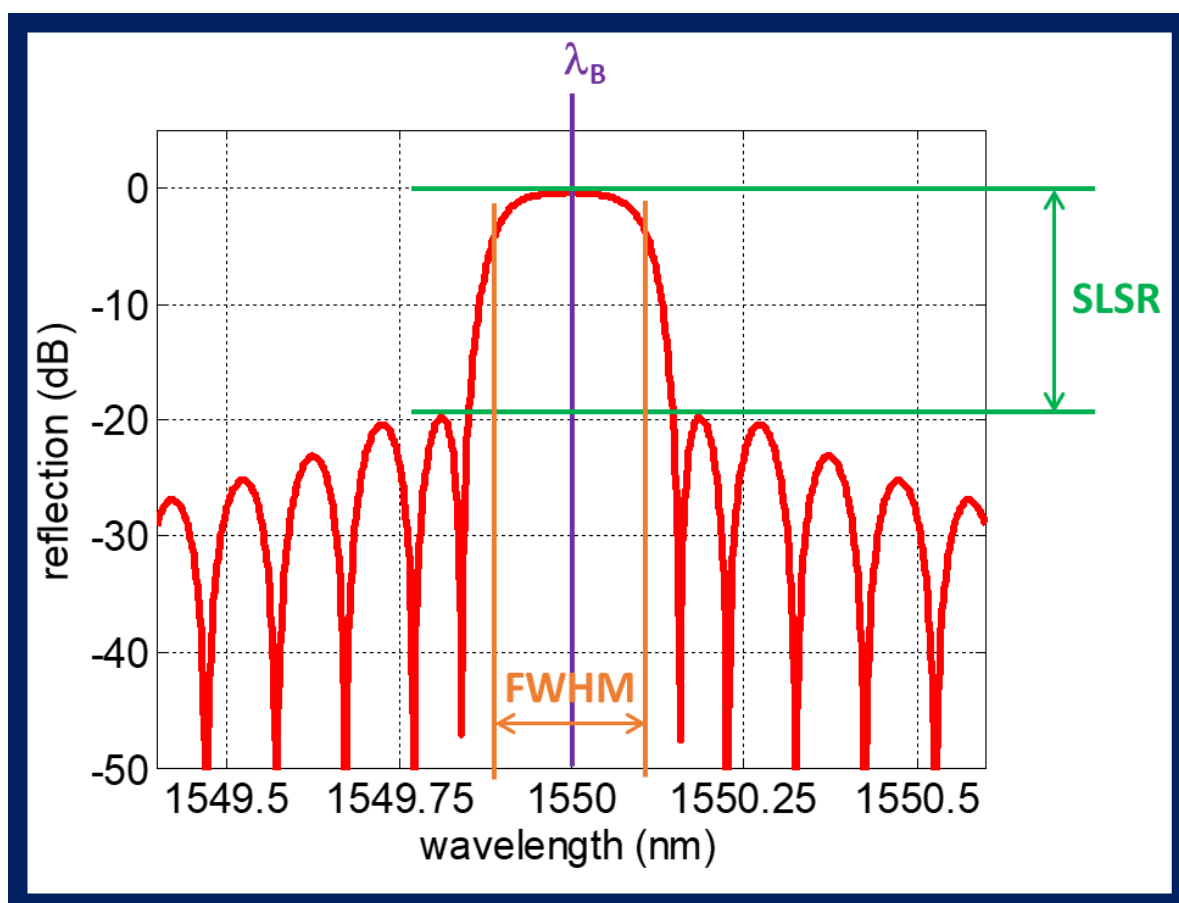# Grating Design Software Manual

January 2024

Important Notice

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1. System requirements

Grating Design Software (GDS) requires the following to run:

- Windows 7 Service Pack 1 / Windows 8 / 8.1 or Windows 10 operating system.
- Any Intel or AMD X86 processor
- 4 GB of hard disk space
- 2 GB of RAM (4 GB is recommended)
- No specific graphic card recommended.
- Screen resolution 1366 x 768 or higher

2. Installation procedure

2.1. Installation of dongle

GDS is delivered on a secure dongle. The dongle is equipped with a flash drive which holds the GDS program, required installation files and this manual. Insert the dongle in a free USB port to gain access to the drive. Note that for GDS to run the dongle needs be present in the system.

2.2. Software installation

No specific installation is required to run GDS. The program can be run directly from the USB dongle or copied onto the hard drive.

3. Starting the GDS program

GDS can be run directly from the dongle by double-clicking the GratingDesiign.exe icon. The GDS program can be copied and installed on multiple PC's, however note that only 1 instance of GDS can run simultaneously.

Figure 1 on the next page shows the GUI startup screen and gives a comprehensive overview of the available functions and parameter settings.

Figure 1: Short description of GDS Graphical User Interface

A.	This graph displays the reflection spectrum of the simulated Fiber Bragg Grating in a linear scale. The "normalize and scale" allows the user to toggle between the a graph displaying the actual grating reflectivity and a grating spectrum which is normalized	**E.**	The simulation result can be saved to disk for further processing or analysis. Once the simulation is finished and results are displayed in A and B, the button "save result" is made available, which will write an ASCII file to disk that and includes the grating simulation parameters (F, G and H), calculation results if available (D) and comments inserted manually by the user.
B.	This graph displays both the simulated grating reflection and transmission spectra in logarithmic scale	**F.**	Here the fiber and gratings refractive index settings are inserted by the user. Default values are provided at start-up. In addition, 2 different apodization schemes can be applied, i.e. Gaussian and Tanh apodization. A button, "calculate index, leading to a separate GUI for calculating the LP01 mode effective index of a specific fiber is available.
C.	The "Calculate" button commences the simulation based on the input parameters in F, G and H.	**G.**	Grating length, phase mask pitch and chirp (if any) are provided by the user here. Default values are given at start-up.
D.	After simulation the "Calculate" button is made available which will allow the user to quickly determine specific grating parameters	**H.**	By default the spectral width of the grating simulation is 4 nm, which will be automatically extended if a chirp rate is applied. The spectral width is divided into 250 calculation points by default. Furthermore, refractive index profile graphs and FBG pitch profiles are made available to the user for reference.

4. Simulation of Fiber Bragg Gratings

4.1. Effective refractive index

The simulation of an Fiber Bragg Grating (FBG) often starts with determining the effective refractive index of the optical fiber selected by the end-user. The effective refractive index, n_{eff}, together with the pitch of the FBG, Λ_{FBG}, determines the central wavelength of the grating, λ_B.

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda_{FBG} \tag{1}$$

Please note that a default value of 1.45 for n_{eff} is normally filled in by GDS, which will give you an approximate value suitable for most fiber types, however keep in mind that the central wavelength of the FBG, λ_B, is not correct unless the effective index is determined accurately.

