Advanced Output Coupling

$\boxed{\text{Intracavity Doubling}}$

Nd:XXX may be a very popular gain medium, but it's the SH that's desired, not the fundamental.

(Not surprising. The optical range is special.)

How do you get the SH?

Eqn of motion for an electron:

$$F = ma$$

$$\ddot{x} = -\frac{eE(t)}{m} \quad \text{free electron}$$

In a medium, we'll have some damping force and the effect of the potential well:

$$\underbrace{\ddot{x}}_{} + \underbrace{\gamma \dot{x}}_{\text{drag}} + \underbrace{\omega_0^2 x}_{\substack{\text{harmonic}\\\text{potential}\\\text{well -}\\\text{linear restoring force}}} + \underbrace{Ax^2 + Bx^3 + \dots}_{\substack{\text{anharmonic}\\\text{potential}}} = -\frac{e}{m}E(t)$$

$\sim \cos \omega t$

If the restoring force is linear: $x(t) = A\cos(\omega t + \phi)$

If not, x will have a more complicated form which must involve other frequencies

$P \equiv$ polarization $\propto x$ (Just giving a rough overview)

$$\vec{E}_{in} \rightarrow \vec{P} \rightarrow \vec{E}_{out}$$

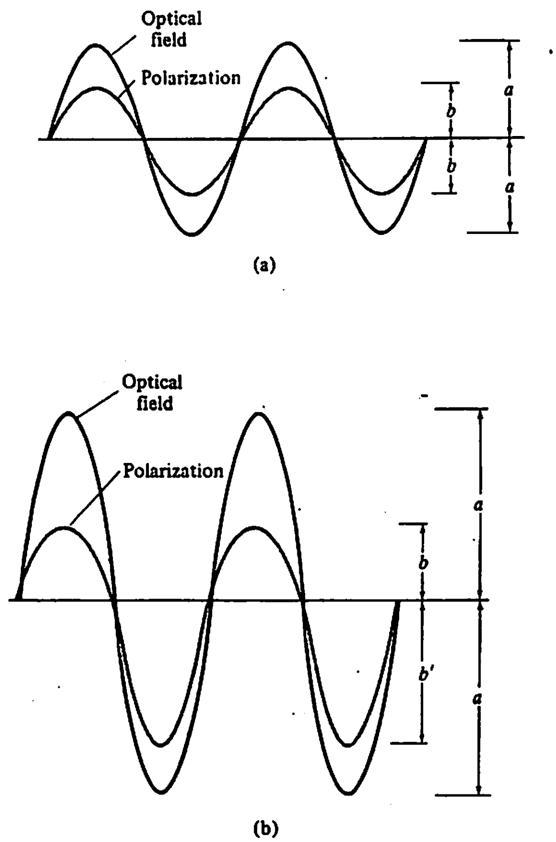


Figure 8-2 An applied sinusoidal electric field and the resulting polarization; (a) in a linear crystal and (b) in a crystal lacking inversion symmetry.

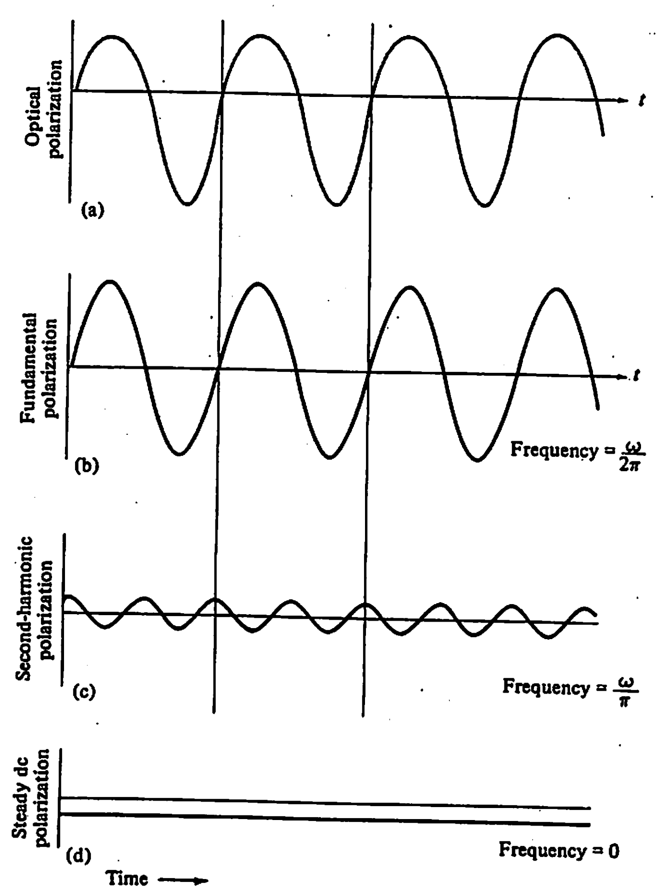


Figure 8-3 Analysis of the nonlinear polarization wave (a) of Figure 8.2(b) shows that it contains components oscillating at (b) the same frequency (ω) as the wave inducing it, (c) twice that frequency (2ω), and (d) an average (dc) negative component.

It's more convenient to express P in terms of E:

$$P = \varepsilon_0 \underbrace{\chi_1 E}_{\omega} + \varepsilon_0 \underbrace{\chi_2 E^2}_{\omega^2,\ \text{zero}} + \varepsilon_0 \underbrace{\chi_3 E^3}_{\omega^3,\ \omega} + \cdots$$

(No effort to use a consistent notation here.)

$n = \sqrt{\varepsilon\mu} \approx \sqrt{\varepsilon\mu_0} \qquad \varepsilon = (1+\chi_1)\varepsilon_0$

$$\boxed{\text{Recall: } \cos\omega_1 t \cos\omega_2 t = \tfrac{1}{2}\left[\cos(\omega_1-\omega_2) - \cos(\omega_1+\omega_2)\right]}$$

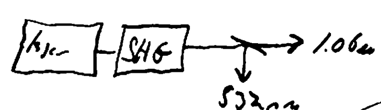
$$E^{2\omega}_{out} \propto P^{2\omega} \propto E_\omega^2 \propto I^\omega$$

$I^{2\omega} \propto (I^\omega)^2$ ⇒ You win big if the intensity is large

(Alternatively, you want a large E to explore the anisotropic regions of the potential.)

