

INTRODUCTION TO Ray Optics Module

Introduction to the Ray Optics Module

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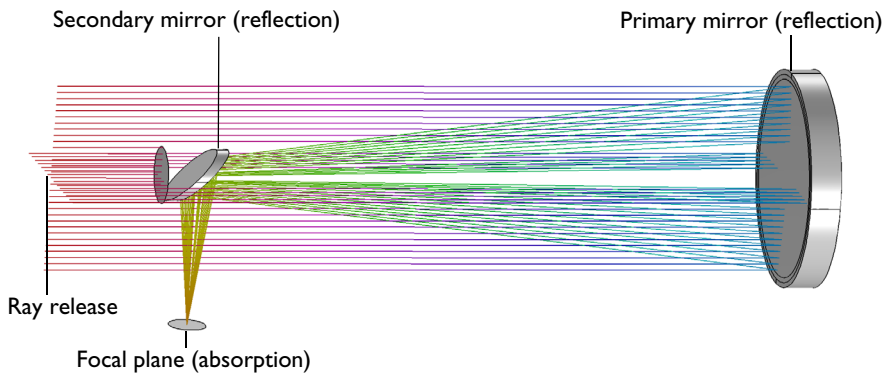
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Introduction

The Ray Optics Module is a computational tool for modeling the propagation of light and other electromagnetic radiation with a ray tracing approach. The rays can propagate through the model geometry while being reflected, refracted, or absorbed at boundaries.

You can control where the rays are released, and in what direction. You can also assign different boundary conditions to every surface in the geometry



A simple Newtonian telescope. The incident rays are focused by a parabolic primary mirror and then redirected to the focal plane by a flat secondary mirror.

The fundamental assumption of ray optics is that the wavelength of the radiation is much smaller than the smallest geometric detail in the model, so that diffraction can be ignored.

The Ray Optics Module employs non-sequential ray tracing with a deterministic ray splitting algorithm at boundaries. In other words, rays can interact with whatever surfaces in the model geometry that they hit, without the order of ray-boundary interactions having to be specified *a priori*. At boundaries between different media, each incident ray can be split into a reflected ray and a refracted ray.

Within the simulation domain, the media can be homogeneous or can have gradients in the refractive index. The Ray Optics Module is also fully compatible with physics interfaces that compute temperature and structural deformation, allowing for high-fidelity Structural Thermal Optical Performance (STOP) analysis. The refractive indices can be both wavelength- and temperature-dependent.

A wide variety of dedicated postprocessing tools are available to visualize ray propagation, extract figures of merit, and export relevant data.





About this Book

The next section of this booklet gives a list of the physics interfaces and multiphysics couplings that are available with the Ray Optics Module.




The subsequent sections explain the different types of physics interface settings and features that are provided for ray optics simulation.

The final section of this book is a detailed, step-by-step tutorial of the setup, ray tracing, and postprocessing of a double Gauss lens system.







Physics Interface Guide by Space Dimension and Preset Study Type

PHYSICS INTERFACE	ICON	TAG	SPACE DIMENSION	AVAILABLE STUDY TYPE
 Optics				
 Ray Optics				
Geometrical Optics		gop	3D, 2D, 2D axisymmetric	ray tracing; bidirectionally coupled ray tracing; time dependent
Ray Heating		—	3D, 2D, 2D axisymmetric	ray tracing; bidirectionally coupled ray tracing; time dependent

Geometrical Optics

The Geometrical Optics interface  is found under the Ray Optics  branch in the Model Wizard . It is used to model the propagation of electromagnetic rays. By default only the ray paths are solved for, but it is possible to solve for additional variables to analyze ray intensity, polarization, phase, optical path length, and more. Rays can propagate through both homogeneous and graded-index media. This interface supports a wide variety of ray sources, and the released rays can be reflected, refracted, or absorbed at any boundary in the model.

Ray Heating

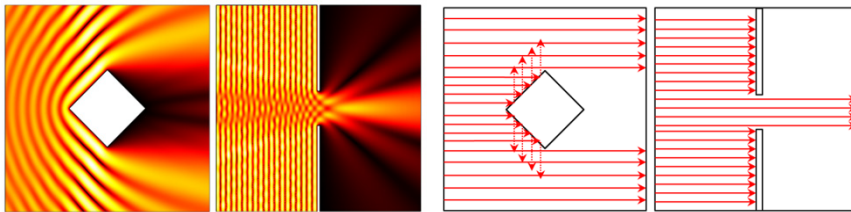
The Ray Heating interface  is found under the Ray Optics  branch in the Model Wizard . It combines the Geometrical Optics  interface with the Heat Transfer in Solids  interface. These two interfaces are coupled together using the Ray Heat Source multiphysics node .

When the rays pass through an absorbing medium, indicated by a complex-valued refractive index, the ray intensity decreases and a deposited heat source is defined within the domain. This heat source can then be combined with other heat sources and boundary conditions to compute the temperature of the domain.

It is possible to set up bidirectionally coupled models in which the temperature perturbation caused by ray attenuation significantly changes the refractive index of the medium or causes thermal deformation of the boundaries. The rays can then be traced through this perturbed system to yield a self-consistent solution.

Ray Tracing Fundamentals

The most essential assumption of a ray optics approach is that the geometry is optically large, meaning that the smallest detail of the model geometry is still much larger than the wavelength of the radiation. This assumption is necessary because the Geometrical Optics interface does not include diffraction effects that occur at the wavelength scale when electromagnetic waves interact with edges or points in the surrounding geometry.



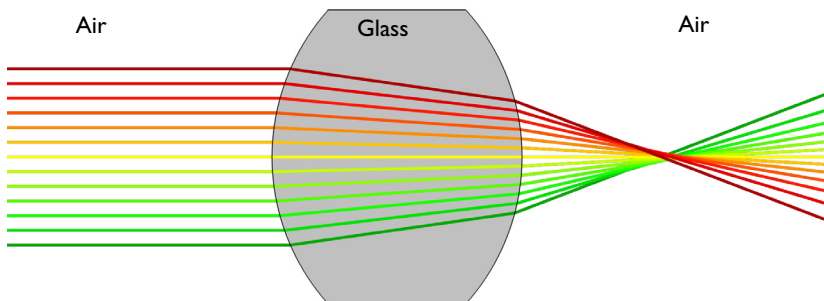
Wave propagation around an obstruction (far left) or through a slit (middle left) comparable to the wavelength produces diffraction patterns. Ray propagation around an optically large obstruction (middle right) or a wide slit (far right) produces clearly defined regions of light and shadow.

Ray Propagation

Ray propagation is controlled by the refractive index of the medium. This affects the speed at which rays propagate through the domain,

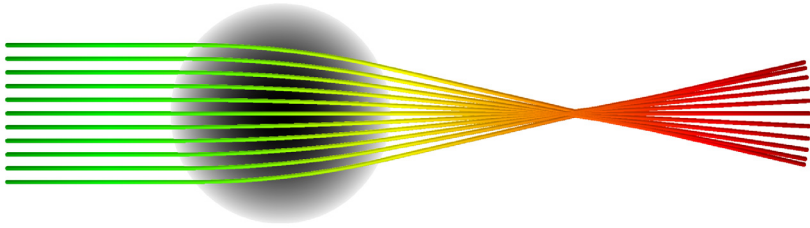
$$\text{Speed of light} = \frac{\text{Speed of light in vacuum}}{\text{Refractive index}} = \frac{299,792,458 \text{ m/s}}{n}$$

If the medium is homogeneous, or spatially uniform in each domain, then rays travel in straight lines in each medium. The rays can only change direction when they are reflected or refracted at boundaries.



Ray propagation through a lens with a homogeneous (non-graded) index.

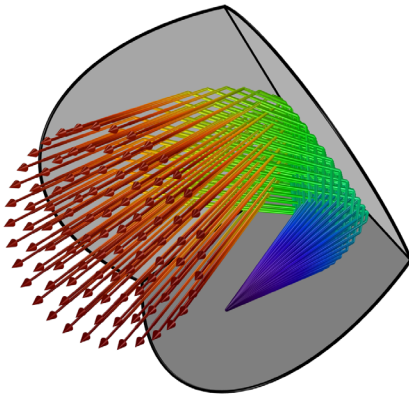
In some cases, the refractive index varies continuously within a domain. Since the gradient of the refractive index is then nonzero, such a material is called a *graded-index medium*. In graded-index media, the rays can follow curved paths. Graded-index media most often arise in coupled simulations, such as nonisothermal domains where the refractive index is temperature-dependent. Graded-index media may also appear in models of chemical diffusion if the refractive index is a function of the concentration of a diluted species.



Rays follow curved paths through the graded-index medium of a Luneburg lens. The color along the rays indicates optical path length (left). The grayscale in the background is the refractive index.

Reflection, Refraction, and Absorption

The rays can interact with any number of boundaries in the model, in any order. It is not necessary to specify the order of the boundary interactions because the intersection points of rays with a boundary are detected non-sequentially. Based on the ray's current position and direction, the next intersection with a surface is detected, and then the ray is extrapolated out to that surface, where the boundary condition can be applied. In a graded-index medium, it is necessary to take small, discrete steps in time (or equivalently in optical path length) to accurately predict the intersection points because the ray path can be nonlinear.



