Enhanced Coating for a Microelectromechanical Mirror

Introduction

Microelectromechanical (MEMS) mirrors are important for spatial light modulators (SLMs), used for instance in projectors and photolithographic exposure equipment. In order to achieve high efficiency, the mirrors must provide a high reflectance. For lithographic applications, short wavelengths — in the ultraviolet (UV), deep ultraviolet (DUV), or vacuum ultraviolet (VUV) spectral regions — are used to obtain a very high resolution. In addition, as the MEMS mirrors are used in consumer electronics and in industrial processing equipment, the mirrors must survive strong illumination for a long time without degradation.

The most common material for MEMS mirrors is aluminum. However, to make the mirrors more durable and to enhance the reflectance, especially for UV wavelengths, different types of coatings are often applied to the bare MEMS metal mirrors.

This model, adapted from Ref. 1, demonstrates how a coating layer can be applied to a metal mirror to maximize the reflectance at a particular operating wavelength. In this case the MEMS mirror is designed for lithographic applications in the VUV region, at a wavelength of 157 nm.

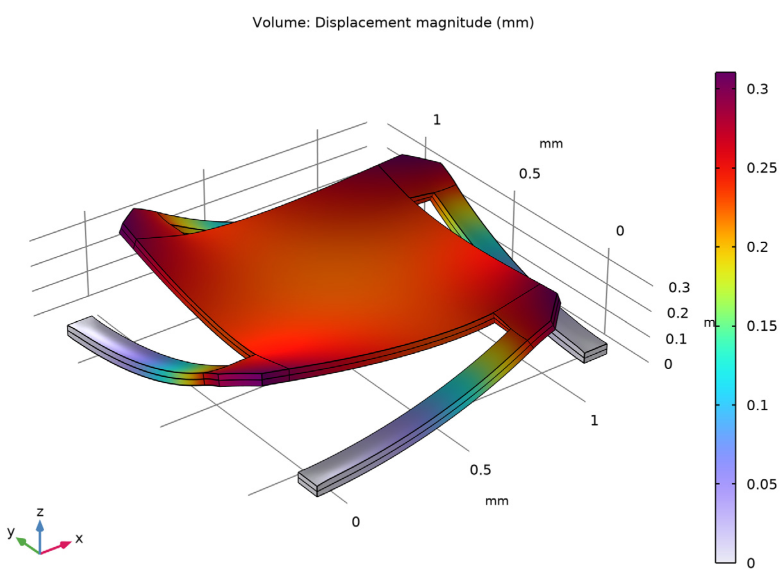


Figure 1: An example of an aluminum MEMS mirror having a reflective center portion, supported by four prestressed plated cantilever springs. This picture is taken from the Prestressed Micromirror model in the MEMS Module Application Library.

Model Definition

The coating layer, lanthanum fluoride (LaF3), and the backing aluminum mirror are modeled using a Layered Impedance Boundary Condition. Thereby neither the coating layer nor the mirror layer need to be modeled using a domain mesh. This can significantly reduce the computation time.

To find the coating thickness that maximizes the reflectance at the operating wavelength, 157 nm, an Optimization study step is used.

Results and Discussion

Figure 2 shows the reflectance versus the coating layer thickness. The reflectance has several maxima, but the highest reflectance is obtained for a thickness of about 30 nm. Thus, the optimization procedure consists in finding the maximizing thickness, in the range 10-50 nm.

