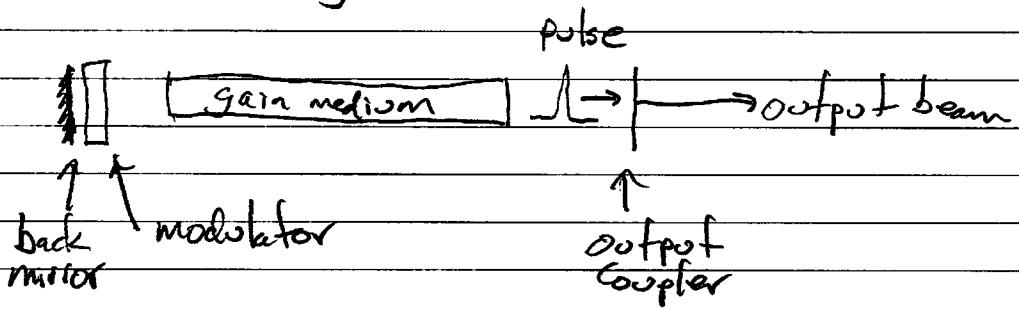


① → Active mode locking - basic mechanism



amplitude modulator (AM) mode locking:

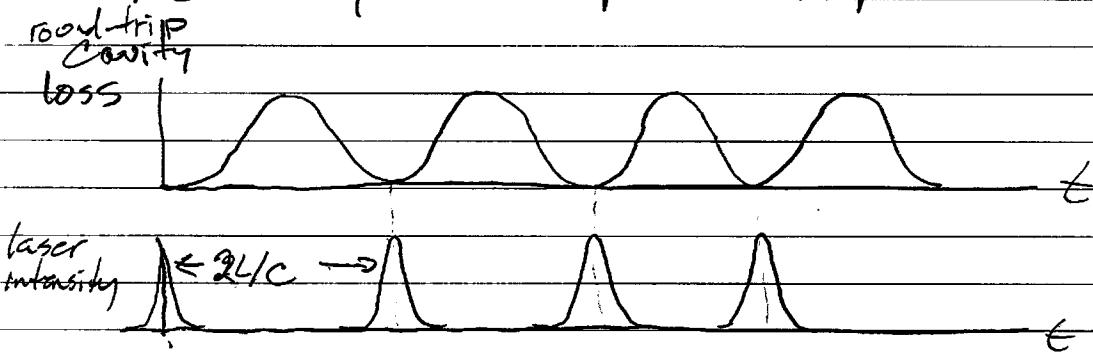
modulator has time varying loss.

transmission of field amplitude through modulator?



If  $c\omega_m = \Delta\omega = 2\pi \frac{c}{2L}$  cavity axial node spacing

then the modulator loss is synchronized to the cavity round trip time. A pulse develops



The modulator loss curve drives the pulse to line up at the minimum loss point. Pulse is also driven towards shorter pulselength.

### - Frequency domain view:

The modulator amplitude modulates each mode.

Amplitude modulation produces sidebands. For mode with  $\cos \omega t$  and modulation  $\cos \omega_m t$ , the modulated field has terms:



When  $\omega_m = \Delta\omega$ , then the modulated field of model injects in-phase signal into adjacent modes  $\ell \pm 1$ . This is occurring simultaneously for all modes. This tends to lock all the mode phases together to create the modelocked pulse, as discussed earlier.

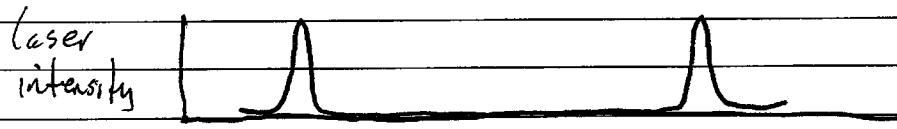
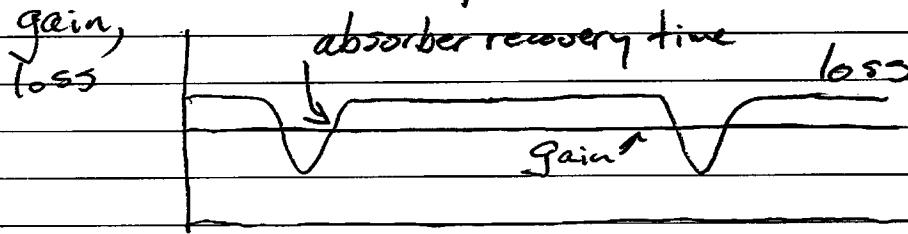
### - Passive mode locking