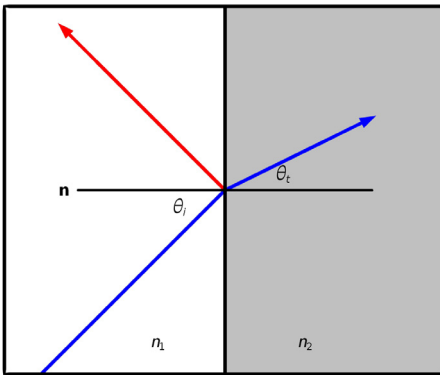
Specular reflection of rays by a corner cube retroreflector.

REFRACTION

Whenever a ray reaches a boundary between two media with different refractive indices, the deterministic ray splitting algorithm generates a refracted ray and a specularly reflected ray. The direction of the refracted ray is computed using Snell's law,

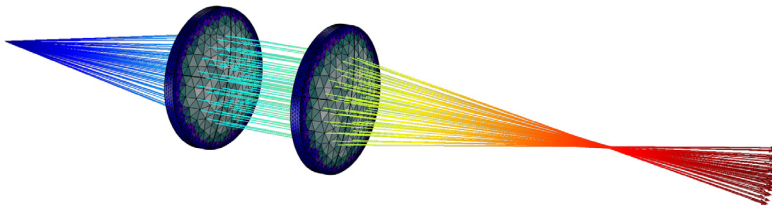
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where n is the refractive index, θ is the angle with respect to the surface normal, and the subscripts 1 and 2 indicate the side of the incident and refracted ray, respectively. The ray splitting algorithm automatically also detects when rays undergo total internal reflection and suppresses the release of refracted rays accordingly.




Refraction of an incident ray (blue) at a boundary. A second, reflected ray (red) is also released.

It is easy to suppress the release of reflected rays at material discontinuities. This allows you to focus exclusively on the refracted rays in lens systems, where the stray light may not be of much interest.

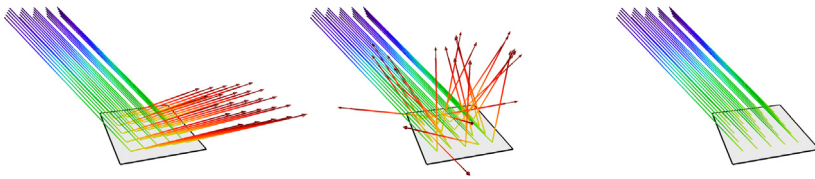


Ray tracing in a pair of convex lenses. The color along the rays is proportional to the optical path length. The color in the lenses is proportional to the mesh element size. The release of reflected rays at the lens surfaces has been suppressed.

REFLECTION AND ABSORPTION

The default behavior of the Geometrical Optics  interface is to treat each surface as a reflecting and refracting boundary between two dielectric media. It is also possible to apply other boundary conditions to specularly or diffusely reflect rays at a surface. In this context, “diffuse” means Lambertian, in which the distribution of reflection angles about the surface normal follows the cosine law.

In addition, you can combine different boundary conditions based on a probability or logical expression. For example, you could specularly reflect 70% of rays and diffusely reflect the remaining 30%; or you could diffusely reflect rays for which $x > 0$ at the intersection point, and absorb all others.



Rays can be specularly reflected (left), diffusely reflected (middle), or absorbed (right) at any boundary.

Polychromatic Light

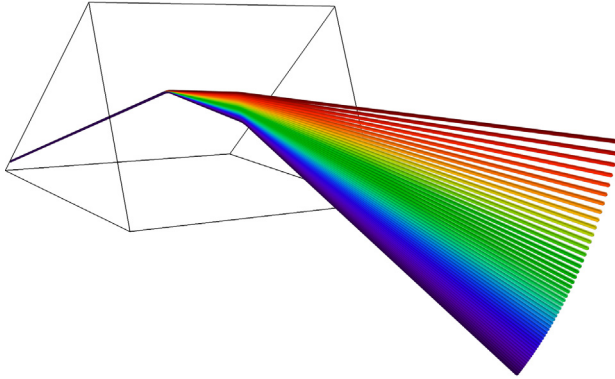
The rays in the Geometrical Optics interface are monochromatic by default but can easily be made polychromatic. You can either specify a list of frequency values or vacuum wavelength values to be released. The frequency can be an expression or an explicit list of values, or it can be sampled from a distribution.

In the Geometrical Optics interface, the main mechanisms for separating light of different wavelengths are to define a dispersive (wavelength-dependent) medium or use a diffraction grating.

DISPERSIVE MEDIA

Many of the built-in materials in the Material Library already define the refractive index as a function of the refractive index, using empirical data compiled from scientific literature. You can also enter user-defined expressions in which the vacuum wavelength or frequency appears explicitly.

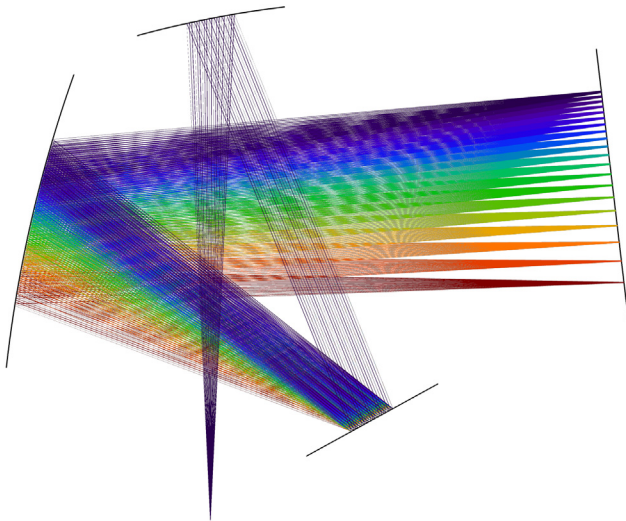
Alternatively, you can enter the coefficients for one of the built-in optical dispersion models, such as Sellmeier coefficients. Many glasses in the Optical Material Library use these standard optical dispersion models. Some glasses also include thermo-optic dispersion coefficients so that the refractive index becomes a function of both wavelength and temperature.



A prism containing a dispersive medium can separate light into different colors.

DIFFRACTION GRATINGS

At a diffraction grating, both reflected and transmitted rays of many diffraction orders can be released. The built-in boundary condition for the diffraction grating automatically computes the direction of each of the specified diffraction orders. If you know the transmittance or reflectance associated with each order, you can specify them as well. A wavelength-scale model, solving the electromagnetic wave equation in the frequency domain, can generate this data.



Czerny-Turner Monochromator: An arrangement of collimating mirror, focusing mirror, and diffraction grating in a crossed Czerny-Turner configuration is used to split polychromatic light into separate colors. The color expression in the ray plot is proportional to the wavelength.

Intensity and Polarization

The intensity of each ray is computed by solving for a set of four variables called the *Stokes parameters*. Because the rays represent electromagnetic waves, in general it is often necessary to store information about the direction of the electromagnetic field vector, not just its amplitude, and the Stokes parameters accomplish this with ease.

Whenever the ray intensity is solved for in the Geometrical Optics interface, the complete state of polarization of the ray is also recorded. Any combination of different polarization states can be included in the same model, meaning that the rays can be any combination of the following:

- Unpolarized,
- Circularly polarized,
- Elliptically polarized,
- Linearly polarized, or
- Partially polarized, with a user-defined degree of polarization between 0 and 1.

It is important to note that ray intensity is always solved for in radiometric, not photometric, units. In other words, the intensity is represented as an energy flux in absolute terms and not the apparent flux seen by the human eye.

Reflected and Refracted Ray Intensity

Information about ray polarization is vital even to the simplest model of reflection and refraction at a material discontinuity. The coefficients of reflection and refraction depend on whether the incident ray is polarized in the plane of incidence (p-polarized) or perpendicular to it (s-polarized). This dependence is shown explicitly in the Fresnel equations,

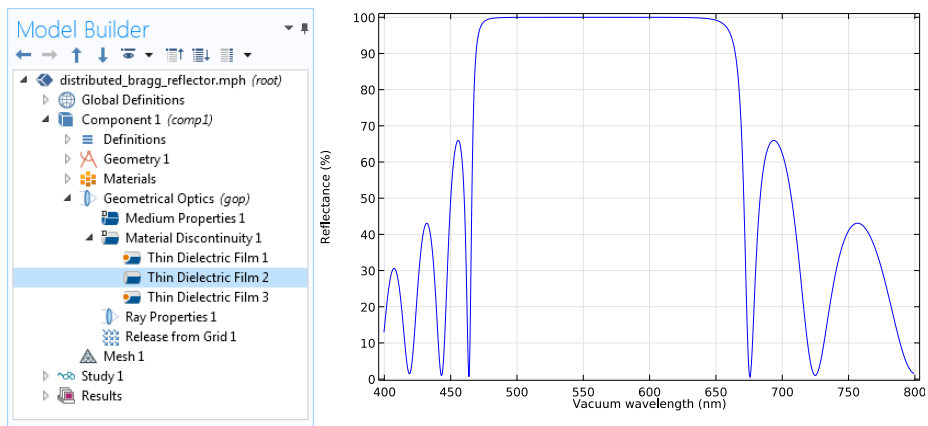
$$\begin{aligned}t_p &= \frac{2n_1 \cos \theta_i}{n_2 \cos \theta_i + n_1 \cos \theta_t} \\t_s &= \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_t} \\r_p &= \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_2 \cos \theta_i + n_1 \cos \theta_t} \\r_s &= \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t}\end{aligned}$$

where the subscripts p and s refer to polarization in the plane of incidence and orthogonal to it, respectively; i.e., p- and s-polarization.