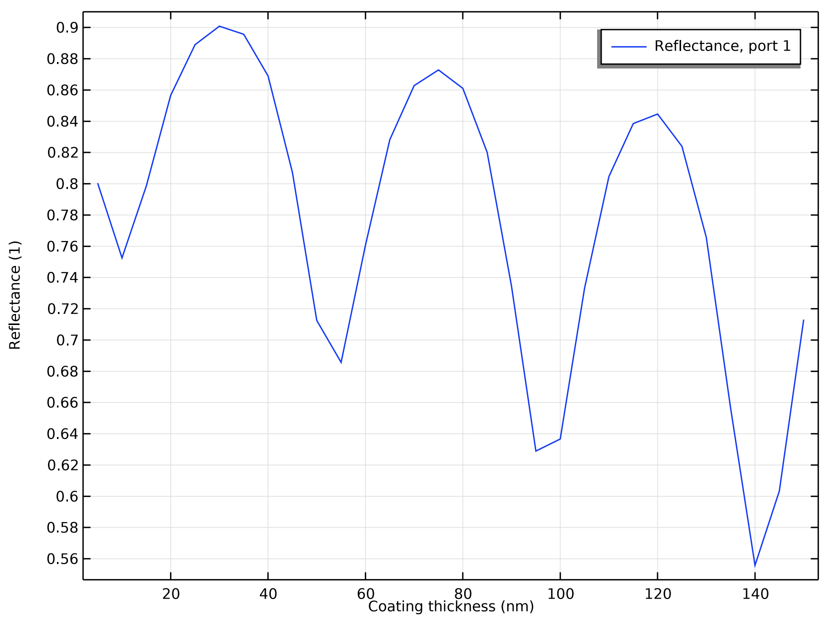


Figure 2: Reflectance versus coating layer thickness.

Figure 3 compares the reflectance spectra with only the bare aluminum MEMS mirror and with the combination of the MEMS mirror and the optimized coating layer. At the operating wavelength, the reflectance is larger when the optimal coating layer is applied.

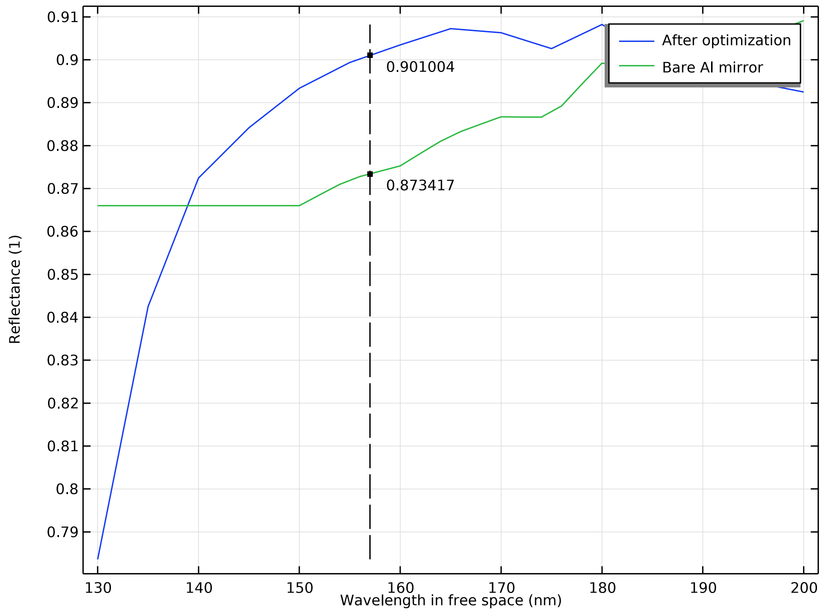


Figure 3: Reflectance spectra for the bare aluminum mirror (denoted Bare Al mirror) and the mirror with the optimized coating layer (denoted After optimization).The optimization procedure allows to achieve a larger reflectance at the 157 nm operation wavelength.

Reference

1. A. Gatto and others, "High-performance coatings for micromechanical mirrors," *Applied Optics*, vol. 45, no. 7, pp. 1602–1607, 2006.

Application Library path: `Wave_Optics_Module/Couplers_Filters_and_Mirrors/enhanced_mems_mirror_coating`

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>Wave Optics>Electromagnetic Waves, Frequency Domain (ewfd)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces> Wavelength Domain**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
`lda0`	`157[nm]`	1.57E-7 m	`Wavelength`
`a`	`lda0`	1.57E-7 m	`Domain side length`
`t_coat`	`50[nm]`	5E-8 m	`Coating thickness`

GEOMETRY 1

Square 1 (sq1)

1 In the **Geometry** toolbar, click **Square**.

2 In the **Settings** window for **Square**, locate the **Size** section.

3 In the **Side length** text field, type `a`.

MATERIALS

Air

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Air` in the **Label** text field.

3 Locate the **Material Contents** section. In the table, enter the following settings:

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

GLOBAL DEFINITIONS

Now, add the material for the MEMS mirror, which is aluminum.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the **Search** text field, type `aluminium`. Note the British English spelling, which is the one used in the library for the material we want to use.