GDS can determine the effective index of the fundamental mode by clicking on the top right button "calculate index". A new popup window will appear, see Figure 2.

Figure 2: popup window for determining the effective refractive index of the fundamental mode in an optical fiber

 To determine the effective index, the user needs to provide 3 parameters, i.e. NA, core diameter, (or cut-off wavelength) and operating wavelength. Both the NA and core diameter are normally found on the specification sheet of the chosen fiber. Sometimes, instead of the core diameter one can use the cut-off wavelength provided by the fiber vendor. Because the refractive index of any material is wavelength dependent the user needs to define an operating wavelength. Here the central wavelength of the FBG is inserted.

Default values for a standard (SMF-28) fiber are already given. Clicking the "Calculate" button processes the given parameters and a number of fiber parameters are calculated and presented. An example is given for the default values in Figure 3.
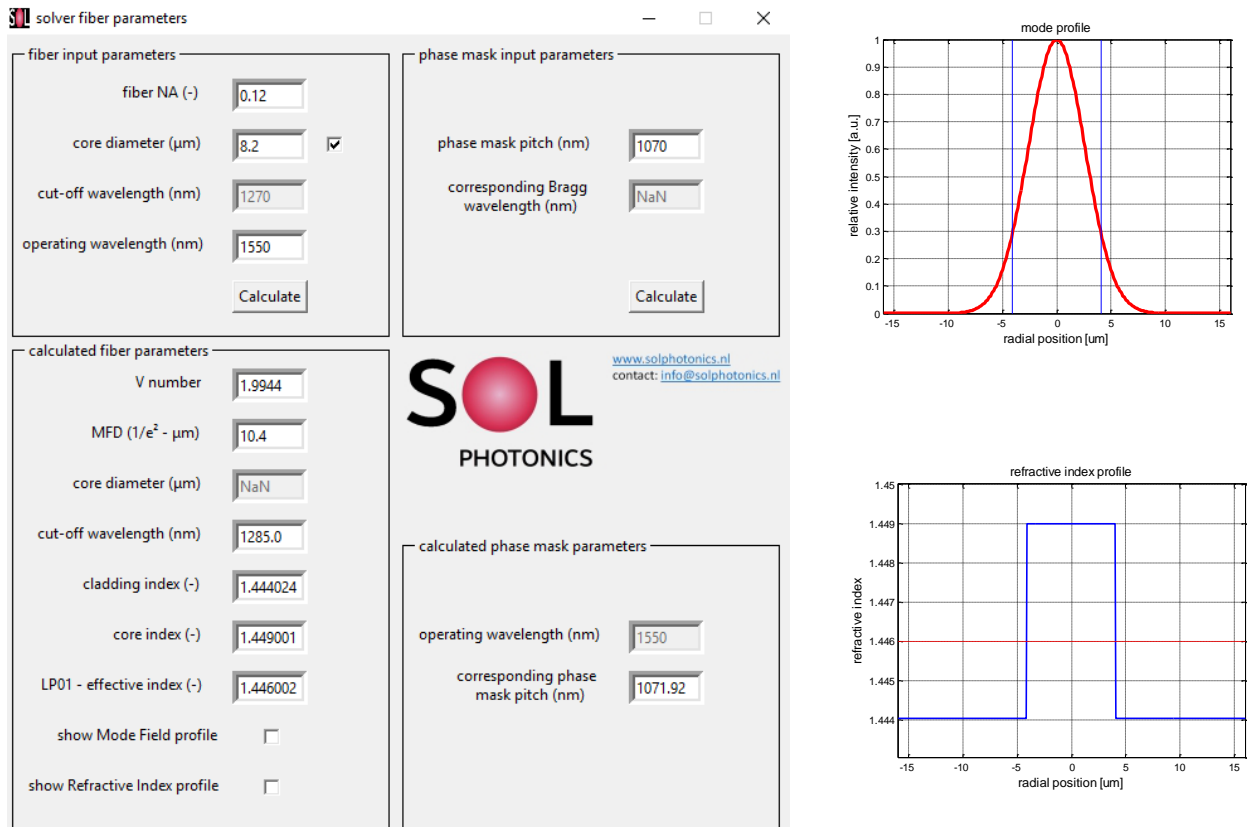
Figure 3: calculation examples of fiber parameters (left) and example graphs of mode profile and the fibers refractive index profile (right)

The calculation result shows values for the V-number, Mode Field diameter, cut-off wavelength (or fiber diameter depending on end-user parameter entry), cladding and core refractive index (determined at the provided operating wavelength) and the effective refractive index. In addition, 2 radio buttons have become visible which by clicking shows graphs of the mode profile distribution and another graph showing the refractive index profile of the fiber (see Figure 3 on the right).

The effective index value at the bottom of the list is what we set out to obtain. The calculated value can be copied and pasted back into the main GUI of the Grating Design Software. (paste the value in the box left of the "Calculate Index" button stating "effective refractive index").

4.1. Limitations

Note that GDS calculates the effective refractive index based on a step index profile of the fiber in which the cladding is assumed to be made out of amorphous fused silica. In short, the model is based on a germanosilicate step index fiber.

The cladding index at the given operating wavelength is calculated based on the Sellmeier dispersion formula:

$$n^2(\lambda) = 1 + \frac{B_1 \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \lambda^2}{\lambda^2 - C_3} \tag{2}$$

In which B_1, B_2, B_3, C_1, C_2 and C_3 are consistent with the properties of amorphous fused silica:

B_1 = 0.684192006218983
B_2 = 0.419200513300583
B_3 = 0.564884246508072
C_1 = 0.00470358580823456
C_2 = 0.0132585313620993
C_3 = 64.494927725852

These values can be accessed through the config.txt file located in the /lib folder on the dongle if needed. Note however that changing these values is not recommended.

4.2. Phase Mask pitch

Equation (1) gives the dependency of the effective index and the FBG pitch on the central wavelength of the FBG. In the previous paragraph the effective index has been determined for a specific fiber, now the FBG pitch needs to determined to obtain the correct/desired central wavelength, λ_B. In the previous paragraph we use 1550 nm for the operating wavelength to determine the effective index. Here we continue using 1550 nm as the FBG central design wavelength.

In GDS, instead of the FBG pitch, the phase mask pitch is used. The background of GDS is to enable users to determine a recipe for manufacturing their FBG's using the phase mask method. Therefore, it is more useful to specify the pitch of the phase mask. Note that the phase mask pitch is twice the FBG pitch, i.e. $\Lambda_{pm} = 2 \cdot \Lambda_{FBG}$. Thus, Equation (1) is rewritten into:

$$\lambda_B = n_{eff} \cdot \Lambda_{pm} \tag{3}$$

The phase mask pitch is entered in the middle section of box G (see Figure 1). The pitch is given in nm, with 2 digits accuracy. This complies to the maximum attainable accuracy obtained by the phase mask manufacturers.

