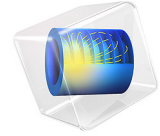


Created in COMSOL Multiphysics 6.0



Anti-Reflective Coating with Multiple Layers

Introduction

An anti-reflective coating is a set of thin, transparent films applied to the surface of an optical device such as a lens to reduce reflection. This reduction of reflected light leads to an increase in the efficiency of the optical system and minimizes stray light, which is important in many imaging applications. Anti-reflective coatings can also be applied to the surfaces of eyeglasses to reduce glare and make the eyes of the wearer more visible.

The simplest example of an anti-reflective coating is a quarter-wavelength layer, a single dielectric film with thickness equal to one quarter of the wavelength of the incident light. This layer can reduce the reflection coefficient to zero if the refractive index of the film is equal to the geometric mean of the refractive indices of the air (n_0) and substrate (n_S). For air (1.0) and common glass substrate (1.5) this optimal refractive index would be $\sqrt{(1.0)(1.5)}$ or approximately 1.22.

Typically no material exists with a refractive index that yields a reflection coefficient of exactly zero. Another drawback of the quarter-wavelength layer is that while it can prevent reflection of light at one wavelength, it reflects a substantial amount of radiation at any other nearby wavelength. The reflectance of the quarter-wavelength layer also depends heavily on the angle of incidence of the light.

An alternative is to use a coating that consists of multiple layers. Compared to single-layer coatings, a multilayer coating is more likely to reduce the reflection coefficient across a band of wavelengths and can be produced using a wider variety of real materials.

In this tutorial, the reflectance of two different multilayer coatings is compared over a wide spectral range: a quarter-quarter coating (two layers), and a quarter-half-quarter coating (three layers). The quarter-half-quarter coating is shown to have more consistently low reflectance across most of the visible spectrum.

Model Definition

Figure 1 shows the simple geometry used in this model. It consists of a box with an interior boundary separating the air and substrate domains. This boundary is also where the **Thin Dielectric Film** features are added.

The red arrow (activated in the **Material Discontinuity** feature) shows the sense in which the thin dielectric layers are stacked. The last Thin Dielectric Film in the Model Builder represents the topmost thin film in the model.

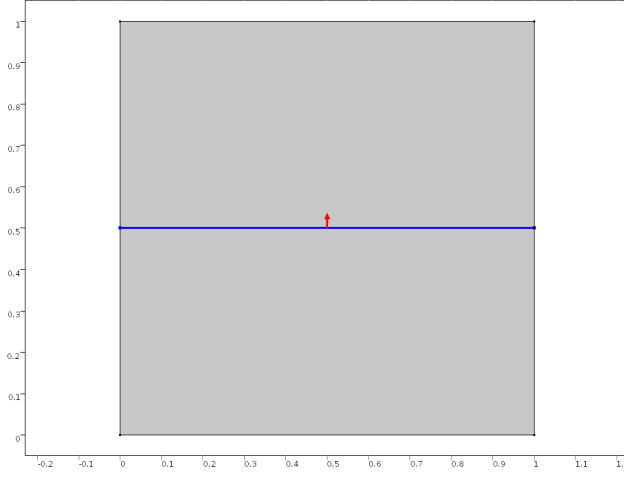


Figure 1: Geometry used to model multilayer anti-reflective coatings.

Simple anti-reflective coatings are designed to minimize the reflectance at a specified vacuum wavelength, λ_0 . More sophisticated coatings can minimize reflectance across a relatively large band of wavelengths by employing multiple thin films with different material properties.

In this tutorial, two different types of multilayer antireflective coating are investigated. The first is a quarter-quarter coating with two layers of different refractive index on the surface of a glass substrate. The name “quarter-quarter coating” comes from the fact that each layer has a thickness of $\lambda_0/(4n)$, where n is the refractive index of the layer.

Theoretically, a quarter-quarter coating can reduce the reflectance to zero at the specified wavelength; however, because real materials with ideal refractive indices are seldom available, zero reflectance is normally not achieved.

In this example, the substrate consists of glass ($n_s = 1.5$) and the first thin dielectric layer is made of magnesium fluoride, MgF_2 ($n_1 = 1.38$). The following expression can be used to determine the optimal refractive index for the second layer, n_2 , so that the reflectance can be reduced to zero:

$$n_2 = \sqrt{\frac{n_1^2 n_s}{n_a}}$$

where the refractive index of the air, n_a , is taken to be 1.

Using this expression the optimal value for n_2 is 1.69. From Table 1, cerium fluoride, CeF_3 , has a refractive index close to this value, 1.63. Using this material a minimum reflectance of less than 1% can be achieved.

