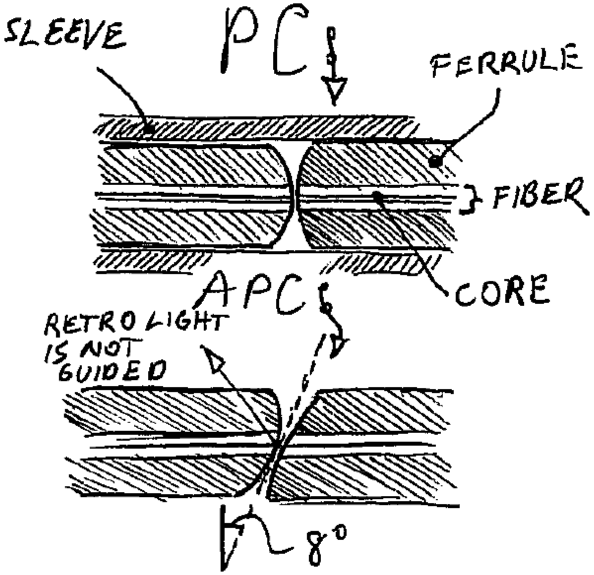
Part 4: fiber components

Fiber optic system components

- Connectors
- Directional couplers
- Lens couplers
- Attenuators
- Delays
- Polarization controllers
- Isolators
- Filters
- Modulators
- Amplifiers
- Detectors

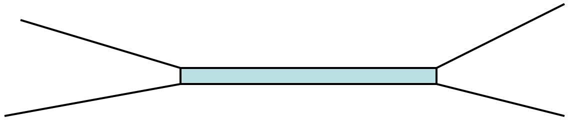
Connectors

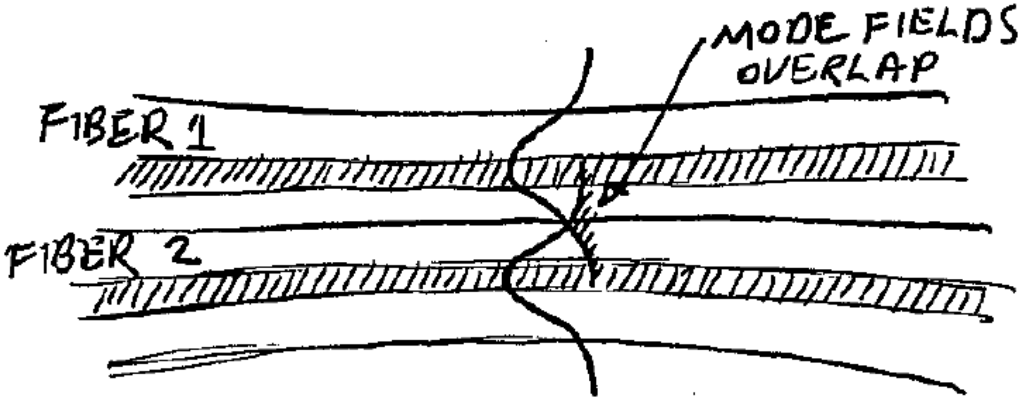
- **Cores must be aligned to sub-micron accuracy**
  - **Sub-micron concentricity between core, cladding, ferrule, sleeve**
  - **Cores in contact avoid loss at interface (PC)**
  - **Loss through is ~0.2dB average, though variable and non-repeatable**
  - **Ends are polished convex, to ensure core contact**
  - **Still some back reflection at discontinuity (see RWV p. 292, esp. 294)**
- **Some back reflection still exists, minimized by 8 degree angle (APC)**
  - **Back reflection loss >60dB**
- **Screw-on and push-on styles (FC, SC, LC)**
- **Mechanical splices**
  - **Push flat cleaved fibers together in a tube or groove**
    - **Fibers are cleaved flat using a good quality "cleaver"**
    - **High loss (~2 dB), but quick and cheap**
- **Fusion splices**
  - **Melt fibers together with hot arc or filament**
  - **Lowest loss (<0.02dB), negligible back reflection**
  - **Align cladding, assume concentricity, or align cores by passing light through**
  - **Some skill, expensive machine needed ($5-100k, depending on complexity)**

