Created in COMSOL Multiphysics 5.5

Tunable Liquid Gradient Refractive Index Lens

Introduction

A liquid graded refractive index (L-GRIN) lens can focus light purely by liquid flow, eliminating the need for mechanical or electrical light-manipulating mechanisms. In this example, a calcium chloride solution is mixed with distilled water; the resulting gradient in the concentration in CaCl2 creates a gradient in the refractive index in the channel, which focuses light from a fiber optic cable. The L-GRIN lens is tunable; by changing the flow rate of the distilled water, it is possible to control the refractive index distribution in the channel and change the location of the focal plane.

Model Definition

The lens device is composed of a PDMS (polydimethylsiloxane) substrate that has a channel, a first fluid path and a second fluid path, both made of two independent inlets and sharing two common outlets. The first and second fluid paths are merged in the channel to form laminar flows and establish a calcium chloride concentration distribution that resembles the hyperbolic secant profile; see Ref. 1. Figure 1 shows the 2D geometry and dimensions used for the simulation.

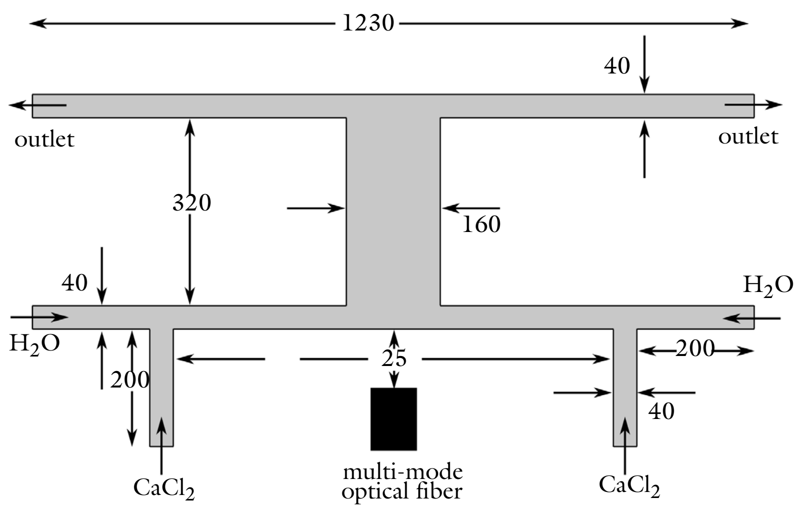

Figure 1: Devices schematics and dimensions (in µm).

An optical fiber light source, is positioned adjacent to the channel. The thickness of PDMS between the aperture of the optical fiber and the microfluidic channel is 25 µm. The wavelength of the source is 532 nm and the core diameter of the multi-mode optical fiber is 50 μm with a numerical aperture of 0.22.

The first fluid path uses a solution of calcium chloride ($CaCl_2$) while the other fluid path uses distilled water. The two fluids have a different refractive index. The refractive index of the mixture depends linearly on the concentration profile in the channel and is defined by:

$$n(c) = \frac{c}{c_1}n_1 + \left(1 - \frac{c}{c_1}\right)n_2 \quad (1)$$

where $c_1 = 3.5$ mol·l^{-1} and $n_1 = 1.41$ are respectively the concentration and refractive index of the $CaCl_2$ solution, and where $n_2 = 1.33$ is the refractive index of the distilled water.

In this model, the flow rates of distilled water is varied from 0.6 to 3.0 μl·min^{-1} while the flow rate of the $CaCl_2$ solution is kept constant at 3.0 μl·min^{-1}.

Results and Discussion

The laminar fluid flow provides an optically smooth fluidic interface. Figure 2 and Figure 3 respectively shows the concentration of CaCl2 in the channel and the effect of the concentration profile on the mixture's refractive index.

The curvature of the fluidic interface and, therefore, the focus point of the fluidic lens can be conveniently adjusted by simply changing the flow rates of the distilled water. Figure 4 shows the ray trajectories for a water flow rate of 3.0 μl·min^{-1}.

Displaying Figure 4 for different flow rates shows that higher water flow rates result in larger refractive index contrast, which causes light to bend toward the lens axis more significantly and leads to the decreased focal distance.

Figure 5 shows the light intensity profiles for different flow rates as they reach the end of the channel. The maximum and smaller half-width maximum of the intensity is observed for a water flow rate of 2.4 μl·min^{-1}.

