OIC 2022 Design Challenge

Organizers:

Jennifer Kruschwitz, *University of Rochester, USA*
Michael Trubetskov, *Max-Planck Institute of Quantum Optics, Germany*

Evaluation:

Jason Keck, *Independent Consultant, USA*

Problem Statement

The design problems for OIC 2022 involve a Black Box coating challenge (Problem A) and a set of White-Balanced, Multi-Bandpass Filters for 3D Movie Glasses (Problem B).

Post-production characterization of multilayer coatings (also known as reverse engineering, or re-engineering) is an important part of coating production. For successful post-production characterization it is necessary to know the theoretical design, and the goal of post-production characterization is to identify deviations in deposition conditions that contribute to the differences between measured spectral characteristics and the theoretical ones.

From time to time the designer may attempt to use multilayer design methods for performing post-production characterization without knowledge of the theoretical design or specifics about the manufacturing process. The designer may use various spectral measurements with differing incidence angles and wavelength regions to discern the exact performance of this fabricated multilayer. A question arises from this procedure: is it possible to reconstruct the exact theoretical design structure using reverse engineering of measured spectra?

To demonstrate how complicated (if even possible) the reconstruction of an unknown design is, we propose a Black Box Coating challenge. The Contest team determined the theoretical designs and generated reflectance and transmittance spectra that can be accessed from a virtual spectrophotometer. The designer needs to create their own design using the materials given for this specific challenge to match the theoretical design to their best ability.

The number of layers, layer thicknesses, and the arrangement of layer materials are unknown in this challenge. One can assume that there are no measurement errors associated with this virtual spectrophotometer.

In Problem A we propose two exercises of different complexity:

- Subproblem A.1: Black Box Antireflection (AR) coating
- Subproblem A.2: Black Box Short-wavelength pass, nonpolarizing filter

For the subproblem A.1 we provide precomputed reflectance and transmittance spectra. For the subproblem A.2 we provide an ability to perform arbitrary queries to obtain transmittance and reflectance spectra using virtual, web-based spectrophotometer. The angle of incidence, light polarization, wavelength ranges and wavelength increments can be configured within some permitted ranges.

Problem B, will involve enabling 3D cinema technology to be accessible during the pandemic for you and your family. The restrictions imposed on entertainment facilities due to COVID-19 have limited your ability to enjoy 3D movies on a big screen. Your extended family are in different parts of the world, and you have all grown very tired of gathering for ‘Movie Nights’ through your computers and watching 2D movies on your televisions. The solution will be to create an outdoor theater so that everyone can recapture the experience of watching 3D movies together without risking safety protocols due to the pandemic. Optical components such as polarizers are in very short supply. However, you have your own coating facility and access to eyewear frames and glass lenses. It is up to you to design a set of White-Balanced, Multi-Bandpass Filters that can be used in a pair of 3D cinema glasses.

The light filtering glasses will be made up of two different blue (B1 and B2), green (G1 and G2), and red (R1 and R2) transmitting wavelength bands to divide up the projector's single LED spectrum, where one part of the RGB spectrum is used by the left eye, and the other is used by the right. The exact same left and right filter will be placed in the projector that you have in your possession. Both filters will need to be white-balanced for daylight at 6500K (D65) while they transmit the projector's LED spectrum, such that both eyes can view the same *metameric* colors on the screen. You are so excited to design these glasses and redesign the projector so that your extended family can benefit from your expertise! One problem, some of your family members live in one of the coldest parts of the world, and the others in one of the hottest. Typical multi-bandpass filters may not work well at different temperatures due to the deposition materials having vastly different changes in refractive index due to temperature (dn/dT). It is your job as the designer to divide the RGB spectrums in such a way that the filters in the glasses vary as little as possible in color to those that are at 20°C in the projector, regardless of the temperature difference outside where the glasses will be worn.

In Problem B the two challenges will include:

- Subproblem B.1: Minimize color differences at a cold location in the world (indices for -50°C are provided).
- Subproblem B.2: Minimize color differences at a hot location in the world (indices for +50°C are provided).

Both the cold and hot locations will be announced with their outdoor temperatures at OIC 2022.

A web-based evaluation program will be provided for problems A.2, B.1 and B.2. The evaluation program allows the user to calculate merit functions for these problems to ensure calculations done at home will match the calculations done by the contest judges. In addition to providing merit functions, the website will contain links to relevant data (e.g., spectral data for problem A.1, LED output for problem B), and provide a "Virtual Spectrometer" for problem A.2. Please report any problems or questions to the evaluation team with the link provided on the website.

The submission deadline will be **April 23, 2022 by 11:59PM** Eastern Standard Time. As always, we hope designers will share their design approaches and insights.

Problem A - Black Box Coatings

For both subproblems reflectances R and transmittances T data are provided without taking into account substrate back side reflections. Therefore, the substrate should be considered as a semi-infinite medium with a coating placed at the boundary between the substrate and incident medium with the refractive index 1.0. In this exercise measurement errors being the main limiting factor for post-production characterization of optical coatings have been eliminated. Accurate data is provided for R and T, where the accuracy is only limited by a very small round-off errors.

Layer materials and substrate

For both cases Problem A1 and Problem A2 we consider a non-absorbing BK7 substrate with the refractive index given by the Sellmeier dispersion formula:

$$n^2(\lambda) - 1 = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \tag{1}$$

with the coefficients presented in Table 1 (λ is given in microns in Eq. (1)). The extinction coefficient of BK7 in the considered wavelength region is zero. Note, that we use rounded-off values in order to simplify data management.

Table 1: Coefficients of the substrate Sellmeier formula Eq. (1).

B_1	B_2	B_3	C_1	C_2	C_3
1.03961	0.23179	1.01047	0.006	0.02	103.56

The substrate is semi-infinite, therefore the reflectance from the back side should not be taken into account. We provide *a priori* information on chemical composition of the coatings. It consists of Nb_2O_5 and SiO_2 materials, but material layer arrangement and layer number within this design are unknown. The refractive indices of Nb_2O_5 and SiO_2 are described by the Cauchy formula:

$$n(\lambda) = A_0 + \frac{A_1}{\lambda^2} + \frac{A_2}{\lambda^4}\,. \tag{2}$$

The coefficients of the Cauchy formula for Nb_2O_5 and SiO_2 are taken from [1] and presented in Table 2 (λ is given in microns in Eq. (2)).

