Part 3: Nonlinear optics and environmental effects

What's nonlinear about nonlinear optics?

- Dielectric polarization is not a linear function of E field
  - Has terms in higher orders of E (see RWV page 695)

$$\mathbf{P} = \varepsilon_0 \left[\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{EE} + \chi^{(3)} \vdots \mathbf{EEE} + \cdots \right]$$

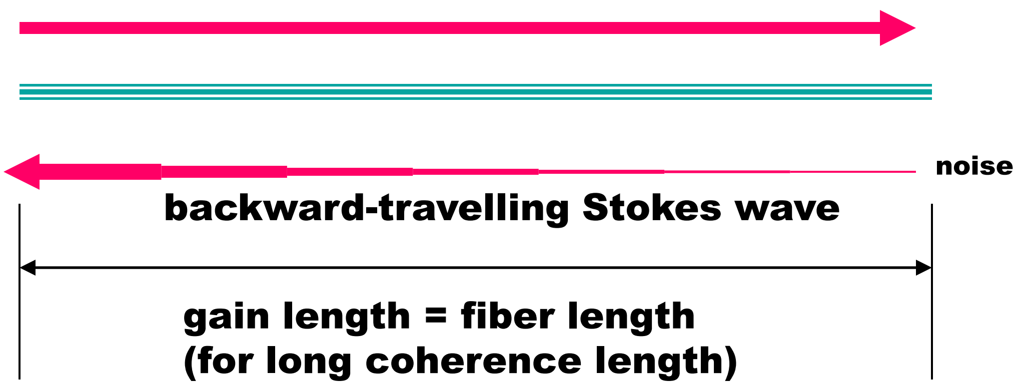
$$\bar{n}(\omega, |E|^2) = n(\omega) + n_2 |E|^2$$

$$n_2 = \frac{3}{8n} \mathrm{Re}(\chi^{(3)}_{xxxx})$$

Stimulated Brillouin scattering

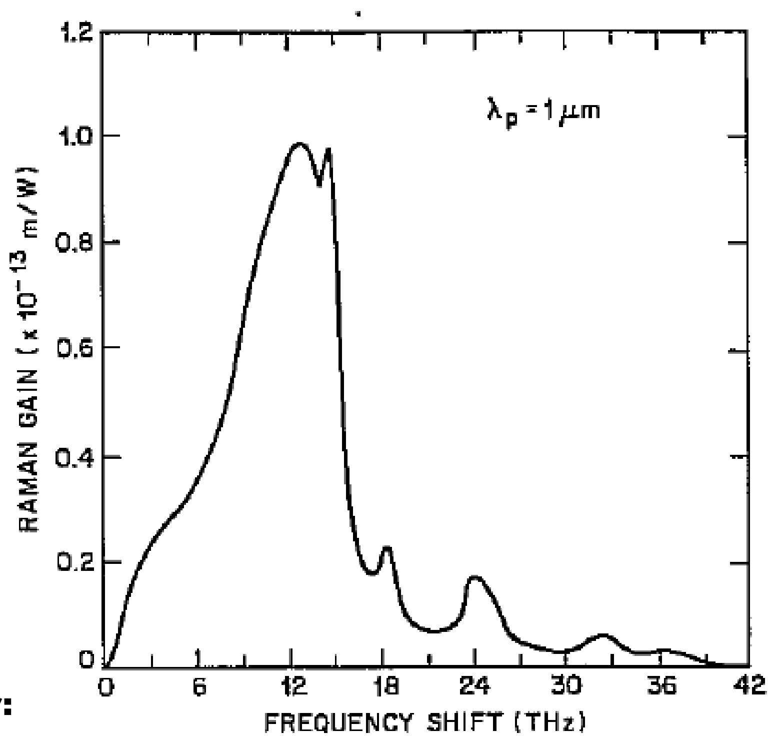
- Problem mainly for CW transmission
- Moving acoustic grating (remember AO frequency shifter) created by the signal (pump) and scattered wave interfering
  - Sends light backwards, efficiently but noisily
- Gain length is fiber length or pulse length
- Numbers for bandwidth, frequency shift
- How to avoid
  - Minimize fiber length
  - Stay below threshold
  - Use short pulses (bandwidth, gain length)
  - Modulate to spread spectrum (beyond bandwidth)
  - Use larger core fiber

$$P_0^{cr} \cong 21 \frac{A_{eff}}{L_{eff}\, g_a}$$



Stimulated Raman scattering (SRS)

- Molecular energy levels
- Problem for high intensity pulses
- With dispersion, the pump and “stokes” pulses will “walk off”, limiting gain length
- If intense enough, Stokes-shifted pulse will generate another order
- How to avoid
  - Minimize fiber length
  - Stay below threshold
  - Increase dispersion (shorten walk-off length)
  - Hard to modulate beyond bandwidth
  - Use larger core fiber
- Has been used as an amplification process



