Published in final edited form as:

Appl Opt. 2020 February 10; 59(5): A31–A39. doi:10.1364/AO.59.000A31.

2019 Topical Meeting on Optical Interference Coatings: Manufacturing Problem Contest [Invited]

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Abstract

For the Seventh Manufacturing Problem Contest, participants were challenged to fabricate an optical filter with transmittance specified for s-polarization at two incident angles 10° and 50° from 400 nm to 1100 nm. The problem required that contestants be equally versed in the design, deposition, and measurement of optical filters in order to achieve good results. Eight teams from five different countries participated in the contest using various deposition techniques. The fabricated filters had a total thickness between 8.2 nm and 17.6 μm and a total number of layers from 74 to 255 layers that were deposited onto one or both sides of the substrate. The performances of the filters were measured by two independent laboratories. The evaluation results were presented at the Topical Meeting on Optical Interference Coating conference held in Santa Ana Pueblo, New Mexico in June 2019.

1. Introduction

At OSA's triennial Topical Meeting on Optical Interference Coatings (OIC), it is traditional to present the results of three events organized for this conference: design, measurement and manufacturing contests. Far from being solely competitive, these contests are instructive to the whole thin-film community, as they feature state-of-the-art technologies and methods while sometimes revealing shortcomings.

This article presents the results of the latest Manufacturing Problem Contest, which challenges participating teams to design and fabricate an optical coating with specific spectral characteristics. This exercise requires the participants to wisely combine their design and measurement skills with a fair dose of 'craftsmanship' in the precise control of complex multilayer optical coating deposition.

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The 2019 Manufacturing Problem Contest is the seventh; results of the first six are found in Refs. [1–6]. This time, participants were required to design and fabricate a filter with specific transmittance T spectra at two different oblique angles of incidence (AOI) for polarized light. The substrates were identical N-BK7 blanks sent to all participants with a maximum of three per team. After design, deposition, and measurements, the teams submitted their samples to the organizers along with certain specifications, some of which were optional. The filters were then evaluated by two independent laboratories: Optical Data Associates (ODA) and the National Institute of Standards and Technology (NIST). After an analysis of these measurements, the results and the rankings were presented at the OIC 2019 conference.

In Sections 2 and 3, the problem is described and discussed. Sections 4 and 5 provide participant information and the independent evaluation, respectively. The results appear in Section 6, followed by conclusions in Section 7.

2. Formulation of the problem

Since the first Manufacturing Problem Contest in 2001, the difficult task for the contest organizers has been to challenge the state-of-art in optical coating capability. In addition, the project must not have any practical use or commercial value so that contestants would not have to reveal any intellectual property. In the past, filter profiles involving relevant geographical and other features have been involved [1–6].

For the 2019 contest, we chose an image of a yucca plant (*Genus Yucca*), one of the state symbols of New Mexico, the host state for this meeting. The plant's profile defined the target spectra (see Fig. 1). The problem involved T spectra specified for wavelengths between 400 nm and 1100 nm, at 10° and 50° AOI and s-polarized light. One incentive was the continuing and unappreciated challenge of making accurate T measurements at oblique AOI. A list of numerical values for the specification appears as a supplement to this article [7].

For the filter design and evaluation, the performance of the filter was assessed using the following merit function (MF):

$$MF = \left\{ \frac{1}{(N_{10} + N_{50})} \left[\sum_{i=1}^{N_{10}} \left(\frac{T_{s10,i} - T_{s10,i}^D}{\Delta T_{s10,i}} \right)^2 + \sum_{i=1}^{N_{50}} \left(\frac{T_{s50,i} - T_{s50,i}^D}{\Delta T_{s50,i}} \right)^2 \right] \right\}^{1/2}, \quad (1)$$

where $T_{s10,i}$, $T_{s10,i}^D$ are the measured and target T values at 10° AOI, and $T_{s50,i}$, $T_{s50,i}^D$ are the measured and target T values at 50° AOI, both for s-polarized light, at the specified wavelength λ_i ; N_{10} and N_{50} are the total number of wavelengths defining $T_{s10,i}^D$ and $T_{s50,i}^D$ targets; $\Delta T_{s10,i}$ and $\Delta T_{s50,i}$ are the T tolerances, set to 0.01 for all wavelengths.

