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_β. The grating constant, or the distance between the wires, is d. A plane-polarized wave traveling through a medium with refractive index n_α is incident on the grating, at an angle α in a plane perpendicular to the grating.

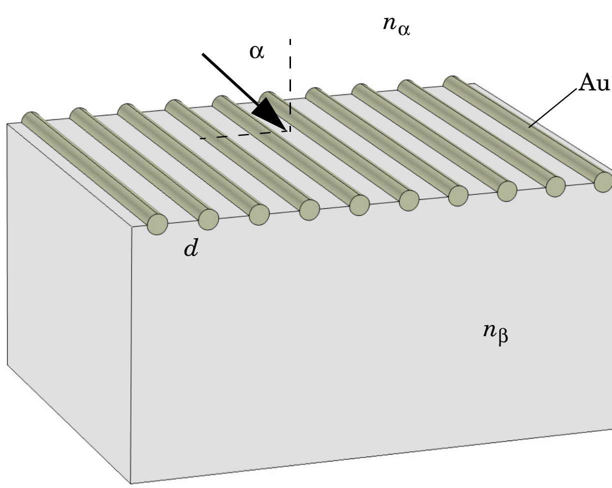


Figure 1: The modeled grating. The model considers a unit cell of a slice through this geometry. The grating is assumed to consist of an infinite number of infinitely long wires.

If the wavelengths involved in the model are sufficiently short compared to 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.

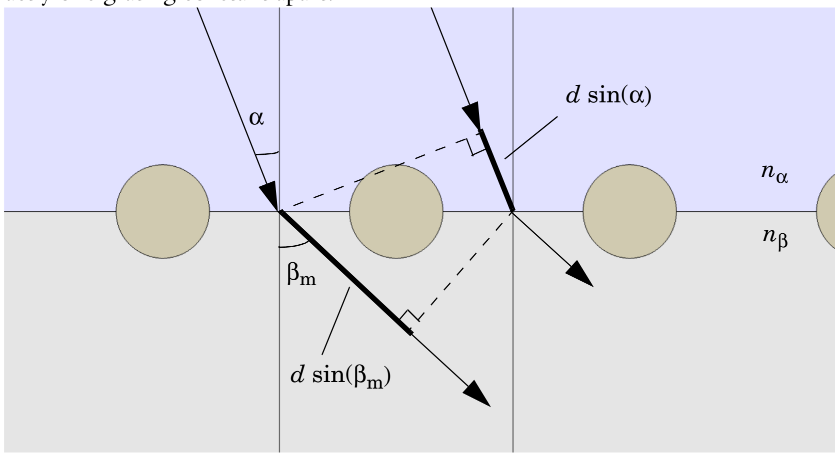


Figure 2: The geometric path lengths of two transmitted parallel beams. The optical path length is the geometric path length multiplied by the local refractive index.

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:

$$m\lambda_0 = d(n_\beta \sin\beta_m - n_\alpha \sin\alpha) \qquad (1)$$

with $m = 0, \pm1, \pm 2, \ldots$, 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:

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

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

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

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

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

Note that for the special cases of perpendicular and grazing incidence, the right-hand side of the inequality evaluates to dn_β and $d(n_\alpha + n_\beta)$ respectively.

Figure 3 shows the corresponding paths of the reflected light.

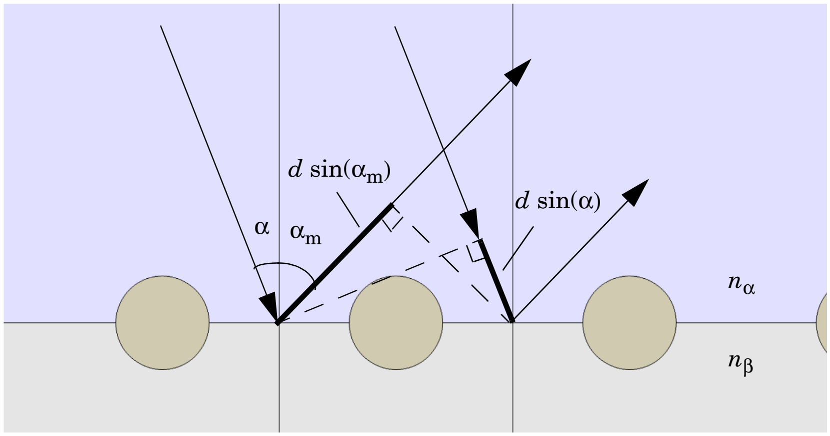


Figure 3: The geometric path lengths of two parallel reflected beams.

