Created in COMSOL Multiphysics 6.0

Diffraction Grating

Introduction

This tutorial uses the Wave Optics Module and the Ray Optics Module to simulate the propagation of rays through a diffraction grating at different angles of incidence. It uses the S-parameters computed by the Electromagnetic Waves, Frequency Domain interface on a unit cell of the grating to specify the reflectance and transmittance of each diffraction order in the Geometrical Optics interface, allowing ray propagation through the grating to be modeled over length scales much larger than the width of the unit cell.

The Geometrical Optics interface includes a **Grating** feature that can be used to simulate propagation of electromagnetic waves on fully scaled optical devices without the need to spatially resolve the wavelength, which would be impractical in many cases due to the large number of mesh elements required.

Although the directions of propagation for the diffraction orders can be derived from the wavelength of radiation, the angle of incidence, and the width of a unit cell in the grating, reinitialization of the ray intensity requires prior calculation of the transmittance and reflectance for all diffraction orders as a function of angle of incidence. These quantities can be obtained by computing the S-parameters of each diffraction order for a single unit cell as a function of the angle of incidence using the **Port** and **Diffraction Order** features for the Electromagnetic Waves, Frequency Domain interface.

This 2D model is separated in two parts.

- First, the transmittance and reflectance of each diffraction order are computed using the Electromagnetic Waves, Frequency Domain interface on a single unit cell of the grating. For this part of the model it is necessary to fully resolve the wavelength. A **Parametric Sweep** is used to compute the transmittance and reflectance as functions of the angle of incidence.
- The second part demonstrates how the transmittance and reflectance values can be used to generate a set of interpolation functions that can be used with the **Grating** feature of the Geometrical Optics interface.

Model Definition

This model simulates the interaction of light of free-space wavelength $\lambda_0 = 441\ \mathrm{nm}$ with a $5\ \mathrm{mm}$ wide dielectric grating of grating constant (the distance between the grooves) $d = 340\ \mathrm{nm}$.

NOTES ON DIFFRACTION ORDERS

For a plane wave incident on a diffraction grating at angle of incidence α (SI unit: rad) as in Figure 1, the diffraction orders correspond to the angles at which the difference in optical path length for wavefronts from adjacent unit cells is an integer multiple of the wavelength. The angle of a transmitted order β_m (SI unit: rad) is defined by the relation

$$n_\beta \sin(\beta_m) - n_\alpha \sin(\alpha) = m\frac{\lambda_0}{d}$$

where the diffraction order m (dimensionless) is an integer.

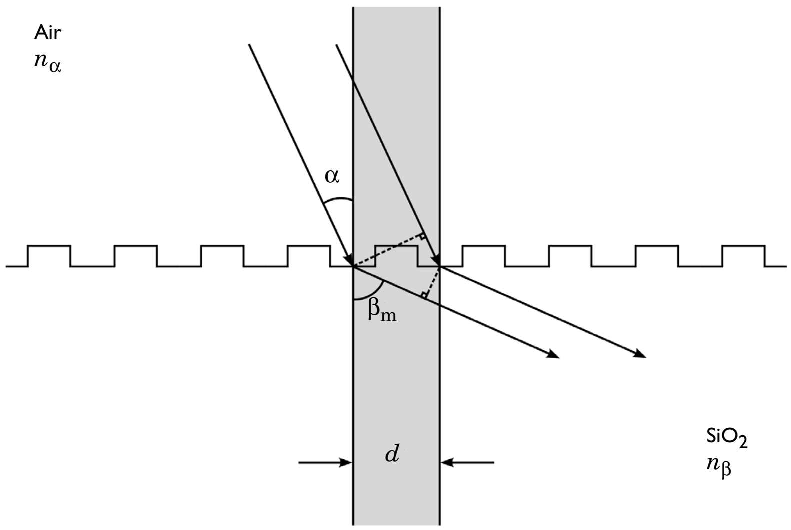

Figure 1: The geometric path lengths of two transmitted parallel rays.The shaded area represents a unit cell of the diffraction grating (SiO_2). For this model the grating constant is d = 340 nm and the monochromatic TE polarized light has a wavelength of λ_0 = 441 nm.