Using Equation (3), the phase mask pitch corresponding to the FBG design wavelength is simply $\frac{\lambda_B}{n_{eff}}$. For convenience GDS already calculated the phase mask pitch corresponding to the provided operating wavelength in the right bottom screen of the mode solver GUI. See the panel stating "Calculated phase mask parameters" in Figure 3 . Here the corresponding operating wavelength is stated as well to avoid confusion.

Alternatively, one could have a number of phase masks on stock and want to determine the central Bragg wavelength for a specific fiber. Here GDS provides a solution in the top right section of the GUI in the panel stating "phase mask input parameters". This is a separate section of the GUI used to determine the central Bragg wavelength when using a phase mask with a known pitch and a fiber type specified in the panel "fiber input parameters". The user inputs the pitch of the mask and correct fiber type parameters, i.e. NA, core diameter or cut-off wavelength and after pressing the

"Calculate" button inside the panel the central Bragg wavelength is determined and displayed. See Figure 4. Note that the operating wavelength is not used.

This calculation from a phase mask pitch to an FBG central wavelength given specific fiber parameters is a bit more difficult. The effective refractive index for a range of wavelengths needs to be determined and fitted to iterate to a solution. GDS is equipped with an automatic iterative process to determine the correct Bragg wavelength.

Figure 4: example of determining the Bragg wavelength using a specific phase mask pitch and fiber type

4.3. Simulation of uniform FBG

With the new effective index and phase mask pitch it is time to start a first simulation. For now we do not bother too much with all the other settings available in the GDS GUI and continue with starting the calculation. The calculation is started by clicking the "Calculate" button on the left (see C. in Figure 1). A wait bar will pop up indicating that the calculation is running and giving the user an idea on the duration. When the calculation is finished the wait bar disappears and the simulation result becomes visible in the 2 graphs (A. and B. of Figure 1).

Extra information on FBG central wavelength, maximum reflectivity, Full Width Half Maximum and Side Lobes Suppression Ratio can obtained by clicking on the "Calculate" button on the bottom left corner. The end result will look exactly like Figure 5 below.
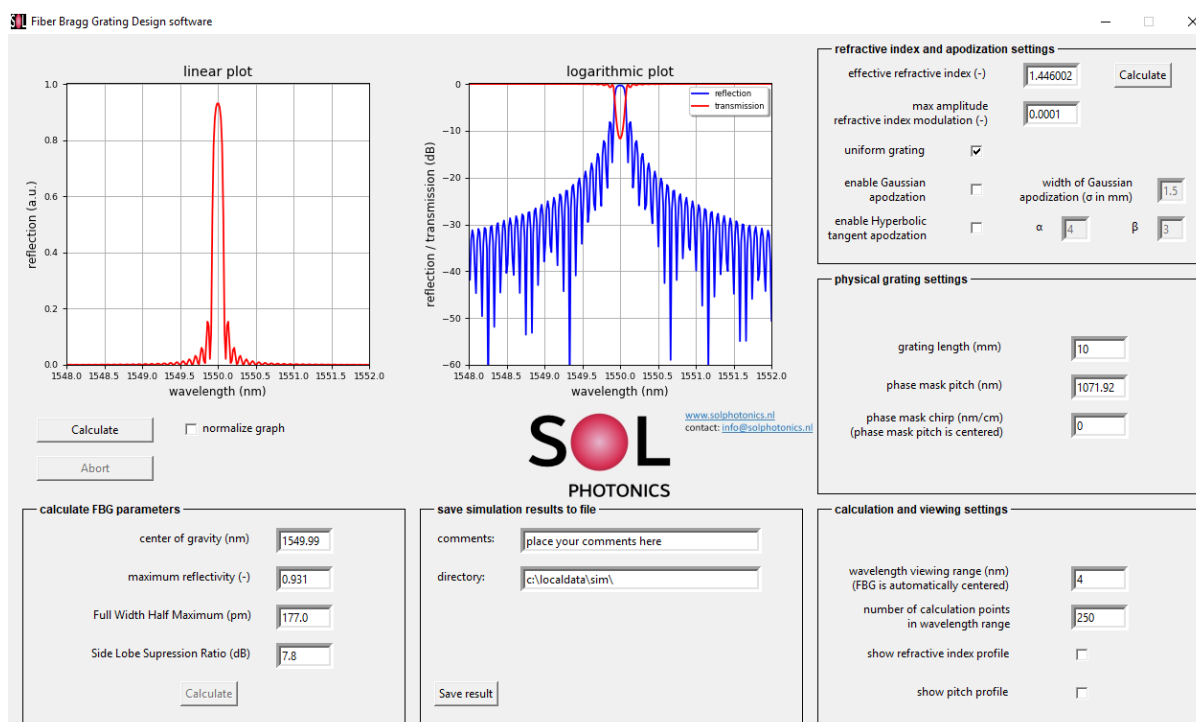
Figure 5: GDS GUI with simulation result of an uniform grating

For now we used the default FBG simulation settings, i.e. a moderate refractive index modulation is applied of 1E-4, no apodization of the grating is used (the index modulation is constant along the grating length), the grating physical length is set at 10 mm and no chirp rate is applied. Below we briefly discuss each parameter setting. The apodization of gratings is discussed in a separate paragraph ( ).

4.3.1. *Refractive index modulation*

Location F. see Figure 1. The textbox gives access to the modulation amplitude of the refractive index. Default setting is 1e-4.
No boundaries are set, however realistic values range from 1E-6 to 1E-2.

4.3.2. *Grating length*

Location G. see Figure 1. The physical length of the grating is given here in millimeters. Default value is 10 mm. No boundaries are set, however note that very large grating lengths also increase the calculation time.

