

# **SimuLase** Analyzer



[Version 1.5]

August 29, 2011

The following is a brief description of the functionality of **SimuLase\_Analyzer**<sup>TM</sup>.

All entries that are typed into any of the fields of **SimuLase\_Analyzer**<sup>TM</sup> have to be confirmed by hitting the enter key. Numerical entries have to be in the format *ABCD.EFG* using a decimal point if necessary. Large numbers can be entered using the format *A.BeN* for  $A.B \times 10^N$ .


You can download a demo-GainDatabase from our website to test all the tools of **SimuLase\_Analyzer**<sup>TM</sup>. There you can also download corresponding experimental PL-spectra for testing the 'PL-Analyzer'-tool.

To download this data go to '[www.nlcstr.com/SimuLaseDemo.htm](http://www.nlcstr.com/SimuLaseDemo.htm)'.

More details about the features of **SimuLase\_Analyzer**<sup>TM</sup> as well as the data- and file-format used within GainDatabases can be found in **SimuLase**<sup>TM</sup>'s main manual that can be downloaded from the above mentioned web page. There you can also check for updates to **SimuLase\_Analyzer**<sup>TM</sup>.

For questions or feedback regarding this product please contact [simulase@nlcstr.com](mailto:simulase@nlcstr.com).

# 1 Main GUI Components

The main GUI components are shown below. To load a gain database select 'File | Open Gain Database' or click the 'Folder' symbol, . Multiple GainDatabases can be loaded

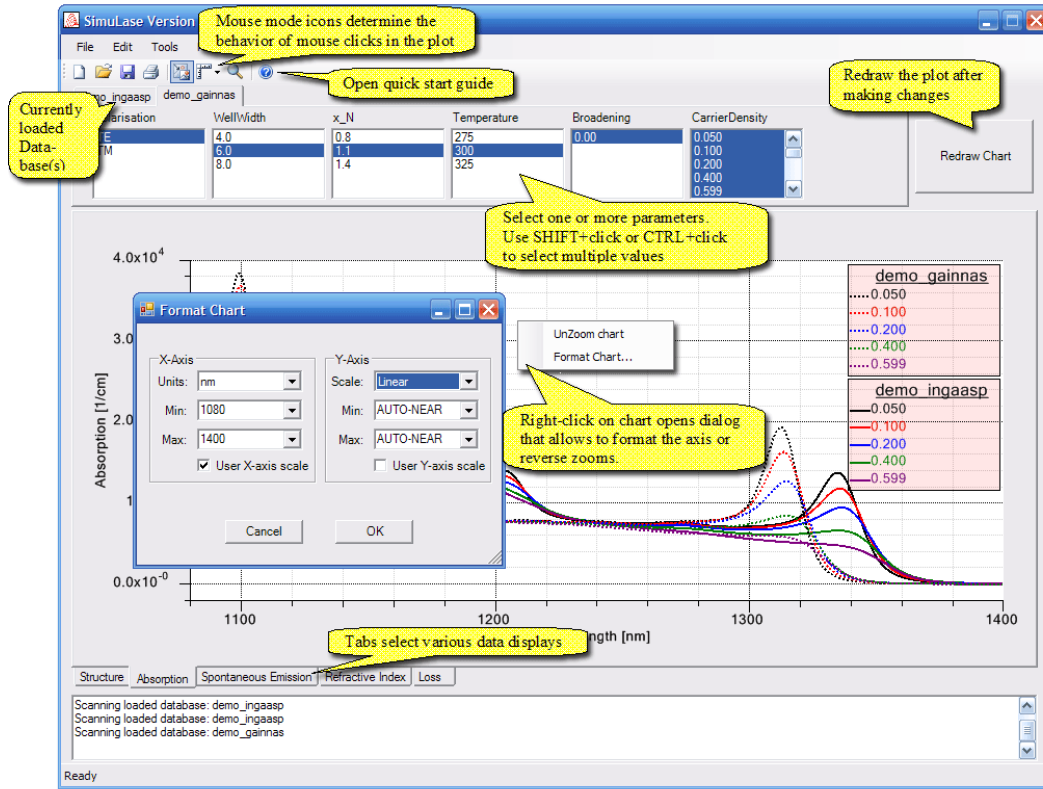


Figure 1: Overview of the main GUI panel.

and analyzed/compared at the same time.