In general, this tends to mean you can't double cw or low energy pulsed beams

10Hz Pulsed ⇒ ~ ½ J/pulse 1.06 μ
(typical, $30-50k) ~ ⅓ J/pulse 532 nm



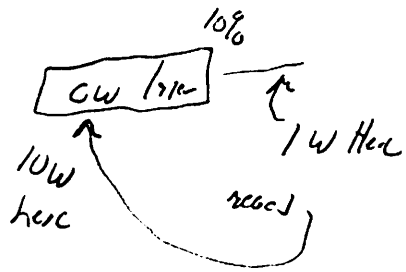
If $P_{ave,Merlin} = P_{ave,GCR}$

1kHz Pulsed ⇒ 1kHz, 200 ns So, all other things being equal, the peak intensity is down by

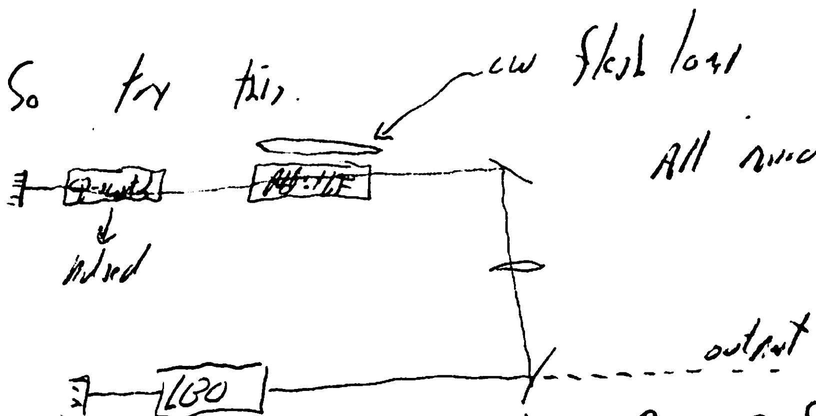
At 1.06μ ⇒ $\dfrac{I_p^{GCR}}{I_p^{Merlin}} = \dfrac{20\text{ Hz}}{1000\text{ Hz}}\,\dfrac{5\text{ ns}}{100\text{ ns}} = \dfrac{1}{50}\,\dfrac{1}{20} = \dfrac{1}{1000}$

(If Merlin used as output coupler) So $I^{2\omega}$ will be down a lot!

But, set:



So try this.

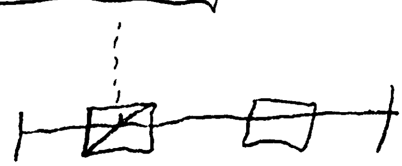


All mirrors have $R=1$ @ $1.06\,\mu$

$R=0$ @ 532 nm

$\tau_{out,532} \approx 150\,ns \gg \tau_{RT} \approx 10\,ns$

Cavity Dumping



All mirrors have $R=1$

state #1 transmits
state #2 reflects.

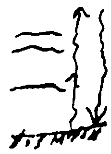
Won't increase the average power, might drop it.

Does increase the peak power compared to optimum output coupling case.

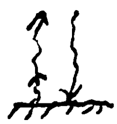
$\tau_D = \tau_{RT}$ for cw pumping

A little more NLO | 113A

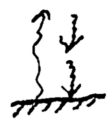
SHG ⇒



SFG ⇒



Photon splitting (optical parametric generation - OPG)
DFG



$P^{(2)} = \chi_2 E^2 \qquad E = E_0(\cos\omega_1 t + \cos\omega_2 t) \qquad \cos\omega_1 t\cos\omega_2 t = \frac{1}{2}[\cos(\omega_1-\omega_2)t - \cos(\omega_1+\omega_2)t]$

$P^{(2)} \propto \chi_2 E_0(\cos^2\omega_1 + 2\cos\omega_1\cos\omega_2 + \cos^2\omega_2)$

$P^{(2)} = P^{DC} + P^{2\omega_1} + P^{2\omega_2} + P^{\omega_1+\omega_2} + P^{\omega_1-\omega_2}$

Only one of these will be phase matched

$E = E_0 + E_\omega\cos\omega t$

$P^{(2)} = \varepsilon_0\chi^{(2)}E_0E_\omega\cos\omega t$

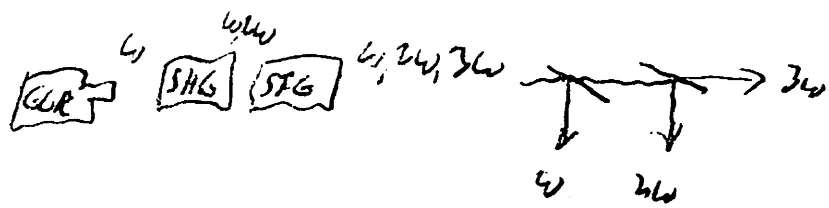
$P = \varepsilon_0\underbrace{(\chi_1 + \chi^{(2)}E_0)}_{\to n(E_0)}E_\omega\cos\omega t$

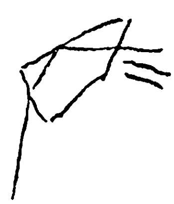
$P = \underbrace{\varepsilon_0\chi}_{\to n} E_\omega\cos\omega t$

Pockels Effect

χ_1 ⇒ index of refraction
χ_2 ⇒ optical rectification. Pockels Effect
SHG, SFG, DFG, OPG
χ_3 ⇒ THG, ... ⇒ not generally important
Kerr effect

THG?