4.3.3. *Phase mask chirp rate*

Location G. see Figure 1. A linear variation in the chirp rate of the grating can be applied by stating the chirp rate of the phase mask in nm/cm. The phase mask pitch stated above the chirp rate textbox is used to define the pitch in the physical center of the grating. To visualize the pitch of the FBG, including chirp the "show FBG pitch profile" toggle button can be used. See for example the calculation of an FBG with 5 nm/cm chirp rate in Figure 6.
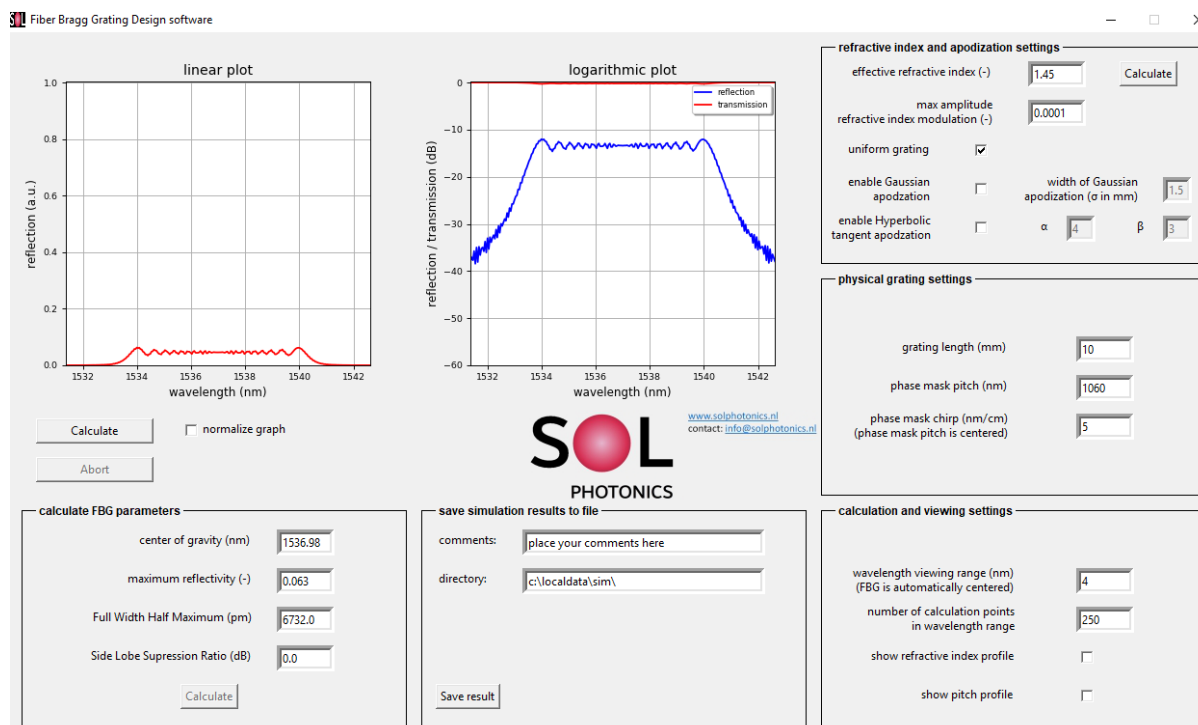
Figure 6: simulation example of an unifrom grating with 5 nm/cm chirp rate in the phase mask.

By clicking the toggle button "show FBG pitch profile" in the right bottom corner as indicated in Figure 6, the following graph is displayed. See Figure 7.
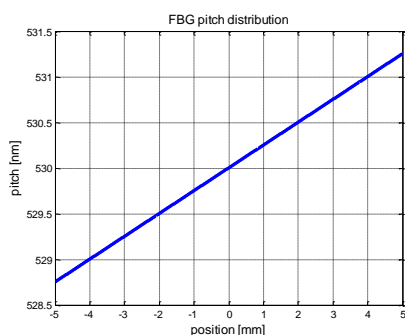
Figure 7: FBG chirp rate corresponding to the simulation of Figure 6.

The FBG chirp rate (note: this is the chirp rate of the phase mask divided by 2) is shown. The grating pitch in the center is 530 nm (corresponding to the stated phase mask pitch of 1060 nm in Figure 6) and the chirp rate starts at 528.75 nm at -5 mm position increasing to 531.25 nm on the other end of the 10 mm long grating. This equals the chirp rate of the phase mask (5 nm) divided by 2 giving the physical chirp in the grating.

4.3.4. Phase mask with π-shift (only from version 1.09 onwards)

GDS version 1.09 introduces π-shifts centered in the middle of the phase mask / Fiber Bragg Grating. This new functionality is added in the GUI of GDS within the "physical grating settings" window block. See Figure 8.

Figure 8: GUI of GDS including pi-shifted grating functionality

The π-shift settings located in the "physical grating settings" section enable the addition of a one π phase shift in the middle of the grating. The definition of the π-shift is (similar to the grating pitch) on phase mask level, i.e. twice the pitch of the Fiber Bragg Grating. When enabling the π-shift functionality via the check button the π-shift settings window will no longer be grayed out. By default, the π-shift value displayed is the phase mask pitch value divided by 2. See Figure 9.
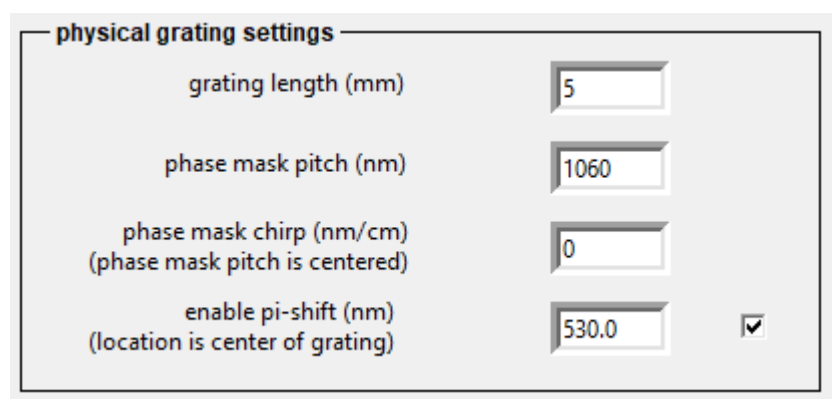
Figure 9: physical grating settings including pi-shift settings

If needed the user can change the pitch of the π-shift to any desired pitch value. For example the effect of not producing an exact 1 π phase shift can be investigated.

Simulation results are normally provided in the 2 graphs, however as of version 1.09 the possibility to include the transmission result in the linear graph display is added. See Figure 10.
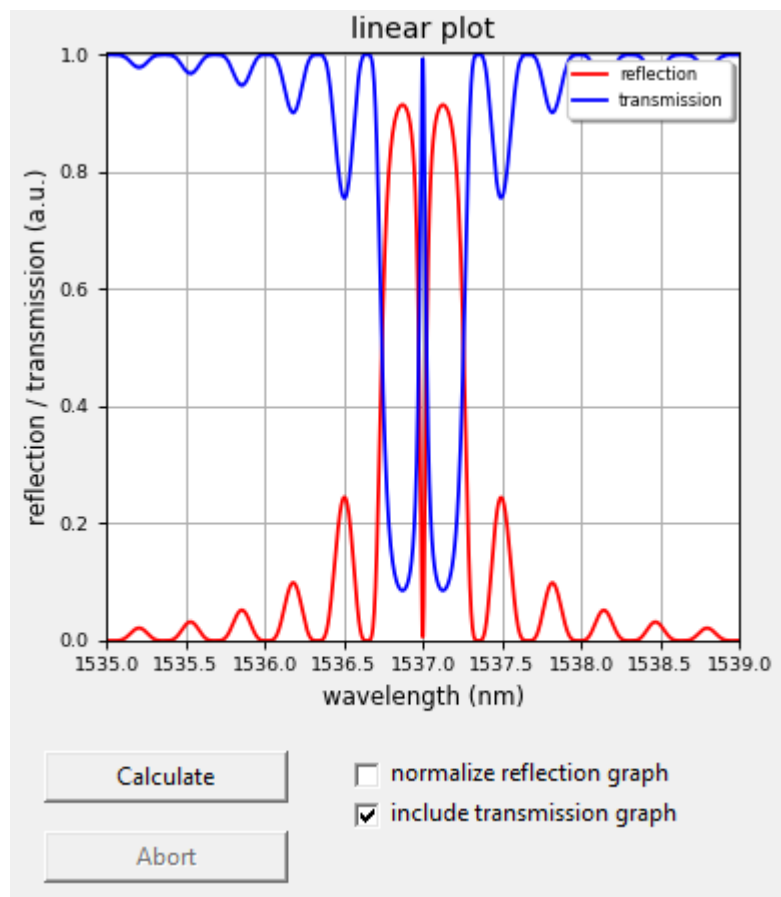
Figure 10: zoom in on linear graph of simulation result including the new functionality to add the transmission spectrum next to the reflection spectrum