For positive interference we get

$$m\lambda_0 = dn_\alpha(\sin\alpha_m - \sin\alpha) \tag{3}$$

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

$$2\lambda_0 > dn_a(1 + |\sin\alpha|) \tag{4}$$

The model uses $n_\alpha = 1$ for air and $n_\beta = 1.2$ 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) and a transverse magnetic (TM) 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.

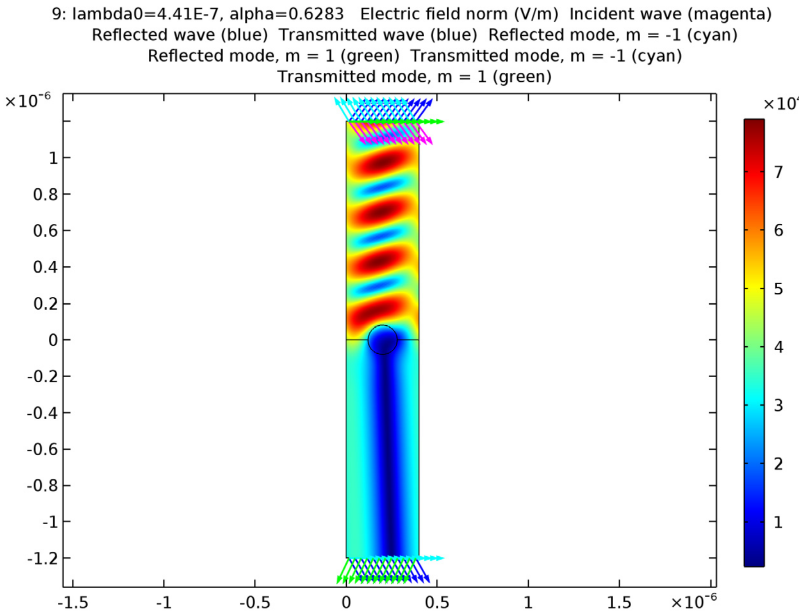


Figure 4: Electric field norm for TE incidence at $\pi/5$.

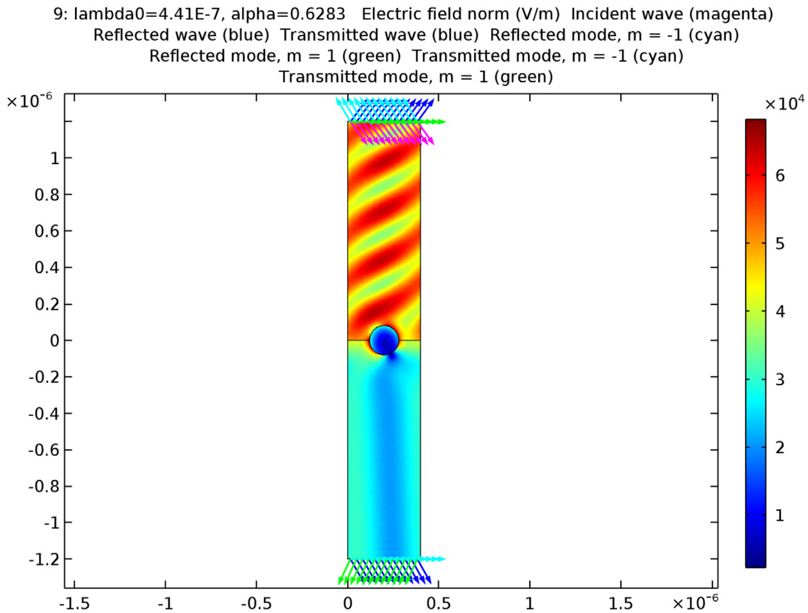


Figure 5: Electric field norm for TM incidence at π/5.

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.

Note first that the sum of all coefficients is consistently less than 1. This is because of 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.