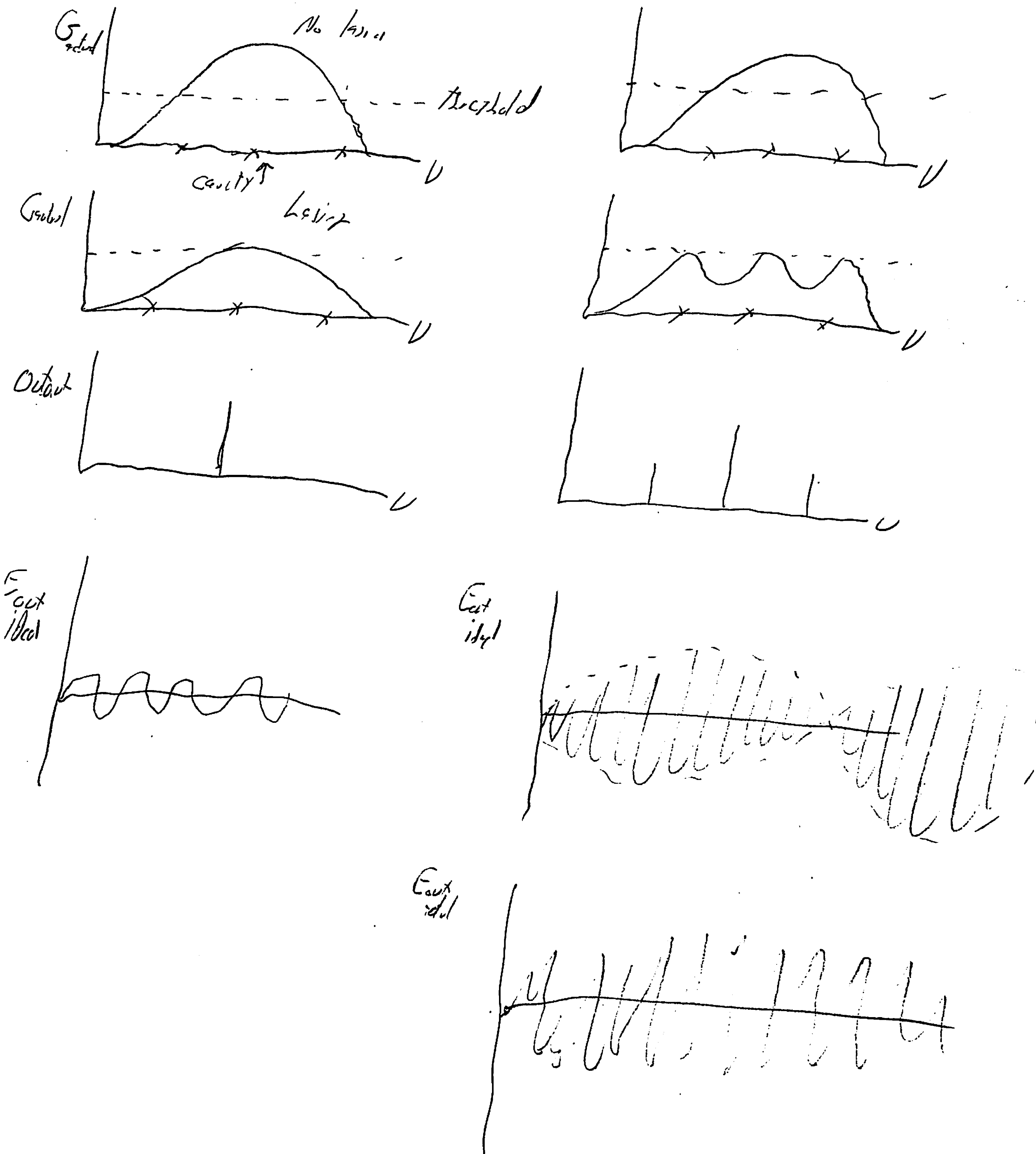




Pellin-Broca

Output Spectrum

Homogeneous Broadening | Inhomogeneous

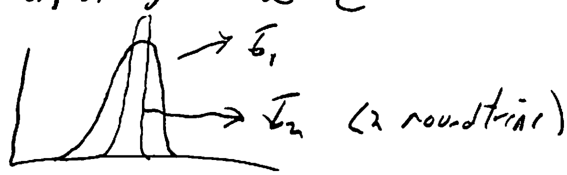


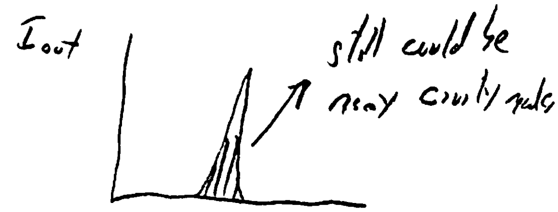
If only you could lock the modes

Line width

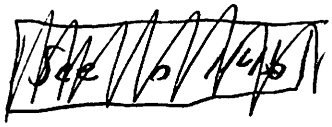
→ roughly a measure of the cross-section (even if the overall linewidth is small)

Small signal gain $\propto e^{\Delta N \sigma \ell}$





Gain narrowing. (Homogeneously broadened case)

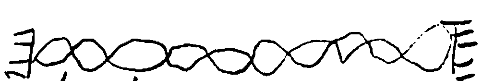


The next step might be to go to a single cavity mode.

Insert line width narrowing elements.

Make the cavity short. (Diode laser cavities can be very short!)

There's a problem, however, in linear cavities



Deplete the gain here } so a different cavity mode might have higher gain (for a while)
not access the gain here }

One solution to this is to go to a ring cavity with an optical diode.

travelling wave!

Model calculation for a single mode HeNe (Yariv, QE)

$\Delta\nu_{1/2}$ is the width of the cavity resonance.

