Tutorial 1:

How to compute thermal lensing for a laser cavity with end pumped rod?

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The project file Tutorial_1.lcd of the example used with this tutorial can be found in the directory "Tutorials" on the CD-ROM or after installation of LASCAD in the sub-directory "Tutorials" of the LASCAD application directory. You can copy this file to a working directory, and start it by double-click.
1. **Starting LASCAD and Defining a Simple Laser Cavity**

- Start LASCAD by selecting Start/Programs/LASCAD/Lascad,
- Define a working directory,
- Click "OK" to open the LASCAD main window,
- Press the "New Project" button on the toolbar (leftmost button) or use the menu item "File",
- Increase the "Number of Face Elements" to 4,
- Enter the appropriate wavelength, and leave the other default settings unchanged,
- Click "OK".

Now you can see the LASCAD main menu at the top and two other windows below, one titled **"Standing Wave Resonator"**, and the other titled **"Parameter Field"** as shown Fig. 1. The upper window shows the mode plot of a simple cavity with four elements, the lower window shows the parameters of the cavity. In the column below the element number the parameters belonging to this element are shown, for instance the radius of curvature of each mirror is shown in the row labeled **"Type-Param."** To change the element type use the drop-down boxes im-

![Fig. 1](image_url)
mediately below the element number. You can select from Mirror, Dielectric Interface, and Lens. The parameters of the columns between the element numbers define the properties of the space between the elements for instance the refractive index, or the "Refractive Parameter" which corresponds to the second derivative of a parabolic refractive index distribution. Information about additional functionalities of these windows for instance "How to insert or clear an element?" can be found in section 3, the Quick Tour or in the manual.

2. Defining and Analyzing an End Pumped Rod

2.1. Selecting crystal type and pump configuration

Click "FEA/Parameter Input & Start of FEA Code" in the main LASCAD window to open the window titled "Crystal, Pump Beam and Materials Parameters", as shown in Fig. 2. Note the six tabs for defining various groups of parameters.

The tab labeled "Models" allows selecting from a list of different crystal and pump configurations. Default setting is "(Dual) end pumped cylindrical rod".

![Fig. 2](image-url)
At the bottom of this window the dimensions of the rod can be defined. For this example, we entered a rod length of 6 mm and a rod diameter of 2 mm, as shown in Fig. 2.

**2.2. Defining the pump light distribution**

Select the tab labeled "**Pump Light**" to open the window shown in Fig. 3.

![Fig. 3](image)

The entries allow approximating the pump light distribution by the use of super-gaussian functions. Super-gaussian function means that the expression used to describe the pump light distribution has the mathematical form of a gaussian distribution but with an exponent that may be different from 2. A super-gaussian function approaches a top hat distribution with increasing exponent. The LASCAD manual is describing this in more detail.

The input boxes within the frame "**Incident pump power, W**" can be used to define the power of two pump beams impinging on the left and or the right end of the crystal, respectively.

Commonly, beams used for end pumping are focused into the rod. The entries "**Spot size at beam waist**", "**Distance of waist from left end face**" and "**Beam divergence**" allow for specifying the related quantities.
If you click into the box labeled "From the right end" you can enter the parameters of the beam coming from the right end.

To see the effect of the "Super-gaussian exponent":

- check the option "x-y-symmetry",
- pull down the box "Super-gaussian exponent" in the y-plane panel, and select for instance 10,
- press the button "Show Pump Light Distribution" (at the bottom right).

The window "Pump Beam Profile" is opened as shown in Fig. 4.

According to the entries for the super-gaussian exponent, the beam profile along x-axis has a common gaussian shape, whereas the profile along y-axis approaches a top hat distribution. Moving the slider, arranged below the plot, from left to right you can see how the absorbed pump power density decreases due to absorption. Click into the plot to rescale the graph to full height.

**Fig. 4**
2.3. *Defining cooling of the rod*

Select the tab labeled *"Boundaries"* to open the window shown in Fig. 5. The entries allow defining cooling conditions individually for each surface of the rod.

You can define cooling by solid and fluid contact. For the latter check additionally the box *"Fluid Cooling"*.

In the first case the surface is kept on constant temperature which is defined by the value in the box *"Temperature, K"*, in second case the latter value defines the bulk temperature of the fluid. In the case of fluid cooling additionally a film coefficient, which describes the heat transfer through the interface solid-fluid, must be defined (bottom row). Section 6.10.3 of the LASCAD manual describes this in more detail.

The entry *"Reference temperature"* is used with computation of deformation and corresponds to the crystal temperature before heating. When boundary temperatures are defined in Kelvin it is important to enter the correct value here.