Table 2: Cauchy formula coefficients Eq. (2) of Nb_2O_5 and SiO_2 layer materials.

Material	A_0	A_1	A_2
Nb_2O_5	2.218485	0.021827	3.99968e-3
SiO_2	1.460472	0.0	4.9867e-4

To simulate possible refractive index differences, including the presence of contaminants in the production process, we added refractive index offsets and possible absorption to both materials.

For each layer these perturbation factors can be different, therefore simulating some instability of the deposition process. For both layer material refractive indices we introduce five refractive index wavelength-independent offsets Δ_m:

$$n_m(\lambda) = n(\lambda) + \Delta_m, \quad \Delta_m = 0.005(m-3), \quad m = 1, \dots, 5. \tag{3}$$

The extinction coefficient is described by the equation (λ is given in microns):

$$k(\lambda) = D_1 \exp(-D_2\lambda) + D_3\,. \tag{4}$$

Equation 4 has typical wavelength dependency, providing higher absorptance at shorter wavelengths. Only Nb_2O_5 has absorptance, all coefficients Eq. (4) for SiO_2 are zeros. Possible values of Eq. (4) for Nb_2O_5 are presented in Table 3, they correspond to "weak", "standard", and "strong" absorptance. The last case can be associated with possible unknown contaminants during production process.

Table 3: Extinction coefficients of formula Eq. (4) of Nb_2O_5 layer material.

Absorption	Index j	D_1	D_2	D_3
"weak"	1	4.0e+5	56.0	1.0e-10
"standard"	2	3.0e+5	50.0	1.0e-8
"strong"	3	4.0e+4	40.0	1.0e-6

Therefore, the complex refractive index is

$$\tilde{n}(\lambda) = n(\lambda) + \Delta_m - ik_j(\lambda)\,, \tag{5}$$

where $n(\lambda)$ is given by Eq. (2), Δ_m is the variation of the real refractive index (Eq. (3)), $k_j(\lambda)$ is zero for SiO_2 and given by formula Eq. (4) for Nb_2O_5 with coefficients selected from Table 3 according to a value of the index j. Figure 1 shows possible refractive index and extinction coefficients for Nb_2O_5, in total it provides 15 possible combinations for the complex refractive index of Nb_2O_5. On the other hand there are only 5 different refractive index variants for SiO_2 layer material. All these variations of Nb_2O_5 and SiO_2 can be present in the Black Box designs.

Problem A.1: Black Box Antireflection Coating

The "measurement" data $\hat{R}_a(\lambda)$ (the reflectance of averaged polarization) and $\hat{T}_a(\lambda)$ (the transmittance of averaged polarization) at 7° incidence (Fig. 2) can be downloaded using the link provided in Appendix A.

This is a 3-column comma-separated values file with the wavelength in nanometer in the first column, $\hat{T}_a(\lambda)$ in the second, and $\hat{R}_a(\lambda)$ in the third column. The wavelength is changing in the range 220–1700 nm with the step 1 nm. The first line is the header line indicating the data in columns and the rest of the lines contain the data.

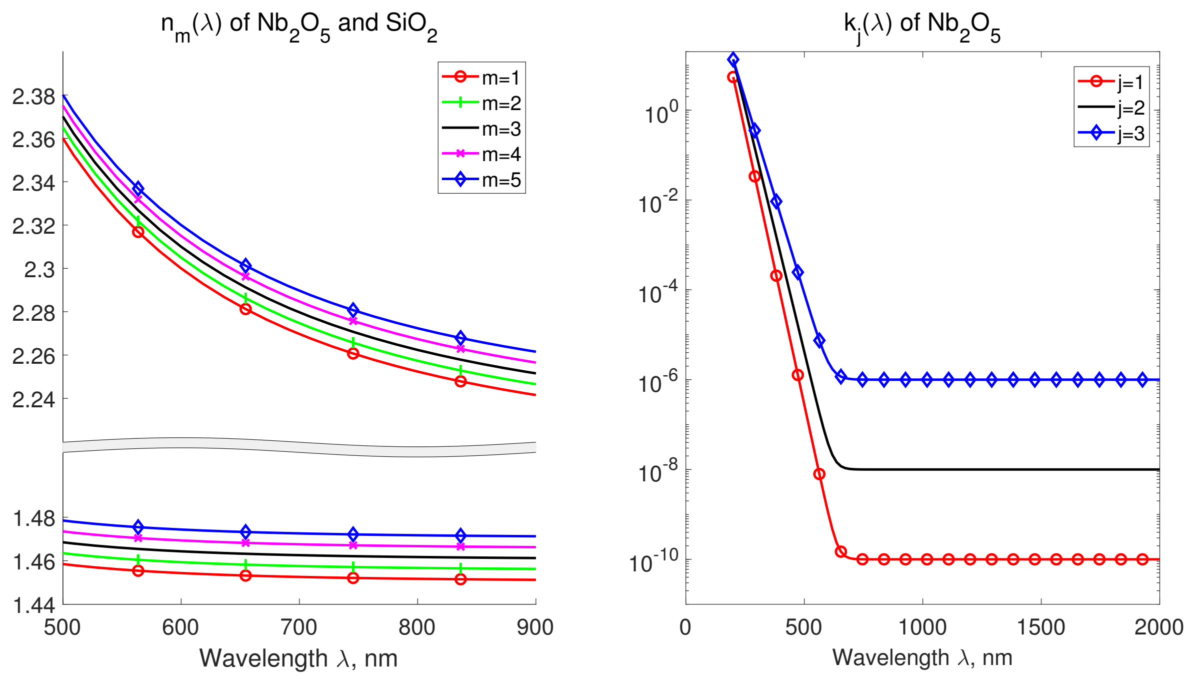


Figure 1: Possible refractive index and extinction coefficient wavelength dependencies for Nb_2O_5 and SiO_2 layer materials.