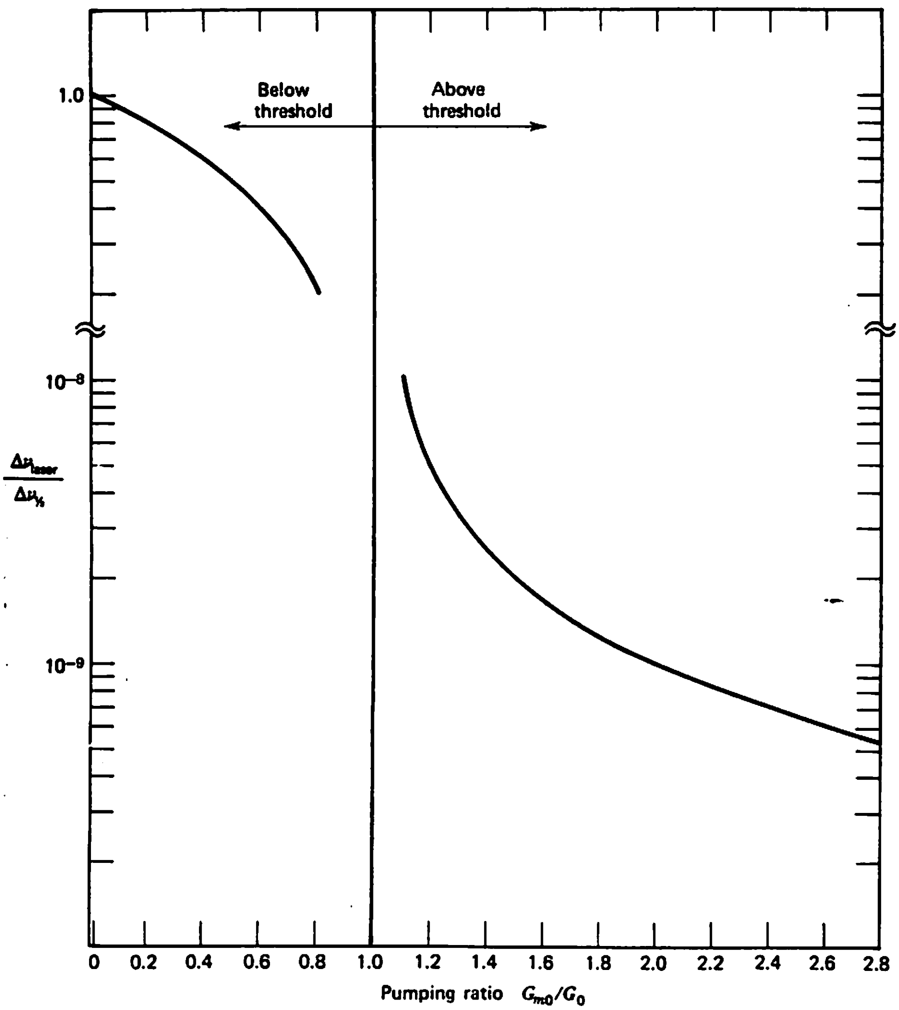


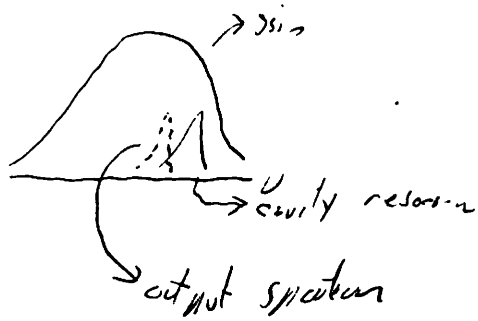
FIGURE 21.5 The laser mode linewidth below threshold [Eq. (21.2-15)] and above threshold [Eq. (21.2-19)]. The data used in the plot correspond to the He-Ne laser example of Section 21.2. Note the break in the ordinate scale.

Frequency Pulling

see Yariv eqn 9.1-21 and preceding derivations

LHZ 114E

Things are a little more complicated



For a homogeneously broadened system

$$\nu_L = \frac{\frac{\nu_0}{\Delta\nu_0} + \frac{\nu_c}{\Delta\nu_c}}{\frac{1}{\Delta\nu_0} + \frac{1}{\Delta\nu_c}}$$

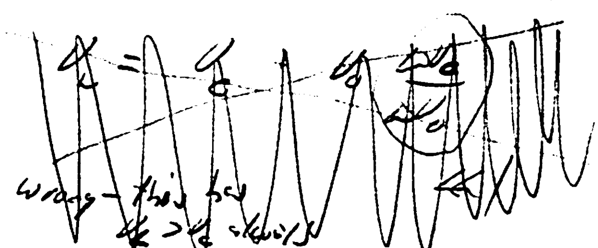
transition-resonance and width

(You'll need this in the next HW assignment)

$$\nu_L = \frac{\frac{\nu_0}{\Delta\nu_0} + \frac{\nu_c}{\Delta\nu_c}}{\frac{1}{\Delta\nu_c}\left(\frac{\Delta\nu_c}{\Delta\nu_0} + 1\right)} \approx \left(\nu_0 \frac{\Delta\nu_c}{\Delta\nu_0} + \nu_c\right)\left(1 - \frac{\Delta\nu_c}{\Delta\nu_0}\right)$$

$$\approx \nu_c + (\nu_0 - \nu_c)\frac{\Delta\nu_c}{\Delta\nu_0}$$

If $\Delta\nu_0 \gg \Delta\nu_c$, the gain spectrum is broad and can't pull much



$\Delta\nu_0 \approx 300\,\text{GHz}$ for some solid state media

$\Delta\nu_c \approx 10\,\text{MHz}$ for low loss, m-line sized cavities

The above is can be a decent approx. for inhomog. systems depending on circumstance

What limits $\Delta\nu_L$?

$$\nu_c = N\frac{c}{2L_{opt}}$$

$$\frac{d\nu_c}{dL_{opt}} = -N\frac{c}{2L_{opt}^2} = \underbrace{\left(\frac{Nc}{2L_{opt}}\right)}_{\nu_c}\left(-\frac{1}{L_{opt}}\right)$$