No specific coating materials were required. However, toxic and radioactive materials, such as ZnSe and ThF₄, were excluded; delicate, soft materials that would be degraded by handling during evaluation were discouraged.

The coatings were to be deposited on N-BK7 substrates (50 mm diameter $\times$ 1 mm thick) provided by the contest organizers. To minimize the influence of any form of anisotropy or thickness non-uniformity on the evaluation, participants were asked to mark their preferred axis of rotation for measurements at oblique incidence with two black dots drawn near the opposite edges on the coating side.

Along with the samples, the participants had to provide their refractive index profiles and their T data. It was suggested that they add some background on their design and fabrication processes.

Samples were evaluated as described in Section 5. Apart from T measurements, the samples were not subjected to any surface analyses, such as Auger spectroscopy or scanning/transmission electron microscopy (SEM/TEM). All samples were returned to the participants after the presentation of the results.

3. Problem Discussion

3.1 Design

To confirm that the Yucca problem could be solved using commonly available coating materials and deposition techniques, we explored designs in which the low index material was SiO_2 and the high index material was selected from TiO_2 , Al_2O_3 , Nb_2O_3 , or Ta_2O_5 . Most optical constants were from Palik [8]. Our investigation revealed that many relatively good design solutions ($MF < 5$) employed various materials, the thicker, more complex designs generally led to lower MF values.

We also examined the effect of coating one or both surfaces of the substrate. Figure 2 shows two examples of designs based on SiO_2 and TiO_2 layers:

- A. 50-layer, 3.8 μm thick coating on the front-side, and a
- B. 30-layer, 2.7 μm thick coating on the front and a 24-layer, 1.7 μm thick coating on the back.

Figures 2(b) and (d) compare the calculated T spectra for these designs with the target spectra (bottom darker part of the green leaf silhouettes). Interestingly, we see that although both designs have roughly the same number of layers and total film thicknesses, the design involving both surfaces of the substrate led to much smoother T spectrum and result in a lower MF value.

To investigate the cause of the smoother T spectra for double-sided designs, we simulated the separate T spectra of the front and back coatings from the design in Fig. 2c. In Fig. 3, we observe that at some wavelengths, T maxima from one side coincide with T minima from the other. This complementarity explains the relative smoothness of the T spectra when compared to a single side design with similar number of layers and total thicknesses. However, for much thicker double-sided solutions, one could expect that the alignment of much finer peaks and valleys required to lower the MF would be more sensitive to fabrication errors.

3.2 Measurement

As mentioned, one of the anticipated difficulties with this problem was the accurate evaluation of filters at oblique angles with polarized light. Commercially available spectrophotometers allow for these measurements. However, this task still demands attention to details such as the exact positioning of the sample, the effect of the beam deviation as it refracts through the sample at non-normal angles, the control of the polarization, and potential anisotropic and non-uniformity effects from the coatings.

We start with the beam deviation by the sample, particularly for measurements involving both visible and near infrared (NIR) light. The common size difference between visible detectors, typically large area photomultipliers (PMs), and smaller area semiconductor-based detectors for the NIR can render the measurement sensitive to a slight misalignment or deviation of the light beam. This may lead to a discontinuity at the wavelength where the detector is switched [9]. Therefore, the introduction of a sample into the sample or reference beam can affect the measurement. For example, Fig. 4 shows the variation of T at 800 nm of an N-BK7 substrate when varying the polarization angle of the sample and reference beams at 0° , 10° , and 50° AOI with the Lambda 1050 instrument described in Table 2. Such a T variation is expected at oblique angles, particularly at 50° which is near the N-BK7 Brewster angle (56.5°) at this wavelength. At normal incidence, it result from a slight beam deviation induced by the polarizer rotation assuming no anisotropy in the N-BK7 substrate. Another example is shown in Fig. 5, where we plot the difference of two T spectra with s-polarization and the same AOI values, but with $+10^\circ$ and -10° azimuthal orientations. Again, these differences can be attributed to misalignment at the detectors due to beam deviation.