Dielectric Coatings on Boundaries

In practice, very few refracting boundaries are simply discontinuities between two domains with different refractive indices. Most lenses and mirrors are coated with one or more thin dielectric layers that cause the reflection and transmission coefficients to differ from a simple implementation of the Fresnel coefficients.

If you know the properties of each layer in a dielectric coating — the thickness and refractive index of each layer, and the order in which the layers appear — then you can build these layers directly into the Material Discontinuity boundary condition. The Fresnel coefficients are then automatically adjusted to take each layer into account, in addition to the refractive indices of the two adjacent domains. You can also specify that some of these dielectric layers are periodic, allowing you to quickly create multilayer coatings with tens or hundreds of layers.



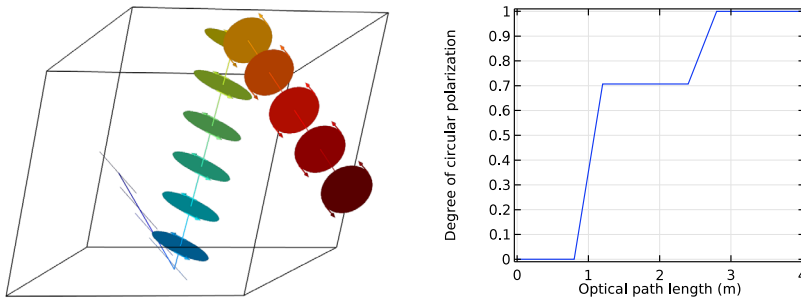
Distributed Bragg Reflector (DBR): Several thin dielectric films can be added to the same boundary, and these layers can be made periodic with a large number of unit cells. Here the reflectance of a DBR with 21 dielectric layers is plotted as a function of wavelength.

Alternatively, if the reflectance or transmittance of a coating is provided by a manufacturer in lieu of the layer properties, you can simply enter the reflectance or transmittance into the model. The specified value need not be a constant; you can also define an arbitrary function of the ray frequency or wavelength if the light in the model is polychromatic.

Visualizing Polarization

You can see the effects of different boundary conditions on polarization by plotting polarization ellipses along the ray during postprocessing. These ellipses show whether the ray is linearly, circularly, or elliptically polarized. They also indicate the direction of polarization and the sense of rotation of the electric field

vector (for elliptical and circular polarizations), so it is easy to distinguish between left-handed and right-handed circular polarization.

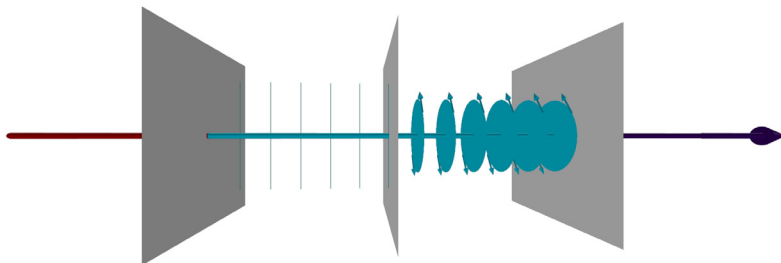


Linearly polarized light is internally reflected twice in a Fresnel rhomb (left). As a result, the ray's polarization ellipse shifts from linear, to elliptical, to circular. This can also be shown by plotting the degree of circular polarization plotted as a function of optical path length (right).

Other Boundary Conditions to Control Polarization

Dedicated boundary conditions to manipulate ray intensity and polarization are available. These boundary conditions don't affect the ray direction but do modify the Stokes parameters of the outgoing ray. These include the following:

- Ideal linear polarizers,
- Linear or circular wave retarders,
- Depolarizers,
- Customized 4 by 4 Mueller matrices that can represent nearly any combination of optical components.



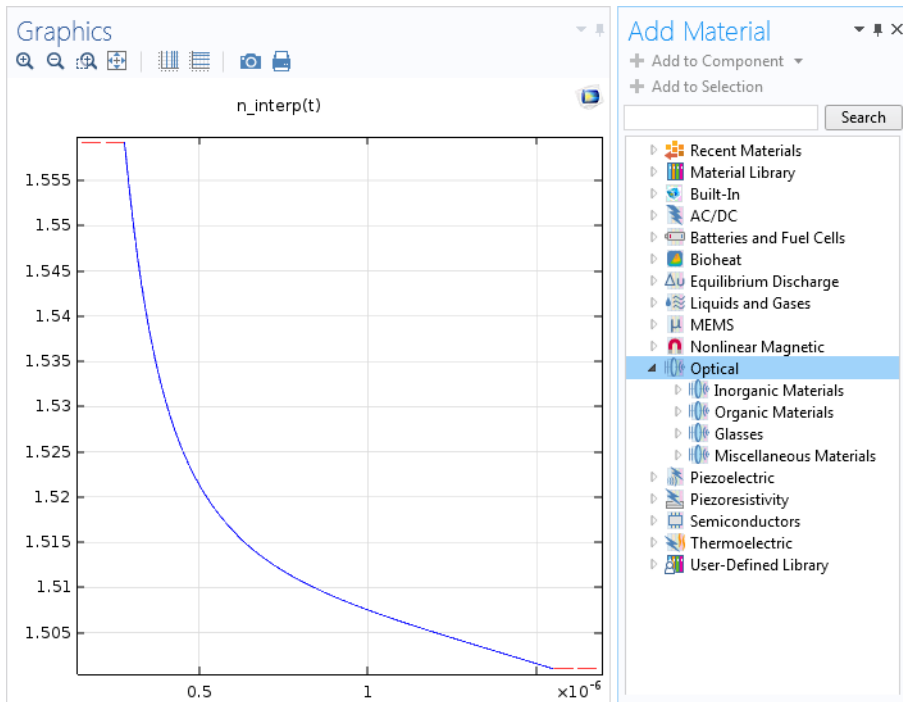
Linear Wave Retarder tutorial: An unpolarized ray (going left to right) passes through a linear polarizer, a quarter-wave retarder, and a second linear polarizer orthogonal to the first. Polarization ellipses are shown in the ray diagram. The color expression indicates the ray intensity.

Modeling Tools

In addition to the physics features described previously, the Ray Optics Module provides a variety of tools to help you set up your model and analyze results.

Optical Material Database

A dedicated material database, the Optical database, is available with the Ray Optics Module. This database includes information on the refractive indices of more than 1,400 materials.



The Optical Material Database (right) and the free-space wavelength dependent refractive index of a typical entry (left).

For many of these materials, the refractive index is a function of ray frequency or vacuum wavelength. Whenever possible, the materials use optical dispersion models, such as Sellmeier coefficients, to conveniently define a continuous function for refractive index. Some materials also include thermo-optic dispersion coefficients to more easily and realistically define refractive index as a function of temperature.

PART LIBRARY

The Ray Optics Module includes a dedicated Part Library. This Part Library contains geometric entities that are frequently used in Ray Optics simulations, including spherical and aspherical lenses, mirrors, retroreflectors, prisms, and beam splitters. These geometry parts are fully parameterized and include a variety of preset selections that allow, for example, anti-reflective coatings to be applied to the exterior surfaces of a large number of lenses with ease.

Part Libraries

Refresh

Update COMSOL Part Libraries

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COMSOL Multiphysics

AC/DC Module

Heat Transfer Module

Microfluidics Module

Mixer Module

Multibody Dynamics Module

Ray Optics Module

2D

3D

Apertures and Obstructions

Aspherical Lenses

Beam Splitters

Cemented Doublets

Cylindrical Lenses

Mirrors

Prisms

Retroreflectors

Spherical Lenses

spherical_equi_concave_lens_3d

spherical_equi_convex_lens_3d

spherical_lens_3d

spherical_meniscus_lens_3d

spherical_plano_concave_lens_3d

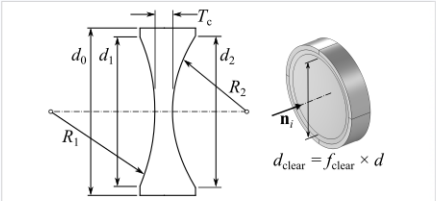
spherical_plano_convex_lens_3d

Legacy

RF Module

Structural Mechanics Module

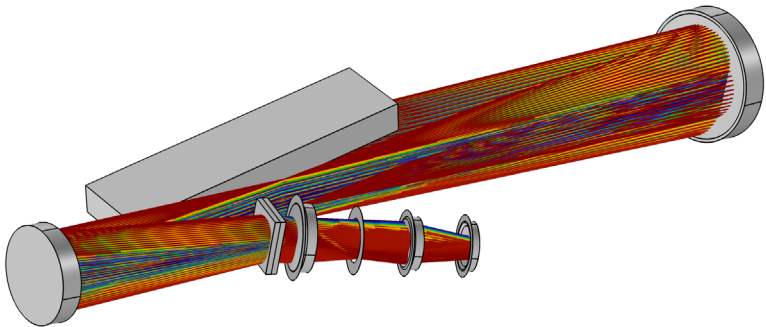
Spherical Lens 3D



Spherical lens with either concave or convex surfaces. The lens surface diameters can be smaller than the outer diameter. Clear apertures which are smaller than the lens surface diameters can be specified.

