Created in COMSOL Multiphysics 6.1

Transparent Light Pipe

Introduction

Light pipes are structures that can be used to transport light between different locations. Light pipes can be used to transport sunlight to locations that it would not otherwise reach, such as underground subway stations. In addition to facilitating the transport of light, it is possible to illuminate a large area by selectively leaking radiation out of the sides of the pipe. Because light may be reflected a large number of times before exiting a light pipe, it can also be used to homogenize a non-uniform light source.

In general, light pipes can be divided into two major groups: tubes lined with a reflective coating and transparent solids that contain light via total internal reflection. In this example, light is transported through a bent light pipe by total internal reflection. The effect of the pipe shape on the transmittance is investigated.

Model Definition

The model simulates the propagation of rays in a bent light pipe with a circular cross-section. The light pipe is composed of solid poly (methyl methacrylate). A **Parametric Sweep** over the radius of curvature of one of the pipe bends is used to measure the effect of pipe shape on transmittance. The rays are released from a point source at one end of the pipe with a cone angle of $\pi/12$.

The transmittance of the pipe is measured by using a **Wall** node with the **Deposited Ray Power** subnode to compute the total incident power that arrives at the opposite end of the pipe.

Results and Discussion

Figure 1 displays the ray trajectories in the pipe when the radius of curvature of the second bent section is 5 mm. The rays are released at the left side and propagate to the right. As rays arrive at the first bend in the pipe, which has the larger radius of curvature of the two, no refracted rays escape because the angle of incidence with respect to the surface normal is greater than the critical angle for all rays. As the rays arrive at the second bend, a significant number of rays undergo reflection and refraction, allowing some light to escape.

The transmittance of the light pipe as a function of the pipe bend radius of curvature is shown in Figure 2. The transmittance is approximately 100 % when the radius of curvature reaches the maximum value of 20 mm.

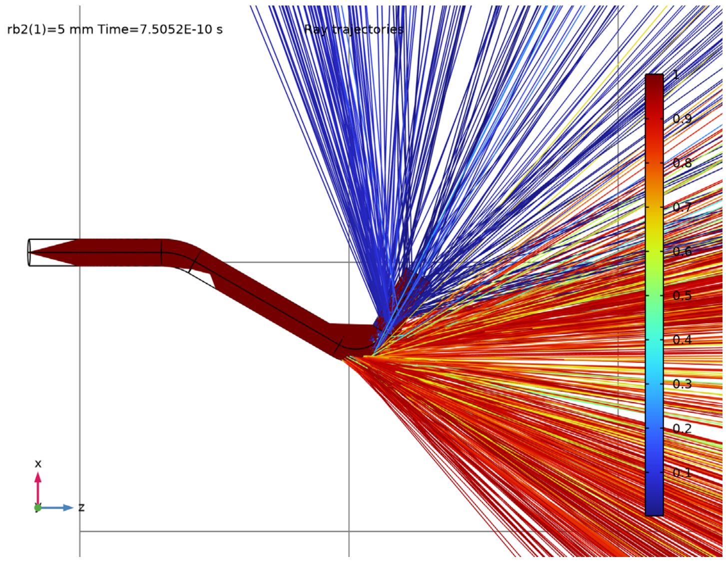

Figure 1: Ray trajectories in a bent light pipe. The color expression for the refracted rays indicates the transmittance as they exit the light pipe.

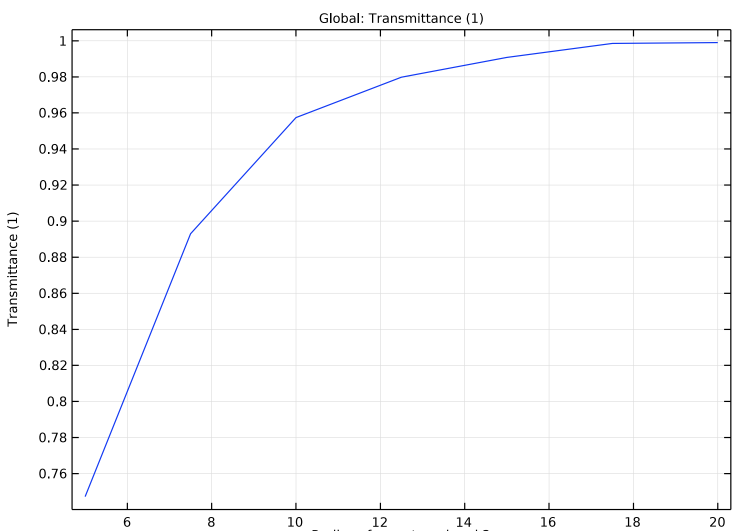

Figure 2: Transmittance as a function of the radius of curvature in the second pipe bend.

