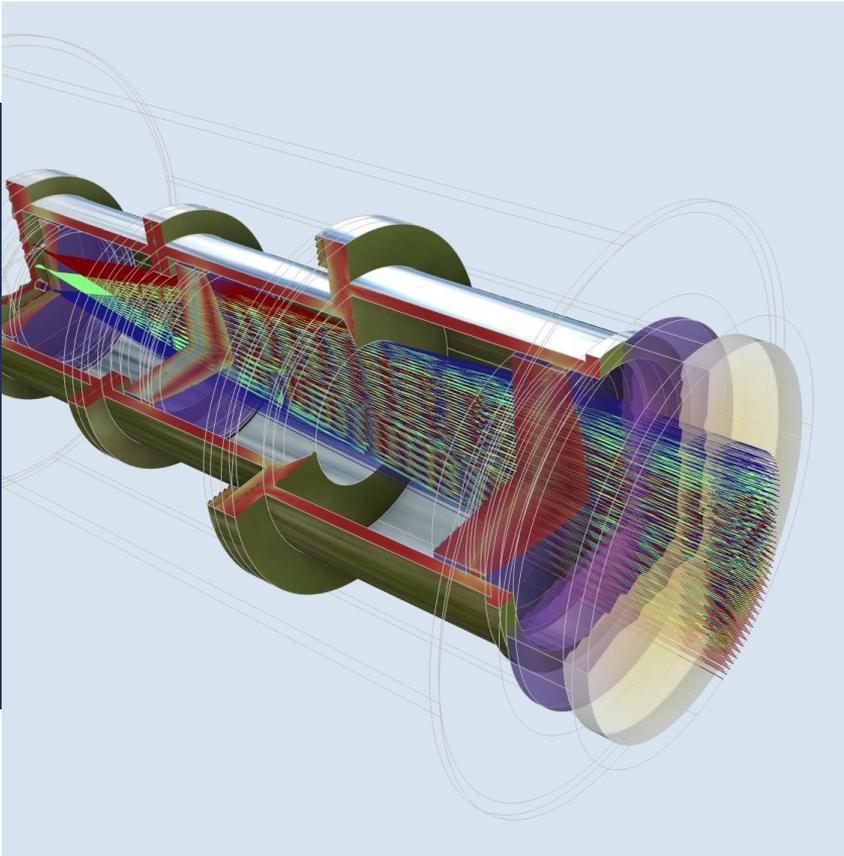


STOP Analysis

Linus Andersson

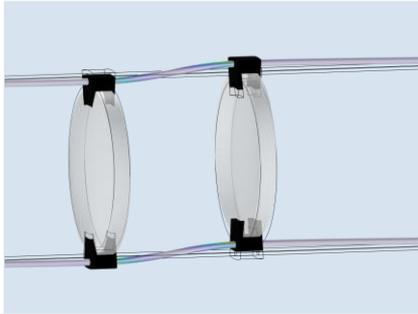
COMSOL



STOP Analysis

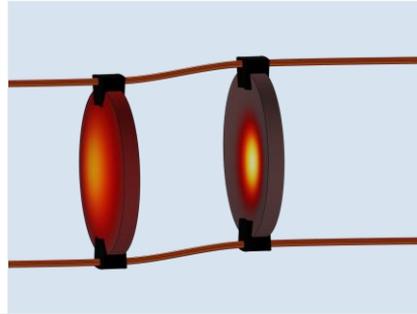
From cellphone cameras to space telescopes, optical systems are regularly subjected to varying temperatures and structural stress. With structural-thermal-optical performance (STOP) analysis, you can find out how these conditions affect their operation. In COMSOL[®], all parts of a STOP analysis can be included in a single self-contained model.

STOP Analysis in COMSOL®



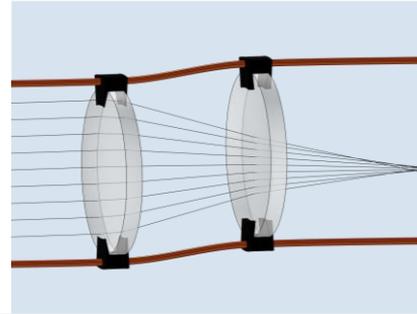
Structural

Model the structural displacements in an optical system.



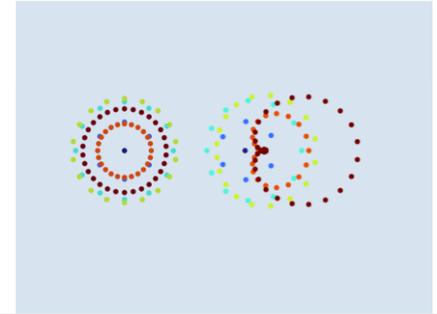
Thermal

Apply a fixed operating temperature or simulate the temperature distribution. Heat sources may include absorption from the beam itself.



Optical

With the local temperature and displacement considered, model how light will propagate through the system.



