Tutorial 33.01 Overview on Ultrashort Pulse Modeling with VirtualLab™

VirtualLab™ enables modeling the propagation of ultrashort pulses through optical systems. This tutorial introduces you to basic techniques.

Keywords: fs pulses, material dispersion, pulse propagation, ultrafast optics, ultrashort pulses

Required Toolboxes: Starter Toolbox

Related Tutorials: Tutorial 41.01

LightTrans

Introduction

Some concepts of pulse modeling with VirtualLab™

Pulse Propagation

- As any electromagnetic field, pulses are represented by the six real valued components of the electric and magnetic fields $\boldsymbol{E}(\boldsymbol{r},t)$ and $\boldsymbol{H}(\boldsymbol{r},t)$. In what follows we denote the components by the function $U(\boldsymbol{r},t)$.

- VirtualLab$^{\text{TM}}$ allows the simulation of pulse propagation. The pulse is defined in an input plane $\bar{\Omega}_{\text{in}}$. Then the pulse is propagated through a system and provided in the output plane $\bar{\Omega}_{\text{out}}$. Mathematically that is given by:

$$U(\boldsymbol{r}\in\bar{\Omega}_{\text{in}},t)\longrightarrow U(\boldsymbol{r}\in\bar{\Omega}_{\text{out}},t) \tag{1}$$

Complex Field

- The propagation time is denoted by $\hat{t}$.
- The pulse has the duration $\Delta\hat{t}$ in time. In general the duration depends on the lateral position and changes by propagation.
- A pulse has the carrier frequency $\bar{\omega}$.
- As typical in optics also VirtualLab™ uses the complex field component U_c instead of the real field component U. They are related by:

$$U(\boldsymbol{r}, t) = 2\Re\left(U_c(\boldsymbol{r}, t)\right) \tag{2}$$

Temporal Fourier Transformation

- At any point $\boldsymbol{r} = (x, y, z)$ the field components in the time domain are related to its counterpart in the frequency domain by a Fourier transformation:

$$
\begin{aligned}
U(\boldsymbol{r}, t) &= \mathcal{F}_\omega^{-1} \tilde{U}(\boldsymbol{r}, \omega) \\
&= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \tilde{E}(\boldsymbol{r}, \omega) \exp(-\mathrm{i}\omega t)\, \mathrm{d}\omega \qquad (3) \\
\tilde{U}(\boldsymbol{r}, \omega) &= \mathcal{F}_\omega U(\boldsymbol{r}, t) \\
&= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} E(\boldsymbol{r}, t) \exp(\mathrm{i}\omega t)\, \mathrm{d}t \qquad (4)
\end{aligned}
$$

- Analogous definitions hold for the complex field components U_c.

Envelope Function

- VirtualLab$^{\mathrm{TM}}$ uses the concept of the envelope function U_{e} in its simulations. The envelope function describes the pulse in the time domain without the carrier factor $e^{-\mathrm{i}\bar{\omega}t}$ and around the position $\hat{t}$. Thus, its definition is given by:

$$U_{\mathrm{c}}(\boldsymbol{r},t) =: U_{\mathrm{e}}(\boldsymbol{r},t-\hat{t})\,e^{-\mathrm{i}\bar{\omega}t} \tag{5}$$

with its spectrum

$$\tilde{U}_{\mathrm{c}}(\boldsymbol{r},\omega) = \tilde{U}_{\mathrm{e}}(\boldsymbol{r},\omega-\bar{\omega})\,e^{\mathrm{i}\omega\hat{t}} \tag{6}$$

Simulation with VirtualLab™: Part I

- VirtualLab™ provides $\tilde{U}_\mathrm{c}(r \in \bar{\Omega}_\mathrm{out}, \omega)$ of (6) as a harmonic field set.
- The frequency sampling is specified in the input plane $\bar{\Omega}_\mathrm{in}$ in the source dialog. It specifies the number of harmonic fields to be propagated.
- In order to reduce the sampling effort, VirtualLab™ ensures proper frequency sampling of $\tilde{U}_\mathrm{e}$ in (6) only.
- The phase factor $e^{\mathrm{i}\omega\hat{t}}$ in (6) is treated analytically before Fourier transformation into the time domain. To this end $\hat{t}$ is provided by the *Optical Path Length (OPL) Analyzer*.

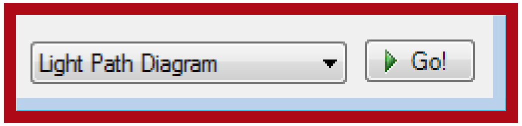
Pulse Propagation Through Homogeneous Media

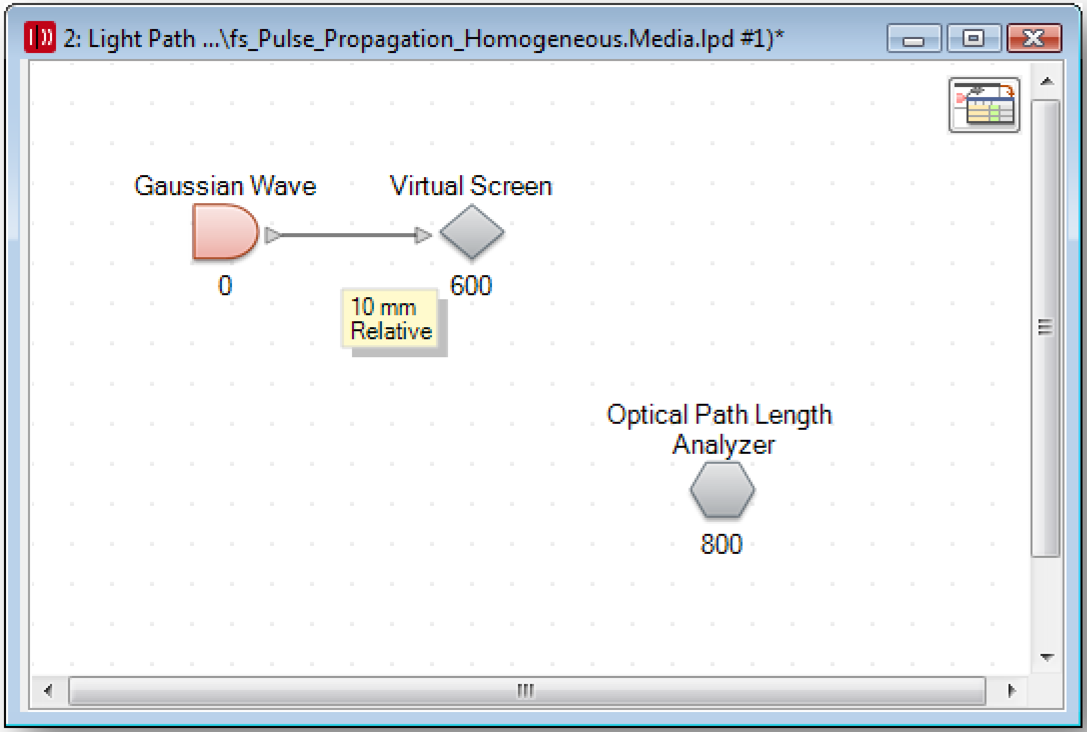
Simulation with VirtualLab™: Example

- Example considers fs pulse propagation through air
- Sample file: Tutorial_33.01_VLF1_free_space_propagation.lpd
- Source specifies 10 fs pulse with carrier wavelength of 800 nm. It uses 29 harmonic fields.
- The pulse propagates 10 mm

Simulation with VirtualLab™: Example

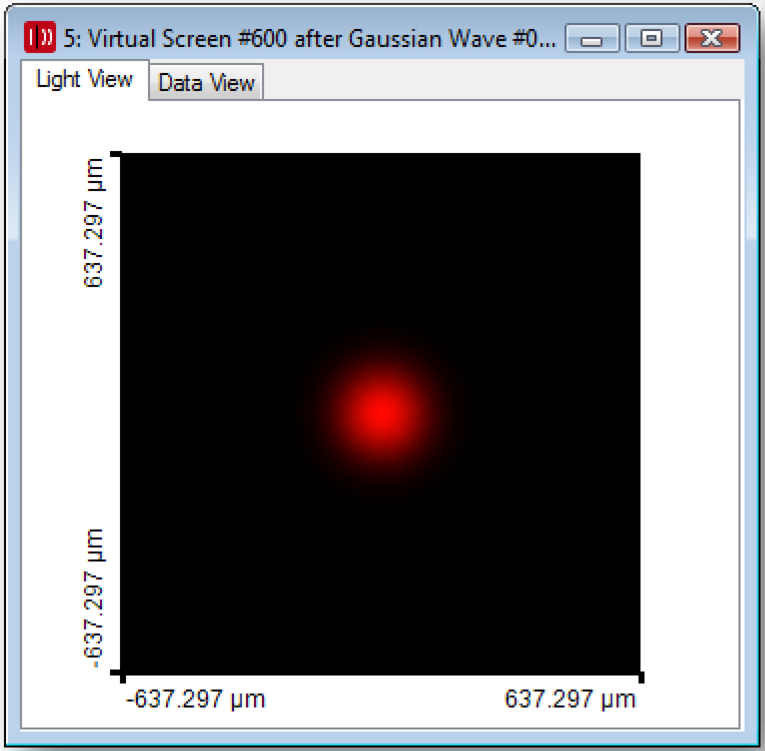
- Run LPD





Simulation with VirtualLab™: Example

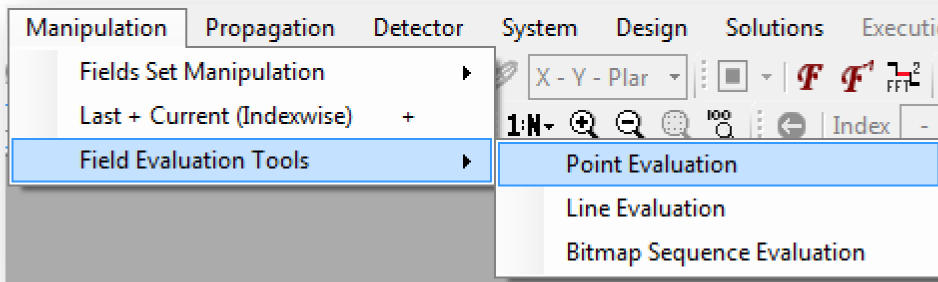
- Resulting Harmonic Field Set (HFS)

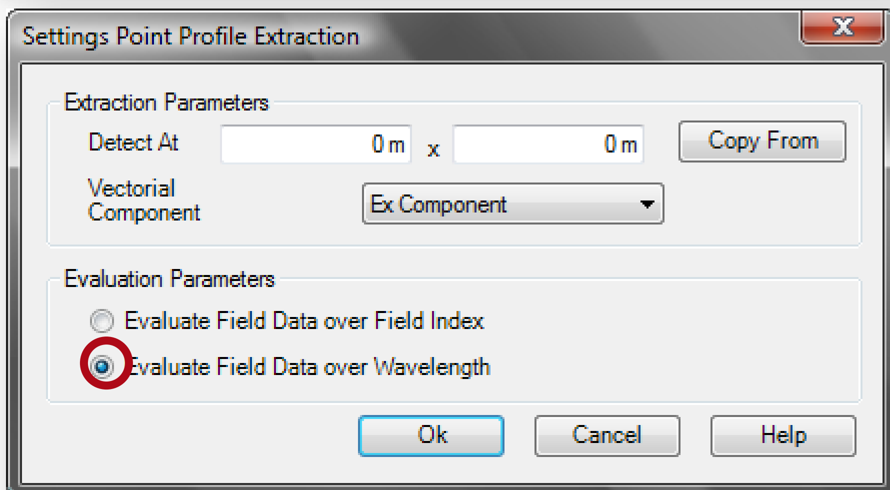


$$\tilde{U}_{\mathrm{c}}(r \in \bar{\Omega}_{\mathrm{out}}, \omega) = \tilde{U}_{\mathrm{e}}(r \in \bar{\Omega}_{\mathrm{out}}, \omega - \bar{\omega})\, e^{\mathrm{i}\omega\hat{t}}$$

