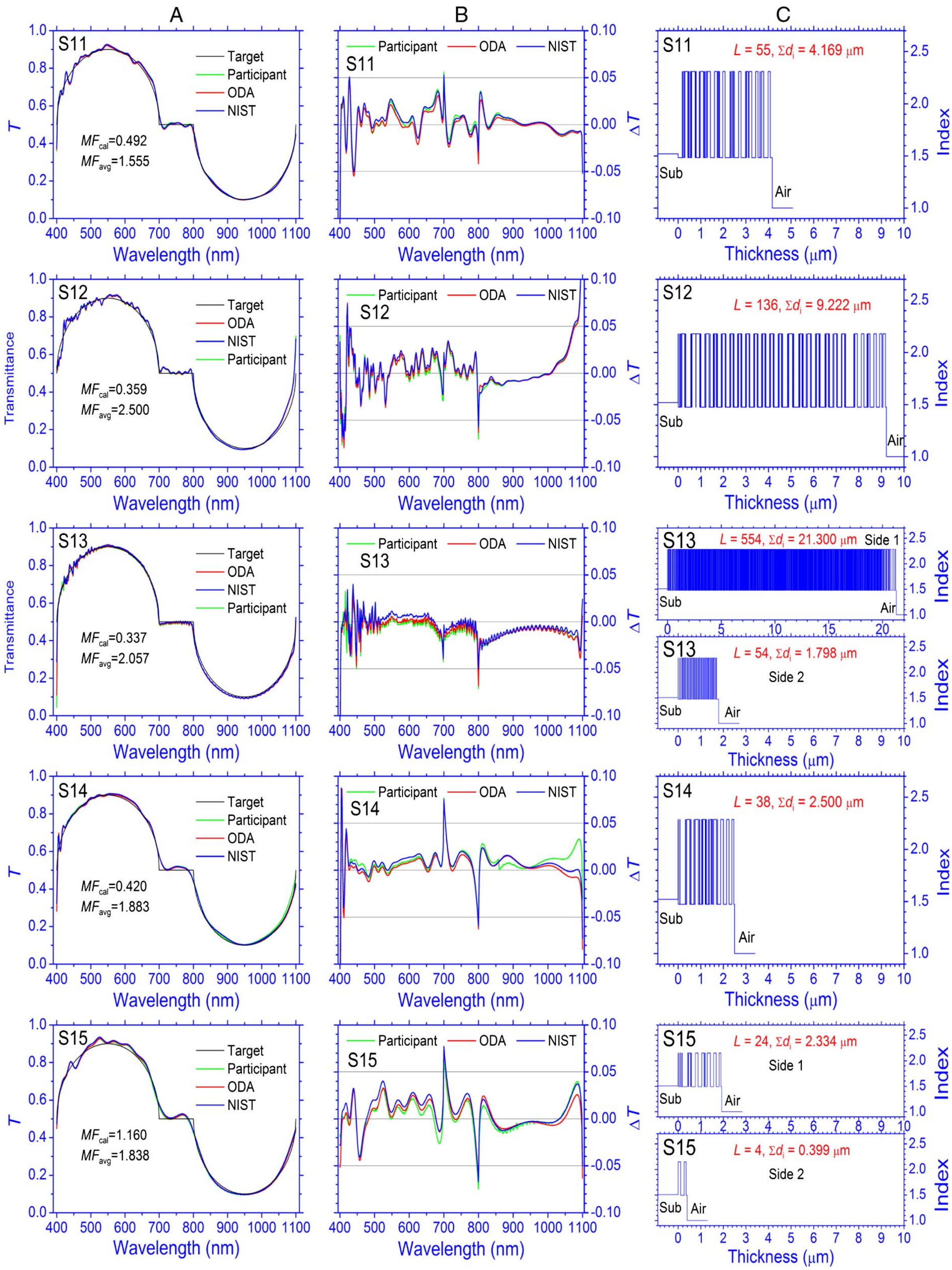


Fig. 5. Evaluation results of samples S11–S15. Column A, target and measured transmittance by participants, ODA, and NIST; column B, transmittance differences by participants, ODA, and NIST; column C, filter designs and index profiles of samples S11–S15.

the filter design with the index profile and the total number of layers and total layer thicknesses.

