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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1364/AO.50.00C408>

APPLIED OPTICS, 50, 9, pp. C408-C419, 2011-03-07

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2010 topical meeting on optical interference coatings: manufacturing problem

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Received 3 August 2010; accepted 4 November 2010;
posted 11 November 2010 (Doc. ID 132816); published 7 March 2011

For the 2010 Manufacturing Problem, the participants were required to produce a filter that had normal incidence transmittances of 0.001, 0.01, 0.1, and 0.96, respectively, in four separate 60 nm wide bands in the 400 to 700 nm wavelength region. The problem is not unlike those that need to be routinely solved in the telecommunication industry. Nine groups submitted a total of 11 different filters for the contest. The number of layers in the filters received ranged from 28 to 678, and the total metric thicknesses varied between 4,038 and 22,513 nm. The transmittances of the filters were measured at two independent laboratories. Some of the performances were quite close to the specifications. © 2011 Optical Society of America

OCIS codes: 120.2440, 310.1620, 310.1860.

1. Introduction

This year was the fourth time that a Manufacturing Problem was held at the OSA Topical Meeting on Optical Interference Coatings (OIC). Reports on the previous three Manufacturing Problems have all appeared in the special OIC issues of *Applied Optics* [1–3]. The basic premise of the Manufacturing Problem—to test the state of the art of manufacturing—has not changed throughout the years. For the problem, only the target performance and substrates are specified and the rest is completely up to the participants. They select the materials, number of layers, and the overall thickness of the thin film design and choose the deposition and monitoring process that they feel will permit them to obtain the closest fit to the specified performance of the coating. There is no need to disclose the materials that they use, but sufficient information must be provided for the plotting of the refractive index profile of their

solution. To facilitate the measurement of the submitted samples at two independent laboratories, the participants are asked to refrain from using toxic materials in their solutions and to deposit their layer systems onto substrates provided by the organizers. Two independent laboratories evaluate the performances of all submitted filters. The only measurements performed on the samples are transmission and/or reflection measurements, and the samples are returned to the participants after the event. The participants are also asked to provide a normal incidence transmittance of their sample—this helps to detect problems during the measurement.

As in the previous manufacturing problem, the results are presented here in an anonymous fashion. All submitted samples were assigned a number and the results are reported here without reference to their source. However, the participants can still recognize their own samples from the refractive index profiles and thus find their ranking compared to the other submitted samples. This policy again resulted in a larger participation in the exercise.

2. Definition of the Problem

For each Manufacturing Problem, the organizers strive to find a filter that will test various aspects of the manufacture of complex multilayer coatings. Each participating team needs to design their filter, characterize their coating processes, manufacture the filter, make measurements, and finally submit their filter to the organizers in order for it to be evaluated by independent measurement laboratories. The 2001 problem tested the ability to produce filters with very irregular spectral transmittance and reflectance characteristics and, for the best results, the solution required the use of nonabsorbing coatings. The 2004 problem was designed to test how closely people could produce polarizing beam splitters for a 60° angle of incidence. Since the two transmitted beams only were specified, absorbing materials were not ruled out. In this problem, the oblique angle measurements were somewhat challenging. In the 2007 problem, participants had to produce samples that would transmit white light, but reflect yellow and blue light from the filter's two surfaces, with all beams appearing to be of equal brightness. This problem certainly could not be solved without the use of absorbing materials.

The 2010 Manufacturing Problem was designed to see how well people could produce coatings with several orders of magnitude differences in transmittance. We decided that the desired performance of the multilayer coating would be specified entirely in terms of normal incidence transmittance, which would also include the contribution of the second surface of the substrate. It did not rule out solutions in which the layers were deposited onto both sides of the substrate.