Writing the simulation results to file has been modified to include if the π-shift functionality was enabled including the value of the π-shift in nanometers.

Special note while simulating π-shifted gratings:

Please be sure to include sufficient calculation points within the defined wavelength range. The width of the spectral dip / peak in transmission can become very narrow. A full width of the peak in transmission can easily be 1 or 2 pm. To ensure sufficient resolution allowing resolving this narrow peak/dip the number of calculation points across the wavelength range needs to be increased. In Figure 8 a number of 1000 calculation points along 4 nanometer spectral range is used. Depending on the length of the grating and the wavelength range of interest this number needs to be increased accordingly.

4.4. Apodization

GDS enables the user to simulate grating with 2 different apodization profiles, i.e. a Gaussian apodization profile and a hyperbolic tangent profile. Each case is discussed separately:

4.4.1. Gaussian apodization

Selecting the radio button "Gaussian apodization" (F. in Figure 1) enables the Gaussian apodization feature. Once selected the text box "width of the Gaussian apodization in mm" becomes editable. For now we will use the default settings and run a simulation, see Figure 12.
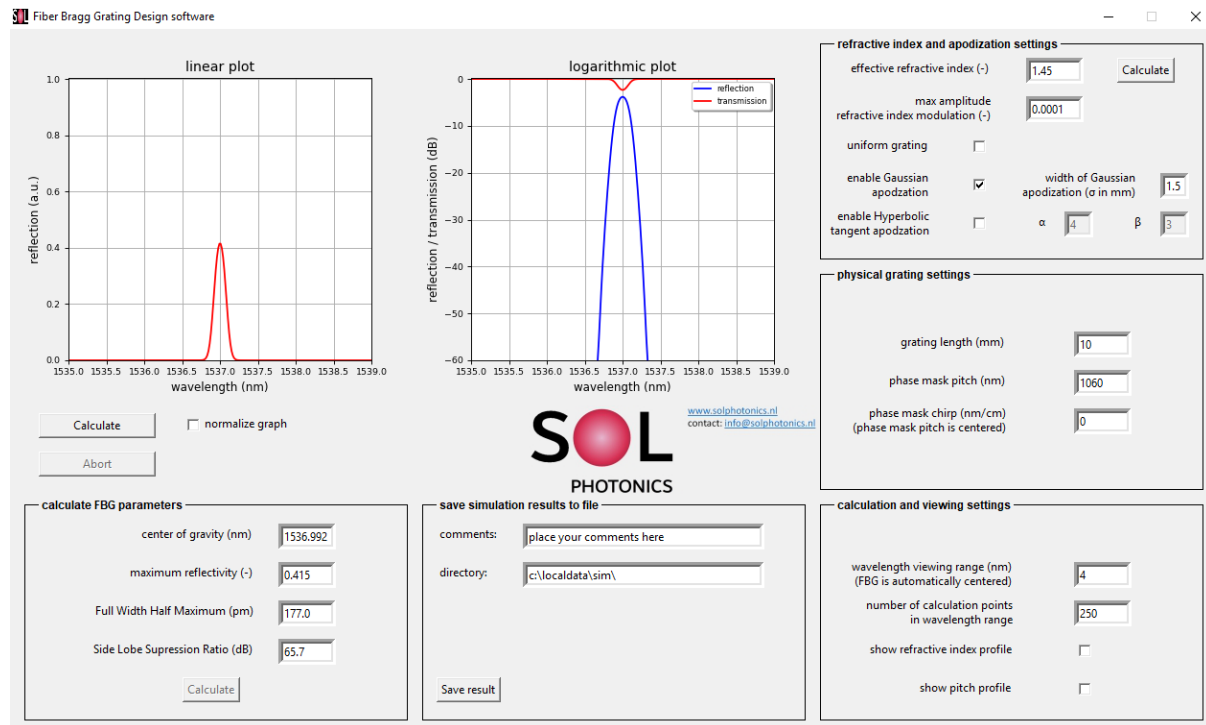
Figure 11: simulation of Gaussian apodized grating

With Gaussian apodization enabled the refractive index profile along the grating length follows a bell curve. The maximum value of the bell curve is the set "max amplitude refractive index modulation", here at 1E-4 and the bell curve width is 1.5 mm, which is the σ value of the Bell curve.

The mathematical description of the Bell curve is:

$$\delta n(x) = \delta n_{max} \cdot e^{\left(\frac{-x^2}{2\sigma^2}\right)} \tag{4}$$

In which x is the position along the grating, $\delta n(x)$ the refractive index at the x position along the grating, δn_{max} the maximum refractive index modulation (centered in the middle of the grating) and σ, the width of the Bell curve (in mm). With the settings in Figure 11, the refractive index distribution along the grating will be in accordance to Figure 12.