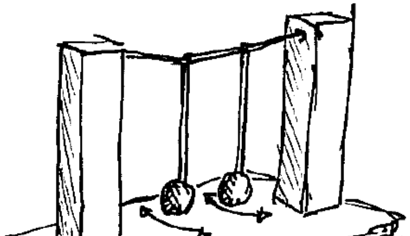


Directional couplers

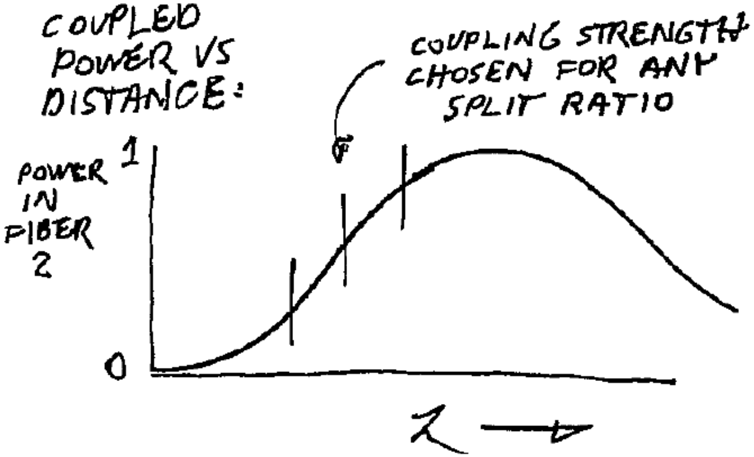
- Evanescent field in cladding couples to nearby core
- High directivity, low loss, easily manufacturable in any coupling ratio
- Tree for multiple splits