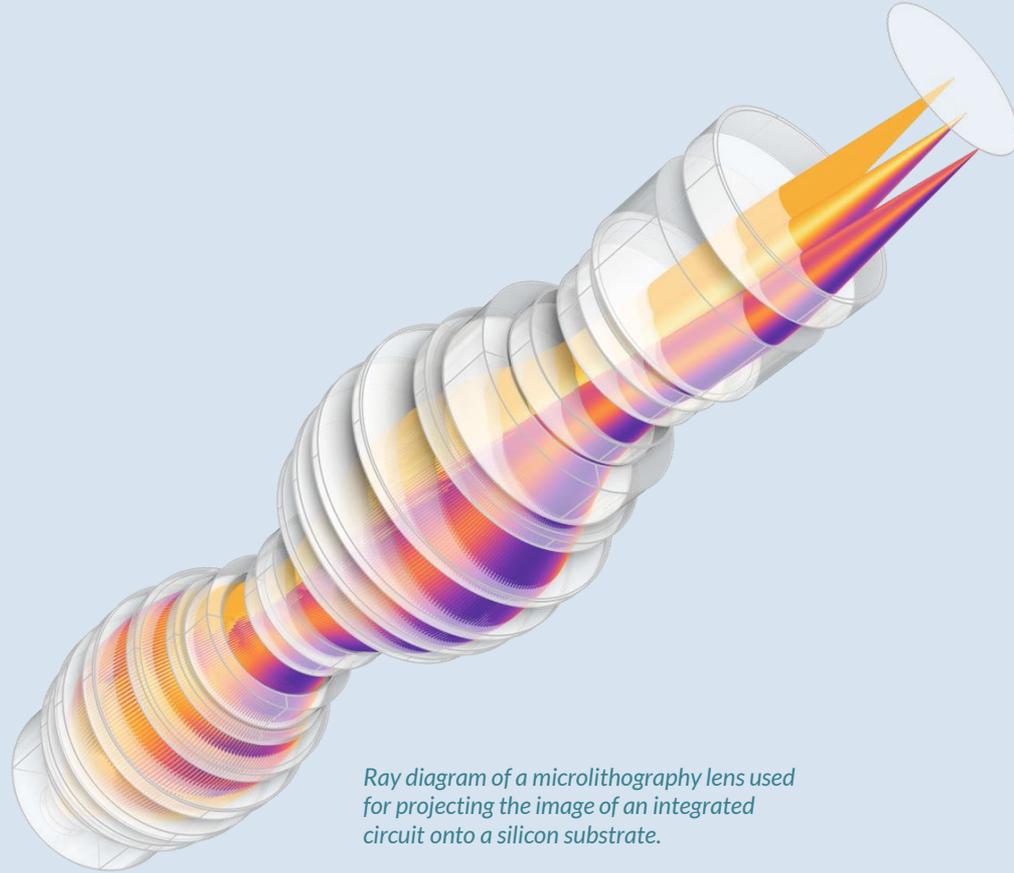
Performance

Evaluate the optical performance under the influence of thermal and structural loads.

OVERVIEW

Geometrical Optics

- Ray tracing in homogeneous and graded media
- Detailed analysis of ray intensity and polarization
- Variety of features for releasing rays and controlling interaction with boundaries
- Functionality for multiscale electromagnetics modeling
- Multiphysics couplings for STOP analysis



Ray diagram of a microlithography lens used for projecting the image of an integrated circuit onto a silicon substrate.

Ray Optics Module Part Library

The Ray Optics Module Part Library contains parameterized geometry parts for optical systems:

- Apertures and obstructions
- Aspheric, cylindrical, doublet, triplet, and spherical lenses
- Beam splitters and prisms
- Mirrors and reflectors

The parts include predefined selections for convenient set up of boundary conditions

The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, Results, and Developer. The main workspace is divided into three panes: Model Builder, Settings, and Graphics.

Model Builder: Shows a hierarchical tree structure for the model 'double_gauss_lens.mph'. The 'Double Gauss Lens' part is selected, showing its sub-components: Lens 1 (pi1), Lens 2 (pi2), Lens 3 (pi3), Stop (pi4), Lens 4 (pi5), Lens 5 (pi6), Lens 6 (pi7), Image (pi8), Form Union (fin), and Cumulative Selections.

Settings: The 'Part Instance' section shows 'Spherical Lens 3D' selected. The 'Input Parameters' table is displayed below:

Name	Expression	Value	Description
R1	R1_3	0 m	Radius of cu
R2	R2_3	25.65 mm	Radius of cu
Tc	Tc_3	2 mm	Center thick
d0	d0_3	51 mm	Lens full dia
d1	d1_3	0 m	Diameter, su
d2	d2_3	40 mm	Diameter, su
d1_clear	d1_clear_3	49 mm	Clear aperu
d2_clear	d2_clear_3	39 mm	Clear aperu
nix	0	0	Local optica
niy	0	0	Local optica
niz	1	1	Local optica
n_extra_r	0	0	Number of i
n_extra_a	0	0	Number of i

The 'Position and Orientation of Output' section shows the work plane set to 'xy-plane' and 'Surface 2 vertex intersec'.

Graphics: Shows a 3D rendering of a doublet lens system, consisting of two spherical lenses. A coordinate system (x, y, z) is visible at the bottom left of the graphics pane.

Optical Material Library

The Optical Material Library has more than 1200 materials, e.g., optical adhesives, antireflective coating materials, glasses, and more.

Glasses in the Optical material library include structural and thermal properties as well as temperature-dependent refractive index and dispersion models.