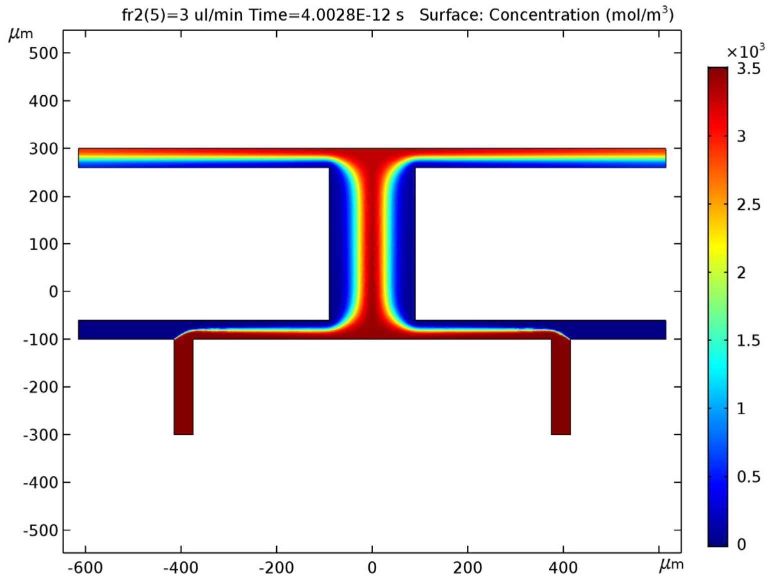

Figure 2: Concentration of $CaCl_2$ for a water flow rate of 3 µm/min.

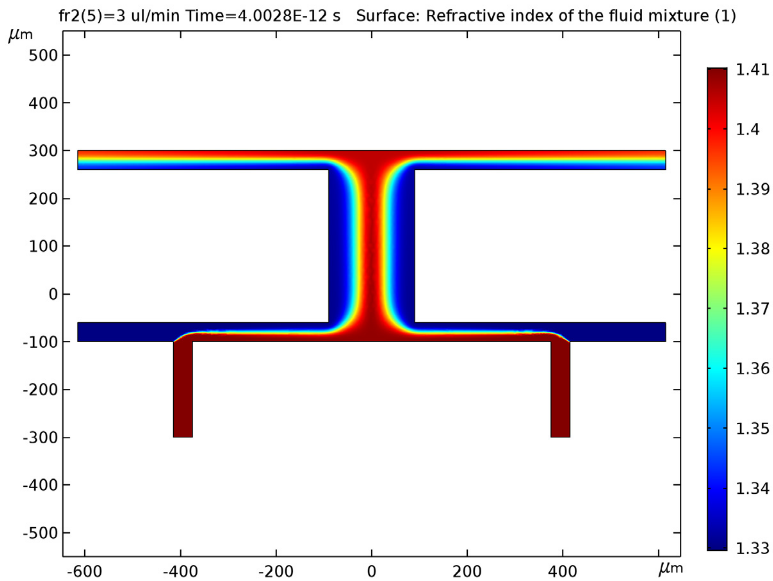

Figure 3: Refractive Index of the mixture for a water flow rate of 3 μm/min.

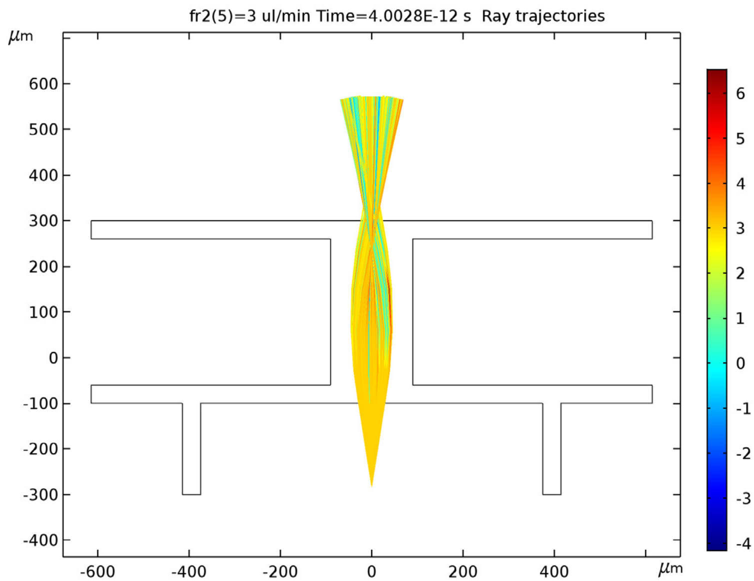

Figure 4: Ray trajectories for a water flow rate of 3 µm/min.