According to Table 1 and Figs. 3 through 6, we indeed see diverse solutions, even though only two coating materials were used by all participants. The total number of layers varies from 26 to 608, the total thickness from 1.859 to 23.099 μm, the calculated MFs from 0.283 to 1.960, and the average

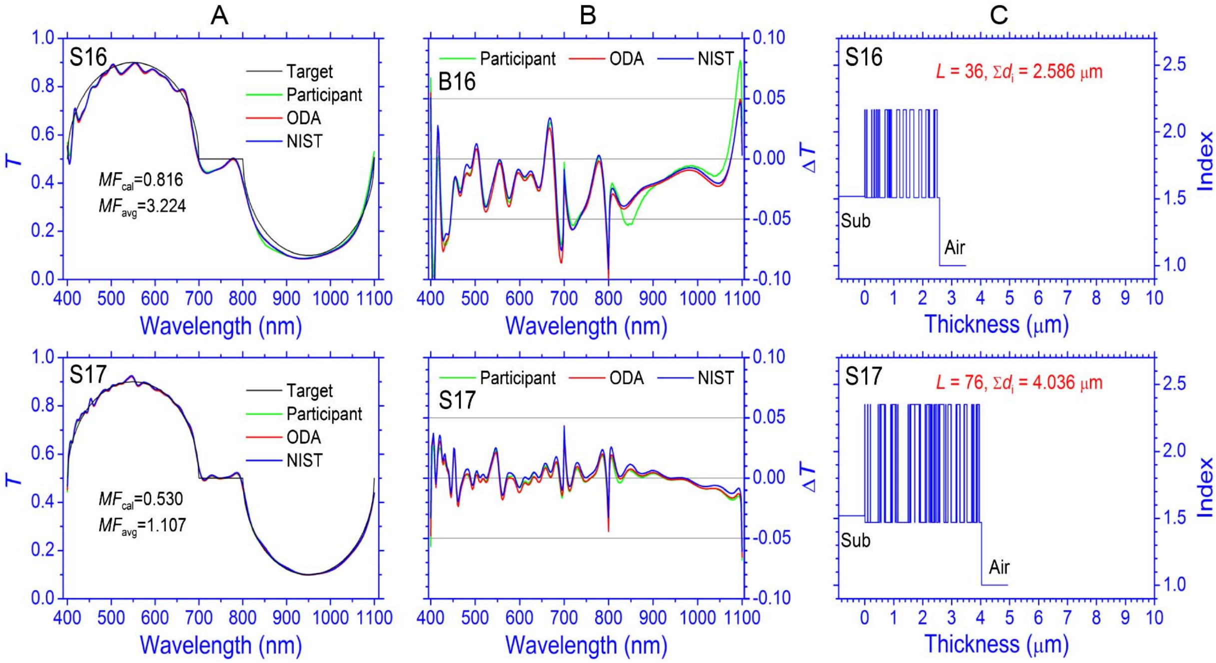


Fig. 6. Evaluation results of samples S16 to S17. Column A, target and measured transmittance by participants, ODA, and NIST; column B, transmittance differences by participants, ODA, and NIST; column C, filter designs and index profiles of samples S16 to S17.

measured MFs from 0.979 to 18.015. Apart from two samples (S03 and S05), the rest of the samples have average measured MFs below 3.1. Samples S07, S13, and S15 have coatings on both sides of the substrates and the rest of the samples have coatings only on one side of the substrates. These samples show a wide range of solutions and demonstrate the capability of making complex filters using present thin film manufacturing technology.

The average measured MFs of all samples are also plotted in Fig. 7 in order from lowest to highest. Three samples, S01, S07, and S09, have the lowest average measured MF of 0.979, 0.983, and 1.005, respectively. The MF differences among them are small and are within the measurement uncertainty of the equipment used; thus, we treated these three samples as having the same performance. This treatment also applies to samples S10 and S11.