The screenshot shows the COMSOL Material Browser interface. The left pane displays a tree view of the Optical Material Library, with 'Schott F2 Glass' selected. The right pane shows the material's properties, including phase, orientation, and a table of physical properties.

Material: Schott F2 Glass

Phase:

Orientation/variation:

Properties

Property	Expression	Unit	Pr
Density	3.6[g/cm ³]	kg/m ³	
Heat capacity at constant pressure	0.557[J/(g*K)]	J/(kg*K)	
Thermal conductivity	0.78[W/(m*K)]	W/(m*K)	
Coefficient of thermal expansion	8.2E-6[1/K]	1/K	
Sellmeier dispersion coefficients	{1.3453359E+00, 2.09073176E-01, 9.37...		S...
Reference temperature	22[degC]	K	S...
Reference pressure	1[atm]	Pa	S...
Schott thermo-optic dispersion coeff...	{1.51E-6, 1.56E-8, -2.78E-11, 9.34E-7, 1...		S...
Reference temperature	20[degC]	K	S...
Young's modulus	57.0[GPa]	Pa	Y...
Poisson's ratio	0.22		Y...
Internal transmittance, 10 mm sampl...	tau10(c_const/freq)	1	I...
Internal transmittance, 25 mm sampl...	tau125(c_const/freq)	1	I...

Property reference:
Select a property in the list above to display its reference.

Inputs

Input	Variable	Unit
Frequency	freq	1/s

The screenshot shows the COMSOL Model Builder interface. On the left is the 'Model Builder' tree, and on the right is the 'Settings' panel for 'Medium Properties'.

Model Builder Tree:

- double_gauss_lens.mph (root)
 - Global Definitions
 - Parameters 1: Lens Prescription
 - Parameters 2: General
 - Geometry Parts
 - Default Model Inputs
 - Materials
 - Component 1 (comp 1)
 - Definitions
 - Double Gauss Lens
 - Materials
 - Ohara S-LAM 3 Glass (mat1)
 - Ohara S-BAH11 Glass (mat2)
 - Schott N-SF5 Glass (mat3)
 - Geometrical Optics (gap)
 - Medium Properties 1
 - Material Discontinuity 1
 - Ray Properties 1
 - Release from Grid 1
 - Obstructions
 - Stop
 - Image
 - Equation View
 - Mesh 1
 - Study 1
 - Step 1: Ray Tracing
 - Solver Configurations
 - Job Configurations
 - Results
 - Datasets
 - Views
 - Derived Values
 - Tables
 - Ray Diagram 1
 - Ray Diagram 2
 - Spot Diagram
 - Optical Aberration Diagram
 - Optical Aberration 1
 - Optical Aberration 2

Settings

Medium Properties

Label: Medium Properties 1

Domain Selection

Override and Contribution

Equation

Model Inputs

Temperature:

T User defined

42[degC]

Medium Properties

Refractive index of domains:

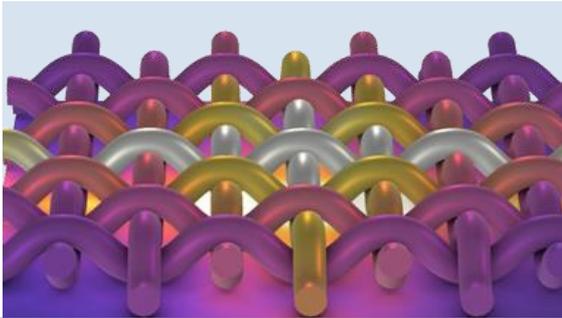
Get dispersion model from material

Temperature Dependency

- To use a temperature-dependent refractive index from a glass in the Model Library at a fixed temperature, simply enter the temperature. The dispersion relation from the material will control both the wavelength dependence and the temperature dependence of the refractive index.
- To use your own material data, pick from a list of dispersion types, enter the refractive index as an arbitrary function of the temperature, or interpolate from a text file with refractive index versus temperature data.
- In a STOP analysis, the modeled local temperature will automatically be fed into the dispersion relation.

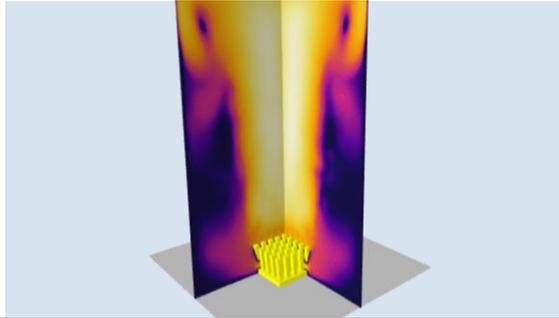
OVERVIEW

Heat Transfer Functionality



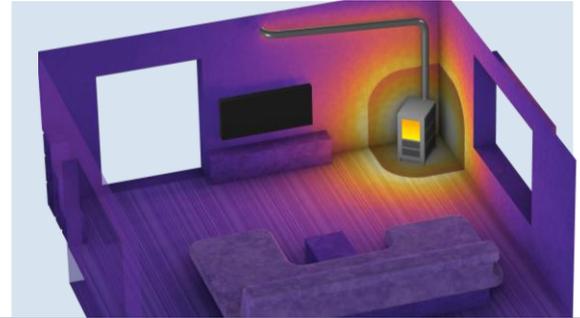
Conduction

- Isotropic, anisotropic, linear, and nonlinear thermal conductivity
- Thermal contact
- Thin layers



