

# Amplification

We have discussed an number of issues in amplification:

Pulse shaping due to saturation

Gain Narrowing

Amplified spontaneous emission

Nonlinear index of refraction

Two and half more issues:

Additional comment on gain narrowing

Self-focusing

Thermal Effects

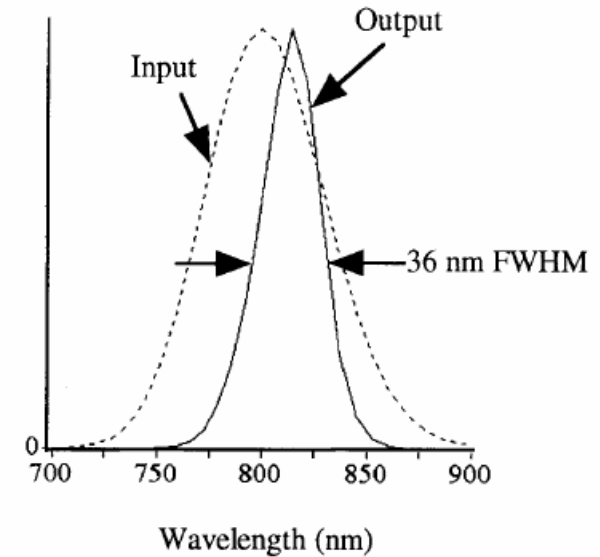
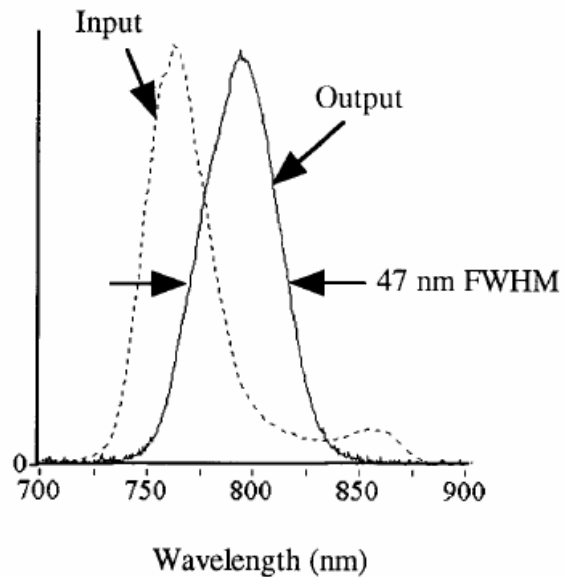
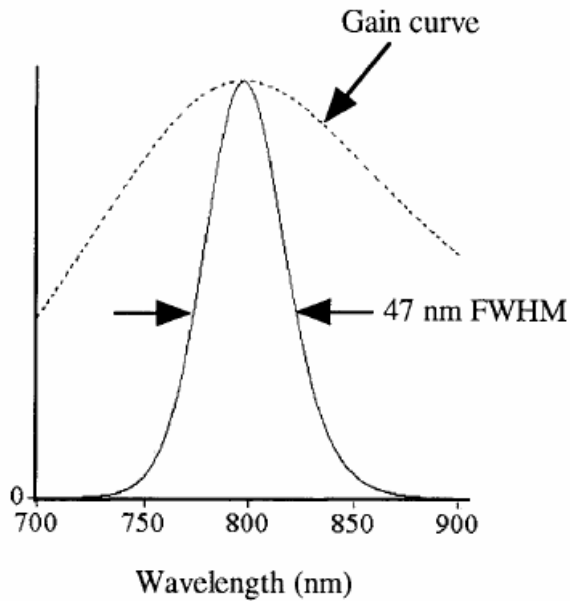
How do we circumvent these?

→ Chirped pulse amplification

Specific amplifier geometries: regenerative, multipass

# Gain Narrowing revisited

Gain narrowing can also shift the center of the pulse,  
However this can be used to compensate for narrowing



# Self-focusing I

For a beam with a Gaussian transverse profile:

the Kerr effect will result in a Gaussian transverse index profile

This in turn results in a Gaussian transverse phase profile

Corresponds to a focusing beam

Self focusing will occur when the focusing due to nonlinearity is stronger than the diverging due to diffraction

Nonlinear phase is

$$\varphi_{sf}(r) = -n_2 \frac{2\pi}{\lambda} z I_0 e^{-(2r^2/w_0^2)} \approx -n_2 \frac{2\pi}{\lambda} z I_0 \left( 1 - 2 \frac{r^2}{w_0^2} \right)$$

Where in the last step we've made our standard parabolic approximation

We need to dust off a few Gaussian beam formulas....