Raman signal increases with distance as

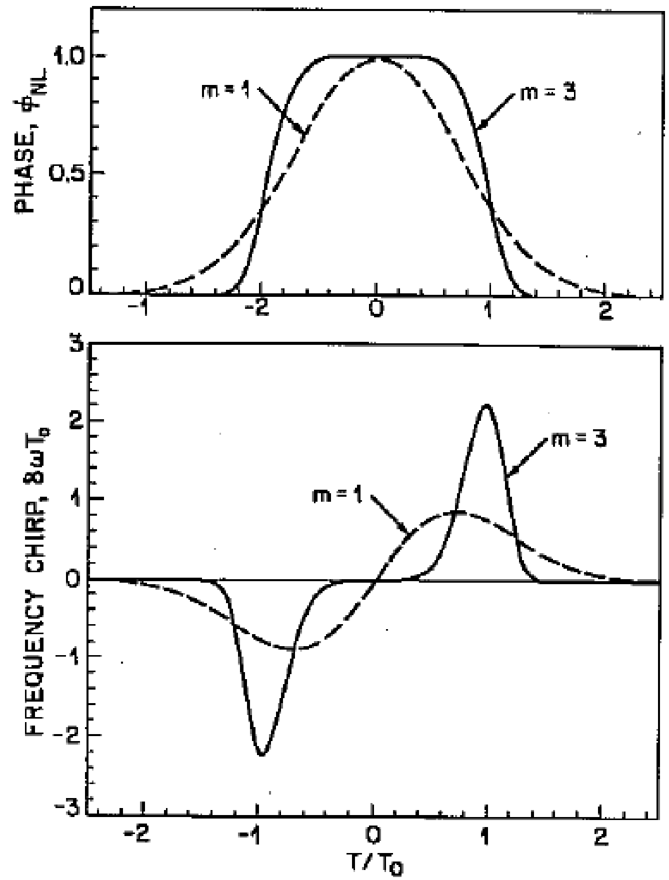
$$\frac{dI_s}{dz} = g_R I_p I_s$$

A rule of thumb for threshold power:

$$g_R P_0^{cr} L_{\mathrm{eff}} / A_{\mathrm{eff}} \simeq 16$$

Self-phase modulation

- Mainly a problem for short, intense pulses
- Intensity-dependent index means that n is changing during the pulse (show equation for accumulated phase, or B integral)
- Phase modulation follows envelope
  - Thus a parabola-like pulse would add phase quadratically, result in linear frequency chirp (derivative of phase)
  - Dispersion will rearrange the frequencies, to spread or compress the pulse (depending on dispersion sign)
- If in a birefringent fiber, can modulate polarization
  - This is common mechanism for modelocking
- Can be used to spread spectrum of pulses to cover larger bandwidth, useful in spectroscopy and stabilizing lasers
  - Special, "highly nonlinear fiber" made for this application (tiny core, low dispersion)



peak phase shift in the fiber

$$\phi_{max} = z_{eff}/L_{NL} = \gamma P_0 z_{eff}$$

$$\gamma = 20\ W^{-1}\ km^{-1}$$

Optical frequency mixing

- With second order nonlinearity, cross terms can include sum and difference
  - RWV p. 697
  - With two input waves of same frequency, sum is the second harmonic
    - Typically used to detect overlap between two pulses (auto or cross-correlation). Second harmonic signal is proportional to overlap of pulses
    - Also used to generate second harmonic for CEO-stabilized lasers
  - Sum and difference mixing is used to translate one laser wavelength to another, to cover a wider spectral range, increasing the utility of a particular laser medium
    - Fiber lasers in the IR can cover visible and mid-IR ranges

