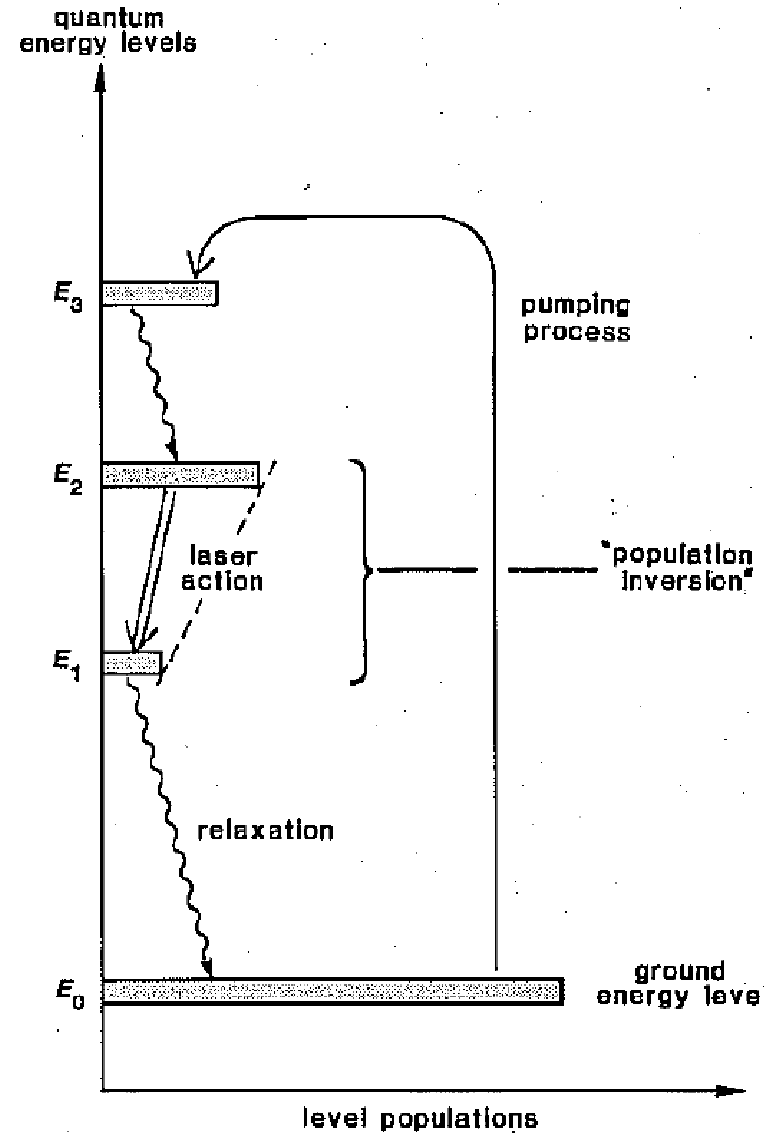
Part 5: Lasers

Amplification

- Atomic (or molecular, or semiconductor) system has energy levels
- Some higher energy states are stable for a short time (ps to ms)
- Incident photon can trigger emission of an identical photon (stimulated emission)
  - Better to think in terms of modified refractive index or susceptibility
- Photons are *coherently* multiplied by this process
- If the probability of emission exceeds that of absorption, there is net gain, and the optical signal is amplified

$$\chi''(\nu) = \frac{c^3}{16\pi^2\nu^3} n'^2 \frac{1}{\tau_{\text{radiative}}} f(\nu)(N_0 - N_1)$$



Saturation

- Excitation of atoms to higher energy level is called “pumping”, the source of energy is the “pump”
  - The atoms retain energy for the excited state (or “raditative” or “fluorescence”) lifetime, on average, then spontaneously re-emit (fluoresce), going back to the ground state
    - Excited state lifetime is like radiative half-life, except it’s the 1/e life
- When energy is extracted from the amplifier, the gain drops, because the density of excited atoms drops
- Saturation limits the output intensity
  - If the laser is pulsed, and the repetition period is much shorter than the excited state lifetime, the amp will see this as continuous. Otherwise, one needs to analyze in terms of output energy density

Saturation intensity is one photon energy per stimulated emission cross section per excited state lifetime

