Optical Filters: Dispersion and Filters

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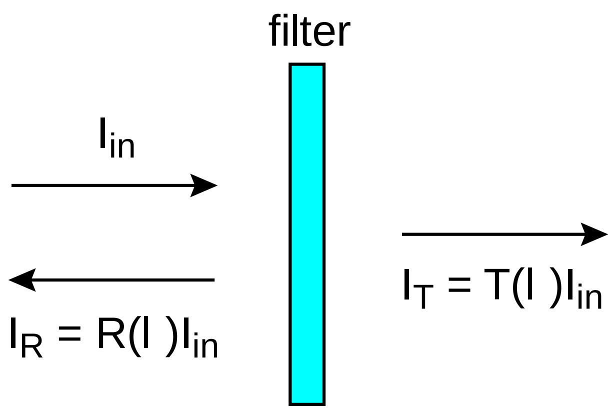
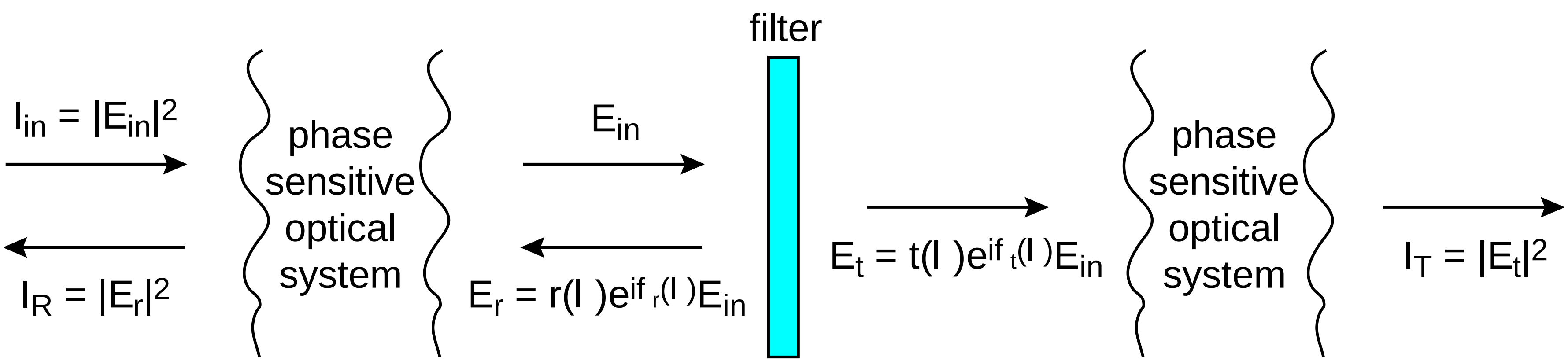
Dispersion matters sometimes

- Often we can sufficiently characterize the spectral performance of an optical filter by determining simply the amount of light intensity (I) it transmits (T(λ)) and it reflects (R(λ))
- T and R are called the “intensity transmission” and “intensity reflection” coefficients