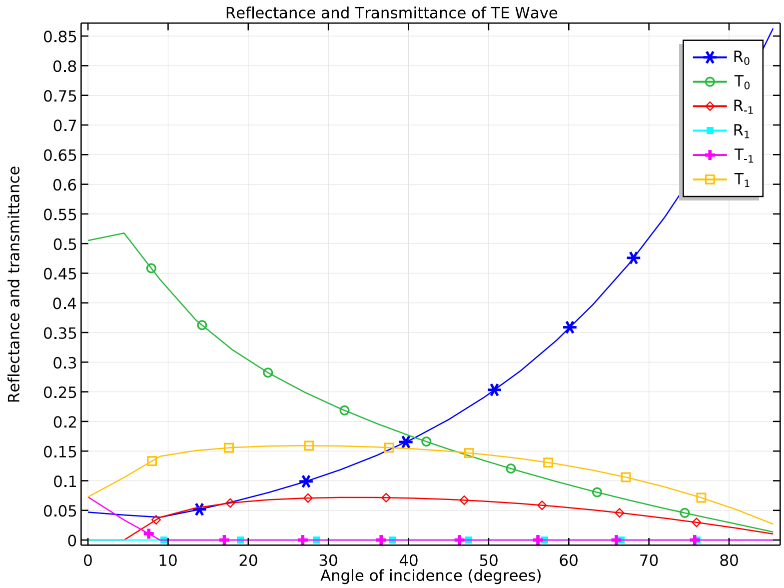


Figure 6: Transmission and reflection coefficients for TE incidence.

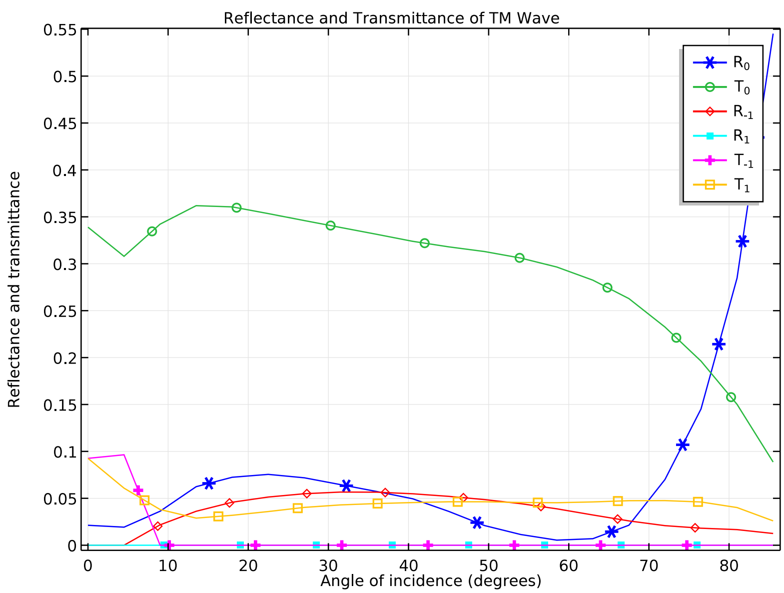


Figure 7: Transmission and reflection coefficients for TM incidence.

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. Because the periodicity boundaries are parallel with the y-axis, only the x-component is required. Note that due to the continuity of the field, the phase factor is the same for the refracted and reflected beams as for the incident wave.

Port conditions are used both for specifying the incident wave and for letting the resulting solution leave the model without any non-physical 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.

The input to each periodic port is an electric or magnetic field amplitude vector and an angle of incidence. The angle of incidence is defined as

$$\mathbf{k} \times \mathbf{n} = k \sin \alpha \mathbf{z}$$

where $\mathbf{k}$ is the propagation vector of the incident wave, $\mathbf{n}$ is the normalized normal vector, k is the wave number, α is the angle of incidence, and $\mathbf{z}$ is the unit vector in the z direction. Note that this definition means that the angle of incidence on the opposite sides have opposite signs. To automatically create ports for the diffraction orders, you also provide the refractive index at the port boundary and the maximum frequency (which in this model is the single frequency that is used).