By clicking on one of the tabs below the plot window, 'Spontaneous Emission', 'Refractive Index', 'Absorption', 'Losses', etc., the respective data are shown for the selected parameters (Polarization(s), Temperature(s), Shift(s), (inhomogeneous) Broadening(s) and Carrier Densities(s)). At least one entry has to be selected for each of these parameters to display data. To hide all data de-select all entries for at least one of the parameters. To de-select an entry use the 'control' key and click on the entry.

## 1.1 Formatting the Axes

The layout of the chart may be formatted by 'right-clicking' the mouse to display a pop-up menu. Selecting the 'Format Chart' option displays the dialog box shown as an insert in Fig.1. Use this dialog to format the X-axis units (electron Volts or nanometers), the Y-axis scale (Linear or Logarithmic) and the physical extents of each axis. **When changing numeral entries these have to be confirmed by hitting the 'enter' key.**


By default a chart will auto-scale the X and Y-axes so as to include all data points within the chart area and also present well-rounded major and minor tick mark spacing of the chart axes. Three auto-scale modes are provided:

'**AUTO-EXACT**' sets the Max and Min value of the axis to the **exact** Max and Min values in the displayed data sets.

'**AUTO-NEAR**' sets the Max and Min value of the axis to the next minor tick mark that encompasses displayed data sets.

'**AUTO-FAR**' sets the Max and Min value of the axis to the next major tick mark that encompasses displayed data sets.

The default auto-scale settings can be overridden by clicking the **User (X or Y)-axis scale** check box and entering specific values for upper and lower bounds.

Chart legends may be repositioned by clicking the  icon on the main toolbar and using the left button mouse to select and move the legend to a new location.

## 1.2 Exporting a GainDatabase for other Software

GainDatabases can be exported into a format that allows to import the data contained in them into other software products for further evaluation using '**File | Export Database as**' from the main menu. Currently, this option allows to export a database in a format that can be imported into Crosslight Inc.'s Lastip software. It also allows to produce reduced GainDatabases containing just subsets of the original database. For more info on this feature see the full manual.

## 1.3 Saving/Printing Chart Images

An image of the current chart (in \*.BMP, \*.JPG, \*.GIF, \*.TIFF or \*.PNG format) may be stored in a file by selecting '**File | Save as Image**' from the main menu.

High resolution print-outs are available by selecting '**File | Print**' from the main menu.

## 1.4 Exporting Data

The currently displayed data can be exported into ASCII-format data files by selecting '**File | Export Data**' from the main menu.

# 2 Potential, Wavefunction and Bandstructure Views

Two additional display options are added to the plot window tabs by selecting '**Tools | Band Structure Views**' from the menu bar. These tabs are '**Band Edge**' and '**Subbands**'. After choosing one or more values from the selection fields '**Temperature**', '**Carrier Density**', etc., one obtains a view of the band edge (confinement potential) diagram after clicking the '**Band Edge**' tab. On top of this diagram one or more energy levels and/or wave functions may be superimposed by choosing the desired number and activating '**Show Wavefunctions**' and/or '**Show Levels**'.

By clicking the '**Subbands**' tab the electron and hole subbands as function of the in-plane momentum are displayed.