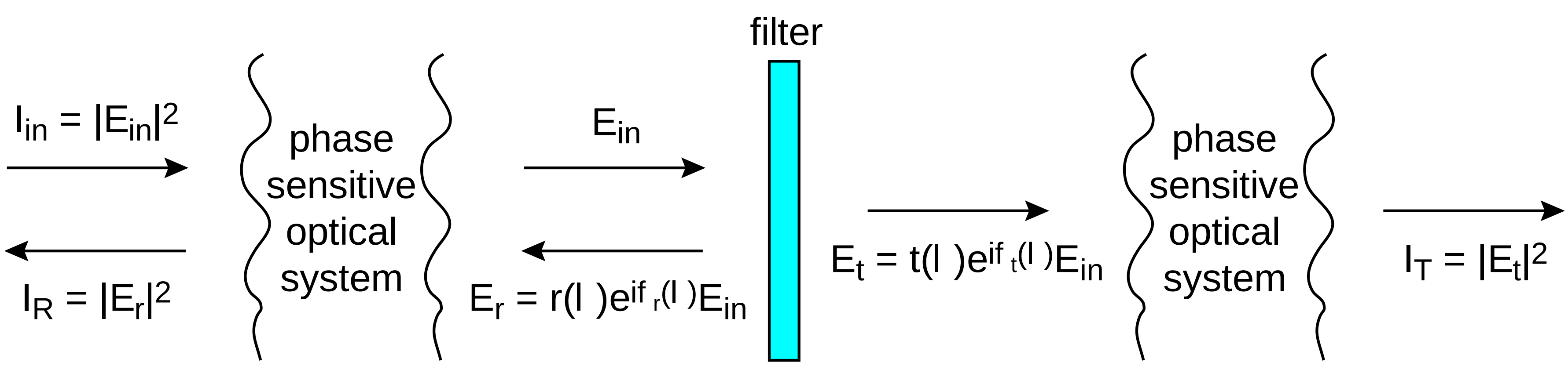
When dispersion matters

- However, if the filter is used in an optical system that is sensitive to the phase of the light, we must use the “amplitude transmission” ($t \exp(i\varphi_t)$) and “amplitude reflection” ($r \exp(i\varphi_r)$) coefficients
- t and r determine the amplitude of the electric field of the light that is transmitted and reflected, respectively, and φ_t and φ_r determine the change in phase of the electric field
- The transmitted and reflected intensity is proportional to the square of the electric field



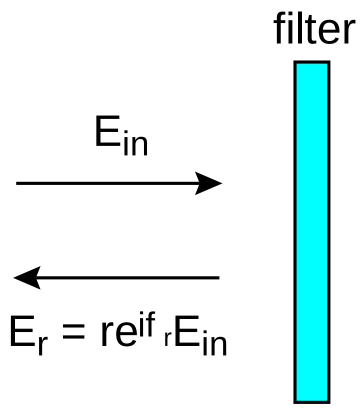
When dispersion matters

- Examples of cases when and where phase matters and the amplitude (rather than intensity) coefficients must be used include:
  - The filter is used in one arm of an interferometer, such that the light transmitted through or reflected off of the filter is coherently combined with light from the other arm or from elsewhere in the system
  - The filter is used to transmit or reflect a short pulse (<< 1 picosecond) such that its phase can cause the pulse to be chirped and therefore broadened or distorted



Impact of optical filter dispersion

- Consider the impact of dispersion on a short pulse reflected off of a filter with amplitude reflection coefficient r $\exp(i\varphi_r)$
  - A little math …



$$E_{in}(z,t) = E_0 e^{i(kz-\omega t)} \qquad \omega = \frac{2\pi c}{\lambda}$$

$$E_r(z,t) = r(\omega) e^{i\phi_r(\omega)} E_{in}(z,t)$$
$$= r(\omega) E_0 e^{i(-kz-\omega t+\phi_r(\omega))}$$

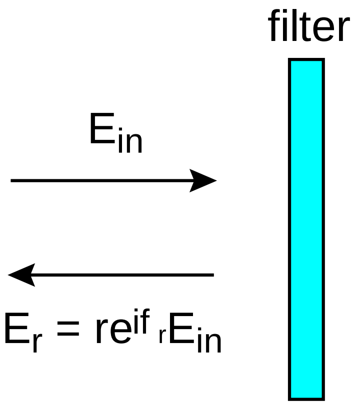
  - We can write the phase response φ_r at frequencies ω near the main frequency of interest ω_0 in terms of a Taylor Series expansion with at least constant, linear, and quadratic terms