For $m = 0$, the angle of refraction is described by Snell's law,

$$\sin(\beta_0) = \frac{n_\alpha}{n_\beta}\sin(\alpha)$$

For reflected rays, $n_\alpha = n_\beta$. For $m = 0$, specular reflection occurs, $\beta_0 = \alpha$.

Because the sine functions can only vary between -1 and 1, the existence of higher diffraction orders requires that

$$-(n_\alpha + n_\beta) < \frac{m\lambda_0}{d} < (n_\alpha + n_\beta)$$

In this example only the diffraction orders 0, 1, and -1 can be released, which means that

$$2\lambda_0 > d(n_\alpha|\sin(\alpha)| + n_\beta)$$

As mentioned in the introduction, the model consists of two parts: the S-parameter calculation using a single unit cell and the ray trajectory computation in an optically large modeling domain.

S-PARAMETER CALCULATION

The transmittance and reflectance for the refraction, specular reflection, and first order diffraction of plane TE waves (electric field component in the z-direction, out of the xy-plane) are computed for a single unit cell.

The Electromagnetic Waves, Frequency Domain interface is used to model wave propagation in a single unit cell of the grating, as outlined in Figure 1. On either side of the unit cell, the **Periodic Condition** boundary condition with **Floquet periodicity** is used. This condition states that the solution on one side of the unit cell equals the solution on the other side multiplied by a complex-valued phase factor. The phase shift between the boundaries is evaluated from the perpendicular component of the wave vector. Note that due to the continuity of the field, the phase factor is the same for the refracted and reflected waves as for the incident wave.

Port boundary conditions are used to release the incident wave and to absorb the reflected and transmitted waves of order 0. To ensure that no non-physical reflections occur, **Diffraction Order** subnodes must be added to the **Port** nodes to absorb outgoing waves of each nonzero diffraction order.

The input to each periodic port is an electric field amplitude vector and an angle of incidence. In this example the angle of incidence is swept from 0° to 90° at 1° intervals.

RAY TRACING

The Geometrical Optics interface computes the intensity of rays of each diffraction order using the transmittance and reflectance computed in the previous study. In order to see the effect of the angle of incidence on the ray trajectories and intensity, 901 rays are released from a point in a 90° cone with a source power density of 901 W/m, or 1 W/m per ray. For each diffraction order, two rays may be released, one transmitted ray and one reflected ray. Because the transmitted ray of order 0 uses the same degrees of freedom as the incident ray, five extra degrees of freedom should be allocated per incident ray: one for the reflected ray of order 0 and two each for the reflected and transmitted rays of order $m = 1$ and $m = -1$. A total of 4505 secondary rays are allocated.

USE OF SIGN CONVENTIONS FOR DIFFRACTION ORDERS

The Electromagnetic Waves physics interfaces use a different sign convention to distinguish between positive and negative diffraction orders, compared to the Geometrical Optics interfaces.

In the Electromagnetic Waves interface in this model, the excited port is at the top of the geometry and the waves propagate downward. Increases in diffraction order correspond to clockwise rotations of both the reflected and transmitted wave vectors on either side of the unit cell. Thus higher reflected orders point more to the right, while higher transmitted orders point more to the left.

In contrast, the Geometrical Optics interface increments the tangential component of the wave vector by the same multiple of the reciprocal lattice vector for both transmitted and reflected rays of each diffraction order. Higher diffraction orders point more to the right for both reflected and transmitted rays.

Therefore, when using the solution of the Electromagnetic Waves interface to reinitialize the power of rays, pay careful attention to how the diffraction orders are negated for transmitted rays:

- For the **Diffraction Order (m = 0)** node, the specified **Reflectance** and **Transmittance** are `R0(alpha_ro)` and `T0(alpha_ro)`, respectively. Here `alpha_ro` is a variable for the angle of incidence of each ray, measured counterclockwise from the surface normal.
- For the **Diffraction Order (m = -1)** node, the specified **Reflectance** is `Rm1(alpha_ro)` and the specified **Transmittance** is `T1(alpha_ro)`. The $m = -1$ order for reflected rays corresponds to the $m = -1$ order for reflected waves, but the $m = -1$ order for transmitted rays corresponds to the $m = +1$ order for transmitted waves.
- For the **Diffraction Order (m = 1)** node, the specified **Reflectance** is `R1(alpha_ro)` and the specified **Transmittance** is `T1(alpha_ro)`. The $m = +1$ order for reflected rays corresponds to the $m = +1$ order for reflected waves, but the $m = +1$ order for transmitted rays corresponds to the $m = -1$ order for transmitted waves.