![Fig. 5](image-url)
2.4. Defining material parameters

Select the tab labeled "Material Param." to open the window shown in Fig. 6. The entries are almost self-explaining.

The absorption coefficient describes the exponential attenuation of the pump beam according to \( I = I_0 \exp(-\alpha z) \) due to absorption of the pump photons; it depends on the doping level of the crystal. For nonisotropic crystals the absorption of the pump light can depend on the polarization of the pump light. In this case the absorption coefficients can be defined for two independent polarization directions. Details are described in the appendix of the manual. For Nd:YAG just enter identical values into the related boxes.

In addition, more sophisticated issues can be defined like temperature dependent material parameters or solids composed of two different materials as described in the manual.

You can save the material parameters to a file and use them later with a new project.

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**Fig. 6**
2.5. Defining composite material

Select the tab labeled "Doping & Mats." to open the window shown in Fig. 7. In the present example we use the entries to define a rod with undoped end-caps: Pumped region extends [mm]

\[
\begin{align*}
 \text{from } z &= 1.0 \text{ to } z = 5.0 \\
\end{align*}
\]

means, that pump light is absorbed only within a doped region \(1 \leq z \leq 5\) mm. Since in our example the crystal is 6 mm long, we are defining in this way two undoped end-caps of 1 mm length.

![Fig. 7](image)

The appearance of this tab depends on options selected in the tab "Material Param."

2.6. Defining options to control the FEA computational procedure

Select the tab labeled "FEA Options" to open the window shown in Fig. 8.

The FEA code uses a regular rectangular mesh inside the crystal which is connected to the boundaries of the crystal by small irregular elements. "Mesh size in x- and y-direction" means the edge length of the voxels perpendicular to the crystal axis. "Mesh size in z-direction" means the edge length of the voxels along the crystal axis.

Press "Estimated number of elements" to get information concerning the RAM memory needed to run the computation. The following rule of thumb can be used: If you have \(n\) elements, you should have more than \(2n/1000\) MB RAM memory in your computer, otherwise the program becomes very slow due to swapping data to the hard disk. (You can use the Windows Task-manager to determine the amount of free RAM currently available: Press Ctrl-Alt-Del with systems WinNT/2k/XP and select Task-manager from the window popping up. Open the Tab "System Performance". The row "available" in the box "Physical Memory" displays the currently available RAM in kilobytes.)

The entries for "Convergence limits" control the convergence of the iterative computational procedure. The default value 1.0E-7 for the thermal analysis stops the code if the temperature maximum does not change within the first 7 digits. The limit for the structural analysis refers to the absolute value of maximum nodal displacement.
Regardless of the convergence limits, the iteration process is stopped, if the number of iterations exceeds the numbers entered in "Maximum number of iterations".

The input box "Directory for output of FEA results" can be used to define a directory where the files created by the FEA code are stored. Default setting is the subdirectory FEA of the Working Directory.

The input box "Position of cutting plane perpendicular to z-axis" allows placing a cutting plane perpendicular to the z-axis to show the distribution of physical quantities inside the crystal with the 3D Visualizer as described in the next section. If the entry into this control is zero, a cutting plane along the rod axis and perpendicular to the y-axis is used. If the entry is greater than zero and smaller than the rod length, a cutting plane perpendicular to the rod axis is used. If the entry is greater than the rod length, the full crystal is shown.

Use the button "Apply and run FEA" to transfer the input data to internal variables and to start the FEA code. The window "Finite Element Analysis" is popping up showing the number of the currently running iteration. In addition, it
shows the maximum temperature during thermal analysis, and the absolute value of maximum nodal displacement during structural analysis. At the end of the computation the message "**FEA finished successfully**" appears, press the "**OK**" button to close the dialog.

Please be aware that initialization of the FEA and generation of the mesh may take some time for large element numbers.

### 2.7. Visualizing results of the FEA

LASCAD provides two tools to visualize the FEA results data.

#### 2.7.1. 3D Visualizer

To show 3D plots of the FEA results click "**FEA/3D Visualizer**" in the main LASCAD menu. It opens an easy to handle 3D Visualizer based on OpenGL. As an example a 3D temperature plot is shown in Fig. 9. Since undoped end-caps have been defined in section 2.5 the rise of the temperature is confined to the inner region of the rod.

![3D Visualizer](image_url)
2.7.2. 2D Data Profiles and Parabolic Fit

Alternatively it is possible to show 2D data profiles at different positions along the z-axis. Click the item "FEA/2D Data Profiles and Parabolic Fit" in the main LASCAD menu to use this second tool.

A dialog pops up, where you can select the directory containing the FEA results data. Keep the default setting, and press the button "Open Fit Window".

