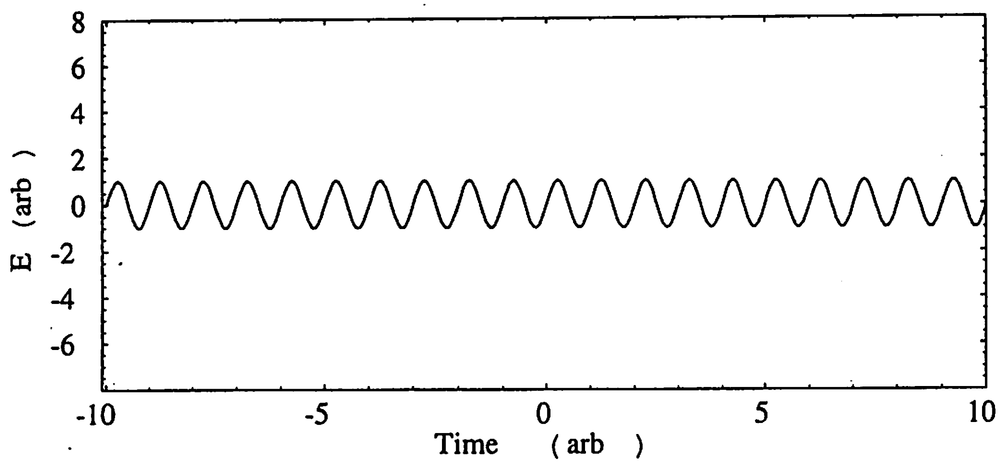
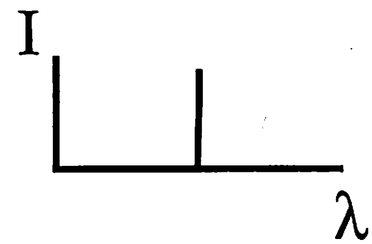
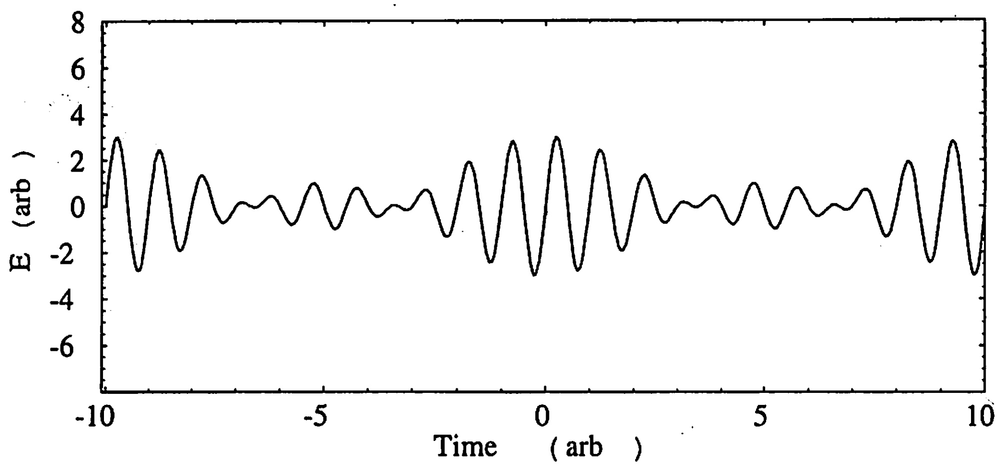
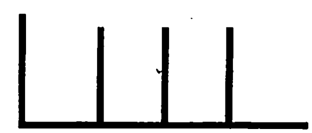
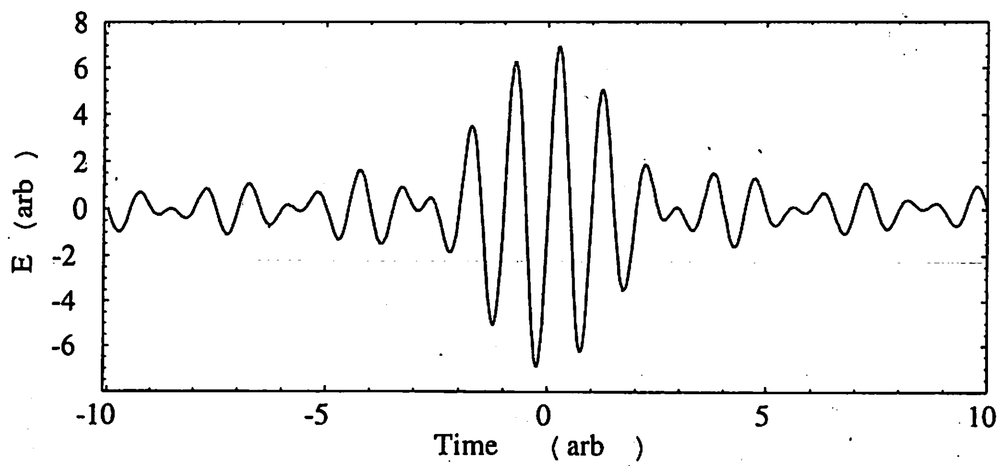
Ultrafast: Superposition

