



Model created in COMSOL Multiphysics 6.4

Plasmonic Wire Grating

Introduction

A plane electromagnetic wave is incident on a wire grating on a dielectric substrate. The model computes transmission and reflection coefficients for the refraction, specular reflection, and first order diffraction.

Model Definition

Figure 1 shows the considered grating, with a gold wire on a dielectric material with refractive index n_b . The grating constant, or the distance between the wires, is d . A plane-polarized wave traveling through a medium with refractive index n_a is incident on the grating, at an angle α in a plane perpendicular to the grating.

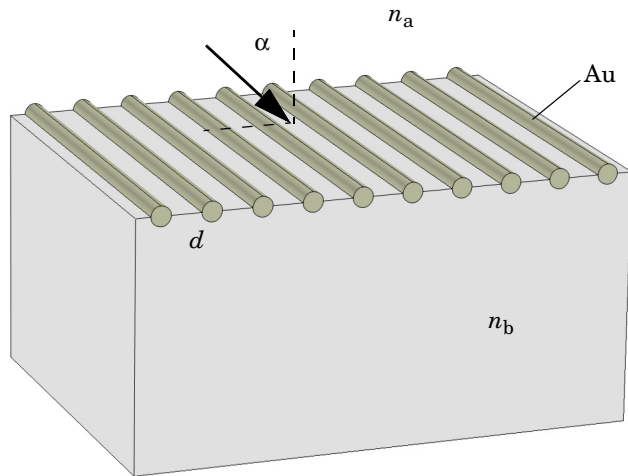


Figure 1: The modeled grating. The model considers a unit cell of a slice through this geometry. The grating is assumed to consist of an infinite number of infinitely long wires.

If the wavelengths involved in the model are sufficiently shorter than the grating constant, one or several diffraction orders can be present. The diagram in Figure 2 shows two

transmissive paths taken by light incident on adjacent cells of the grating, exactly one grating constant apart.

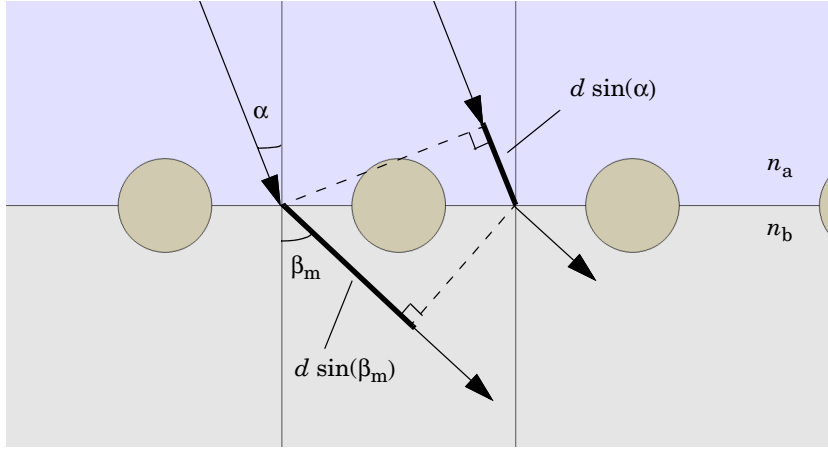


Figure 2: The geometric path lengths of two transmitted parallel beams. The optical path length is the geometric path length multiplied by the local refractive index.

The criterion for positive interference is that the difference in optical path length along the two paths equals an integer number of vacuum wavelengths, or:

$$m\lambda_0 = d(n_b \sin \beta_m - n_a \sin \alpha) \quad (1)$$

with $m = 0, \pm 1, \pm 2, \dots$, λ_0 the vacuum wavelength, and β_m the transmitted diffracted beam of order m . For $m = 0$, this reduces to refraction, as described by Snell's law:

$$\sin \beta_0 = \frac{n_a}{n_b} \sin \alpha$$

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

$$-(n_a + n_b) < \frac{m\lambda_0}{d} < (n_a + n_b)$$

The model instructions cover only first order diffraction, and are hence only valid under the condition

$$2\lambda_0 > d(n_a |\sin \alpha| + n_b) \quad (2)$$

Note that for the special cases of perpendicular and grazing incidence, the right-hand side of the inequality evaluates to $d n_b$ and $d(n_a + n_b)$, respectively.

Figure 3 shows the corresponding paths of the reflected light.