The window "2D Data Profiles and Parabolic Fit" is opened as shown in Fig. 10.

![Fig. 10](image_url)

The window displays transverse profiles of FEA results data. Use the drop-down box at the right upper corner of the window, and select a position along the crystal axis to show the transverse temperature profile at this position. The wheel of the mouse can be used to scroll to different positions. The available positions correspond to the mesh subdivisions created by the FEA. The drop-down box "Show Profile" in the frame "FEA Results" can be used to show profiles of other quantities for instance the pump light distribution.
2.8. Computing gaussian modes

To use the FEA results with the gaussian mode-algorithm the profiles of the temperature induced refractive index and of the deformation of the end faces of the crystal must be fitted parabolically transverse to the optical axis.

In advance, a "Range of Fit" has to be defined that depending on the expected spot size of the mode usually can be much smaller than the diameter of the crystal. We are using the default settings for the present example.

Press the button "Refresh & Fit" in the window "2D Data Profiles and ..." to carry through the parabolic fit which is shown in Fig. 11.

The red lines represent the parabolic curves, the blue lines the FEA results, respectively. The fit is being accomplished for all subsections along the crystal axis generated by the FEA meshing procedure. That means that the crystal is subdivided into a series of GRIN lenses each of them having its individual parabolic refractive index distribution. The left end face of the leftmost subsection coincides with the
left end face of the crystal, in the same way the right face of the rightmost subsection coincides with the right end face of the crystal. The deformation of these end faces is taken into account by fitting the radii of curvature to these astigmatic end faces.

Again you can use the drop-down box in the right upper corner of the window to show the fit at different positions along the z-axis. The parabolic coefficients obtained for each individual fit are shown in the frame "Parab. Coeff.". Additionally, they are written into the file FIT.dat, which is being stored to the FEA subdirectory.

2.9. Inserting the crystal into the mode plot

Press the ALT key and click into the mode plot for instance between element 1 and 2 to insert the crystal between these two face elements. A yellow element appears in the mode plot symbolizing the thermally lensing crystal. The face elements 1 and 2 have been converted into the left and right end face of the crystal, respectively; and their distance has been adjusted to the length of the crystal. To compute the mode shape, ABCD matrices for all FEA subsections and the deformed end face of the crystal are taken into account by fitting the radii of curvature to these astigmatic end faces.
faces of the crystal have been built by the use of the computed parabolic coefficients, and have been combined with the matrices of the end mirrors of the cavity. Then all matrices have been multiplied with each other to compute the full round-trip ABCD matrix that finally delivers the gaussian fundamental mode shape as shown in Fig. 12.

Notice, that several parameters in the window "Parameter Field" have been changed in comparison with Fig. 1.

3. Modifying cavity parameters

To modify parameters of a resonator configuration for instance the cavity shown in Fig. 12 many tools are provided in LASCAD.

You can shrink and stretch the plot by the use of the two arrows immediately below the mode plot.

You can click on the end mirrors and move them with the mouse.

Also the yellow symbol for the crystal can be moved with the mouse.

To insert an additional element press the SHIFT key and click into the mode plot at a position where you would like to insert the new element. The "Insert Element" window is popping up as shown in Fig. 13. The setup of this window corresponds to the "Parameter Field" window. For the sake of simplicity new face elements are inserted together with a new definition of the properties of the medium at the left-hand side of the new element. Use the entries to define the type of the element, focal distance or radius of curvature etc.

![Insert Element Window](image)

**Fig. 13**

To clear an element, position the mouse pointer over the element, press the CTRL key and then the left mouse button. Also the thermal lens can be cleared in this way.
The curvature of the end mirrors can be modified by changing the entries into the related boxes in the row "Type-Param." in the window "Parameter Field".

Another way to change parameters works as follows: click into one of the boxes in the window "Parameter Field" and then move the slider below the mode plot to change the related quantity as described in the manual and in the Quick Tour.

To investigate dependence of the thermal lensing effect on the pump power, proceed as follows: click the tab "Miscellaneous" in the window "Parameter Field" and enter a new value into the box "Pump power for rescaling" (not available with the demo version). All thermal effects will be linearly rescaled corresponding to the ratio between original pump power and the value entered for rescaling.

Additional tools are described in the LASCAD manual.

4. Tools to analyze the properties of a laser cavity

LASCAD provides several tools to analyze the properties of the cavity. Some of them are explained below in context with the present example.

4.1. Analyzing stability of a laser cavity

Click the menu item "Show Additional Items/Stability Diagram" in the mode plot window to open the window "Stability Diagram" as shown in Fig. 14.