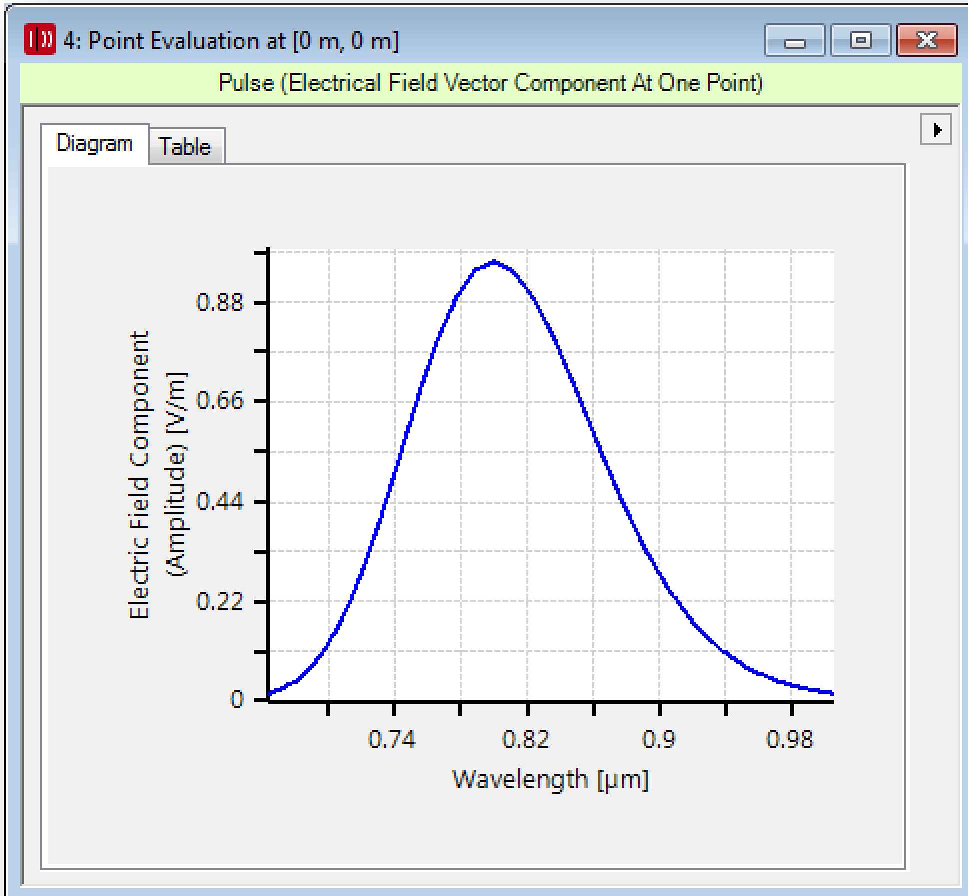
Field Evaluation Tools

- VirtualLab™ 4.5 allows investigation of pulse in time domain by *Field Evaluation Tools*





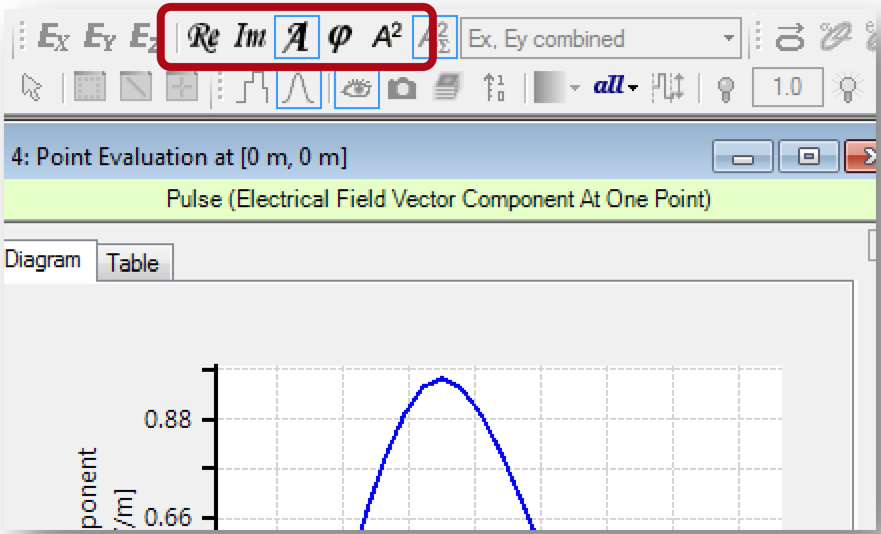
Simulation with VirtualLab™: Example



$$\tilde{U}_{\mathrm{c}}(0,0,z_{\mathrm{out}},\omega) = \tilde{U}_{\mathrm{e}}(0,0,z_{\mathrm{out}},\omega-\bar{\omega})\, e^{i\omega\hat{t}}$$

Simulation with VirtualLab™: Example

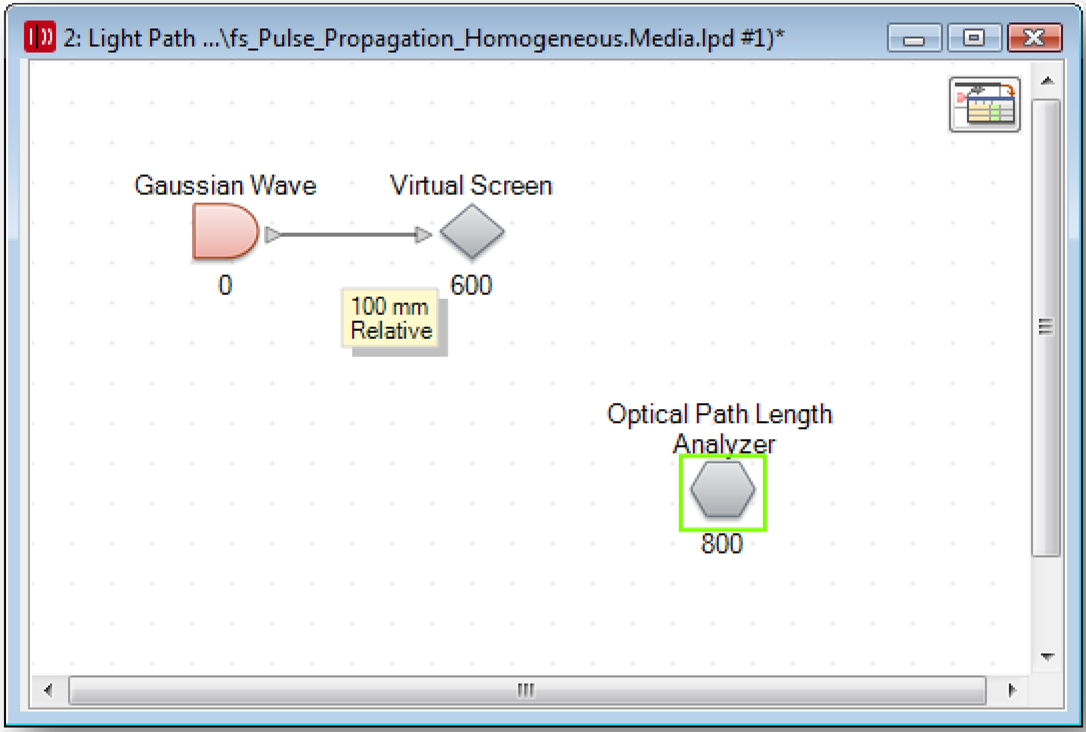
- For pulse modeling a new diagram type has been introduced.
- It allows investigation of amplitude, phase, ...



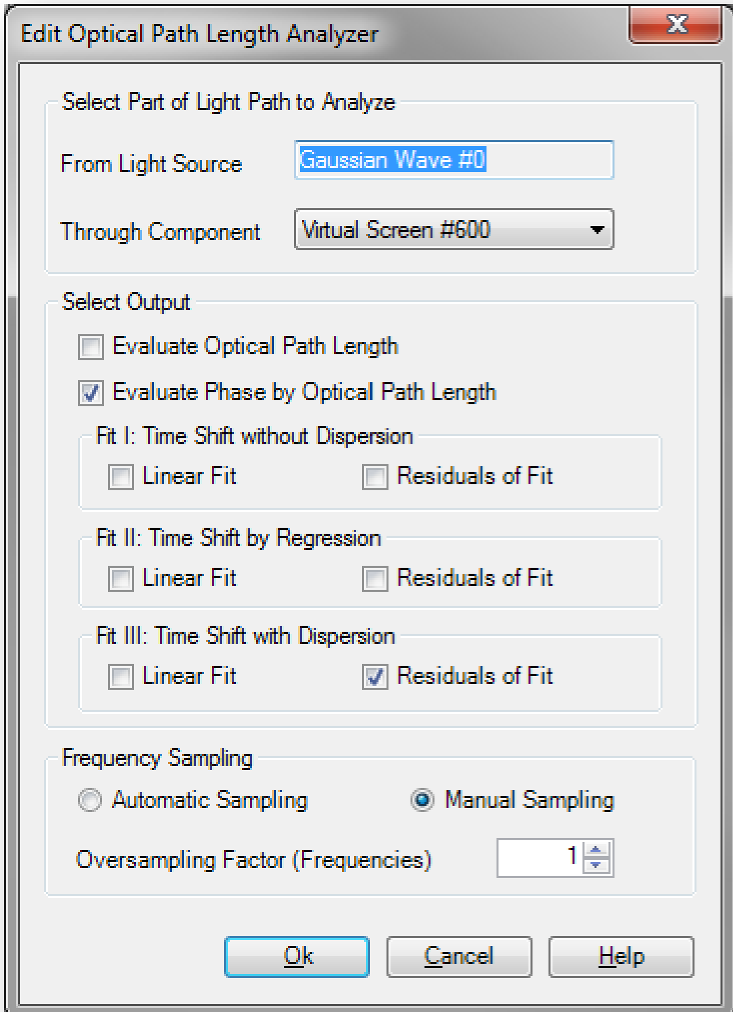
- In particular it allows the temporal Fourier transformation

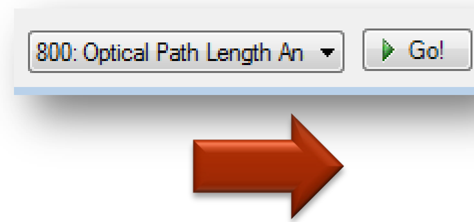
Optical Path Length (OPL) Analyzer

- Before Fourier transformation, time shift must be calculated by *OPL Analyzer*.