# Self-focusing: Gaussian Beam Refresher

$$E(x, y, z) = E_0 \left[ \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w^2(z)}\right) \right] \exp\left[-i\left(kz - \tan^{-1}\left(\frac{z}{z_0}\right)\right)\right] \exp\left[-i\frac{kr^2}{2R(z)}\right]$$

where **amplitude**

**longitudinal phase**

**radial phase**

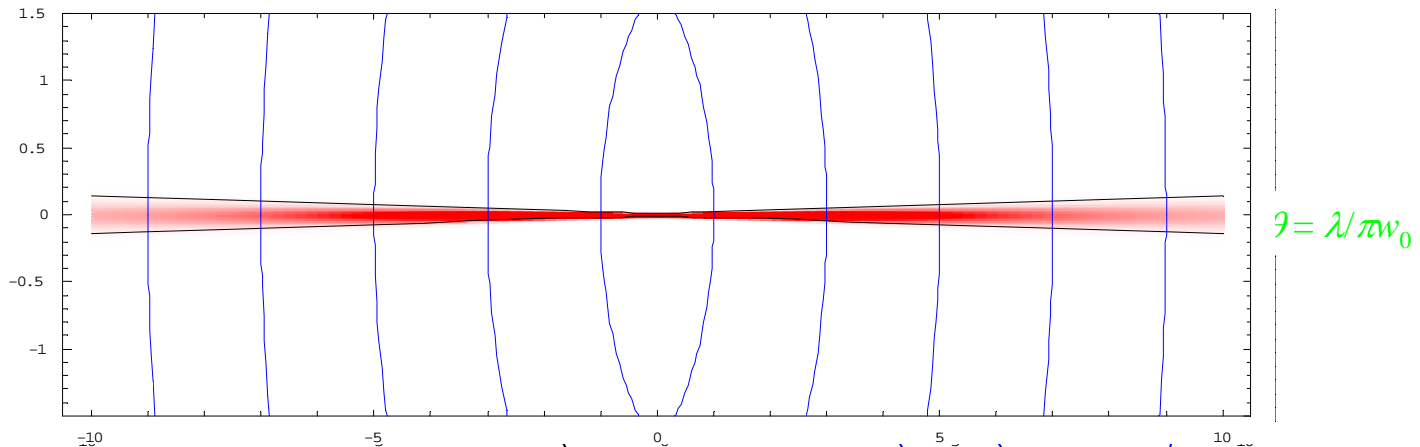
$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

Determines radius as function of  $z$

$$R(z) = z \left[ 1 + \left(\frac{z_0}{z}\right)^2 \right]$$

Radius of curvature of phase fronts as function of  $z$

$$z_0 = \frac{\pi w_0^2}{\lambda}$$



$w(z)$

**Phase Fronts**

$\theta$  – far field divergence angle

# Self Focusing II

Compare the phase of a diffracting Gaussian beam

$$\varphi_{diff} = -\frac{k}{2R(z)} r^2 \approx -\frac{kz}{2z_0^2} r^2$$

Where in the second expression we've assume  $z$  small so  $R(z) = z \left[ 1 + \left( \frac{z_0}{z} \right)^2 \right] \approx \frac{z_0^2}{z}$

To the nonlinear phase

$$\varphi_{sf}(r) \approx n_2 \frac{4\pi}{\lambda} z I_0 \frac{r^2}{w_0^2}$$

They are equal magnitude when

$$I_0 \frac{\pi w_0^2}{2} = \frac{\lambda^2}{8\pi n n_2}$$

Where we have used  $z_0 = \frac{\pi n w_0^2}{\lambda}$

A tighter focus means higher intensity and more nonlinearity, but also less curvature to the phase front to be overcome, these cancel

Note that the left side is a **power** we define this as the critical power  $P_{cr}$   
Above the critical power, nonlinearity wins and self-focusing occurs