This tutorial would require further extension if rays could also be released from the upper-right quadrant, propgating downward and to the left. As currently defined, `alpha_ro` is negative for rays propagating downward and to the left. The interpolation functions used to specify the reflectance and transmittance for rays of each diffraction order are only defined for positive angles.

Results and Discussion

The electric field norm for a TE wave with an angle of incidence of 45° is shown in Figure 2. In order to get reliable results one has to use a very fine mesh to resolve the wavelength. To resolve a wave properly, it is necessary to use about 10 mesh elements per wavelength when using linear shape functions, or 5 elements per wavelength when using the default quadratic shape functions.

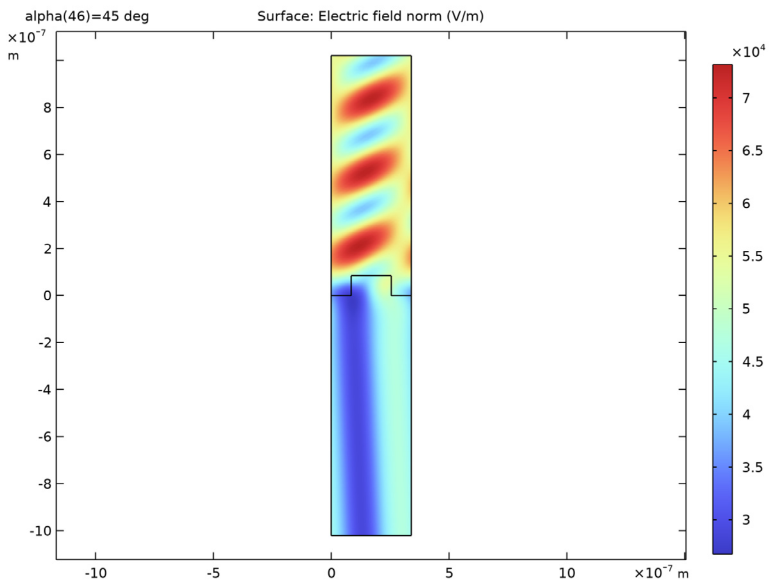

Figure 2: Norm of the electric field for a TE wave with an angle of incidence of 45 degrees.

The transmittance and reflectance of each diffraction order as functions of the angle of incidence are shown in Figure 3. Most of the radiation is transmitted at diffraction order 0, except at very large angles of incidence for which most of the radiation is reflected.

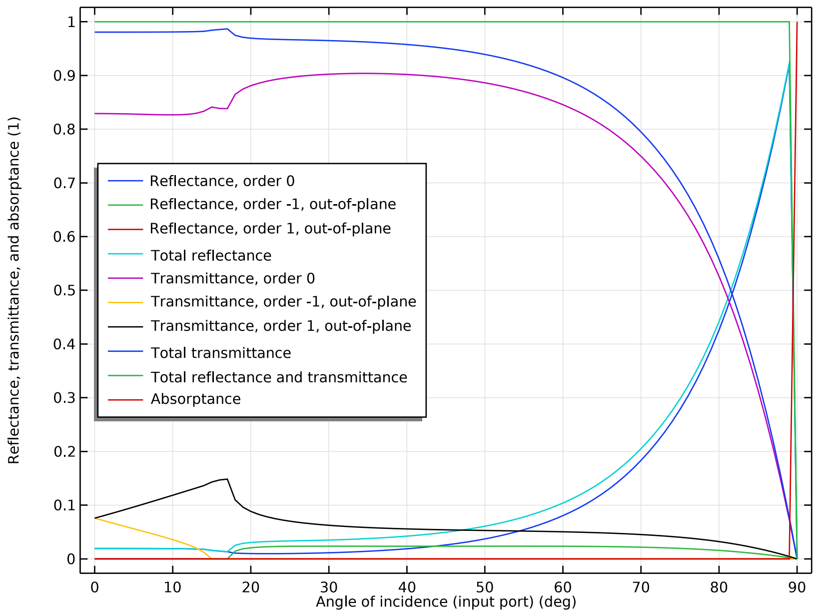

Figure 3: Reflectance and transmittance of diffraction orders 0, 1, and -1 as functions of the angle of incidence.