Environmental effects on fiber

- Temperature
- Pressure (sound)
- Bend loss
- Radiation
- Stress birefringence

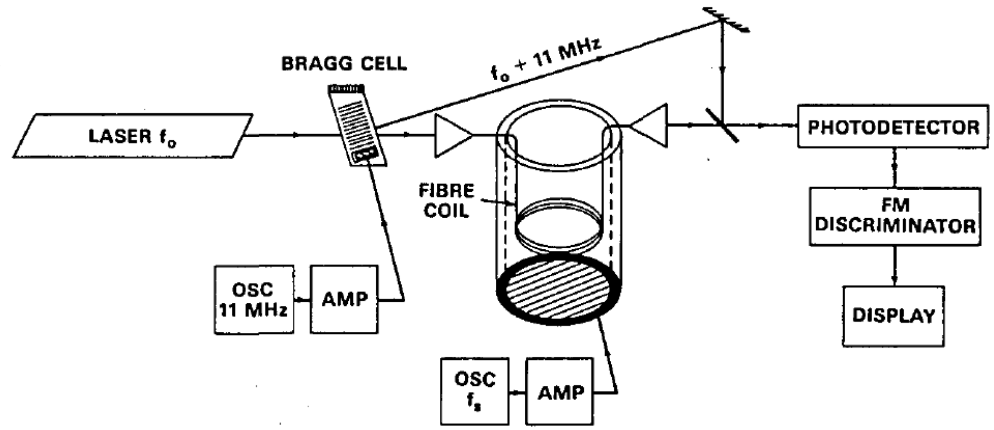
Thermal effect

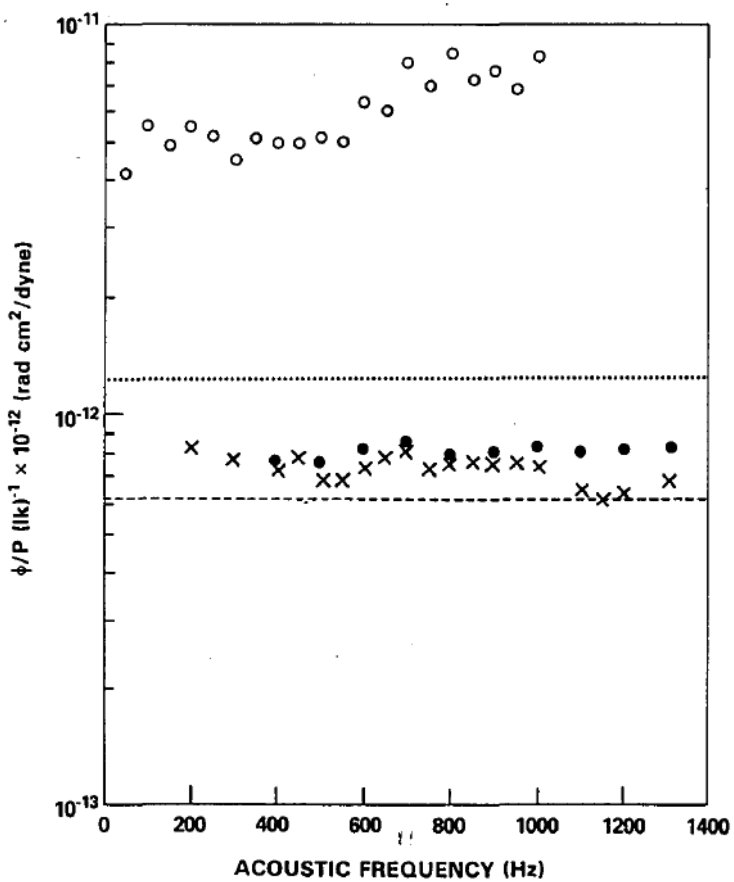
- **Changes optical delay**
  - **Changes both index of refraction (remember temp. coefficients in Sellmeier equation), and length via coefficient of thermal expansion**
  - **$\Delta n/n = (\alpha + \zeta)\ \Delta T$**
  - **α (expansion coefficient) = 0.55e-6/C for silica**
  - **ζ (thermooptic coefficient) = ~6.7e-6/C for Ge-doped silica**
  - **Thus $\Delta n/n$ = ~7e-6/C (we observe 1e-5 or so)**
    - **May increase due to plastic buffer**
- **For km lengths outdoors, this is hundreds of ps**
  - **For $\Delta n/n$ = 1e-5/C, 2km of fiber (10μs delay), and 10C temperature change, delay changes by 1ns**
  - **Requires long optical delay controller**
- **Hard to measure on spools, due to thermal expansion of spool and nonuniform heating**

Pressure effect

- **Fiber sensors for sound and pressure**

J. A. Bucaro, T. R. Hickman, Appl. Opt. 18, 938 (1979)





For this case, a uniform glass cylinder experiences a radial strain ϵ_r and an axial strain ϵ_a. If E and σ are Young's modulus and Poisson ratio, respectively,[7]

$$\epsilon_r = -[P(1-\sigma)]/E, \tag{4}$$

$$\epsilon_a = 2\sigma P/E. \tag{5}$$

The corresponding index change for the linearly polarized HE_{11} mode can be calculated by means of the appropriate Pockels coefficients[8] P_{ij} with the result that

$$\mu \equiv \frac{dn}{dP} + \frac{n}{l}\frac{dl}{dP} = \frac{n^3}{2}(P_{11}+P_{12})\frac{(1-\sigma)}{E} - \frac{n^3 P_{12}\sigma}{E} + \frac{2n\sigma}{E}. \tag{6}$$

In the right-hand side of Eq. (6) the first term is the index change associated with the radial strain, the second is the index change associated with the axial strain, and the third is the contribution from the length change directly.