Simulation with VirtualLab™: Example





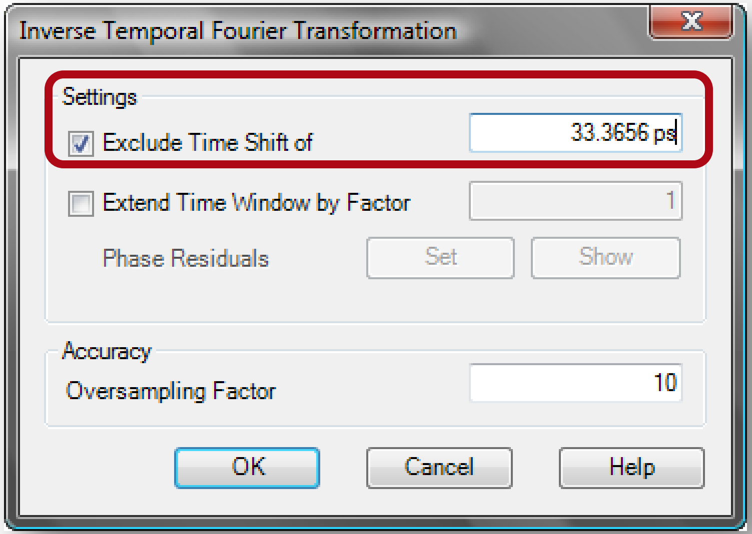
Simulation with VirtualLab™: Example

Detector Results

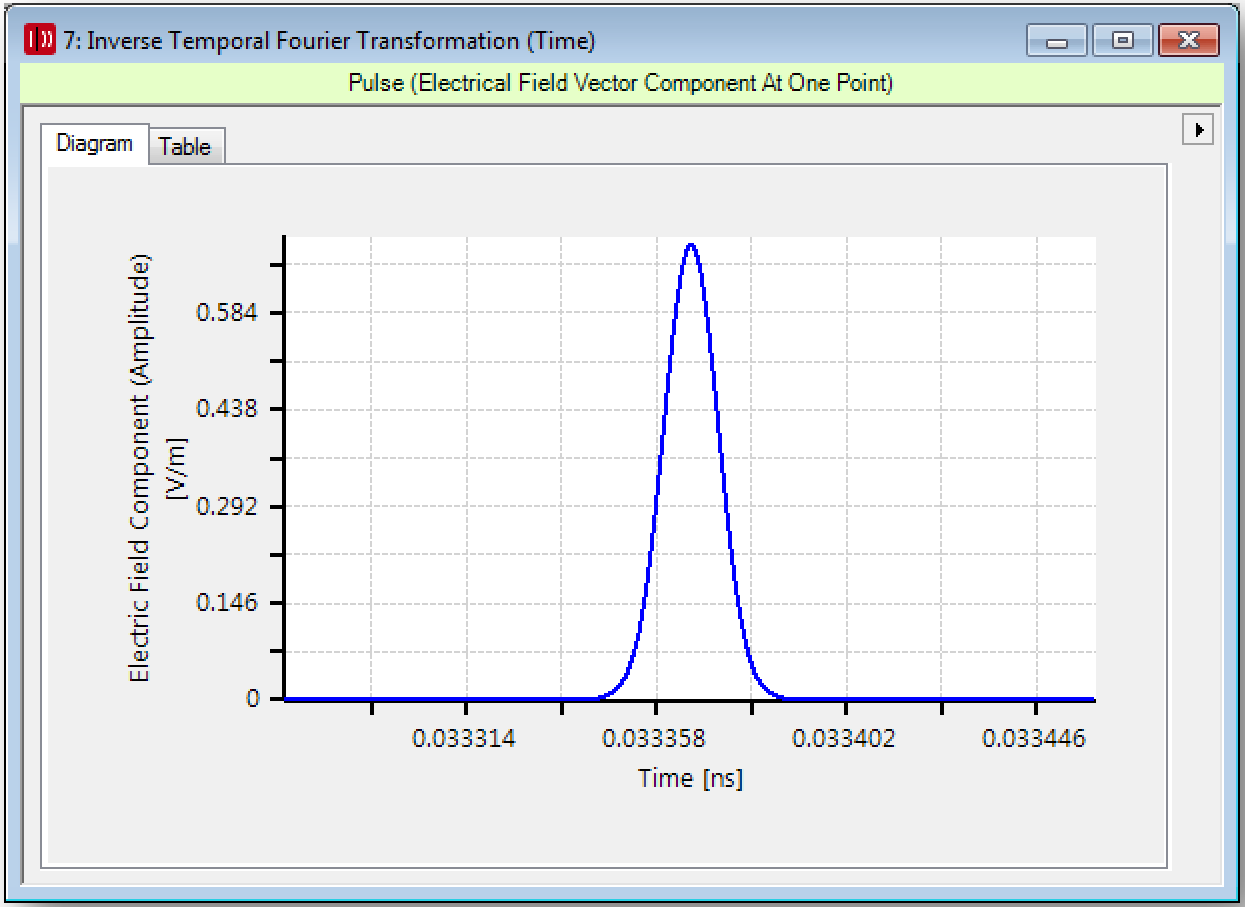
Result
33.366 ps

- 33.366 ps is the time shift
- By copy and paste it can be introduced in the Fourier transformation step

Temporal Fourier Transformation



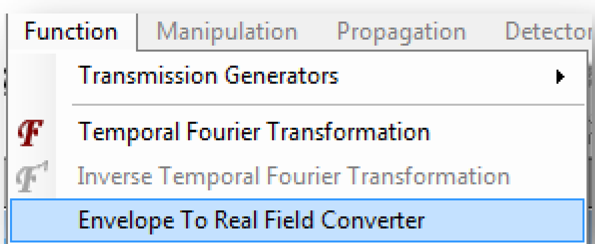
Simulation with VirtualLab™: Example



$$U_{\mathrm{e}}(0, 0, z_{\mathrm{out}}, t - \hat{t})$$

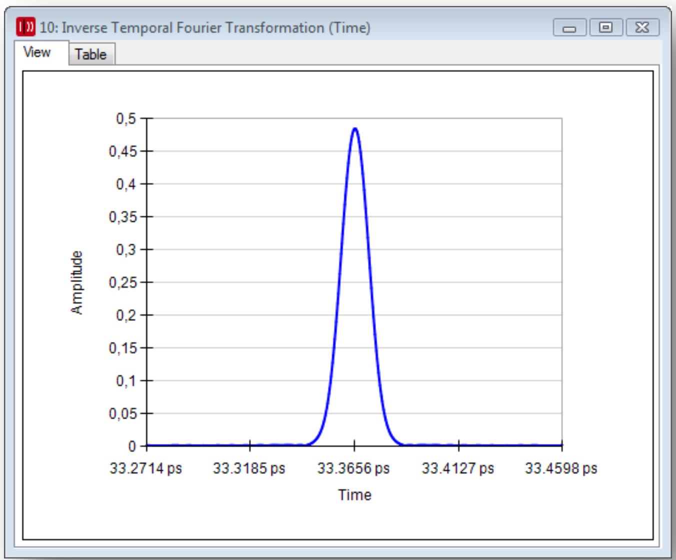
Envelope to Real Field Converter

- The inverse temporal Fourier transformation yields the envelope function in he time domain.
- The *Envelope to Real Field Converter* multiples $e^{-\mathrm{i}\bar{\omega}t}$ to the envelope function. That includes the carrier frequency. Then equation (2) is implemented to obtain the real field component.
- Because of the high carrier frequency, best results are obtained for oversampling in time domain by factor 10 and more.

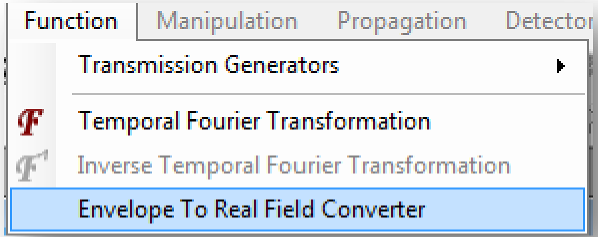


Simulation with VirtualLab™: Example

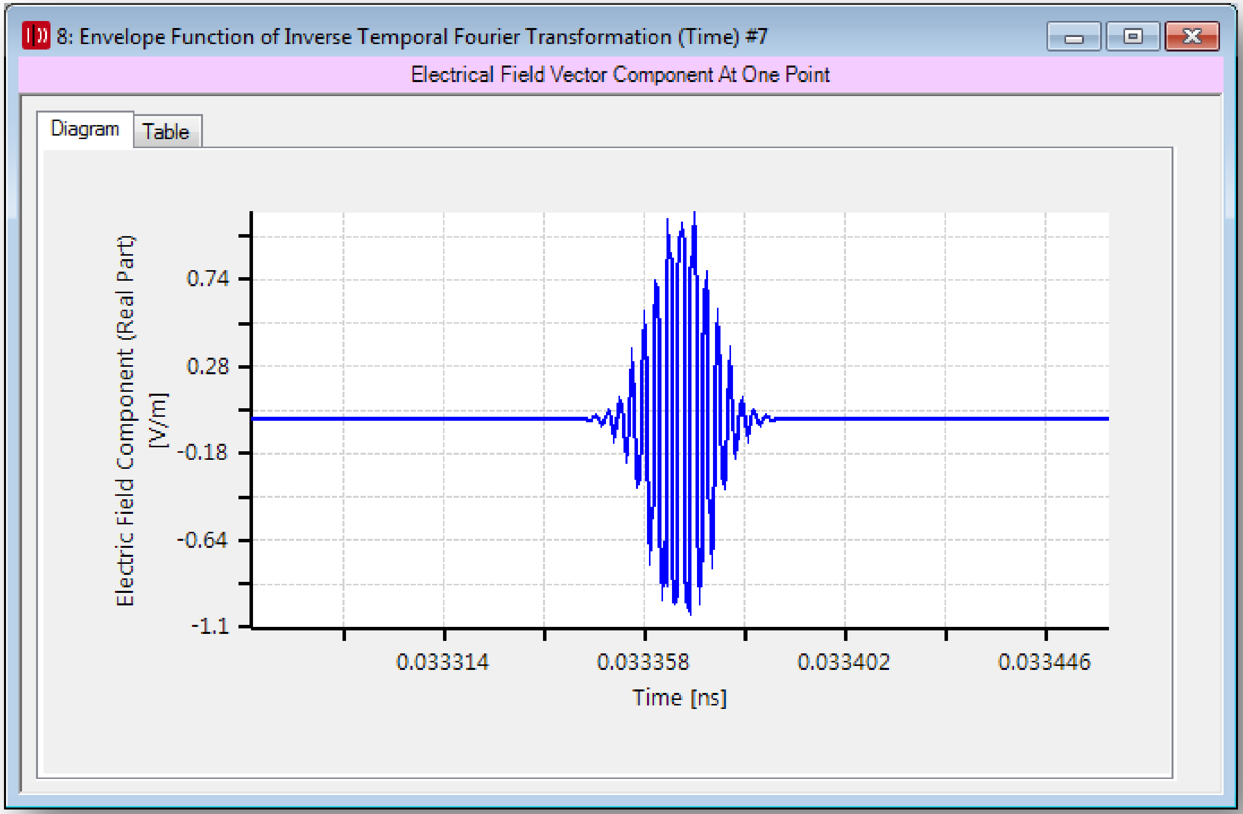
- Calculate envelope function by inverse FT with oversampling factor 20.