The raw data from Figure 3 was used to define a series of six interpolation functions, each corresponding to the reflectance or transmittance of a diffraction order. These interpolation functions were used in the Geometrical Optics interface to define the reinitialized intensity of the transmitted and reflected rays.

In Figure 4 the total intensity of the reflected and transmitted rays, indicated by points at discrete angle intervals, is compared to the sum of the reflectance and transmittance functions defined with the solution data from full wave solution.

The curves for the Electromagnetic Waves, Frequency Domain interface and the Geometrical Optics interface agree closely, which is to be expected because the transmittance and reflectance of the grating in the latter are defined explicitly in terms of the solution to the former.

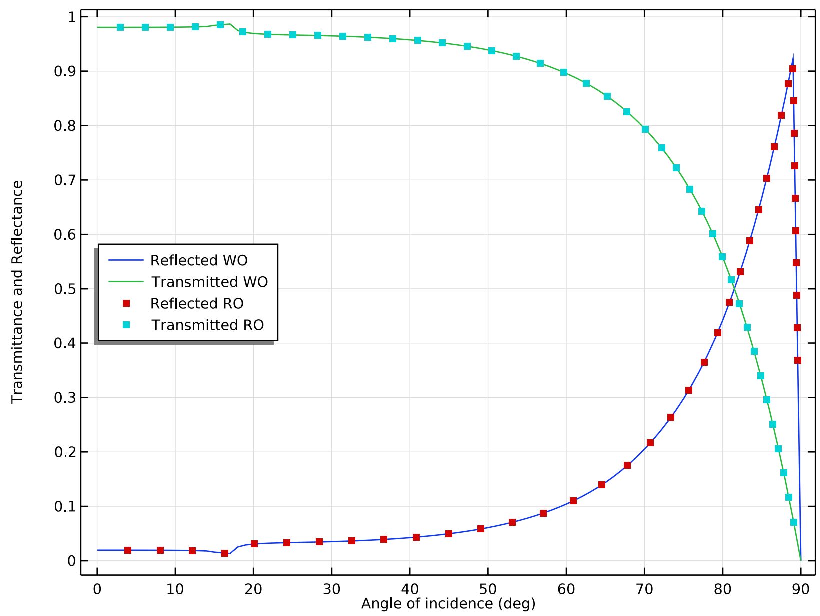

Figure 4: The transmittance and reflectance computed by both the wave optics and ray optics models.

Application Library path: `Ray_Optics_Module/Verification_Examples/diffraction_grating`

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 **General Studies>Frequency 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
n_air	1	1	Refractive index air
n_sio2	1.54874	1.5487	Refractive index SiO2
d	340[nm]	3.4E-7 m	Grating constant
lam0	441[nm]	4.41E-7 m	Vacuum wavelength of incident light
f0	c_const/lam0	6.798E14 1/s	Frequency of incident light
alpha	0.0[deg]	0 rad	Angle of incidence (input port)

Because this model uses two model Components with different geometries but the same material properties, it is convenient to define global materials before setting up the individual physics interfaces.

Air

1 In the **Model Builder** window, under **Global Definitions** 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 Properties** section. In the **Material properties** tree, select **Electromagnetic Models>Refractive Index>Refractive index, real part (n)**.

4 Click **Add to Material**.

5 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	`n_air`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

SiO2

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `SiO2` in the **Label** text field.

3 Locate the **Material Properties** section. In the **Material properties** tree, select **Electromagnetic Models>Refractive Index>Refractive index, real part (n)**.

4 Click + **Add to Material**.

5 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	`n_sio2`	1	Refractive index
Refractive index, imaginary part	ki_iso ; kiii = ki_iso, kiij = 0	0	1	Refractive index

GEOMETRY 1

Create the geometry of a single unit cell in the grating.

Rectangle 1 (r1)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `d`.

4 In the **Height** text field, type `6*d`.

5 Locate the **Position** section. In the **y** text field, type `-3*d`.

Rectangle 2 (r2)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `d`.

4 In the **Height** text field, type `3*d`.

5 Locate the **Position** section. In the **y** text field, type `-3*d`.

Rectangle 3 (r3)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `d/2`.

4 In the **Height** text field, type `d/4`.

5 Locate the **Position** section. In the **x** text field, type `d/4`.

Union 1 (uni1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Union**.