The below table lists the parameters names used in the model. “Internal” means that the variable is not provided as an input parameter

TABLE 4-1: PARAMETER NAMES

MODEL DESCRIPTION	MODEL	DESCRIPTION
n_α	na	Refractive index, air
n_β	nb	Refractive index, dielectric
α	alpha	Angle of incidence
α_1	Internal	Reflected diffraction angle, order 1
α_{-1}	Internal	Reflected diffraction angle, order -1
β_0	beta	Refraction angle

TABLE 4-1: PARAMETER NAMES

MODEL DESCRIPTION	MODEL	DESCRIPTION
β_1	`Internal`	Refracted diffraction angle, order 1
β_{-1}	`Internal`	Refracted diffraction angle, order -1

Application Library path: `Wave_Optics_Module/Gratings_and_Metamaterials/plasmonic_wire_grating`

Modeling Instructions

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

NEW

1 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>Wavelength Domain**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters

1 On the **Home** toolbar, click **Parameters**.

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	0	Angle of incidence
beta	asin(na*sin(alpha)/nb)	0 rad	Refraction angle

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.

GEOMETRY 1

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

Rectangle 1 (r1)

1 On the **Geometry** toolbar, click **Primitives** and choose **Rectangle**.

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

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

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

5 Right-click **Component 1 (comp1)>Geometry 1>Rectangle 1 (r1)** and choose **Build Selected**.

Rectangle 2 (r2)

1 On the **Geometry** toolbar, click **Primitives** and choose **Rectangle**.

2 In the **Settings** window for Rectangle, locate the **Size** 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 Right-click **Component 1 (comp1)>Geometry 1>Rectangle 2 (r2)** and choose **Build Selected**.

Circle 1 (c1)

1 On the **Geometry** toolbar, click **Primitives** and choose **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 Right-click **Component 1 (comp1)>Geometry 1>Circle 1 (c1)** and choose **Build Selected**.

6 Click the **Zoom Extents** button on 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 (uni1)

1 On 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 Right-click **Component 1 (comp1)>Geometry 1>Union 1 (uni1)** and choose **Build Selected**.

Delete Entities 1 (del1)

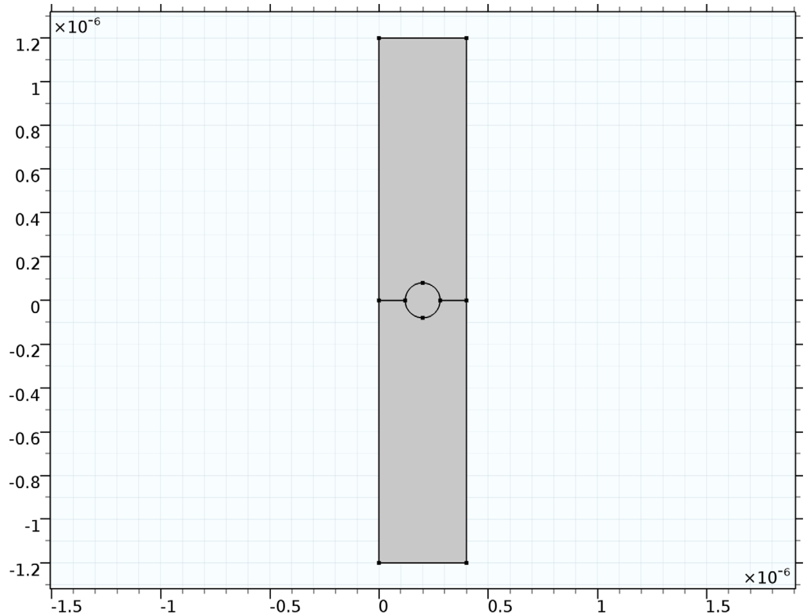
1 Right-click **Geometry 1** and choose **Delete Entities**.

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

Form Union (fin)

1 Right-click **Component 1 (comp1)>Geometry 1>Delete Entities 1 (del1)** and choose **Build Selected**.

2 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Form Union (fin)** and choose **Build Selected**.



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, type `Air` in the **Label** text field.

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

Property	Name	Value	Unit	Property group
Refractive index	n	na	1	Refractive index

Material 2 (mat2)

1 In the **Model Builder** window, 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	Name	Value	Unit	Property group
Refractive index	n	nb	1	Refractive index

5 On the **Home** toolbar, click **Windows** and choose **Add Material**.

ADD MATERIAL

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

2 In the tree, select **Optical>Inorganic Materials>Au (Rakic)**, to select gold from the Optical Materials Database.

3 Click **Add to Component** in the window toolbar.

MATERIALS

Au (Rakic) (mat3)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Au (Rakic) (mat3)**.

2 Select Domain 3 only.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EWFD)

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 (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**.

Now define the excitation port. A periodic port assumes that the structure is periodic and simplifies the setup of ports for the diffraction orders.