$$U_{\mathrm{e}}(0,0,z_{\mathrm{out}},t-\hat{t})$$



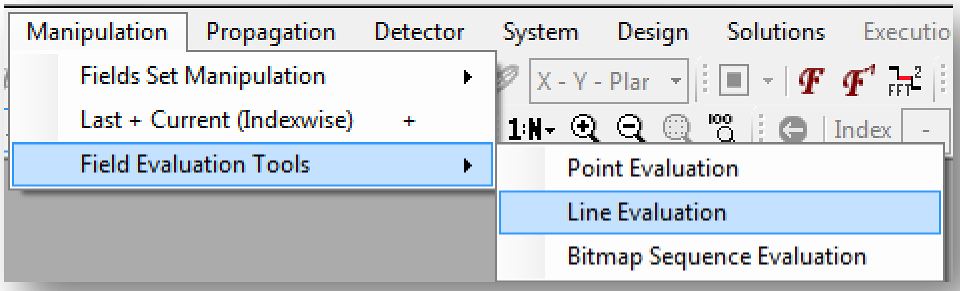
Simulation with VirtualLab™: Example



$$U(0,0,z_{\text{out}},t)$$

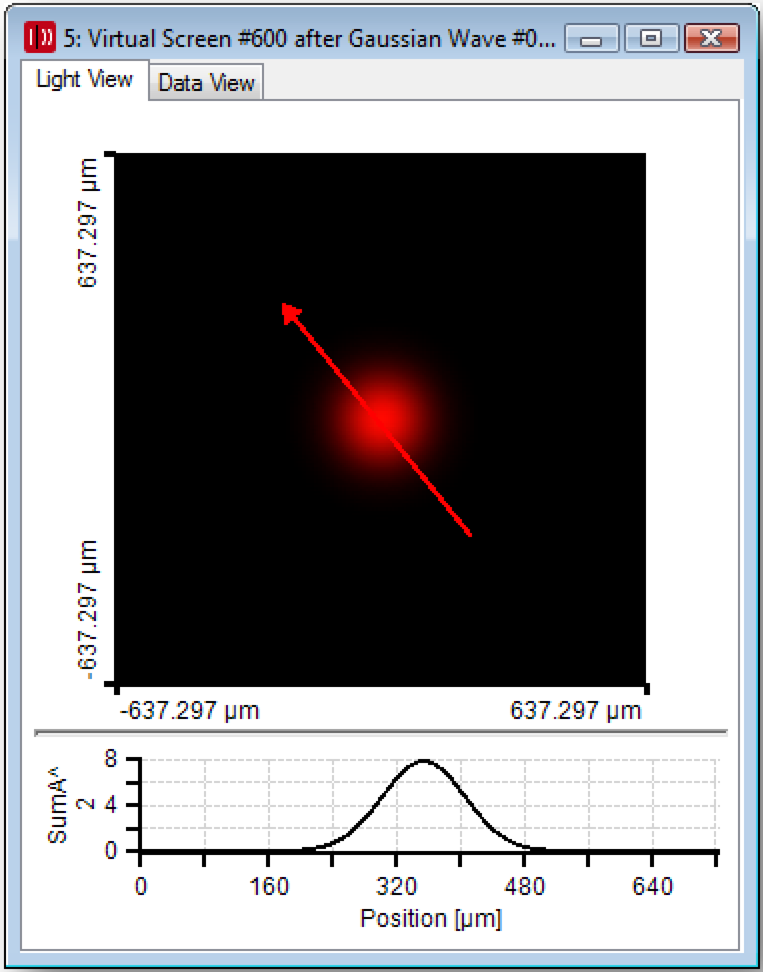
Line Evaluation Tool

- Instead of *Point Evaluation* the *Line Evaluation* can be used to obtain
  $$\tilde{U}_{\mathrm{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathrm{out}}, \omega) = \tilde{U}_{\mathrm{e}}(\boldsymbol{r} \in \bar{\Omega}_{\mathrm{out}}, \omega - \bar{\omega})\, e^{\mathrm{i}\omega \hat{t}}$$
  along a line in the plane.

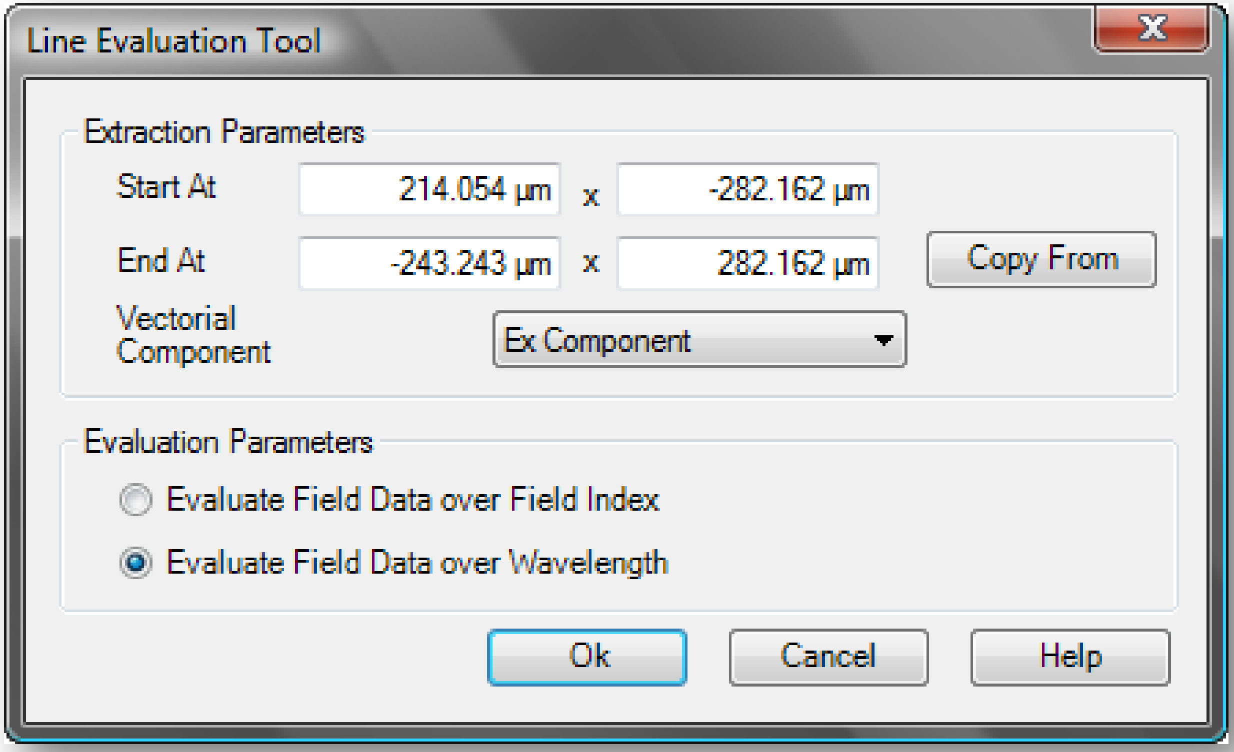


Simulation with VirtualLab™: Example

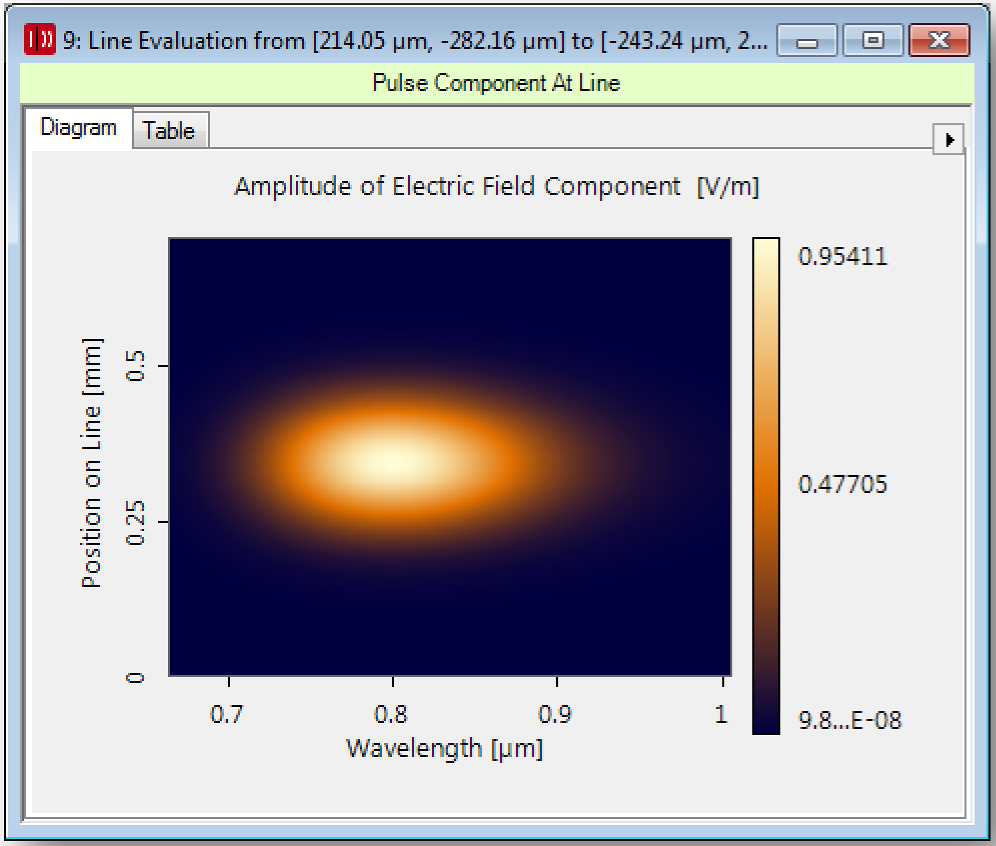
- Start with line selection in simulated HFS
- Use *Line Evaluation* Tool



Simulation with VirtualLab™: Example

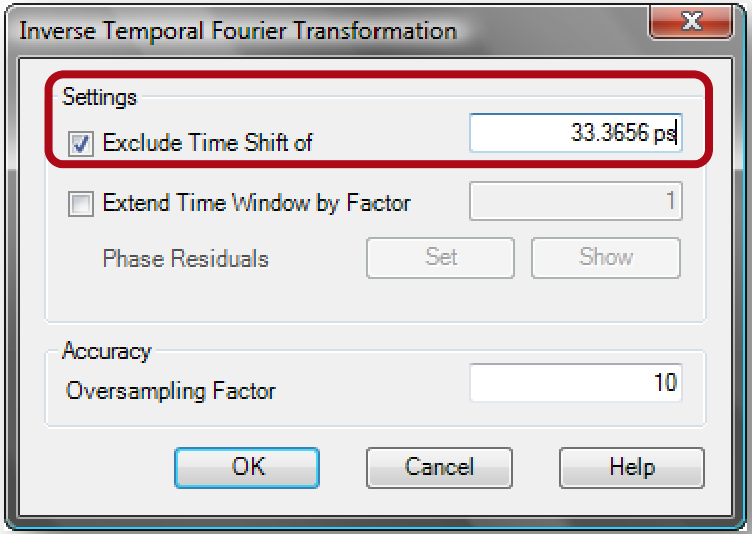


Simulation with VirtualLab™: Example

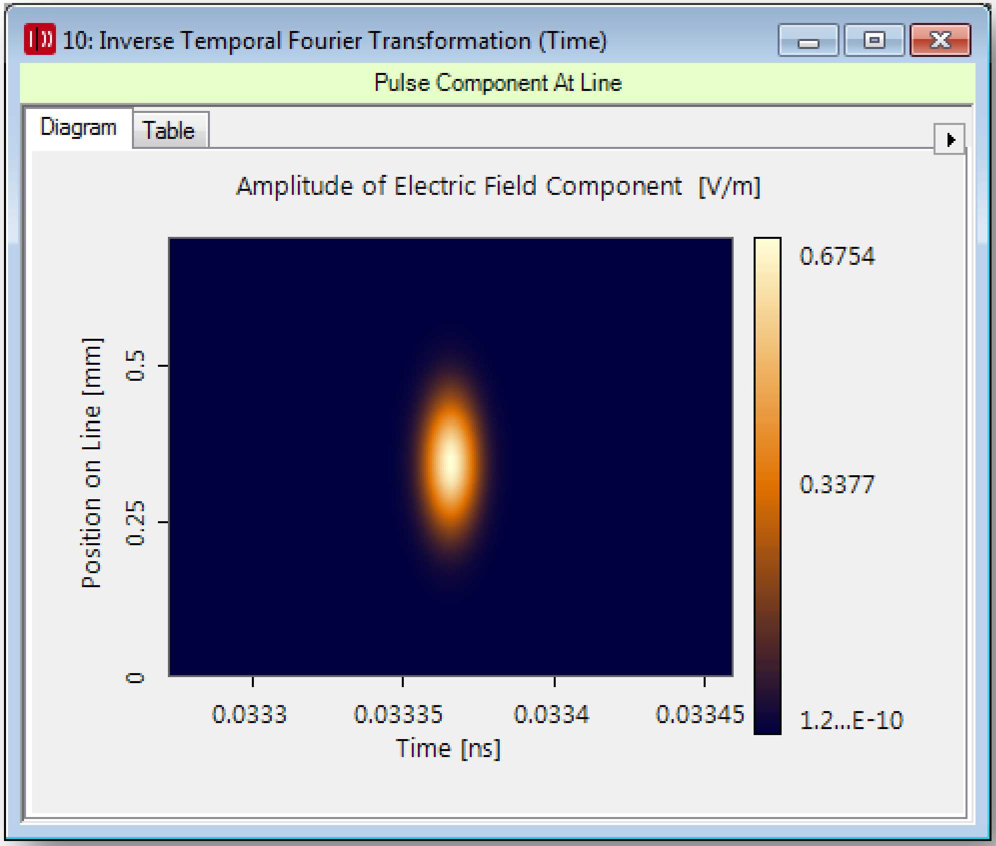


$$\tilde{U}_{\mathrm{c}}(r \in \mathrm{Line}, \omega) = \tilde{U}_{\mathrm{e}}(r \in \mathrm{Line}, \omega - \bar{\omega})\, e^{\mathrm{i}\omega\hat{t}}$$