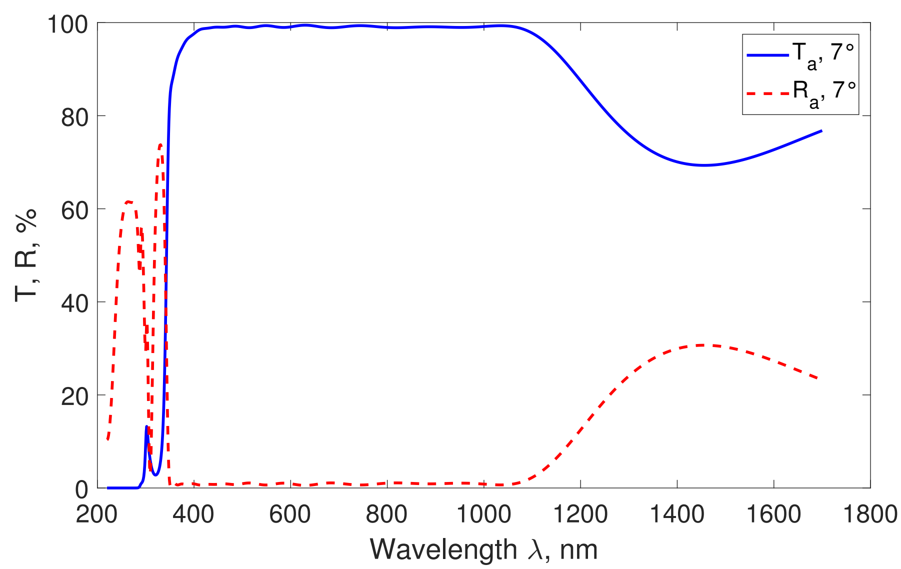


Figure 2: Reflectance and transmittance of the antireflection coating at 7°, numerical values can be downloaded using the link in Appendix A.

We estimate the submissions using the merit function D_1:

$$D_1 = \left\{ \frac{1}{2 \cdot 1481} \sum_{\lambda=220}^{1700} \left[R_a(\lambda) - \hat{R}_a(\lambda) \right]^2 + \left[T_a(\lambda) - \hat{T}_a(\lambda) \right]^2 \right\}^{1/2} . \tag{6}$$

Here $\hat{T}_a(\lambda)$ and $\hat{R}_a(\lambda)$ are the "measurement" data and $T_a(\lambda)$ and $R_a(\lambda)$ are transmittances and reflectances of the non-polarized light of the submitted solution.

The physical thickness of the antireflection coating cannot be greater than 3500 nanometers and the number of layers cannot exceed 35. We will not accept the solutions violating these limits. The winner will be defined on the basis of the merit function Eq. (6). In a possible case of tie breaker, the Contest Committee will select the winner as the one who submits the best description (i.e., most informative, carefully written, very detailed, etc.) of the approach used to solve the problem.

Problem A.2: Short-wave pass nonpolarizing filter

A short-wave pass non-polarizing filter was designed for 45° incidence (Fig. 3) with the separation wavelength of 900 nm. For this problem a virtual, web-based spectrophotometer should be used to obtain "measurement" spectra for different angles of incidence and polarizations. Minimum allowed wavelength step is 0.1 nm (configurable). Wavelength limits can be selected in the range 220–1700 nm. Angle of incidence can be from 0° (normal incidence) up to 65° for the transmittance and from 7° up to 60° for the reflectance. It is possible to obtain *s*-, *p*-, and average-polarized spectral characteristics for each of the angle of incidence.

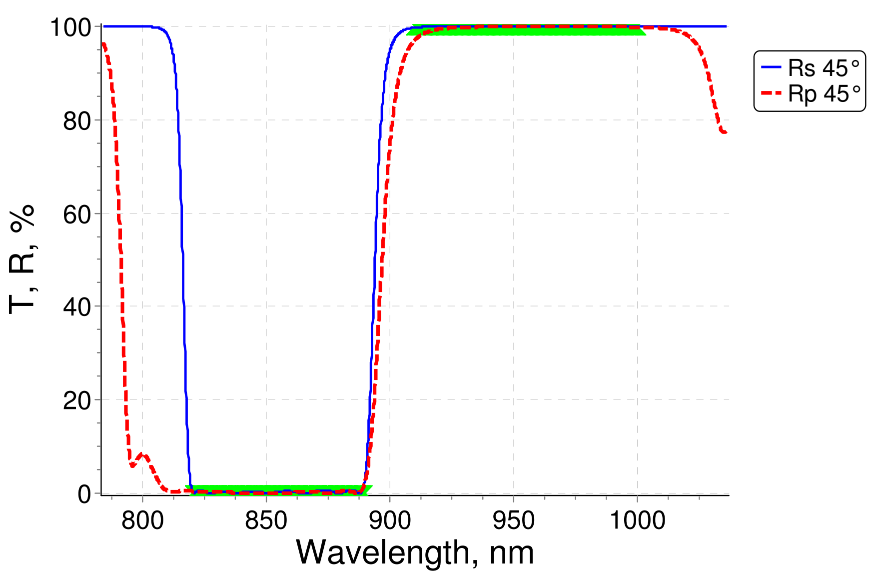


Figure 3: Reflectance of the short-wave pass filter at 45° for *s*- (blue solid) and *p*-polarized (red dashed) light. Target specifications for the reflectance are shown with thick, solid green horizontal lines.

We estimate the submissions using the merit function D_2:

$$D_2 = \left\{ \frac{1}{6 \cdot 1481} \sum_{\lambda=220}^{1700} \left(\left[R_a(\lambda, 7^\circ) - \hat{R}_a(\lambda, 7^\circ)\right]^2 + \left[T_a(\lambda, 7^\circ) - \hat{T}_a(\lambda, 7^\circ)\right]^2 + \left[R_s(\lambda, 60^\circ) - \hat{R}_s(\lambda, 60^\circ)\right]^2 + \left[T_s(\lambda, 60^\circ) - \hat{T}_s(\lambda, 60^\circ)\right]^2 + \left[R_p(\lambda, 60^\circ) - \hat{R}_p(\lambda, 60^\circ)\right]^2 + \left[T_p(\lambda, 60^\circ) - \hat{T}_p(\lambda, 60^\circ)\right]^2 \right) \right\}^{1/2} . \quad (7)$$

It is additionally known that the short-wave pass filter cannot be thicker than 12 μm total physical thickness, and the number of layers cannot exceed 75. We will not accept the solutions violating these limits. The winner will be defined on the basis of the merit function Eq. (7). In a possible case of tie breaker, the Contest Committee will select as a winner the contestant who submits the best description (i.e., most informative, carefully written, very detailed, etc.) of the approach used to solve the problem.