Convection

- Free and forced convection
- Laminar and turbulent flow
- Effective material properties



Radiation

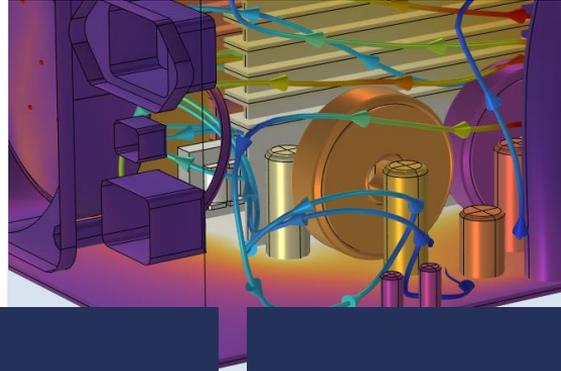
- Surface-to-ambient and surface-to-surface radiation
- External radiation sources
- Radiation in participating media

Heat Transfer Modeling in Ray Optics



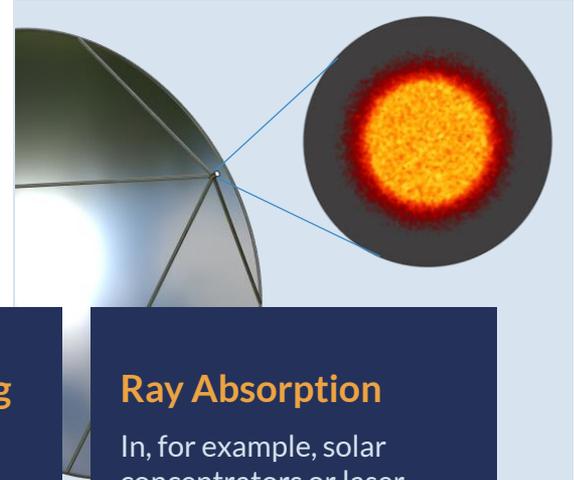
Thermal Radiation

Model radiation from distant sources, such as the Sun, or radiative heat exchange between optical components



Convective Cooling

Model passive or active convective cooling, removing excess heat from the optical system, including its power supply and connected electronics



Ray Absorption

In, for example, solar concentrators or laser focusing systems, find the absorbed power from the rays, and the resulting temperature increase

EXAMPLE

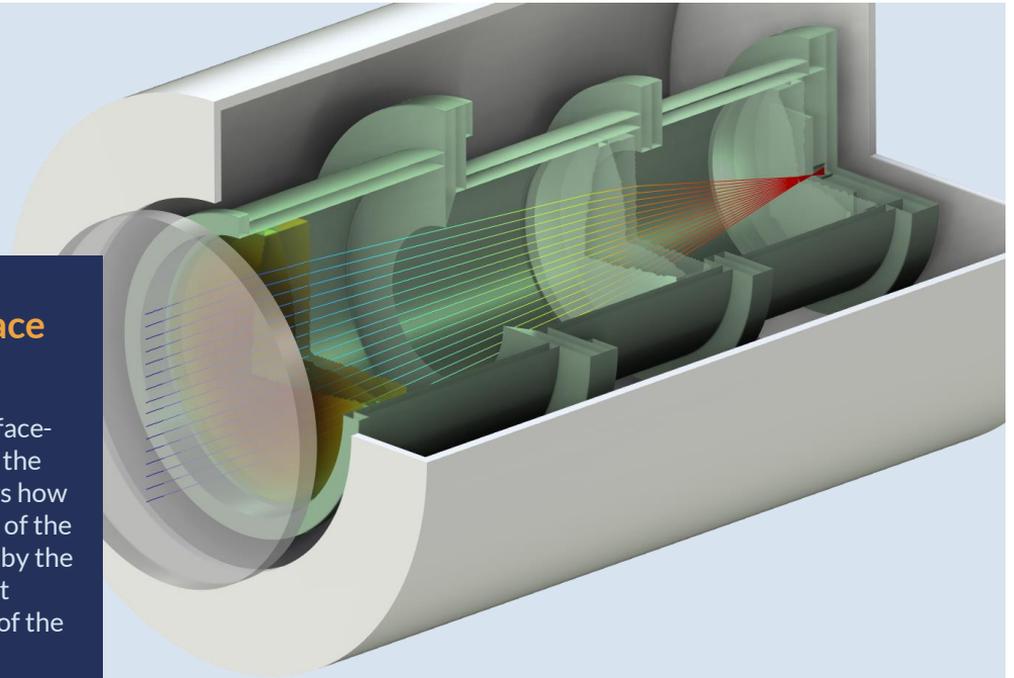
Radiative Heat Transfer in a Lens System

Lens Assembly in Thermal Shroud

This Petzval lens assembly is placed in a thermal shroud at a constant low temperature, inside a vacuum chamber. Heat radiating in through the thermal window primarily affects the first lens.

Surface-to-Surface Radiation

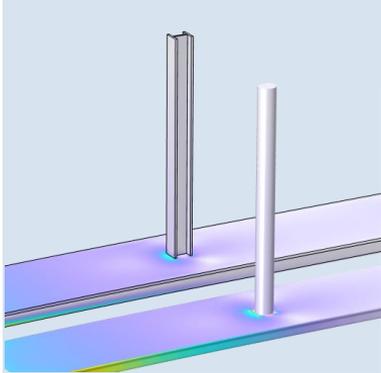
The model features surface-to-surface radiation for the heat transfer, and shows how the location and quality of the focal point are affected by the temperature-dependent glass refractive indices of the glasses.