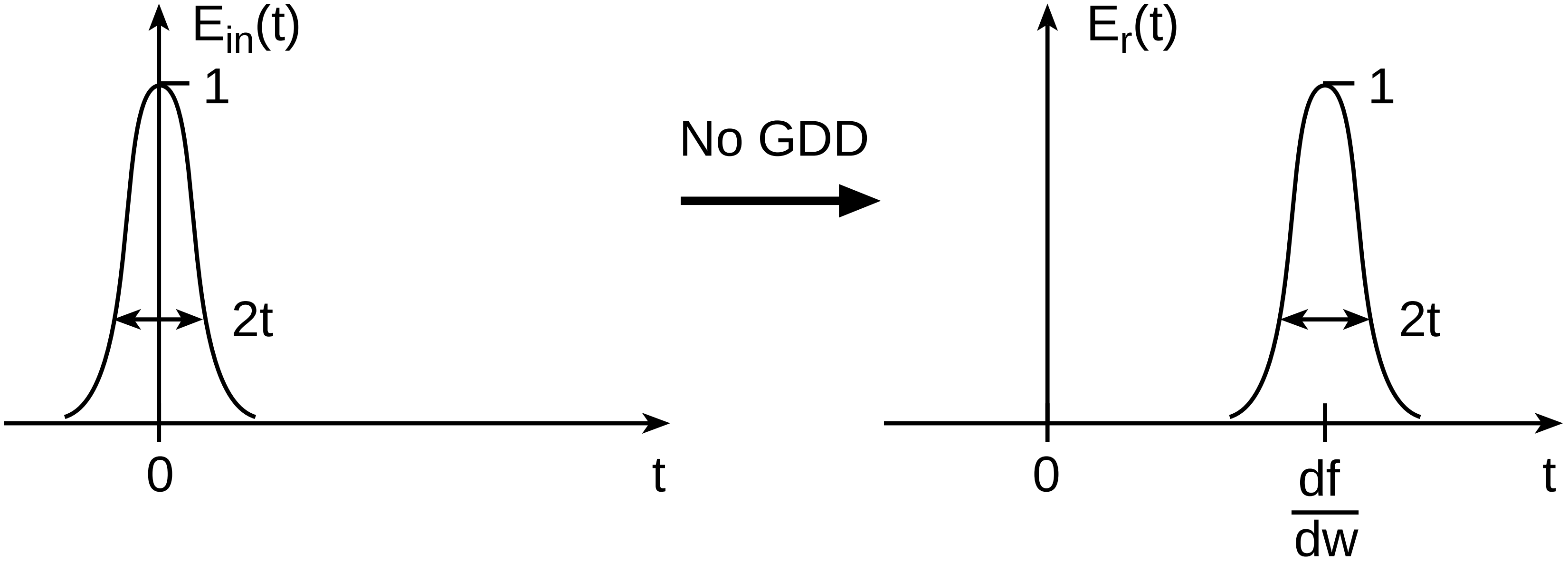
$$\phi_r(\omega) = \phi_r(\omega_0) + (\omega-\omega_0)\left.\frac{\partial\phi_r}{\partial\omega}\right|_{\omega_0} + \frac{1}{2}(\omega-\omega_0)^2 \left.\frac{\partial^2\phi_r}{\partial\omega^2}\right|_{\omega_0} + \cdots$$

Constant phase **Time delay** **Group Delay Dispersion (GDD)**

Reflected short pulse

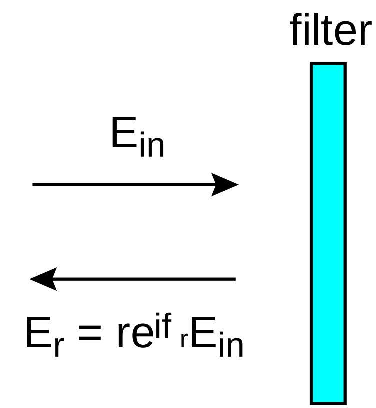
- First consider the case of no dispersion (**GDD = 0**)
- The entire pulse is delayed in time, but its shape (height and width) remains unchanged