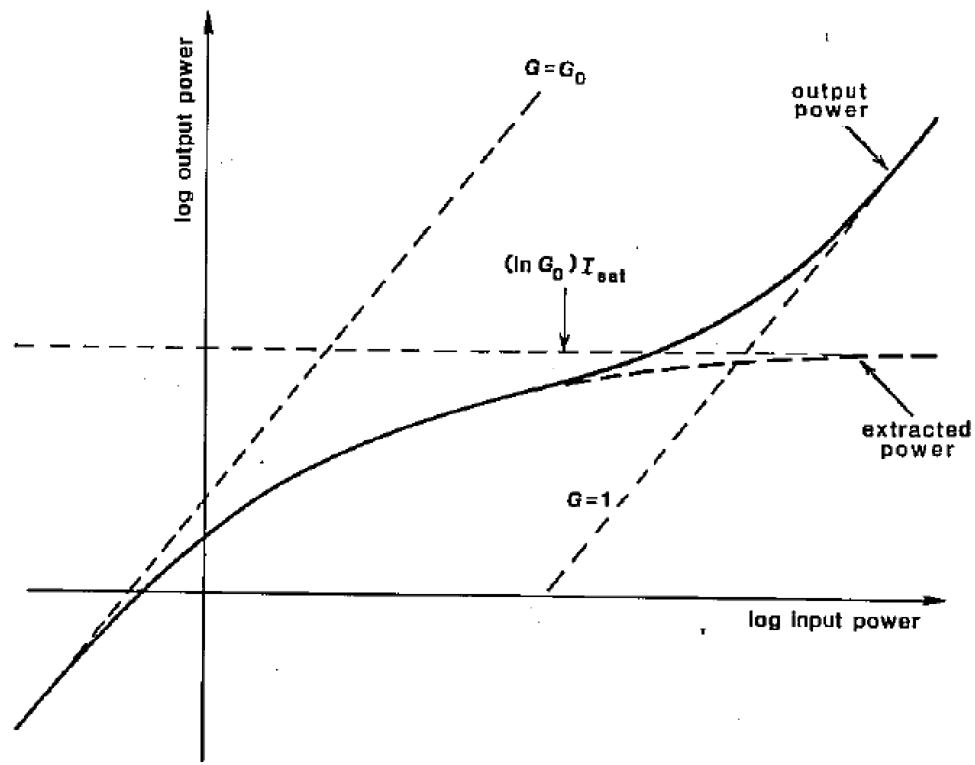
$$I = I_{\rm sat} \equiv \frac{\hbar\omega}{\sigma\tau_{\rm eff}}.$$

G is the saturated gain, which decreases as the output intensity increases

$$G \equiv \frac{I_{\rm out}}{I_{\rm in}} = G_0 \times \exp\left[-\frac{I_{\rm out}-I_{\rm in}}{I_{\rm sat}}\right],$$