Figure 12: refractive index distribution along the grating

4.4.2. Hyperbolic tangent apodization

Selecting the radio button "Tanh apodization" (F. in Figure 1) enables the Hyperbolic Tangent apodization feature. Once selected the text boxes "alpha" and "beta" become editable. For now we will use the default settings and run a simulation of a chirped grating similar to the simulation in Figure 6, however with the Hyperbolic Tangent apodization feature, see Figure 13.
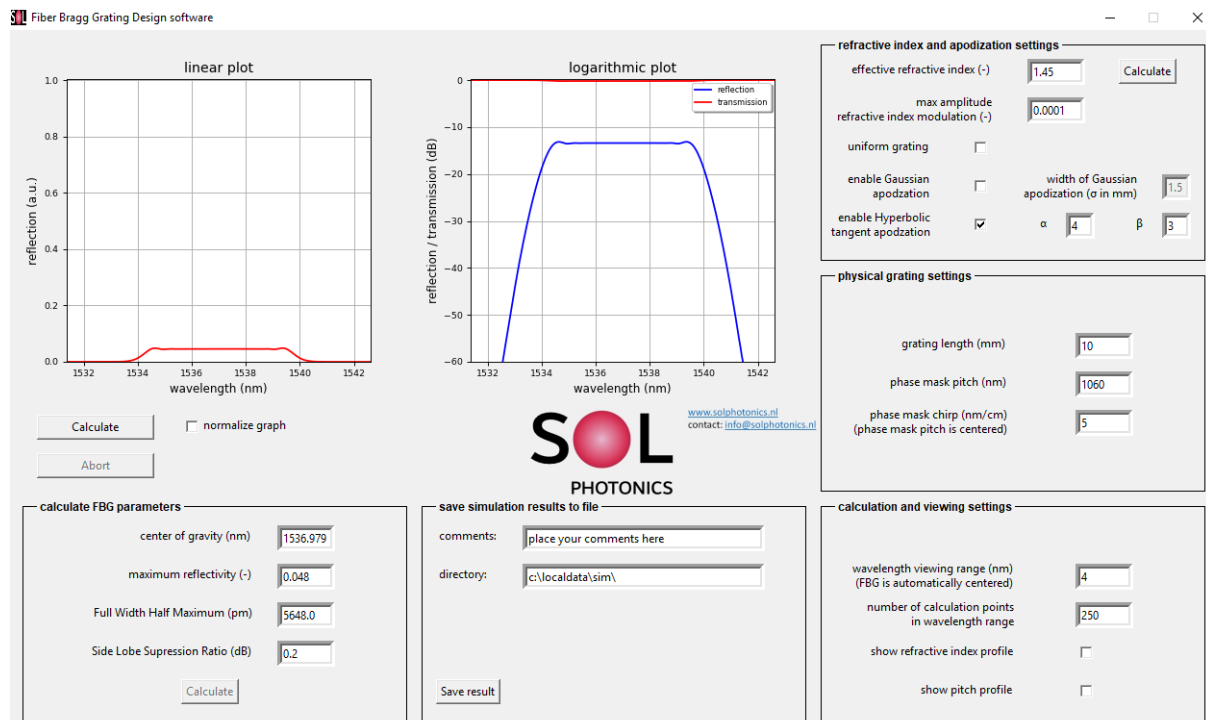
Figure 13: simulation of chirped grating with hyperbolic tangent apodization

With Tanh apodization enabled the refractive index profile along the grating length follows a hyperbolic tangent curve. The maximum value of the bell curve is the set "max amplitude refractive index modulation", here at 1E-4 and the alpha and beta values describe the shape of the curve.

The mathematical description of the Tanh curve is:

$$\delta n(x) = \delta n_{max} \cdot \frac{1}{2}\left[1 + \tanh\left(\beta \cdot \left(1 - 2 \cdot \left|\frac{2x}{L}\right|^{\alpha}\right)\right)\right] \tag{5}$$

In which x is the position along the grating, $\delta n(x)$ the refractive index at the x position along the grating, δn_{max} the maximum refractive index modulation (centered in the middle of the grating), α and β describe the shape of the curve and L the total length of the grating (in mm).

With the settings in Figure 13, the refractive index distribution along the grating will be in accordance to Figure 14.
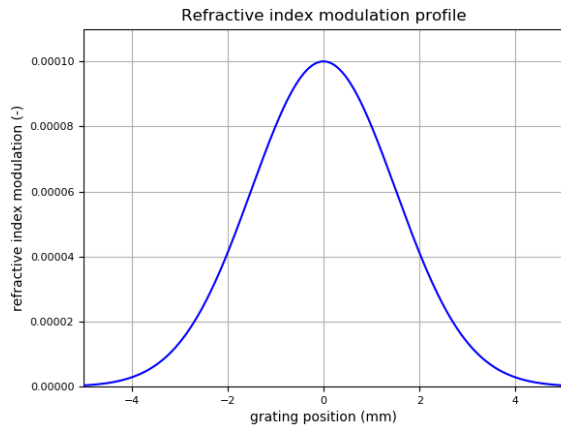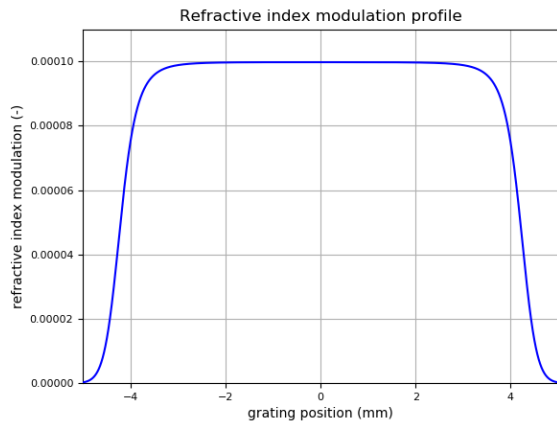

Figure 14: example of hyperbolic tangent apodization curve

4.4.3. Raised cosine apodization (from version 1.0.6 onwards)

GDS version 1.0.6 received an upgrade as per request from a customer to include the raised cosine function for apodization. The mathematical description of the raised cosine function is:

$$\delta n(x) = \delta n_{max} \cdot \left[\alpha + \beta \cdot \cos\left(\frac{x \cdot \pi}{L}\right)\right] \qquad (6)$$

In which x is the position along the grating, $\delta n(x)$ the refractive index at the x position along the grating, δn_{max} the maximum refractive index modulation (centered in the middle of the grating), α and β describe the shape of the curve and L the total length of the grating (in mm).

With the release of GDS v1.0.6 the GUI layout has been modified to add the raised cosine apodization function, see Figure 16.