# Self-focusing III

An alternative derivation based on assuming a top-hat intensity profile and calculating the condition for total-internal reflection yields

$$P_{cr} = \frac{(1.22)^2 \pi \lambda^2}{32n n_2}$$

Note this has same dependence on  $\lambda$ ,  $n$  and  $n_2$ , as our previous result, just differ by a constant (numerical simulations give different constant)

Key point:

It is a critical power, not intensity

Because nonlinear focusing and diffraction scale identically with beam diameter

For a power  $> P_{cr}$ , beam comes to a focus in distance

$$z_{SF} = \frac{0.5 z_0}{\sqrt{P/P_{CR} - 1}}$$

Assuming a waist at the entrance to the nonlinear medium

Once it reaches a focus, higher order linear and nonlinear effects come into play – either the beam totally diffracts away or forms a stable waveguide (filament)

# Self-focusing in amplifiers

Check numbers:  $n_2$  for sapphire is  $8 \times 10^{-16} \text{ cm}^2/\text{W}$

$$P_{cr} = \frac{\lambda^2}{8\pi n n_2} = \frac{(0.8 \times 10^{-4})^2}{8\pi \cdot 1.7 \cdot 8 \times 10^{-16}} = 200 \text{ kW}$$

Easily achievable peak power

Directly from oscillator for 10 fs pulse, but 10 fs usually disperses

Furthermore, ripples in the transverse profile can get “amplified”

Self-focusing can be tolerated if length of amplifying medium  $< z_{SF}$

How do we avoid this?

# Thermal effects

The pump pulse deposits significant energy into the gain medium

At best fraction of energy extracted by light is  $h\nu_{sig}/h\nu_{pump} \sim 0.6$  for Ti:sapphire, remainder goes into heat

Temperature dependence of index of refraction at room temperature

$$\frac{dn}{dT} \sim 10^{-5} (\text{°C})^{-1}$$

This can cause significant distortion of signal beam

If the pump is cylindrically symmetric, looks like a simple lens

Design optics to compensate

Work at temperature where  $dn/dT \sim 0$  (possible for aqueous dye lasers at 4 C)

Maximize thermal conductivity

Sapphire is high, at liquid nitrogen temperatures is 10 times higher yet

# Chirped Pulse Amplification

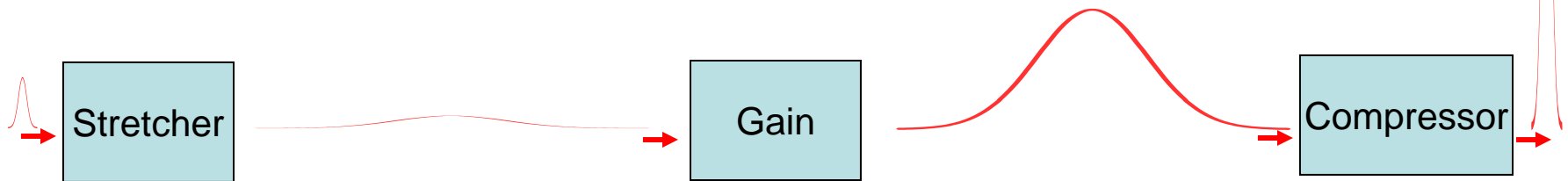
How can the deleterious effects of high peak power be avoided?

## → Chirped pulse amplification

Chirp the pulse to stretch it in time (~1000 times) and lower peak power

Amplify

Recompress it



Concept originally developed for radar

First demonstration in optics

Strickland and Mourou, Opt. Commun. **56**, 219 (1985)

# Stretcher I

We need the stretcher and compressor to have opposite signs of GVD

Generally the stretcher has normal dispersion

In our discussion of dispersion, we concentrated on generating anomalous dispersion, how can we generate large amounts of normal dispersion?

- 1) Large amounts of material
- 2) Gratings?