$$\frac{I_{\rm in}}{I_{\rm sat}} = \frac{1}{G-1}\ln\left(\frac{G_0}{G}\right)$$

$$\frac{I_{\rm out}}{I_{\rm sat}} = \frac{G}{G-1}\ln\left(\frac{G_0}{G}\right)$$

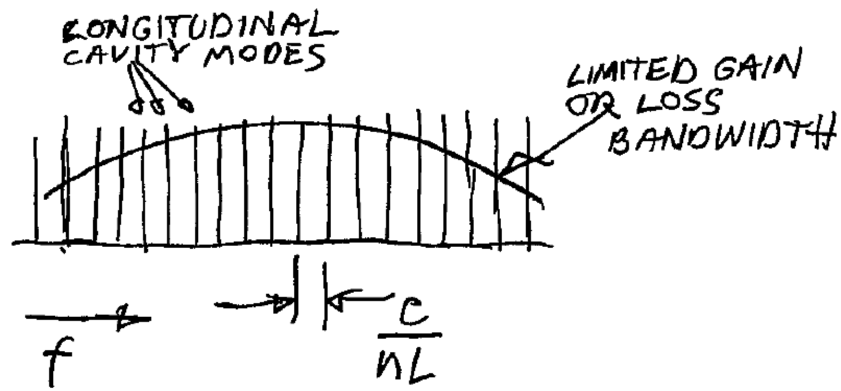


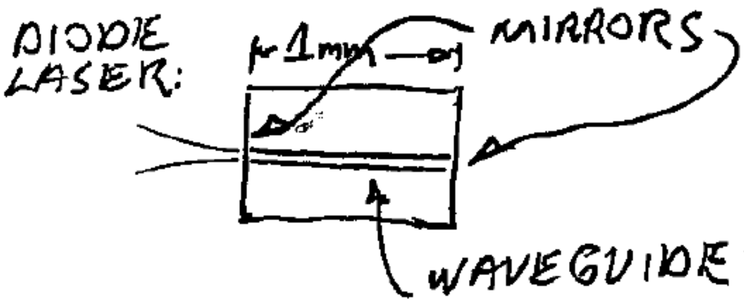
Oscillation

- Laser oscillator is like radio or microwave oscillator
  - Amplifier (laser)
  - Resonator (cavity or loop)
  - Feedback (beam path back to amplifier)
    - Laser amplifiers are located inside the resonator, so feedback is just the return path for the wave in the resonator
- With feedback, oscillation initially builds up from noise until an equilibrium power is reached (amplifier gain is saturated)
- All modes with gain will lase. Different modes may have different spatial distributions or frequencies. If all the spatial locations overlap, and all the frequencies are amplified by all the excited atoms, the modes “compete” for gain, eating each other’s lunch and elbowing for position at the table, creating noise
  - Even if there were several stable modes at multiple frequencies, the addition results in periodically time-varying intensity, which is undesirable
  - The situation is very sensitive to perturbations and not reproducible
- Solution: control the modes somehow

Optical resonators

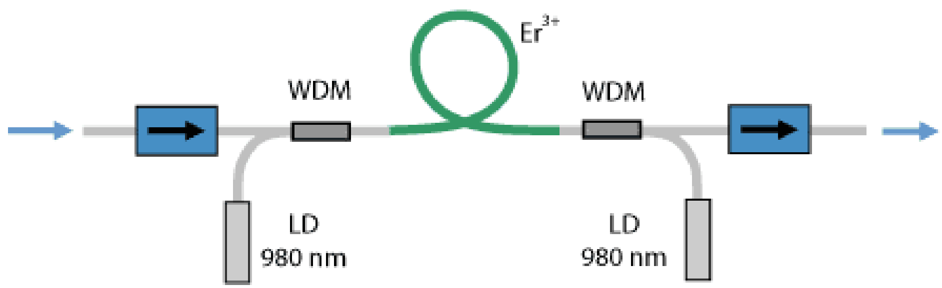
- For purposes of fiber lasers, we will consider only longitudinal modes
  - Any mode has to be in phase after a round trip
    - There are many optical periods in the resonator cavity (~10^3 to 10^7)
    - The frequency spacing of the modes is c/(nL), where L is the resonator <u>round</u> <u>trip</u> length
      - in a linear cavity of length L, spacing is c/(2nL)
- Fabry-Perot cavity: two mirrors
- Distributed Feedback (DFB): two Bragg gratings
- Ring resonator: mirrors or fiber in a loop



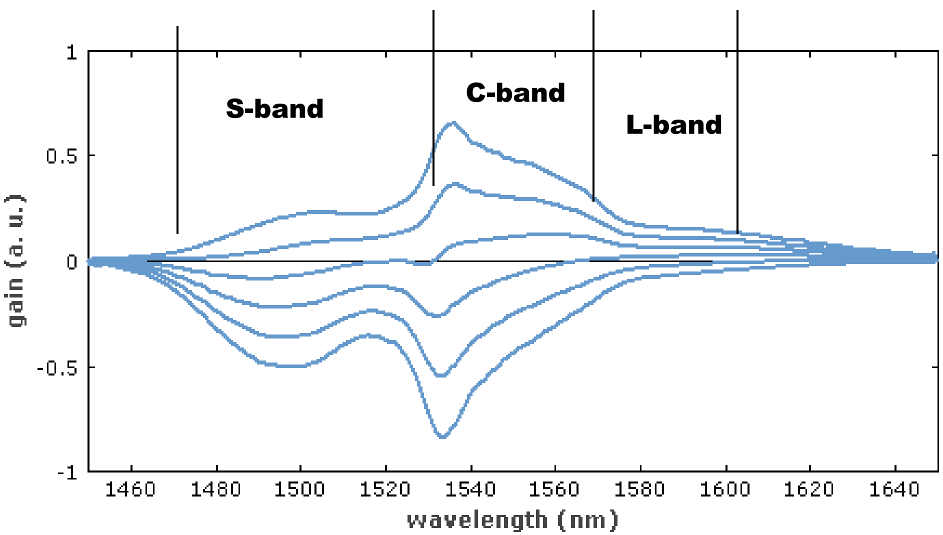


Erbium-doped fiber amplifier (EDFA)