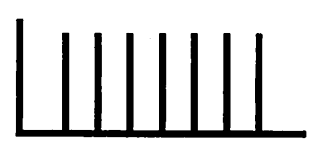












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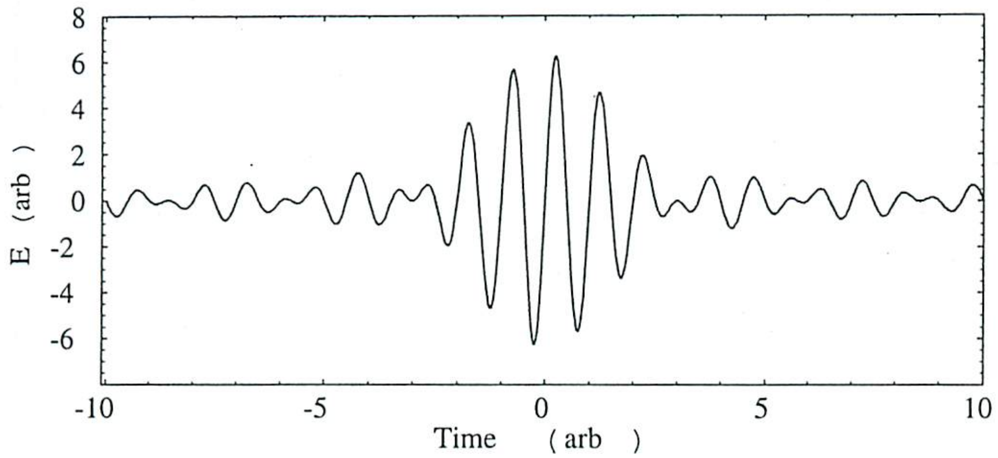
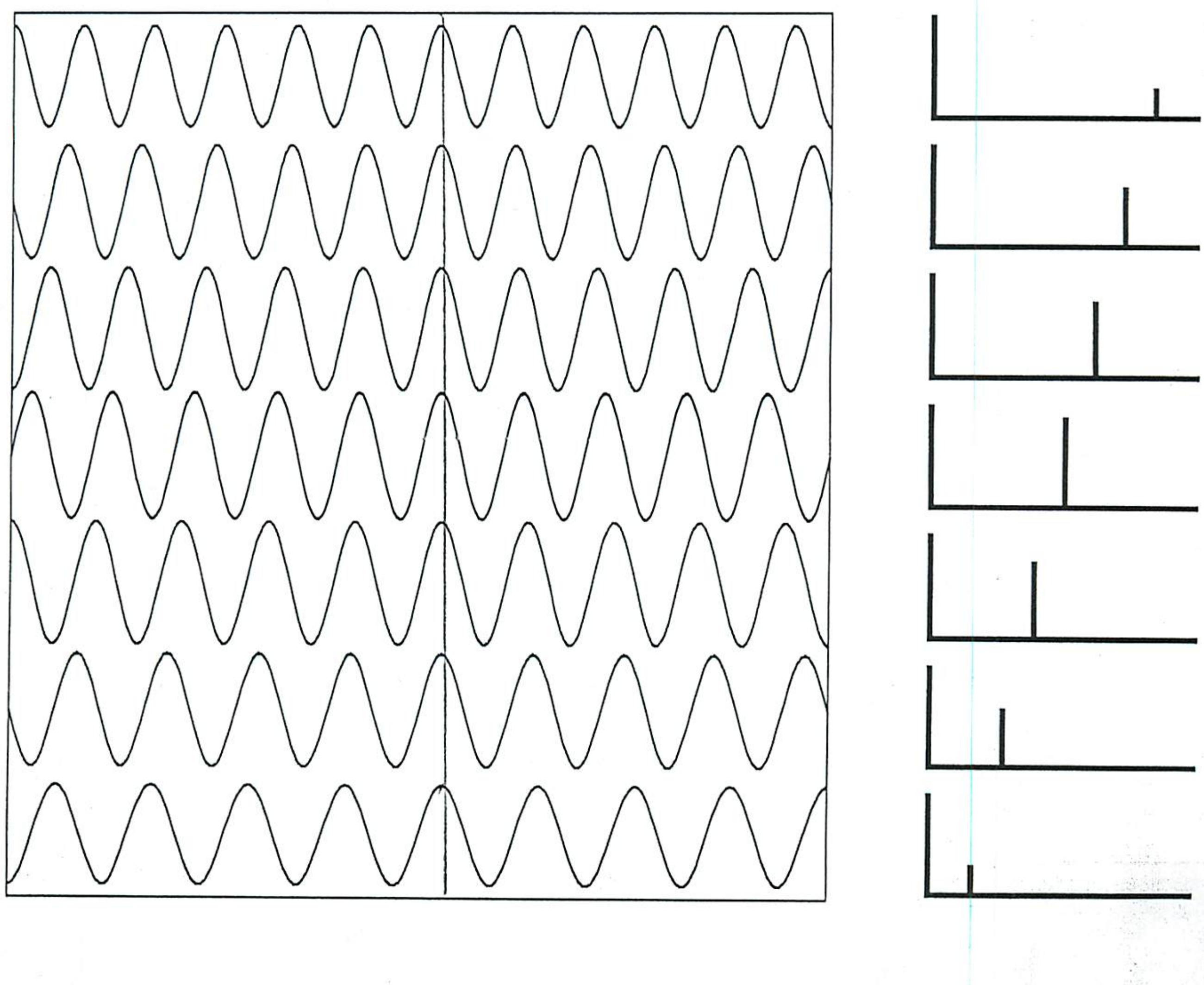