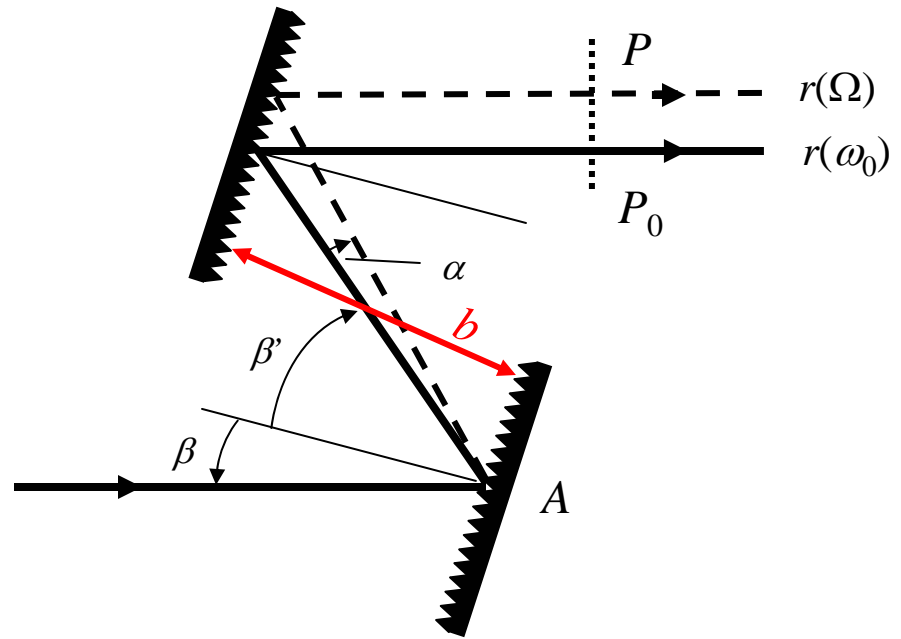
Recall grating generated much more anomalous dispersion than prisms...promising but we need to change the sign

Standard grating pair has second order phase

$$\frac{d^2\Psi}{d\Omega^2} = -\frac{\lambda_0}{2\pi c^2} \left(\frac{\lambda_l}{d}\right)^2 \frac{b}{\sqrt{r}} \frac{1}{r}$$

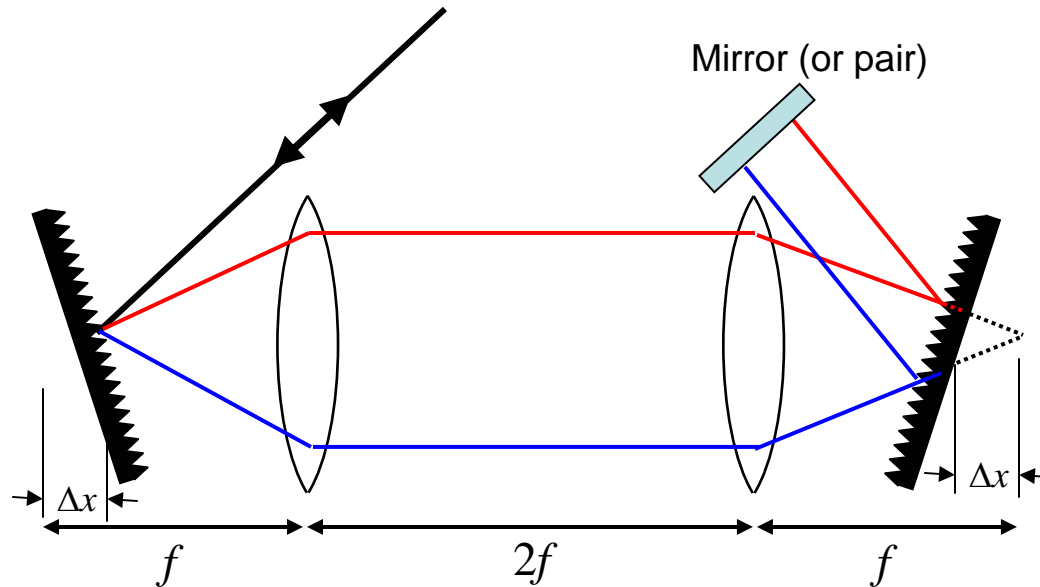
How can we change the sign?

→ Make  $b$  negative?