TABLE 1: REFRACTIVE INDICES OF MATERIALS FREQUENTLY USED IN THIN FILMS.

MATERIAL	REFRACTIVE INDEX
Magnesium Fluoride (MgF_2)	1.38
Silicon Dioxide (SiO_2)	1.46
Cerium Fluoride (CeF_3)	1.63
Zirconium Oxide (ZrO_2)	2.2
Silicon (Si)	3.5

The reflectance as a function of vacuum wavelength is shown in Figure 2. A noticeable drawback of the two-layer coating is that the reflectance is only significantly reduced in a narrow band around a single wavelength.

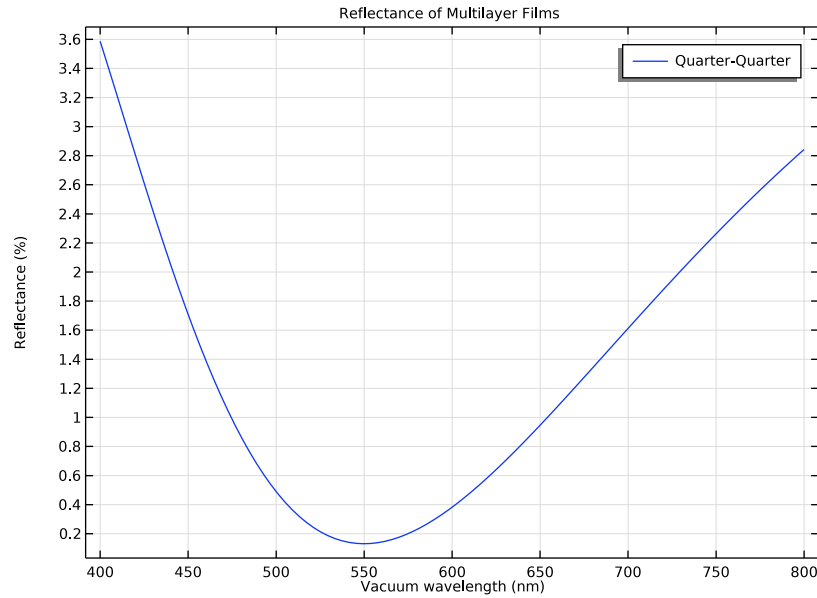


Figure 2: Reflectance of a quarter-quarter coating.

The reflectance can be reduced over a wider range of wavelengths by using a dielectric film with three or more layers. An example of a three-layer coating is the quarter-half-quarter coating, in which a thin layer of thickness $\lambda/2$ is placed between the two quarter-wavelength layers.

Results and Discussion

Figure 3 compares the reflectance of the quarter-quarter and quarter-half-quarter films. Because the refractive indices of real materials are used, the reflectance of the quarter-quarter coating does not decrease to zero. The quarter-half-quarter film exhibits slightly greater reflectance at the center of the band, but the reflectance remains lower than 1% over a much wider spectral range.

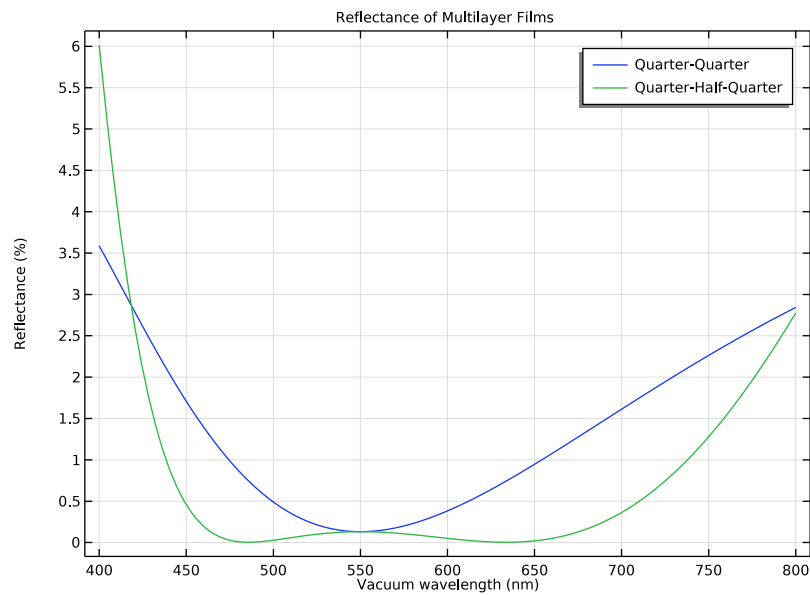



Figure 3: Reflectance response for a quarter-quarter and quarter-half-quarter coating configurations.