4 Click **Search**.

5 In the tree, select **Optical>Inorganic Materials>Al - Aluminium and aluminates>Experimental data>Al (Aluminium) (McPeak et al. 2015: n,k 0.15-1.7 um)**.

6 Right-click and choose **Add to Global Materials**.

7 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

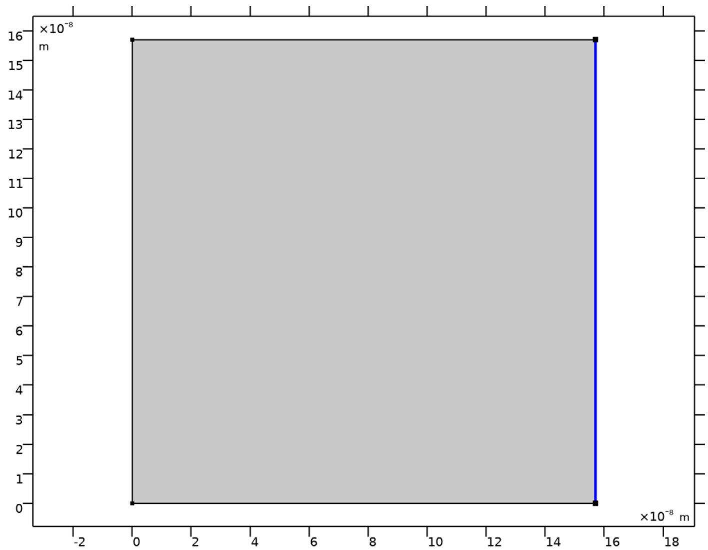
Aluminum

1 Right-click **Materials** and choose **More Materials>Material Link**.

2 In the **Settings** window for **Material Link**, type `Aluminum` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 4 only.



ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (ewfd)**.

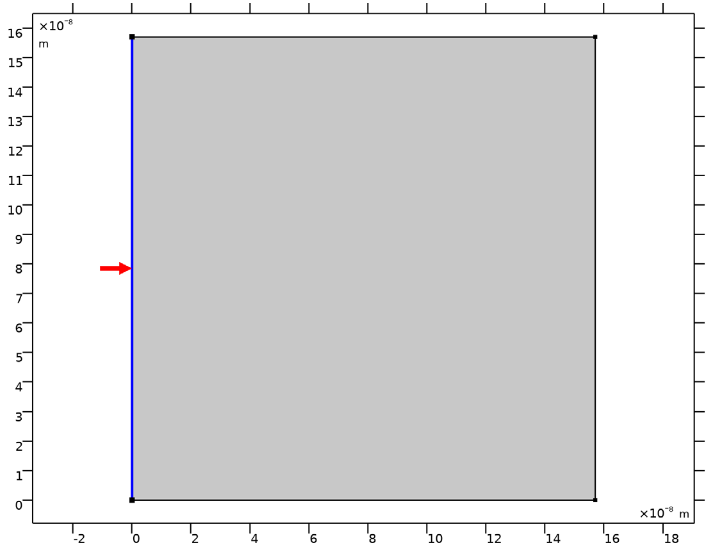
2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.

3 From the **Electric field components solved for** list, choose **Out-of-plane vector**.

Port 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 Select Boundary 1 only.



3 In the **Settings** window for **Port**, locate the **Port Mode Settings** section.

4 Specify the $\mathbf{E}_0$ vector as

0	x
0	y
1	z

5 In the β text field, type `ewfd.k0`.

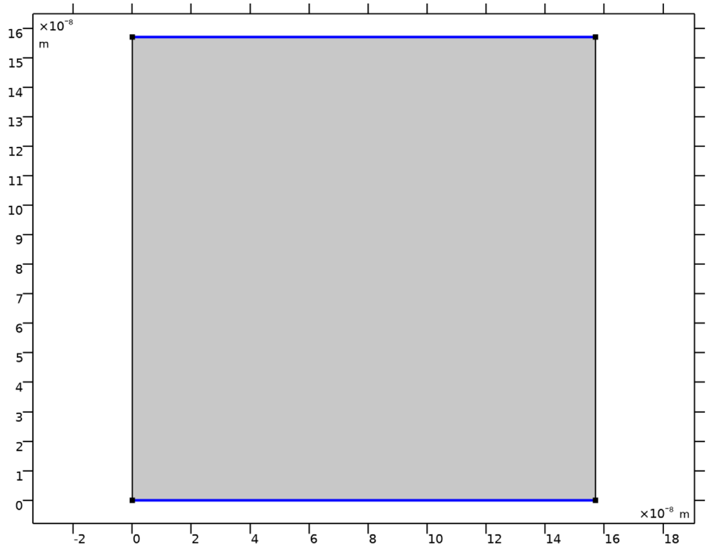
These Port settings represent a plane wave polarized in the z direction.