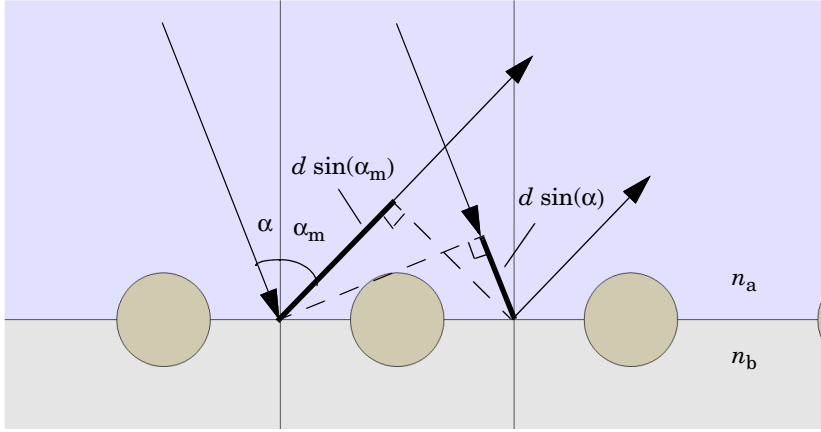


Figure 3: The geometric path lengths of two parallel reflected beams.

For positive interference we get

$$m\lambda_0 = dn_a(\sin\alpha_m - \sin\alpha) \quad (3)$$

where α_m is the reflected beam of diffraction order m . Setting $m = 0$ in this equation renders

$$\sin\alpha_0 = \sin\alpha$$

or specular reflection. The condition for no reflected diffracted beams of order 2 or greater being present is

$$2\lambda_0 > dn_a(1 + |\sin\alpha|) \quad (4)$$

The model uses $n_a = 1$ for air and $n_b = 1.2$ for the dielectric substrate. Allowing for arbitrary angles of incidence and with a grating constant $d = 400$ nm, Equation 2 sets the validity limit to vacuum wavelengths greater than 440 nm. The model uses $\lambda_0 = 441$ nm. For the wire, a complex-valued permittivity of $-1.75 - 5.4i$ approximates that of gold at the corresponding frequency.

The performance of the grating depends on the polarization of the incident wave. Therefore both a transverse electric (TE) (also called s-polarization) and a transverse magnetic (TM) (or p-polarization) case are considered. The TE wave has the electric field component in the z direction, out of the modeling xy -plane. For the TM wave, the electric field vector is pointing in the xy -plane and perpendicular to the direction of propagation,

whereas the magnetic field has only a component in the z direction. The angle of incidence is for both cases swept from 0 to $\pi/2$, with a pitch of $\pi/40$.

Results and Discussion

As an example of the output from the model, Figure 4 and Figure 5 show the electric field norm for an angle of incidence equal to $\pi/5$, for the TE and TM case respectively.

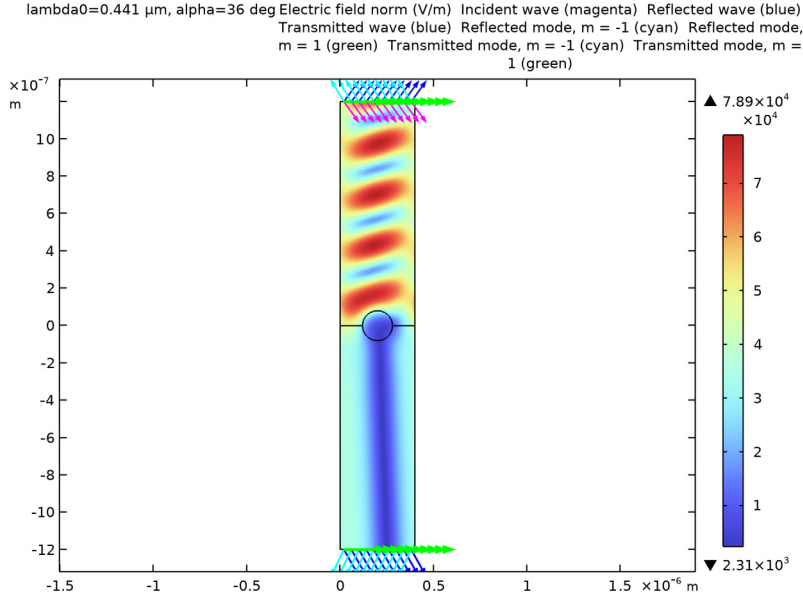


Figure 4: Electric field norm for TE incidence at $\pi/5$.