# Stretcher II

Use telescope to image first grating “behind” second grating  $\rightarrow$  effective negative distance



The effective grating separation is  $-2\Delta x$

Neglecting non-ideality of lenses, this has exactly opposite dispersion (to all orders) of standard grating pair

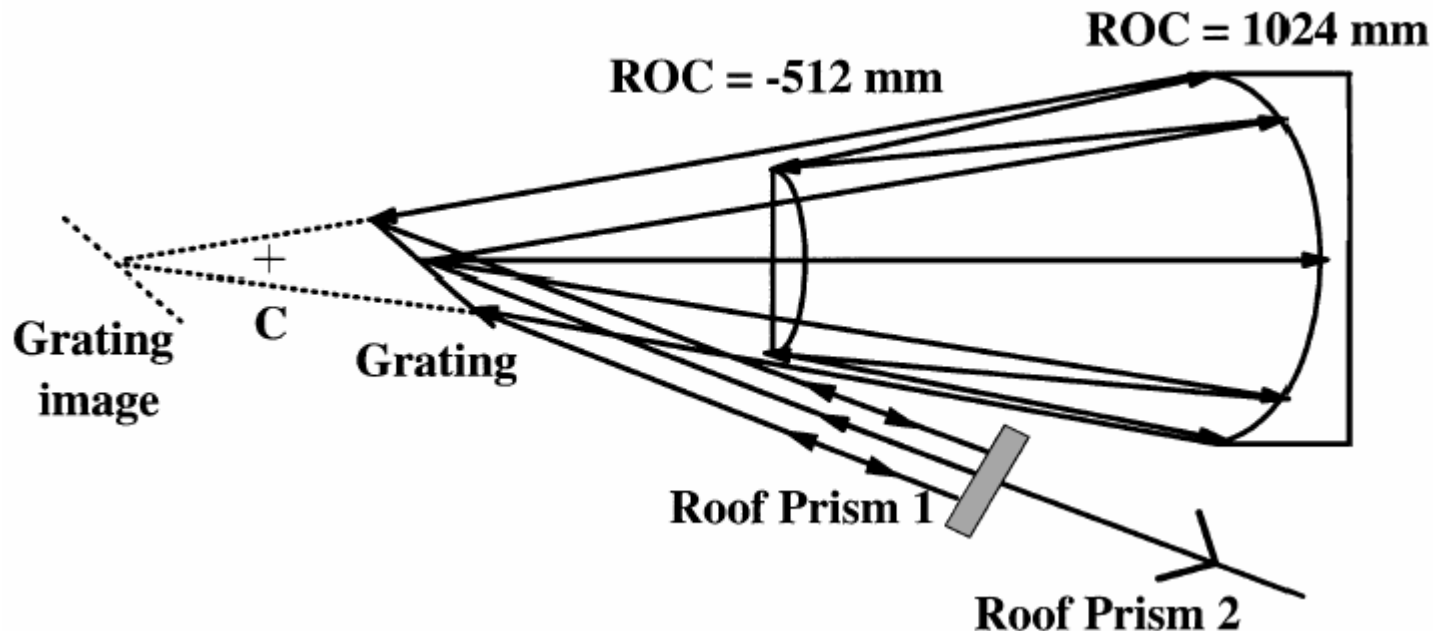
# Stretcher III

Of course the lenses introduce problems:

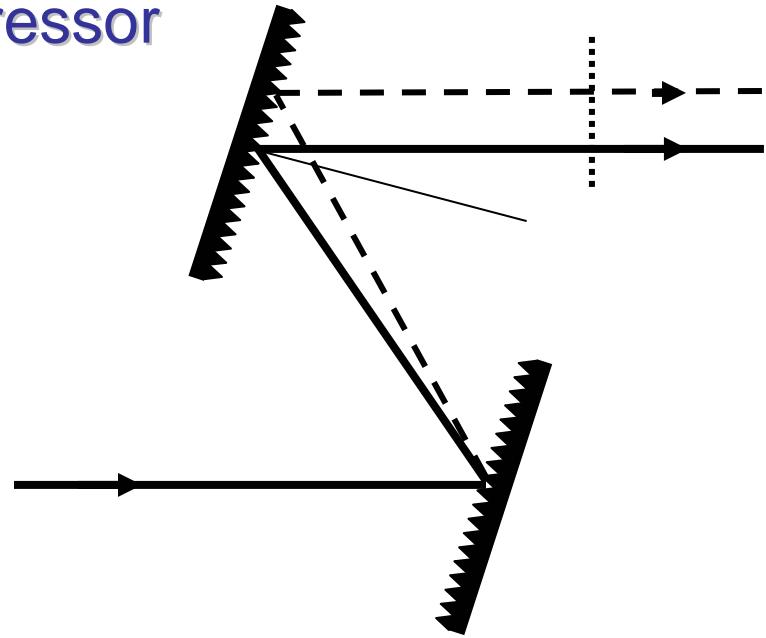
Chromatic dispersion

Spherical Aberration

These are eliminated by using an all reflective design. For example:



## Compressor



The compressor is typically the standard 2-grating pair

This can perfectly compensate the grating stretcher, but material dispersion in gain section must be included:

Gain medium

Pockel's cell

These will have different higher-order coefficients → for shortest pulses may need additional dispersion control, e.g. prisms as well.

# How much stretching?

Usually the first effect of high intensity is nonlinear phase shift

$$\varphi_{NL}(t) = \int \frac{2\pi}{\lambda} n_2 I(t, l) dl$$

The peak value of this expression is known as the “B integral”  
Estimate of nonlinear group delay

$$\frac{d\varphi}{d\omega} = \frac{B}{\Delta\omega}$$

Where  $\Delta\omega$  is the half-width of the amplified spectrum

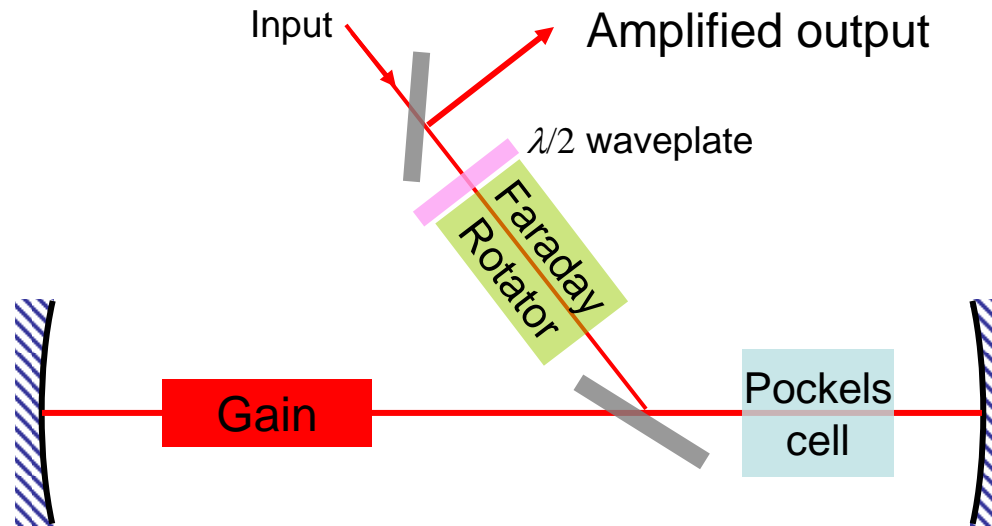
If  $B = 1$  rad and  $\Delta\omega = 20$  nm, the nonlinear group delay variation is 17 fs

This can to some extent be compensated by the compressor, but keeping  $B$  less than 1 rad is a good goal