- **Er dopant added to core**
- **Pump at 980nm with laser diode**

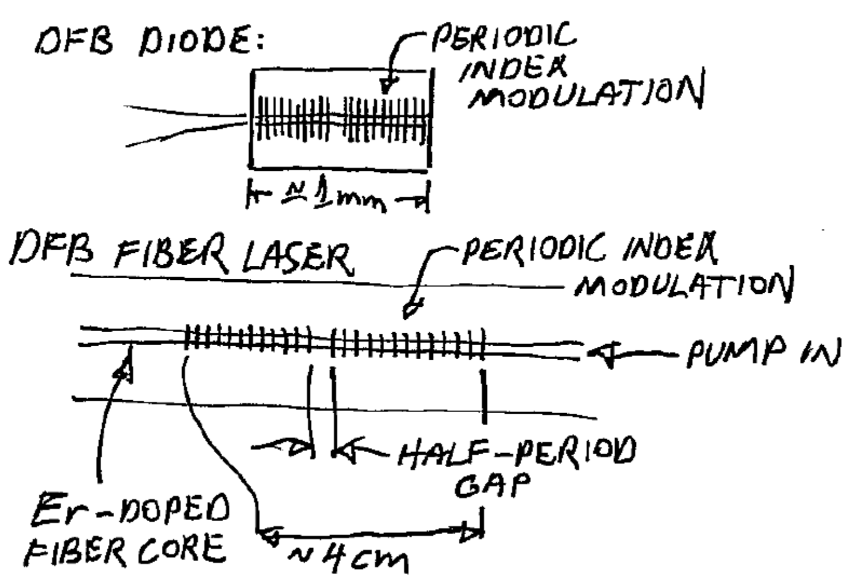


Gain or loss spectrum with increasing pump power.
Note that a lot of power is needed just to achieve transparency.



Single mode, CW lasers typical of telecom

- One longitudinal mode has least loss
- The other modes diminish to zero as the one mode collects all the available power as the oscillator saturates (mode competition in a homogeneously broadened laser)
- How this is achieved:
  - Short resonator for wide frequency spacing of modes
  - Narrow bandwidth diffraction grating reflector
    - Bragg grating in fiber (DFB or Distributed Feed Back)
      - Index modulation period is half the optical wavelength in fiber
    - Bragg grating in waveguide (DFB diode)
    - Diffraction grating with narrow slit (ECL, or External Cavity Laser)
- Tune DFB fiber laser by temperature (slow) and piezo stretch (fast)
  - Fractional tuning is 0.76 times strain, or 7.3e-6 per degree C



Modelocked laser

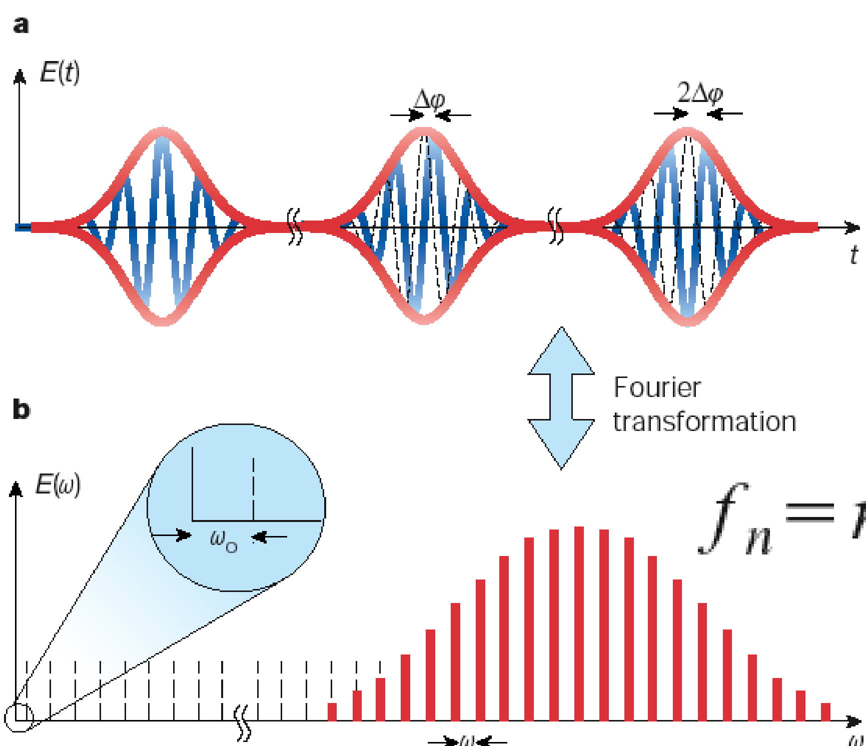
- All longitudinal modes are locked in phase, creating a short pulse
  - A mechanism in the cavity reduces loss for increasing intensity (active modelocking) or minimizes loss at a particular time (active modelocking)
  - We will be dealing mainly with actively modelocked lasers
  - An initial noise spike will see lower loss, and increase in power, taking all the available power due to saturation (like mode competition as before, but with one mode and its modulation sidebands)
- Common fiber laser modelocking mechanisms:
  - Passive (fast, lower phase noise)
    - Nonlinear polarization rotation
    - Semiconductor saturable absorber mirror (SESAM)
    - Pulse repetition rate free-runs, controlled by PLL to lock to external clock
  - Active (slow, higher phase noise)
    - Intracavity amplitude or phase modulator
    - External clock determines repetition rate directly (cavity length has to be controlled to follow)