Perfect Magnetic Conductor 1

Because the incoming wave is polarized in the z direction, change the top and bottom boundary conditions to **Perfect Magnetic Conductor**.

1 In the **Physics** toolbar, click **Boundaries** and choose **Perfect Magnetic Conductor**.

2 Select Boundaries 2 and 3 only.

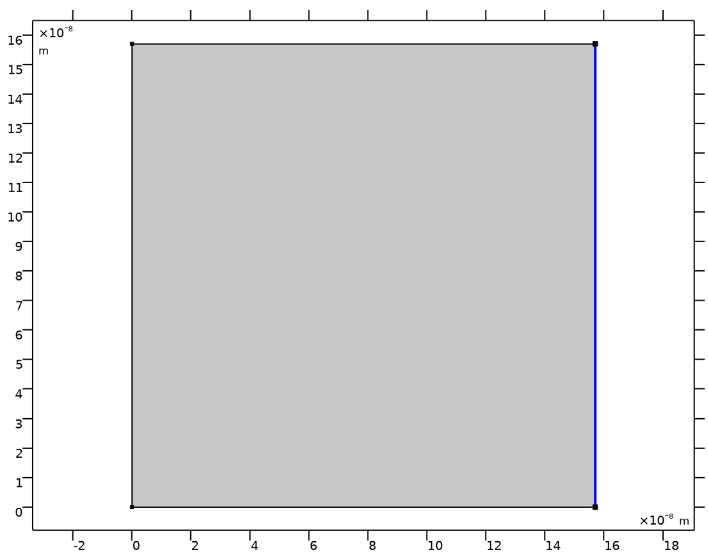


Impedance Boundary Condition 1

Initially, use an Impedance boundary condition to represent the MEMS mirror.

1 In the **Physics** toolbar, click **Boundaries** and choose **Impedance Boundary Condition**.

2 Select Boundary 4 only.



STUDY 1

Now, compute a reflectance spectrum for the uncoated aluminum MEMS mirror.

Step 1: Wavelength Domain

1 In the **Model Builder** window, under **Study 1** click **Step 1: Wavelength Domain**.

2 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.

3 From the **Wavelength unit** list, choose **nm**.

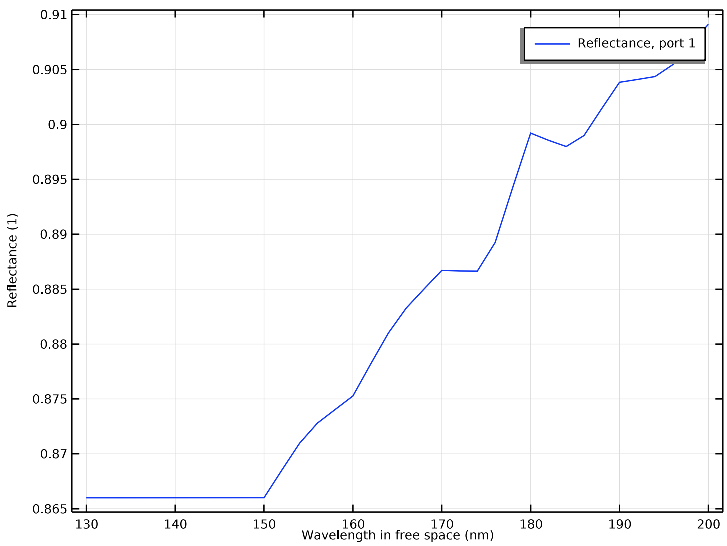
4 In the **Wavelengths** text field, type `range(130[nm],2[nm],200[nm])`.

5 In the **Home** toolbar, click **Compute**.

RESULTS

Reflectance (ewfd)

1 In the **Model Builder** window, under **Results** click **Reflectance (ewfd)**.



The plot shows that the reflectance decreases the shorter the wavelength is and at 157 nm it is a bit larger than 87%.