Problem B - White-Balancing Multi-Bandpass Filters

The second design challenge involves creating two white-balancing, multi-spectral filters for a set of 3D cinema glasses that will be used by your extended family for an outdoor theater. Your projector has been optically modified to create two sets of offset images to create the necessary parallax. You need an additional effect either through polarization or color metamerism to complete the 3D experience. Due to the pandemic, polarizers are in short supply. Fortunately, you have a coating facility and eyewear frames with lenses that you can coat. You also have enough glass to replicate each filter to be placed in the projector such that the projector channels can be color-matched for the appropriate eye as illustrated in Figure 4.

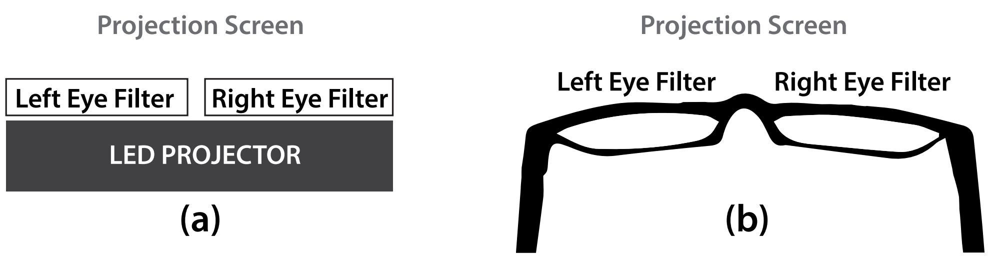


Figure 4: Position of Left and Right Eye Filters (a) in projector, and (b) in cinema glasses

The goal of this challenge will be to create multilayer coating designs for the left and right filters that will be placed in the projector and in the eye frames to meet the specification at 20°C. However, your designs should change as little as possible spectrally at a very cold temperature and a very hot temperature. Each material will have a specific change of refractive index with temperature (dn/dT), it is up to the designer to choose the materials from those available that will limit the change at a different temperature. The projector will stay at the specified 20°C, but the glasses will experience the temperature change. Two merit functions, one for the glasses at a cold temperature (Problem B.1) and one for a hot temperature (Problem B.2) will be used to determine the amount of change for the design. Refractive indices of the substrate and layer materials for two temperature extremes (-50°C and +50°C) are provided for the designer in each respective section.

The projector has the appropriate optics to divide the image into two separate paths to be offset on the projection screen. However, the projector has only one set of red, green, and blue LEDs inside. The LED RGB spectrum is shown in Figure 5. In order to fully create the 3D effect, the designer will need to split the wavelength regions for each LED such that only half of each spectrum (R, G, and B) will end up in each eye, therefore enabling the color metamerism effect. The wavelength spectrums may be split as follows (an example is shown in Figure 6):

Table 4: Wavelength bands (Spectrum 1 or Spectrum 2) for each color primary without LED source (i.e., with Uniform Spectral Illumination).

Color LED	**Spectrum 1**		**Spectrum 2**	
	30%>T≥100%	T<1%	T<1%	30%>T≥100%
Blue (B)	380 - 435 nm	440 - 474 nm	380 - 432 nm	436 - 480 nm
Green (G)	480 - 530 nm	539 - 568 nm	485 - 525 nm	531 - 570 nm
Red (R)	580 - 635 nm	642 - 780 nm	586 - 626 nm	636 - 780 nm

For example, if Spectrum 1 is included for the blue (B) in the left eye, Spectrum 2 shall represent B in the right eye. Spectrum 1 and Spectrum 2 have high transmission regions that are in opposite spectral bands. Both spectrums will divide each color LED in half for all three color channels (R, G, and B.) Crosstalk between the left and right eye is minimized. A transmission example where both surfaces of the left and right eye lenses are coated is shown in Figure 6. The left eye filter in the example transmits B1, G1, and R1 and the right eye filter transmits B2, G2, and R2.

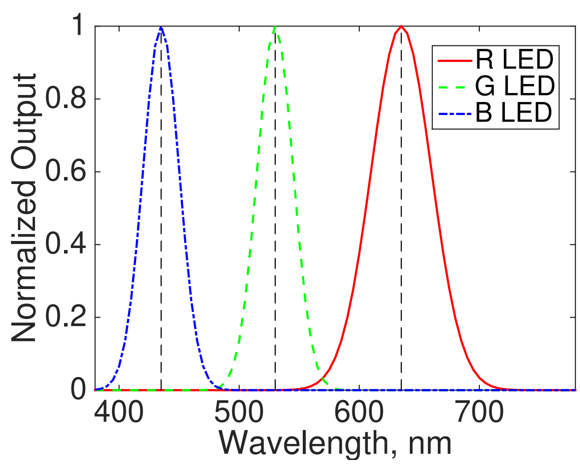
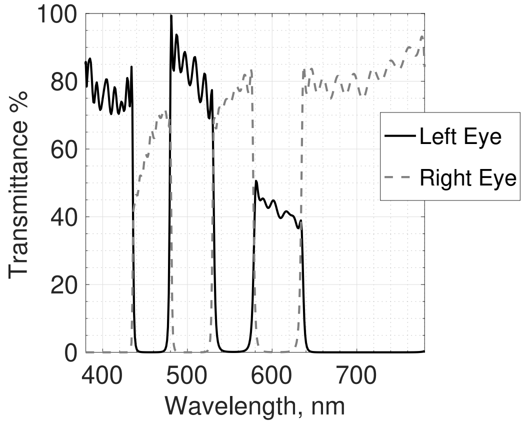