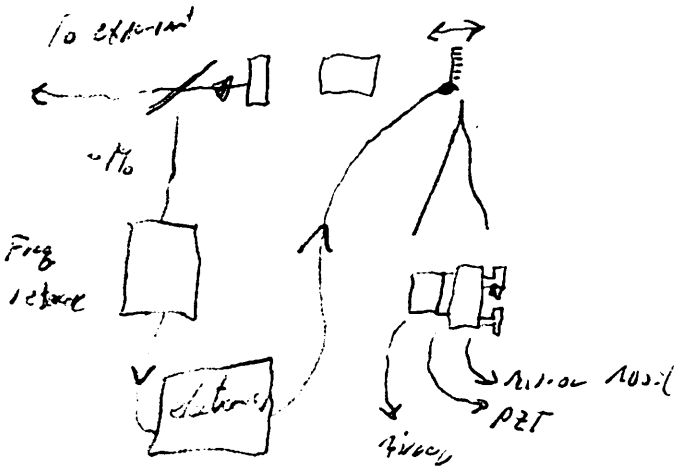
(Assuming N doesn't change!)

$$\frac{\Delta\nu_c}{\nu_c} \approx \frac{\Delta L_{opt}}{L_{opt}}$$

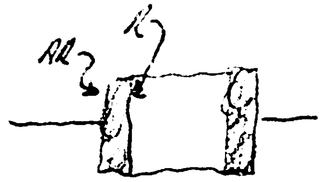
and L_{opt} can change due to thermal fluctuation, gain fluctuations, mirror movement

For a 1 m cavity, $\lambda = 532\,\text{nm}$, $\Delta\nu_c = 10\,\text{MHz} \Rightarrow \Delta L_{opt} \approx 20\,\text{nm}$ ✓

Not surprisingly, then, active stabilization is often used in critical applications ⇨



(PZT effect is related to SHG!)



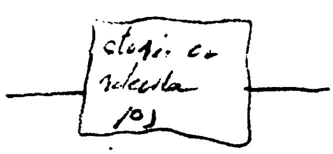
air space etalon

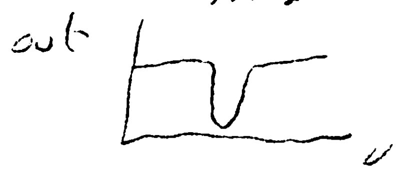
"Fabry-Perot" etalon

- temp stabilized
- enclosed
- careful design

can be whatever you want

- Careful, don't let intensity fluctuations fool you.
- The most obvious ways to use this signal are all bad.



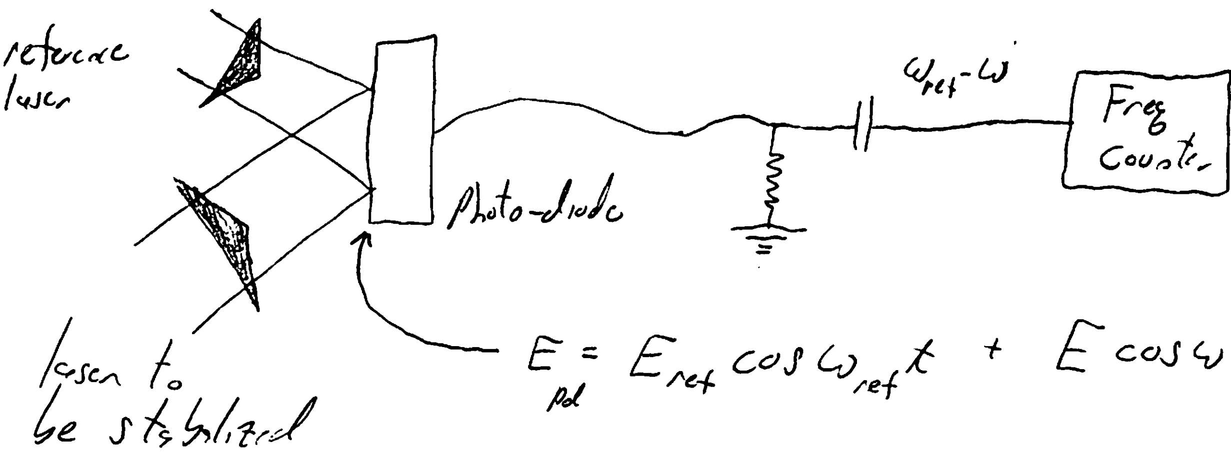


linear absorption line (limited by Doppler width)

↓

There are non-linear absorpt. spectroscopic techniques that can beat this

Once you have a stable laser operating at a single narrow line, you can use it to stabilize other lasers sometimes.



$$E_{pd} = E_{ref}\cos\omega_{ref}t + E\cos\omega t$$

This will work if $|\omega_{ref}-\omega| \lesssim$ GHz.

However, a new technique has been developed* that, in principle, allows you to measure (and hence stabilize) a laser operating anywhere in or near the optical spectrum.

Amazingly, the heart of the system is a short pulse laser which necessarily has a broad linewidth:

$$\Delta\nu\,\tau \approx 1$$

For $\tau = 50$ fs, $\Delta\nu \approx 2\cdot10^{13}$ Hz.
If $\lambda = 800$ nm, $\Delta\nu/\nu = 5\%$!

* See the class web page for a reference.

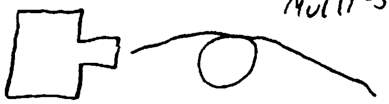
* $p^{(3)} = \chi^{(3)} \tilde{E}_1^* \tilde{E}_2 \tilde{E}_3$ ($\tilde{E}$ complex)
  Degenerate case: only one term: $\chi^{(3)} E E^* E = \chi^{(3)} I E$
* Compare to $p^{(1)} = \chi^{(1)} E$
* $n \to n(I) = n_0 + n_2 I$
* If $I = I(t)$:
  $E \propto E^{i\phi}$

$\phi = kz - \omega t = k_{vac} n z - \omega t = k_{lin} z - \omega t + k_{vac} n_2 I$

$\omega_{inst} = -\frac{d\phi}{dt} = \omega - k_{vac} n_2 z \frac{dI}{dt}$

Here's how it works:

"multi-structure fiber"