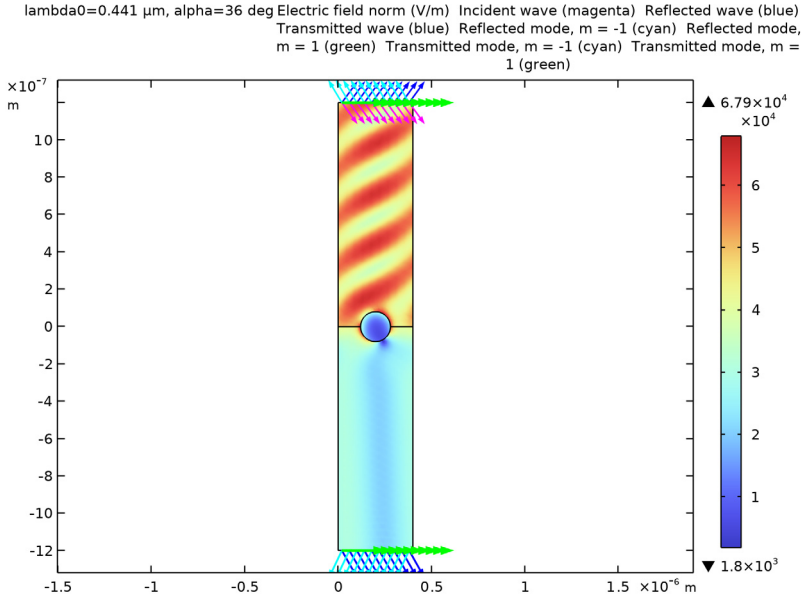


Figure 5: Electric field norm for TM incidence at $\pi/5$.

All the computed transmission and reflection coefficients for TE incidence are plotted in Figure 6. R_0 , the coefficient for specular reflection, increases rather steadily with the angle of incidence. This is both because of reflection in the material interface and because the wave “sees” the wire as increasingly wider at greater angles — the same effect as achieved by a Venetian blind. T_0 , the refracted but not diffracted transmission, decreases accordingly. For the considered wavelength to period length ratio, the transmitted diffracted beam T_1 is propagating only for nearly perpendicular incidence. The reflected diffraction order R_1 would need a shorter wavelength or a larger grating period to show up. Instead, the most prominent diffraction orders are R_{-1} and T_{-1} .

The sum of all coefficients is consistently less than 1 due to the dielectric losses in the wire. This is even more apparent for TM incidence, as Figure 7 shows. Here, approximately half of the wave is absorbed in the wire. Another important feature of the TM case is that there is very little specular reflection (R_0) around 60 degrees.

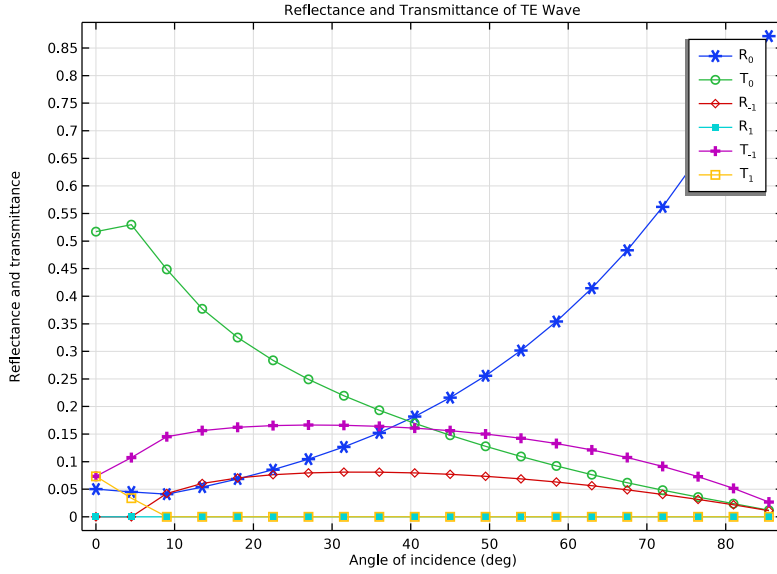


Figure 6: Transmission and reflection coefficients for TE incidence.