The target transmittance is plotted in Fig. 1 on a logarithmic scale, and consists of four wavelength bands: 400–460, 480–540, 560–620, and 640–700 nm. Each wavelength (WL) region is defined at $m = 31$ wavelengths that are 2 nm apart (Table 1). The target transmittances T_k^D and their tolerances ΔT_k for the four regions k ($1 < k < 4$) are 0.001, 0.01, 0.1, 0.96, and 0.0001, 0.0005, 0.002, and 0.01, respectively. These values of the tolerances were chosen because it was felt that they would be approximately equally difficult to achieve. Note that the above definition did not rule out solutions in which the layers were deposited onto one surface of the substrate only. The merit function MF used to rate the performances of the submitted samples was defined by the equation

$$\text{MF} = \left\{ \frac{1}{mk} \sum_{j=1}^4 \sum_{i=1}^{31} \left(\frac{T_{ij} - T_j^D}{\Delta T_j} \right)^2 \right\}^{1/2}, \quad (1)$$

where T_{ij} is the measured transmittance at the i th wavelength in the j th transmission region.

3. Discussion of the Problem

The problem is not unlike the problems that need to be solved in the telecommunication industry, and we

Fig. 1. (Color online) Definition of the 2010 Manufacturing Problem.

felt that the challenges in this problem would be the reproducibility of the optical constants, the precise layer thickness control, and the accurate measurement of the low transmittance values.

As on previous occasions, to ensure that the problem was reasonable, we investigated different solutions to ensure that there were at least some that were not unduly sensitive to random layer thickness errors, either relative in percentage or absolute in nm. We also wanted to make sure that solutions existed that consisted of a reasonable number of layers; we felt that otherwise, the number of participants in the exercise would be sharply reduced.

In our exploratory calculations we used nondispersive, nonabsorbing optical constants with refractive indices that roughly corresponded to those of SiO_2 and Nb_2O_5 . It is our experience that any solution obtained in this way will be very close to one obtained with dispersive constants after a little refinement of the layer thicknesses. Figure 2(a) represents the refractive index profile of a 40-layer solution with a

Table 1. Definition and Tolerances for the 2010 Manufacturing Problem

k	Wavelength Range (nm)	Target T_k^D	Tolerance ΔT_k	WL Interval	Number of WL (m)
1	400–460	0.001	0.0001	2 nm	31
2	480–540	0.01	0.0005	2 nm	31
3	560–620	0.1	0.0020	2 nm	31
4	640–700	0.96	0.01	2 nm	31

total metric thickness $\Sigma(d) = 2,770$ nm. The target and calculated transmittance curves for this system are depicted in Fig. 2(b). The merit function for this system calculated using Eq. (1) has a value $MF = 2.96$. In Figs. 2(c) and 2(d) are the corresponding results for a 56-layer system with $\Sigma(d) = 5,300$ nm and with a six-time reduction in the merit function value $MF = 0.500$. Finally, Figs. 2(e) and 2(f) show the results for a 130-layer system with $\Sigma(d) = 11,937$ nm. The calculated merit function value is now only 0.0012. Clearly, by further increasing the number of layers and the total metric thickness of the system, even lower values of the merit function could have been obtained.

In Figs. 3(a) and 3(b) are shown the effects of 1% and 1 nm random errors of the thicknesses of the individual layers of the system depicted in the first row of Fig. 2. The error corridors plotted in these figures are based on the transmittance curves of 50 ran-

domly generated layer systems. The transmittance curves of about 66% of the generated filters with such errors lie within these corridors. Such narrow error corridors indicate that the filter can be satisfactorily manufactured if the specified errors were accurate. Rows 2 and 3 of this same figure show the corresponding error corridors for the systems depicted in rows 2 and 3 of Fig. 2. It can be seen that, for the same random thickness errors, although the filters have lower designed merit function values, they are more sensitive to thickness errors, as demonstrated by the increased error corridor widths. This means that the full benefit of the lower merit function values can be realized only if more accurate deposition processes are available, and therefore, that the complexity of the filter designs should take into consideration the capability of the deposition process to be used.