What might you get if you lock the modes?

Modelocking

Suppose we have $2n+1$ longitudinal modes. At the output coupler, suppose we have:

$$E(t) = \sum_{l=-n}^{n} E_0 e^{i(\omega_0 + l\omega_c)t} \qquad \omega_c = 2\pi\nu_c = 2\pi \frac{c}{2L_{opt}}$$

$$\equiv A(t)\, e^{i\omega_0 t}$$

$$A(t) = E_0 \sum_{-n}^{n} e^{il\omega_c t}$$

$$= E_0 \frac{\sin\left[\frac{1}{2}(2n+1)\omega_c t\right]}{\sin\left[\frac{1}{2}\omega_c t\right]}$$

(if $x \equiv e^{i\omega_c t}$, then $= E_0(\ldots + x^{-1} + 1 + x + x^2 + \ldots)$

$\left[\text{using: } 1 + y + y^2 + \ldots + y^{n-1} = \frac{1-y^n}{1-y}\right]$)

$A(t)$ is a maximum when $\sin\left[\frac{1}{2}\omega_c t\right] = 0 \Rightarrow t = 0, \frac{1}{\nu_c}, \frac{2}{\nu_c} \ldots$

So the spacing between pulses $= \frac{1}{\nu_c} = \tau_{RT}$ ✓

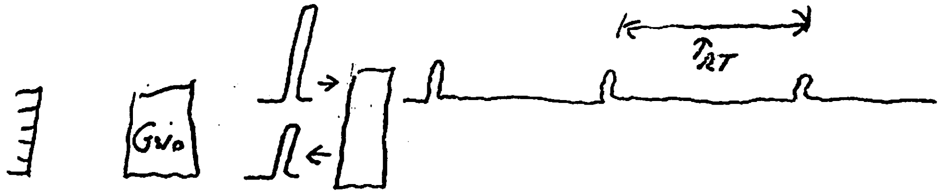
Note the numerator is also $= 0$ at these times, so using $(\sin\theta \approx \theta)$:

$$A(t) \propto \frac{\frac{1}{2}(2n+1)\omega_c t}{\frac{1}{2}\omega_c t} = 2n+1$$

$E_{max} = (2n+1)E_0 \Rightarrow I_{max} \propto (2n+1)^2 E_0^2$ ✓

For an incoherent sum, $I_{max} \propto (2n+1)E_0^2$

The carrier frequency $= \omega_0$ ✓



Consider the pulse at $t = 0$. Its width is given roughly by the next zero in the numerator:

$$\tfrac{1}{2}(2n+1)\,\omega_c t = \pi \Rightarrow t = \frac{1}{(2n+1)\nu_c} = \frac{1}{\text{total bandwidth}}$$