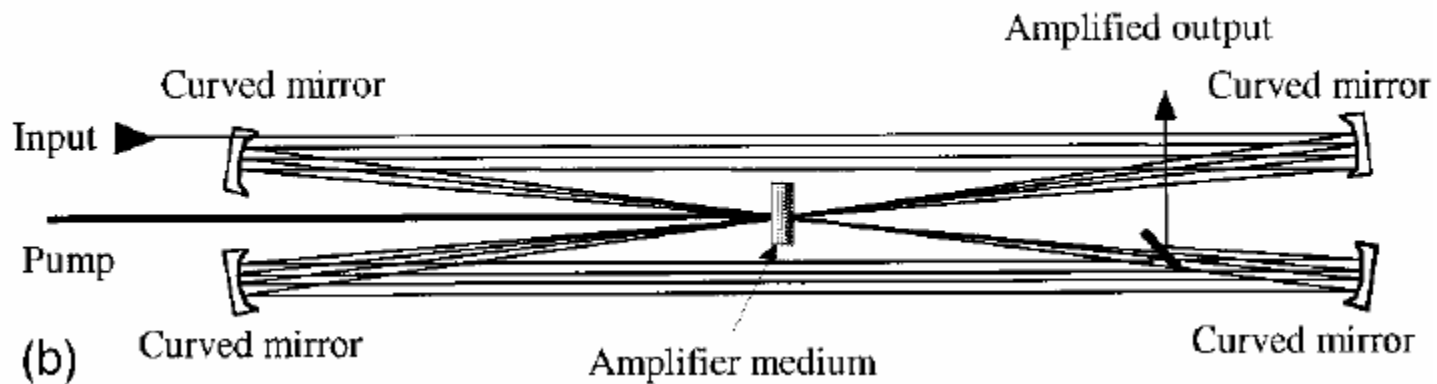
# Gain Section

Two primary types:

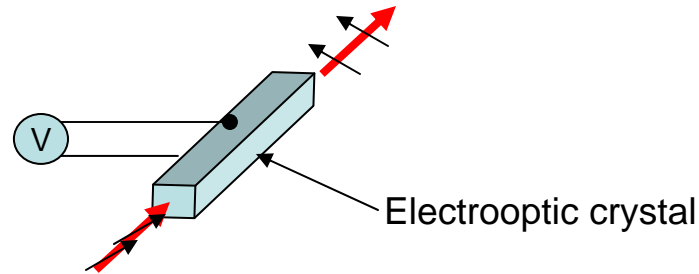
1) Regenerative



2) Multi-pass



# Pockels Cell



## Electrooptic phase modulator

Index of refraction depends on applied field

Tensorial relationship, typically

index increases for light polarized along field direction

decreases for light polarized orthogonal to field

Can act as as voltage controlled waveplate

Typical “quarter-wave voltage” ~ 5 kV

switching 5 kV in ~10 ns is challenging, but doable

Only  $\frac{1}{4}$  wave needed for double passed cell at end of cavity

Common materials:

Lithium Niobate

KDP (potassium dihydrogen phosphate)

# Regenerative Amplifiers

## Advantages

- Good signal/pump overlap in cavity → high efficiency
- Relatively compact and simple to align (one pass through gain medium)
- Easily obtain large number of passes through gain medium

## Disadvantages

- Need to keep gain low to prevent ASE or even lasing
- Many passes through dispersive & nonlinear Pockels cell crystal