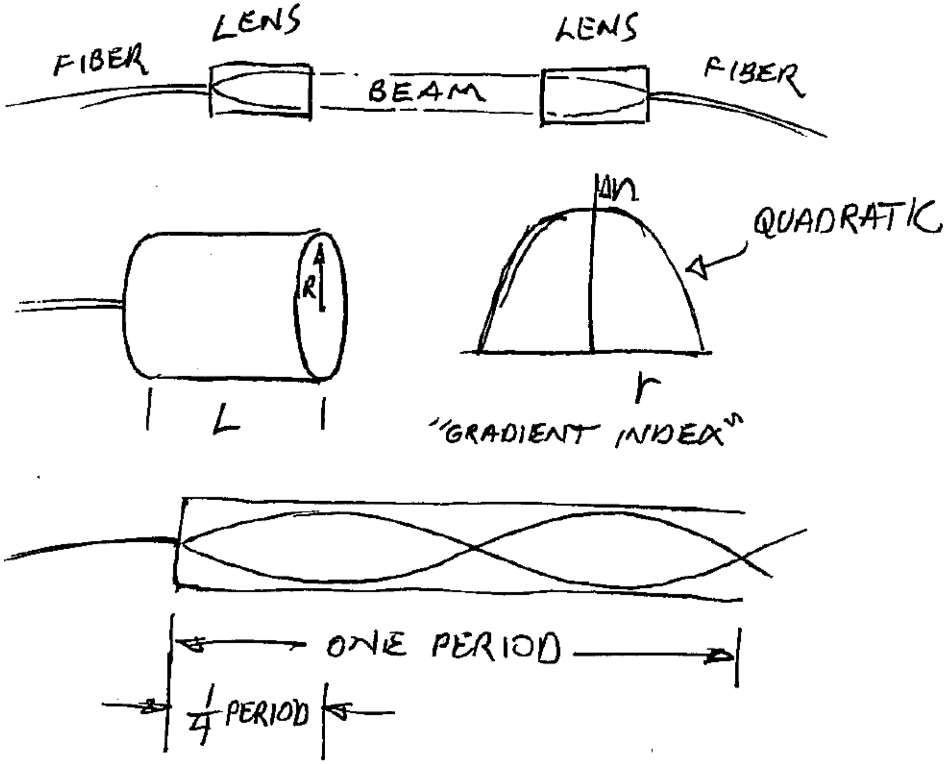


COUPLED OSCILLATORS



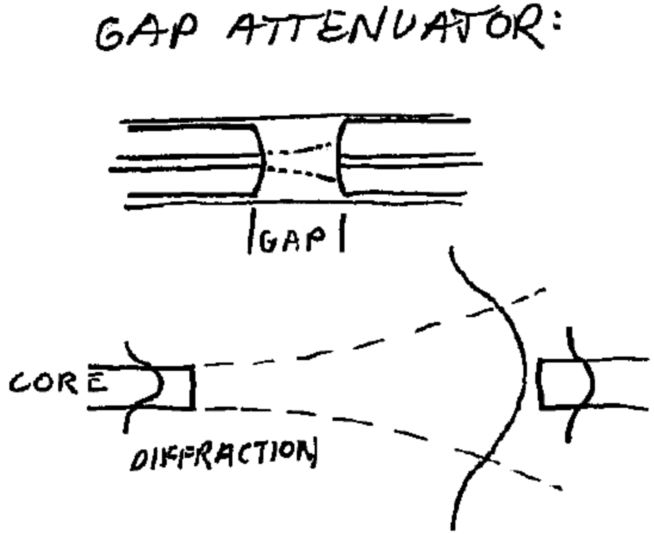
Lens coupler

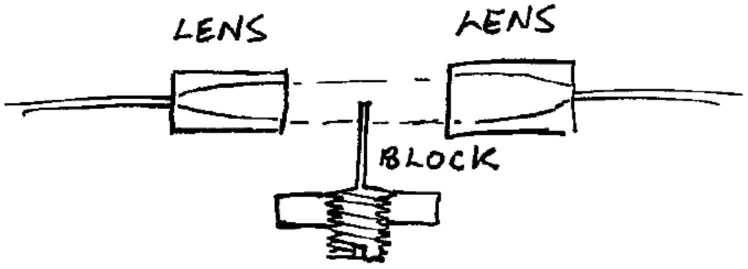
- **To break out of fiber for a short distance, to insert some optical element**
- **Use lenses to make collimated beam between fibers**
- **Typical gradient index (GRIN) lens (RWV page 754)**
- **Less than 1dB loss**

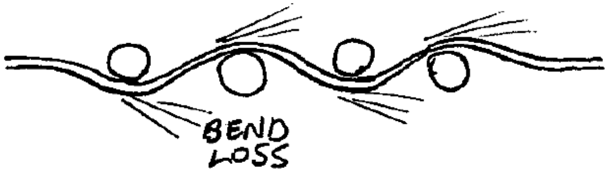


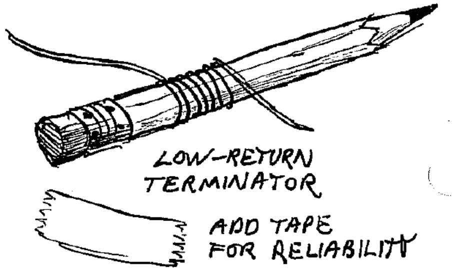
Attenuators

- Pulling connectors apart (see RWV p. 783)
  - Adjustable
  - Fixed ring
- Blocking free space beam
  - Digitally controlled versions
- Bend loss
  - Loops or s-curves
- Short sections of lossy fiber
  - Packaged like RF attenuators