Name	spherical_lens_3d
Model version	6
Space dimension	3
Used products	COMSOL Multiphysics
Created in	COMSOL Multiphysics 5.4 (Build: 175)
Author	COMSOL
Last modified	Jul 26, 2018 8:48:06 AM
Created	Jul 26, 2018 8:47:04 AM

The Part Library for the Ray Optics Module.



Ray diagram in a white pupil Échelle spectrograph. The off-axis parabolic mirrors and aspheric lenses are all available in the Part Library for the Ray Optics Module.

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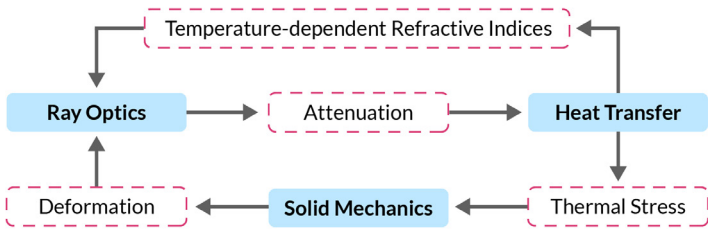
Ray-Thermal Coupling

If the refractive indices in a ray optics model are complex-valued, then the imaginary part is treated as an absorption term. A ray propagating through a complex-valued refractive index loses some of its energy through this attenuation, and it is possible to deposit an equal amount of energy into the surrounding domain as a heat source term.

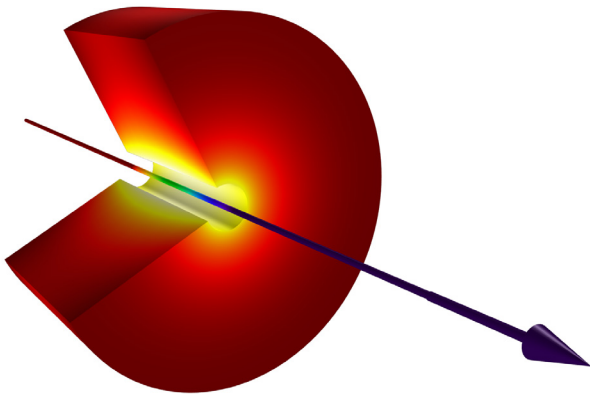
A dedicated Multiphysics interface, the Ray Heating interface, is available to use the heat generated by ray propagation in absorbing media with another physics interface for computing temperature, such as the Heat Transfer in Solids interface. The Ray Heating interface enables bidirectional couplings to be set up, allowing phenomena such as thermal lensing to be modeled.



Unidirectional (one-way) coupling from ray optics to heat transfer.



Bidirectional (two-way) coupling between ray optics and heat transfer, including thermal stress



A ray passes through a layer of absorbing material, causing the temperature in the layer to increase.

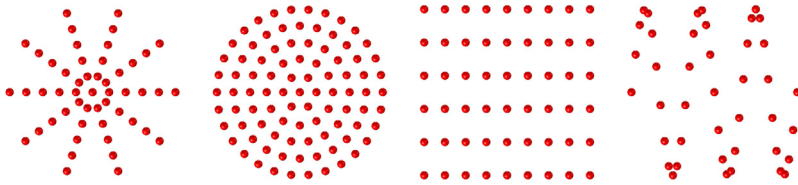
Ray Sources

The Geometrical Optics interface provides a variety of ray sources, or ray *release features*, to specify the initial position and direction of rays. Any number of ray sources of different types can be used in the same model.

GRID SOURCES

The most direct way to specify the ray release positions is with a grid-based release. As shown below, there are several ways to control the initial positions of the rays.

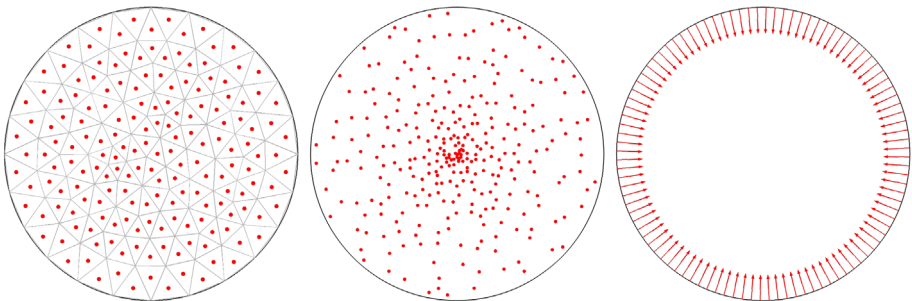
At each release position, the rays can propagate outward in a single direction or in a spherical, hemispherical, conical, or Lambertian (cosine law) distribution. A dedicated Solar Radiation feature is also available to initialize the ray direction based on the location on the Earth's surface and the date and time.



Rays can be released in a cylindrical (far left), hexapolar (middle left), rectangular (middle right), or nonuniform grid (far right).

DOMAIN AND BOUNDARY SOURCES

You can release rays from a selected set of domains or boundaries. The distribution of release points can be uniform, proportional to a user-defined density function, random, or based on the underlying finite element mesh.



Release positions based on the domain mesh (left), nonuniform density expression (middle), and uniformly distributed along a boundary (right).

There is also a dedicated release feature to release light from a specularly reflecting or refracting illuminated surface. You can release the reflected or refracted rays just by providing the location of the external radiation source.

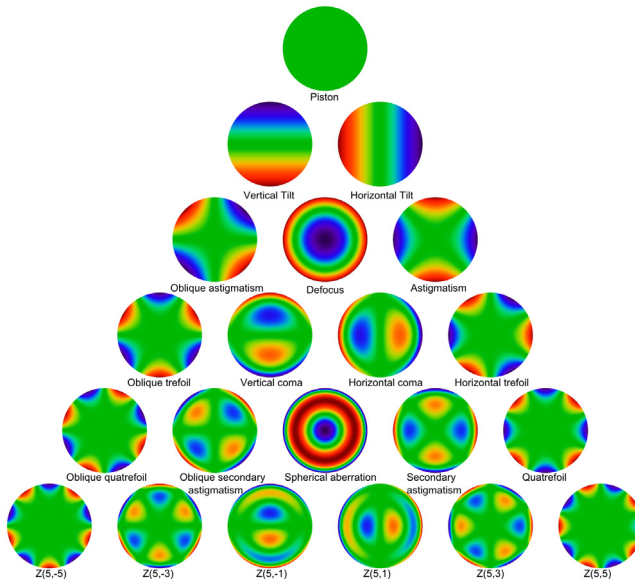
OTHER SOURCES

Rays can be released from selected point in a geometry. In 3D, they can also be released in selected edges. Thus, rays can be released from geometric entities of any dimension, up to the full dimension of the model.

It is also possible to load the release positions and initial directions from a text file, where each column corresponds to one of the position or direction vector components.

Analyzing Optical Aberrations

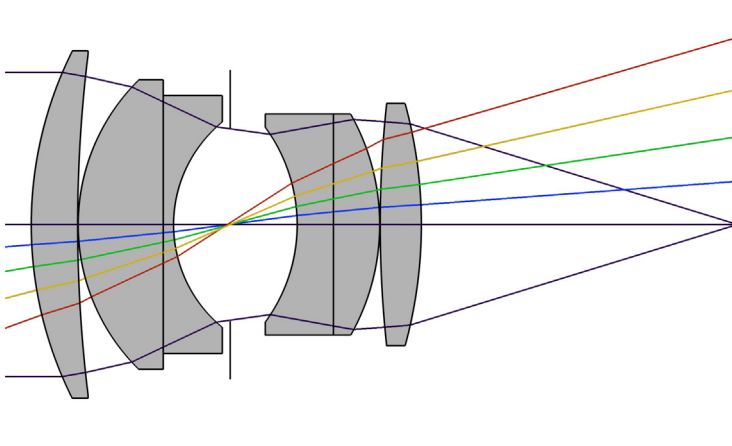
The Ray Optics Module can be used to investigate monochromatic aberrations in a lens system. To do so, use the Optical Aberration plot or the Aberration Evaluation feature. These features compute the wavefront error for the rays that are focused by a system of lenses and mirrors, then expresses the wavefront error as a linear combination of Zernike polynomials.



The Zernike polynomials, a standard orthogonal polynomial basis that is often used to describe monochromatic aberrations.