Figure 5: RGB Light Source

These filters will also need to be white-balanced so that all of the images that are produced by the projector will appear to be the same color. Each filter has two surfaces that can be coated, as such the total transmission can be maximized and white-balanced. The process to determine the color of the filters will be to calculate the tristimulus values (XYZ) from the transmittance of the left or right filters, using the 10-degree observer color matching functions and the projector's LED source from 380 nm - 780 nm, every 1 nm. When CIELAB values are calculated using the filter's XYZ tristimulus values, the white point (XYZ_n) used for comparison, will be those calculated from daylight (D65) and the 10-degree color matching functions (XYZ_n values and formulas for CIELAB are listed in Appendix B). The design example shown in Figure 6B has both filters using the LED source, to produce a white point in CIELAB equal to daylight at 6500K (D65) using a 10-degree observer's color matching functions from 380 nm - 780 nm, every 1 nm. The 10-degree color matching function data can be found at the Rochester Institute of Technology (RIT) Munsell Color Science Lab Educational Resources page [2] and will provided at the Design Challenge link in Appendix B.



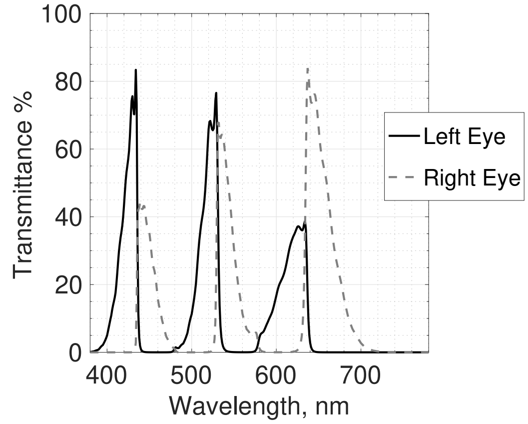


Figure 6: (A) Wavelength distribution for two example filters: Left Eye high %T is B1, G1, and R1 (solid). Right Eye high %T is B2, G2, R2 (dashed) that meets specifications in Table 4. Both filters are at normal incidence with coated front and back surfaces of the substrate without LED light source. (B) Filters in Figure **A** transmitting the LED light source through the Left and Right Eye filters.

The Example filter shown in Figure 6A transmits B1, G1, and R1 for the left eye using three bandpass filters on the front surface and the color-correcting coating on the back. The right eye filter transmits B2, G2, and R2 where the front surface is also a multiple bandpass filter and the back surface is the color correcting coating.

The link to the example designs for the left and right eye filters can be found in Appendix B. The submitted designs will be based on the refractive index materials found in Table 5 for 20°C, which will be the temperature that will be maintained in the projector. The color transmitted using the projector's LED spectrum, for each of the two filters at 20°C shall measure CIELAB color coordinates in a* and b* coordinates at 0.0 ± 0.4, 0.0 ± 0.4 respectively to a D65 reference white using the 10° observer. The designs' transmitted spectrums are converted to CIELAB color coordinates so that the amount of light transmitted through these filters can be calculated by using the CIELAB value for lightness, or L*. CIELAB calculations for L*, a*, and b* plus other formulas and links to necessary data are found in Appendix B.

Table 5: Index of refraction for the substrate, medium, and each material at 20°C.

Substrate	Air	H	L	F	T	M
1.52	1.0	2.250	1.450	2.000	2.150	1.380

Submitted designs will be accepted that meet the following criteria at 20°C:

1. The angle of incidence for both the left and right eye coatings will be 0 degrees (i.e., normal incidence.)
2. The designs for both the left and right eyes (both front and back surfaces in series, incorporating multiple reflections) should meet the Spectrum 1 and Spectrum 2 transmittance

requirements in Table 4 for the filters without using the LED projector source (i.e., using uniform spectral illumination across the visible wavelength region).

3. The designs for both the left and right eyes should be color-corrected while transmitting the projector's LED source to obtain a white point that is similar to a D65 reference white, using the 10-degree observer color matching functions from 380 nm - 780 nm (see link to data in Appendix B) to obtain CIELAB a^* and b^* coordinates equal 0.0 ± 0.4, 0.0 ± 0.4.
4. Each eye should receive one of the red, green, and blue LED spectrums from R1, R2, G1, G2, B1, and B2 (see Table 4). The designer can choose which way to distribute the spectrums based on their design. The example design shown in Figure 6 shows one way to distribute the spectrums, but not the only way.
5. The CIELAB transmitted lightness, L^*, using the projector's LED spectrum for either filter (both surfaces) shall be ≥ 60.
6. The designs submitted will only use the index data for the layer materials from Table 5.
7. No layer thickness for any surface design shall be < 5nm.
8. No single surface design can exceed 100 layers total.
9. Each surface of the two filters shall be coated with at least one layer.

The designer will indicate if the design will be used for the cold temperature, the hot temperature, or both in the design submission .TXT file (see page 15.) Each designer can submit up to two pairs of designs per cold temperature and two pairs for the hot temperature (the designs for the right and left eye are considered one pair, four coated surfaces). If the designs are to be used for both temperatures, then a total limit of four submissions will be permitted. In the event that multiple submissions from different designers produce an identical merit function, the designs with the least total physical thickness for both sides of the left and right lenses will be deemed the winner (i.e., left front surface design total thickness + left back design total thickness + right front design total thickness + right back surface design total thickness.)

Problem B.1 - Outdoor 3D Family Theater at Cold Temperatures

You have sent one of your adapted projectors and some of your 3D cinema glasses to your family that live in one of the coldest regions of the world so they can enjoy getting out of the house and watching a 3D movie outdoors. The filters that are in the projector will be at a temperature of 20°C, but the glasses will be worn on a family member's face outdoors. We will assume that the family member is bundled up so that they are warm and comfortable, but the glasses remain exposed to low temperatures at their location.