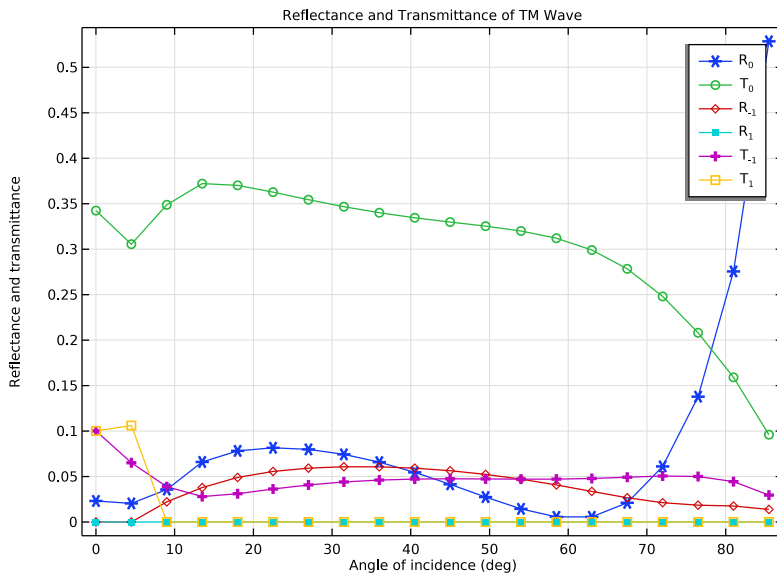


Figure 7: Transmission and reflection coefficients for TM incidence.

Notes About the COMSOL Implementation

The model is set up for one unit cell of the grating, flanked by Floquet boundary conditions describing the periodicity. As applied, this condition states that the solution on one side of the unit 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. Due to the continuity of the field, the phase factor for the refracted and reflected beams is the same as for the incident wave.

Port conditions are used for specifying the incident wave and also for letting the resulting solution leave the model without any unphysical reflections. In order to achieve perfect transmission through the port boundaries, one port for each mode ($m = 0, m = -1, m = 1$) in each direction must be present. This gives a total of 6 ports.

To add the port and periodic conditions, a Periodic Structure node is added. It automatically adds and configures its subnodes — the ports and the periodic conditions.

The table below lists the parameters names used in the model.

TABLE 1: PARAMETER NAMES.


MODEL DESCRIPTION	MODEL	DESCRIPTION
n_a	na	Refractive index, air
n_b	nb	Refractive index, dielectric
α	alpha	Angle of incidence

Application Library path: RF_Module/Tutorials/plasmonic_wire_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 **Radio Frequency > Electromagnetic Waves, Frequency Domain (emw)**.

- 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
na	1	1	Refractive index, air
nb	1.2	1.2	Refractive index, dielectric
d	400[nm]	4E-7 m	Grating constant
lam0	441[nm]	4.41E-7 m	Vacuum wavelength
f0	c_const/lam0	6.798E14 1/s	Frequency
alpha	0[deg]	0 rad	Angle of incidence

Although the angle of incidence will not remain constant at 0, it needs to be specified as a parameter to be accessible to the parametric solver.

STUDY 1


Step 1: Frequency Domain

- 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.


GEOMETRY 1

Create the geometry entirely in terms of the grating constant, for easy scalability.


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 $3*d$.

5 Click  **Build Selected**.

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 $-3*d$.

6 Click  **Build Selected**.

Circle 1 (c1)


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

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

3 In the **Radius** text field, type $d/5$.

4 Locate the **Position** section. In the **x** text field, type $d/2$.

5 Click  **Build Selected**.

6 Click the  **Zoom Extents** button in the **Graphics** toolbar.

The geometry now consists of two rectangular domains for the air and the dielectric, and a circle centered on their intersection. You can remove the line through the circle if you first create a union of the objects.

Union 1 (un1)

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

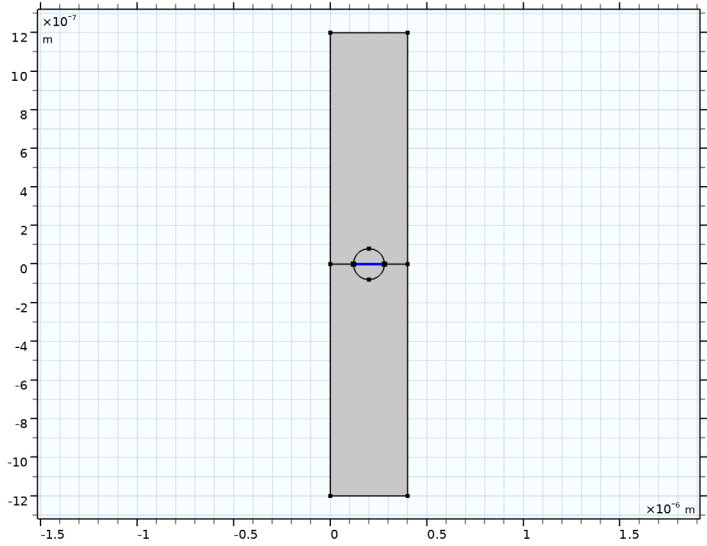
2 Click in the **Graphics** window and then press **Ctrl+A** to select all objects.