The default values of α and β are 0.55 and 0.45 respectively. As an example, the resulting refractive index distribution for a 10 mm long grating is displayed in Figure 15.
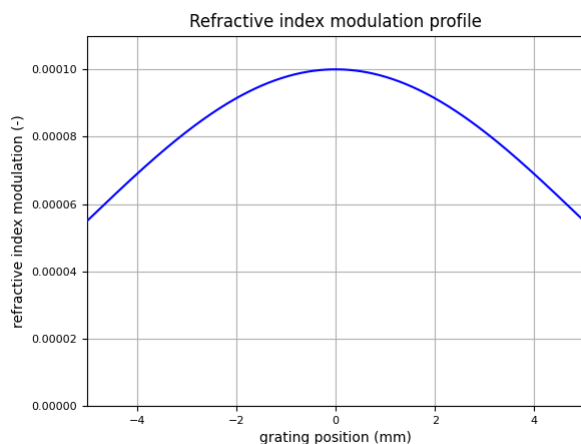
Figure 15: example of raised cosine apodization function with default values
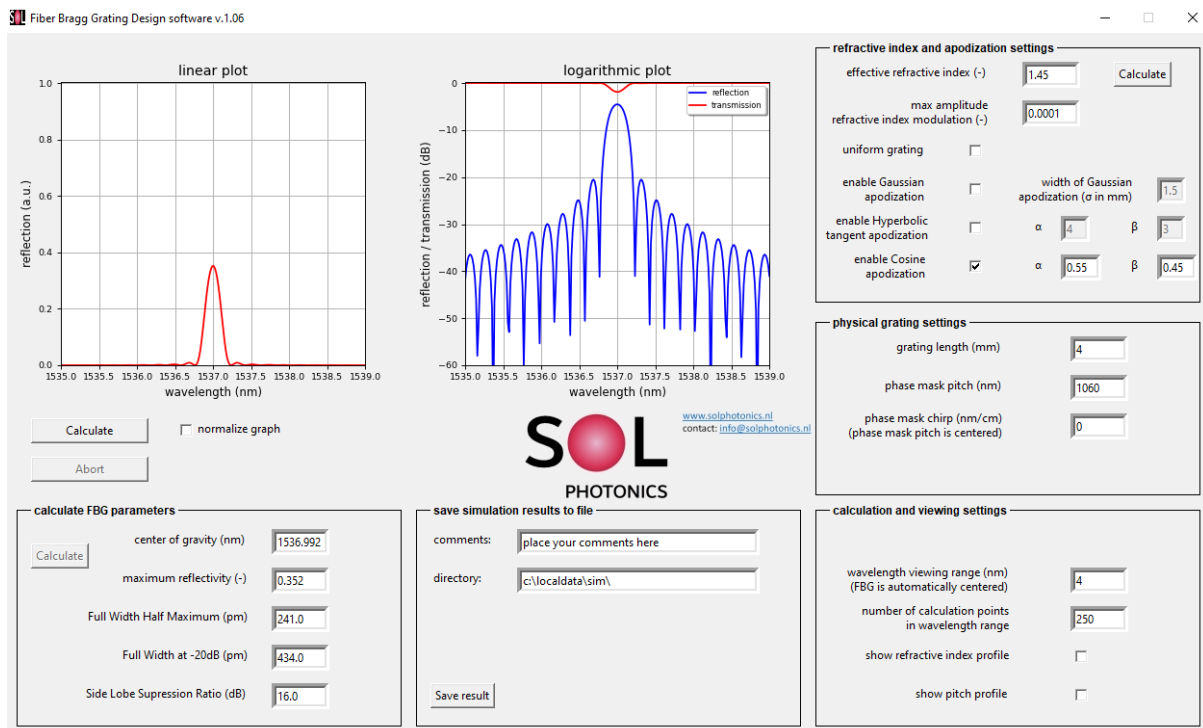
Figure 16: GUI of GDS version 1.0.6 onwards including the raised cosine apodization feature

4.4.4. User defined apodization (from version 1.0.8 onwards)

From GDS version 1.08 allows the use of user define apodization profiles. The apodization profile is created via a csv file created by the end-user and loaded into GDS. The csv file should contain a 1 dimensional array of the apodization profile defined by the end-user which is normalized to 1.

As an example an csv file named "triangle.csv" located in the folder \apodization-profiles is included on the USB drive. "triangle.csv" contains a 1000 elements which comprises a triangular shaped profile normalized to 1. Once loaded into GDS the amplitude of the profile is multiplied by the "max amplitude of the refractive index modulation" and mapped to the "grating length" as set by the user.

The apodization profile can be displayed by the user via the "show refractive index profile" radio button in the right-bottom corner of the GDS main GUI, see Figure 17.
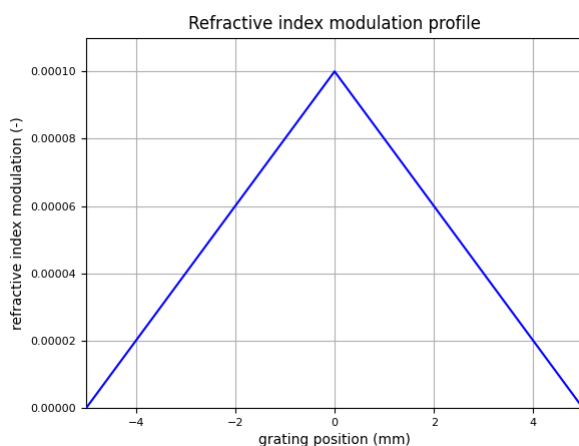
Figure 17: triangular shaped apodization profile

The updated GUI of GDS in which the user-defined apodization functionality is added is given in Figure 18 below.
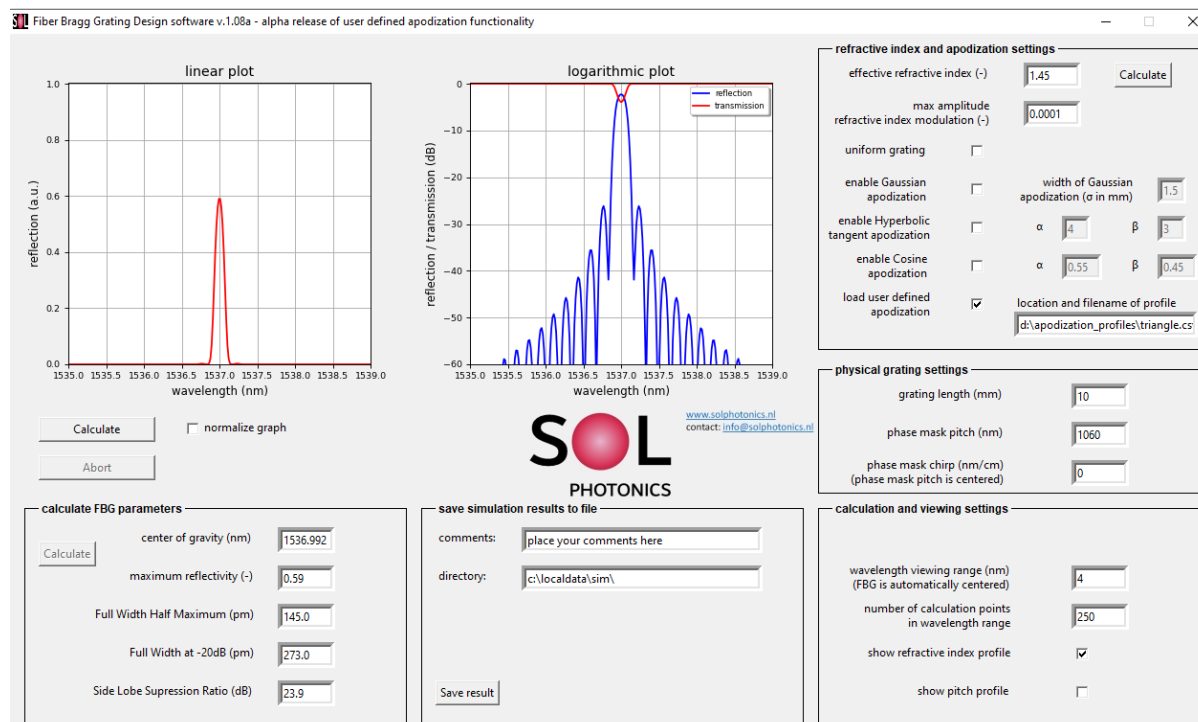
Figure 18: GUI of GDS including user-defined apodization profile functionality

4.5. Calculation and viewing parameters

Parameters to adjust calculation resolution and viewing width are available in H. (see Figure 1). The default width of the grating is set at 4 nm. If an chirped grating is being simulated the program automatically adjust the viewing width to ensure that the full grating is visualized in the 2 graphs.