The designs in Figure 6 are the white-balanced transmittance for both the left and right eye at 20°C. When the designs are used at a very cold temperature the physical thicknesses of all of the layers will stay the same, but the design will shift based on the refractive indices for the materials at the very cold temperature. The refractive indices for all layer materials for -50°C (worst case) are given in Table 6. The transmitted color changes for both the left and right eyes for the design example is shown in Figure 7. The designer must calculate the Merit Function (Equation 11). The MF_{Cold} is broken down into three main parts:

1. the first part adds the color differences (ΔE) of the left and right eye filters between 20°C and the cold temperature, with an appropriate weighting (see Equations 8, 9, and 10).
2. the second part calculates the absolute value of the deviation between the left eye filter and the right eye filter color difference between the filter at 20°C and the cold temperature. The closer the two color differences (ΔE) for the left and right lens are, the smaller this part of the equation. It is important to not only have a small color shift, but it should be relatively equal for both left and right eyes.
3. the last part is based on the L^* value for both filters at 20°C. The higher L^* is for the submitted design at 20°C the lower that value will become.

The winning design will minimize the color change due to the change in refractive index of the layer materials used at cold temperatures, while maximizing the amount of transmitted light, L^*, at 20°C for both the left and the right eye filters. The worst case of -50°C was used for $\mathrm{MF_{Cold}}$ for the example design, and a value of 11.053635 was calculated.

Table 6: Index of refraction for each material at -50°C.

	Substrate	Air	H	L	F	T	M
-50°C	1.513	1.0	2.131	1.499	1.811	2.101	1.359

$$\begin{aligned}\Delta L^*_{\text{left,Cold}} &= L^*_{\text{left},20^\circ C} - L^*_{\text{left,Cold}}\\ \Delta a^*_{\text{left,Cold}} &= a^*_{\text{left},20^\circ C} - a^*_{\text{left,Cold}}\\ \Delta b^*_{\text{left,Cold}} &= b^*_{\text{left},20^\circ C} - b^*_{\text{left,Cold}}\end{aligned} \tag{8}$$

$$\begin{aligned}\Delta L^*_{\text{right,Cold}} &= L^*_{\text{right},20^\circ C} - L^*_{\text{right,Cold}}\\ \Delta a^*_{\text{right,Cold}} &= a^*_{\text{right},20^\circ C} - a^*_{\text{right,Cold}}\\ \Delta b^*_{\text{right,Cold}} &= b^*_{\text{right},20^\circ C} - b^*_{\text{right,Cold}}\end{aligned} \tag{9}$$

$$\begin{aligned}\Delta E_{\text{left,Cold}} &= \sqrt{(\Delta L^*_{\text{left,Cold}})^2 + (\Delta a^*_{\text{left,Cold}})^2 + (\Delta b^*_{\text{left,Cold}})^2}\\ \Delta E_{\text{right,Cold}} &= \sqrt{(\Delta L^*_{\text{right,Cold}})^2 + (\Delta a^*_{\text{right,Cold}})^2 + (\Delta b^*_{\text{right,Cold}})^2}\end{aligned} \tag{10}$$

$$\begin{aligned}\mathrm{MF_{Cold}} = &\left(\frac{\Delta E_{\text{left,Cold}}}{20} + \frac{\Delta E_{\text{right,Cold}}}{20}\right) + \left|\Delta E_{\text{left,Cold}} - \Delta E_{\text{right,Cold}}\right|\\ &+ \left((70/L^*_{\text{left max, }20^\circ C}) + (70/L^*_{\text{right max, }20^\circ C})\right)\end{aligned} \tag{11}$$

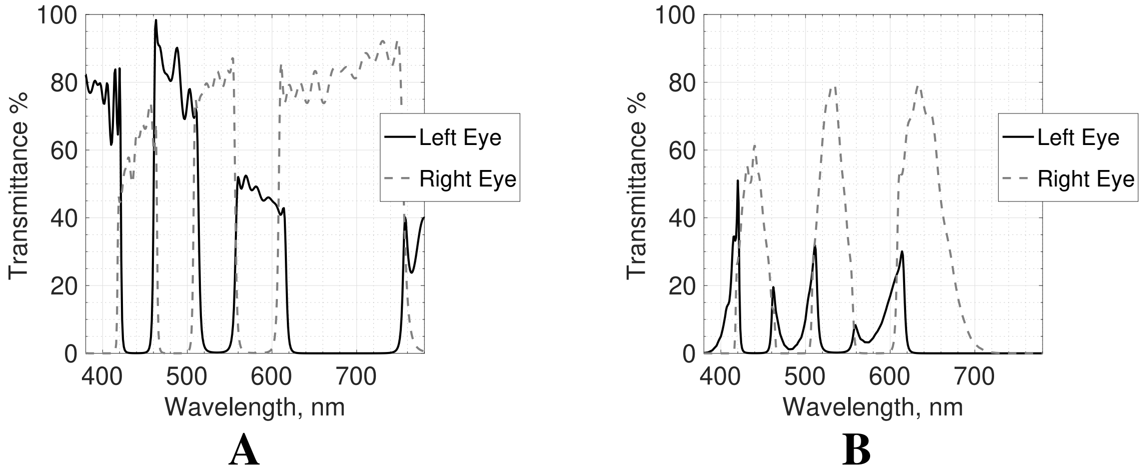


Figure 7: Left and Right Eye's Transmittance, -50°C. Figure A shows filters transmitting uniform spectral illumination, and B shows the filters transmitting the projector's LED spectrum.

Problem B.2 - Outdoor 3D Family Theater at Hot Temperatures

You have also sent one of your adapted projectors and some of your 3D cinema glasses to your family that live in one of the hottest regions of the world so they too can enjoy getting out of the house and watching a 3D movie outdoors. The filters that are in the projector will be at a temperature of 20°C, but the glasses will be worn on a family member's face outdoors. We will assume that the family member is able to stay cool and comfortable, but the glasses remain exposed to hot temperatures at their location.

The designs in Figure 6 are the white-balanced transmittance for both the left and right eye at 20°C. When the designs are used at a very hot temperature the physical thicknesses of all of the layers will stay the same, but the design will shift based on the refractive indices for the materials at the very hot temperature. The refractive indices for all layer materials for +50°C (worst case) are given in Table 7. The transmitted color changes for both the left and right eyes for the design example is shown in Figure 8. The designer must calculate the Merit Function (Equation 15). The MF_{Hot} (similar to $MF_{Cold)}$) is broken down into three main parts:

1. the first part adds the color differences (ΔE) of the left and right eye filters between 20°C and the hot temperature, with an appropriate weighting (see Equations 12, 13, and 14).
2. the second part calculates the absolute value of the deviation between the left eye filter and the right eye filter color difference between the filter at 20°C and the hot temperature. The closer the two color differences (ΔE) for the left and right lens are, the smaller this part of the equation. It is important to not only have a small color shift, but it should be relatively equal for both left and right eyes.
3. the last part is based on the L^* value for both filters at 20°C. The higher L^* is for the submitted design at 20° the lower that value will become.