or $\tau_p = \dfrac{T_{RT}}{2n+1}$

8.6 • *Mode Locking*

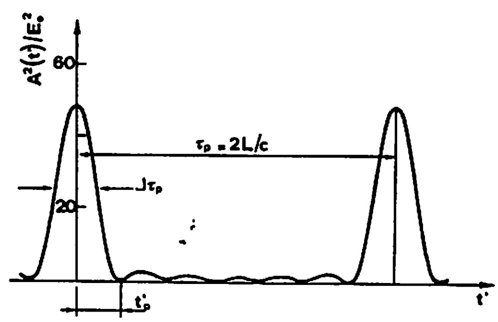
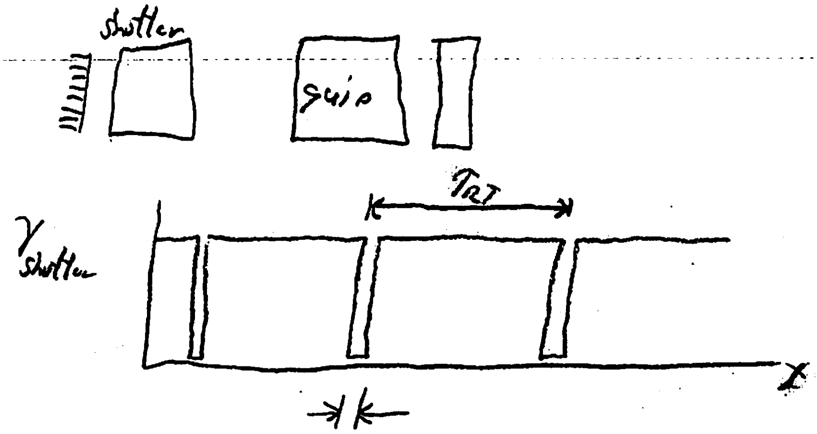


FIG. 8.17. **Time behavior of the squared amplitude of the electric field for the case of seven oscillating modes with locked phases and equal amplitudes. E_0.**

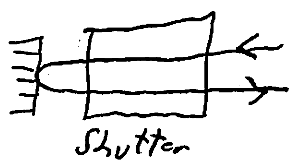
How do you lock the modes?

You arrange things so that a pulsed mode is the mode that has the highest gain.

Low brow ⇒ AM Modelocking = Put a fast shutter in the cavity

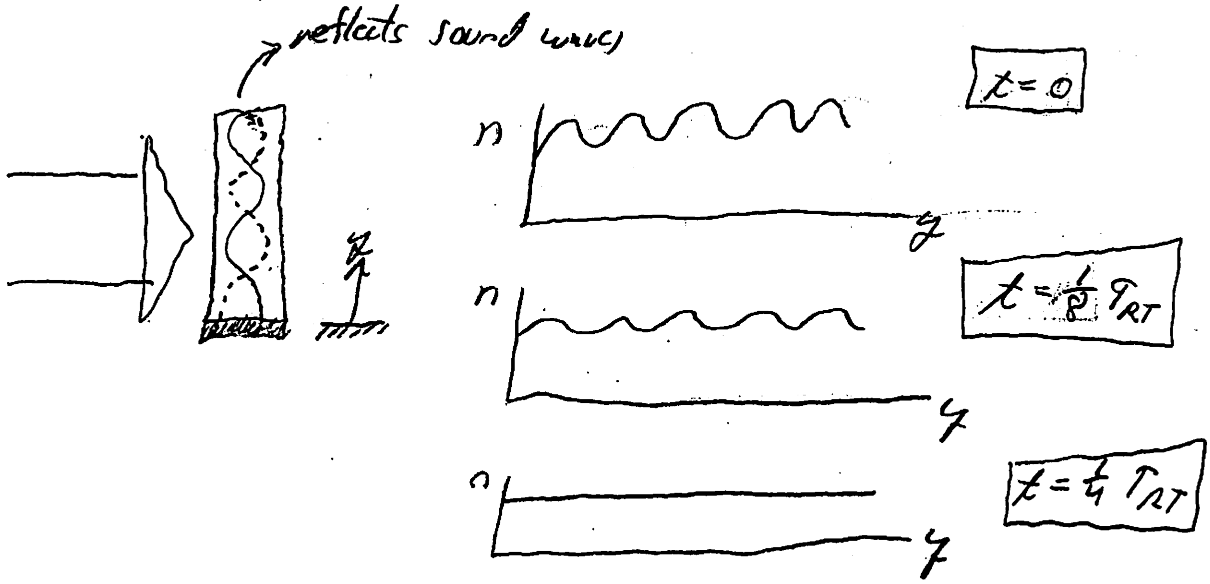


cavity length and ML frequency need to be matched and stable for this to work



$2\nu_{shutter} = \nu_c \approx 100\,\text{MHz}$

⇒ use acousto-optics typically



Note, you go through the zero-crossing (in time) very quickly ⇒ effective open-shutter time is short.