2 Select the objects **r2** and **r3** only.

3 In the **Settings** window for **Union**, locate the **Union** section.

4 Clear the **Keep interior boundaries** check box.

5 Click **Build All Objects**. The geometry should look like the unit cell in Figure 1.

MATERIALS

Material Link 1 (matlnk1)

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

2 Select Domain 2 only.

Material Link 2 (matlnk2)

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

2 Select Domain 1 only.

3 In the **Settings** window for **Material Link**, locate the **Link Settings** section.

4 From the **Material** list, choose **SiO2 (mat2)**.

STUDY 1

Step 1: Frequency Domain

It is convenient to specify the frequency in the sweep before setting up the physics, since it can then be used to automatically compute the diffraction orders for the **Port** boundary conditions.

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

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

3 In the **Frequencies** text field, type `f0`.

In this model the S-parameters of a TE wave are computed. Select **Out-of-plane vector** as the component of the electric field to be solved for.

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**.

Create a periodic input port. To model a TE wave, keep the **Electric field** as the **Input quantity** and enter the value `1` in the z-component field.

Port 1

1. In the **Physics** toolbar, click **Boundaries** and choose **Port**.
2. Select Boundary 5 only.
3. In the **Settings** window for **Port**, locate the **Port Properties** section.
4. From the **Type of port** list, choose **Periodic**.
5. Locate the **Port Mode Settings** section. Specify the $\mathbf{E}_0$ vector as

0	x
0	y
1	z

6. In the α text field, type `alpha`.
7. Locate the **Automatic Diffraction Order Calculation** section. Clear the **Include in automatic diffraction order calculation** check box, as the **Diffraction Order** nodes need to be manually added for this port for normal incidence.
8. In the n text field, type `n_air`.

Use **Diffraction Order** nodes to absorb the reflected waves of nonzero diffraction order.

Diffraction Order 1

1. In the **Physics** toolbar, click **Attributes** and choose **Diffraction Order**.
2. In the **Settings** window for **Diffraction Order**, locate the **Port Mode Settings** section.
3. From the **Components** list, choose **Out-of-plane vector**.
4. In the m text field, type `-1`.

Port 1

In the **Model Builder** window, click **Port 1**.

Diffraction Order 2

1 In the **Physics** toolbar, click **Attributes** and choose **Diffraction Order**.

2 In the **Settings** window for **Diffraction Order**, locate the **Port Mode Settings** section.

3 From the **Components** list, choose **Out-of-plane vector**.

4 In the *m* text field, type 1.

Add the output port. In this case the excitation is set to **Off**.

Port 2

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

2 Select Boundary 2 only.

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

4 From the **Type of port** list, choose **Periodic**.

5 Locate the **Port Mode Settings** section. Specify the $\mathbf{E}_0$ vector as

0	x
0	y
1	z

6 Locate the **Automatic Diffraction Order Calculation** section. In the *n* text field, type n_sio2.

Add the **Diffraction Order** nodes for the second periodic port by clicking the **Add Diffraction Orders** button on the first periodic port.

Port 1

1 In the **Model Builder** window, click **Port 1**.

2 In the **Settings** window for **Port**, locate the **Automatic Diffraction Order Calculation** section.

3 Click **Add Diffraction Orders**.

Add the periodic boundary condition to the sides of the unit cell.

Periodic Condition 1

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

2 Select Boundaries 1, 3, 10, and 11 only.

3 In the **Settings** window for **Periodic Condition**, locate the **Periodicity Settings** section.

4 From the **Type of periodicity** list, choose **Floquet periodicity**.

5 From the **k-vector for Floquet periodicity** list, choose **From periodic port**.

STUDY 1

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
alpha (Angle of incidence (input port))	`range(0,1,90)`	`deg`

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

RESULTS

Electric Field (ewfd)

1 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

2 From the **Parameter value (alpha (deg))** list, choose **45**.

3 In the **Electric Field (ewfd)** toolbar, click **Plot**.

4 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot to Figure 2.

Global Evaluation 1

1 In the **Results** toolbar, click **Global Evaluation**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`ewfd.Rorder_0`	1	R0
`ewfd.Torder_0`	1	T0
`ewfd.Rorder_n1_op`	1	R-1
`ewfd.Torder_n1_op`	1	T-1
`ewfd.Rorder_p1_op`	1	R1
`ewfd.Torder_p1_op`	1	T1

4 Click **Evaluate**. The resulting table shows the reflectance and transmittance values as functions of the angle of incidence.