Port 1

1 On 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 From the **Wave excitation at this port** list, choose **On**.

Notice that you define the electric field by only setting the amplitude. A phase factor should not be entered.

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

0	x
0	y
1	z

7 In the α text field, type `alpha`.

8 In the n text field, type `na`.

9 In the f_{max} text field, type `f0`.

The order in which you set up the ports will determine how the S-parameters are labeled. You have just created Port 1 for the excitation. If you set up the next port for the transmission of the purely refracted beam, the S21-parameter will contain information on the zero order transmission.

Port 2

1 On 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

The angle of incidence on the exit side corresponds to the angle of incidence an incident wave on that side would have to provide the correct propagation angle in the material. Notice that this also means that the sign is opposite that on the entry side.

6 In the α text field, type `-beta`.

7 In the n text field, type `nb`.

8 In the f_{max} text field, type `f0`.

Port 1

Continue with the ports for the reflected diffraction orders. Since these diffraction orders are not propagating at normal incidence, you have to add the ports manually.

Diffraction Order 1

1 On 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.

Diffraction Order 2

1 Right-click **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)>Port 1>Diffraction Order 1** and choose **Duplicate**.

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

3 In the **Port name** text field, type 4.

4 Locate the **Port Mode Settings** section. In the *m* text field, type 1.

The transmitted diffraction orders are propagating at normal incidence. Thus, you can create them automatically by clicking the **Compute Diffraction Orders** button.

Port 2

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)** click **Port 2**.

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

3 Click **Compute Diffraction Orders**. You now find the **Diffraction Order** ports as subfeatures to **Port 2**.

Periodic Condition 1

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

2 Select Boundaries 1, 3, 7, and 8 only.

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

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

The wave vector in the direction for the periodicity is used by the periodic port. Thus, you can use that wave vector also for the Floquet periodic condition.

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

MESH 1

The periodic boundary conditions perform better if the mesh is identical on the periodicity boundaries. This is especially important when dealing with vector degrees of freedom, as will be the case in the TM version of this model.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

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

3 From the **Sequence type** list, choose **User-controlled mesh**.

Free Triangular 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Free Triangular 1** and choose **Delete**. Click **Yes** to confirm.

Size

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** click **Size**.

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

3 From the **Predefined** list, choose **Extra fine**.

Edge 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **More Operations>Edge**.

2 Select Boundaries 1 and 3 only.

Copy Edge 1

1 Right-click **Mesh 1** and choose **More Operations>Copy Edge**.

2 Select Boundary 3 only.

3 In the **Settings** window for Copy Edge, locate the **Destination Boundaries** section.

4 Select the **Active** toggle button.

5 Select Boundary 8 only.

Copy Edge 2

1 Right-click **Mesh 1** and choose **More Operations>Copy Edge**.

2 Select Boundary 1 only.

3 In the **Settings** window for Copy Edge, locate the **Destination Boundaries** section.

4 Select the **Active** toggle button.

5 Select Boundary 7 only.

Free Triangular 1

1 Right-click **Mesh 1** and choose **Free Triangular**.

2 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Free Triangular 1** and choose **Build All**.

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

STUDY 1

Step 1: Wavelength Domain

1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Wavelength Domain**.

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

3 In the **Wavelengths** text field, type `lam0`.

4 Click to expand the **Study extensions** section. Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
alpha		

7 Click **Range**.

8 In the **Range** dialog box, type `0` in the **Start** text field.

9 In the **Step** text field, type `pi/40`.

10 In the **Stop** text field, type `pi/2-pi/40`.

11 Click **Replace**.

12 On the **Home** toolbar, click **Compute**.

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

RESULTS

Electric Field (ewfd)

1 In the **Model Builder** window, under **Results** right-click **Electric Field (ewfd)** 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kIncx_1,ewfd.kIncy_1 - Incident wave vector.

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

4 Locate the **Expression** section. Select the **Description** check box.

5 In the associated text field, type `Incident wave (magenta)`.

6 In the **Model Builder** window, right-click **Electric Field (ewfd)** and choose **Arrow Line**.

7 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_1,ewfd.kModey_1 - Port mode wave vector**.

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

9 Locate the **Expression** section. Select the **Description** check box.

10 In the associated text field, type `Reflected wave (blue)`.

11 Right-click **Electric Field (ewfd)** and choose **Arrow Line**.

12 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_2,ewfd.kModey_2 - Port mode wave vector**.