Simulation with VirtualLab™: Example



Simulation with VirtualLab™: Example



$$U_{\mathrm{e}}(r \in \mathrm{Line}, t - \hat{t})$$

Specification of fs Pulse Source

Separable Field in Time and Space

- It is quite common to assume a separable approach in the input plane in pulse modeling, that means

$$U_{\mathsf{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathsf{in}}, t) = T(t) U_{\mathsf{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathsf{in}}) \,.$$

- Using the concept of the envelope function leads to

$$U_{\mathsf{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathsf{in}}, t) = T_{\mathsf{e}}(t)\, U_{\mathsf{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathsf{in}})\, e^{-\mathrm{i}\bar{\omega} t}$$

when we assume $\hat{t} = 0$ in the input plane.

- That results in the spectrum

$$\tilde{U}_{\mathsf{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathsf{in}}, \omega) = \tilde{T}_{\mathsf{e}}(\omega - \bar{\omega})\, U_{\mathsf{c}}(\boldsymbol{r} \in \bar{\Omega}_{\mathsf{in}}) \,.$$

Gaussian Type Envelope Function

- Of special concern are pulses of the separable form with a Gaussian envelope function

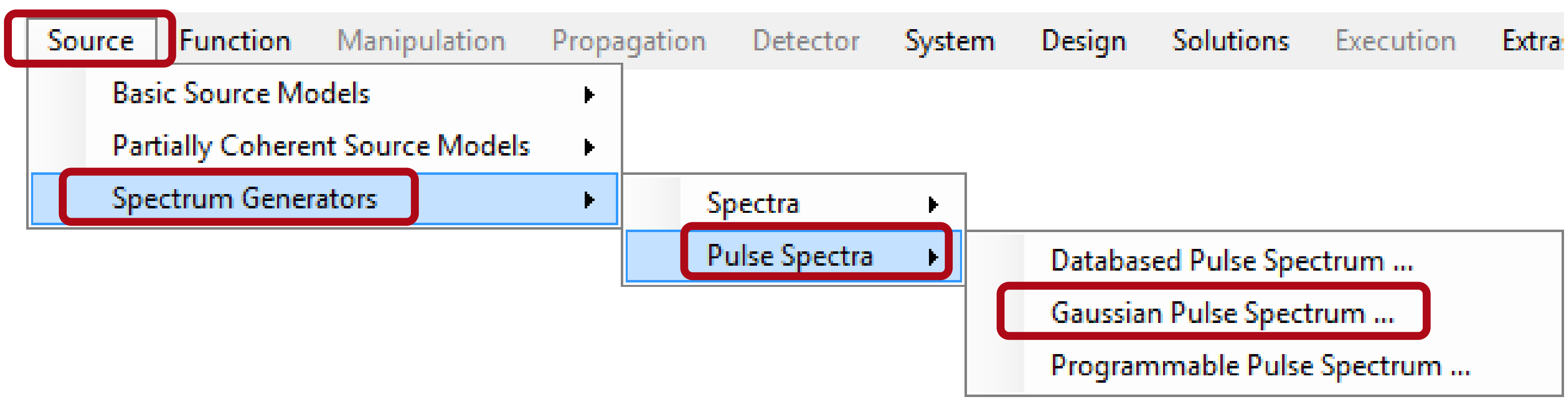
$$T_{\mathrm{e}}(t) = \exp[-a\,t^2]\,.$$

- For a Gaussian envelope function in time the frequency spectrum can be calculated analytically and is also Gaussian:

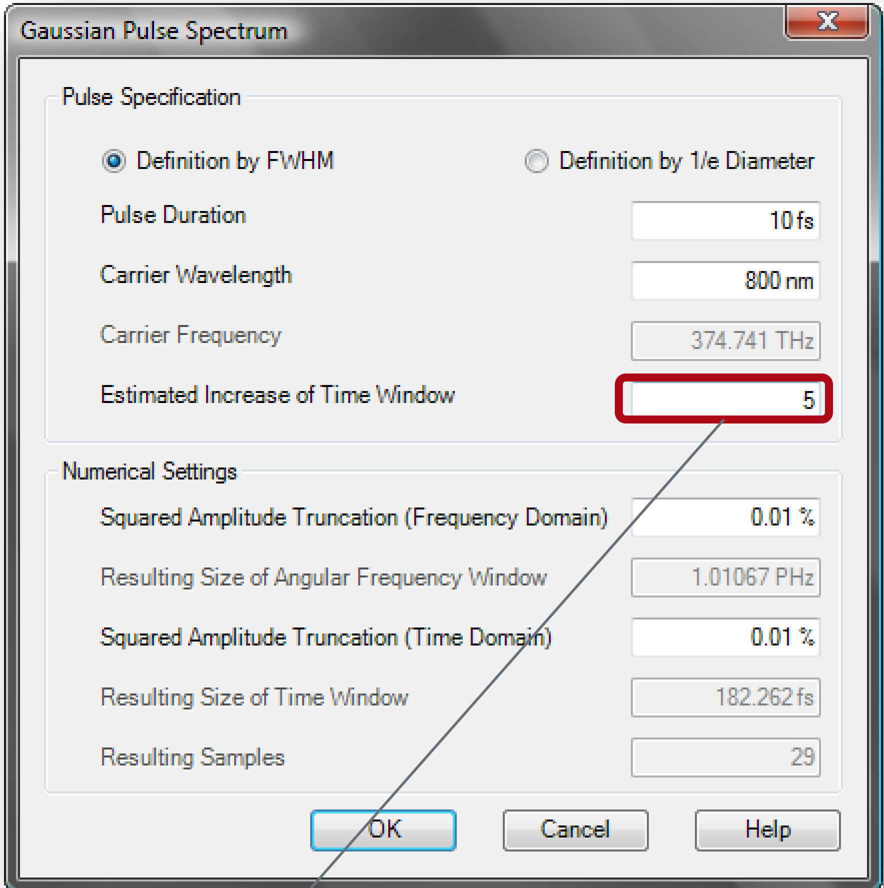
$$\tilde{T}_{\mathrm{e}}(\omega) = \frac{1}{\sqrt{2\,a}}\,\exp\left[-\frac{\omega^2}{4\,a}\right]$$

Gaussian Type Envelope Function

- In VirtualLab™ the Gaussian pulse spectrum is defined by specification of the pulse duration as FWHM or $1/e$ values (related to intensity), the carrier wavelength and truncation of the Gaussian in time and frequency domain.

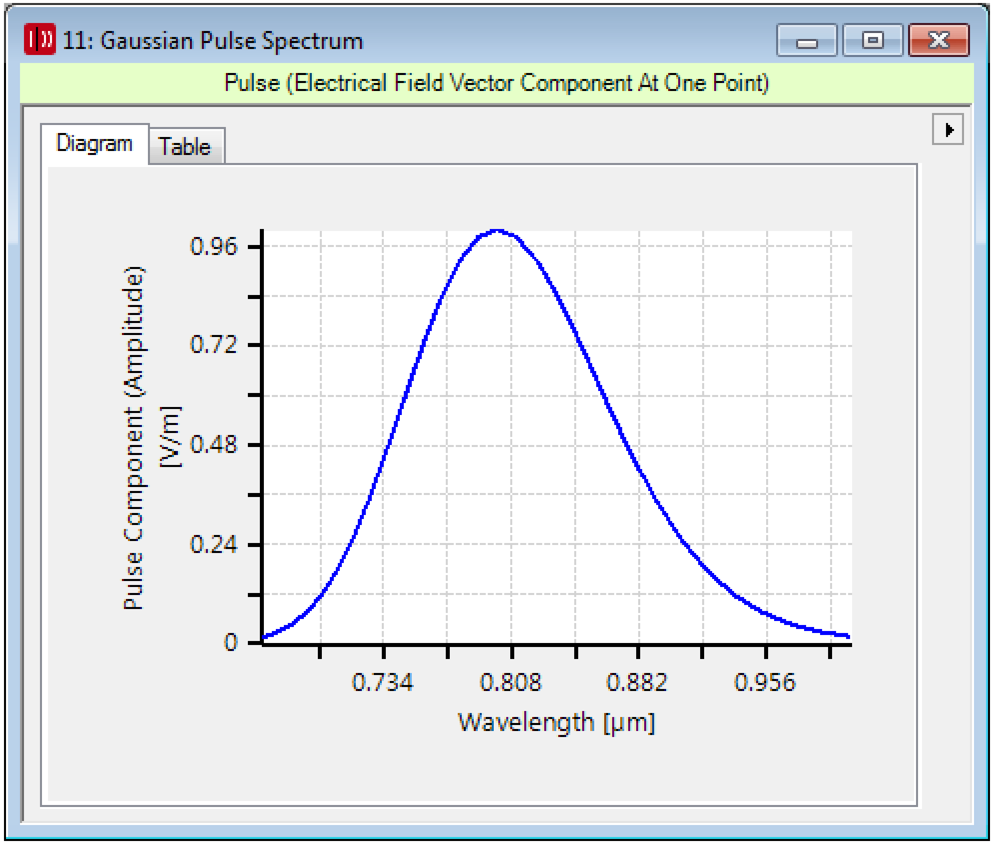


Gaussian Type Envelope Function



Typically propagating pulses increases their duration. The time window must be chosen accordingly.