The winning design will minimize the color change due to the change in refractive index of the layer materials used at hot temperatures, while maximizing the amount of transmitted light, L^*, at

20°C for both the left and the right eye filters. The worst case of +50°C was used for MF_{Hot} for the example design, and a value of 5.806175 was calculated.

Table 7: Index of refraction for each material at +50°C.

	Substrate	Air	H	L	F	T	M
50°C	1.523	1.0	2.301	1.429	2.081	2.171	1.389

$$\begin{aligned}\Delta L^*_{\text{left,Hot}} &= L^*_{\text{left},20°C} - L^*_{\text{left,Hot}}\\ \Delta a^*_{\text{left,Hot}} &= a^*_{\text{left},20°C} - a^*_{\text{left,Hot}}\\ \Delta b^*_{\text{left,Hot}} &= b^*_{\text{left},20°C} - b^*_{\text{left,Hot}}\end{aligned} \tag{12}$$

$$\begin{aligned}\Delta L^*_{\text{right,Hot}} &= L^*_{\text{right},20°C} - L^*_{\text{right,Hot}}\\ \Delta a^*_{\text{right,Hot}} &= a^*_{\text{right},20°C} - a^*_{\text{right,Hot}}\\ \Delta b^*_{\text{right,Hot}} &= b^*_{\text{right},20°C} - b^*_{\text{right,Hot}}\end{aligned} \tag{13}$$

$$\begin{aligned}\Delta E_{\text{left,Hot}} &= \sqrt{(\Delta L^*_{\text{left,Hot}})^2 + (\Delta a^*_{\text{left,Hot}})^2 + (\Delta b^*_{\text{left,Hot}})^2}\\ \Delta E_{\text{right,Hot}} &= \sqrt{(\Delta L^*_{\text{right,Hot}})^2 + (\Delta a^*_{\text{right,Hot}})^2 + (\Delta b^*_{\text{right,Hot}})^2}\end{aligned} \tag{14}$$

$$\begin{aligned}MF_{\text{Hot}} = &\left(\frac{\Delta E_{\text{left,Hot}}}{20} + \frac{\Delta E_{\text{right,Hot}}}{20}\right) + \left|\Delta E_{\text{left,Hot}} - \Delta E_{\text{right,Hot}}\right|\\ &+ \left((70/L^*_{\text{left max, }20°C}) + (70/L^*_{\text{right max, }20°C})\right)\end{aligned} \tag{15}$$

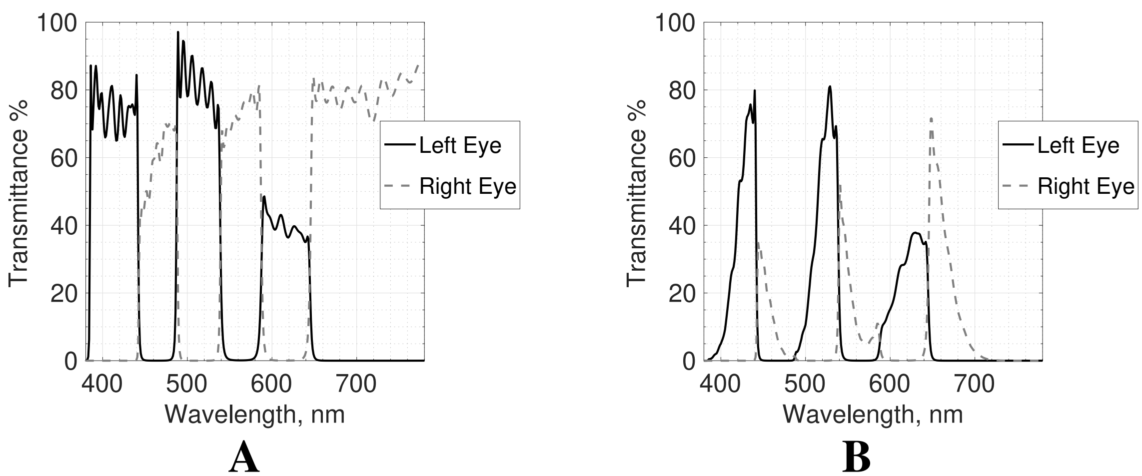


Figure 8: Left and Right Eye's Transmittance, +50°C. Figure A shows filters transmitting uniform spectral illumination, and B shows the filters transmitting the projector's LED spectrum.

Submission

Participants are welcome to submit up to two designs for Problem A.1 and/or Problem A.2 (totaling a maximum of four designs per designer). Participants are also welcome to submit up to two designs for Problems B.1 and/or B.2 (again, a maximum of four designs per designer). Depending on merit, a submitted design may be published as part of a paper presented at OIC 2022, and later in a special OIC 2022 issue of Applied Optics. Until then, any submitted design will be known (and kept confidential) only by the OIC Design Contest team, the OIC 2022 General and Program Chair persons, and some OSA staff members.

The evaluation webpage can be found at URL: http://www.osa.org/oic/designcontest and will be available for use on November 1, 2021 until **April 23, 2022 by 11:59PM** Eastern Standard Time, when the submitted designs are due.

Submit your final designs to design.contest@clearapertures.com with the email subject line: OIC Submission.

The only requirement for participation in the contest is the submission of a design in the correct text format prior to the submission deadline. However, design authors are encouraged to accompany their designs with an explanation of how they arrived at their solutions. Questions regarding the evaluation program and the virtual spectrophotometer should be directed to Jason Keck at jkeck@clearapertures.com. With questions regarding the design problems and explanations of design submissions please contact Jennifer Kruschwitz and Michael Trubetskov at design.contest@clearapertures.com.