For comparison, we also plot in Fig. 7 the corresponding calculated MFs for each sample. We can see that lower calculated MFs do not always result in lower measured MFs or better performance. The measured performance of the filters depends on many factors besides the filter design. One important factor is the thickness errors or refractive index errors in the manufacturing equipment used. The benefit of increasing the calculated filter performance by increasing the number of layers is often offset by these errors. Thus, in manufacturing thin film optical filters, compromises must be made to consider all issues that would affect the final performance of the filter and the manufacturing cost.

Another thing we would like to point out is that some participants' measured transmittances show larger differences from those of the two labs in some parts of the spectral region. We did not investigate the differences because it was not part of the requirement of the contest.

The total layer thicknesses of all samples are also plotted in Fig. 8 in order from lowest to highest on the left side of the plot; on the right side of the plot is the total number of layers. Sample S02 has the smallest number of layers ($L = 22$) and the total layer thickness ($\Sigma di = 1.859$ μm) and obtained an average MF of 2.29, which is very close to the calculated value of 1.96. Samples S05, S08, S12, S14, S15, and S16 have similar total layer thicknesses, falling between 2.154 and 2.773 μm, as do samples S19, S09, and S11, with total layer thicknesses between 4.036 and 4.169 μm. Samples S04, S07, S06, S01, S03, and S12 have a total layer thickness between 5.243 and 9.222 μm. Sample S13 is in a class by itself with the highest number of layers ($L = 608$) and the

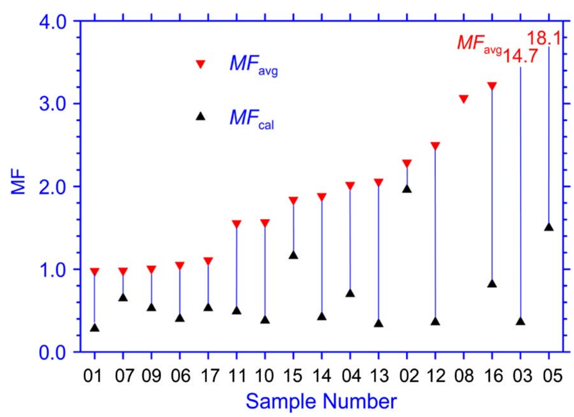
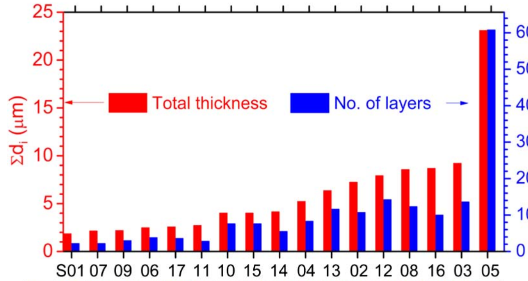


Fig. 7. Calculated MFs plotted against the average measured MFs for samples S01–S17.



MF_{avg}	2.29	18.1	3.07	1.88	3.22	1.84	1.11	1.01	1.56	1.57	2.02	0.98	1.052	0.98	14.7	2.500	2.06
Rank	9	14	11	6	12	5	3	1	4	4	7	1	2	1	13	10	8

Fig. 8. Total layer thickness (left axis) and the number of layers (right axis) for samples 01 to 17.

largest total layer thickness (Σdi = 23.099 μm), and achieved an average measured MF of 2.06 (calculated MF 0.337). For sample S13, except for a few wavelengths around 400 nm, the match between the measured transmittance and the target S13 is quite good. This is remarkable considering the very high L and Σdi.

The transmittances of the best samples S01, S07, and S09, having an average MF around 1.0, are also plotted in Fig. 9, with the wavelength region 400–750 nm on the top and 1100–750 nm on the bottom to form a graphically concise "transmittance circle." These samples were submitted by Nybank, Gerig, and Kato, respectively. We can see that the performance in the near infrared region is better matched to the target than in the visible because the thickness errors are smaller with respect to near-IR wavelengths than to visible wavelengths. This result is true for most of the other samples submitted.