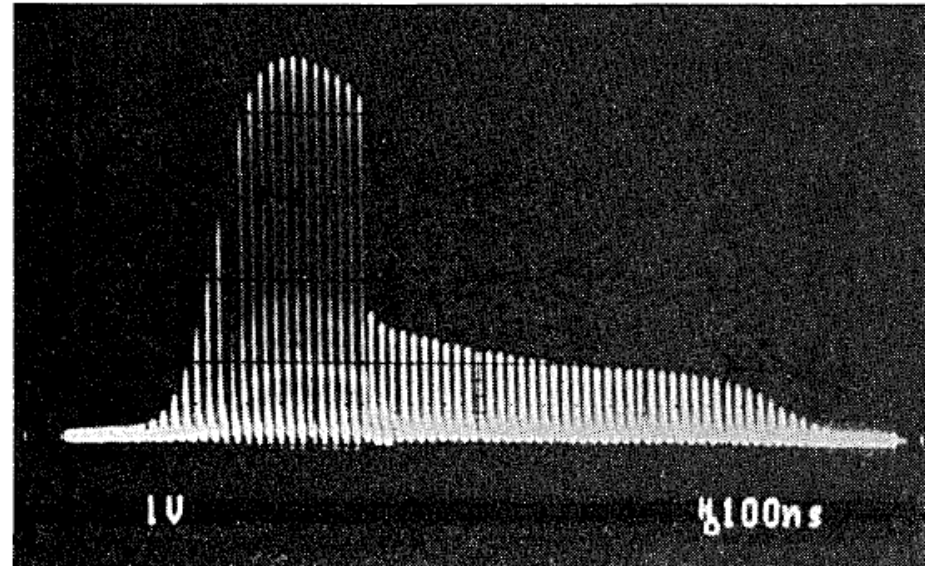
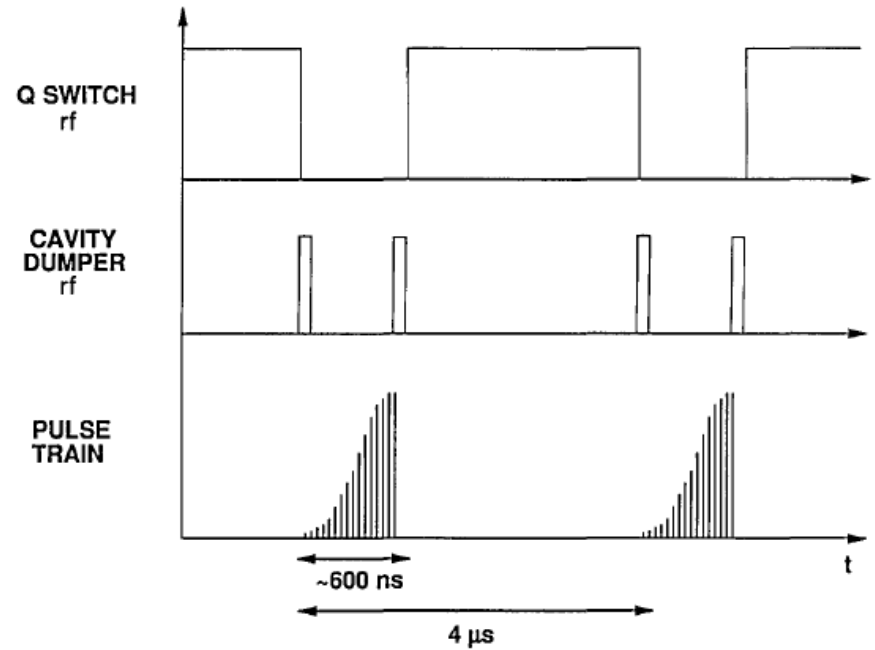
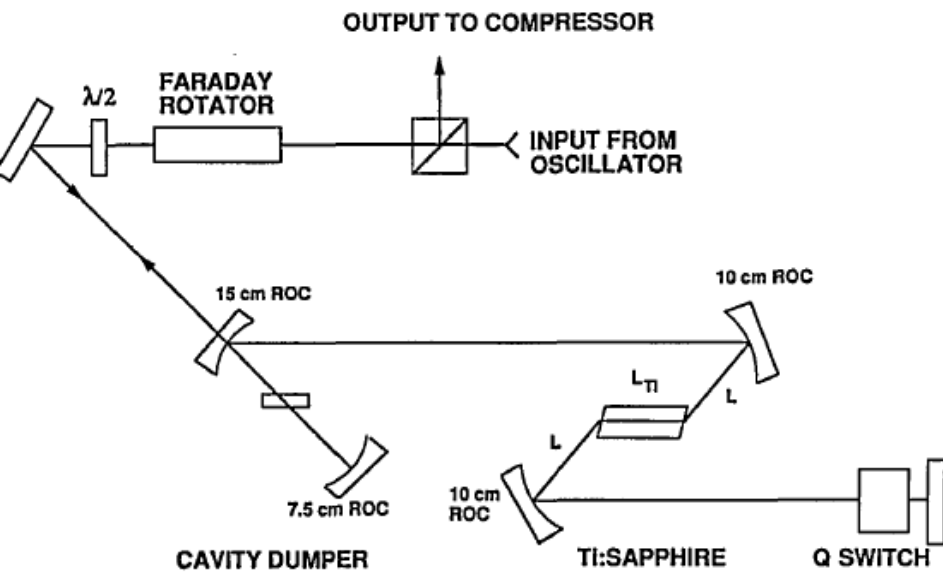
Note Regen's can be pumped with either

Q-switched lasers (10 ns pulses, kHz repetition rates) yielding mJ pulses

Or

CW yielding  $\mu\text{J}$  pulses at 100's of kHz repetition rate

# 100 kHz Regenerative Amplifier



# Multipass Amplifiers

## Advantages

Single pass through Pockels cell on input, less dispersion and nonlinearity

No need to switch out, obtained by spatial separation

Higher gain per pass (no danger of lasing, just ASE)

→ fewer passes needed → less dispersion and nonlinearity from gain crystal

## Disadvantages

Lower efficiency, pump-signal overlap changes every pass to allow spatial separation between passes

Larger and more difficult to align