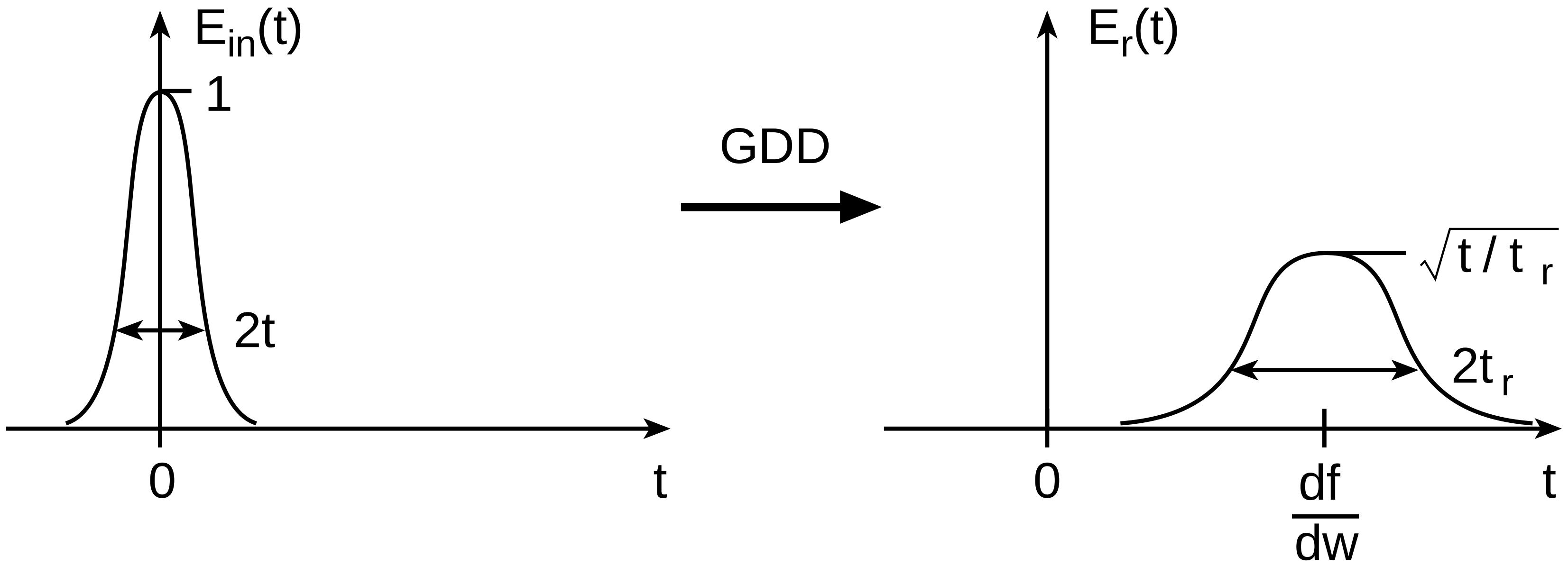




Reflected short pulse

- Now consider the case of dispersion (**GDD ≠ 0**)
- As with no GDD, the entire pulse is delayed in time, but now its height (intensity) is decreased and its width is broadened



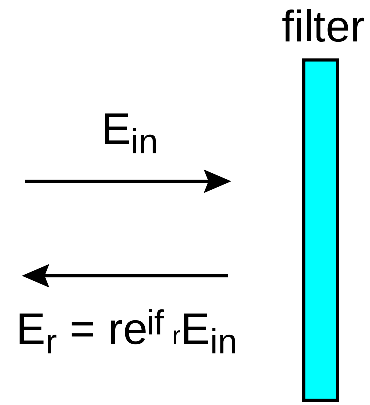


Reflected short pulse

- How much is a short pulsed reflected off of a filter with GDD “squished” and “broadened”?
  - Consider a “Gaussian” pulse (math is easy)

$$E_{in}(t) = e^{-(t/\tau)^2}$$

$$E_r(t) = \sqrt{\frac{\tau}{\tau_r}}\, e^{-\left(\left[t-\frac{\partial\phi}{\partial\omega}\right]/\tau_r\right)^2}$$