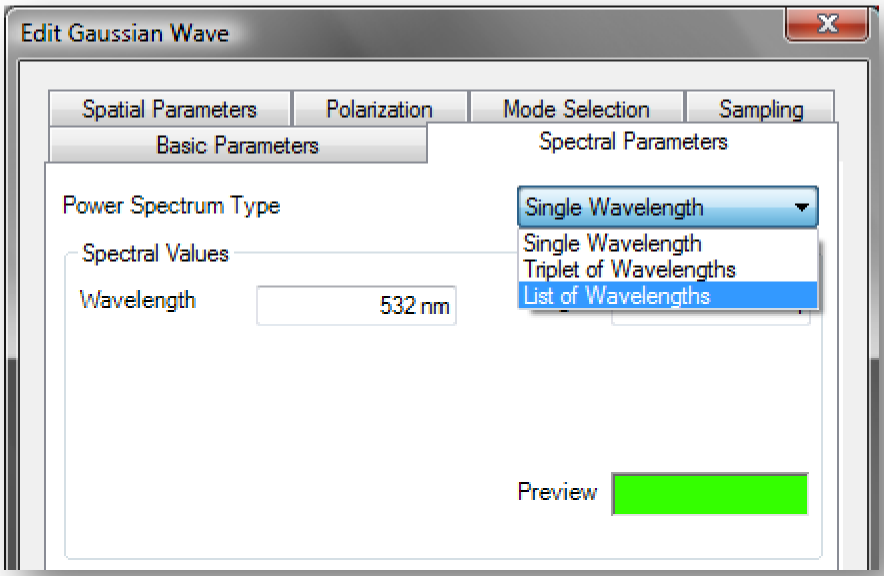
Gaussian Type Envelope Spectrum



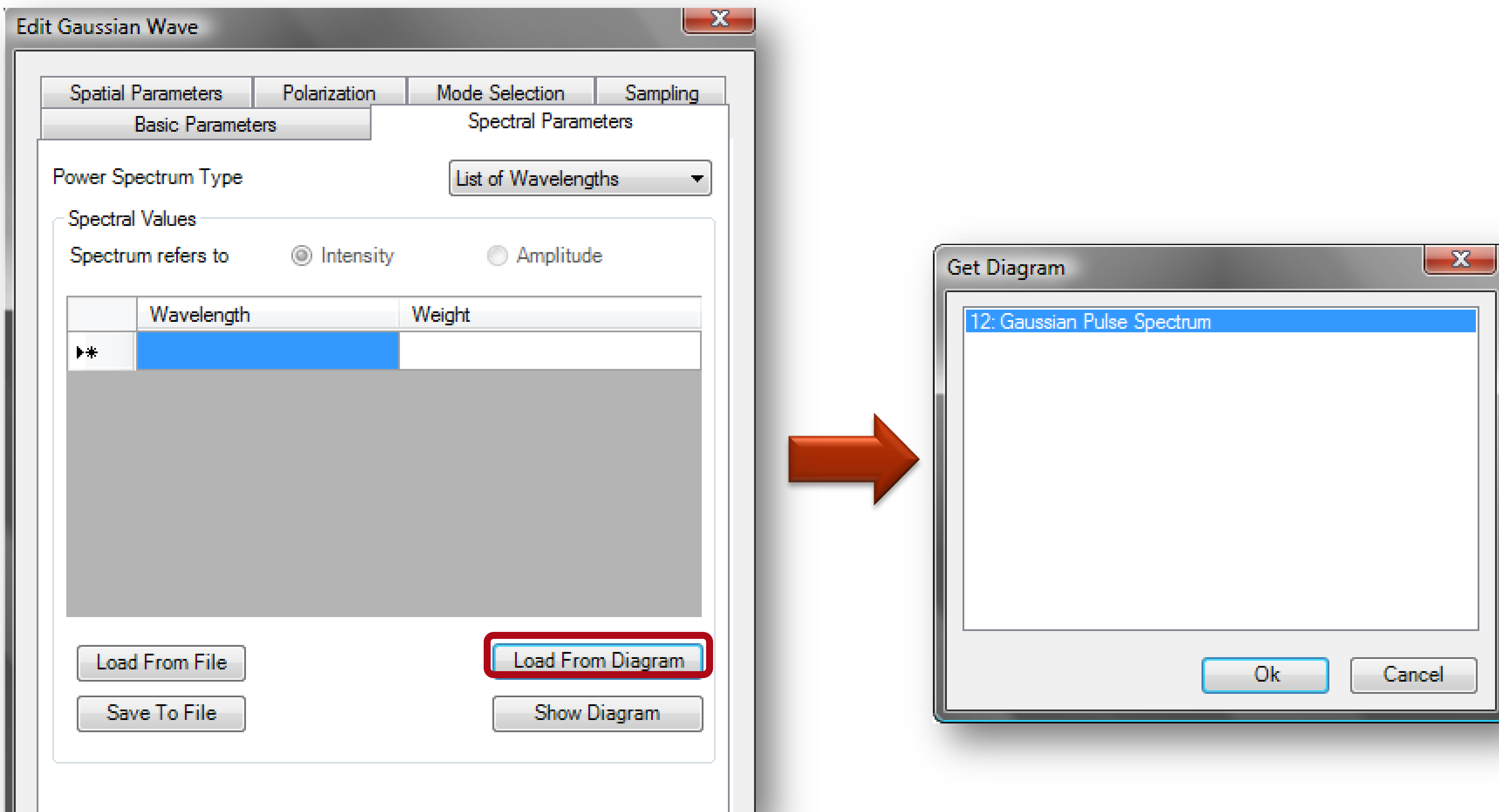
$$\tilde{T}_{\mathrm{e}}(\omega) = \frac{1}{\sqrt{2\,a}} \exp\left[-\frac{\omega^2}{4\,a}\right]$$

Pulse Specification

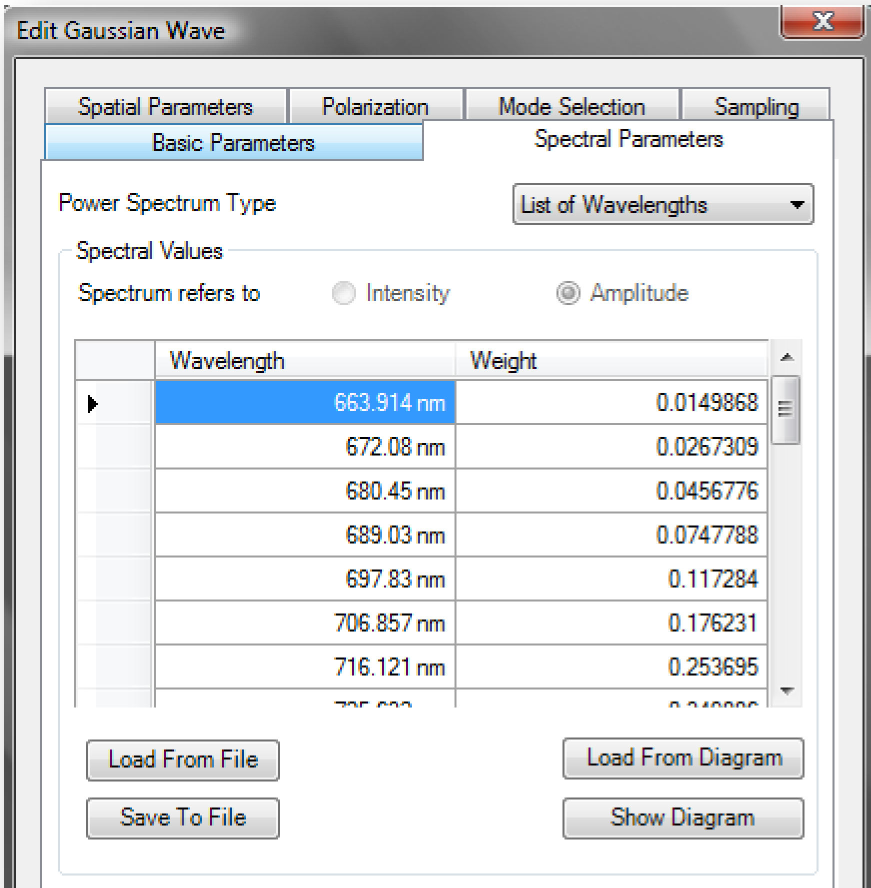
- The envelope spectrum can be introduced in any source of VirtualLab™ using the *Spectral Parameters Tab*.



Pulse Specification



Pulse Specification

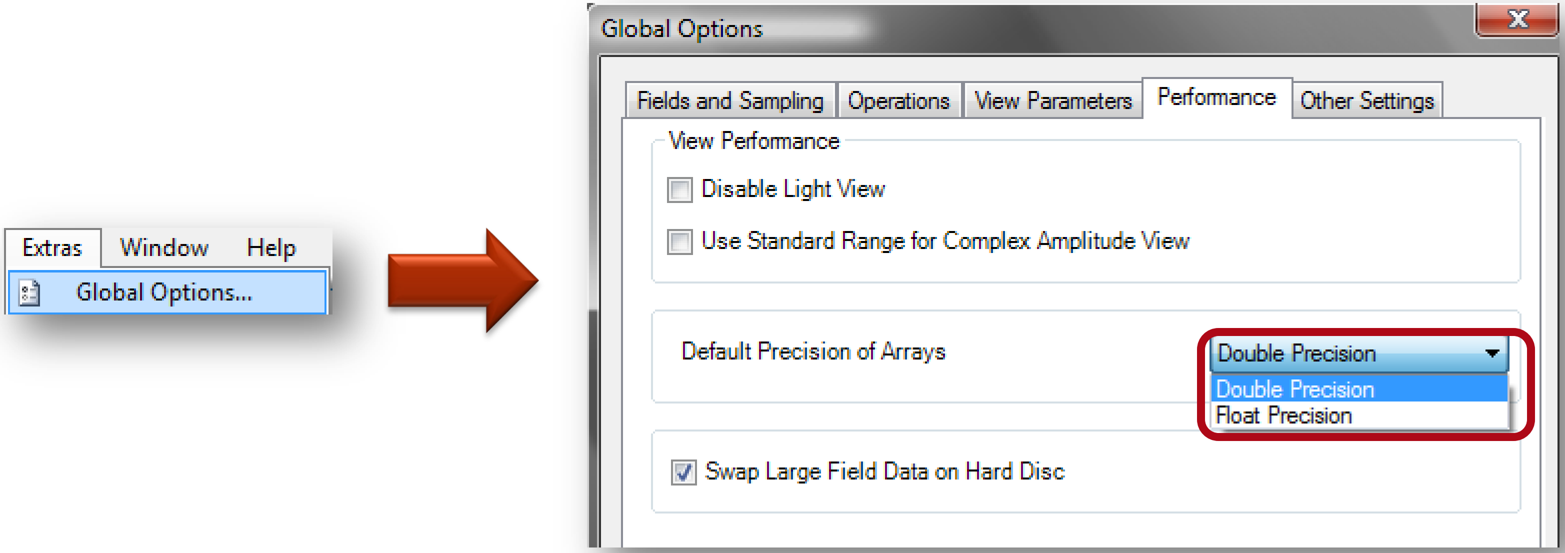


Pulse source is ready for simulations!

Smart Sampling Reduction for Material Dispersion

Double Precision Required

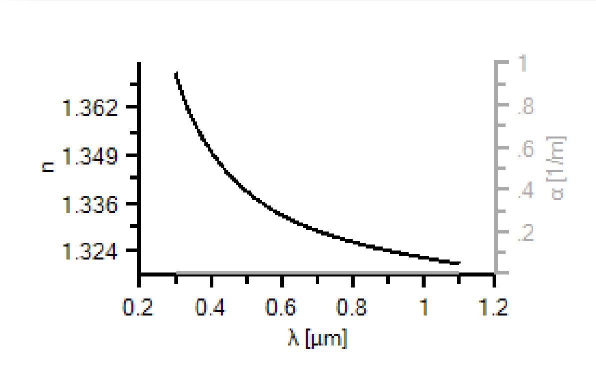
- In fs pulse modeling with material dispersion effects we urgently recommend the use of double precision for VirtualLab™ simulations