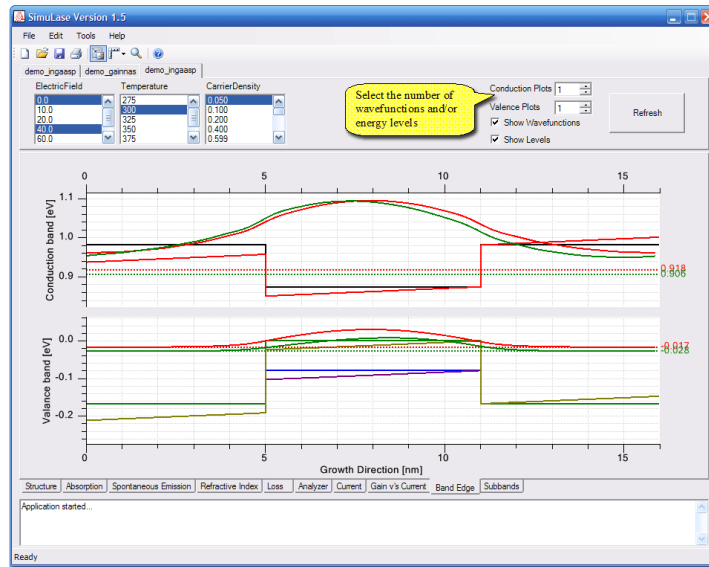


Figure 2: 'Bandstructure Views' Window.

### 3 PL Analysis Tool

The PL Analyzer tool allows comparing theoretical PL-spectra to measured data in order to obtain information about the inhomogeneous broadening and spectral mismatches between nominal and actual structure. The results provide direct insight into device growth quality. Demo-data that allows to test this tool can be downloaded from our web-page.

The tool may be activated by selecting 'Tools | Analyze Experimental PL' from the main menu. Performing a PL analysis requires the following steps:

- 1) Select a gain database that matches the material system of the experimental PL spectra to be analyzed. Click on 'Gain Database' and select a pre-computed gain database.
- 2) Select the parameters, like polarization and temperature, that most closely match the experimental conditions. The corresponding theoretical PL spectra from the database are plotted.
- 3) Import the experimental PL data (in order of increasing excitation power) by clicking the 'Experimental PL' tab and importing the data. In the current version of **SimuLase\_Analyzer**<sup>TM</sup> the experimental data has to be in two-column ASCII format. The first column containing the transition energy in [eV] or the wavelength in [nm]. The second column containing the PL data. Specify the data format using the 'Experimental data file units' selector box.
- 4) If available, load an experimental background noise spectrum data file using the 'background' tab. This background will be subtracted from all experimental spectra.
- 5) Click the 'Analyze PL' button to perform an analysis).
- 6) Analysis results may be improved by "clipping" noisy tails from the experimental data and selecting suitable control points on the 'Advanced' tab.

On the 'Advanced' tab, details of the analysis can be influenced by choosing low-energy matching points, high energy cut-off, the desired accuracy ('FWHM accuracy' tab), as

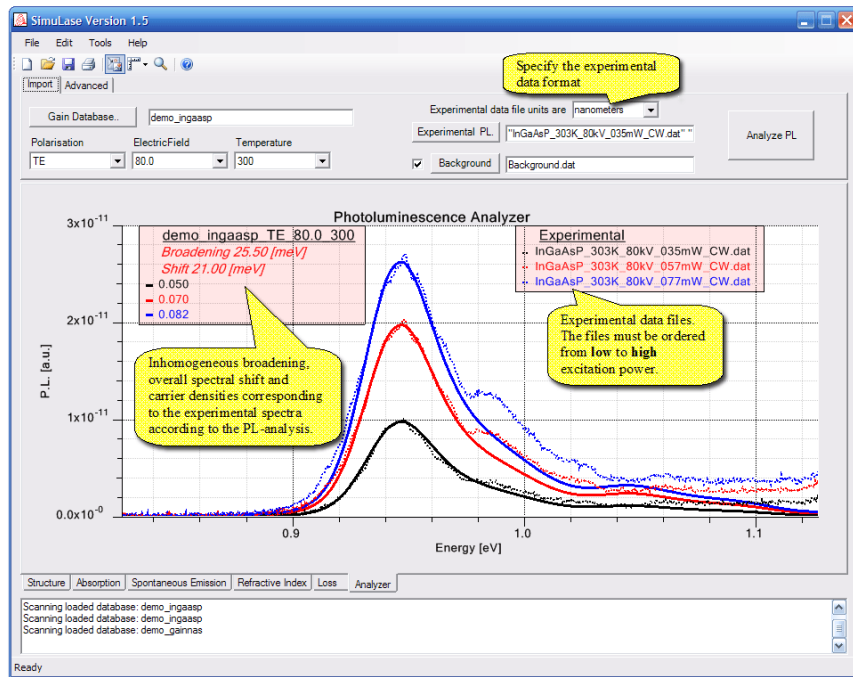


Figure 3: Main PL-Analysis panel.