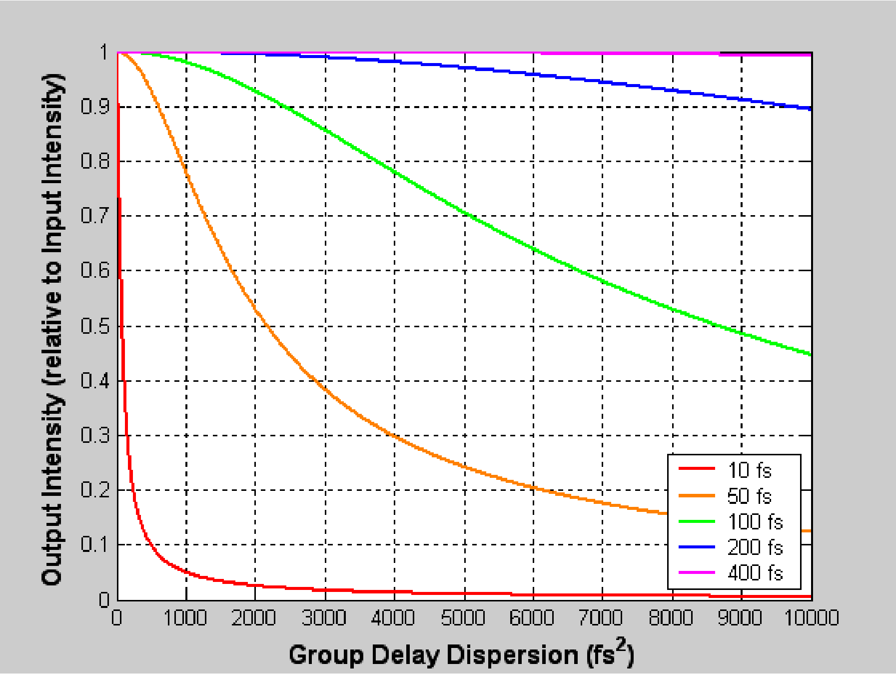


  - Notice three things:
    - Pulse is **delayed** in time by $\dfrac{\partial\phi}{\partial\omega}$
    - Pulse is **broadened** from width τ to $\tau_r > \tau$, where $\tau_r = \tau\sqrt{1+\left(2\dfrac{\partial^2\phi}{\partial\omega^2}\Big/\tau^2\right)^2}$
    - Pulse intensity (~ $|E|^2$) is **squished** by a factor $\dfrac{\tau}{\tau_r}$

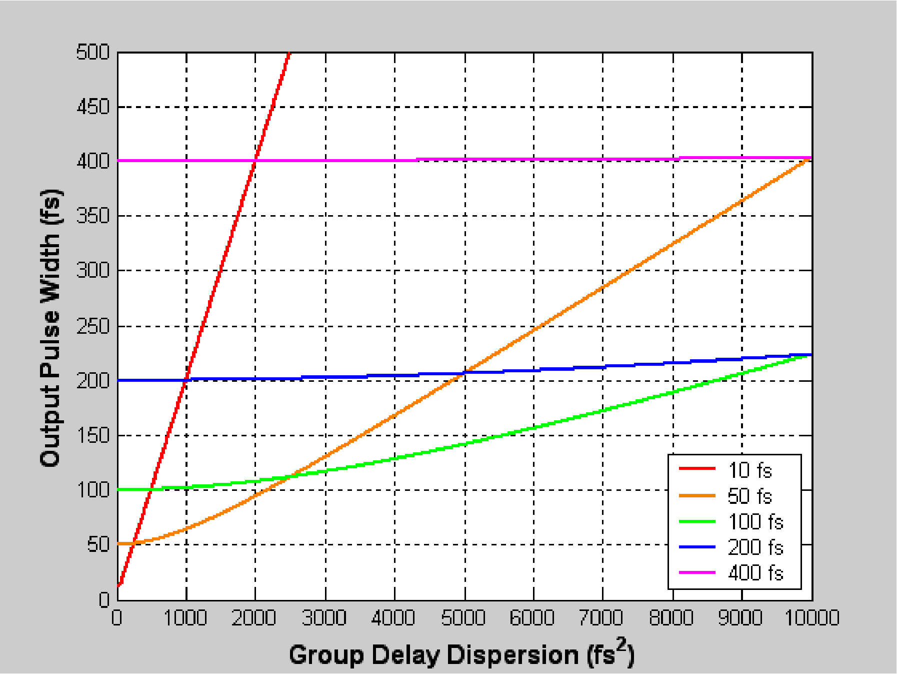
Reflected short pulse

- How much is a short pulsed reflected off of a filter with GDD “squished” and “broadened”?
  - Examples for input pulse widths 10, 50, 100, 200, and 400 fs and optical filter dispersion (GDD) ranging from 0 to 10,000 fs^2

“Squishing”



“Broadening”