Fig. 2. (Color online) Exploratory 40- (a), (b), 56- (c), (d), and 130-layer (e), (f) solutions with $MF = 2.96$, 0.500, and 0.0012, respectively. Column 1, the refractive index profiles; column 2, the target and calculated transmittances of the three designs.

Fig. 3. (Color online) Error corridors for the 40- (a), (b), 56- (c), (d), and 130-layer (e), (f) solutions shown in Fig. 2. Columns 1 and 2 show the sensitivity to 1% and 1 nm rms metric thickness errors in the individual layers, respectively.

Apart from the above direct solutions, we also considered several other approaches to the design of such filters. We tried superimposing three minus filters with transmittances of 0.001, 0.01, and 0.1 in the appropriate spectral regions on either one, or both surfaces of the substrate. Both of these approaches required additional layers and were more sensitive to thickness errors than the direct solutions. Depositing identical coatings on the two surfaces with a transmittance equal to the square root of the desired transmittance was also not promising. Finally, we hoped that someone would try to deposit the filter in two stages. In the first stage they would design, deposit, and measure a filter with a transmittance that is just slightly higher at all wavelengths than the target values, and then, after a careful measurement of the performance of this

first filter, design and deposit a second correcting coating on the second surface of the substrate. This second coating should be simpler, consist of fewer layers, and presumably be easier to deposit accurately. Together with the first coating, one would expect a better final result.

4. Measurement Equipment

This time again we were fortunate to have the collaboration of Optical Data Associates (ODA) and of the National Institute for Standards and Technology (NIST) with the measurement of the submitted samples. Michael Jacobson at ODA used an Agilent Cary 5000 UV-Vis-NIR double grating, double beam spectrophotometer ($180 < \lambda < 3300$ nm). This instrument used tungsten-halogen/deuterium lamp sources and UV-extended photomultiplier/cooled lead sulfide

detectors. The horizontal and vertical f -numbers and the maximum departures of the illuminating beam from the principal direction were 9, 7.2, and 0.8°, 1.9°, respectively. A conservative error estimate for measurements on this instrument in the $400 < \lambda < 600$ nm spectral region is 0.2%.

David Allen, at NIST, used a Lambda 1050 Perkin Elmer double grating, double beam spectrophotometer ($180 < \lambda < 3300$ nm) with a 3D detector accessory for his measurements. The instrument used a tungsten-halogen lamp light source and a photomultiplier detector. The normal incidence transmittance was measured in the 400 nm to 700 nm wavelength range at 2 nm increments with a 1.5 nm bandpass. Please note that the mention of a commercial product by NIST is intended to foster understanding and not to imply a product endorsement.

5. Participants

The 2010 Manufacturing Problem, as defined in Section 2, was posted in advance on the OIC web site, as usual. Nine different teams contributed a total of 11 samples to the Manufacturing Problem. Two groups submitted two samples, which were nominally the same. This means that there were nine distinct solutions. Participant names with their institutions, postal, and e-mail addresses are arranged in Table 2 in alphabetical order of the first team member. The participants come from four different countries and three different continents and represent commercial companies, research institutions as well as universities.

The participants once again provided some details about the processes used for the manufacture of their samples. To maintain anonymity, the comments listed below do not provide information on the number of layers, overall thicknesses, or materials used in the samples because such details might make possible the linking of the samples to the participants.

All three teams from JDS Uniphase (JDSU), K. Hendrix *et al.*, A. Hulse *et al.*, and G. Ockenfuss *et al.*, used their fast-cycle magnetron sputter platform (Ucp-1), and they used deposition rates of about 1 nm/s to produce their samples. A good description of their apparatus will be found in Ref. [4].