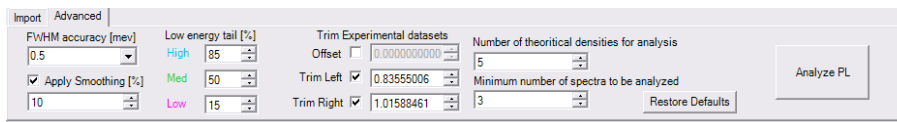


Figure 4: Advanced PL-Analysis panel.

well as the number of theoretical spectra used for the analysis.

The '**Offset**' can be used to subtract a constant background value from the experimental spectra - similarly to subtracting a background-noise spectrum.

'**Trim Left**' and '**Trim Right**' allow to exclude low- and high-energy tails in the experimental spectra from the analysis. Low energy tails are often covered by noise where the ideal spectra fall off below the bandgap. On the high energy side experimental spectra often show enhancements of the PL beyond the ideal theoretical PL. This is usually due to non-thermal carriers in the experiment which arise in particular when using CW-excitation. These carriers have not relaxed toward the bottom of the wells - occupying higher subbands - and lead to an enhancement beyond the ideal thermal equilibrium situation assumed in the theory (see e.g. the features at  $0.98\text{ eV}$  in Fig.3). These parts should be excluded from the analysis.

The Analysis should focus on the spectral region around the main peak that gives the best information about the inhomogeneous broadening and spectral shifts - starting where the PL reaches about 20 % of the maximum to where the PL falls off again to about 50 % of the peak value.

The theoretical spectra to the lowest carrier densities are used since experimental data usually is taken under low excitation conditions. The '**Number of theoretical densities for analysis**' should be increased if no good match is found when considering only the lowest densities.

If one has a very large experimental database loaded, one might want to save compu-

tation time and/or to focus on the qualitatively best spectra one can choose a subset of spectra to be analyzed by specifying the '**Minimum number of spectra to be analyzed**'. The analysis tool internally selects then a subset of experimental spectra of that size that matches closest average criteria. The final results are displayed only for these spectra.

In case of noisy experimental spectra one can apply a smoothing algorithm by choosing '**Apply Smoothing**' in order to eliminate artificial local peaks in the spectra which might obscure the true spectral location of the PL maximum. The percentage value chosen for smoothing is given as the percentage of the estimated inhomogeneous broadening present in the experimental data.

After choosing the desired settings, click the '**Analyze PL**' tab. After a short calculation, the best matching theoretical curves appear on the screen superimposed to the experimental data. In order to obtain the agreement, usually it is necessary to inhomogeneously broaden the ideal theoretical spectra (to take into account the experimentally unavoidable local composition and/or well width fluctuations) and to apply a spectral shift. Physically, this shift often appears as a consequence of deviations between nominal and actual composition and/or quantum-well width. The computed broadening and shift can be read from the legend in the display window. This legend also shows the theoretical densities chosen for the best agreement with the experimental data.

The analyzer requires that the experimental datasets be imported in order of increasing excitation power. Internally, the analyzer arranges the imported data files by sorting the file names in alphabetical order. The resulting ordering of the data files is visible in the '**Experimental**' legend that appears on the plot window next to the experimental data plots. If, after clicking the '**Analyze PL**', button the analyzer determines that the experimental data files are NOT in correct order the following dialog is displayed.