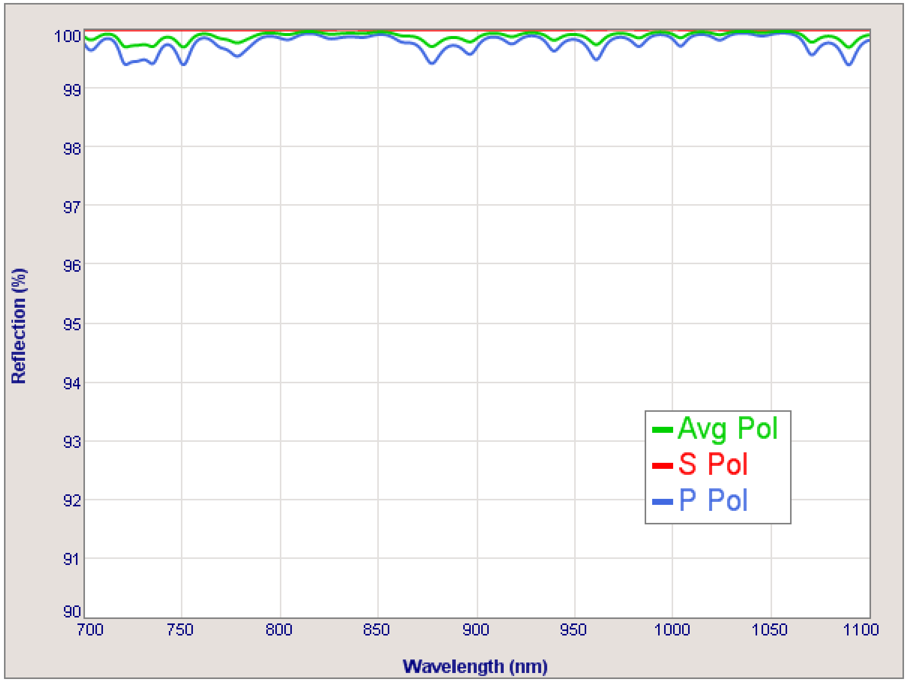


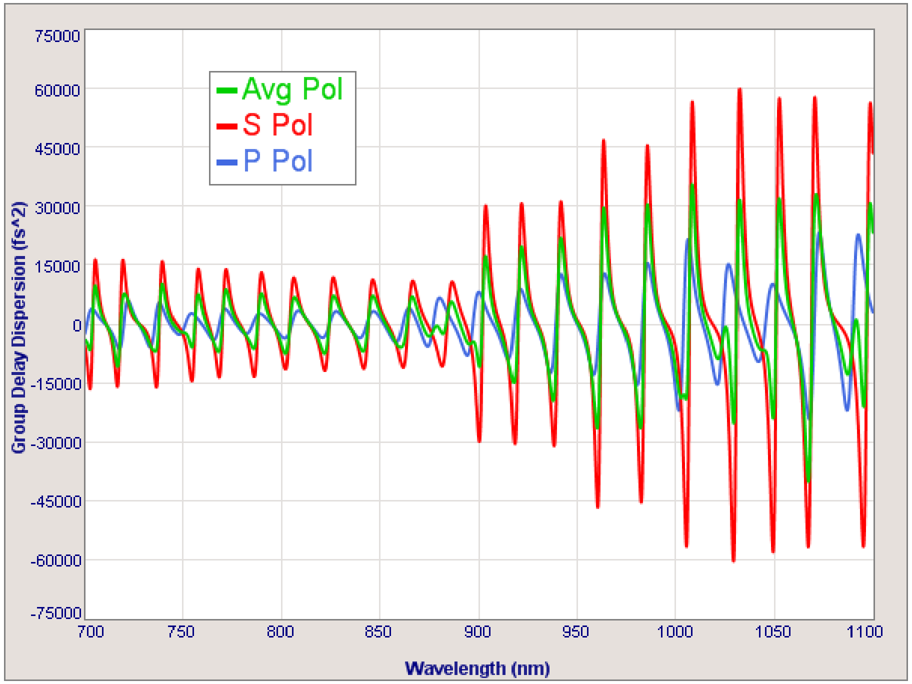
Practical impact of dispersion on a pulse

- In multiphoton fluorescence imaging and nonlinear-optical biological imaging (e.g., second-harmonic-generation imaging), very short pulses (typically ~ 100 fs) are used to achieve extremely high peak intensities, since the nonlinear response is proportional to the peak intensity raised to a power (squared for 2-photon and SHG imaging)
- However, the average intensity of the laser beam must be limited to a reasonably low value (similar to that of a cw laser beam used in scanning confocal microscopes) to prevent damaging the biological sample
- To maximize signal most researchers operate near the sample-damage limit of average intensity – therefore dispersion squishes the peak pulse intensity
  - since the nonlinear response is proportional to the peak intensity squared, then a two-fold pulse squishing means a four-fold reduction in the amount of signal generated
- A significant reduction in signal limits the depth into tissue that can be imaged – one of the main advantages of multiphoton/nonlinear imaging!