Modelocked laser, basic concepts

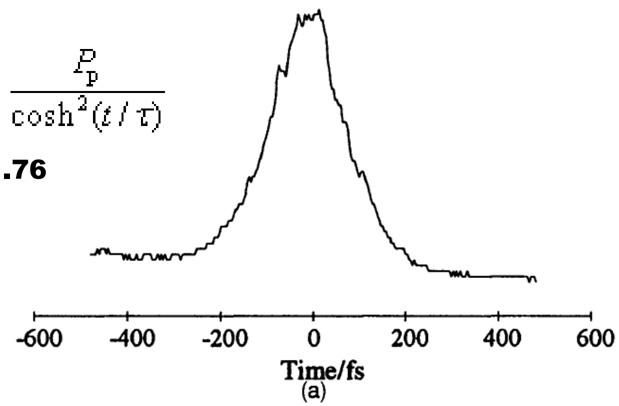
- **A comb in frequency Fourier transforms to a comb in time, if the frequency components are locked in phase**
- **The cavity modes provide the comb in frequency, but they must be properly phased, or it's a mess**
- **Very wide bandwidth gain medium can support very short pulses**
  - **~5fs from titanium sapphire (tisaf) oscillator**
  - **~30fs from ytterbium-doped fiber oscillator**
- **Most applications only consider the pulse envelope**
  - **Typical shape for passively modelocked lasers is hyperbolic secant squared (sech^2)**
  - **Fourier transform relates FWHM BW to FWHM PW by 0.315, if "transform limited" (no chirp)**
    - **For Gaussian, it's 0.45**

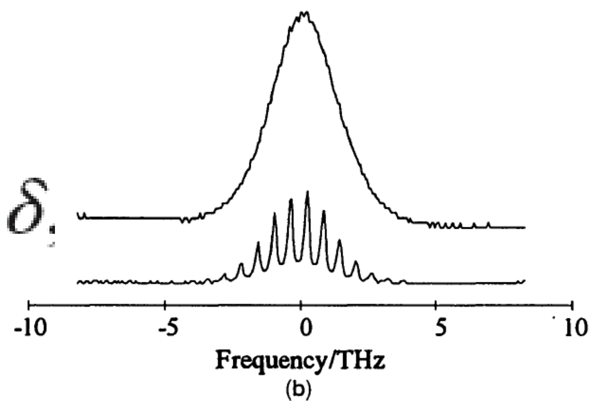
$$P(t) = P_p \operatorname{sech}^2(t/\tau) = \frac{P_p}{\cosh^2(t/\tau)}$$