![Stability Diagram](image)

Press the button "Plot g1*x g2*" to show the stability of the actual resonator configuration. A red cross symbol is being plotted whose position within the diagram is representing the stability of the cavity. After changing a cavity parameter, for instance the curvature of a mirror, press the button again to plot a second cross whose
position is showing the influence of the parameter modification on the stability of the cavity. You can continue in this way and plot a series of crosses; the color of the latest one always is red, that of the previously plotted crosses changes to blue.

An important issue is the dependence of the cavity stability on the pump power. To analyze this, rescale the pump power as described in section 3 (not available with the demo version).

Check the box "Show y-plane diagram" to additionally show the stability diagram for the y-plane mode.

Theoretical explanations for instance the definition of the generalized g-parameters can be found in the manual Sect. 6.5.

**4.2. Showing transverse gaussian mode profiles and their overlap with the pump profile**

Click the menu item "Show Additional Items/Transverse Gaussian Mode Profile" in the mode plot window to open the window "Gaussian Mode Profile" as shown in Fig. 15.

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**Fig. 15**

- 16 -
Click with the mouse into the vertical magenta colored bar at the right end of the mode plot window (see Fig. 1), and move it into the mode plot to see the transverse gaussian profile at the position of the bar.

If you move the bar over the crystal in addition to the mode profile the transverse pump light profile (blue line) is being shown to visualize the overlap between both profiles. By the use of the up-down arrow controls at the right lower corner of the window higher order transverse modes can be displayed allowing for estimating the probability of higher order modes being excited.

The different shape of the pump profile along x- and y-axis is caused by the different entries for the super-gaussian exponent in Fig. 3.

4.3. Computing the laser power output

Click the menu item "Laser Power" in the main LASCAD window, to open the window "Laser Power Output" as shown in Fig. 16.

Press the button "Apply & Plot" to compute the laser power output as a function of the incident pump power. At the end of this computation you are getting a warn-
ing concerning the mesh size, discard it for the moment. To adjust the plot to the
limits of the coordinate axes, press the button "Adjust Scale". To compute this
graph the thermal lensing effects are linearly rescaled as described in section 3,
"Modifying cavity parameters". The number of points computed can be adjusted,
by the use the up-down arrow control in the right upper corner of the window.
Select the option "Single Point" in the frame "Plot ... (Options)" to plot a single
point.
Select the option "Use output mirror reflectivity" in the frame "Define X-Axis
Variable" to plot the laser output power as a function of the output mirror reflect-
itivity.
Check the box "Multimode Operation" to plot the laser output power for multi-
mode operation. In this case the mode shape corresponding to the superposition of
several transverse modes is approximated by a top-hat shape whose width is ad-
justed to the width of the highest order transverse mode being excited. In doing so
the variation of the width of this mode along the cavity axis is taken into account.
For additional information see "Tutorial 2".
Pulsed operation is approximated by the use of rectangular pulses; check the box
"Pulsed Operation" to enter pulse duration and frequency.

5. **The Beam Propagation Code (BPM)**

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*Fig. 17*
Parabolic approximation and ABCD matrix code are not always sufficient. In these cases the FEA results can be alternatively used as input for a physical optics beam propagation code. This code provides full 3D simulation of the interaction of a propagating wave front with the hot, thermally deformed crystal, without using parabolic approximation. Here only a short instruction is given how to start the BPM code using default settings, for details the reader is referred to the manual.

Click "BPM/Run BPM" in the menu bar of the main LASCAD window to open a window with entries to control the execution of the BPM code as shown in Fig. 18.

![Beam Propagation Method](image)

**Fig. 18**

Leave the default settings of this window unchanged and press "Run BPM" to start the BPM code. Together with the BPM main window two graphics windows are opened. One of them is displaying the mode profile at the right end mirror as shown in Fig. 17, the other one the convergence of the beam radius with increasing cavity iteration as shown in Fig. 19. The scale "Cavity Iteration" is showing the number of full round trips of the wave front propagating forth and back between the mirrors. The large scale fluctuations are caused by interference of the fundamental mode with higher order transverse modes. Use the box "Enter Yrange" to adjust the vertical scaling of the plot.
The convergence limit shown in Fig. 19 is in good agreement with the mode spot sizes shown in Fig. 20 obtained by the use of the gaussian algorithm in combination with parabolic approximation as described above. Notice, that the spot sizes are different in x- and y-plane. This is a consequence of the strongly asymmetric pump light distribution as shown in Fig. 4 which is generating an astigmatic thermal lens. Fig. 19 is showing the spot size averaged with respect to the azimuth angle around the cavity axis.
Please refer to "Tutorial 2" for instructions, how to run the BPM code for multimode operation.