Ray diagram and temperature distribution in the lenses and the surrounding barrel.

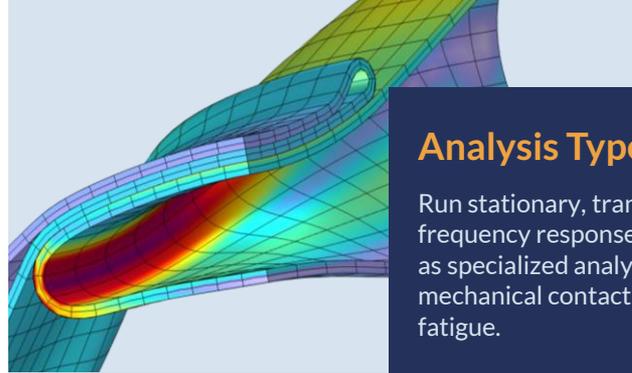
OVERVIEW

Structural Mechanics Functionality



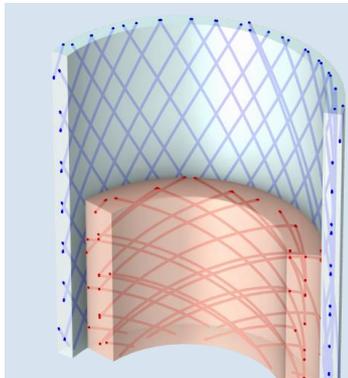
Formulations

Combine solids, single and layered shells, plates, membranes, beams, pipes, trusses, and wires.



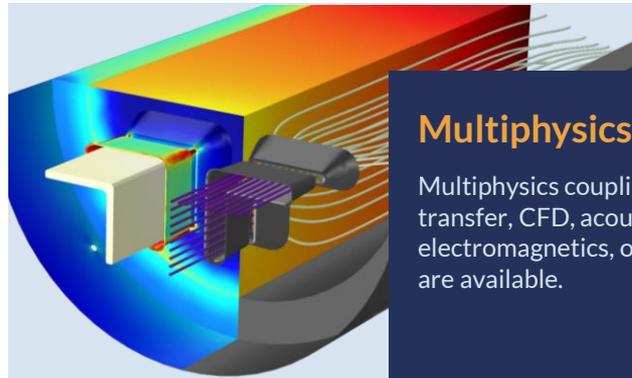
Analysis Types

Run stationary, transient, and frequency response analyses, as well as specialized analyses such as mechanical contact, buckling, and fatigue.



Material Models

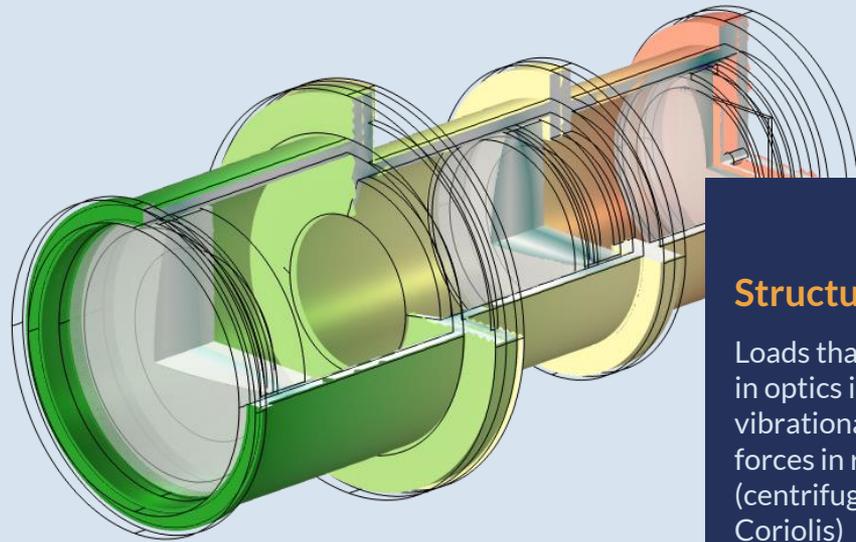
Choose from a wide variety of elastic, viscoelastic, hyperelastic, elastoplastic, and composite material models. Materials can be spatially varying, anisotropic, and dependent on other variables.



Multiphysics

Multiphysics couplings with heat transfer, CFD, acoustics, electromagnetics, optics, and more are available.