Reflected short pulse – MaxMirror®

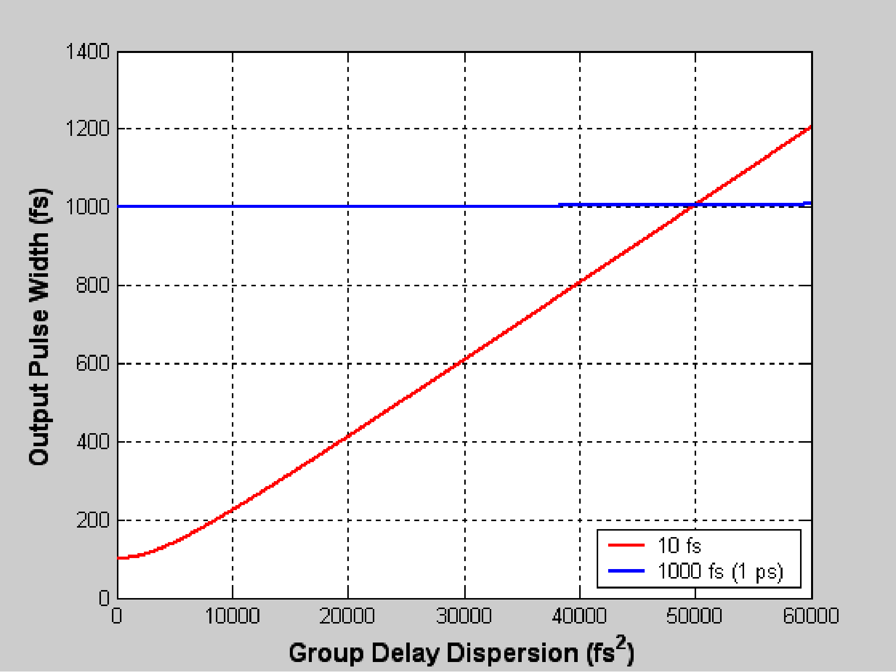
- The MaxMirror is not designed to reflect short pulses – the special design required to achieve high reflection for all polarizations and angles over a very wide wavelength range also introduces some GDD
- Example: GDD over Ti:Sapphire laser wavelengths (700 – 1100 nm) can be as high as 60,000 fs^2 (though typically much lower)