Tutorial: Tracing Rays Through a Double Gauss Lens

In this section a simple multi-element lens will be simulated. The model will use an $f/1.7$, 100.2 mm focal length Double Gauss lens by Lautebacher & Brendel (Agfa Camera Werk Ag, U.S. Patent 2784643). Further details of the lens simulated in this study can be found in the tutorial *Double Gauss Lens*. An overview of the lens can be seen in the figure below. The table below gives the optical prescription.



Overview of a Double Gauss lens. In this view the marginal rays of an on-axis trace are shown, together with the chief ray of 4 additional fields.

It should be emphasized that the ray tracing method used by Geometrical Optics interface is inherently non-sequential, so the same results can be obtained by constructing the geometry in any order. However, in this simulation the lens geometry is constructed by repeated insertions of part instances from the COMSOL Part Library with each lens element (including the stop) being inserted sequentially. Each subsequent lens is placed relative to work planes that have been defined in each of the lens (and stop) part instances.



For full details on creating the lens geometry, see Appendix — Geometry Instructions of the tutorial for the *Double Gauss Lens*. An extension of this tutorial involving a parametric sweep over multiple wavelengths and field angles can be found in the tutorial *Double Gauss Lens Parametric Sweep*.



DOUBLE GAUSS LENS OPTICAL PRESCRIPTION

INDEX	NAME	RADIUS (MM)	THICKNESS (MM)	MATERIAL	CLEAR RADIUS (MM)
—	Object	∞	∞	—	—
1	Lens 1	75.050	9.000	LaF3	33.0
—	—	270.700	0.100	—	33.0
2	Lens 2	39.270	16.510	BaF11	27.5
3	Lens 3	∞	2.000	SF5	27.5
—	—	25.650	10.990	—	19.5
4	Stop	∞	13.000	—	18.6
5	Lens 4	-31.870	7.030	SF5	18.5
6	Lens 5	∞	8.980	LaF3	21.0
—	—	-43.510	0.100	—	21.0
7	Lens 6	221.140	7.980	BaF11	23.0
—	—	-88.790	61.418	—	23.0
—	Image	∞	—	—	42.5






Model Wizard

Note: These instructions are for the user interface on Windows but apply, with minor differences, also to Linux and Mac.


- 1 To start the software, double-click the COMSOL icon on the desktop. When the software opens, you can choose to use the Model Wizard  to create a new COMSOL model or Blank Model  to create one manually. For this tutorial, click the Model Wizard button.

If COMSOL is already open, you can start the Model Wizard by selecting New  from the File menu and then click Model Wizard .

The Model Wizard guides you through the first steps of setting up a model. The next window lets you select the dimension of the modeling space.

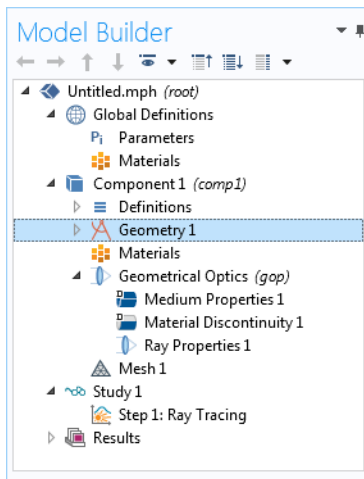
- 2 In the Select Space Dimension window click the 3D button .
- 3 In the Select Physics tree under Optics  > Ray Optics , click Geometrical Optics .
- 4 Click Add, then click the Study  button.

- 5 In the tree under Preset Studies, click Ray Tracing .

The Ray Tracing study step functions like the Time Dependent  study step, but has additional settings and defaults that are well suited for computing ray trajectories. The rays are either traced to a maximum time or a maximum optical path length, to prevent them from propagating outward to an arbitrarily large distance.



- 6 Click the Done  button.

The Geometrical Optics interface is created with the default nodes shown below.





Global Definitions


Load the global parameters for the Double Gauss lens from a text file. The detailed lens prescription will be added when the geometry sequence is inserted.

- 1 On the Home toolbar, Click Parameters . Alternatively, click the Parameters  node in the Model Builder window.

Note: On Linux and Mac, the Home toolbar refers to the specific set of controls near the top of the Desktop.

- 2 In the Parameters  settings window, type Parameters 1: Lens Prescription in the Label text field. The lens prescription will be added when the geometry sequence is inserted.

- 3 On the Home toolbar, Click Parameters  and choose Add Parameters. This will add a second node where parameters may be entered.

- 4 In the Parameters P_1 settings window, type Parameters 2: General in the Label text field.
- 5 Click Load from File .
- 6 Browse to the model's Application Libraries folder and double-click the file double_gauss_lens_parameters.txt. The location of the files used in this exercise varies based on your installation. For example, if the installation is on your hard drive, the file path might be similar to C:\Program Files\COMSOL\COMSOL54\Multiphysics\applications\.


The parameter list should look like the following:

Settings			
Parameters			
Label: Parameters 2: General			
Parameters			
Name	Expression	Value	Description
lam_vac	550[nm]	5.5E-7 m	Nominal vacuum wavelength
theta_x	0[deg]	0 rad	Nominal x field angle
theta_y	0[deg]	0 rad	Nominal y field angle
N_ring	18	18	Number of hexapolar rings
P_nom	58.941[mm]	0.058941 m	Nominal entrance pupil diameter
vx	tan(theta_x)	0	Ray direction vector, x-component
vy	tan(theta_y)	0	Ray direction vector, y-component
vz	1	1	Ray direction vector, z-component
z_stop	Tc_1+T_1+Tc_2+T_2+Tc_3+T_3		Stop z-coordinate
z_image	Tc_1+T_1+Tc_2+T_2+Tc_3+T_3+Tc_4+T_4+Tc_5+T_5+Tc_6+T_6+Tc_7+T_7		Image plane z-coordinate
P_fac1	-1.15	-1.15	Pupil shift constant 1
P_fac2	-0.60	-0.6	Pupil shift constant 2
P_fac	P_fac1+P_fac2*sin(sqrt(theta_x^2+theta_y^2))	-1.15	Pupil shift factor
dx	(dz+P_fac*z_stop)*tan(theta_x)	m	Pupil center, x-coordinate
dy	(dz+P_fac*z_stop)*tan(theta_y)	m	Pupil center, y-coordinate
dz	-5[mm]	-0.005 m	Pupil center, z-component

Name:	lam_vac
Expression:	550[nm]
Description:	Nominal vacuum wavelength

The lines in red indicate that there are missing parameters and hence the expression cannot yet be evaluated. The remaining parameters will be added when the geometry sequence is inserted from another file.



Component

- 1 In the Model Builder window, click Component 1 (comp 1) .
- 2 In the Settings window for Component, locate the General section.
- 3 Find the Mesh frame coordinates subsection. From the Geometry shape order list, choose Cubic.

The ray tracing algorithm computes reflected and refracted ray directions based on a discretized geometry via the underlying finite element mesh. A cubic geometry shape order usually introduces less discretization error compared to the default, which uses linear and quadratic polynomials.

Geometry

Insert the prepared geometry sequence from file. See Appendix — Geometry Instructions of the tutorial for the *Double Gauss Lens* for details on how to create the lens geometry.

- 1 In the Model Builder window, under Component 1 (comp1) click Geometry 1 .
- 2 In the Settings window for Geometry, type **Double Gauss Lens** in the Label text field.
- 3 On the Geometry toolbar, click Insert Sequence .
- 4 Browse to the model's Application Libraries folder and double-click the file `double_gauss_lens_geom_sequence.mph`. Following insertion, the lens prescription details will be available in the Parameters 1: Lens Prescriptions P_i node. In addition, all expressions in the Parameters 2: General node can now be evaluated. The lens prescription parameter list should now look like the following:



Settings

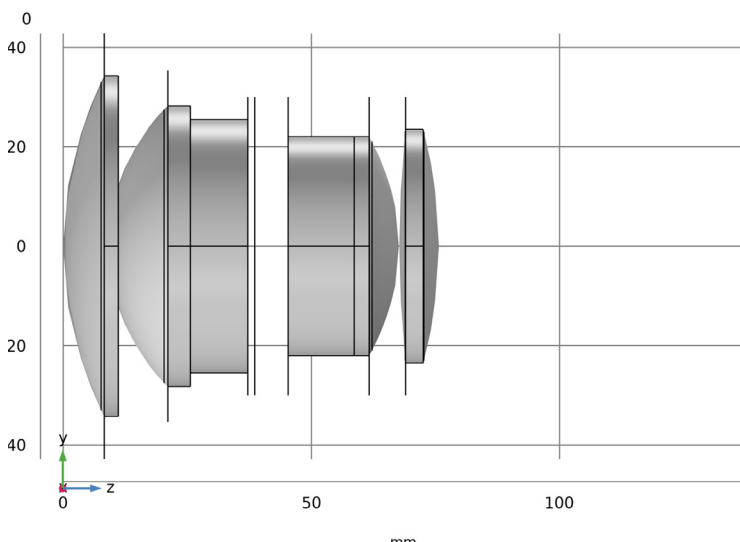
Parameters

Label: Parameters 1: Lens Prescription

Parameters

Name	Expression	Value	Description
nix	0	0	Global optical axis, x component
niy	0	0	Global optical axis, y component
niz	1	1	Global optical axis, z component
R1_1	75.050[mm]	0.07505 m	L1, surface 1 radius of curvature
R2_1	270.700[mm]	0.2707 m	L1, surface 2 radius of curvature
Tc_1	9.000[mm]	0.009 m	L1 center thickness
d0_1	68.500[mm]	0.0685 m	L1, outer diameter
d1_1	0	0	L1, surface 1 diameter
d2_1	67.500[mm]	0.0675 m	L1, surface 2 diameter
d1_clear_1	66.000[mm]	0.066 m	L1, surface 1 clear aperture diameter
d2_clear_1	66.000[mm]	0.066 m	L1, surface 2 clear aperture diameter
T_1	0.100[mm]	1E-4 m	L1 to L2 spacing
R1_2	39.270[mm]	0.03927 m	L2, surface 1 radius of curvature
R2_2	0	0	L2, surface 2 radius of curvature
Tc_2	16.510[mm]	0.01651 m	L2 center thickness
d0_2	56.500[mm]	0.0565 m	L2, outer diameter
d1_2	0	0	L2, surface 1 diameter
d2_2	50.000[mm]	0.05 m	L2, surface 2 diameter
d1_clear_2	55.000[mm]	0.055 m	L2, surface 1 clear aperture diameter
d2_clear_2	49.000[mm]	0.049 m	L2, surface 2 clear aperture diameter
T_2	0.000[mm]	0 m	L2 to L3 spacing
R1_3	0	0	L3, surface 1 radius of curvature
R2_3	25.650[mm]	0.02565 m	L3, surface 2 radius of curvature
Tc_3	2.000[mm]	0.002 m	L3 center thickness
d0_3	51.000[mm]	0.051 m	L3, outer diameter
d1_3	0	0	L3, surface 1 diameter
d2_3	40.000[mm]	0.04 m	L3, surface 2 diameter
d1_clear_3	49.000[mm]	0.049 m	L3, surface 1 clear aperture diameter
d2_clear_3	39.000[mm]	0.039 m	L3, surface 2 clear aperture diameter
T_3	10.990[mm]	0.01099 m	L3 to Stop spacing
Tc_4	0.000[mm]	0 m	Stop center thickness
d0_5	60.000[mm]	0.06 m	Stop maximum diameter
d1_5	37.200[mm]	0.0372 m	Stop clear diameter
T_4	13.000[mm]	0.013 m	Stop to L4 spacing
R1_5	-31.870[mm]	-0.03187 m	L4, surface 1 radius of curvature
R2_5	0	0	L4, surface 2 radius of curvature

- On the Geometry toolbar, click Build All .
- Click the Zoom Extents  button on the Graphics toolbar. The geometry should look like the figure below:









Geometry sequence for the Double Gauss Lens. Light propagates from left to right (in the positive z-direction) through the lens.

The geometry dimensions shown are in millimeters; this was automatically changed to match the length unit of the imported geometry sequence.

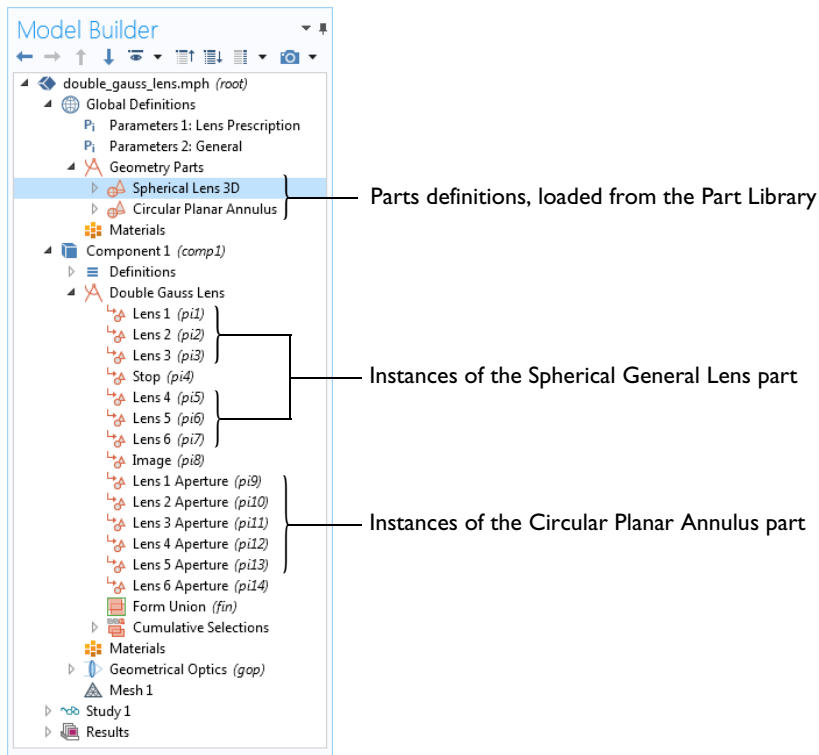
A Note on Parts and Part Instances

The geometry sequence setup was omitted from these instructions to save time, but it is worthwhile to view the geometry nodes in the Model Builder to observe how this geometry sequence was created.

Under Global Definitions  >Geometry Parts , two part definitions have been loaded: the Spherical Lens 3D  and the Circular Planar Annulus . Then in under Component 1  >Geometry 1 , a number of part instances have been created.




Each part instance calls one of the part definitions, functioning as a subsequence of geometry instructions with various input parameters. For example, the Spherical General Lens part accepts input parameters for the radii of curvature of the surfaces, the lens center thickness, and the surface diameters, and then uses this information to construct a lens.


Part instances are used heavily in optical simulations with the Ray Optics Module because they make it easy to load a standard lens prescription into the geometry sequence.



Materials

The following commands are used to add and assign material properties to each of the lenses. These materials are part of a dedicated Optical Material Library that is available with the Ray Optics Module or Wave Optics Module.

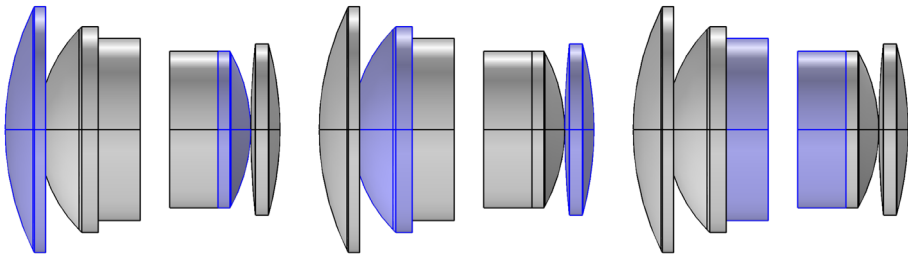
- 1 On the Materials toolbar, click Add Material  to open the Add Material window.
- 2 Go to the Add Material window.
- 3 In the tree, select Optical>Glasses>Optical Glass Hoya>HOYA LAF3.
- 4 Click Add to Component  in the window toolbar.
- 5 In the tree, select Optical>Glasses>Optical Glass>HOYA BAF11.
- 6 Click Add to Component  in the window toolbar.

- 7 In the tree, select Optical>Glasses>Optical Glass Schott>SCHOTT N-SF5.
- 8 Click Add to Component **+** in the window toolbar.
- 9 On the Materials toolbar, click Add Material  to close the Add Material window.

Next, assign this material to the relevant lenses:

- 1 In the Settings window for Material HOYA LAF3 (mat1), locate the Geometric Entity Selection section.
- 2 From the Selection list, choose Lens Material 1.
This is a Cumulative Selection that was defined in the geometry sequence. Each of the 6 lenses has been assigned to one of three lens material selections.
- 3 In the Settings window for Material HOYA BAF11 (mat2), locate the Geometric Entity Selection section.
- 4 From the Selection list, choose Lens Material 2.
- 5 In the Settings window for Material SCHOTT N-SF5 (mat3), locate the Geometric Entity Selection section.
- 6 From the Selection list, choose Lens Material 3.



The material selections should look like the following figures.



Selections for the HOYA LaF3 (left), HOYA BaF11 (middle), and SCHOTT N-SF5 (right) glasses.

Physics interfaces

Now that the geometry and materials have been inserted into the model, set up the physics interface. Before adding any ray sources or boundary conditions, change some of the physics interface properties that control the ray tracing simulation.

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


- 2 In the Maximum number of secondary rays text field, type 0. In this tutorial stray light is not being traced, so reflected rays will not be produced at the lens surfaces.
- 3 Select the Use geometry normals for ray-boundary interactions check box. This ensures that geometry normals are used to apply the boundary conditions on all refracting surfaces. This is appropriate for the highest accuracy ray traces in single-physics simulations, where the geometry is not deformed.

The following variables are not needed to trace the rays but may be useful during postprocessing.

- 1 Locate the Additional Variables section. Select the Compute optical path length check box.
- 2 Select the Count reflections check box.
- 3 Select the Store ray status data check box.