Application Library path: Ray_Optics_Module/Prisms_and_Coatings/
antireflective_coating_multilayer




Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click  **Model Wizard**.

MODEL WIZARD

- 1 In the **Model Wizard** window, click  **2D**.
- 2 In the **Select Physics** tree, select **Optics>Ray Optics>Geometrical Optics (gop)**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.
- 6 Click  **Done**.

GLOBAL DEFINITIONS


Parameters I

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters I**.
- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 In the table, enter the following settings:

Name	Expression	Value	Description
n_air	1	1	Refractive index of air
n_glass	1.5	1.5	Refractive index of glass
n_CeF3	1.63	1.63	Refractive index of CeF3
n_MgF2	1.38	1.38	Refractive index of MgF2
n_ZrO2	2.2	2.2	Refractive index of ZrO2
lam0	550[nm]	5.5E-7 m	Vacuum wavelength

GEOMETRY I

Square I (sq1)

- 1 In the **Geometry** toolbar, click  **Square**.
- 2 In the **Settings** window for **Square**, click to expand the **Layers** section.
- 3 In the table, enter the following settings:

Layer name	Thickness (m)
Layer 1	0.5

- 4 Click  **Build All Objects**.

MATERIALS

Material 1 (mat1)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, locate the **Material Contents** section.
- 3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	n_air	1	Refractive index

Material 2 (mat2)

- 1 Right-click **Materials** and choose **Blank Material**.
- 2 Select Domain 1 only.
- 3 In the **Settings** window for **Material**, locate the **Material Contents** section.
- 4 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_iso ; nii = n_iso, nij = 0	n_glass	1	Refractive index

GEOMETRICAL OPTICS (GOP)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometrical Optics (gop)**.
- 2 In the **Settings** window for **Geometrical Optics**, locate the **Intensity Computation** section.
- 3 From the **Intensity computation** list, choose **Compute intensity and power**.
- 4 Locate the **Ray Release and Propagation** section. From the **Wavelength distribution of released rays** list, choose **Polychromatic, specify vacuum wavelength**.
- 5 In the **Maximum number of secondary rays** text field, type 0.


Set up the quarter-quarter anti-reflective coating using two **Thin Dielectric Film** features.

It is useful to display the boundary normal in the **Graphics** window since this indicates the order in which the thin films are arranged. The arrow points in the direction away from the substrate, so the first layer that appears in the Model Builder is adjacent to the substrate and the last layer that appears is adjacent to the air domain.

Material Discontinuity 1

- 1 In the **Model Builder** window, under **Component 1 (comp1)>Geometrical Optics (gop)** click **Material Discontinuity 1**.
- 2 In the **Settings** window for **Material Discontinuity**, locate the **Advanced Settings** section.
- 3 Select the **Show boundary normal** check box.
- 4 Locate the **Coatings** section. From the **Thin dielectric films on boundary** list, choose **Add layers to surface**.
- 5 Locate the **Rays to Release** section. From the **Release reflected rays** list, choose **Never**. It is still possible to analyze the reflectance of the coating based on the intensity of the transmitted rays, even if no reflected rays are actually released at the boundary.


Thin Dielectric Film 1

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Thin Dielectric Film**.
The first layer (directly touching the glass substrate) is the CeF_3 layer with a refractive index of 1.63. The thickness is set to be a quarter of the wavelength in this material.
- 2 In the **Settings** window for **Thin Dielectric Film**, locate the **Film Properties** section.
- 3 In the n text field, type n_{CeF_3} .
- 4 In the t text field, type $1\text{am0}/(4*n_{\text{CeF}_3})$.

Material Discontinuity 1


In the **Model Builder** window, click **Material Discontinuity 1**.

Thin Dielectric Film 2

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Thin Dielectric Film**.
The second layer (on top of layer 1) is the MgF_2 layer with a refractive index of 1.38. The thickness of this layer is also set to a quarter of the wavelength.
- 2 In the **Settings** window for **Thin Dielectric Film**, locate the **Film Properties** section.
- 3 In the n text field, type n_{MgF_2} .
- 4 In the t text field, type $1\text{am0}/(4*n_{\text{MgF}_2})$.


Next, set up the **Release From Grid** feature to release a number of rays of different wavelengths from 400 nm to 800 nm.

Release from Grid 1

- 1 In the **Physics** toolbar, click  **Global** and choose **Release from Grid**.
- 2 In the **Settings** window for **Release from Grid**, locate the **Initial Coordinates** section.
- 3 In the $q_{x,0}$ text field, type 0.5.