Issues of beam deviation were expected and led the organizers to select 1 mm thick substrates compared to 4 mm thick for previous contests. However, thinner substrates are more likely to be deformed by stress in thicker coating solutions, which could also affect the beam [10, 11]. Other than beam deviations, potential thin film structural anisotropy [12, 13] or thickness non-uniformity could also affect the measurements at oblique angles.

In addition, inaccurately setting the AOI could lead to error. In some accessories, the AOI is set manually with an imprecise goniometer; other instruments are equipped with automated goniometers that can lose their calibration.

4. Participation

The Yucca Problem was posted on the OSA website in September 2018. Nine teams requested substrates to participate; eight submitted nine coated samples on time, with one team generating two entries. The teams alphabetically listed in Table 1 were from five different countries and three continents and represent governmental laboratories and private companies.

We applied the same anonymity rule as in previous contests. All participants and their affiliations were disclosed at the OIC 2019 conference, however, their identities were not linked to any particular sample, except for the winning team whose identity was announced

at the conference. This anonymity rule stimulates participation. In the next sections, the samples are named only by number.

As required by the organizers, the participating teams provided the refractive index profile and measured T for each of their submitted samples. Some requested additional information about the deposition and thickness monitoring techniques were provided by some participants; these can be related to film performance.

5. Sample Evaluation

On delivery, the samples were randomly marked with a serial number from S01 to S09, and all references to the submitting team were removed. The samples were repackaged in identical boxes and sent for evaluation to the two independent laboratories, ODA and NIST. The s-polarization transmittance at the specified AOI and wavelengths were measured with double-beam spectrophotometers with specifications listed in Table 2. The spectra from both labs were collected, averaged, compared to the targets by MF s calculated from Eq. (1). These MF averages were then used to rate and rank the samples.

6. Results and Discussion

The results obtained for the nine submitted samples appear in Table 3, with the following information included:

- Number of layers and total thicknesses on the front and back sides of the substrate,
- Calculated MF s from the designs,
- Measured MF values evaluated by the participants, and from the measurements done at ODA and NIST, and
- Fabrication methods.

Error estimates were added to certain MF s, based on known measurement uncertainties provided by the evaluation labs (Table 2) [14].

Many participants employed sputtering, which is not surprising given the known film stability and quality of sputtered films. Two teams used plasma-assisted evaporation. Most participants utilized optical monitoring systems for film thickness control; at least one team employed direct [stop-watch] deposition-time monitoring.

The results, with the ODA/NIST spectra compared to the target curves and the participants' measurements, are shown in Figs. 6 and 7 and Table 3. On these figures, left-hand graphs represent each sample by its corresponding refractive index profile; right-hand graphs compare its s-polarization T spectra for both 10° and 50° AOI, measured by the participant and both evaluation labs, with the target curves. The result for the average MF from ODA/NIST is also displayed for each sample, along with its total thickness and number of layers.

Even though the sample identification numbers were not linked to particular participants, they should be able to recognize their samples based on the information that they provided.

We prefer that they maintain anonymity to facilitate future contest participation. The only exception is the winner, Zach Gerig, from *FiveNine Optics* in Boulder CO, USA. His sample, S02, had the lowest evaluated average MF value, 1.164, as shown in Table 3. Surprisingly, a stop-watch was used to control layer thicknesses in this effort!

