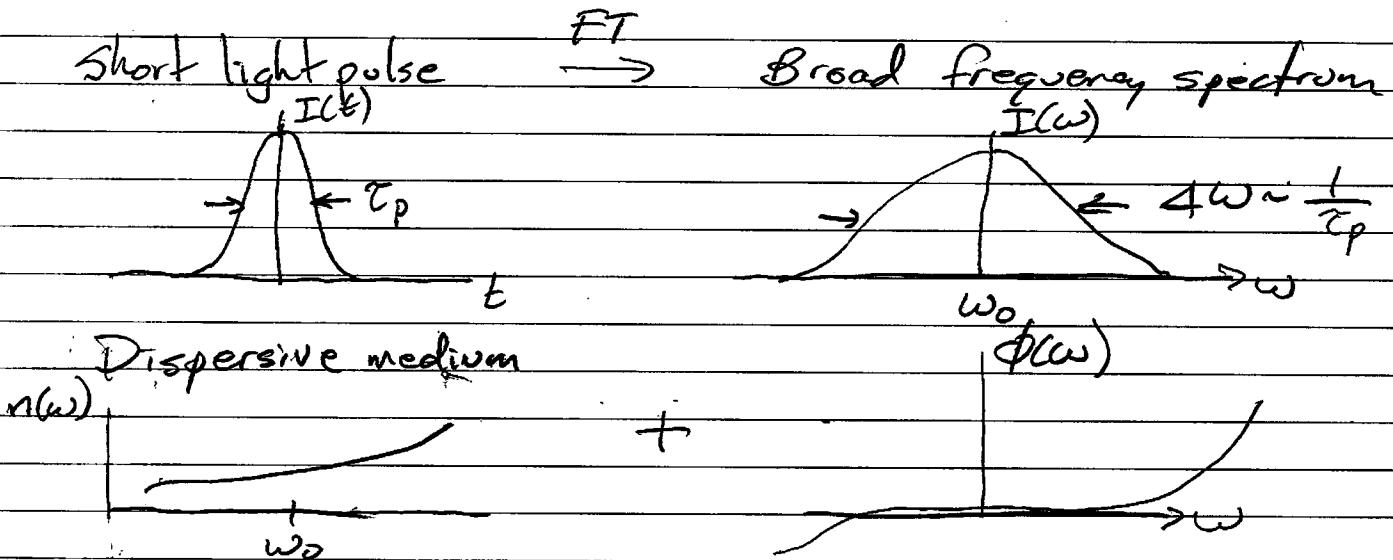
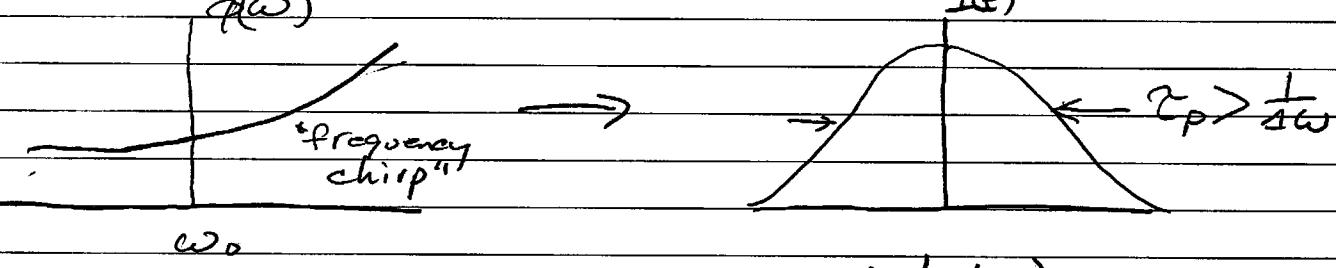


III - Femtosecond lasers

Group velocity dispersion (GVD) - key issue in femtosecond laser design and in using femtosecond pulses



After passage through dispersive medium

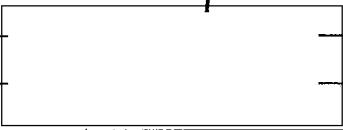


For monochromatic wave: $E = A_0 e^{j(\omega_0 t - k z)}$

$$\text{Phase velocity } V_p = \frac{\omega_0}{k} = \frac{c}{n}$$

For a pulse, with moderate bandwidth $\Delta \omega$,

The pulse envelope, $A(t - \frac{z}{v_g})$ propagates at the group velocity.