tau = FWHM/1.76



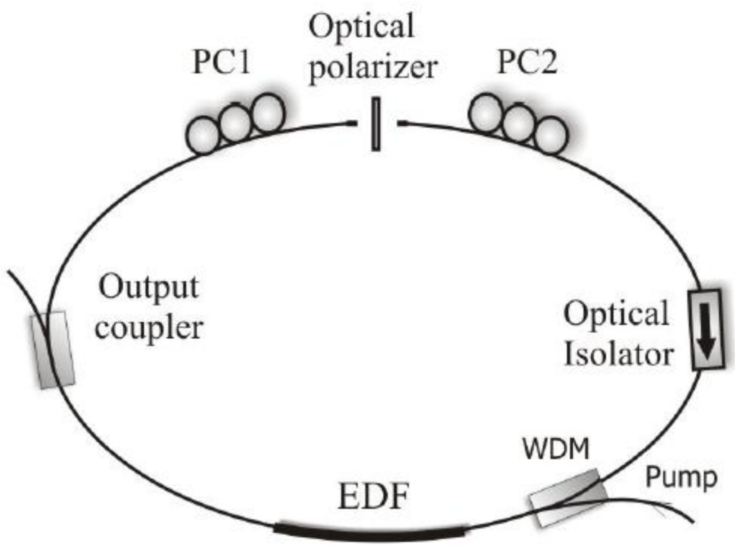
$$f_n = n f_{rep} + \delta$$

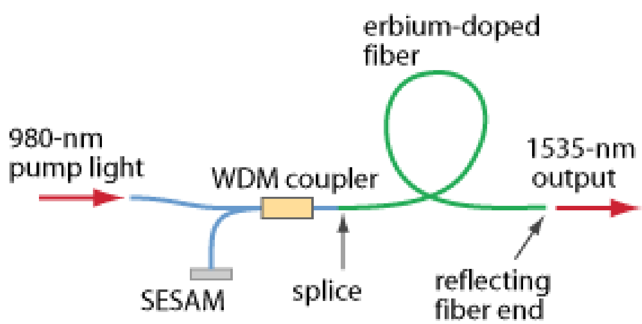


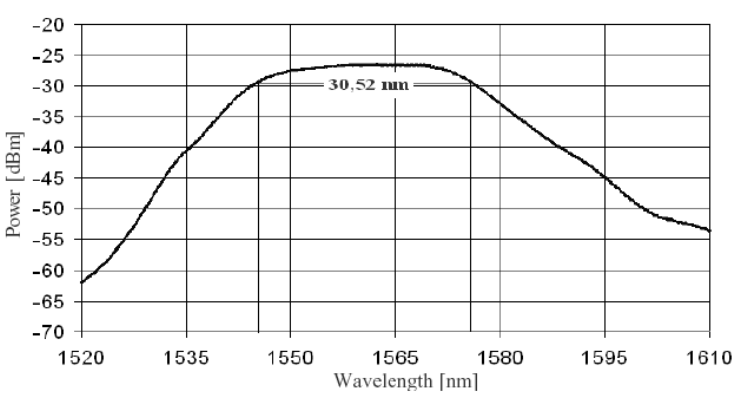


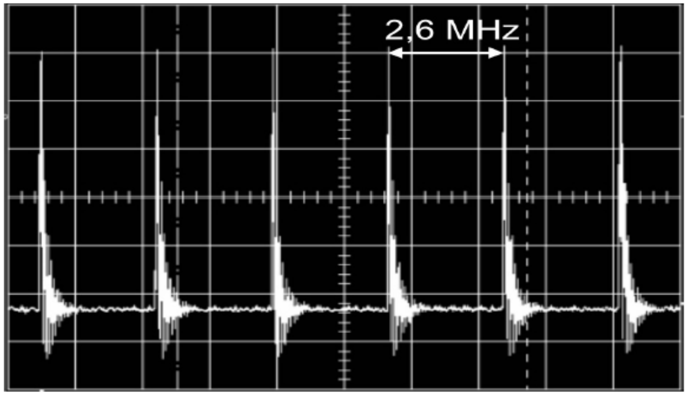
Passively modelocked fiber laser

- A "modelocking mechanism" can be understood in the time domain:
  - Exhibits lower loss for a higher intensity
    - Nonlinear processes
      - Kerr lens (tisaf)
      - Nonlinear polarization rotation (fiber lasers)
      - Semiconductor saturable absorber mirror (SESAM)
        - » More reflective for higher intensity









Nonlinear polarization rotation

- R. Stolen et al, Optics Letters 7, 512 (1982)
- Input polarization resolved into two orthogonal components
- One component is more intense, induces a greater nonlinear index change
- Accumulated extra phase from nonlinear index change is different for the two components
- The relative phase change manifests as a rotated polarization state at the output
- This passes through a polarizer. For lower power, the polarizer causes higher loss