M. Lappschies and S. Jakobs, Optics Balzers Jena GmbH, utilized the plasma-assisted reactive magnetron sputtering (PARMS) process provided with the Leybold Optics HELIOS deposition plant [5,6]. Optical broadband monitoring was used for thickness control; it measures the transmittance on a witness sample placed among the substrates, which rotate at 240 rpm. The deposition rates were 0.5 nm/s and 0.35 nm/s. C.C. Lee and C.C. Kuo, Thin Film Technology Center National Central University, used a dual electron beam gun coating system with a 16 cm RF ion-beam source [7,8]. The substrate was heated to 220 °C and the deposition rates for the dielectric layers were 0.25 and 1.0 nm/s.

P. Ma and F. Lin, National Research Council, produced their sample on a fully automated magnetron sputtering system equipped with an *in situ* wideband optical monitor. The layers were reactively sputtered from two metallic targets, using deposition rates of 0.3 to 0.5 nm/s.

C. Montcalm, M. Briere, and R. Rinfret, Iridian Spectral Technologies, deposited their sample in a fully automated deposition system using reactive magnetron sputtering and *in situ* optical monitoring [9].

D. Poitras and X. Tong, National Research Council, deposited their layer system in a dual ion-beam sputtering system (SPECTOR, by Veeco-IonTech) equipped with a NRC-developed wideband optical monitor. The system was fully automated and incorporated thickness determination and design re-optimization. No attempts were made to measure the performance of the coating, other than to check the final monitoring transmission curve obtained when the fabrication was finished [10].

Table 2. Participants in the Manufacturing Problem

Team	Name, Institution	Postal Address	E-mail Address
1	K. Hendrix <i>et al.</i> , JDSU	2789 Northpoint Pkwy, Santa Rosa, CA 95407, USA	Karen.Hendrix@jdsu.com
2	A. Hulse <i>et al.</i> , JDSU	2789 Northpoint Pkwy, Santa Rosa, CA 95407, USA	Andy.Hulse@jdsu.com
3	M. Lappschies and S. Jakobs, Optics Balzers Jena GmbH	Carl-Zeiss-Promenade 10, 07745 Jena, Germany	Marc.Lappschies@opticsbalzers.com
4	C. C. Lee and C.C. Kuo, Thin Film Technology Center, National Central University	300 Chung-Da Rd. Chung-Li, Taiwan	CCLee@dop.ncu.edu.tw
5	P. Ma and F. Lin, National Research Council of Canada	1200 Montreal Rd., Ottawa, Ontario K1A 0R6, Canada	Penghui.Ma@nrc.gc.ca
6	C. Montcalm, M. Briere, and R. Rinfret, Iridian Spectral Technologies	1200 Montreal Rd., Ottawa, Ontario K1A 0R6, Canada	Claude.Montcalm@iridian.ca
7	G. Ockenfuss <i>et al.</i> , JDSU	2789 Northpoint Pkwy, Santa Rosa, CA 95407, USA	Georg.Ockenfuss@jdsu.com
8	D. Poitras and X. Tong, National Research Council of Canada	1200 Montreal Rd., Ottawa, Ontario K1A 0R6, Canada	Daniel.Poitras@nrc.ca
9	D. Rademacher and M. Vergöhl, Fraunhofer Institute for Surface Engineering and Thin Films	Bienroder Weg 54E, 38108 Braunschweig, Germany	Daniel.Rademacher@ist.fraunhofer.de

Fig. 4. (Color online) Spectral transmittances and refractive index profiles of the distinctive solutions submitted to the 2010 Manufacturing problem: sample S02 ($MF_{\text{avg}} = 13.12$) and sample S04 ($MF_{\text{avg}} = 1.037$)

D. Rademacher and M. Vergöhl, Fraunhofer Institute for Surface Engineering and Thin Films, deposited their filter in a rotating/oscillating pattern

sputter coater (DYSCUS) equipped with mid-frequency magnetron sputter sources (ISTMag 650). Process stabilization was performed by oxygen