The group delay is just

$$\tau_g = \frac{l}{v_g} = l \frac{dk}{d\omega} = l \frac{n}{c} \frac{dn}{d\omega}$$

In transparent media, generally both n and $\frac{dn}{d\omega}$ are increasing functions of ω .

For large pulse bandwidth, τ_g is not constant, but depends on ω . The "blue" parts of the pulse have longer group delay than the "red" parts of the pulse. This broadens the pulse.

The pulse broadening from this effect can be expressed to lowest order as



where $\Delta\omega_c$ is the pulse bandwidth.

$\frac{d^2k}{d\omega^2}$ is called the group velocity dispersion (GVD)

Inside a femtosecond laser cavity, the ultimate pulse width is set by competition between pulse narrowing + broadening mechanisms.

Narrowing: net gain window due to sat absorber or ELM

Broadening: ① finite gain bandwidth
② group delay dispersion



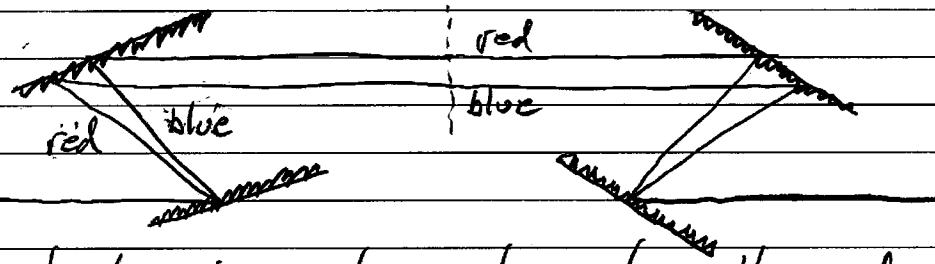
Dispersion compensation (pulse compression)

In a Ti:Sapphire laser, the GDD in the sapphire crystal $\sim 2\text{mm}^{-1}$ limits pulsewidth to $\sim 170\text{ fs}$.

The full gain bandwidth is $\sim 100\text{ THz}$, and could produce $\sim 4\text{fsec}$ pulse.

GDD can be compensated. Normal materials have positive GDD. Negative GDD can be produced using special optical set-ups.

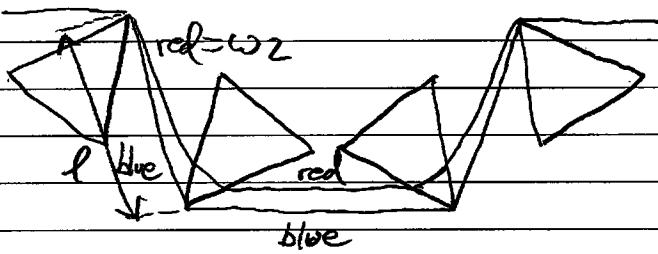
Grating Pairs: Consider this arrangement of identical, parallel gratings



Just by inspection, it is clear the red components experience larger group delay than the blue.

A single pair is adequate when the beam diameter is large compared to the offset between red-blue.

Prism pairs: Similar effect can be obtained using prisms



• Be careful! The book explanation is wrong. The ω_1 path is clearly the blue path [$\omega_1 > \omega_2$!].

• The phase delay for the blue components is longer than for the red components.