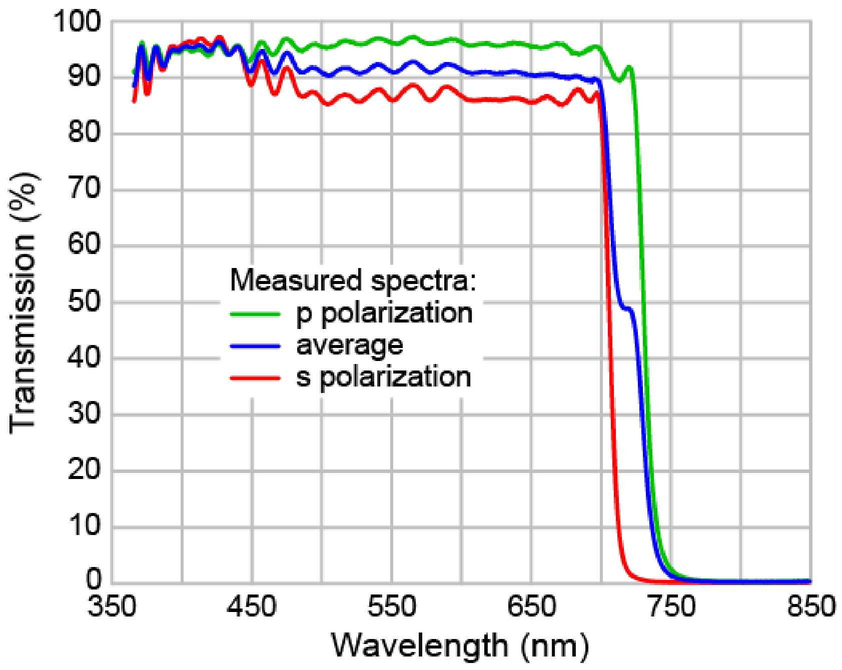
Reflected short pulse – MaxMirror®

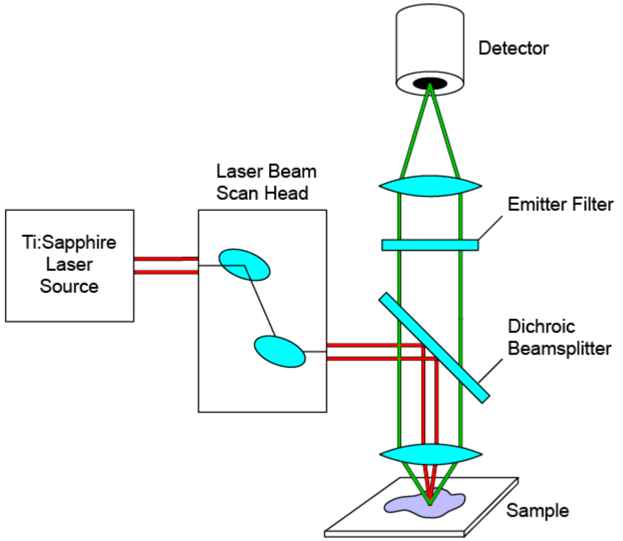
- MaxMirror GDD specification guideline (from catalog):
  - “The MaxMirror will not introduce appreciable pulse broadening for most laser pulses that are > 1 picosecond; however, pulse distortion is likely for significantly shorter laser pulses, including femtosecond pulses.”



Short-wave-pass dichroic for "SHG" imaging

- Excellent dispersion and polarization properties make this filter ideal for Second Harmonic Generation (SHG) imaging
- Optimized for excitation at ~ 810 nm and imaging of the nonlinear scattered light (which is not fluorescence!) at ~ 405 nm

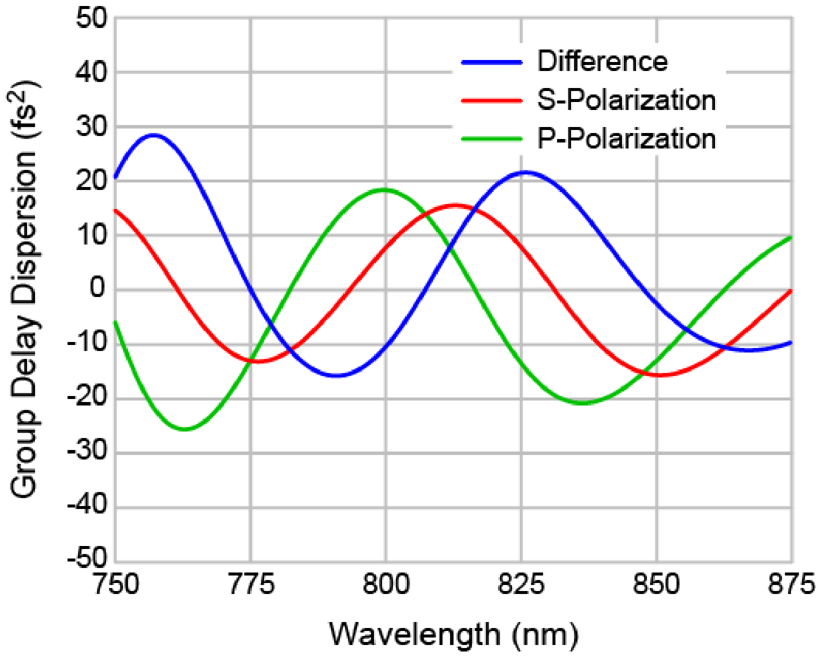




Configuration for using a short-wave-pass dichroic beamsplitter

Short-wave-pass dichroic for "SHG" imaging

- Extremely low group delay dispersion minimizes pulse squishing
- Narrower pulses mean a higher peak intensity for a given average intensity – which is limited by sample damage – thus allowing the deepest sample penetration



Maintaining the GDD below ± 30 fs^2 means that a 100 fs laser pulse broadens by much less than 1% after reflection off the filter

Thank you!