Fig. 5. (Color online) Spectral transmittances and refractive index profiles of the distinctive solutions submitted to the 2010 Manufacturing problem: samples S05 ($MF_{\text{avg}} = 1.711$) and S06 ($MF_{\text{avg}} = 1.793$).

partial pressure control using a lambda probe. Here the power output of the generator was the control value. The refractive indices of the materials were determined by *ex situ* spectral ellipsometry prior to

the coating. A broadband transmission monitoring system (part of MOCCA+) was used for fully automated coating. In order to determine the remaining oscillations of the substrate beneath the target, layer

Fig. 6. (Color online) Spectral transmittances and refractive index profiles of the distinctive solutions submitted to the 2010 Manufacturing problem: samples S07 ($MF_{\text{avg}} = 23.19$) and S08 ($MF_{\text{avg}} = 2.526$).

thicknesses were calculated by *in situ* monitoring. Then, the deposition rate was continuously fitted and the remaining oscillations were calculated and used to stop each layer. In this process, the transition mode with mean power densities of approximately

2 W/cm² was used, which resulted in deposition rates of about 0.5 nm/s. This relatively low deposition rate was used to counterbalance the systematically created thickness errors by the oscillating pattern, which resulted in discrete layer growth.

Fig. 7. (Color online) Spectral transmittances and refractive index profiles of the distinctive solutions submitted to the 2010 Manufacturing problem: samples S09 ($MF_{\text{avg}} = 1.608$) and S10 ($MF_{\text{avg}} = 11.22$).

6. Measurement Results

In this section, we provide the refractive index profile of the layer system for the nine significantly different submitted samples, as well as a comparison with the

target values of the transmittance measurements provided by the two measurement laboratories and by the participants. However, on diagrams of the type used in Figs. 1–3 in which the transmittance is

Fig. 8. (Color online) Spectral transmittances and refractive index profiles of the distinctive solutions submitted to the 2010 Manufacturing problem: sample S11 ($MF_{\text{avg}} = 4.335$).

plotted on a four-decade long logarithmic y axis, it would be difficult to discern the four different curves, especially if the measurements were in good agreement with each other. We have therefore decided to present the measurement results for each sample in a set of four graphs—three one-decade long logarithmic diagrams for the lower transmittance ranges, and a linear scale diagram for the highest transmission level. However, with such a representation, this set of graphs is displayed here as multiple images in Figs. 4–8.

The number of layers and the overall metric thickness of the systems are listed within the refractive index profile graph for each sample, and the average merit function of the NIST and ODA measurements is provided in the figure caption. For example, the layer system of sample S02 was 7,239 nm thick and it consisted of 102 layers, and the average merit function value was $MF_{\text{avg}} = 13.124$ (see Fig. 9). It will be seen from an examination of these diagrams that the number of layers in the filters received ranged in value from as small as 28 to as large as 678, and that the total metric thicknesses varied between 4,038 and 22,513 nm. In two of the samples (S04, S05), the layers were applied to both sides of the substrate. The refractive index profile for the 678-layer solution (S04) had to be represented using two lines. For this, and some other solutions consisting of many layers, the refractive index profiles provide little more than just an idea of the great complexity of

the coatings. It will also be seen from these diagrams that some of the measured transmittances were remarkably close to the target values. On the whole, the results obtained at the two measurement laboratories were in quite close agreement with each other. As we suspected, a few of the participants experienced difficulties in performing low-transmittance measurements.

Fig. 9. (Color online) Measured MF_{avg} versus calculated merit function values.