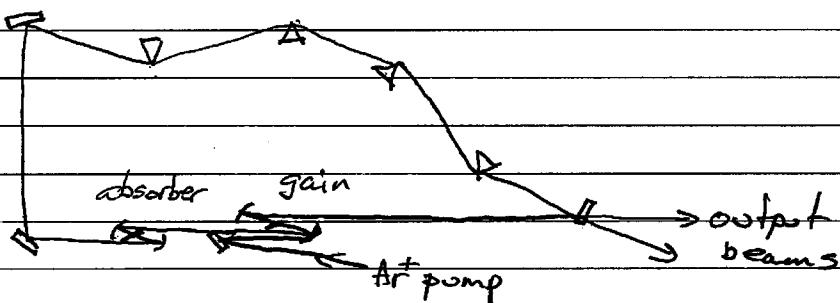
- Let the group delay for the red components can be longer than for the blue, because the red components pass through more quartz, which has longer group delay than air. Only for l exceeding some critical value is the GDD negative. See [cf 25, L.L. Fork et al, Opt. Lett. 9, 150 (1984)] for full analysis. GDD can also be adjusted by translating tiny prism perpendicular to base, introducing extra path in quartz.
- With correct design, the prisms are at minimum deviation (no anamorphic distortion) and the rays enter and exit at Brewster's angle.
- Gratings have high loss, but the 4 prism sequence can have low enough loss for use inside laser cavities.

Examples of femtosecond lasers

Two lasers configurations survive today for fs pulse generation. Most popular is the KLM Ti:sapphire laser. Gives shortest pulses (< 10 fs), but center $\lambda \approx 850$ nm.

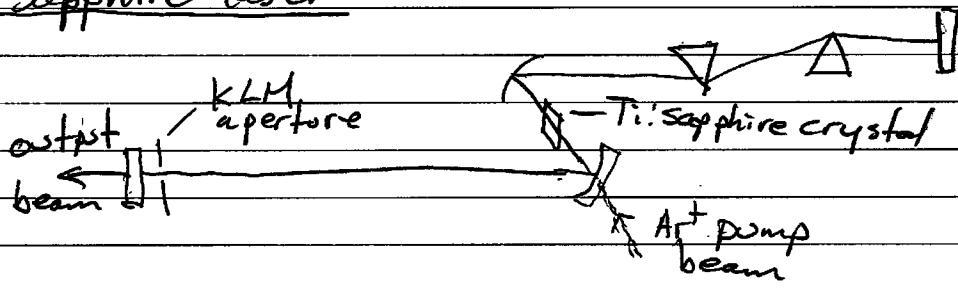
For visible wavelength, $\lambda \approx 580$ nm, the CPM dye laser is used.

CPM dye laser



- Pulses circulate in both directions and meet at saturable absorber. \rightarrow enhances saturation

Ti:Sapphire laser

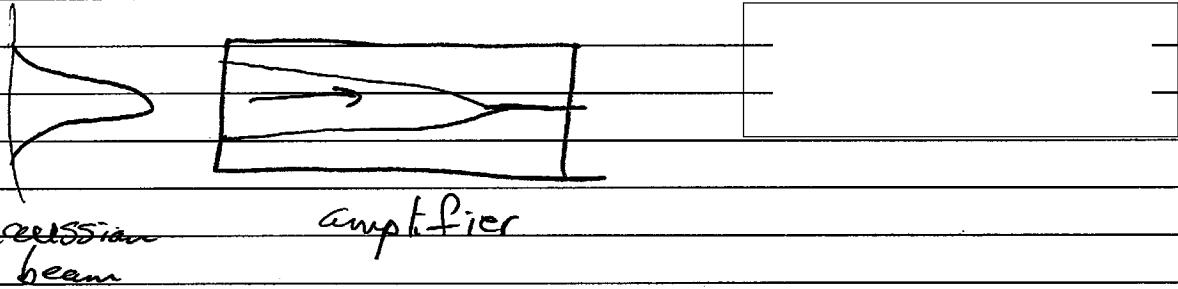


- To get shortest pulses - third order group delay must be compensated. Special mirror coatings are used.

II Amplifying fssec lasers; "Chirped pulse amplifier"
 [read Svelto 12.3.1, 12.5.2]

- Amplifying ultrashort pulses is limited by damage to the amplifiers by self-focusing.