The order of data files may be rearranged by selecting a file name and using the '**Move**

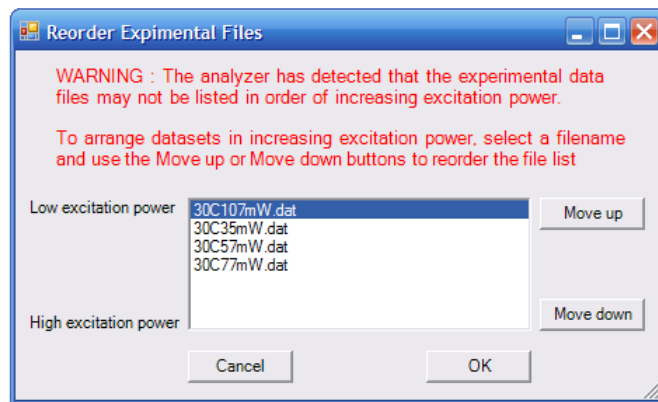


Figure 5: Re-arrange experimental PL panel.

**up**' or '**Move down**' buttons. Once all file have been correctly reordered from low (on top) to high excitation power (at the bottom) click OK, the experimental PL data will be redisplayed in the plot window and the PL analysis may be reapplied by clicking the '**Analyze PL** button.

## 4 Generating Shifted and Broadened Databases

Shifted and inhomogeneously broadened copies of existing GainDatabases may be generated by selecting **Tools | Shift and Broaden Database** from the main menu bar. The dialog Fig.6 will be displayed. Select an existing GainDatabase using the **'Gain Database'** button, enter the desired shift and broadening, select a directory into which the new database shall be stored and click OK. A new database will be generated in the destination directory with all spectra shifted and broadened by the requested amount. All other data unaffected by the shift and broaden operations, like wavefunctions and band structure etc., will be copied to the destination directory. The new database that may be loaded into the viewer, like any other Gain Database, using the **'File | Open Gain Database'** from the main menu bar.

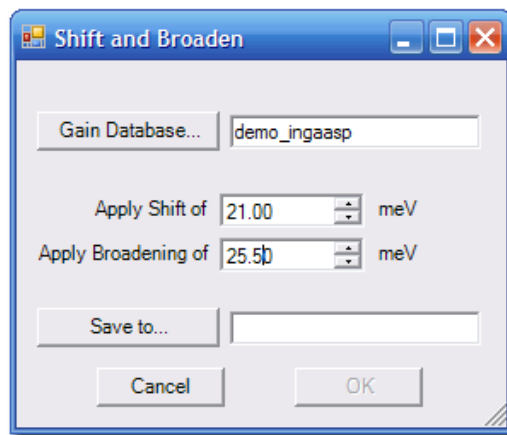


Figure 6: Dialog to create shifted and/or broadened copies of existing GainDatabases.

## 5 Current Calculator Tool

The loss current calculator tool may be activated by selecting **Tools | Current Calculator** from the menu bar. This tool allows determining the radiative loss current (due to spontaneous emission) and, if available, Auger loss current and total loss current (sum of radiative and Auger losses) for a given operating wavelength and/or given material loss (sum of out-coupling loss and internal loss). If your Gain Database contains no information about Auger-losses, only the radiative losses are plotted.

When selecting the check-box for **'Material Loss'**, the loss currents are plotted as function of the wavelength for the specified material loss value. This allows to look for the wavelength with minimum losses - i.e. the wavelength at which, for example, an edge-emitter without wavelength selective gratings would operate. When the check-box for **'Wavelength'** is selected, the loss currents are plotted as function of the material loss for the specified wavelength. This corresponds to the situation in a device with wavelength sensitivity, for example, a VECSEL.