3 In the **Settings** window for **Union**, click  **Build Selected**.

Delete Entities 1 (dell)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Delete Entities**.

- 2 On the object **uni1**, select Boundary 6 only. This is the horizontal diameter of the circle in the center of the geometry.

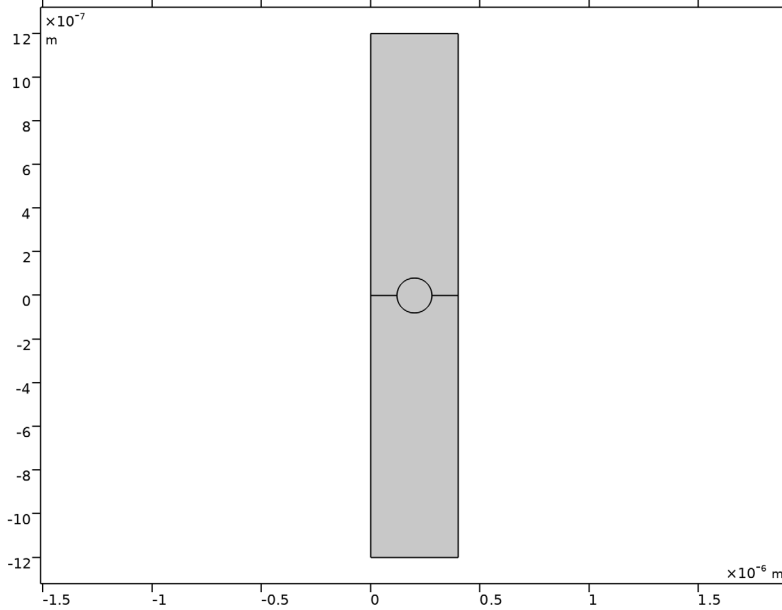


- 3 In the **Settings** window for **Delete Entities**, click  **Build Selected**.

Form Union (fin)

- 1 In the **Model Builder** window, click **Form Union (fin)**.

- 2 In the **Settings** window for **Form Union/Assembly**, click  **Build Selected**.



ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

In the first version of this model, you will assume a TE-polarized wave. This means that E_x and E_y will be zero throughout the geometry, and that you consequently only need to solve for E_z .

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

Periodic Structure 1

Now, add the periodic structure node that contains the ports and the periodic boundary condition.


In the **Physics** toolbar, click  **Domains** and choose **Periodic Structure**.

Before setting up the materials, define which constitutive relations you want to use in the Electromagnetic Waves interface.

Wave Equation, Electric 1

- 1 In the **Model Builder** window, expand the **Periodic Structure 1** node, then click **Wave Equation, Electric 1**.
- 2 In the **Settings** window for **Wave Equation, Electric**, locate the **Electric Displacement Field** section.
- 3 From the **Electric displacement field model** list, choose **Refractive index**.

Wave Equation, Electric 2

- 1 In the **Physics** toolbar, click  **Domains** and choose **Wave Equation, Electric**.
- 2 Select Domain 3 only.
It might be easier to select the correct domain by using the **Selection List** window. To open this window, in the **Home** toolbar click **Windows** and choose **Selection List**. (If you are running the cross-platform desktop, you find **Windows** in the main menu.)
- 3 In the **Settings** window for **Wave Equation, Electric**, locate the **Electric Displacement Field** section.
- 4 From the **Electric displacement field model** list, choose **Dielectric loss**.

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} ; $n_{ii} = n_{iso}$, $n_{ij} = 0$	na	l	Refractive index

Dielectric

- 1 Right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, type Dielectric in the **Label** text field.
- 3 Select Domain 1 only.
- 4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n_{iso} ; $n_{ii} = n_{iso}$, $n_{ij} = 0$	nb	l	Refractive index

Gold

- 1 Right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, type Gold in the **Label** text field.
- 3 Select Domain 3 only.
- 4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity (imaginary part)	epsilonBis_iso ; epsilonBisii = epsilonBis_iso, epsilonBisij = 0	5.4	l	Dielectric losses
Relative permittivity (real part)	epsilonPrim_iso ; epsilonPrimii = epsilonPrim_iso, epsilonPrimij = 0	-1.75	l	Dielectric losses
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	l	Basic
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

Periodic Structure 1

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain (emw)** click **Periodic Structure 1**.
- 2 In the **Settings** window for **Periodic Structure**, locate the **Port Mode Settings** section.
- 3 In the α text field, type alpha.
- 4 Locate the **Port Handling** section. Click **Add Diffraction Orders**, to add **Diffraction Order** ports for the higher diffraction orders.