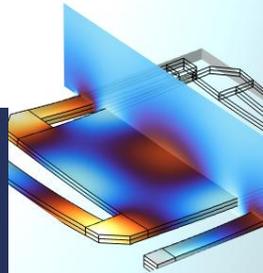
Structural Mechanics Modeling in Optics



Structural Loads

Loads that are often useful in optics include gravity, vibrational loads, and forces in rotating frames (centrifugal, Euler, Coriolis)

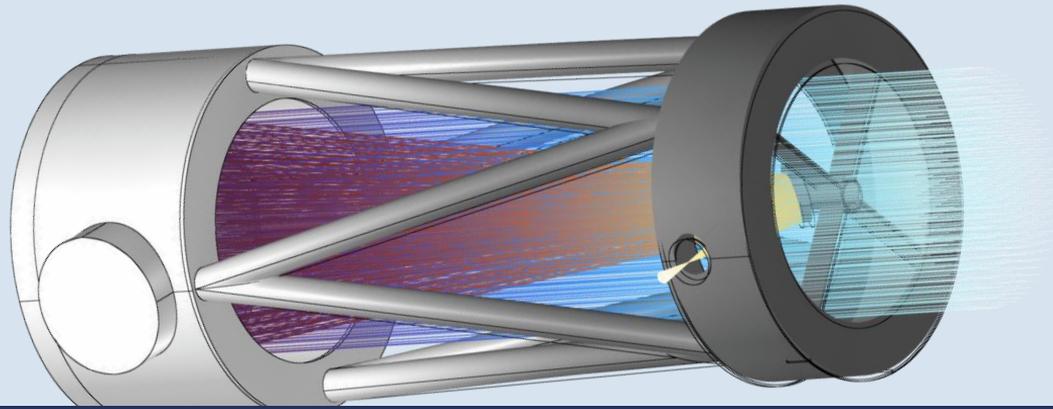
Displacements and stresses in a Petzval lens with hyperelastic supports.



Material Models

Piezoelectricity for microactuators, nonlinear material models for mounts, translating and rotating rigid body materials

Vibrating micromirror with prestress and viscous damping.



Settings

Ray Tracing

Compute Update Solution

Label: Ray Tracing

Study Settings

Time-step specification: Specify time steps

Time unit: ns

Output times: range(0,0.1,10) ns

Tolerance: Physics controlled

Stop condition: None

Include geometric nonlinearity

Results While Solving

Physics and Variables Selection

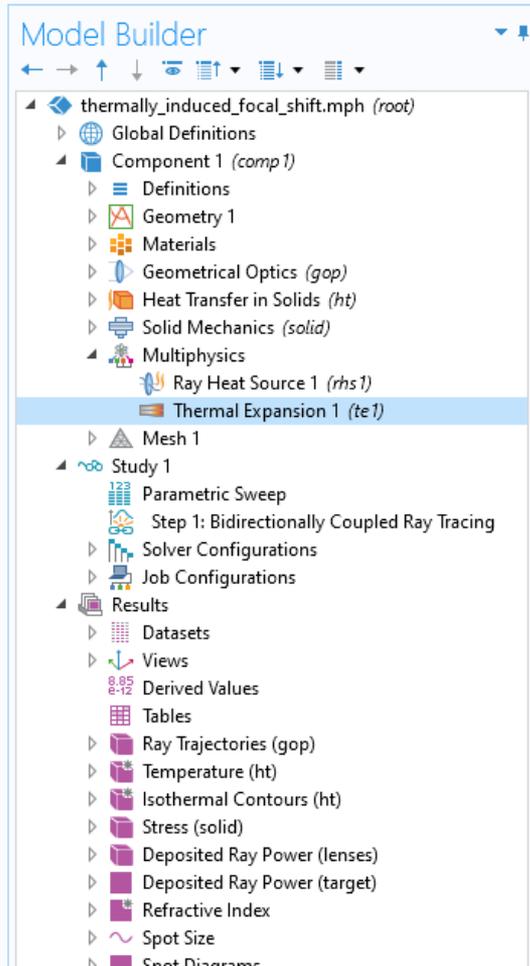
Modify model configuration for study step

Physics interface	Solve for	Equation form
<input checked="" type="checkbox"/> Geometrical Optics (g...)	<input checked="" type="checkbox"/>	Automatic (Time...)
<input type="checkbox"/> Solid Mechanics (solid)	<input type="checkbox"/>	Automatic (Stati...)

EXAMPLE

Gravitational Analysis of a Telescope

In this model of a Newtonian telescope, a structural mechanics study computes the deformations under gravity. The *Include geometric nonlinearity* check box in the subsequent ray tracing study ensures that it is run in the deformed geometry.