The wavelength range is divided into discrete calculation points given by the box "number of calculation points divided by wavelength range". The default value is 250, which is suitable for many of the simulations. However, if one is simulating large chirp rates the 250 points can be too coarse. Increasing the calculation points can be done here. Note that this will also increase the required calculation time.

5. Save simulation data

After successful simulation of a grating the result is displayed in the 2 graphs at the top of the GUI. The simulation data can however also be stored to disk for further processing. Once the simulation is finished, a button in section E. (see Figure 1) stating "save result" is made available. After pressing this button all spectral data of the simulation will be stored to disk. The default location is "c:\LocalData\Simulation\". If this directory does not exist the program will create it[1]. For easy tracking the user can add simulation remarks in the text box below the directory location.

---

[1] Note that if the directory does not exist GDS will try to create it. On some computers this will not be allowed and nothing happens. To circumvent this please add a directory location which exists, e.g. "c:/". This will provide a popup window to save an ascii file on any location on the harddrive or USB dongle.

Important notice: the stored data also includes the center wavelength, maximum reflection, FWHM and SLSR. However these values need to be calculated first by pressing the "Calculate" button. If no values are available the logfile will return NaN.

5.1. Logfile layout

An example of a simulation logfile is given below in Figure 19. The logfile header includes the date and time at which the simulation is made and the remarks inserted by the end user (if any). In addition, settings related to the simulation are stored as a reference and calculation results are given.

```
---------------------------------------------------------------------------------
|                                                                               |
|                      Grating Design Simulation file                           |
|                                                                               |
|                                                                               |
|                                                                               |
|   file created on Tue Jul 10 20:31:19 2018                                    |
|   comments : place your comments here                                         |
|                                                                               |
|                                                                               |
|   simulation parameters:                                                      |
|                                                                               |
|   effective refractive index          = 1.45                                  |
|   maximum refractive index modulation = 0.0001                                |
|   uniform grating                     = 0                                     |
|   gaussian apodized grating           = 0                                     |
|   width of gaussian apodization       = 1.5 mm                                |
|   hyperbolic tangent apodized grating = 1                                     |
|   alpha                               = 4.0                                   |
|   beta                                = 3.0                                   |
|   grating length                      = 10.0 mm                               |
|   phase mask pitch                    = 1060.0 nm                             |
|   phase mask chirp rate               = 5.0 nm/cm                             |
|   wavelength viewing range            = 4.0 nm                                |
|   number of calculation points        = 250                                  |
|                                                                               |
|                                                                               |
|   calculation results:                                                        |
|                                                                               |
|   center of gravity grating           = 1536.979 nm                           |
|   maximum reflectivity                = 0.048                                 |
|   FWHM                                = 5648.0 pm                              |
|   SLSR                                = 0.2 dB                                 |
|                                                                               |
|                                                                               |
---------------------------------------------------------------------------------

wavelength (nm), reflectivity (-), transmission (-), reflectivity (db), transmission (dB)
1531.375, 9.811402e-10, 0.9999863, -90.08269309997559, -5.953813342784997e-05
1531.4201807228917, 1.128818e-09, 0.99998295, -89.47376251220703, -7.403450126730604e-05
```

Figure 19: logfile layout example

Next to the header is the comma separated spectral data, i.e. wavelength (in nm), reflection coefficient, transmission coefficient, reflection in logarithmic scale and transmission in logarithmic scale. The amount of data points is directly related to the amount of calculation points used in the simulation (250 by default).

The file extension is .sim and can easily be loaded into Matlab, Excel, or any text editor.

6. Troubleshooting

GDS is unrestricted in what is parsed to the program. This flexibility can cause errors in the program, for instance if instead of a number text is parsed to the program an error will occur. GDS will not give a popup with error message or any sound to indicate that a problem has occurred. Furthermore, no popup window showing that the calculations have started will be displayed. Correcting the faulty entry and restarting the calculation is required.

Without the dongle GDS can be started and simulation values can be edited, however without the dongle present in the it system is not possible to run any simulation. Instead the program will issue a pop up screen stating that the required dongle is missing or has lost its validity. See for example Figure 20.
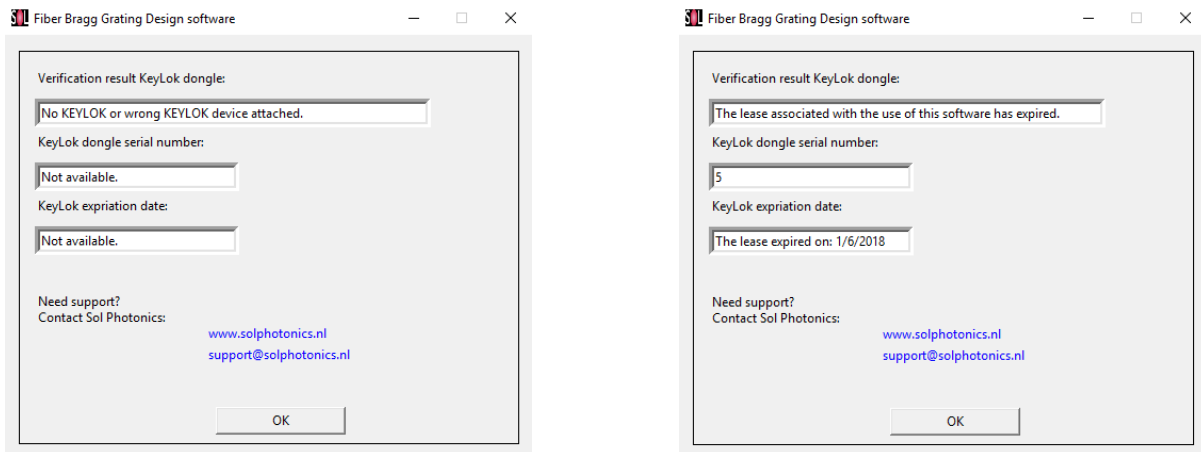
Figure 20: Example dongle not found error (left), example dongle expired (right).

Clicking "OK" will close the popup and return to the GDS window

Any support or problems please contact: info@solphotonics.nl or your local distributor.