Comparing different solutions, we gain insight into the importance of manufacturability. Table 3 indicates that total thicknesses ranged from 8.24 μm (S08) to 17.6 μm (S01), and layer totals from 74 (S08) to 224 (S01).

Looking at the spectra in Figs. 6 and 7, we can easily observe that the problem was not trivial and that no team succeeded in reproducing the targets with high fidelity. From a design perspective, it is instructive to note that no samples incorporated more than two materials. For problems involving only normal AOIs, it has been proved that the optimal design solution never involves more than two materials [15]; however, for oblique or multiple angle problems specifying one or both polarizations, intermediate index materials can simplify the design [16, 17].

Figure 8 compares the different designs and their expected and measured performances (read the figure caption for a detailed description). Figures 9 and 10 provide complementary information. From these figures, as well as Table 3, several observations can be made:

- Only three samples (S01, S03 and S04) were single-sided; although they were among the thickest, none of them were in the top three performers.
- The three samples with the lowest MF values were double-sided.
- All of the double-sided samples had relatively similar total thicknesses and layer numbers on each side.
- Two samples, S02 and S03, had smaller differences between design and measured MF values, indicating a good knowledge and control of the fabrication process, as well as a design less sensitive to small thickness errors.
- Some samples with complex designs and low design MF s resulted in relatively high measured MF s, suggesting unforeseen sensitivity issues.

As mentioned, most teams employed sputtering. Samples S06 and S08, the only two samples made using evaporation had largest differences between design and measured MF . This could be an indication of more difficult deposition rate control (although S08 MF matches well with sputtering samples). Without further details, we cannot elaborate further on the relative merits of these techniques.

Generally, the T spectra generated by the participants and by ODA/NIST matched well, with slightly higher discrepancies for those done at 50° AOI. This indicates that the previously considered difficulties related to T measurements at oblique angles did not significantly affect the data presented. This result may also be a strong vindication of our choice to supply thin substrates. Measurement accuracy is a key contributor to the manufacture of high performance coatings.

7. Conclusions

We conclude that the 2019 Manufacturing Problem Contest was a success, with diverse participation (nine teams from France, Germany, Japan, Russia and USA), a well-attended presentation at the conference, and an eclectic mix of sample designs and fabrication techniques.

Given the number of samples, it is difficult to draw general conclusions that could provide precepts for making filters of this type. However, we can still make some observations based on the results:

- The smoother results favor double-sided solutions with similar optical thickness coatings on both sides;
- Although measurements at oblique AOI still demand attention and care, the data provided by the participating teams were similar to those from our evaluation labs, showing that these issues are under control.

The next contest announcement should be posted in September 2021. Team interested in participating to a future edition of the contest can contact the corresponding author (DP).

Acknowledgments

We are grateful to all the participants and their respective institutions for their considerable efforts involving the design, fabrication, and analysis of their samples. We also thank Edmund Optics for its continuing support through the donation of substrates to these contests.

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Figure 1 –.

The Yucca Problem, with s-polarization T targets at 10° and 50° AOI. For better visibility, the plots show a reduced number of target points.

Figure 2 –.

Two examples of possible designs for the Manufacturing Problem, involving only the front side (Column A) or both the front and back sides (Column B) of a substrate. (Row 1) Refractive index profiles, (Row 2) Calculated transmittance spectra, compared to the target curves (darker dot-dash line at the bottom side of the green silhouettes).

Figure 3 –.

Comparison of the transmittance spectra from the front- and back-coatings of the two-side design presented in Fig. 2(c) and (d), simulated individually for (a) 10° AOI and (b) 50° AOI. One can observe the correspondence of position of peaks and valleys, particularly at shorter wavelengths.

Figure 4. Measured variation of the transmittance of a N-BK7 substrate when changing the polarization angle of the incoming light (at a wavelength of 800 nm), for (a) normal incidence 0°, (b) 10° AOI and (c) 50° AOI.

Figure 5.