GLOBAL DEFINITIONS

Next, replace the pure aluminum MEMS mirror with a coated mirror. First, add the coating material. Then, replace the Impedance boundary condition with a Layered impedance boundary condition. The Layered impedance boundary condition represents both the aluminum mirror and the coating.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the **Search** text field, type `Lanthanum`.

4 Click **Search**.

5 In the tree, select **Optical>Inorganic Materials>F - Fluorides>Thin film> LaF3 (Lanthanum fluoride) (Rodrìguez-de Marcos et al. 2017: n,k 0.03-2.0 um)**.

6 Click **Add to Global Materials** in the window toolbar.

7 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

GLOBAL DEFINITIONS

Layered Material 1 (lmat1)

1 In the **Model Builder** window, under **Global Definitions** right-click **Materials** and choose **Layered Material**.

2 In the **Settings** window for **Layered Material**, locate the **Layer Definition** section.

3 In the table, enter the following settings:

Layer	Material	Rotation (deg)	Thickness	Mesh elements
`Layer 1`	LaF3 (Lanthanum fluoride) (Rodrìguez-de Marcos et al. 2017: n,k 0.03-2.0 um) (mat3)	`0.0`	`t_coat`	2

This layer represents the coating layer, on top of the aluminum mirror.

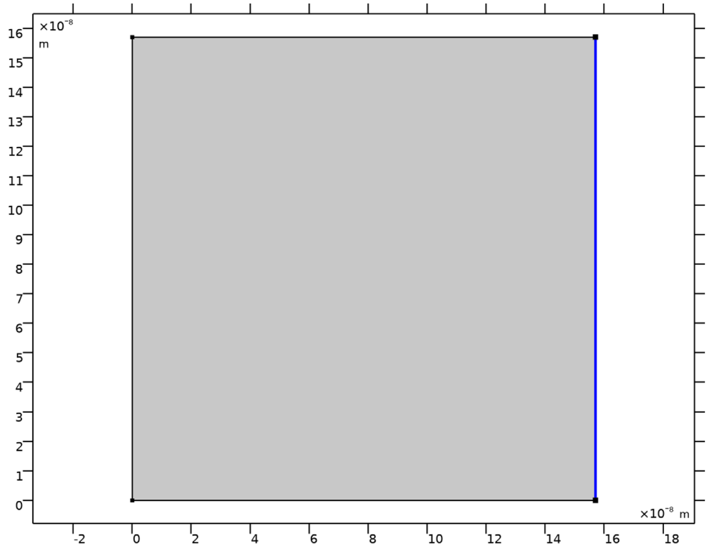
MATERIALS

Coating Layer

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Layers>Layered Material Link**.

2 In the **Settings** window for **Layered Material Link**, type `Coating Layer` in the **Label** text field.

3 Select Boundary 4 only.

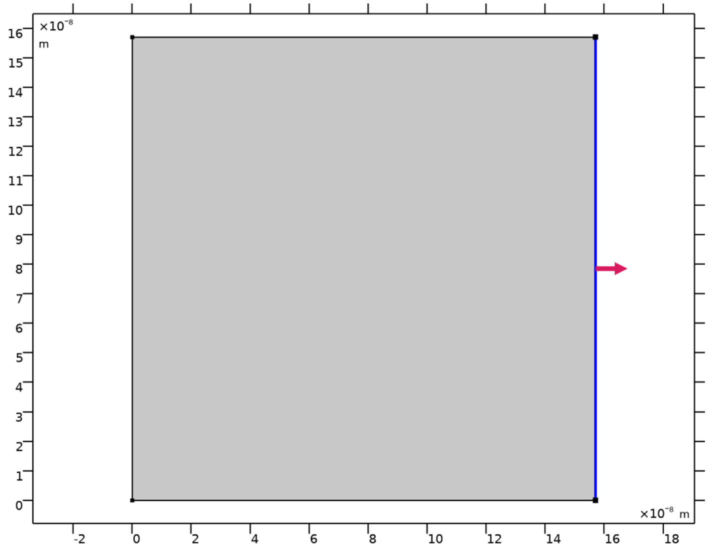


ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

Layered Impedance Boundary Condition 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Layered Impedance Boundary Condition**. Notice that the **Layered Impedance Boundary Condition** can only be added to boundaries where there is a **Layered Material**. That is why the **Layered Material Link** was first added to Boundary 4.