Reflectance, Transmittance, and Absorptance (ewfd)

A line plot for the reflectances, transmittances, and absorptance is also generated by default. Move the legend panel to not cover the line plots.

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

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

3 From the **Position** list, choose **Middle left**. Compare the resulting plot to Figure 3.

Now add a second model Component to compute the ray trajectories.

ADD COMPONENT

In the **Model Builder** window, right-click the root node and choose **Add Component>2D**.

GEOMETRY 2

Rectangle 1 (r1)

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

2 In the **Settings** window for **Rectangle**, locate the **Position** section.

3 From the **Base** list, choose **Center**.

4 Locate the **Size and Shape** section. In the **Width** text field, type `5[mm]`.

5 In the **Height** text field, type `1.35[mm]`.

Rectangle 2 (r2)

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

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `5[mm]`.

4 Locate the **Position** section. From the **Base** list, choose **Center**.

5 Locate the **Size and Shape** section. In the **Height** text field, type `0.675[mm]`.

6 Locate the **Position** section. In the **y** text field, type `-0.675[mm]/2`.

7 Click **Build All Objects**.

DEFINITIONS (COMP2)

Use the reflectance and transmittance data from the previous study to define a series of interpolation functions for the large-scale geometrical optics analysis.

Interpolation 1 (int1)

1 In the **Home** toolbar, click f(x) **Functions** and choose **Local>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **Result table**.

4 Find the **Functions** subsection. In the table, enter the following settings:

Function name	Position in file
R0	1
T0	2
Rm1	3
Tm1	4
R1	5
T1	6

5 Locate the **Units** section. In the **Argument** table, enter the following settings:

Argument	Unit
Column 1	deg

6 In the **Function** table, enter the following settings:

Function	Unit
R0	1
T0	1
Rm1	1
Tm1	1
R1	1
T1	1

Now set up the Geometrical Optics interface.

ADD PHYSICS

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

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

3 In the tree, select **Optics>Ray Optics>Geometrical Optics (gop)**.

4 Click **Add to Component 2** in the window toolbar.

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

MATERIALS

Material Link 3 (matlnk3)

1 In the **Model Builder** window, under **Component 2 (comp2)** right-click **Materials** and choose **More Materials>Material Link**.
2 Select Domain 2 only.

Material Link 4 (matlnk4)

1 Right-click **Materials** and choose **More Materials>Material Link**.
2 Select Domain 1 only.
3 In the **Settings** window for **Material Link**, locate the **Link Settings** section.
4 From the **Material** list, choose **SiO2 (mat2)**.

GEOMETRICAL OPTICS (GOP)

1 In the **Model Builder** window, under **Component 2 (comp2)** 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. In the **Maximum number of secondary rays** text field, type `4505`.

Ray Properties 1

1 In the **Model Builder** window, under **Component 2 (comp2)>Geometrical Optics (gop)** click **Ray Properties 1**.
2 In the **Settings** window for **Ray Properties**, locate the **Ray Properties** section.
3 From the **Ray property specification** list, choose **Specify frequency**.
4 In the ν text field, type `f0`.

Define the angle of incidence as a function of the wave vector.

DEFINITIONS (COMP2)

Variables 1

1 In the **Model Builder** window, under **Component 2 (comp2)** 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
alpha_ro	atan2(kx,-ky)	rad	

GEOMETRICAL OPTICS (GOP)

Grating 1

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

2 Select Boundary 4 only.

3 In the **Settings** window for **Grating**, locate the **Device Properties** section.

4 In the d text field, type `d`.

5 Select the **Store total transmitted power** check box.

6 Select the **Store total reflected power** check box.

These check boxes create variables that can be used to compute the total power of all transmitted rays and all reflected rays, respectively, for each angle of incidence.

By default a **Diffraction Order** subnode is created to release rays of order 0. Modify this default subnode, then create additional **Diffraction Order** subnodes to release rays of diffraction orders +1 and -1.