Effect of the sample orientation in the plan of incidence, with light incident at the same AOI but from two different directions [(a), (b)]; the resulting differences in transmittance are shown in (c) for AOI $\pm 10^\circ$ and $\pm 50^\circ$.

Figure 6.

Evaluation results for the submitted samples S01 to S05. For each sample: left graph is the refractive index 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 dot-dash green line along the lower sides of lighter green leaf silhouettes). The merit function MF_{avg} is an average of MF s calculated from ODA and NIST spectra (details are in the text).

Figure 7.
 Evaluation results for the submitted samples S06 to S09. (Continuation of Figure 6)

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 MFs , and the triangle symbols represent the corresponding calculated design MFs (as provided by the participants).

Figure 9.

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 10.

Comparison of the calculated MFs and the average measured MFs , for all the samples (ordered according to their rank).

Table 1

List of participating teams and their affiliations

Team	Organization
Zach Gerig	FiveNine Optics, Boulder CO, USA
Julien Lumeau, Thomas Begou, Antonin Moreau, Frédéric Lemarquis, Cihan Koc and Fabien Lemarchand	Institut Fresnel, Marseille, France.
Vladimir Ponomarev and Vitaly Dogel	OptiSpark, Moscow, Russian Federation.
Marc Lappschies and Jan Brossmann	Optics Balzers, Jena, Germany
Masahiro Akiba	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 2

Summary of the Measurement Equipment

	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	400 nm to 1100 nm, 1.0 nm steps
Light-source	Tungsten-halogen / deuterium	Tungsten-halogen / deuterium
Detectors	Photomultiplier / PbS	Photomultiplier / InGaAs
Transmittance accuracy	±0.4 % in visible and NIR	±0.4 % in visible and NIR

Table 3.

Summary of the submitted filter designs, *MF* values and final ranking

	Information from participants				Information from evaluation labs			Additional information from participants
	Nb. layers (front+back coatings)	Total thickness (μm)	MF Design	MF Meas	MF ODA	MF NIST	MF Ave.	
S01	224	17.6	2.030	3.671	3.574+/-0.011	3.830+/-0.011	3.020+/-0.008	Magnetron sputtering
S02	125 (68+57)	11.8 (6.5+5.3)	0.59	0.88	0.891+/-0.011	1.436+/-0.011	1.164+/-0.008	(Winning Sample.) Ion-beam sputtering; deposition time monitoring
S03	178	12.9	2.14	2.53	2.530+/-0.011	2.640+/-0.011	2.585+/-0.008	Magnetron sputtering
S04	255	16.1	1.106	2.411	2.539+/-0.011	2.451+/-0.011	2.495+/-0.008	Magnetron sputtering
S05	164 (86+78)	12.97 (6.57+6.40)	0.445	1.608	1.728+/-0.011	1.644+/-0.011	1.686+/-0.008	Plasma-assisted magnetron sputtering (Bühler Helios800), optical broadband monitoring
S06	126 (64+62)	13.92 (7.32+6.60)	0.740	7.130	6.478+/-0.011	6.141+/-0.011	6.309+/-0.008	Plasma-assisted evaporation (Bühler SYRUSpro); Bühler OMS5000 monitoring
S07	138 (70+68)	12.53 (6.47+6.06)	0.439	2.353	2.272+/-0.011	2.090+/-0.011	2.181+/-0.008	
S08	74 (42+32)	8.24 (3.73+4.51)	0.46	2.646	2.890+/-0.011	3.001+/-0.011	2.945+/-0.008	Plasma-assisted evaporation (Bühler SYRUSpro710); Bühler OMS5000 monitoring
S09	138 (74+64)	14.03 (7.36+6.67)	0.46	2.61	2.489+/-0.011	2.852+/-0.011	2.670+/-0.008	Plasma-assisted magnetron sputtering (Bühler HELIOS); monitoring Bühler OMS5100