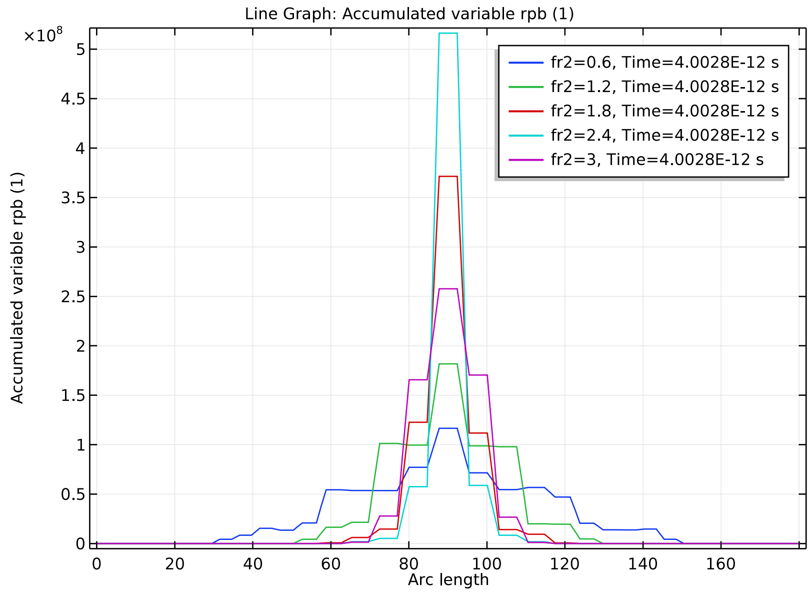

Figure 5: Intensity profiles at the end of the microfluidic channel for different water flow rates.

Reference

1. X. Mao and others, "Tunable Liquid Gradient Refractive Index (L-GRIN) lens with two degrees of freedom," *Lab Chip*, vol. 9, no. 14, pp. 2050–2058, 2009.

Application Library path: `Ray_Optics_Module/Lenses_Cameras_and_Telescopes/tunable_liquid_gradient_refractive_index_lens`

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 **Fluid Flow>Single-Phase Flow>Creeping Flow (spf)**.
3 Click **Add**.
4 In the **Select Physics** tree, select **Chemical Species Transport>Transport of Diluted Species (tds)**.
5 Click **Add**.
6 Click **Study**.
7 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Stationary**.
8 Click **Done**.

GLOBAL DEFINITIONS

Parameters

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

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.
2 In the **Settings** window for **Variables**, locate the **Variables** section.
3 Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `tunable_liquid_gradient_refractive_index_lens_variables.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 **µm**.

Rectangle 1 (r1)

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

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

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

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

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

Rectangle 2 (r2)

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

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

3 In the **Width** text field, type `(w_sub-w_chan)/2`.

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

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

6 In the **x** text field, type `-(w_chan+w_sub)/4`.

7 In the **y** text field, type `(h_sub-h_chan)/2-d_io`.

Copy 1 (copy1)

1 On the **Geometry** toolbar, click **Transforms** and choose **Copy**.

2 Select the object **r2** only.

3 In the **Settings** window for **Copy**, locate the **Displacement** section.

4 In the **x** text field, type `(w_sub+w_chan)/2`.

Rectangle 3 (r3)

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

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

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

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

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

6 In the **x** text field, type `-(w_sub-l_in)/2`.

7 In the **y** text field, type `-(h_sub-h_sub/3)/2`.

Copy 2 (copy2)

1 On the **Geometry** toolbar, click **Transforms** and choose **Copy**.

2 Select the object **r3** only.

3 In the **Settings** window for **Copy**, locate the **Displacement** section.

4 In the **x** text field, type `w_sub-l_in`.

Rectangle 4 (r4)

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

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

3 In the **Width** text field, type `w_sub-2*(d_io+l_in)`.

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

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

6 In the **y** text field, type `-(h_sub-h_sub/3)/2`.

Difference 1 (dif1)

1 On the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **r1** only.

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

4 Find the **Objects to subtract** subsection. Select the **Active** toggle button.

5 Select the objects **r3**, **r4**, **copy1**, **r2**, and **copy2** only.

Line Segment 1 (ls1)

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

2 In the **Settings** window for **Line Segment**, locate the **Start Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 In the **x** text field, type `-w_chan/2`.