MEDIUM PROPERTIES

Each of the materials added above contain the optical dispersion coefficients which can be used to compute the refractive index as a function of wavelength.

- 1 In the Model Builder window, under Component 1 (comp1)>Geometrical Optics (gop) click Medium Properties 1 .
- 2 In the Settings window for Medium Properties, locate the Medium Properties section.
- 3 From the Optical dispersion model list, choose Get dispersion model from material.


MATERIAL DISCONTINUITY

The Material Discontinuity is the default boundary condition in the Geometrical Optics interface. It reflects and refracts the rays based on the refractive index on either side of the boundary.

- 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.



Note: The Geometrical Optics interface always uses deterministic ray splitting at Material Discontinuities, producing both a reflected and a refracted ray, unless either (i) reflected rays are intentionally suppressed (as is the case here), or (ii) there is total internal reflection, or (iii) intensity and/or power is being computed, and the reflected ray would have very low intensity.

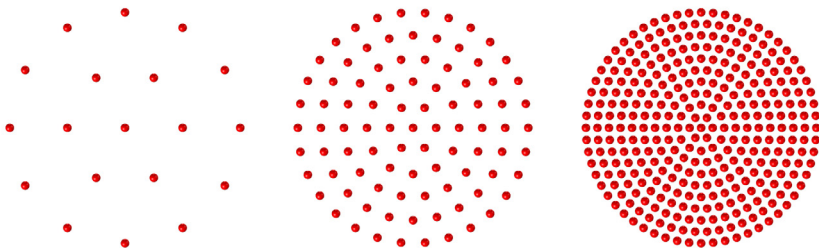
RAY PROPERTIES

- 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 Vacuum wavelength text field, type 1 μ m_vac. This wavelength was defined in the Parameters node.

RELEASE FROM GRID

Release the rays from a hexapolar grid, using quantities defined in the Parameters node.

- 1 On the Physics toolbar, click Global  and choose Release from Grid .
- 2 In the Settings window for Release from Grid, locate the Initial Coordinates section.
- 3 From the Grid type list, choose Hexapolar. The number of radial positions will determine the total number of rays that are launched. As can be seen in the figure below, the hexapolar distribution gives a uniform spatial distribution.



The hexapolar grid. From left to right, these grids have 2, 5 and 10 radial rings respectively. The number of rays launched would be 19, 91, and 331 in each case.

- 4 Specify the center location ($\mathbf{q_c}$) vector as:

Center location:

$\mathbf{q_c}$	<input type="text" value="dx"/>	<input type="text" value="x"/>	m
	<input type="text" value="dy"/>	<input type="text" value="y"/>	
	<input type="text" value="dz"/>	<input type="text" value="z"/>	

The center location ($[x_c, y_c, z_c]=[dx, dy, dz]$) of the hexapolar grid will change according to the field angle. This ensures that the chief rays will coincide on the optical axis at the location of the stop.

5 Specify the cylinder axis direction (\mathbf{r}_c) vector as:

Cylinder axis direction:

r_c	nix	x	1
	niy	y	
	niz	z	

The cylinder axis direction is the same as the global optical axis, the positive z -direction. This is the direction normal to the ray distribution, so the hexapolar grid of release points will lie in a plane parallel to the xy -plane.



- 6 In the radius (R_c) text field, type $P_{nom}/2$. The nominal pupil diameter is P_{nom} .
- 7 In the number of radial positions (N_c) text field, type N_{ring} . Below the edit field, the Settings window will report that the hexapolar grid contains a total of 1027 release positions.
- 8 Locate the Ray Direction Vector section. Specify the ray direction vector (\mathbf{L}_0) as:

Ray direction vector:



L_0	vx	x	1
	vy	y	
	vz	z	

The ray direction vector is calculated using the field angles defined in the Parameters node. In this example, the field angle is zero, but it can easily be recomputed for a nonzero field angle simply by adjusting the model parameters.

OBSTRUCTIONS



- 1 On the Physics toolbar, click Boundaries  and choose Wall .

The Wall is a general-purpose boundary condition that can absorb rays or reflect them specularly, diffusely, or in a user-defined direction. In this example, an absorbing Wall is defined on all lens edges and on the aperture stop. Any rays that encounter these surfaces will be removed.

- 2 In the Settings window for Wall, type **Obstructions** in the Label text field.
- 3 Locate the Boundary Selection section. From the Selection list, choose Lens Obstructions. These selections were made within the geometry sequence and include the lens surfaces outside the clear aperture as well as the lens edges.
- 4 Locate the Wall Condition section. From the Wall condition list, choose Disappear.
- 5 On the Physics toolbar, click Boundaries  and choose Wall .
- 6 In the Settings window for Wall, type **Stop** in the Label text field.


- 7 Locate the Boundary Selection section. From the Selection list, choose Aperture Stop.
- 8 Locate the Wall Condition section. From the Wall condition list, choose Disappear.

IMAGE PLANE


- 1 On the Physics toolbar, click Boundaries  and choose Wall .
- 2 In the Settings window for Wall, type Image Plane in the Label text field.
- 3 Locate the Boundary Selection section. From the Selection list, choose Image Plane. The default Wall condition (Freeze) will be used. Any ray that reaches the image plane will stop propagating, but it will not be removed from the simulation.


Mesh

The default physics-controlled mesh settings can be used in this simulation.

- 1 On the Mesh toolbar, click Build Mesh .


Study

Review the settings for Study 1 .

- 1 In the Settings window for Ray Tracing , locate the Study Settings section.
- 2 From the Time step specification list, choose Specify maximum path length.
- 3 From the Length unit list, choose mm.
- 4 In the Lengths text field, type 0 200. The maximum optical path length is sufficient for rays released at large field angles to reach the image plane.

Note: The Ray Tracing study step is similar to the Time Dependent study step, but has a different default time step size and termination criteria. For this study, the maximum time step is specified in terms of the maximum path length which can be easily estimated from the geometry dimensions. It should also be noted that while only two time steps are specified (corresponding to optical path lengths of 0 and 200 mm), the study does of course refract the rays at all material discontinuities at intermediate times, even when these don't match up with any of the specified output times.

The ray tracing algorithm can apply a very large number of reflections and refractions between consecutive time steps or optical path length intervals taken by the solver. The maximum number of interactions per ray, per time step is 1000 by default but can be adjusted in the physics interface Advanced Settings.

5 On the Home toolbar, click Compute .

Results






In the following steps, two different ray diagrams and a spot diagrams are created.

RAY DIAGRAMS

When the Geometrical Optics interface is present, the first time a Ray Tracing study is run, a Ray Trajectories plot is produced by default. The plot settings allow the rays to be colored using arbitrary expressions, and the rays can be filtered (and thereby hidden from view) using logical expressions.

Begin by slightly modifying and duplicating the default Ray Trajectories plot.

Ray Trajectories

- 1** In the Model Builder window, under Results , click Ray Trajectories (gop). This is a 3D Plot Group .
- 2** In the Settings window for 3D Plot Group, type Ray Diagram 1 in the Label text field.
- 3** Locate the Plot Settings section. Clear the Plot data set edges check box.
- 4** Click to expand the Title section. From the Title type list, choose None.
- 5** Right-click Results  > Ray Diagram 1  and choose Duplicate .
- 6** In the Settings window for 3D Plot Group, type Ray Diagram 2 in the Label text field.

Cut Planes



Cut planes are used for rendering the lens cross-section and for creating the spot diagram.

- 1** On the Results toolbar, click Cut Plane. The first cut plane (Cut Plane 1) is in the sagittal plane. The default settings can be used for this cut plane.
- 2** On the Results toolbar, click Cut Plane.
- 3** Locate the Data section. From the Data set list choose Ray 1.
- 4** Locate the Plane Data section. From the Plane list, choose xy-planes.





- 5 In the z-coordinate text field, type `z_image`. The second cut plane (Cut Plane 2) is coincident with the image plane.

RAY DIAGRAM 1


For the first ray diagram a cross-section of the lens is shown and the rays are colored according to the optical path length.

- 1 In the Model Builder window, expand the Results  > Ray Diagram 1  node.




Filter 1

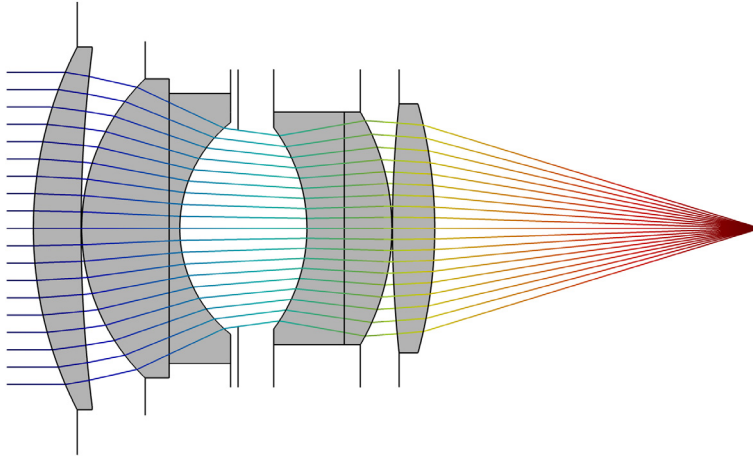
- 1 In the Model Builder window, expand the Results  > Ray Diagram 1  > Ray Trajectories 1  node, then click Filter 1 .
- 2 Locate the Ray Selection section. From the Rays to include list, choose Logical expression.
- 3 In the Logical expression for inclusion text field, type `at(0,abs(gop.deltaqx)<0.1[mm]) && gop.fs==2`. This ensures that only rays that reach the image plane will be rendered. That is, the final ray status (`fs`) is 2 (frozen). Also, only sagittal rays are rendered in this view.