Diffraction Order (m = 0)

1 In the **Model Builder** window, expand the **Grating 1** node, then click **Diffraction Order (m = 0)**.

2 In the **Settings** window for **Diffraction Order**, locate the **Device Properties** section.

3 In the R text field, type `R0(alpha_ro)`.

4 In the T text field, type `T0(alpha_ro)`.

Grating 1

In the **Model Builder** window, click **Grating 1**.

Diffraction Order (m = 1)

1 In the **Physics** toolbar, click **Attributes** and choose **Diffraction Order**.

2 In the **Settings** window for **Diffraction Order**, locate the **Device Properties** section.

3 In the m text field, type `-1`.

4 In the R text field, type `Rm1(alpha_ro)`.

5 In the T text field, type `T1(alpha_ro)`.

Grating 1

In the **Model Builder** window, click **Grating 1**.

Diffraction Order (m = 1)

1 In the **Physics** toolbar, click **Attributes** and choose **Diffraction Order**.

2 In the **Settings** window for **Diffraction Order**, locate the **Device Properties** section.

3 In the R text field, type `R1(alpha_ro)`.

4 In the T text field, type `Tm1(alpha_ro)`.

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 $q_{y,0}$ text field, type `1e-6`. The ray will be released an extremely short distance above the grating so that even rays at very large angles of incidence will reach the boundary fairly quickly.

4 Locate the **Ray Direction Vector** section. From the **Ray direction vector** list, choose **Conical**.

5 In the N_{w} text field, type `901`.

6 In the α text field, type `pi/4`.

7 Specify the **r** vector as

1	x
-1.01	y

Define a power density of 901 W/m so that each ray has a power density of 1 W/m.

8 Locate the **Total Source Power** section. In the P_{src} text field, type `901[W/m]`.

9 Locate the **Initial Polarization** section. From the **Initial polarization type** list, choose **Fully polarized**.

10 In the $a_{xy,0}$ text field, type `0`.

11 In the $a_{z,0}$ text field, type `1`. The released ray is S-polarized. This is consistent with the use of TE waves in the previous study.

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 **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Electromagnetic Waves, Frequency Domain (ewfd)**.

4 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Ray Tracing**.

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

6 In the **Model Builder** window, click the root node.

7 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 unit** list, choose **ps**.

3 In the **Output times** text field, type `0 1`.

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

RESULTS

Ray Trajectories (gop)

The default plot shows the paths of the rays as they interact with the grating.

Transmittance and Reflectance (ewfd and gop)

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Transmittance and Reflectance (ewfd and gop)` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section. Select the **x-axis label** check box.

5 In the associated text field, type `Angle of incidence (deg)`.

6 Select the **y-axis label** check box.

7 In the associated text field, type `Transmittance and Reflectance`.

8 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

Global 1

1 Right-click **Transmittance and Reflectance (ewfd and gop)** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`abs(ewfd.S11)^2+abs(ewfd.S21)^2+ abs(ewfd.S31)^2`	1	
`abs(ewfd.S41)^2+abs(ewfd.S51)^2+ abs(ewfd.S61)^2`	1	

These expressions give the total reflectance and transmittance, respectively, for all diffraction orders.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `alpha`.

6 From the **Unit** list, choose **°**.

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

8 In the table, enter the following settings:

Legends
`Reflected WO`
`Transmitted WO`

Transmittance and Reflectance (ewfd and gop)

In the **Model Builder** window, click **Transmittance and Reflectance (ewfd and gop)**.

Ray 1

1 In the **Transmittance and Reflectance (ewfd and gop)** toolbar, click **More Plots** and choose **Ray**.

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

3 From the **Dataset** list, choose **Ray 1**.

4 From the **Time selection** list, choose **Last**.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `gop.Qgr`.

6 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

7 In the **Expression** text field, type `at(0,alpha_ro)`.

8 From the **Unit** list, choose **°**.

9 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **None**.

10 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

11 In the **Number** text field, type `40`.

12 Click to expand the **Legends** section. Select the **Show legends** check box.

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

14 In the table, enter the following settings:

Legends
`Reflected R0`

Ray 2

1 Right-click **Ray 1** and choose **Duplicate**.

2 In the **Settings** window for **Ray**, locate the **y-Axis Data** section.

3 In the **Expression** text field, type `gop.Qgt`.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends
`Transmitted R0`

5 In the **Transmittance and Reflectance (ewfd and gop)** toolbar, click **Plot**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar. Compare the resulting plot to Figure 4.