2 Select Boundary 4 only.



3 In the **Settings** window for **Layered Impedance Boundary Condition**, locate the **Substrate Properties** section.

4 From the **Substrate material** list, choose **Al (Aluminium) (McPeak et al. 2015: n,k 0.15-1.7 um) (mat2)**.

Now, the coated mirror is defined, with the **Layer Properties** taken from the **Coating Layer** and the **Substrate Properties** from the mirror material.

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>Wavelength Domain**.

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: Wavelength Domain

1 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.

2 In the **Wavelengths** text field, type `lda0`.

Make a **Parametric Sweep** to explore how the reflectance depends on the coating thickness, given a fixed wavelength of 157 nm.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	**Parameter value list**	**Parameter unit**
t_coat (Coating thickness)		`m`

5 Click **Range**.

6 In the **Range** dialog box, type `5[nm]` in the **Start** text field.

7 In the **Step** text field, type `5[nm]`.

8 In the **Stop** text field, type `150[nm]`.

9 Click **Replace**.

10 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

11 In the table, enter the following settings:

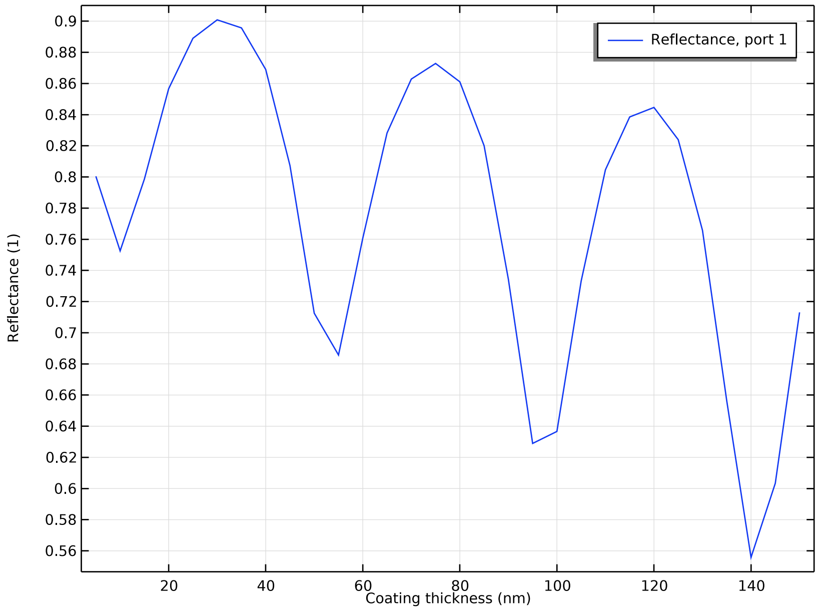
Parameter name	**Parameter value list**	**Parameter unit**
t_coat (Coating thickness)	`range(5[nm],5[nm], 150[nm])`	`nm`

12 In the **Study** toolbar, click **Compute**.

RESULTS

Reflectance (ewfd) 1

1 In the **Model Builder** window, under **Results** click **Reflectance (ewfd) 1**.



The plot shows that there are several resonances for different coating thicknesses. However, the highest reflectance is at the first peak, around 30 nm.

DEFINITIONS (COMP1)

Now, add an **Optimization** study, to find the coating thickness that gives the maximum reflectance.

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
T_Eval	ewfd.Rport_1		Evaluated transmittance
T_Objective	abs((comp1.T_Eval-1)/comp1.T_Eval)		Objective function

These variables will be used when defining the objective function in the **Optimization** study.

ADD STUDY

1 In the **Study** 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>Wavelength Domain**.

4 Click **Add Study** in the window toolbar.

5 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 3

Step 1: Wavelength Domain

1 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.

2 In the **Wavelengths** text field, type `lda0`.

Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Optimization**.

2 In the **Settings** window for **Optimization**, locate the **Objective Function** section.

3 In the table, enter the following settings:

Expression	Description	Evaluate for
comp1.T_Objective	Objective function	Wavelength Domain

4 Locate the **Control Variables and Parameters** section. Click **Add**.

5 In the table, enter the following settings:

Parameter name	Initial value	Scale	Lower bound	Upper bound
t_coat (Coating thickness)	30[nm]	1[nm]	10[nm]	50[nm]

6 In the **Study** toolbar, click **Compute**.

Table 1 shows that the optimal coating thickness is 31.03125 nm, with a reflectance of just above 90%.