With the field **'Number of Wells'** you can specify the number of wells in your structure. The material loss is then rescaled to a value corresponding to a single well before looking

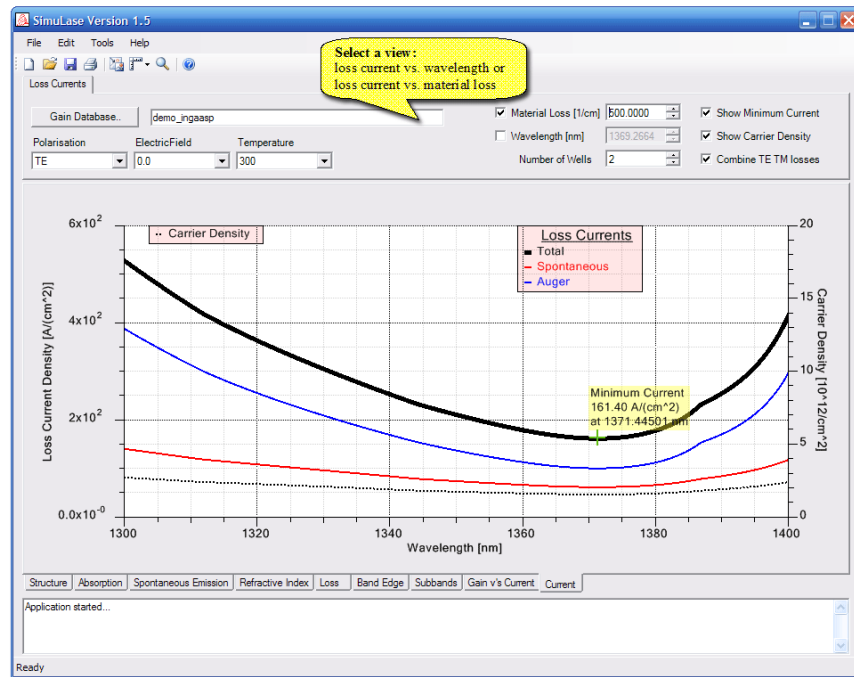


Figure 7: Current Calculator tool.

in the gain database (which is typically set up for single wells) for the required carrier density that yields enough gain to overcome this loss. Finally, the loss currents for this carrier density in a single well is again rescaled according to the number of wells in order to give the loss for the full structure.

By selecting the check-box '**Show Minimum Current**' a label with the exact values at the minimum total current is activated. When the check-box '**Show Carrier Density**' is selected the sheet carrier density that is required to overcome the material losses is plotted together with the loss currents.

If the box '**Combine TE TM loss**' is checked, the radiative loss current,  $J_{rad}$  is calculated by combining the TE and TM loss currents using  $J_{rad} = 2/3 J_{TE,rad} + 1/3 J_{TM,rad}$ . Otherwise,  $J_{rad} = J_{TE,rad}$  and/or  $J_{rad} = J_{TM,rad}$  is used depending on which polarization has been chosen through the selector field '**Polarization**'.

You can change the selected values for material loss, wavelength, etc. by clicking on the number field and using the scroll button of your mouse. You can also scroll in somewhat finer increments by clicking on the up- and down-arrows on the right sides of the number boxes or type in specific values. You can also type in numbers directly.

## 6 Gain vs. Current Tool

The '**Gain vs. Current**' tool allows investigating the absorption/gain for a specific current. This tool helps e.g. to see how the gain for a fixed pump-current changes with temperature. This is an important analysis if one looks for a structure which has constant gain at a given wavelength independent of the temperature.

After loading a database using '**File | Open Gain Database**' the gain vs. current tool may