- **Do it now!!!**

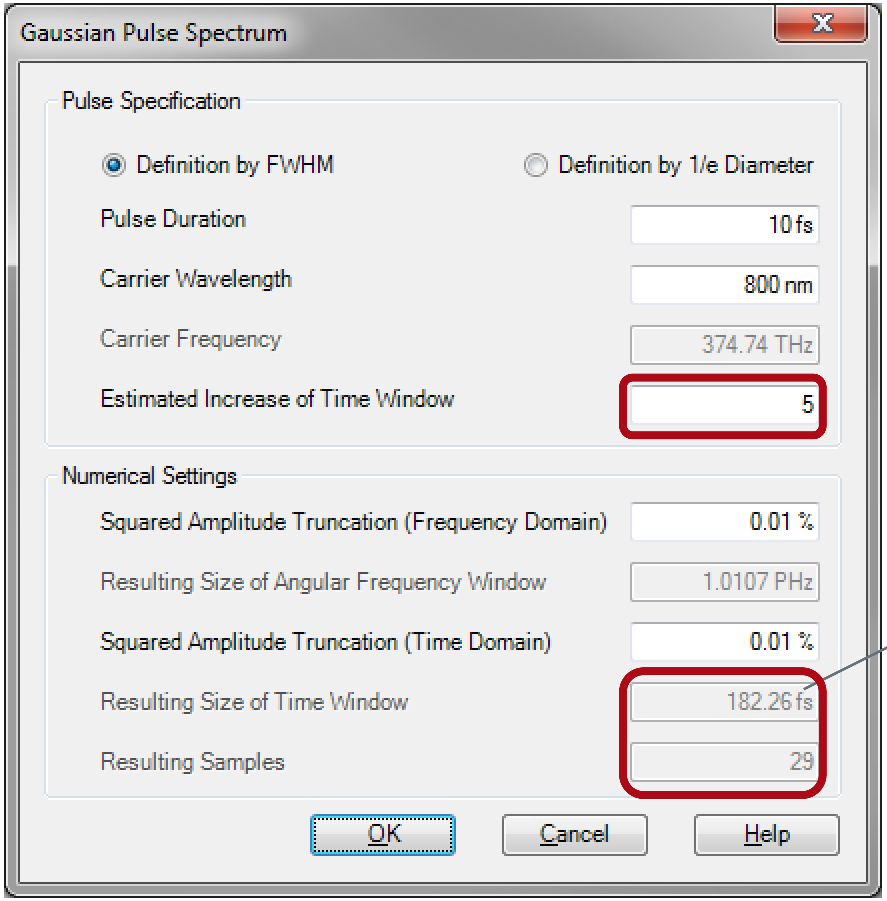
Simulation with VirtualLab™: Example

- Example considers fs pulse propagation through water
- Sample file: Tutorial_33.01_VLF2_material_dispersion.lpd
- Source specifies 10 fs pulse with carrier wavelength of 800 nm. It uses 29 harmonic fields.
- The pulse propagates 100 mm
- Dispersion curve of water:



Initial Time Window

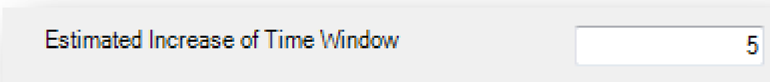
- Envelope spectrum is specified by



Time window: 182.3 fs

Initial Time Window

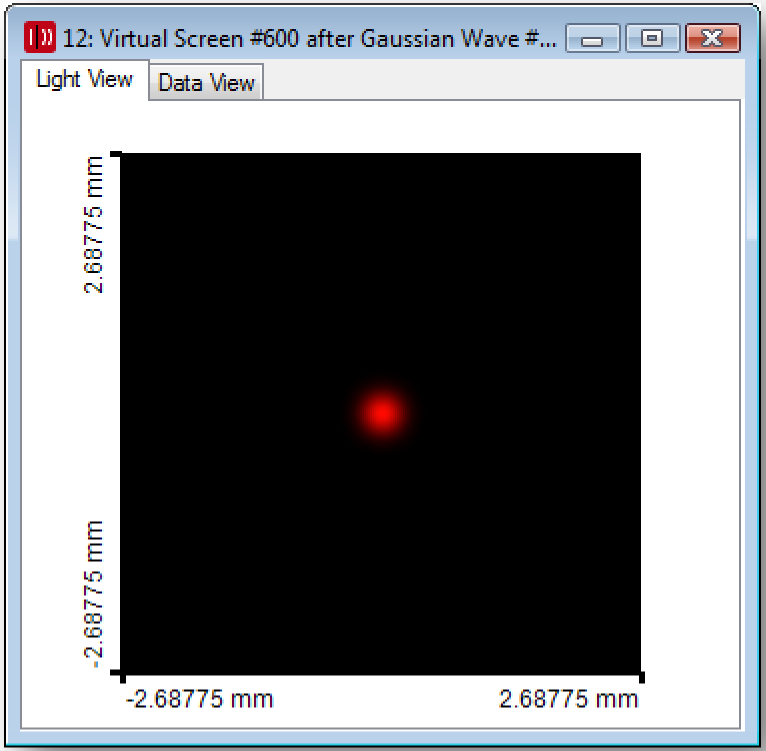
- Specification of pulse envelope function includes determination of time window available in simulation.
- Time window can be icreased by higher factor in:



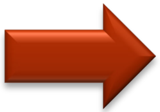
- However, then the number of harmonic fields to be propagated increases also.
- Problem: Material dispersion typically leads to significant entlargement of pulse. Resulting pulse must fit into time window to avoid aliasing.
- Example of this problem is shown next.

Simulation with VirtualLab™: Example

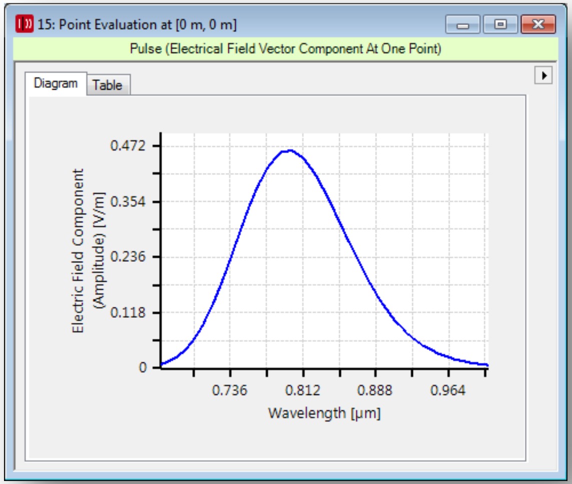
- Running sample file leads to



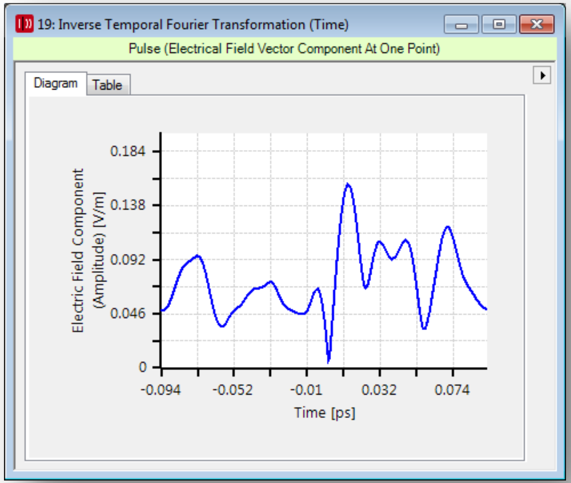
Point evaluation at (0,0)



Simulation with VirtualLab™: Example



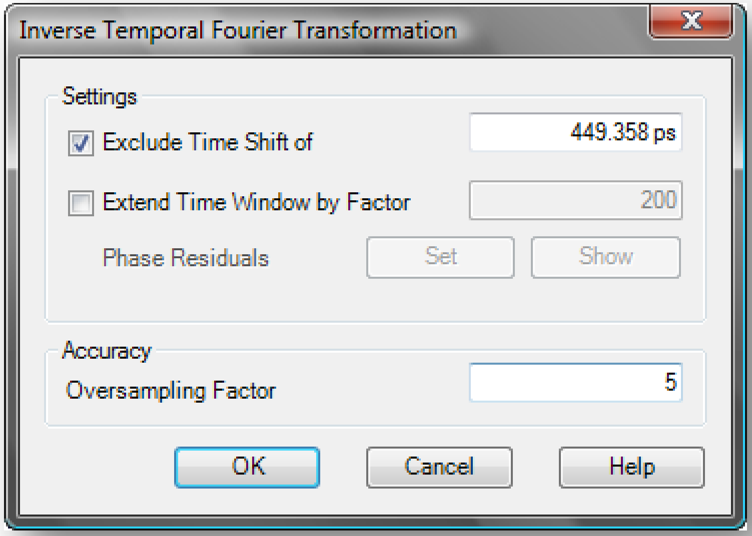
- Magnitude of envelope spectrum



- Phase of envelope spectrum
- Looks random-like
- Assumption: undersampled

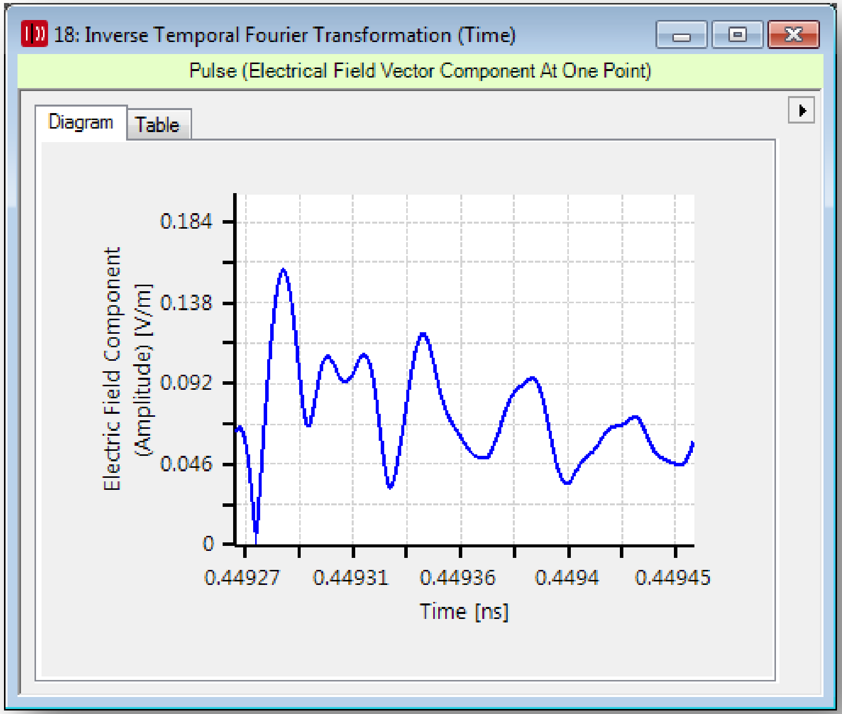
Simulation with VirtualLab™: Example

- Run OPL Analyzer
- Calculated time shift: 449.358 ps
- Perform inverse Fourier transformation



Simulation with VirtualLab™: Example

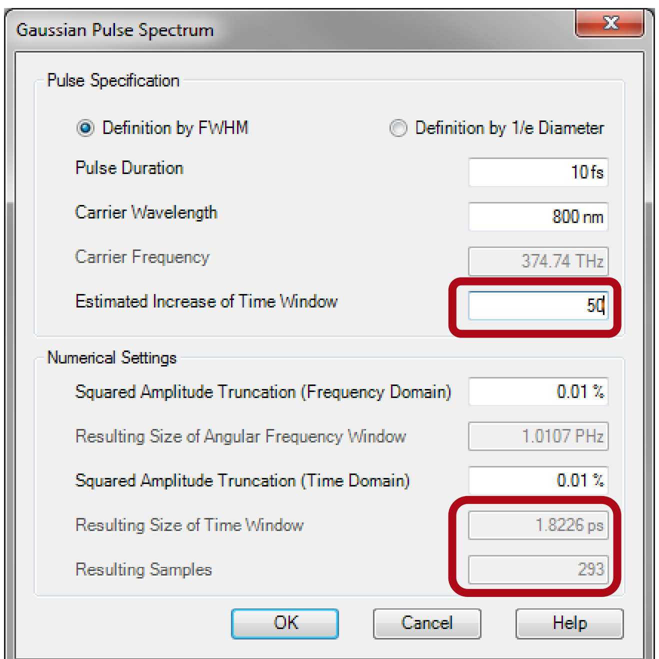
- Resulting pulse envelope:



- Result has no physical meaning. Time window too small to house pulse.

Initial Time Window Size?