Indices are a function of power

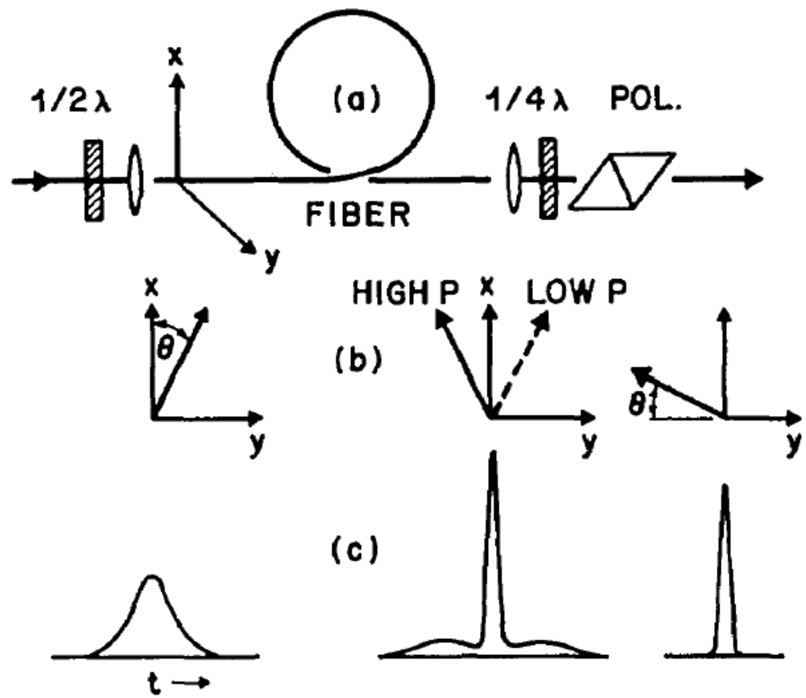
$$n_x = n_{x0} + n_x'(P),$$
$$n_y = n_{y0} + n_y'(P);$$
$$n_x' = \chi \left(P_x + \frac{2}{3} P_y\right),$$
$$n_y' = \chi \left(P_y + \frac{2}{3} P_x\right);$$
$$\chi = \frac{4\pi n_2 \times 10^7}{ncA_{\text{eff}}}.$$

Power transmitted is a function of input power and angle

$$P_t = P_0 \sin^2(\phi/2) \sin^2(2\theta),$$
$$\phi = \frac{2\pi L}{\lambda} (n_y' - n_x') = \frac{2\pi L\chi}{3\lambda} (P_x - P_y),$$
$$\theta = \tan^{-1} (P_x/P_y)^{1/2}.$$

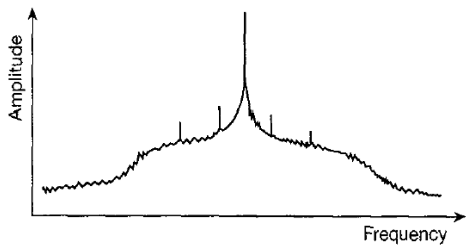
Accumulated nonlinear phase shift is a function of power and interaction length

$$\phi = \frac{2\pi\chi L}{3\lambda} P \cos(2\theta).$$

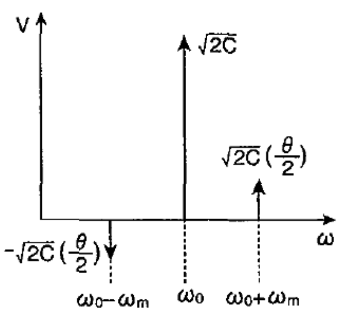


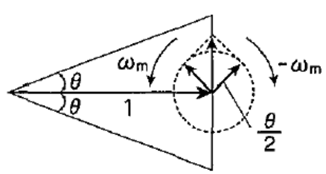
Phase noise in the passively modelocked laser

- **Phase noise will produce phase modulation sidebands on the envelope detected harmonics**

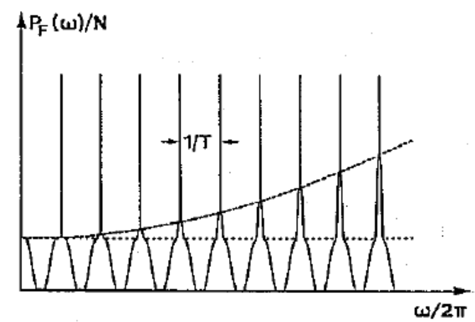


- **Random noise added to the E vector (by amplified spontaneous emission, for instance) will produce white phase noise**