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

14 Locate the **Expression** section. Select the **Description** check box.

15 In the associated text field, type `Transmitted wave (blue)`.

16 Right-click **Electric Field (ewfd)** and choose **Arrow Line**.

17 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_3,ewfd.kModey_3 - Port mode wave vector**.

18 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

19 Locate the **Expression** section. Select the **Description** check box.

20 In the associated text field, type `Reflected mode, m = -1 (cyan)`.

21 Right-click **Results>Electric Field (ewfd)>Arrow Line 4** and choose **Duplicate**.

22 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_4,ewfd.kModey_4 - Port mode wave vector**.

23 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

24 Locate the **Expression** section. Select the **Description** check box.

25 In the associated text field, type `Reflected mode, m = 1 (green)`.

26 Right-click **Arrow Line 4** and choose **Duplicate**.

27 In the **Settings** window for Arrow Line, locate the **Expression** section.

28 In the **x component** text field, type `ewfd.kModex_5`.

29 In the **y component** text field, type `ewfd.kModey_5`.

30 Select the **Description** check box.

31 In the associated text field, type `Transmitted mode, m = -1 (cyan)`.

32 In the **Model Builder** window, under **Results>Electric Field (ewfd)** right-click **Arrow Line 5** and choose **Duplicate**.

33 In the **Settings** window for Arrow Line, locate the **Expression** section.

34 In the **x component** text field, type `ewfd.kModex_6`.

35 In the **y component** text field, type `ewfd.kModey_6`.

36 Select the **Description** check box.

37 In the associated text field, type `Transmitted mode, m = 1 (green)`.

38 In the **Model Builder** window, click **Electric Field (ewfd)**.

39 In the **Settings** window for 2D Plot Group, type `2D Plot Group TE` 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.

40 Locate the **Data** section. From the **Parameter value (alpha)** list, choose **0.6283**.

Make the title slightly shorter.

41 Click to expand the **Title** section. From the **Title type** list, choose **Custom**.

42 Find the **Type and data** subsection. Clear the **Type** check box.

43 On the **2D Plot Group TE** toolbar, click **Plot**.

44 Click the **Zoom Extents** button on the **Graphics** toolbar. The plot should now look like Figure 4.

Add a 1D plot to look at the various orders of reflectance and transmittance versus the angle of incidence.

1D Plot Group 2

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

2 In the **Settings** window for 1D Plot Group, click to expand the **Title** section.

3 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. Select the **x-axis label** check box.

6 In the associated text field, type Angle of incidence (degrees).

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

8 In the associated text field, type Reflectance and transmittance.

9 On the **1D Plot Group 2** toolbar, click **Global**.

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

11 In the table, enter the following settings:

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

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

13 In the **Expression** text field, type alpha*180/pi.

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

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

16 In the table, enter the following settings:

Legends
R₀
T₀
R₋₁
R₁
T₋₁
T₁

17 On the **1D Plot Group 2** toolbar, click **Plot**.

18 In the **Model Builder** window, click **1D Plot Group 2**.

19 In the **Settings** window for 1D Plot Group, type `1D Plot Group TE` in the **Label** text field. The plot should now look like Figure 6.

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

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 **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.

Port 1

The easiest way to specify a TM wave is to define the magnetic field, since only the z component is used.

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

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

3 From the **Input quantity** list, choose **Magnetic field**.

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

0	x
0	y
1	z

Diffraction Order 1

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

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

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

Diffraction Order 2

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)>Port 1** click **Diffraction Order 2**.

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

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

Port 2

1 In the **Model Builder** window, under **Component 1 (comp1)>Electromagnetic Waves, Frequency Domain (ewfd)** click **Port 2**.
2 In the **Settings** window for Port, locate the **Port Mode Settings** section.
3 From the **Input quantity** list, choose **Magnetic field**.
4 Specify the $\mathbf{H}_0$ vector as

0	x
0	y
1	z

5 Click **Compute Diffraction Orders** to change components for the diffraction orders that are propagating at normal incidence.