ROOT

Finally, compute a new reflectance spectrum using the optimal coating thickness.

ADD STUDY

1 In the **Study** 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>Wavelength Domain**.

4 Click **Add Study** in the window toolbar.

5 In the **Study** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 4

Step 1: Wavelength Domain

1 In the **Settings** window for **Wavelength Domain**, locate the **Study Settings** section.

2 From the **Wavelength unit** list, choose **nm**.

3 In the **Wavelengths** text field, type `range(130[nm],5[nm],200[nm])`.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep** to specify the optimal coating thickness for this calculation.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
t_coat (Coating thickness)	31.03125[nm]	nm

5 In the **Study** toolbar, click **Compute**.

RESULTS

Global 1

1 In the **Model Builder** window, expand the **Results>Reflectance (ewfd)** node.

2 Right-click **Global 1** and choose **Copy**.

Reflectance (ewfd) 2

In the **Model Builder** window, under **Results** right-click **Reflectance (ewfd) 2** and choose **Paste Global**.

Global 2

1 In the **Model Builder** window, click **Global 2**.

2 In the **Settings** window for **Global**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
Bare Al mirror

Graph Marker 1

1 Right-click **Global 2** and choose **Graph Marker**.

2 In the **Settings** window for **Graph Marker**, locate the **Display** section.

3 From the **Display mode** list, choose **Line intersection**.

4 In the **x-coordinates** text field, type 157.

5 Click to expand the **Coloring and Style** section. From the **Anchor point** list, choose **Upper left**.

6 Right-click **Graph Marker 1** and choose **Copy**.

Global 1

1 In the **Model Builder** window, under **Results>Reflectance (ewfd) 2** click **Global 1**.

2 In the **Settings** window for **Global**, locate the **Legends** section.

3 From the **Legends** list, choose **Manual**.

4 In the table, enter the following settings:

Legends
After optimization

5 Right-click **Results>Reflectance (ewfd) 2>Global 1** and choose **Paste Graph Marker**.

Graph Marker 1

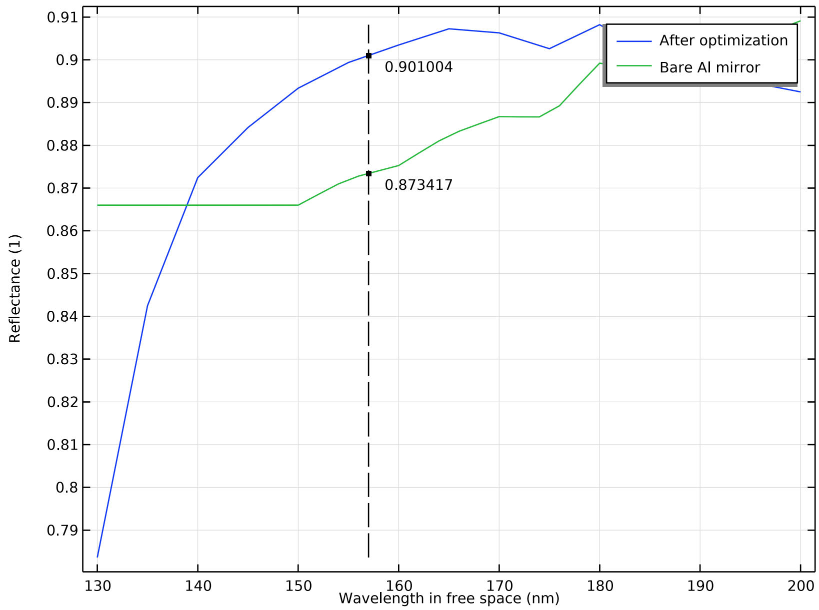
1 In the **Model Builder** window, click **Graph Marker 1**.

2 In the **Settings** window for **Graph Marker**, locate the **Display** section.

3 Select the **Show lines** check box.

4 Click to expand the **Line Style** section. From the **Line** list, choose **Dashed**.

5 In the **Reflectance (ewfd) 2** toolbar, click **Plot**.



This plot shows that using a coating layer with optimal thickness results in a larger reflectance, at the operation wavelength of 157 nm.