Application Library path: `Ray_Optics_Module/Tutorials/light_pipe`

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 **3D**.

2 In the **Select Physics** tree, select **Optics>Ray Optics>Geometrical Optics (gop)**.

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

ROOT

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in the appendix.

GEOMETRY 1

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

2 Browse to the model's Application Libraries folder and double-click the file `light_pipe_geom_sequence.mph`.

3 In the **Geometry** toolbar, click **Build All**.

ADD MATERIAL

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

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

3 In the tree, select **Optical>Organic Materials>Polymers> (C5H8O2)n (Poly(methyl methacrylate), PMMA) (Sultanova et al. 2009: n 0.437-1.052 um)**.

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

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

GEOMETRICAL OPTICS (GOP)

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

2 In the **Settings** window for **Geometrical Optics**, locate the **Intensity Computation** section.

3 From the **Intensity computation** list, choose **Compute intensity and power**.

4 Locate the **Ray Release and Propagation** section. In the **Maximum number of secondary rays** text field, type `1000`.

The secondary rays are needed to produce reflected rays whenever a ray escapes via refraction across the pipe wall.

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 **Ray Direction Vector** section.

3 From the **Ray direction vector** list, choose **Conical**.

4 In the N_{w} text field, type `2000`.

5 Specify the $\mathbf{r}$ vector as

0	x
0	y
1	z

6 In the α text field, type `pi/12`.

Use a **Wall** node with a **Deposited Ray Power** subnode to compute the transmittance of the light pipe.

Wall 1

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

2 Select Boundary 22 only.

Deposited Ray Power 1

In the **Physics** toolbar, click **Attributes** and choose **Deposited Ray Power**.

The mesh should be fine on the curved surfaces of the light pipe, but can be coarse elsewhere. This can be controlled by specifying a low value for the **Curvature factor**.

MESH 1

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

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

3 From the **Element size** list, choose **Finer**.

4 Locate the **Sequence Type** section. From the list, choose **User-controlled mesh**.

Create another **Size** node to refine the mesh on the boundary where the deposited ray power will be computed.

Size 1

1. Right-click **Component 1 (comp1)>Mesh 1** and choose **Size**.
2. Right-click **Size 1** and choose **Move Up**.
3. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
4. From the **Geometric entity level** list, choose **Boundary**.
5. Select Boundary 22 only.
6. Locate the **Element Size** section. Click the **Custom** button.
7. Locate the **Element Size Parameters** section.
8. Select the **Minimum element size** check box. In the associated text field, type `0.1`.
9. Select the **Curvature factor** check box. In the associated text field, type `0.1`.

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
rb2 (Radius of curvature, bend 2)		mm

5. Click to select row number 1 in the table.
6. Click **Range**.
7. In the **Range** dialog box, type `5` in the **Start** text field.
8. In the **Step** text field, type `2.5`.
9. In the **Stop** text field, type `20`.
10. Click **Replace**.

Step 1: Ray Tracing

1. In the **Model Builder** window, click **Step 1: Ray Tracing**.

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

3 From the **Time-step specification** list, choose **Specify maximum path length**.

4 From the **Length unit** list, choose **mm**.

5 Click **Range**.

6 In the **Range** dialog box, type `15` in the **Step** text field.

7 In the **Stop** text field, type `150`.

8 Click **Replace**.

9 In the **Settings** window for **Ray Tracing**, locate the **Study Settings** section.

10 In the **Characteristic group velocity** text field, type `c_const/1.5`.

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

RESULTS

Ray Trajectories (gop)

After the study is complete, a **Warning** node may appear in the solver sequence, indicating that some rays have been removed from the simulation because an intersection point with the boundary was not found. This occasionally happens because of the discretization of the pipe walls using the finite element mesh, which is an imperfect representation of a pipe with a circular cross section. Usually the number of removed rays is very small compared to the total number of rays and can safely be ignored.

If it is absolutely necessary to prevent any rays from disappearing in this manner, you can reduce the probability of rays failing to detect boundary intersections by further refining the mesh. Also consider selecting **Linear** from the **Geometry shape order** list in the **Component 1** settings; linear shape order is more robust than the default shape order, which is mostly quadratic, at the expense of some accuracy.

Ray Trajectories 1

1 In the **Model Builder** window, expand the **Ray Trajectories (gop)** node, then click **Ray Trajectories 1**.

2 In the **Settings** window for **Ray Trajectories**, locate the **Extra Time Steps** section.

3 From the **Maximum number of extra time steps rendered** list, choose **All**.

Color Expression 1

Plot the ratio of the final and initial intensity for each ray.