BRINGING IT TOGETHER

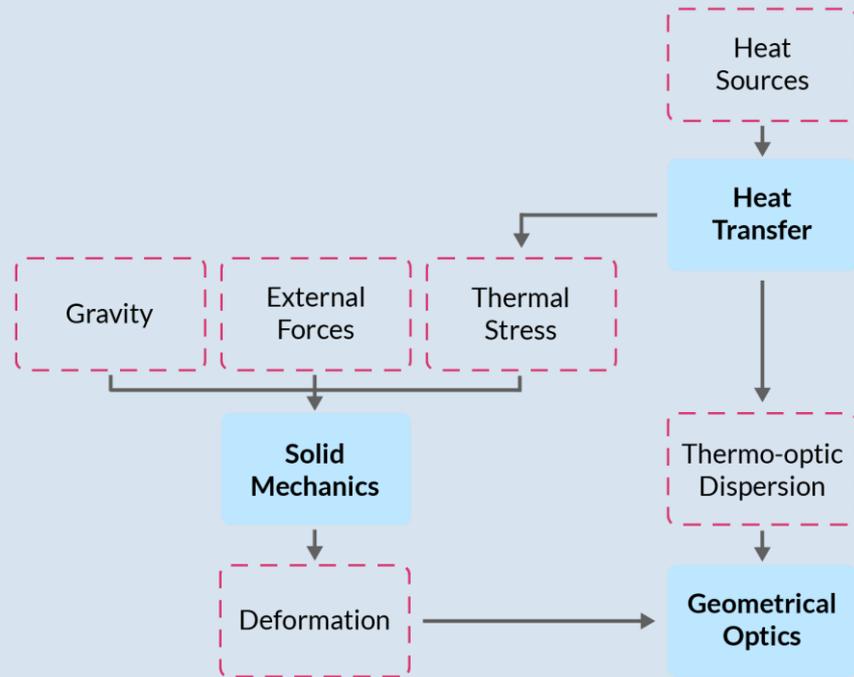
Thermal Expansion

Thermal expansion is readily available as a multiphysics coupling. The glasses in the Optical material library include thermal expansion coefficients, and many of them also come with complete elastic and thermal material properties.

BRINGING IT TOGETHER

STOP Analysis

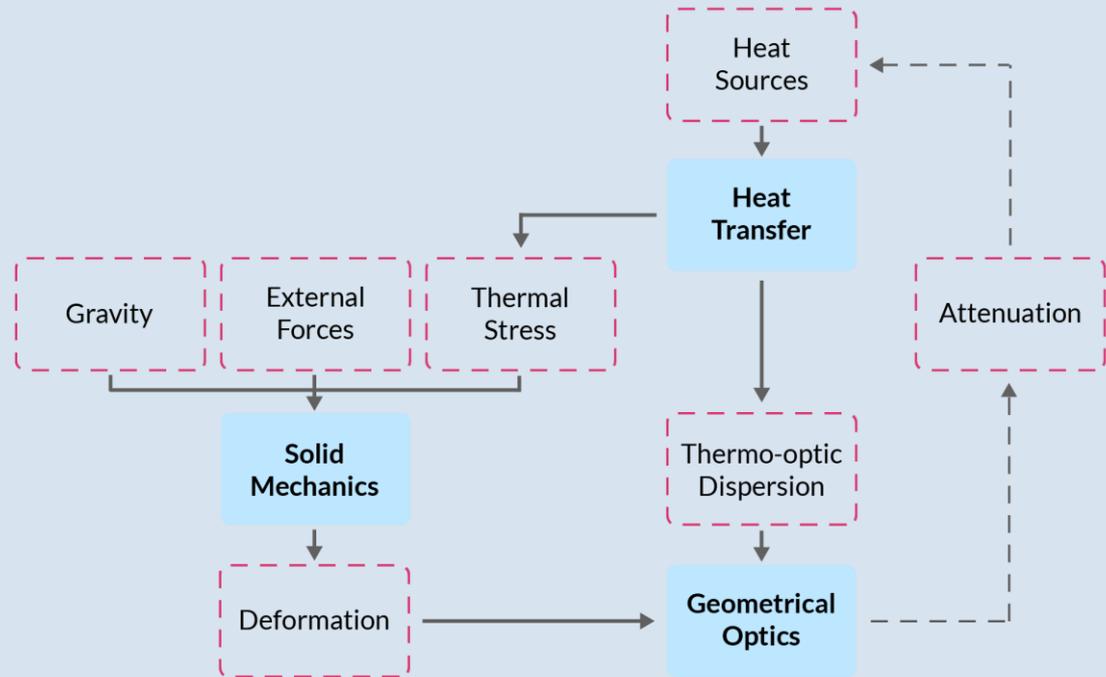
The flowchart shows how the structural and thermal effects come together and affect the rays in a one-way coupled STOP analysis.



BRINGING IT TOGETHER

STOP Analysis

The flowchart shows how the structural and thermal effects come together and affect the rays in a one-way coupled STOP analysis.



Study Setup

The screenshot shows the Model Builder tree for a study named "thermally_induced_focal_shift.mph (root)". The tree structure is as follows:

- thermally_induced_focal_shift.mph (root)
 - Global Definitions
 - Parameters 1
 - Geometry Parts
 - Default Model Inputs
 - Materials
 - Component 1 (comp 1)
 - Definitions
 - Geometry 1
 - Materials
 - Geometrical Optics (gap)
 - Heat Transfer in Solids (ht)
 - Solid Mechanics (solid)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Step 1: Heat Transfer in Solids
 - Step 2: Solid Mechanics
 - Step 3: Geometrical Optics
 - Solver Configurations
 - Job Configurations

One-Way Coupled STOP Analysis

With the temperatures affecting the deformations, and both temperatures and deformations influencing the ray paths, you can solve for the different physics interfaces one at a time.