STUDY 1

To set up the study to sweep for the angle of incidence, some modifications of the study step is required.

Step 1: Frequency Domain

- 1 In the **Model Builder** window, under **Study 1** click **Step 1: Frequency Domain**.
- 2 In the **Settings** window for **Frequency Domain**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** checkbox.

4 Click  **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)		rad

6 Click  **Range**.

7 In the **Range** dialog, type 0[rad] in the **Start** text field.

8 In the **Step** text field, type $\pi/40$ [rad].


9 In the **Stop** text field, type $(\pi/2 - \pi/40)$ [rad].

10 Click **Replace**.

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

12 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)	range(0[rad], $\pi/40$ [rad], $(\pi/2 - \pi/40)$ [rad])	deg

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

RESULTS

Add arrow plots for the incident wave vector of the excitation port and the mode wave vector of each diffraction order.

Arrow Line 1

1 Right-click **Electric Field (emw)** and choose **Arrow Line**.

2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.klncx_1, emw.klncy_1 - Incident wave vector**.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Magenta**.

4 Locate the **Expression** section.

5 Select the **Description** checkbox. In the associated text field, type Incident wave (magenta).

6 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type 10.

7 Locate the **Coloring and Style** section.

8 Select the **Scale factor** checkbox. In the associated text field, type $1e-14$.

Selection 1

1 Right-click **Arrow Line 1** and choose **Selection**.

2 Select Boundary 5 only.

Arrow Line 2

1 In the **Model Builder** window, under **Results > Electric Field (emw)** right-click **Arrow Line 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_1, emw.kModey_1 - Port mode wave vector, port 1**.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Blue**.

4 Locate the **Expression** section.

5 Select the **Description** checkbox. In the associated text field, type Reflected wave (blue).

Arrow Line 3

1 Right-click **Arrow Line 1** and choose **Duplicate**.

2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_2, emw.kModey_2 - Port mode wave vector, port 2**.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Blue**.

4 Locate the **Expression** section.

5 Select the **Description** checkbox. In the associated text field, type Transmitted wave (blue).

Selection 1

1 In the **Model Builder** window, expand the **Arrow Line 3** node, then click **Selection 1**.

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

3 Click  **Clear Selection**.

4 Select Boundary 2 only.

Arrow Line 4

1 In the **Model Builder** window, under **Results > Electric Field (emw)** right-click **Arrow Line 1** and choose **Duplicate**.

- 2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_3, emw.kModey_3 - Port mode wave vector, port 3**.
- 3 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.
- 4 Locate the **Expression** section.
- 5 Select the **Description** checkbox. In the associated text field, type Reflected mode, $m = -1$ (cyan).

Arrow Line 5

- 1 Right-click **Arrow Line 4** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_4, emw.kModey_4 - Port mode wave vector, port 4**.
- 3 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.
- 4 Locate the **Expression** section. In the **Description** text field, type Reflected mode, $m = 1$ (green).



Arrow Line 6

- 1 In the **Model Builder** window, under **Results > Electric Field (emw)** right-click **Arrow Line 3** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, locate the **Expression** section.
- 3 In the **X-component** text field, type `emw.kModex_5`.
- 4 In the **Y-component** text field, type `emw.kModey_5`.
- 5 In the **Description** text field, type Transmitted mode, $m = -1$ (cyan).
- 6 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

Arrow Line 7

- 1 In the **Model Builder** window, right-click **Arrow Line 6** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, locate the **Expression** section.
- 3 In the **X-component** text field, type `emw.kModex_6`.
- 4 In the **Y-component** text field, type `emw.kModey_6`.
- 5 In the **Description** text field, type Transmitted mode, $m = 1$ (green).
- 6 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

TE Electric Field

- 1 In the **Model Builder** window, under **Results** click **Electric Field (emw)**.
- 2 In the **Settings** window for **2D Plot Group**, type TE Electric Field in the **Label** text field.
The default plot shows the electric field norm for the last solution, almost tangential incidence. Look at a more interesting angle of incidence.
- 3 Locate the **Data** section. From the **Parameter value (alpha (deg))** list, choose **36**.
Make the title slightly shorter.
- 4 Click to expand the **Title** section. From the **Title type** list, choose **Custom**.
- 5 Find the **Type and data** subsection. Clear the **Type** checkbox.
- 6 In the **TE Electric Field** toolbar, click  **Plot**.
- 7 Click the  **Zoom Extents** button in the **Graphics** toolbar. The plot should now look like [Figure 4](#).