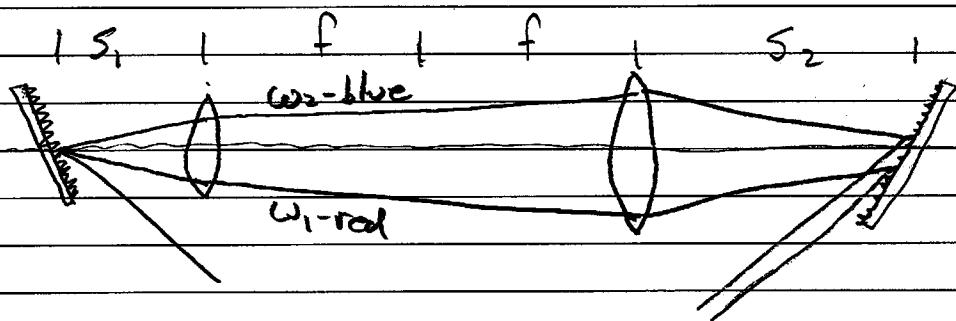
Self focusing comes from optical Kerr effect:



As beam propagates down amplifier, Kerr effect focuses beam, increasing I , which increases the focusing effect. This can lead to a runaway condition and the beam collapses to a very compact filament which causes catastrophic damage to the material.

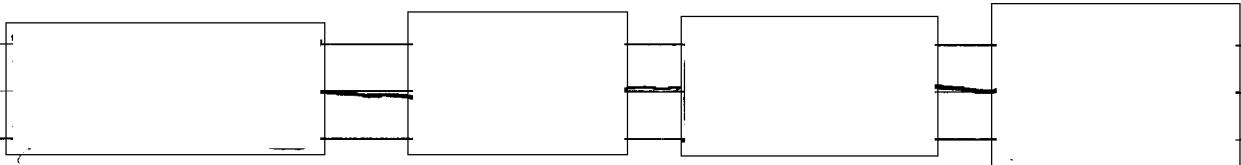
Solution: First stretch out the pulse. Then amplify, then re-compress.

Pulse stretcher using grating pair anti-parallel



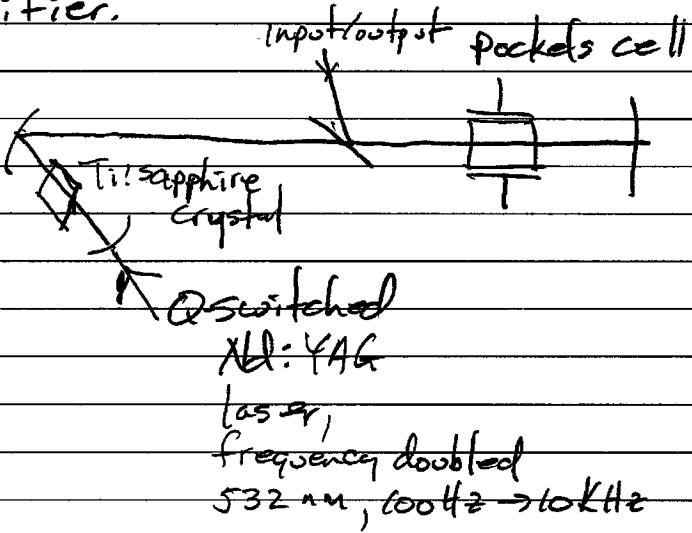
- 2 lenses, equal f , $S_1, S_2 < f$
- identical gratings, same incidence angles, but opposite sign
- blue path (w_2) \rightarrow red path (w_1) which is positive (GDD)

This type of stretcher can be perfectly (except for lens dispersion and aberrations) compensated by a complementary grating compressor. Stretch/Compress ratios can be > 5000 . Starting pulse 100 fs
 \rightarrow stretched pulse 500 psec



CPA system

1st stage of amplification for Ti:sapphire is regen amplifier.



Subsequent stages of single-pass amplifiers are possible using lower re-rate, high energy Q-switched, doubled YAG pump pulses