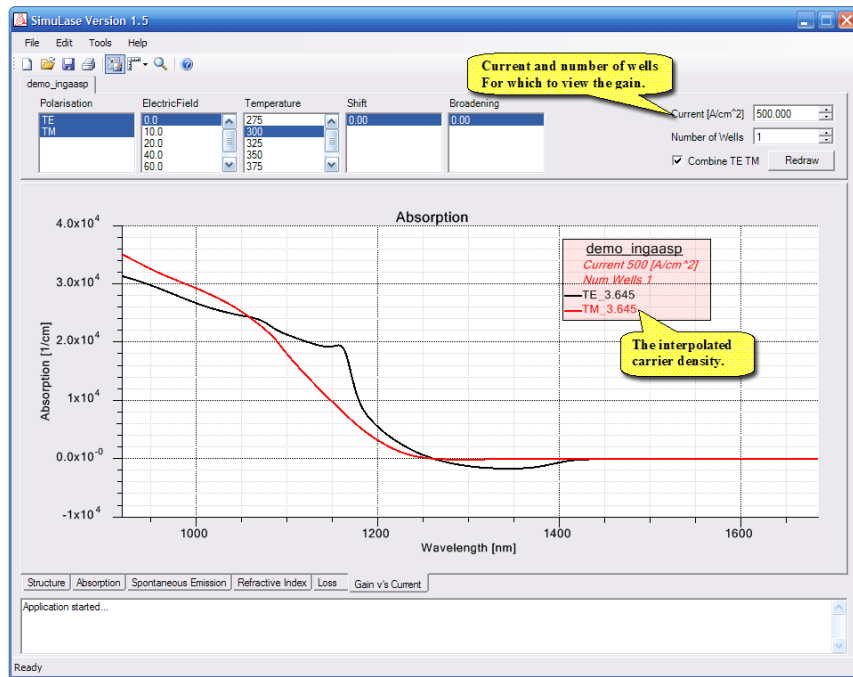


Figure 8: Gain vs. Current tool.

be activated by selecting '**Tools | Gain V's Current**' from the menu bar. After selecting a parameter set the user may view plots of the gain (absorption) as function of the current and the number of wells.

The '**Current**' is the assumed intrinsic loss current density due to radiative and - if available - Auger losses as included in the Gain Database. In order to determine the corresponding external pump current density, this value has to be divided by the internal efficiency.

The '**Number of Wells**' is the number of repeats of the active structure for which the Gain Database has been set up. The '**Current**' is divided by this number in order to obtain the current density corresponding to the loss values as included in the Gain Database. The displayed spectra are the ones as interpolated from the Gain Database, properly rescaled according to this number of repeats - assuming that the optical confinement factor scales linearly with the number of repeats.

If the box '**Combine TE TM loss**' is checked, the radiative loss current,  $J_{rad}$  is calculated by combining the TE and TM loss currents using  $J_{rad} = 2/3 J_{TE,rad} + 1/3 J_{TM,rad}$ . Otherwise,  $J_{rad} = J_{TE,rad}$  and/or  $J_{rad} = J_{TM,rad}$  is used depending on which polarization has been chosen through the selector field '**Polarization**'.

## 7 Linewidth Enhancement Factor Tool

The linewidth enhancement factor tool may be activated by selecting **Tools | Linewidth Enhancement Factor** from the menu bar.

## 7.1 Linewidth Enhancement Factor | Carrier Density

This tool calculates the linewidth enhancement factor spectrum ( $\alpha(\omega)$ ) for a specified carrier density ( $N$ ) using:

$$\alpha(\omega, N) = \frac{n(\omega, N + \Delta_N) - n(\omega, N)}{a(\omega, N + \Delta_N) - a(\omega, N)}, \quad (1)$$

where  $n$  is the refractive index in the units as displayed in the 'Refractive Index'-window,  $a$  is the material absorption and  $\Delta_N$  is an infinitesimal density change.

Since the linewidth enhancement factor is given by the ratio of two differentials, it can vary dramatically when viewed on an extended energy/spectral-range. One usually has to zoom into the relevant region of the spectra.