TE Reflectance and Transmittance

Modify the generated 1D plot of the diffraction efficiencies for the different orders versus the angle of incidence.

- 1 In the **Model Builder** window, under **Results** click **S-Parameter (emw)**.
- 2 In the **Settings** window for **ID Plot Group**, type TE Reflectance and Transmittance in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
- 4 In the **Title** text area, type Reflectance and Transmittance of TE Wave.
- 5 Locate the **Plot Settings** section. In the **y-axis label** text field, type Reflectance and transmittance.

Global 1

Plot the linear-scale reflectances and transmittances, instead of the dB-scale S-parameters.

- 1 In the **Model Builder** window, expand the **TE Reflectance and Transmittance** node, then click **Global 1**.
- 2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.
- 3 In the table, enter the following settings:

Expression	Unit	Description
$\text{abs}(\text{emw.S11})^2$	1	
$\text{abs}(\text{emw.S21})^2$	1	


Expression	Unit	Description
$\text{abs}(\text{emw.S31})^2$	1	
$\text{abs}(\text{emw.S41})^2$	1	
$\text{abs}(\text{emw.S51})^2$	1	
$\text{abs}(\text{emw.S61})^2$	1	

4 Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

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

6 In the table, enter the following settings:

Legends
R ₀
T ₀
R ₋₁
R ₁
T ₋₁
T ₁

7 In the **TE Reflectance and Transmittance** toolbar, click  **Plot**. The plot should now look like [Figure 6](#).

Smith Plot TE

1 In the **Model Builder** window, under **Results** click **Smith Plot (emw)**.

2 In the **Settings** window for **Smith Plot Group**, type Smith Plot TE in the **Label** text field.

Reflection Graph I

In the **Model Builder** window, expand the **Smith Plot TE** node.

Color Expression I

1 In the **Model Builder** window, expand the **Reflection Graph I** node, then click **Color Expression I**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type α .

4 From the **Unit** list, choose $^\circ$.

Reflection Graph I

1 In the **Model Builder** window, click **Reflection Graph I**.

2 In the **Settings** window for **Reflection Graph**, click to expand the **Title** section.

- 3 In the **Title** text area, type Reflection Graph TE: S-parameter, Color: Angle of Incidence (degrees).

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)



The remaining instructions show how to alter the physics so that you solve for an incident TM wave.

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.
- 2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.
- 3 From the **Electric field components solved for** list, choose **In-plane vector**.
You will now solve for E_x and E_y instead of E_z ; for a TM wave, E_z is zero.
Note that the **Components** parameter in the **Settings** for the **Diffraction Order** nodes is automatically updated, when you change the parameter **Electric field components solved for** in the **Settings** for the physics.

ROOT

Add a new study in order not to overwrite the TE solution.

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 **General Studies > Frequency Domain**.
- 4 Click the **Add Study** button in the window toolbar.
- 5 In the **Home** toolbar, click  **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Frequency Domain

- 1 In the **Settings** window for **Frequency Domain**, locate the **Study Settings** section.
- 2 In the **Frequencies** text field, type f_0 .
- 3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.
- 4 Click **+ Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)		rad

6 Click  **Range**.

7 In the **Range** dialog, type 0[rad] in the **Start** text field.

8 In the **Step** text field, type $\pi/40$ [rad].

9 In the **Stop** text field, type $(\pi/2-\pi/40)$ [rad].

10 Click **Replace**.

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

12 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha (Angle of incidence)	range(0[rad], $\pi/40$ [rad], $(\pi/2-\pi/40)$ [rad])	deg

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

RESULTS

Arrow Line 1

1 Right-click **Electric Field (emw)** and choose **Arrow Line**.

2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.klnx_1, emw.klny_1 - Incident wave vector**.

3 Locate the **Coloring and Style** section. From the **Color** list, choose **Magenta**.

4 Locate the **Expression** section.

5 Select the **Description** checkbox. In the associated text field, type Incident wave (magenta).

6 Locate the **Arrow Positioning** section. In the **Number of arrows** text field, type 10.

7 Locate the **Coloring and Style** section.

8 Select the **Scale factor** checkbox. In the associated text field, type $1e-14$.

Selection 1

1 Right-click **Arrow Line 1** and choose **Selection**.

2 Select Boundary 5 only.


Arrow Line 2

- 1 In the **Model Builder** window, under **Results > Electric Field (emw)** right-click **Arrow Line 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_1, emw.kModey_1 - Port mode wave vector, port 1**.
- 3 Locate the **Coloring and Style** section. From the **Color** list, choose **Blue**.
- 4 Locate the **Expression** section.
- 5 Select the **Description** checkbox. In the associated text field, type **Reflected wave (blue)**.