- In this example the resulting pulse has a size of several ps (we will see that soon).
- Preparation in the initial time window would require more than 250 harmonic fields!

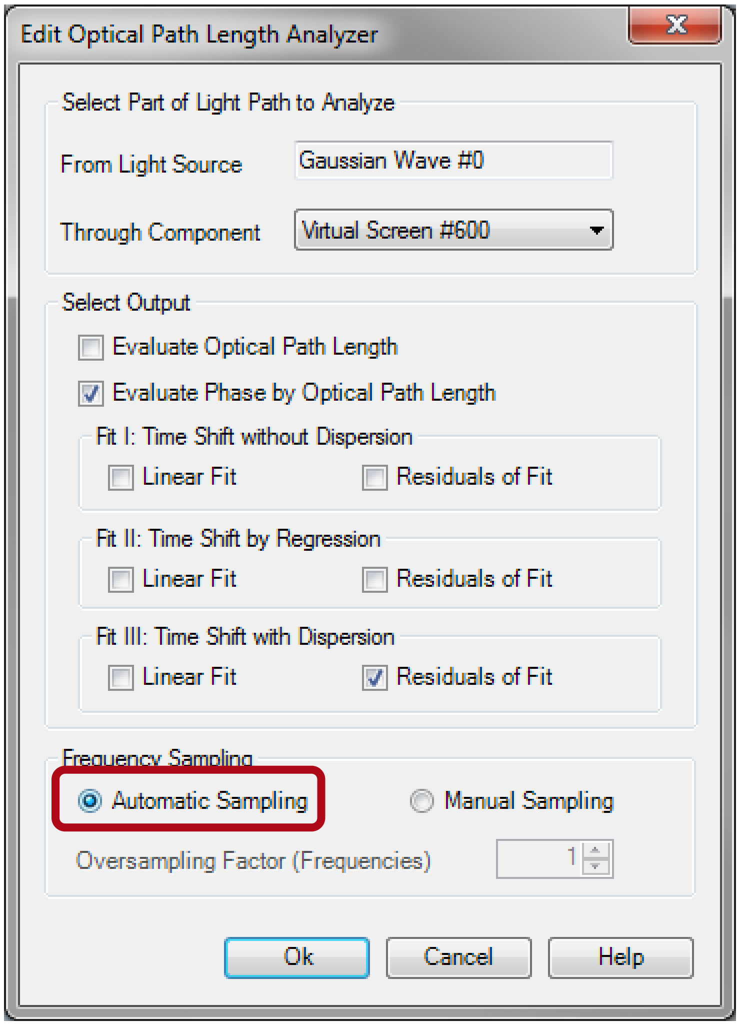


Not practical for fast simulation!

Smart Inclusion of Material Dispersion

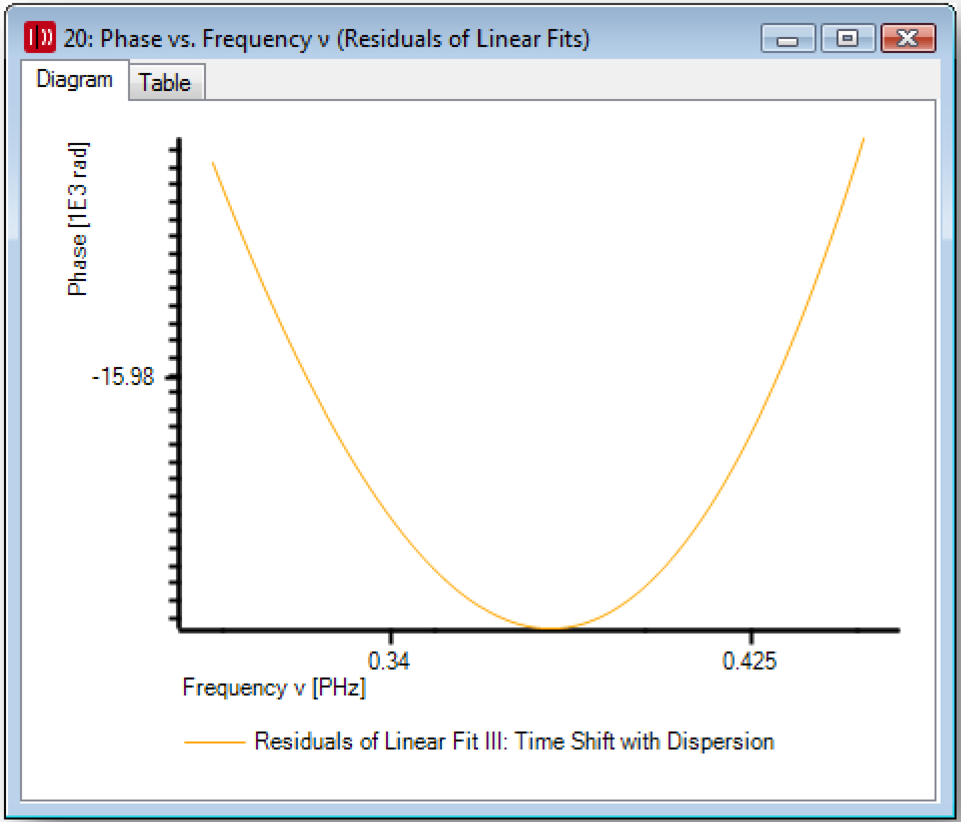
- VirtualLab™ offers a smart solution of this problem.
- OPL analyzer provoides change of phase due to material dispersion: phase residual
- That can be calculated for an arbitrarily fine frequency sampling.
- Smart processing allows increase of time window in order to house pulse without increase of initial time window.
- Next this technique is demostrated.

Phase Residual Calculation by OPL Analyzer



- Set Frequency Sampling to automatic mode.
- Run OPL Anlyzer.

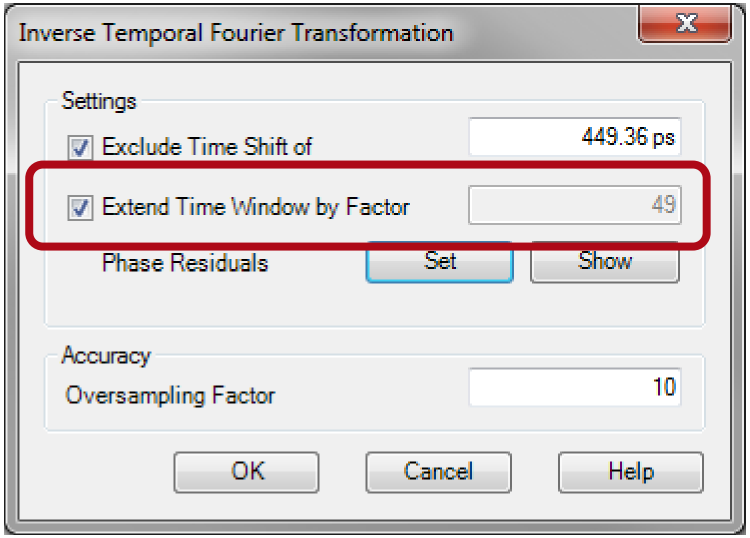
Simulation with VirtualLab™: Example



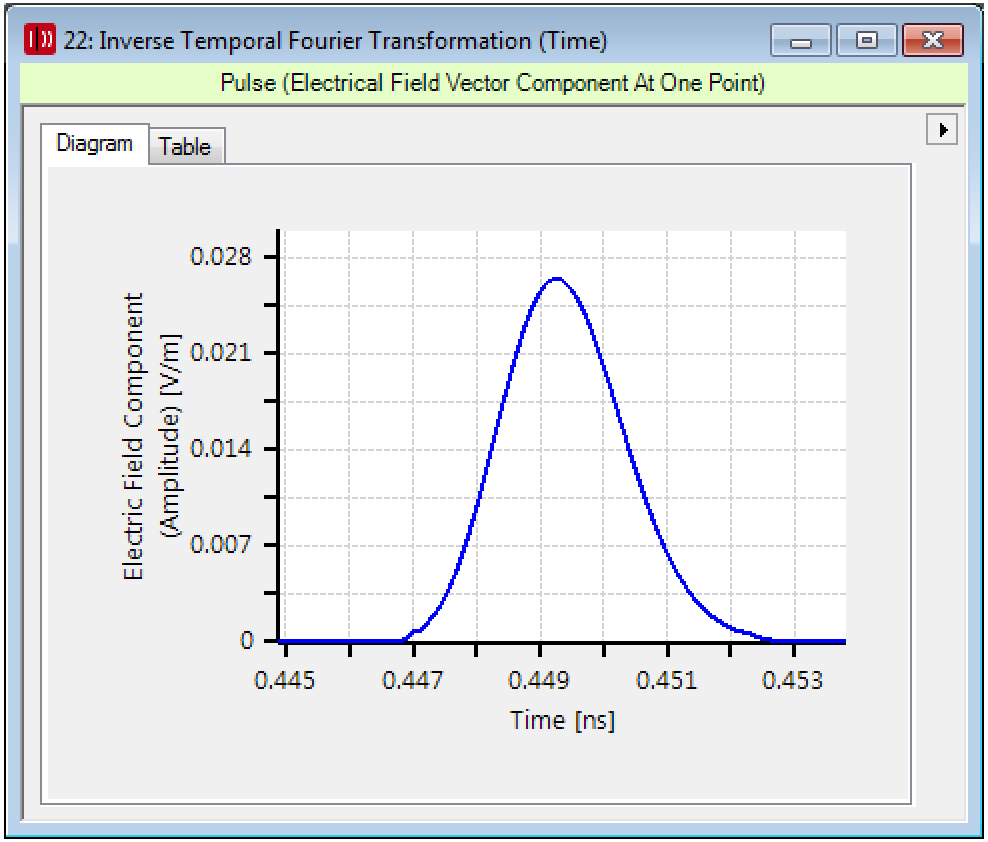
Phase residual due to material dispersion

Simulation with VirtualLab™: Example

- Perform inverse Fourier transformation
- Include calculated phase residual diagram



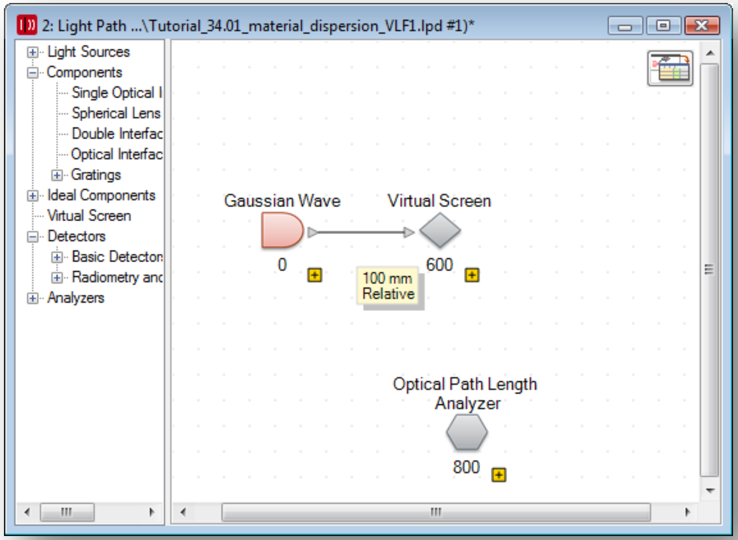
Simulation with VirtualLab™: Example



Resulting pulse envelope in time domain

Simulation with VirtualLab™: Example

- Inclusion of phase residual enables increase of time window without propagtion of 1000 harmonic fields!
- Essential technique for pulse modeling.



Outlook

- Available soon: Application scenarios for pulse modeling on
  - fs pulse diffraction at apertures
  - fs pulses diffraction at gratings
- Please help us to develop the fs pulse modeling features of VirtualLab™. Send us your suggestions and demands for new features and improvements of existing featurtes.
- Thank you for your interest in VirtualLab™.