ROOT

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

ADD STUDY

1 On 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>Wavelength Domain**.
4 Click **Add Study** in the window toolbar.
5 On the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Wavelength Domain

1 In the **Model Builder** window, expand the **Study 2** node, then click **Step 1: Wavelength Domain**.
2 In the **Settings** window for Wavelength Domain, locate the **Study Settings** section.
3 In the **Wavelengths** text field, type `lam0`.
4 Click to expand the **Study extensions** section. Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.
5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	**Parameter value list**	**Parameter unit**
alpha		

7 Click **Range**.

8 In the **Range** dialog box, type `0` in the **Start** text field.

9 In the **Step** text field, type `pi/40`.

10 In the **Stop** text field, type `pi/2-pi/40`.

11 Click **Replace**.

12 On the **Home** toolbar, click **Compute**.

RESULTS

Electric Field (ewfd)

1 In the **Model Builder** window, under **Results** right-click **Electric Field (ewfd)** 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kIncx_1,ewfd.kIncy_1 - Incident wave vector**.

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

4 Locate the **Expression** section. Select the **Description** check box.

5 In the associated text field, type `Incident wave (magenta)`.

6 In the **Model Builder** window, right-click **Electric Field (ewfd)** and choose **Arrow Line**.

7 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_1,ewfd.kModey_1 - Port mode wave vector**.

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

9 Locate the **Expression** section. Select the **Description** check box.

10 In the associated text field, type `Reflected wave (blue)`.

11 Right-click **Electric Field (ewfd)** and choose **Arrow Line**.

12 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_2,ewfd.kModey_2 - Port mode wave vector.

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

14 Locate the **Expression** section. Select the **Description** check box.

15 In the associated text field, type `Transmitted wave (blue)`.

16 Right-click **Electric Field (ewfd)** and choose **Arrow Line**.

17 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_3,ewfd.kModey_3 - Port mode wave vector**.

18 Locate the **Coloring and Style** section. From the **Color** list, choose **Cyan**.

19 Locate the **Expression** section. Select the **Description** check box.

20 In the associated text field, type `Reflected mode, m = -1 (cyan)`.

21 Right-click **Results>Electric Field (ewfd)>Arrow Line 4** and choose **Duplicate**.

22 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>Electromagnetic Waves, Frequency Domain>Ports>ewfd.kModex_4,ewfd.kModey_4 - Port mode wave vector**.

23 Locate the **Coloring and Style** section. From the **Color** list, choose **Green**.

24 Locate the **Expression** section. Select the **Description** check box.

25 In the associated text field, type `Reflected mode, m = 1 (green)`.

26 Right-click **Arrow Line 4** and choose **Duplicate**.

27 In the **Settings** window for Arrow Line, locate the **Expression** section.

28 In the **x component** text field, type `ewfd.kModex_5`.

29 In the **y component** text field, type `ewfd.kModey_5`.

30 Select the **Description** check box.

31 In the associated text field, type `Transmitted mode, m = -1 (cyan)`.

32 In the **Model Builder** window, under **Results>Electric Field (ewfd)** right-click **Arrow Line 5** and choose **Duplicate**.

33 In the **Settings** window for Arrow Line, locate the **Expression** section.

34 In the **x component** text field, type `ewfd.kModex_6`.

35 In the **y component** text field, type `ewfd.kModey_6`.

36 Select the **Description** check box.

37 In the associated text field, type `Transmitted mode, m = 1 (green)`.

38 In the **Model Builder** window, click **Electric Field (ewfd)**.

39 In the **Settings** window for 2D Plot Group, type `2D Plot Group TM` in the **Label** text field.

40 Locate the **Data** section. From the **Parameter value (alpha)** list, choose **0.6283**.

41 Click to expand the **Title** section. From the **Title type** list, choose **Custom**.

42 Find the **Type and data** subsection. Clear the **Type** check box.

43 On the **2D Plot Group TM** toolbar, click **Plot**.

44 Click the **Zoom Extents** button on the **Graphics** toolbar. You have now reproduced Figure 5.

For the reflectance and transmittance of the TM waves, copy and reuse the 1D plot for the TE waves.

1D Plot Group TE 1

1 In the **Model Builder** window, under **Results** right-click **1D Plot Group TE** and choose **Duplicate**.

2 In the **Settings** window for 1D Plot Group, type `1D Plot Group TM` 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 **Data set** list, choose **Study 2/Solution 2**.

5 On the **1D Plot Group TM** toolbar, click **Plot**. Compare the resulting plot with that in Figure 7.