The submission should be in the form of a DOS/Windows-based text file (ANSI or UTF-8 encoding) (i.e., a '.txt' extension) that should be either tab or space delimited. The filename should be the last name of the author shortened to six letters followed by three identifying characters for Problem A or two identifying characters for Problem B. (If the author name is less than six characters, underscore characters should fill the extra spaces.) Examples of files for Problem A and Problem B are shown below.

Submission for Problem A

Three identifying characters for the problem A should be as follows. The first symbol is **A**, the second should be either **1** or **2** for the subproblems A1 and A2, respectively. The third symbol is the number of submission. We limit the number of submissions for each subproblem by two, therefore the third symbol can be also either **1** or **2**.

For the Problem A the layers should be listed from substrate to incident medium, each line should consist of the alpha-numeric layer material specification and physical layer thickness in nanometer. For Nb_2O_5 layer material the specification should have 3 characters, the first one is "**H**", the second is the number corresponding to the index m (limits: $1, \ldots, 5$) of the refractive index offset (Eq. (3), the third one is the index j (limits: $1, \ldots, 3$) describing the extinction coefficient (Table 3). For SiO_2 layer material the specification should have 2 characters, the first one is "**L**", the second is also the number corresponding to the index m (limits: $1, \ldots, 5$) of the refractive index offset (Eq. (3).

Filename: TrubetA11.txt [six characters for name, problem A, the first subproblem of AR coating, 1st submission]

line 1	Name, Affiliation
line 2	Email address
line 3	- *blank* - [delimits start of design]
line 4	H21 201.2 [material Nb_2O_5 with m = 2 and j = 1, and layer thickness in nm for layer 1]
line 5	L5 55.3 [material SiO_2 with m = 5 and layer thickness in nm for layer 2]
line 6	H43 215.2 [material Nb_2O_5 with m = 4 and j = 3, and layer thickness in nm for layer 3]
. . .	
line end	L1 315.2 [material SiO_2 with m = 1 and layer thickness in nm for last layer]

Submission for Problem B

There will be four designs that will accompany each submission:

- Left Eye Front Surface (LEFS)
- Left Eye Back Surface (LEBS)
- Right Eye Front Surface (REFS)
- Right Eye Back Surface (REBS)

For Problem B submissions, line 1 should give the designer name and affiliation, and line 2 the designer's email. Line 3 should designate if the submission should be used for the COLD environment, the HOT environment, or BOTH. Skip a line below the email information line to delimit that the design for the Left Eye, Front Surface (LEFS) design is starting. There should be four total designs with delimiter skipped lines between each design. The format for the Problem B example design is shown below. Each of the submitted designs can have up to 100 layers. In this case line numbers are changed accordingly. A blank line should always separate designs LEFS, LEBS, REFS, and REBS. The example design has 71 layers for LEFS, 4 for LEBS, 68 for REFS, and 5 layers for REBS.

Filename: KruschB1.txt [six characters for name, problem B, 1st submission]

line 1	Name, Affiliation
line 2	Email address
line 3	COLD [Indicates the use of the submission for COLD, HOT, or BOTH]
line 4	- *blank* - [delimits start of Left Eye, Front Surface Design (LEFS)]
line 5	M 91.947 [material and layer thickness in nm for layer 1]
line 6	H 103.383 [material and layer thickness in nm for layer 2]
line 6	L 100.965 [material and layer thickness in nm for layer 3]
line 8	H 22.733 [material and layer thickness in nm for layer 4]
. . .	
line 75	M 66.742 [material and layer thickness in nm for layer 71 of LEFS Design]
line 76	- *blank* - [delimits start of Left Eye, Back Surface Design (LEBS)]
line 77	M 43.148 [material and layer thickness in nm for layer 1 of LEBS]
line 78	H 77.413 [material and layer thickness in nm for layer 2 of LEBS]
. . .	
line 80	H 83.016 [material and layer thickness in nm for layer 4 of LEBS]
line 81	- *blank* - [delimits start of Right Eye, Front Surface Design (REFS)]

line 82 M 109.697 [material and layer thickness in nm for layer 1 of REFS]
. . .
line 149 H 39.431 [material and layer thickness in nm for layer 68 of REFS Design]
line 150 - *blank* - [delimits start of Right Eye Back Surface (REBS)]
line 151 H 124.122 [material and layer thickness in nm for layer 1 of REBS]
. . .
line 155 H 44.207 [material and layer thickness in nm for layer 5 of REBS Design]

References

[1] T. Amotchkina, M. Trubetskov, V. Pervak, and A. Tikhonravov, "Design, production, and reverse engineering of two-octave antireflection coatings,´´ Appl. Opt. **50**, 6468-6475 (2011).

[2] https://www.rit.edu/science/munsell-color-science-lab-educational-resources, **Useful Color Data**, accessed 7/5/2021.

Appendix A

A web interface is provided that evaluates transmission and reflection of the black box coating at different angles and polarizations. Spectral data is plotted and available for download in a text format.

The link to access the data for Problem A and any other necessary evaluation tools can be found at http://www.osa.org/oic/designcontest.

Appendix B

CIELAB Calculations

The tristimulus values for daylight at 6500K (D65) for the 10 degree observer calculated from the RIT data [2] are :

$$\begin{aligned} X_n &= \ \ 94.8107 \\ Y_n &= 100.0000 \\ Z_n &= 107.3040 \end{aligned} \tag{16}$$

Assuming X, Y, and Z are the tristimulus values for the transmission of the left or right eye filters using the LED spectrum (i.e., Figure 5) and the 10-degree observer every 1nm increment [2], the formulas for calculation are:

$$f(x) = \begin{cases} (x)^{1/3}, & x > 0.008856 \\ 7.787x + 16/116, & x \leq 0.008856 \end{cases} \tag{17}$$

$$\begin{aligned} L^* &= 116\, f(Y/Y_n) - 16 \\ a^* &= 500\, [f(X/X_n) - f(Y/Y_n)] \\ b^* &= 200\, [f(Y/Y_n) - f(Z/Z_n)] \end{aligned}$$

Data for the projector's LED spectrum, the example design for Problem B, and the evaluation for the Merit Functions for both the hot and cold design challenges can be found at http://www.osa.org/oic/designcontest.