## 7.2 Linewidth Enhancement Factor | Electric Field

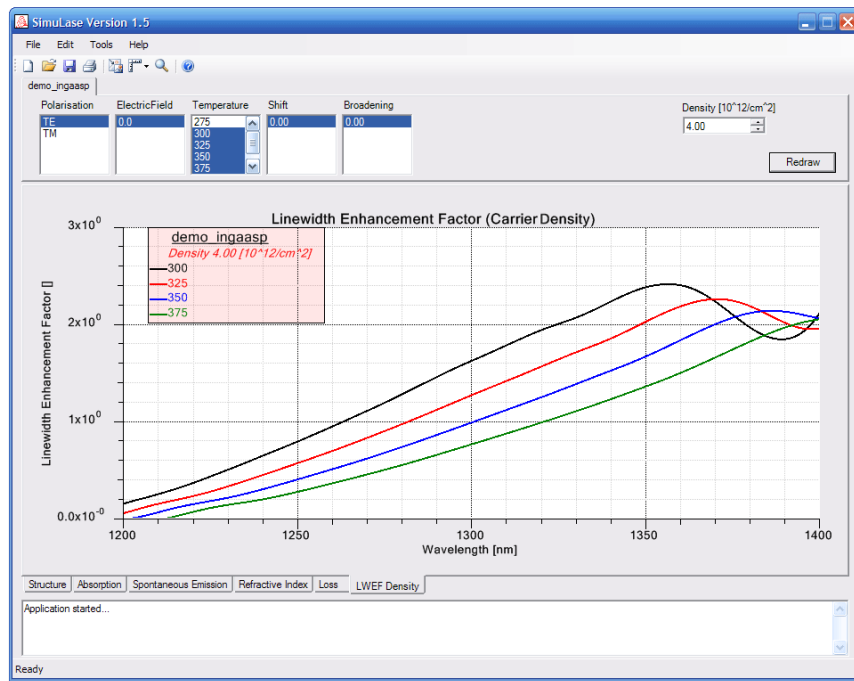


Figure 9: Linewidth Enhancement Factor tool for the calculation of the LWEF for a given carrier density.

This tool calculates the linewidth enhancement factor spectrum ( $\alpha(\omega)$ ) for a change in electric field/applied Voltage ( $F$ ) using:

$$\alpha(\omega, F_0, F_1) = \frac{n(\omega, F_0) - n(\omega, F_1)}{a(\omega, F_0) - a(\omega, F_1)}, \quad (2)$$

where  $n$  is the refractive index in the units as displayed in the 'Refractive Index'-window,  $a$  is the material absorption and  $F_0, F_1$  are two electric field values from the list of fields

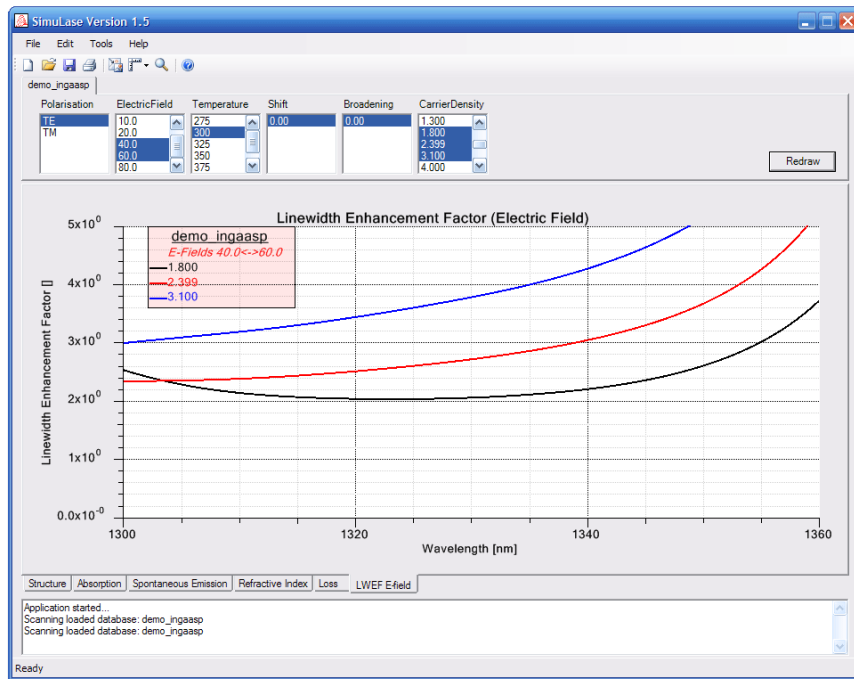


Figure 10: Linewidth Enhancement Factor tool for the calculation of the LWEF for a change in the electric field across the active region.

for which the database has been set up. This definition of the linewidth enhancement factor follows the definition as given in N. Suzuki, Y. Hirayama, IEEE Photon. Technol. Lett. 7, 1007 (1995).