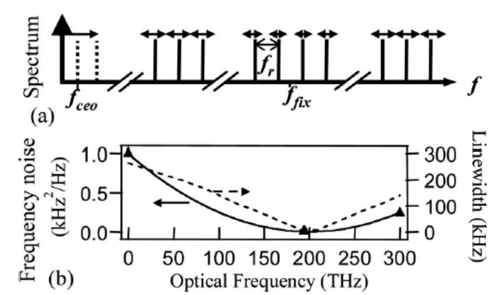




- **The power of the phase mod sidebands increases as the square of the harmonic number, allowing one to better detect the (noisy) phase of the repetition rate**

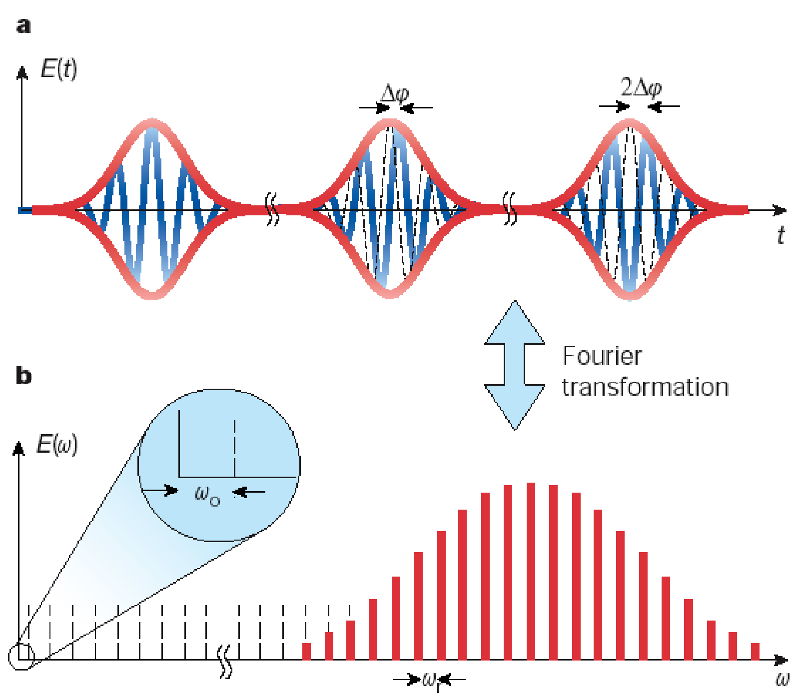


- **Noise on the pump creates "breathing" of the optical comb about a center frequency**



Comb control 1

- A comb of mutually coherent optical frequencies Fourier transforms to a comb of optical pulses in time
  - These pulses can be considered as an amplitude modulated optical carrier, where the modulation envelope is a short pulse
- A photodiode can detect only the envelope of the pulse train. The fourier transform of this detected envelope is a comb of RF frequencies, spaced by the reprate
  - The comb consists of the fundamental reprate and its harmonics, up to the bandwidth of the photodiode and electronics
- The phase of a harmonic is the harmonic number times the phase of the fundamental
  - By detecting the phase of a higher harmonic, one can more sensitively measure the phase of the fundamental, for controlling the laser in a PLL
  - Also, the amplitude noise component decreases with increasing harmonic number, improving signal-to-noise ratio



Comb control 2

- If the phase of the carrier is the same for each pulse, the “carrier/envelope offset frequency” (CEO) is zero
- If the phase of the carrier “rolls” under the pulse envelope, the offeset frequency is nonzero, and is simply the time rate of change of the carrier phase with respect to the envelope
- The CEO frequency shifts the optical frequency comb with respect to the RF frequency comb. When CEO frequency is zero, the optical frequencies are exact harmonics of the repetition rate. Thus their frequencies can be precisely known if the reprate is precisely known and vice versa (laser clocks). (The situation is not much different if the CEO is nonzero, but stable and known)
- A CEO-stabilized laser with octave bandwidth would have optical comb frequencies at exactly f and 2f. One could derive such frequencies from an unstabilized laser by frequency doubling f to get 2f. One then could compare 2f with what the laser is actually emitting, to know the unwanted CEO offset. This can be used as an error signal to control the CEO offset