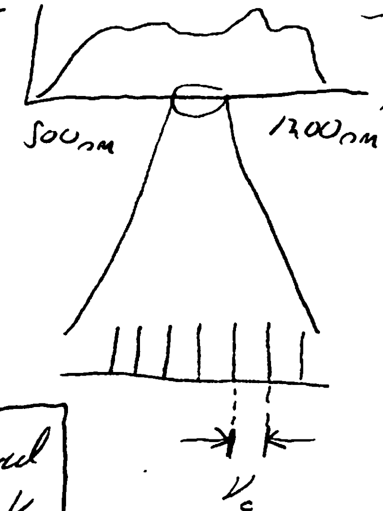


KLM laser

~ 10-100 fs

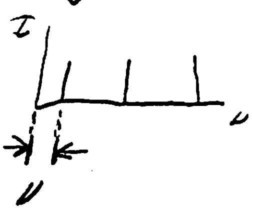
100-1000 MHz

~ $\frac{1}{2}$ W



$\boxed{\text{Can be measured with atomic clock precision}}$

$\nu = \nu_0 + n \nu_c$



If ν_c is stable

and

You can determine one of the lines accurately

then

You know them all and all are available as references (in principle)

Measure ν_0!

* So pick a line, say one @ 1.064 μ

  $\nu_{1.06} = \nu_0 + n_{1.06} \nu_c$

* Double it

  $\nu_{532} = 2\nu_0 + 2 n_{1.06} \nu_c$

* Now, go to this line in the "comb"

  $\nu_{532'} = \nu_0 + 2 n_{1.06} \nu_c$

* Measure ν_{532} and $\nu_{532'}$ on a photodiode

  The beat frequency is: ν_0!

$\boxed{\nu_0 \text{ can be measured with atomic clock precision}}$

Q-Switching (Text section 8.4)

Q-switching involves switching the cavity Q from an initially low value (high loss) to a high value (low loss).

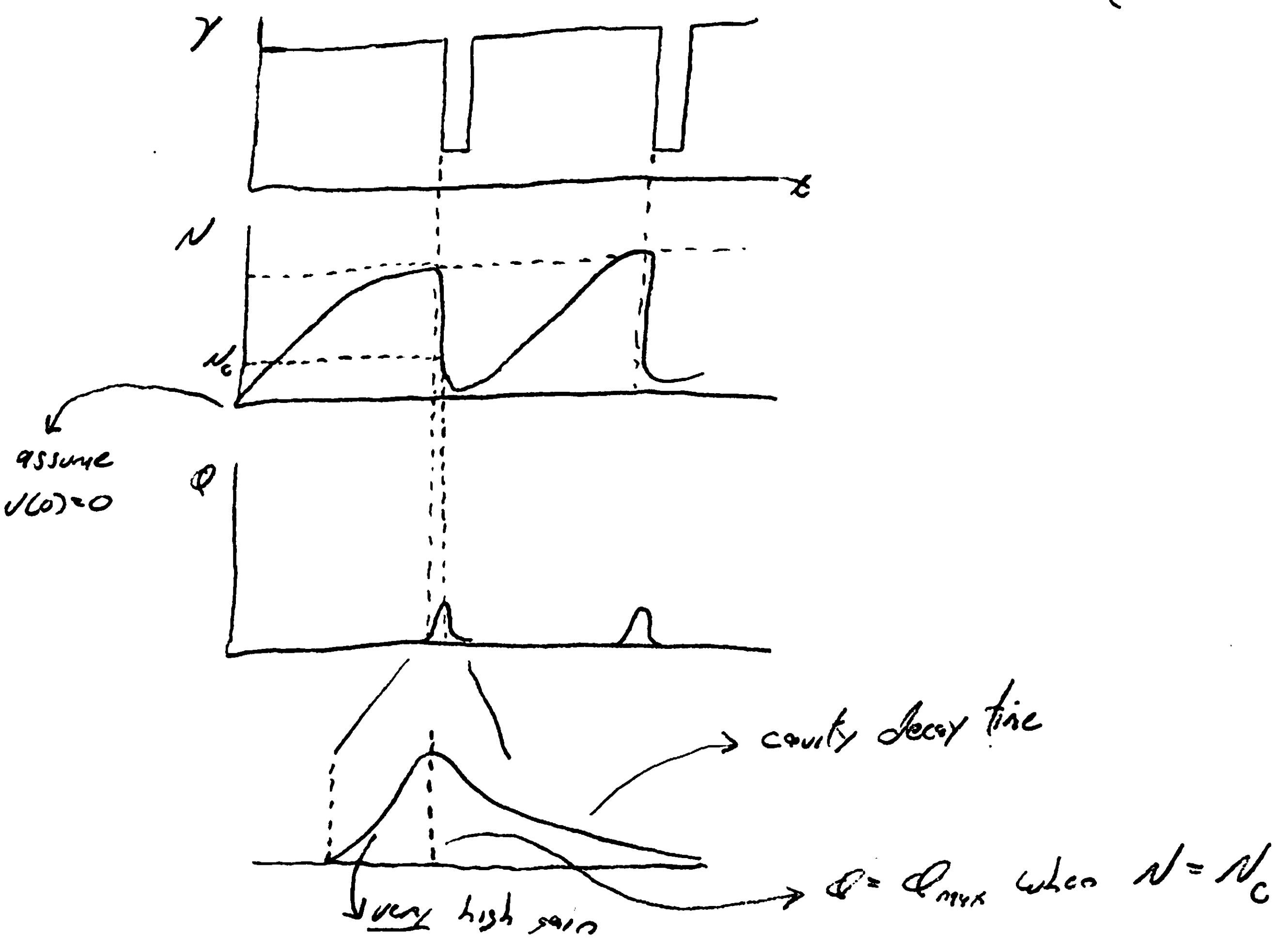
It can allow the generation of high energy pulses with pulse width on order τ_{RT}.