2 types in common use:

- "fast" saturable absorber
- Kerr lens mode locking

#### • Fast saturable absorber mode locking

- Saturable absorber placed near end mirror, similar to passive Q-switching.
- Laser is pumped CW,
- absorber relaxation (recovery time) is fast compared to cavity round trip time
- Gain recovery is slow



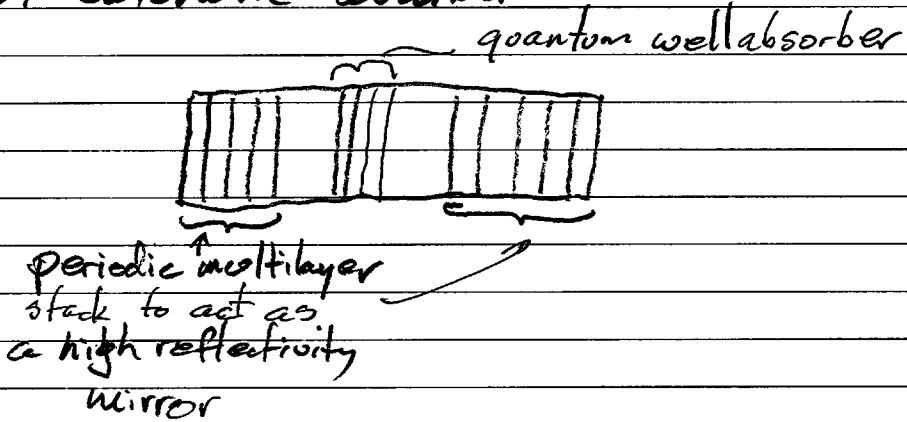
• Fast absorber recovery tends to "chop off" the trailing edge of the circulating pulse

Fast saturable absorber materials - need short  $\tau$  and large  $\sigma$  for low  $I_{sat}$

- Organic dye solution - cyanine dyes with lifetime  $\tau \approx 10 \text{ psec}$

- Semiconductor QW absorber - has multiple time constants, with fastest component  $\approx 100 \text{ fs}$ . Also doesn't degrade like dyes, no need for liquid recirculation system and dye jet.

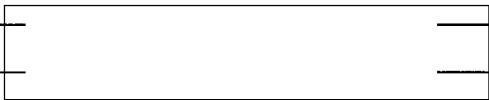
- Fabry-Pérot saturable absorber



- Spacing between the mirror coating stacks is chosen for high reflection.
- The intensity inside the structure - saturates the quantum well absorber.
- Entire structure is only  $< 100 \mu\text{m}$  thick - used in place of conventional cavity mirror.
- Intensity at absorber can be engineered to differ from intensity in the main cavity providing more control

## - Kerr-lens modelocking

Optical Kerr effect: intensity dependent refractive index:



$$n_2 = 4.5 \times 10^{-16} \text{ cm}^2/\text{W} \text{ for fused quartz}$$

For  $I \sim 2 \times 10^{12} \text{ W/cm}^2$ ,  $\Delta n = n_2 I \sim 10^{-3}$  which is large enough to bend the beam slightly for mm scale slab.

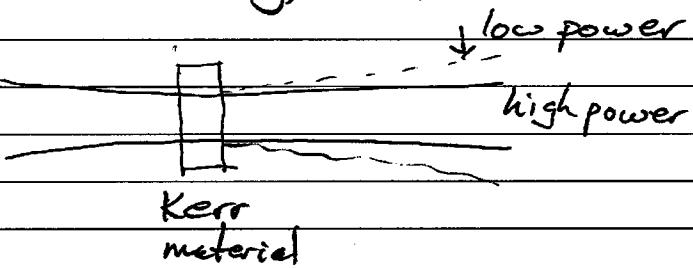
How big is  $10^{13} \text{ W/cm}^2$ ?

- Take pulselength of 100 fs =  $10^{-13}$  sec. Inside a stable laser cavity focus, take  $w_0 \sim 10 \mu\text{m}$ . Area  $\pi w_0^2 \sim 3 \times 10^{-6} \text{ cm}^2$

## - Pulse energy

For a 30 cm cavity,  $V = 100 \text{ MHz} = 10^8 \text{ Hz}$ , the internal average power is  $\sim 60 \text{ W}$

For a gaussian beam, the Kerr effect causes higher index at center  $\rightarrow$  focusing.  
(self focusing)



A hard aperture is placed in the cavity such that the loss for the high power pulse is low.

The net effect is the same as a saturable absorber. Kerr effect relaxation time is extremely fast  $\sim 1 \text{ fsec}$ .