Arrow Line 3

- 1 Right-click **Arrow Line 2** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_2, emw.kModey_2 - Port mode wave vector, port 2**.
- 3 Locate the **Coloring and Style** section. From the **Color** list, choose **Blue**.
- 4 Locate the **Expression** section.
- 5 Select the **Description** checkbox. In the associated text field, type **Transmitted wave (blue)**.

Selection 1

- 1 In the **Model Builder** window, expand the **Arrow Line 3** node, then click **Selection 1**.
- 2 In the **Settings** window for **Selection**, locate the **Selection** section.
- 3 Click  **Clear Selection**.
- 4 Select Boundary 2 only.

Arrow Line 4

- 1 In the **Model Builder** window, under **Results > Electric Field (emw)** right-click **Arrow Line 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) >**

Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_3, emw.kModey_3 - Port mode wave vector, port 3.

- 3 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.
- 4 Locate the **Expression** section.
- 5 Select the **Description** checkbox. In the associated text field, type Reflected mode, $m = -1$ (cyan).

Arrow Line 5

- 1 Right-click **Arrow Line 4** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1) > Electromagnetic Waves, Frequency Domain > Ports > Wave vectors > emw.kModex_4, emw.kModey_4 - Port mode wave vector, port 4.**
- 3 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.
- 4 Locate the **Expression** section. In the **Description** text field, type Reflected mode, $m = 1$ (green).

Arrow Line 6



- 1 In the **Model Builder** window, under **Results > Electric Field (emw)** right-click **Arrow Line 3** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, locate the **Expression** section.
- 3 In the **X-component** text field, type `emw.kModex_5`.
- 4 In the **Y-component** text field, type `emw.kModey_5`.
- 5 In the **Description** text field, type Transmitted mode, $m = -1$ (cyan).
- 6 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

Arrow Line 7

- 1 In the **Model Builder** window, right-click **Arrow Line 6** and choose **Duplicate**.
- 2 In the **Settings** window for **Arrow Line**, locate the **Expression** section.
- 3 In the **X-component** text field, type `emw.kModex_6`.
- 4 In the **Y-component** text field, type `emw.kModey_6`.
- 5 In the **Description** text field, type Transmitted mode, $m = 1$ (green).
- 6 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

TM Electric Field

- 1 In the **Model Builder** window, under **Results** click **Electric Field (emw)**.


- 2 In the **Settings** window for **2D Plot Group**, type TM Electric Field in the **Label** text field.
- 3 Locate the **Data** section. From the **Parameter value (alpha (deg))** list, choose **36**.
- 4 Locate the **Title** section. From the **Title type** list, choose **Custom**.
- 5 Find the **Type and data** subsection. Clear the **Type** checkbox.
- 6 In the **TM Electric Field** toolbar, click  **Plot**.
- 7 Click the  **Zoom Extents** button in the **Graphics** toolbar. You have now reproduced [Figure 5](#).

S-Parameter (emw)

Delete this plot and duplicate 1D Plot Group TM instead, to create the TM reflectance and transmittance plot.

- 1 In the **Model Builder** window, right-click **S-Parameter (emw)** and choose **Delete**.

TM Reflectance and Transmittance

- 1 In the **Model Builder** window, right-click **TE Reflectance and Transmittance** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type TM Reflectance and Transmittance in the **Label** text field.
- 3 Locate the **Title** section. In the **Title** text area, type Reflectance and Transmittance of TM Wave.
- 4 Locate the **Data** section. From the **Dataset** list, choose **Probe Solution 2 (sol2)**.
- 5 In the **TM Reflectance and Transmittance** toolbar, click  **Plot**.
Compare the resulting plot with that in [Figure 7](#).

Smith Plot TM

- 1 In the **Model Builder** window, under **Results** click **Smith Plot (emw)**.
- 2 In the **Settings** window for **Smith Plot Group**, type Smith Plot TM in the **Label** text field.

Reflection Graph 1

In the **Model Builder** window, expand the **Smith Plot TM** node.

Color Expression 1

- 1 In the **Model Builder** window, expand the **Reflection Graph 1** node, then click **Color Expression 1**.
- 2 In the **Settings** window for **Color Expression**, locate the **Expression** section.
- 3 In the **Expression** text field, type alpha.

4 From the **Unit** list, choose °.

Reflection Graph 1

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

2 In the **Settings** window for **Reflection Graph**, locate the **Title** section.

3 In the **Title** text area, type Reflection Graph TM: S-parameter, Color: Angle of Incidence (degrees).