Surface 1

- 1 On the Ray Diagram 1 toolbar, click Surface .
- 2 Locate the Data section. From the Data set list, choose Cut Plane 1. This is the sagittal cut plane defined above.
- 3 Locate the Coloring and Style section. From the Coloring list, choose Uniform.
- 4 From the Color list, choose Gray.

Line 1

- 1 On the Ray Diagram 1 toolbar, click Line .
- 2 Locate the Data section. From the Data set list, choose Cut Plane 1.
- 3 Locate the Coloring and Style section. From the Coloring list, choose Uniform.
- 4 From the Color list, choose Black.
- 5 On the Ray Diagram 1 toolbar, click Plot .
- 6 Click Zoom Extents  in the window toolbar. The figure should look like the figure below.




RAY DIAGRAM 2





For the second ray diagram rays will be colored according to the radial distance from the ray's location in the image plane to the centroid. This makes it possible to visualize which rays are contributing to the image plane spot aberrations.

First, add a mesh plot to render the lenses as solids:



Mesh 1

- 1 On the Ray Diagram 2 toolbar, click Mesh .
- 2 Locate the level section. From the Level list, choose Volume.
- 3 Locate the Color section. From the Element color list, choose Gray.
- 4 From the Wireframe color list, choose Gray.

Surface 1

- 1 On the Ray Diagram 2 toolbar, click Surface .
- 2 Locate the Coloring and Style section. From the Coloring list, choose Uniform.
- 3 From the Color list, choose Gray.
- 4 Right-click Results  > Ray Diagram 2  > Surface1  and choose Selection.
- 5 Select Boundaries 2 and 13 only. These are the Aperture Stop and Image Plane surfaces.

Color Expression







- 1 In the Model Builder window, expand the Results  > Ray Diagram 2  > Ray Trajectories 1  node, then click Color Expression 1 .

- 2 Locate the Expression section. In the Expression text field, type `at('last',gop.rall)`. This is the radial coordinate relative to the centroid at the image plane.

This color expression makes use of the time-like nature of the Ray Tracing study. That is, the “at” operator is used to color the rays along their whole path based on some characteristic at a specific point in time (in this case, “last”).

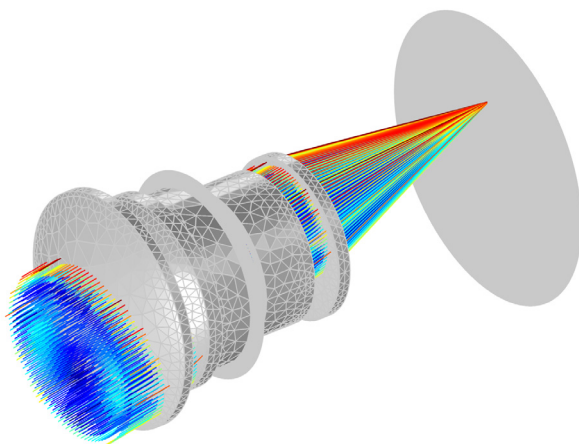
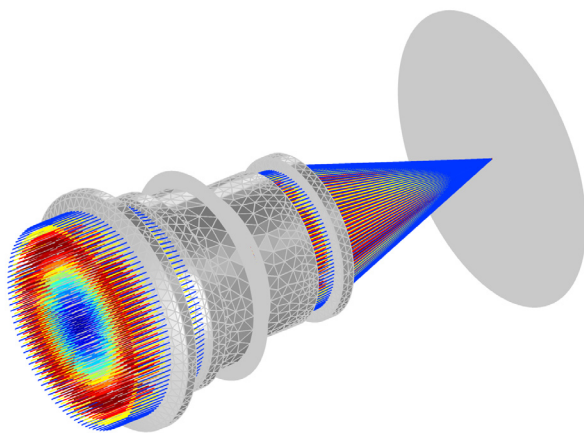
- 3 From the Unit list, choose μm .

Filter

- 1 In the Model Builder window, under Results  > Ray Diagram 2  > Ray Trajectories 1  click Filter 1 .
- 2 Locate the Ray Selection section. From the Rays to include list, choose Logical expression.
- 3 In the Logical expression for inclusion text field, type `gop.fs==2`. Plot only the rays that reach the image plane.
- 4 On the Ray Diagram 2 toolbar, click Plot .
- 5 Click Zoom Extents  in the window toolbar. Orient the view so that the color expression in the object plane can be clearly seen. The figure should look like the first figure below.

As noted above, in this figure the rays are colored according to their radial distance from the centroid. This makes it possible to visualize which rays contribute most to the overall spot size.


The study can be repeated with another field angle parameter. The second figure below shows the result with `theta_x = 10[deg]`. Again, the rays are colored according to their radial distance from the centroid. In this case, it is apparent that the relationship between the position of the rays on the image plane and the distribution of rays of these same rays at the entrance pupil is quite different.



SPOT DIAGRAM


In the following steps, a spot diagram is created, and a custom color expression is added.

2D Plot Group


- 1 On the Results toolbar, click 2D Plot Group .
- 2 In the Settings window for 2D Plot Group, type Spot Diagram in the Label text field.
- 3 Click to expand the Title section. From the Title type list, choose None.
- 4 Locate the Plot Settings section. Select the x-axis label check box.
- 5 In the associated text field, type x-coordinate.
- 6 Select the y-axis label check box.
- 7 In the associated text field, type y-coordinate.
- 8 Locate the Color Legend section. Select the Show units check box.

Poincaré Map


Using a Poincaré Map is one of several ways it is possible to create a spot diagram.

- 1 On the Spot Diagram toolbar, click More Plots and choose Poincaré Map .
- 2 Locate the Data section. From the Cut plane list, choose Cut Plane 2.
- 3 Locate the Coloring and Style section. Select the Radius scale factor check box and the Fixed size check box.

Color Expression


- 1 Right-click Poincaré Map 1 and choose Color Expression .
- 2 Locate the Expression section. In the Expression text field, type `at(0,gop.ra11)`. This is the radial coordinate relative to the centroid at the entrance pupil. This allows the origin of each ray to be visualized.



Annotation 1

- 1 In the Model Builder window, under Results right-click Spot Diagram and choose Annotation .
- 2 Locate the Data section. From the Data set list, choose Study 1/Solution 1 (sol1).
- 3 Locate the Annotation section. In the Text text field, type Wavelength:
`λ = eval(lam_vac/1[nm]) nm \ \ Field:`
`$\left[\theta_x,\theta_y\right]$ =`
`\left[eval(\theta_x/1[deg])^\circ,eval(\theta_y/1[deg])^\circ\right]`.
- 4 Select the Allow evaluation of expressions check box.

- 5 From the Geometry level list, choose Global.
- 6 Locate the Position section. In the X text field, type `gop.qavex`. In the Y text field, type `gop.qavey+1.5*gop.rmaxall`.
- 7 Click to expand the Advanced section. In the Expression precision text field, type 4.
- 8 Locate the Coloring and Style section. Select the LaTeX markup check box.
- 9 Clear the Show point check box.
- 10 From the Anchor point list, choose Upper middle.
- 11 Select the Show frame check box.

Annotation 2

- 1 Right-click Results>Spot Diagram>Annotation 1 and choose Duplicate .
- 2 Locate the Annotation section. In the Text text field, type Size:

$$r_{\text{rms}} = \text{eval}(\text{gop.rrms}/1[\text{um}]) \sim \mu\text{m}; r_{\text{max}} = \text{eval}(\text{gop.rmaxall}/1[\text{um}]) \sim \mu\text{m} \quad \backslash \text{ Centroid: } [x,y] = [\text{eval}(\text{gop.qavex}), \text{eval}(\text{gop.qavey})] \text{ mm}.$$
- 3 Locate the Position section. In the Y text field, type `gop.qavey-1.5*gop.rmaxall`.
- 4 Locate the Advanced section. In the Expression precision text field, type 3.
- 5 Locate the Coloring and Style section. From the Anchor point list, choose Lower middle.
- 6 On the Spot Diagram toolbar, click Plot .
- 7 Click Zoom Extents  in the window toolbar. Compare the resulting image to first figure below.

As noted, the color expression indicates the location of the ray at the entrance pupil. This complements the ray diagrams above.

The same study is repeated with the field angle parameter set to `theta_x = 10[deg]`. The results can be seen in the second figure below. As with the ray diagram, the use of a custom color expression makes it possible to discern which rays contribute most to the overall spot size.