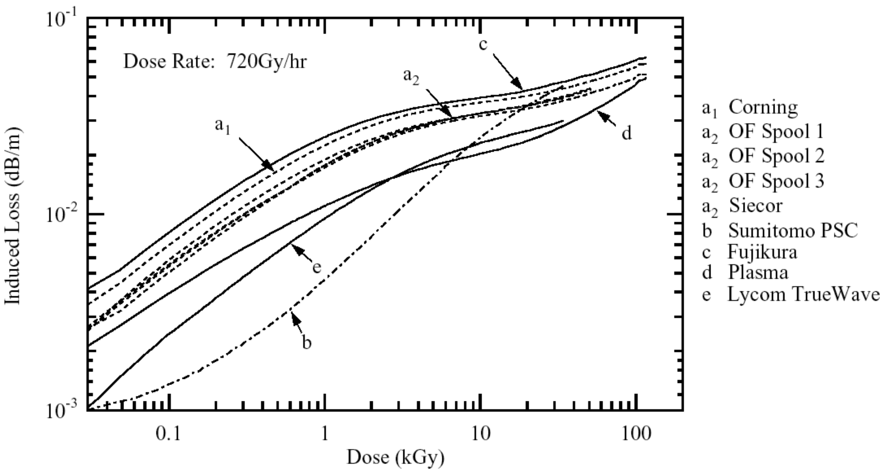
Bend loss

- Stress changes the index of refraction of cladding, wave is not strongly guided
  - Secondary effect of sharp geometric bend
- Can cause large accumulated losses
  - Some attenuators work this way
- How to avoid
  - Maintain minimum radii (>~1” for thin fibers in chassis)
  - Prevent shifting of components and kinks
  - Properly lay out components in chassis, use routing aids
  - Route fibers in conduit carefully, preferably using special conduit
  - Use robust cables that resist bending

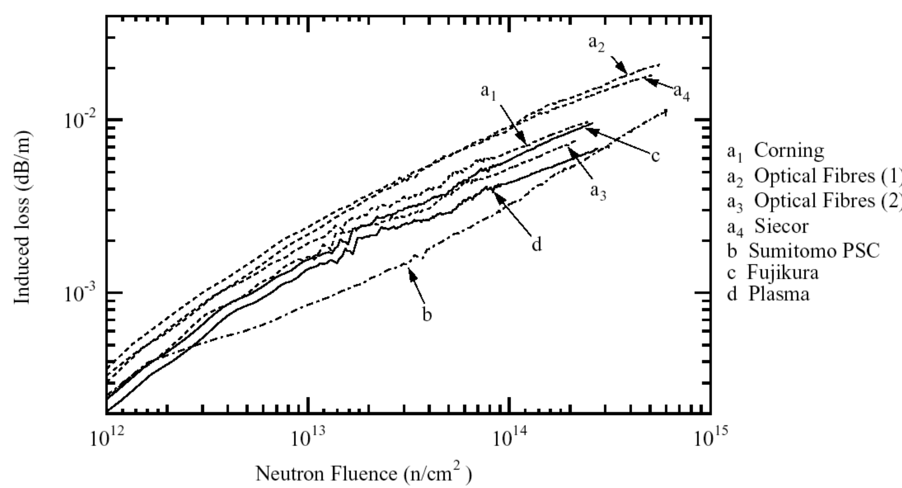
Radiation effects

- Radiation creates displaced charges (color centers)
- Color centers absorb light, causing loss
- Measurements have been done with gammas and neutrons
  - Loss reduces by “self-annealing” (charges recombine)
  - Loss is rate-dependent
- Radiation-hard fiber is manufactured
  - Doesn’t use Ge in core, rather dopes cladding to reduce n
    - Pure silica core has lower radiation absorption
  - Some fibers include a dopant to make charges more mobile, so they recombine

gammas:



neutrons:



Troska et al, SPIE vol. 3440

Stress-induced birefringence

- Stress in one direction changes index differently for parallel and perpendicular directions
- Just bending the fiber causes stress
- Small changes in radius or direction of bend will create large variations in polarization
  - Possible to make a convenient polarization controller using loops
- How to avoid
  - Make all components polarization-independent (most common telecom solution)
  - Mechanically fix fiber
  - Use PM or PZ fiber
    - PM is only good for a few meters, polarization couples for longer lengths
    - PZ is hard to work with, high loss, expensive, difficult to manufacture, hard to splice…
  - Use an active polarization controller
    - Commercially available, using EO, liquid crystals, stress, rotating waveplates etc.