5 In the **y** text field, type `h_sub/2`.

6 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

7 In the **x** text field, type `w_chan/2`.

8 In the **y** text field, type `h_sub/2`.

9 Click **Build All Objects**.

CREEPING FLOW (SPF)

Inlet 1

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

2 Select Boundaries 8 and 18 only.

3 In the **Settings** window for **Inlet**, locate the **Boundary Condition** section.

4 From the list, choose **Laminar inflow**.

5 Locate the **Laminar Inflow** section. Click the **Flow rate** button.

6 In the V_0 text field, type `fr1`.

7 In the L_{entr} text field, type `100[um]`.

8 In the D_z text field, type `100[um]`.

Inlet 2

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

2 Select Boundaries 1 and 21 only.

3 In the **Settings** window for **Inlet**, locate the **Boundary Condition** section.

4 From the list, choose **Laminar inflow**.

5 Locate the **Laminar Inflow** section. Click the **Flow rate** button.

6 In the V_0 text field, type `fr2`.

7 In the L_{entr} text field, type `100[um]`.

8 In the D_z text field, type `100[um]`.

Outlet 1

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

2 Select Boundaries 4 and 22 only.

Change the concentration discretization to quadratic in order to obtain a better evaluation of the concentration gradients.

TRANSPORT OF DILUTED SPECIES (TDS)

1 In the **Model Builder** window's toolbar, click the **Show** button and select **Discretization** in the menu.

2 In the **Model Builder** window, under **Component 1 (comp1)** click **Transport of Diluted Species (tds)**.

3 In the **Settings** window for **Transport of Diluted Species**, click to expand the **Discretization** section.

4 From the **Concentration** list, choose **Quadratic**.

Transport Properties 1

1 In the **Model Builder** window, expand the **Transport of Diluted Species (tds)** node, then click **Transport Properties 1**.

2 In the **Settings** window for **Transport Properties**, locate the **Convection** section.

3 From the $\mathbf{u}$ list, choose **Velocity field (spf)**.

4 In the **Model Builder** window, click **Transport of Diluted Species (tds)**.

Concentration 1

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

2 Select Boundaries 8 and 18 only.

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

4 Select the **Species c** check box.

5 In the $c_{0,c}$ text field, type `c1`.

Concentration 2

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

2 Select Boundaries 1 and 21 only.

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

4 Select the **Species c** check box.

Outflow 1

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

2 Select Boundaries 4 and 22 only.

COMPONENT 1 (COMP1)

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

ADD PHYSICS

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

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

3 Find the **Physics interfaces in study** subsection. In the table, enter the following settings:

Studies	Solve
Study 1	

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

In order to avoid modeling reflections at the channel interface, set the **Maximum number of secondary rays** to zero.

GEOMETRICAL OPTICS (GOP)

1 In the **Settings** window for **Geometrical Optics**, locate the **Ray Release and Propagation** section.

2 In the **Refractive index of exterior domains** text field, type `n_pdms`.

3 In the **Maximum number of secondary rays** text field, type `0`.

4 Locate the **Intensity Computation** section. From the **Intensity computation** list, choose **Compute intensity in graded media**.

Material Discontinuity 1

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

2 In the **Settings** window for **Material Discontinuity**, locate the **Rays to Release** section.

3 From the **Release reflected rays** list, choose **Never**.

Ray Properties 1

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

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

3 In the λ_0 text field, type `lambda0`.

4 In the **Model Builder** window, click **Geometrical Optics (gop)**.

Release from Grid 1

1 On the **Physics** toolbar, click **Global** and choose **Release from Grid**.

Use the projected direction of a three-dimesional cone release on the 2D plane in order to achieve a more realistic ray distribution.

2 In the **Settings** window for **Release from Grid**, locate the **Initial Coordinates** section.

3 In the $q_{x,\,0}$ text field, type `range(-1.0e-9,2.0e-9/(Np-1),1.0e-9)`.

4 In the $q_{y,\,0}$ text field, type `-100[um]-l_of-f`.

5 Locate the **Ray Direction Vector** section. Specify the $\mathbf{L}_0$ vector as

ex	x
ey	y

Add an accumulator at the end of the channel in order to estimate the intenisty profiles at this location.

Material Discontinuity 2

1 On the **Physics** toolbar, click **Boundaries** and choose **Material Discontinuity**.

2 Select Boundary 12 only.

3 In the **Settings** window for **Material Discontinuity**, locate the **Rays to Release** section.

4 From the **Release reflected rays** list, choose **Never**.

Accumulator 1

1 On the **Physics** toolbar, click **Attributes** and choose **Accumulator**.

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

3 In the R text field, type 1.

Add water as a material for the fluid properties and manually add the refractive index of the mixture in the property.

4 On the **Home** toolbar, click **Windows** and choose **Add Material from Library**.

ADD MATERIAL

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

2 In the tree, select **Built-In>Water, liquid**.

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

4 On the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Water, liquid (mat1)

1 In the **Settings** window for **Material**, locate the **Material Contents** section.

2 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Refractive index, real part	n	n	1	Refractive index
Refractive index, imaginary part	ki	0	1	Refractive index

MESH 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Creeping Flow (spf)** node, then click **Component 1 (comp1)>Mesh 1**.