Recall, for cw pumping and no Q-switching:

$$\left.\begin{aligned} N_0 &= N_c = \frac{\gamma}{\sigma \ell} \\ \phi_0 &= V_a \tau_c \left[R_p - N_0/\tau \right] \end{aligned}\right\} \text{ after steady-state is reached.}$$

$$\left(\begin{aligned} \frac{dN}{dt} &= R_p - N/\tau \\ N_{20} &= R_p \tau \end{aligned} \right.$$

If you Q-switch w/ cw pumping:



- This does not allow you to more efficiently use your pump source $\Rightarrow$ this is not a way to increase P_{ave}

  IF $P_{cw} = 10W = 10\ J/s$
  $E_{pulse,10Hz} = 1J$ $\quad P = \frac{1J}{10ns} = 10^8 W$

- Because we can have $N \gg N_c$, this does allow <u>fast extraction</u> of energy $\Rightarrow$ giant pulses

- Once you reach N_{max} you should Q-switch, otherwise you reduce the rep. rate and P_{ave} available.

  $\tau = 200\mu s$ $\quad$ IF 1 kHz rep rate:
  $P_{cw} = 10W = 10\ J/s \Rightarrow E_{pulse} \leq 10mJ$ $\quad P \approx \frac{10mJ}{100ns} = 10^5 W$

- Often the pump is pulsed. You want $\tau_{pump} < \tau$ or you waste pump power.

  $\boxed{\begin{array}{l} \dot{N}_2 = R - \frac{N_2}{\tau} = 0 \\ N_{2,steady\ st} = R\tau \end{array}}$

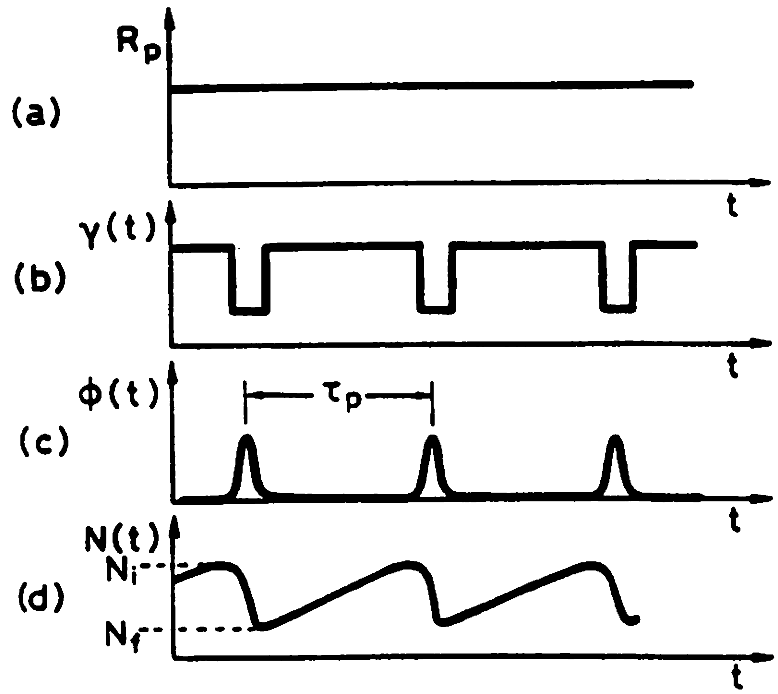
☆ Q-switching is usually reserved for media with $\tau \approx 100\ \mu s$ and above (Nd:xxx, but not He:Ne, Ar^+).

- CW-pumped: max rep rate $\approx \frac{1}{\tau} \approx$ kHz
  (limited by time to reach N_{max})

  pulsed-pumped max rep rate $\approx$ Hz
  (limited by flash lamps, heating of gain medium)

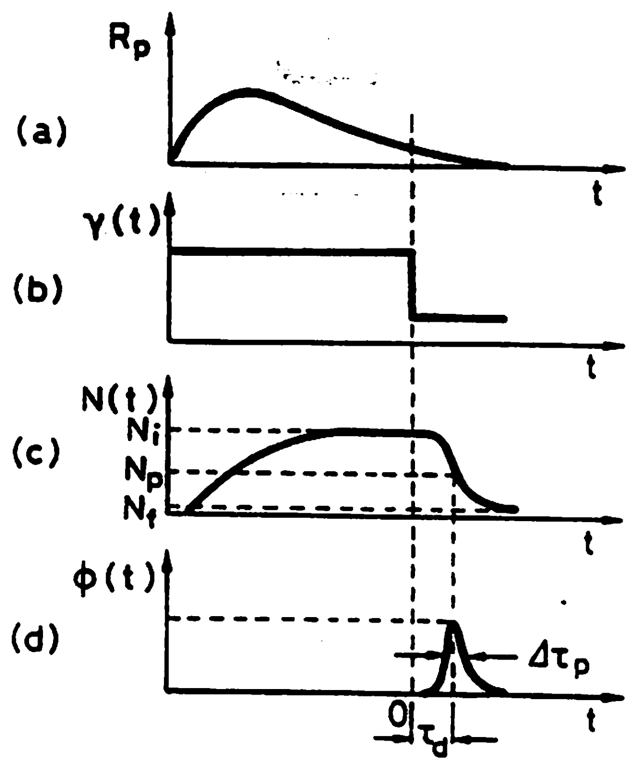
- Mode competition can be less effective.
  Injection!

- In all this, we assume $\tau_{switch} \ll \tau_c$



cw pumped

(Fig 8.10)



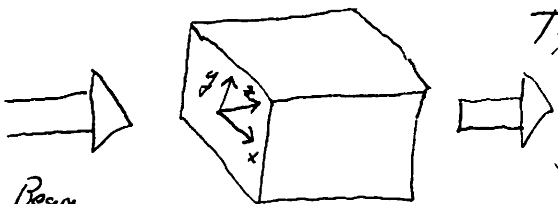
Pulsed pump

(Fig 8.9)

Most common methods use the electro-optic or acousto-optic effects.