1 In the **Model Builder** window, expand the **Ray Trajectories 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 `gop.Q/1[W]*2000`.

4 In the **Ray Trajectories (gop)** toolbar, click **Plot**.

5 In the **Graphics** window toolbar, click ▾ next to **Go to Default View**, then choose **Go to ZX View**.

Ray Trajectories (gop)

Compare the results for the maximum and minimum values of the pipe radius. Notice that the number of refracted rays increases as the radius of curvature is reduced.

1 In the **Model Builder** window, under **Results** click **Ray Trajectories (gop)**.

2 In the **Settings** window for **3D Plot Group**, locate the **Data** section.

3 From the **Parameter value (rb2 (mm))** list, choose **5**.

4 In the **Ray Trajectories (gop)** toolbar, click **Plot**. Compare the resulting plot to Figure 1.

Plot the transmittance of the light pipe for each value of the pipe bend radius of curvature.

Transmittance

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` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

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

5 Locate the **Plot Settings** section.

6 Select the **x-axis label** check box. In the associated text field, type `Radius of curvature, bend 2`.

Global 1

1 Right-click **Transmittance** 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
gop.wall1.bsrc1.Qp_int/(1[W])	1	Transmittance

4 Locate the **x-Axis Data** section. From the **Axis source data** list, choose **Outer solutions**.

5 Click to expand the **Legends** section. Clear the **Show legends** check box.

6 In the **Transmittance** toolbar, click **Plot**. Compare the resulting plot to Figure 2.

Appendix A — Geometry Instructions

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **3D**.

GEOMETRY 1

The geometry consists of three straight sections connected by two bent sections. To simplify the geometry setup, import a list of parameters from a text file.

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. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `light_pipe_parameters.txt`.

GEOMETRY 1

1. In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
2. In the **Settings** window for **Geometry**, locate the **Units** section.
3. From the **Length unit** list, choose **mm**.

Cylinder 1 (cyl1)

1. In the **Geometry** toolbar, click **Cylinder**.
2. In the **Settings** window for **Cylinder**, locate the **Size and Shape** section.
3. In the **Radius** text field, type `rpipe`.
4. In the **Height** text field, type `L1`.
5. Locate the **Position** section. In the **x** text field, type `x0`.
6. In the **y** text field, type `y0`.
7. In the **z** text field, type `z0`.

Torus 1 (tor1)

1. In the **Geometry** toolbar, click **Torus**.
2. In the **Settings** window for **Torus**, locate the **Size and Shape** section.

3 In the **Major radius** text field, type `rb1`.

4 In the **Minor radius** text field, type `rpipe`.

5 In the **Revolution angle** text field, type `theta1`.

6 Locate the **Position** section. In the **x** text field, type `xc1`.

7 In the **y** text field, type `yc1`.

8 In the **z** text field, type `zc1`.

9 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

10 Locate the **Rotation Angle** section. In the **Rotation** text field, type `270-theta1`.

Cylinder 2 (cyl2)

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

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

3 In the **Radius** text field, type `rpipe`.

4 In the **Height** text field, type `L2`.

5 Locate the **Position** section. In the **x** text field, type `xL2`.

6 In the **y** text field, type `yL2`.

7 In the **z** text field, type `zL2`.

8 Locate the **Axis** section. From the **Axis type** list, choose **Cartesian**.

9 In the **x** text field, type `-sin(theta1)`.

10 In the **z** text field, type `cos(theta1)`.

Torus 2 (tor2)

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

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

3 In the **Major radius** text field, type `rb2`.

4 In the **Minor radius** text field, type `rpipe`.

5 In the **Revolution angle** text field, type `theta2`.

6 Locate the **Position** section. In the **x** text field, type `xc2`.

7 In the **y** text field, type `yc2`.

8 In the **z** text field, type `zc2`.

9 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

10 Locate the **Rotation Angle** section. In the **Rotation** text field, type `90-theta1`.

Cylinder 3 (cyl3)

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

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

3 In the **Radius** text field, type `rpipe`.

4 In the **Height** text field, type `L3`.

5 Locate the **Position** section. In the **x** text field, type `xL3`.

6 In the **y** text field, type `yL3`.

7 In the **z** text field, type `zL3`.

8 Locate the **Axis** section. From the **Axis type** list, choose **Cartesian**.

9 In the **x** text field, type `sin(theta2-theta1)`.

10 In the **z** text field, type `cos(theta2-theta1)`.

11 Click **Build All Objects**.

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

Union 1 (uni1)

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**, locate the **Union** section.

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

5 In the **Geometry** toolbar, click **Build All**.