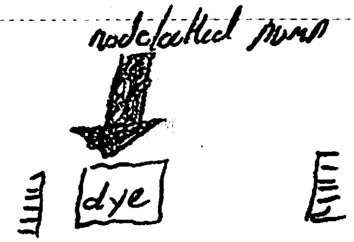
cw modelocked Nd:YAG, Ar^+ lasers are the most common commercial AM modelocked systems.

Typically ⇒ $\nu_c \approx 100\,\text{MHz}$ ($L_{opt} \approx 1.5\,\text{m}$)

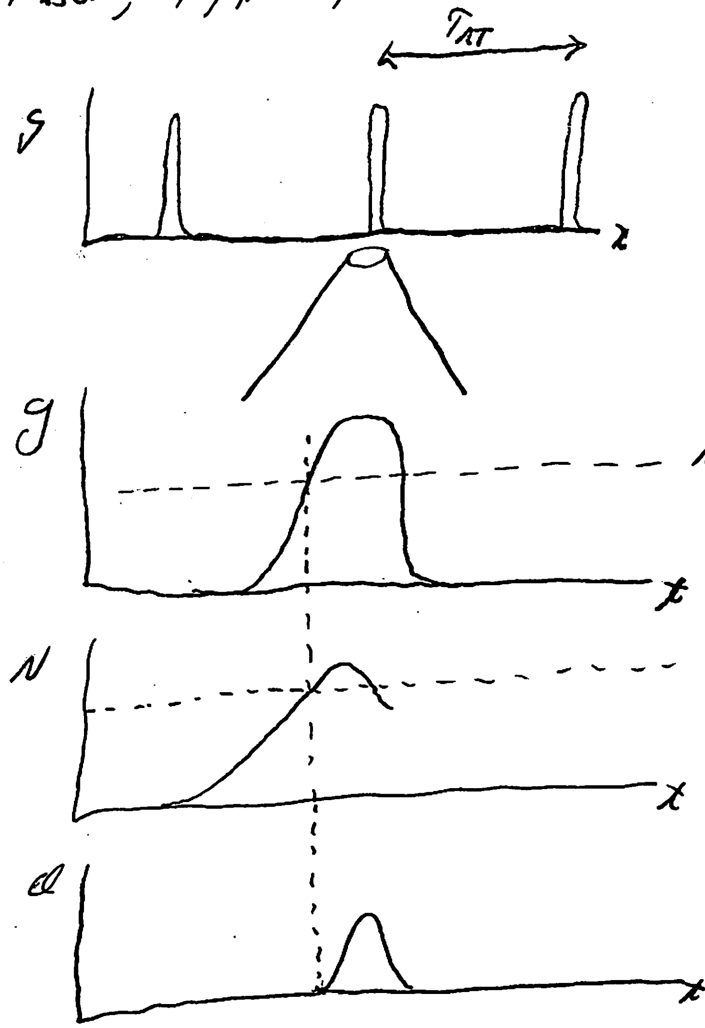
$\tau_p \approx 100\,\text{ps} \rightarrow 2n+1 \approx \frac{1}{\tau_p \nu_c} \approx 100$

Synchronous Modelocking

Take modelocked laser and use it to pump another laser, typically a dye laser.



You need $\tau_{RT,dye} = \tau_{RT,pump}$



Run with a fairly high threshold {large output coupling ($R_2 = 80-90\%$)}

Also, dyes have large cross-sections and so saturate easily.

For R590, 100 ps & 1W pump ⇒

$\tau < 1 ps$ & $\frac{1}{10} W$

Now $2n+1 > 1000$.

For ultra-short pulse generation, a number of mechanisms come into play.