Electro-optic switching

Uses the response of an anisotropic crystal to an electric field $\Rightarrow$ Pockels Effect

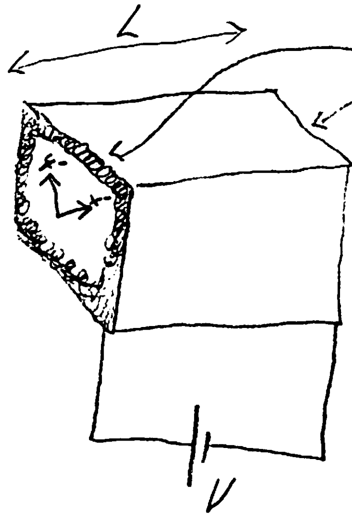


Typically, $n_x = n_y \neq n_z$

still polarized along y

Beam, polarized along y (or x)

electrodes on input & output faces



For $V \neq 0 \Rightarrow n_{x'} \neq n_{y'} \neq n_{z'}$

$$\Delta\phi = \frac{L_{opt}}{\lambda} 2\pi = n L k_0$$

Suppose, initially: $\vec{E}_i = \hat{E}_0 \hat{y} = E_0\left(\frac{1}{\sqrt{2}}\hat{x}' + \frac{1}{\sqrt{2}}\hat{y}'\right)$

At the output face: $\vec{E}_f = E_0\left(\frac{1}{\sqrt{2}}\hat{x}' e^{ik_0 n_{x'} L} + \frac{1}{\sqrt{2}}\hat{y}' e^{ik_0 n_{y'} L}\right)$

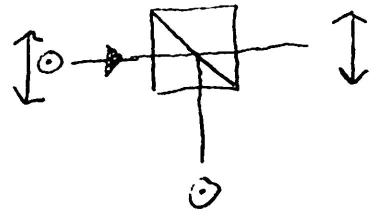
$$= \frac{E_0}{\sqrt{2}}\left(\hat{x}' + \hat{y}' e^{i\phi(V)}\right) e^{ik_0 n_{x'} L} \qquad \phi \equiv k_0 L (n_{y'} - n_{x'})$$

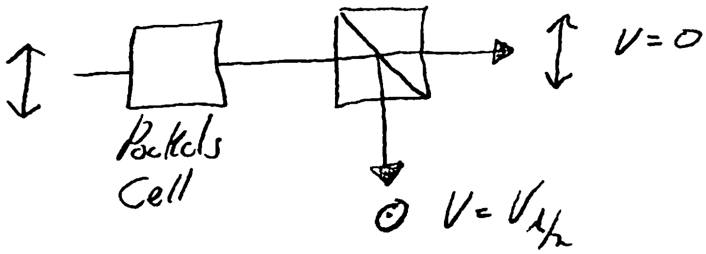
$$e^{ik_0 n_{x'} L} = e^{i\phi_c}$$

Select $V = V_{1/2}$ meaning $\phi = \pi$.

$$\vec{E}_f = \frac{E_0}{\sqrt{2}}(\hat{x}' - \hat{y}')e^{i\phi_c} = E_0 \hat{x} e^{i\phi_c}$$

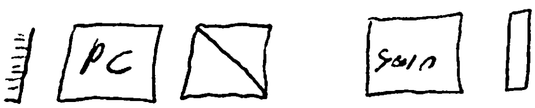
Suppose we add a polarizer





Typically, $V_{\lambda/2} \approx 5000V$

Actually, in a laser cavity, you are more likely to see this:



and using $V = V_{\lambda/4}$.

Advantages

- Fast switching times
- Capable of very high and low loss (~99% + ~2%)
- Can be scaled to large diameter - suitable for high power

Disadvantage

- Low rep. rate.

Acousto-optic switching

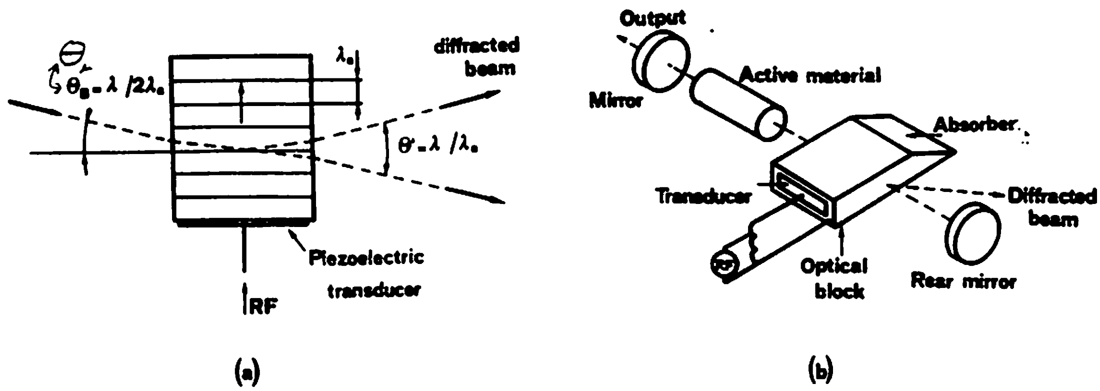
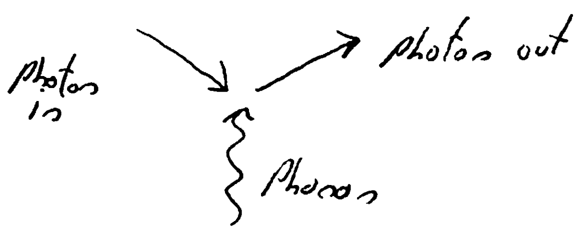


FIG. 8.7. (a) Incident, transmitted, and diffracted beams in an acoustooptic modulator (Bragg regime). (b) *Q*-switched laser arrangement incorporating an acoustooptic modulator.



$$h\nu_{out} = h\nu_{in} + E_{phonon}$$

So this is a way to change the frequency a little

Advantages

- Rep. rate by ability to modulate RF ⇒ much faster than $1/\tau$
- Low insertion loss

Disadvantages

- maximum loss is modest
- Large apertures are possible, but harder