- 4 In the $q_{y,0}$ text field, type 1.
- 5 Locate the **Ray Direction Vector** section. Specify the \mathbf{L}_0 vector as


0	x
-1	y

- 6 Locate the **Vacuum Wavelength** section. From the **Distribution function** list, choose **List of values**.
- 7 Click  **Range**.
- 8 In the **Range** dialog box, choose **Number of values** from the **Entry method** list.
- 9 In the **Start** text field, type 400[nm].
- 10 In the **Stop** text field, type 800[nm].
- 11 In the **Number of values** text field, type 100.
- 12 Click **Replace**.

Set up a **Ray Tracing** study step to compute the ray trajectories to a maximum optical path length of 1.1 m.


STUDY I

Step 1: Ray Tracing

- 1 In the **Model Builder** window, under **Study I** click **Step 1: Ray Tracing**.
- 2 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.
- 3 From the **Time-step specification** list, choose **Specify maximum path length**.
- 4 In the **Lengths** text field, type range(0,0.01,1.1).
- 5 In the **Home** toolbar, click  **Compute**.


RESULTS

Reflectance

- 1 In the **Home** toolbar, click  **Add Plot Group** and choose **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type Reflectance in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Ray 1**.
- 4 From the **Time selection** list, choose **Last**.
- 5 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 6 In the **Title** text area, type Reflectance of Multilayer Films.
- 7 Locate the **Plot Settings** section. Select the **x-axis label** check box.

- 8 In the associated text field, type Vacuum wavelength (nm).
- 9 Select the **y-axis label** check box.
- 10 In the associated text field, type Reflectance (%).

Ray 1

- 1 In the **Reflectance** toolbar, click  **More Plots** and choose **Ray**.
Plot the percentage reflectance.
- 2 In the **Settings** window for **Ray**, locate the **y-Axis Data** section.
- 3 In the **Expression** text field, type $100 * (gop.relg1.Q0 - gop.Q) / gop.relg1.Q0$.
- 4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 5 In the **Expression** text field, type $gop.lambda0$.
- 6 From the **Unit** list, choose **nm**.
- 7 Click to expand the **Legends** section. Select the **Show legends** check box.
- 8 From the **Legends** list, choose **Manual**.
- 9 In the table, enter the following settings:

Legends
Quarter-Quarter

- 10 In the **Reflectance** toolbar, click  **Plot**. The plot should look like [Figure 2](#).


Next, to simulate a quarter-half-quarter layer, add another **Thin Dielectric Film** feature. The material of the middle layer is chosen to be Zirconium Oxide, ZrO_2 , with refractive index 2.2. Set the thickness to half the specified wavelength.

GEOMETRICAL OPTICS (GOP)

Material Discontinuity 1

In the **Model Builder** window, under **Component 1 (comp1)>Geometrical Optics (gop)** click **Material Discontinuity 1**.



Thin Dielectric Film 3

- 1 In the **Physics** toolbar, click  **Attributes** and choose **Thin Dielectric Film**.
This layer will sit between the other two thin layers so its node must be moved in the Model Builder.
- 2 Right-click **Thin Dielectric Film 3** and choose **Move Up**.
- 3 In the **Settings** window for **Thin Dielectric Film**, locate the **Film Properties** section.

- 4 In the n text field, type n_{ZrO_2} .
- 5 In the t text field, type $1\text{am0}/(2*n_{\text{ZrO}_2})$.


Add another study so that the two films can be compared.

ADD STUDY

- 1 In the **Home** toolbar, click  **Add Study** to open the **Add Study** window.
- 2 Go to the **Add Study** window.
- 3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.
- 4 Click **Add Study** in the window toolbar.
- 5 In the **Home** toolbar, click  **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Ray Tracing

- 1 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.
- 2 From the **Time-step specification** list, choose **Specify maximum path length**.
- 3 In the **Lengths** text field, type $\text{range}(0, 0.01, 1.1)$.
- 4 From the **Stop condition** list, choose **No active rays remaining**.
- 5 In the **Home** toolbar, click  **Compute**.

RESULTS

Ray 2

- 1 In the **Model Builder** window, under **Results>Reflectance** right-click **Ray 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Ray**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Ray 2**.
- 4 From the **Time selection** list, choose **Last**.
- 5 Locate the **Legends** section. In the table, enter the following settings:

Legends
Quarter-Half-Quarter

- 6 In the **Reflectance** toolbar, click  **Plot**. Compare the result with [Figure 3](#).