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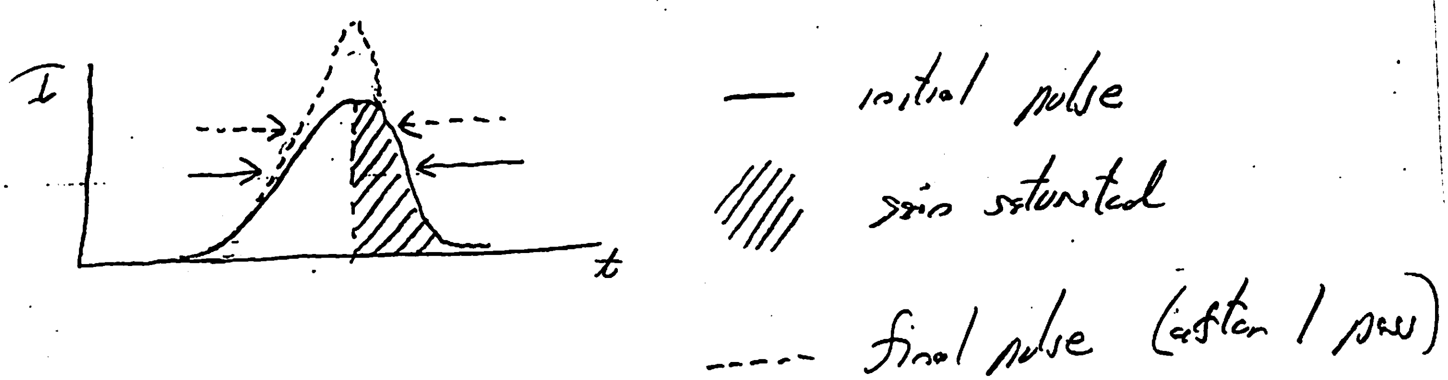
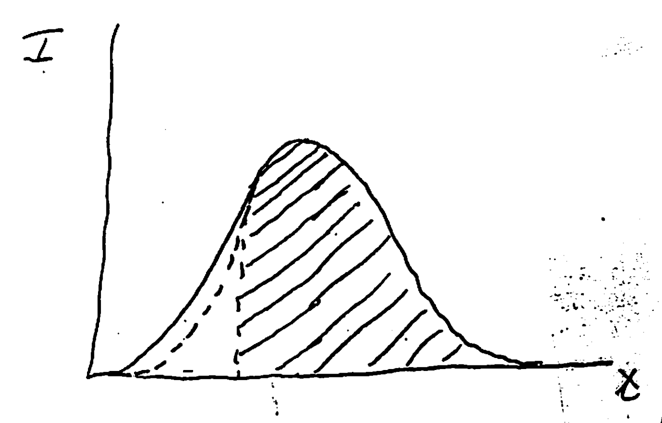
fast gain saturation

- gain saturates (population inversion significantly depleted) during passage of pulse
- leading edge selectively amplified
- fraction reduction in pulse width $\propto$ $\dfrac{\text{energy density gained at leading edge}}{\text{total pulse energy density}}$

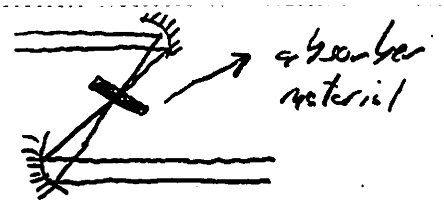


fast loss saturation

- loss saturates during pulse passage
- leading edge selectively clipped.



☆ The simplest example of loss saturation is absorber bleaching:



- large energy density
- finite # of absorbers in the small intersection region

⇨ but, the absorber only has T_{RT} to recover (or less).

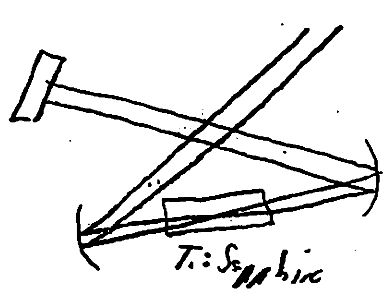
Good fast saturable absorber materials:

- dyes in solvents
- colored glasses
- quantum well systems

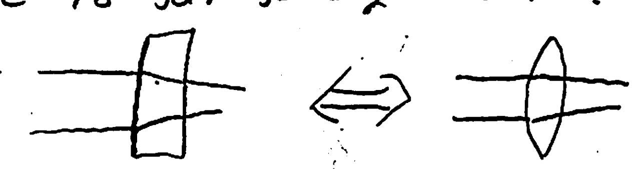
☆ KLMs achieve loss saturation via self-lensing.