The screenshot shows the Model Builder tree for a study named "thermally_induced_focal_shift.mph (root)". The tree structure is as follows:

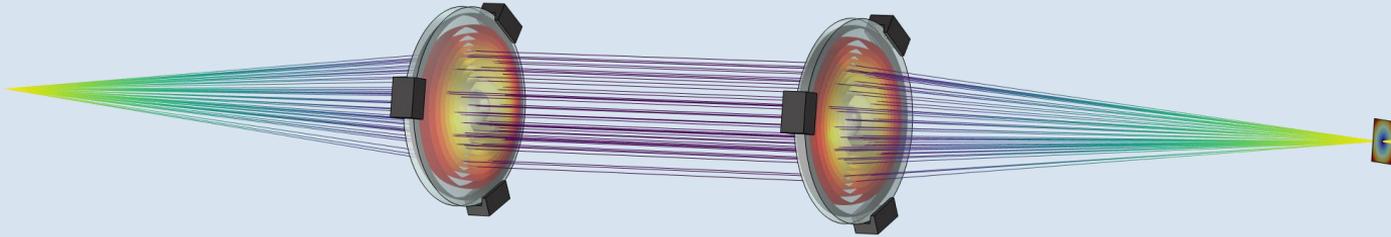
- thermally_induced_focal_shift.mph (root)
 - Global Definitions
 - Parameters 1
 - Geometry Parts
 - Default Model Inputs
 - Materials
 - Component 1 (comp 1)
 - Definitions
 - Geometry 1
 - Materials
 - Geometrical Optics (gap)
 - Heat Transfer in Solids (ht)
 - Solid Mechanics (solid)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Parametric Sweep
 - Step 1: Bidirectionally Coupled Ray Tracing
 - Solver Configurations
 - Job Configurations
 - Results

STOP Analysis with Ray Heating

The dedicated *Bidirectionally Coupled Ray Tracing* study type, along with the *Ray Heat Source* feature, will automatically follow the iteration scheme in the previous slide.

DEMO

Thermally Induced Focal Shift



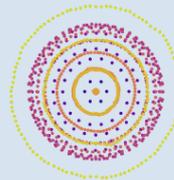
Double Lens System

In this demo model, a high-powered laser is sent through two lenses, focusing after the second one. The laser is strong enough to significantly heat up the lenses.

STOP Analysis

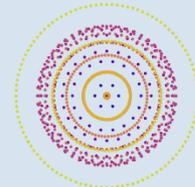
Use a bidirectionally coupled ray tracing study to see how the heat absorption changes the refractive index and deforms the lenses, thereby affecting the ray paths.

$$r_{rms} = 67.4 \mu\text{m}$$



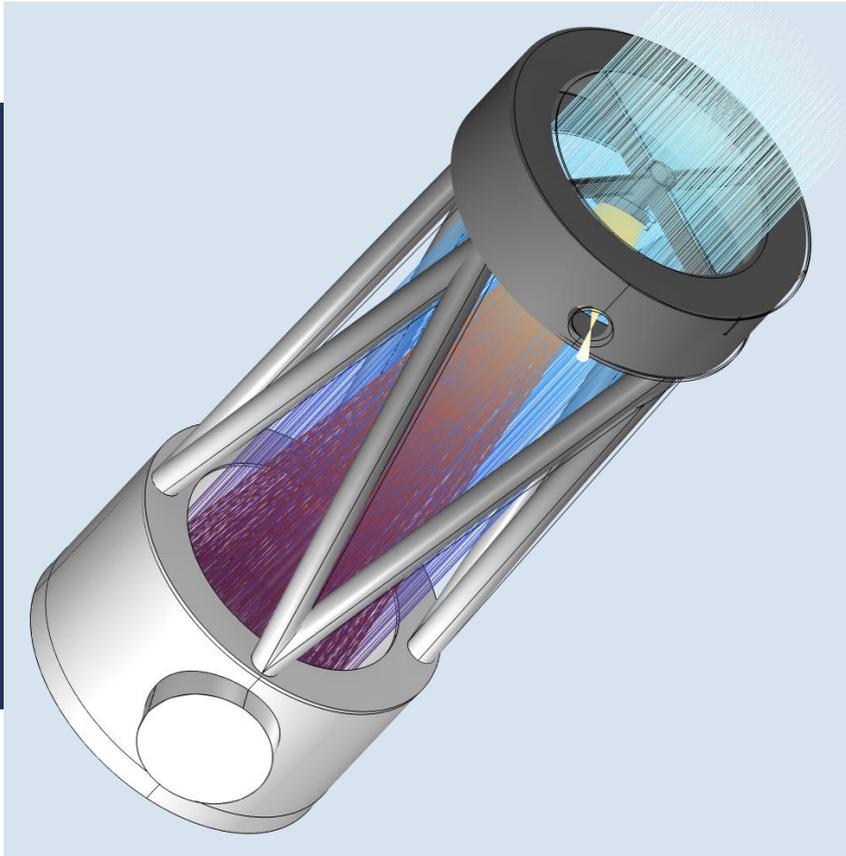
$$y_c = 204.2 \text{ mm}$$

$$r_{rms} = 76.6 \mu\text{m}$$



$$y_c = 206.5 \text{ mm}$$

Spot diagram, focal coordinates, and RMS radius of an undeformed (left) and deformed (right) system.



SUMMARY

Advantages

COMSOL Multiphysics® has unique capabilities for modeling all aspects of STOP analysis in a single software environment. A meshed formulation in lenses allows for continuously varying refractive indices, while a mesh-free formulation in air and vacuum makes it trivial to include the effects of structural deformations on the ray paths. Extensive libraries of optical components and materials with temperature and dispersion relations make setting up a model robust and convenient.

CONCLUDING REMARKS

STOP Analysis in COMSOL®

The COMSOL® software features a wide range of capabilities for modeling ray optics, heat transfer, structural mechanics, and the interaction between them. It provides unique functionality for fully self-consistent STOP analysis.