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

3 From the **Element size** list, choose **Extra fine**.

4 Click **Build All**.

STUDY 1

Step 2: Ray Tracing

1 On the **Study** toolbar, click **Study Steps** and choose **Time Dependent>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 In the **Lengths** text field, type `range(0,0.1,1)*2*h_sub`.

5 Locate the **Physics and Variables Selection** section. In the table, enter the following settings:

Physics interface	Solve for	Discretization
Creeping Flow (spf)		physics
Transport of Diluted Species (tds)		physics

6 Click to expand the **Values of dependent variables** section. Locate the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

7 From the **Method** list, choose **Solution**.

8 From the **Study** list, choose **Study 1, Stationary**.

Parametric Sweep

1 On 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
fr2 (Flow rate of distilled water)		`ul/min`

5 Click **Range**.

6 In the **Range** dialog box, type `0.6` in the **Start** text field.

7 In the **Step** text field, type `0.6`.

8 In the **Stop** text field, type `3`.

9 Click **Add**.

Set the time-stepping method to manual for better accuracy.

Solution 1 (sol1)

1 On the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time stepping** section.

4 Locate the **Time Stepping** section. From the **Steps taken by solver** list, choose **Manual**.

5 In the **Time step** text field, type `tstep`.

6 In the **Model Builder** window, click **Study 1**.

7 In the **Settings** window for **Study**, locate the **Study Settings** section.

8 Clear the **Generate default plots** check box.

9 On the **Study** toolbar, click **Compute**.

RESULTS

In the **Model Builder** window, expand the **Results** node.

Ray 1

1 On the **Results** toolbar, click **More Data Sets** and choose **Ray**.

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

3 From the **Solution** list, choose **Parametric Solutions 1 (sol3)**.

4 From the **Ray geometry specification** list, choose **From physics interface**.

5 From the **Physics interface** list, choose **Geometrical Optics (gop)**.

2D Plot Group 1

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

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

3 Locate the **Data** section. From the **Data set** list, choose **Study 1/ Parametric Solutions 1 (sol3)**.

Surface 1

1 Right-click **Concentration** and choose **Surface**.

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

3 In the **Expression** text field, type `c`.

4 On the **Concentration** toolbar, click **Plot**.

5 Click the **Zoom Extents** button on the **Graphics** toolbar. The plot should look like Figure 2.

Concentration 1

1 In the **Model Builder** window, under **Results** right-click **Concentration** and choose **Duplicate**.

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

Surface 1

1 In the **Model Builder** window, expand the **Results>Refractive Index** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `n`.

4 On the **Refractive Index** toolbar, click **Plot**.

5 Click the **Zoom Extents** button on the **Graphics** toolbar. The plot should look like Figure 3. Select a different parameter value to see the effect of the water flow rate on the refractive index of the lens.

2D Plot Group 3

1 On the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

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

3 Locate the **Data** section. From the **Data set** list, choose **Ray 1**.

Color Expression 1

1 On the **Ray Trajectories** toolbar, click **More Plots** and choose **Ray Trajectories**.

2 In the **Model Builder** window, right-click **Ray Trajectories 1** and choose **Color Expression**.

3 In the **Settings** window for **Color Expression**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1> Geometrical Optics>Intensity and polarization>gop.logI - Log of intensity**.

4 On the **Ray Trajectories** toolbar, click **Plot**.

5 Click the **Zoom Extents** button on the **Graphics** toolbar. The plot should look like Figure 4. Select a different parameter value to see the effect of the water flow rate on the focal length of the lens.

1D Plot Group 4

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

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

3 From the **Data set** list, choose **Study 1/Parametric Solutions 1 (sol3)**.

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

5 In the **Label** text field, type `Intensity Profiles`.

Line Graph 1

1. Right-click **Intensity Profiles** and choose **Line Graph**.
2. Click the **Zoom Extents** button on the **Graphics** toolbar.
3. Select Boundary 12 only.
4. In the **Settings** window for **Line Graph**, click **Replace Expression** in the upper-right corner of the **y-axis data** section. From the menu, choose **Component 1>Geometrical Optics> Accumulated variables>Accumulated variable comp1.gop.matd2.bacc1.rpb> gop.matd2.bacc1.rpb - Accumulated variable rpb**.
5. Click to expand the **Legends** section. Select the **Show legends** check box.
6. On the **Intensity Profiles** toolbar, click **Plot**.
7. Click the **Zoom Extents** button on the **Graphics** toolbar. The plot should look like Figure 5.