Ti:Sapphire has a <u>Kerr nonlinearity</u>

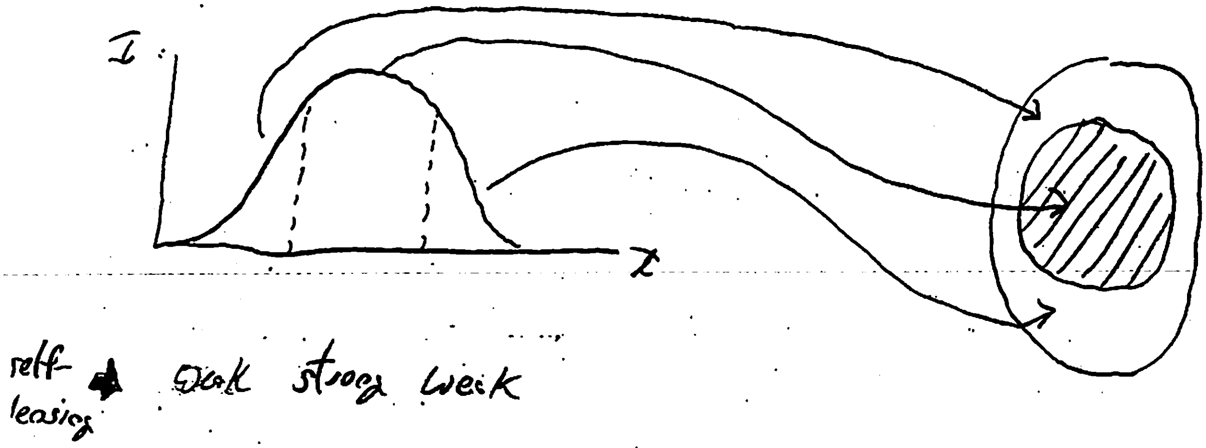
The beam is focussed into the gain medium



but there is additional lensing due to self-focusing however.

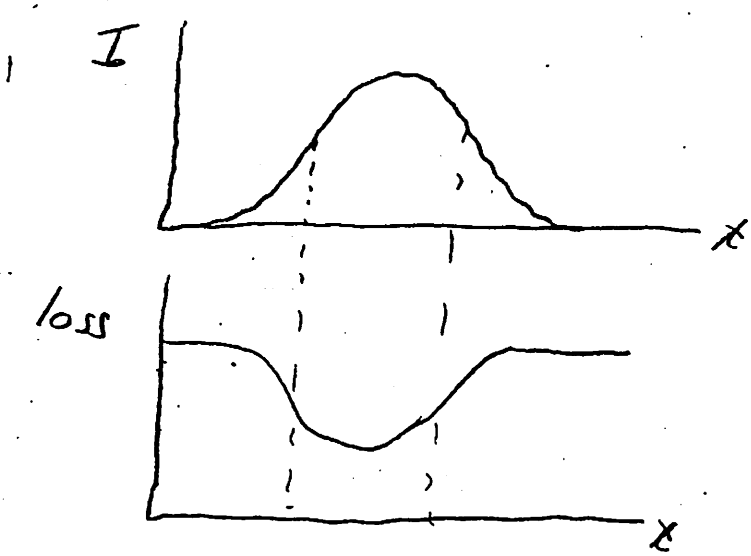


$n = n_0 + n_2 I$



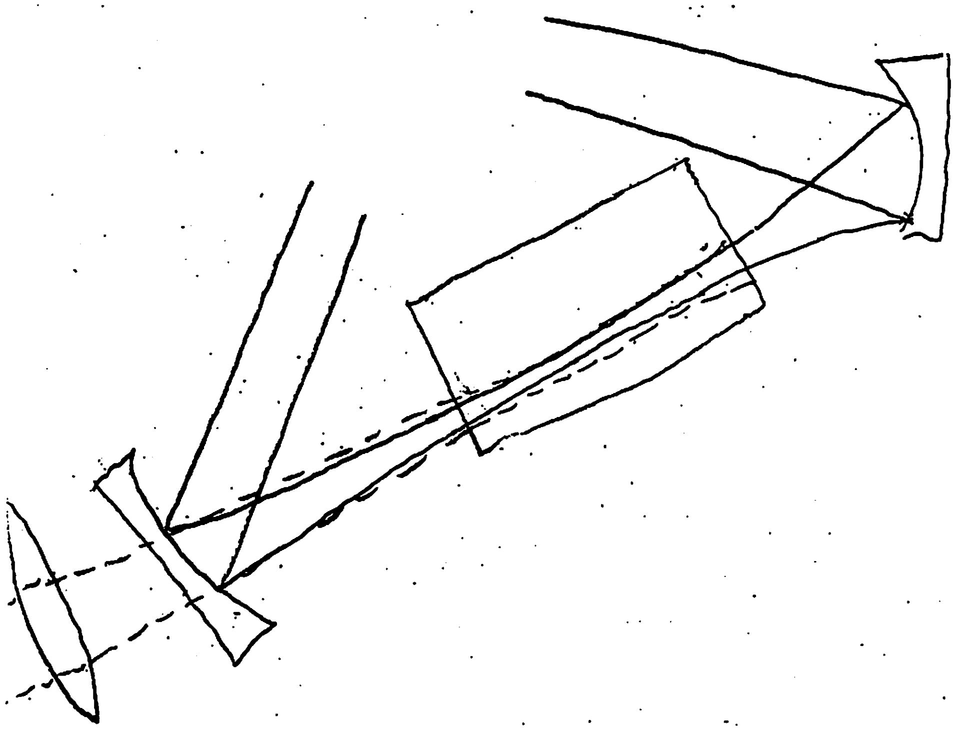
So, the leading and trailing edges will have a slightly different spatial mode than the pulse center.