To achieve a MF comparable to the best results of about 1.0, previous error simulations performed on the filter designs 1 to 3 by the organizers indicate that the RMS layer thickness error has to be 0.25 nm or less if no *in situ* optical measurement and real-time refinement are available. The simulations also show that, as total layer thickness and number of layers increase, the performance gets worse even for the same layer thickness errors. In

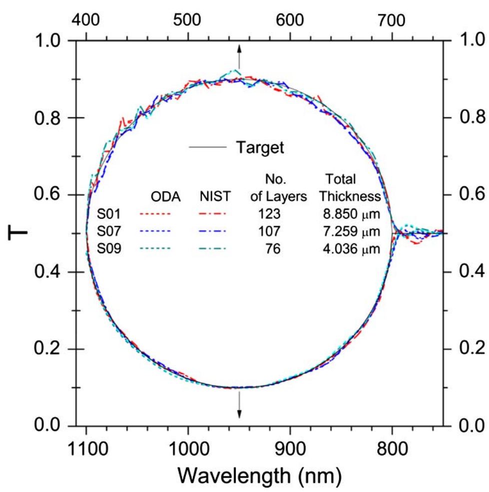


Fig. 9. Samples with the best result S01, S07, and S09.

view of this, the performance of sample S13 is remarkable, with the highest number of layers (608) and the largest total thickness of 23.099 μm.

7. Conclusion

A challenging broadband transmission filter, specified from 400 to 1100 nm, was selected for the 2013 Manufacturing Problem Contest. A total of 37 people from 15 teams participated in the contest and 17 samples were submitted with designs ranging from 22 to 608 layers and total layer thicknesses ranging from 1.859 to 23.099 μm. Two independent labs, ODA and NIST, carried out the sample evaluation measurements. The MFs calculated from the two labs' measurements were averaged to rank the samples. The MF values for all samples were between 0.979 and 18.015, and most were below 3.1. The samples with the best resulting MFs were nominally identical at around 1.0. Error simulations show that, as the total layer thickness and the number of layers increase, the performance gets worse. The diverse filter designs and obtained performance in the contest demonstrate the capability of the current thin film manufacturing technology in making complex optical coatings.

We would like to thank all the participants and their generous organizations. Clearly, their efforts are essential for the success of the contest. We are especially grateful to Edmund Optics for their continuing support in providing substrates to the contests since 2001.

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.

We here express our deep sorrow for the loss of our dear colleague, J. A. (George) Dobrowolski, on Feb. 12, 2013. George Dobrowolski and Steven Browning initiated the OIC Manufacturing Problem Contest in 2001 and George had been an organizer of all the contests since.

References

1. J. A. Dobrowolski, L. Li, M. Jacobson, and D. W. Allen, "2010 topical meeting on optical interference coatings: manufacturing problem," Appl. Opt. **50**, C408–C419 (2011).
2. J. A. Dobrowolski, S. Browning, M. Jacobson, and M. Nadal, "2007 topical meeting on optical interference coatings: manufacturing problem," Appl. Opt. **47**, C231–C245 (2008).
3. J. A. Dobrowolski, S. Browning, M. R. Jacobson, and M. Nadal, "2004 Optical Society of America's topical meeting on optical interference coatings: manufacturing problem," Appl. Opt. **45**, 1303–1311 (2006).
4. J. A. Dobrowolski, S. Browning, M. Jacobson, and M. Nadal, "Topical meeting on optical interference coatings (OIC'2001): manufacturing problem," Appl. Opt. **41**, 3039–3052 (2002).
5. L. Li and J. A. Dobrowolski, "2013 OIC Manufacturing Problem Contest," in *Optical Interference Coatings*, M. Tilsch and D. Ristau, eds., OSA Technical Digest (online) (Optical Society of America, 2013), paper WC.1.