Table 3. Summary of the Designs and Merit Functions

Sample	Sides Coated	Total Layer		MF by Participants		MF by Metrologists			Rank
		N	$\Sigma(d)$	Theory	Measured	NIST	ODA	Average	
S01	1	45	4037.6	1.000	2.341	2.692	2.549	2.621	6
S02	1	102	7238.6	0.133	14.596	13.455	12.793	13.124	9
S03	1	102	7238.6	0.133		12.883	13.566	13.225	10
S04	2	480 + 198	22512.9	0.042	0.973	0.996	1.078	1.037	1
S05	2	92 + 14	8663.3	0.213	1.855	1.669	1.753	1.711	3
S06	1	73	5480.3	0.447	1.663	1.770	1.815	1.793	4
S07	1	59	5326.3	0.616	27.138	22.754	23.630	23.192	11
S08	1	45	4037.6	1.000	2.396	2.593	2.458	2.526	5
S09	1	97	9133.8	0.195	1.386	1.683	1.532	1.608	2
S10	1	58	4868.0	0.664	13.724	11.242	11.187	11.215	8
S11	1	28	4213.7	4.210	6.310	4.189	4.480	4.335	7

Fig. 10. (Color online) Bar charts of the measured merit functions MF_{avg} , the number of layers N , and the total metric thicknesses $\Sigma(d)$ for the various samples.

Fig. 11. (Color online) Manufacturing Problem team (left to right): David Allan, Li Li, Michael Jacobson, and George Dobrowolski. Unfortunately, David was unable to attend the conference.

7. Discussion and Conclusions

Because Figs. 4–8 extend over several pages, it was deemed necessary to summarize the results in Table 3, where some additional information is also provided. For each sample, the table lists the number of substrate sides coated, the total number of layers and overall metric thickness of the system, the theoretical and measured values of the merit functions provided by the participants, the merit function values measured by the two laboratories and their mean value MF_{avg} , and finally, the ranking of the sample. Note that this table provides also information for the two nominally identical samples that were not included in the diagrams of Figs. 4–8, where only the better of each pair is shown.

In the double logarithmic scale diagram of Fig. 9, the measured MF_{avg} are plotted as a function of the calculated merit function values for all the submitted samples. If the experimental and calculated merit functions were the same, they would lie on the heavy dotted curve in this diagram. Of course, it is not

surprising that as the calculated merit function gets smaller and smaller, the discrepancy between the measured and the calculated values gets larger. Only one of the submitted samples (S11) was located on this line. But this system consisted of only 28 layers and thus was the simplest design submitted, and clearly the process used for its deposition was sufficiently well controlled to achieve close to the calculated merit function value. It will also be seen from this diagram, that, with progressively lower calculated merit function values, for most of the samples submitted, the measured merit functions tended towards an asymptotic value of about 1.0. This is in agreement with the conclusion arrived at in the discussion of Fig. 3, namely that a lower calculated merit function for this example is useful only if it is accompanied by a higher layer-thickness monitoring precision.

For an even better overview, we also provide a bar chart (Fig. 10). Here the submitted samples are arranged in order of increasing measured average merit function values (i.e., according to their ranking in Table 3). Also shown in this diagram are the corresponding numbers of layers and the overall thicknesses of the solutions. Not surprisingly, the better solutions are obtained with systems that consist of a larger number of layers and have greater overall thicknesses.

In general, the organizers of this Manufacturing Problem (Fig. 11) were quite pleased with the response from the optical thin film community. The number of participants and samples was smaller than at the 2007 meeting, but it was still very satisfactory. The lower participation probably was due to the difficulty of the problem. The organizers had hoped that some participant would have chosen to deposit the filter in two stages, with the second surface carrying a correcting coating, as outlined in Section 3.

Before the conference, we polled all past and present participants concerning their views on the anonymity question. Most responses favored maintaining anonymity, but would not object if the name and affiliation of the team with the best result were disclosed. This would permit the organizers to prepare a special plaque for this event.

The organizers are always glad to receive suggestions for the next Manufacturing Problem.

We would like to thank Edmund Optics once again for donating substrates for this year's Manufacturing Problem. We are also very grateful to the OIC organizing committee for covering the cost of shipping of the samples between the measurement laboratories, for providing money to purchase small mementos for each team that participated in this year's event, and for covering the page charges for this article.

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