An aperture placed in the laser will effectively give the cavity a fast absorber with this temporal response:



operates to clip the leading and trailing edges.

Frequently, there is no explicit aperture.
Instead, the finite region pumped by the pump laser acts as a "soft aperture"



☆ In general, you want the loss to saturate <u>before</u> the gain.

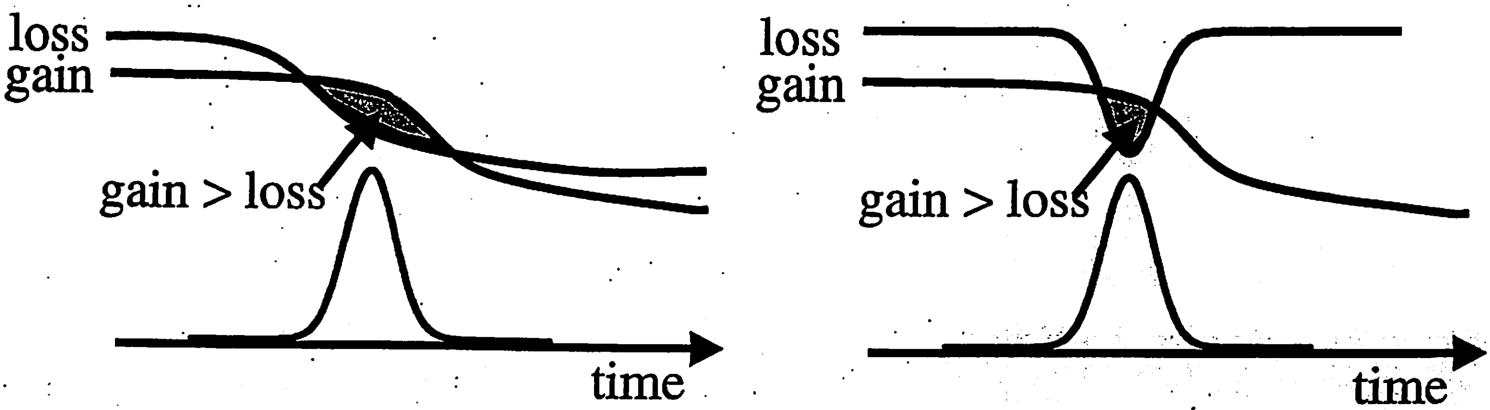


TABLE 8.1. Most common media providing picosecond and femtosecond laser pulses together with the corresponding values of: (a) Gain linewidth, $\Delta\nu_0$; (b) peak stimulated-emission cross-section, σ; (c) upper state lifetime, τ; (d) shortest pulse duration so far reported, $\Delta\tau_p$; (e) shortest pulse duration, $\Delta\tau_{mp}$, achievable from the same laser

Laser medium	$\Delta\nu_0$	σ $[10^{-20}\ cm^2]$	τ $[\mu s]$	$\Delta\tau_p$	$\Delta\tau_{mp}$
Nd:YAG $\lambda = 1.064\ \mu m$	135 GHz	28	230	5 ps	3.3 ps
Nd:YLF $\lambda = 1.047\ \mu m$	390 GHz	19	450	2 ps	1.1 ps
$Nd:YVO_4$ $\lambda = 1.064\ \mu m$	338 GHz	76	98	<10 ps	1.3 ps
Nd:glass $\lambda = 1.054\ \mu m$	8 THz	4.1	350	60 fs	55 fs
Rhodamine 6G $\lambda = 570$ nm	45 THz	2×10^4	5×10^{-3}	27 fs	10 fs
Cr:LiSAF $\lambda = 850$ nm	57 THz	4.8	67	18 fs	8 fs
Ti:sapphire $\lambda = 850$ nm	100 THz	38	3.9	6–8 fs	4.4 fs

For $\tau_p = 10\ fs$, $(2n+1) \approx 10^6$!!!

State of the art short pulse generation has $\tau_p < 1\ fs$, but this involves non-linear techniques outside of the cavity (and this course!)