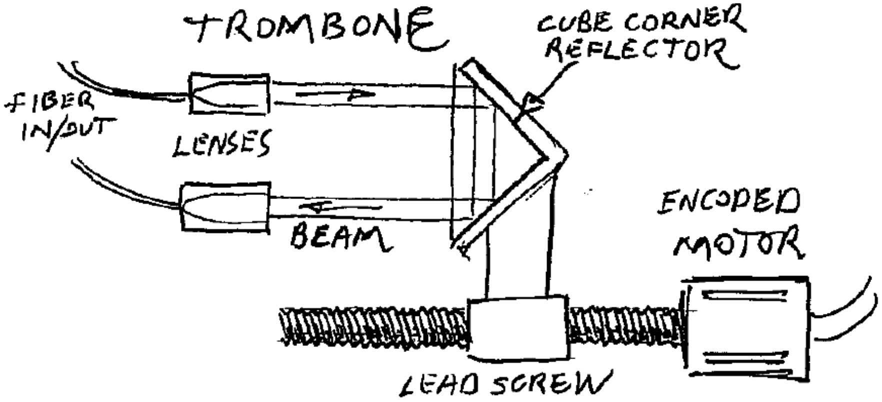


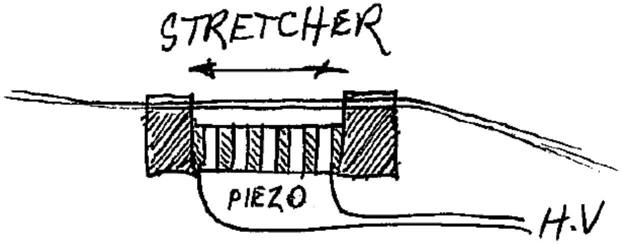
Variable phase/time delays

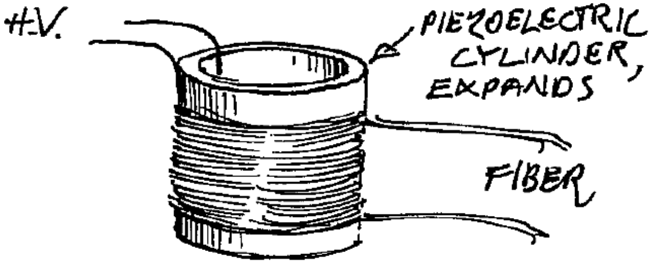
- **Optical trombone**
- **Piezo fiber stretcher**
- **Heated fiber spool**
- **AO fiber frequency shifter**
- **Optical IQ modulator**
- **RF IQ modulator**

Trombone, stretcher, heater

- **Optical trombone**
  - **A moving mirror or prism on a rail with motor**
  - **Slow, long range, few dB loss, stable with power removed**
- **Piezo fiber stretcher**
  - **Pulls on fiber to change delay**
    - **Equation, note stress and lengthening both**
  - **Acoustic frequency, low loss, short range (~10^-4 to 10^-5 of total length, 12ps for 40m spool)**
- **Heated fiber spool**
  - **~10^-5/C thermal delay coefficient**
  - **Very slow, low loss, cheap**



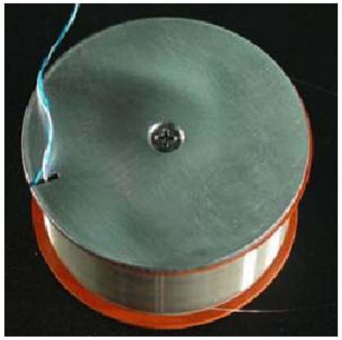




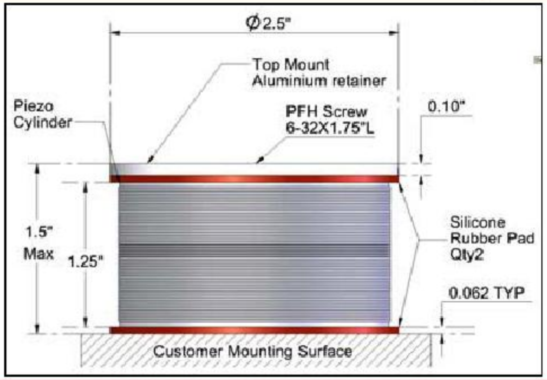
Piezo stretcher

$$\Delta t/t = \varepsilon\left\{1 + -\frac{n_o^2}{2}[P_{12} - \nu(P_{11} + P_{12})]\right\}$$

$$= (0.78 \text{ to } 0.81)\varepsilon \text{ (depending on ref.)}$$



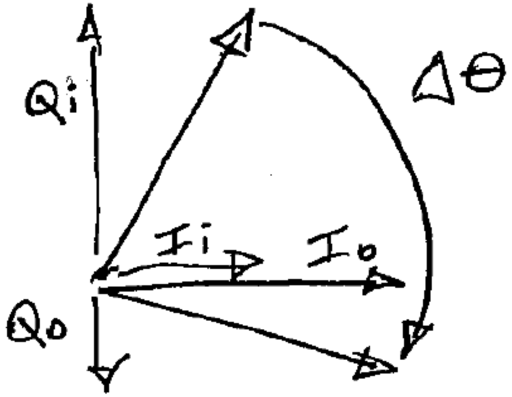
Bare Lead Fiber Stretcher with Mounting Kit

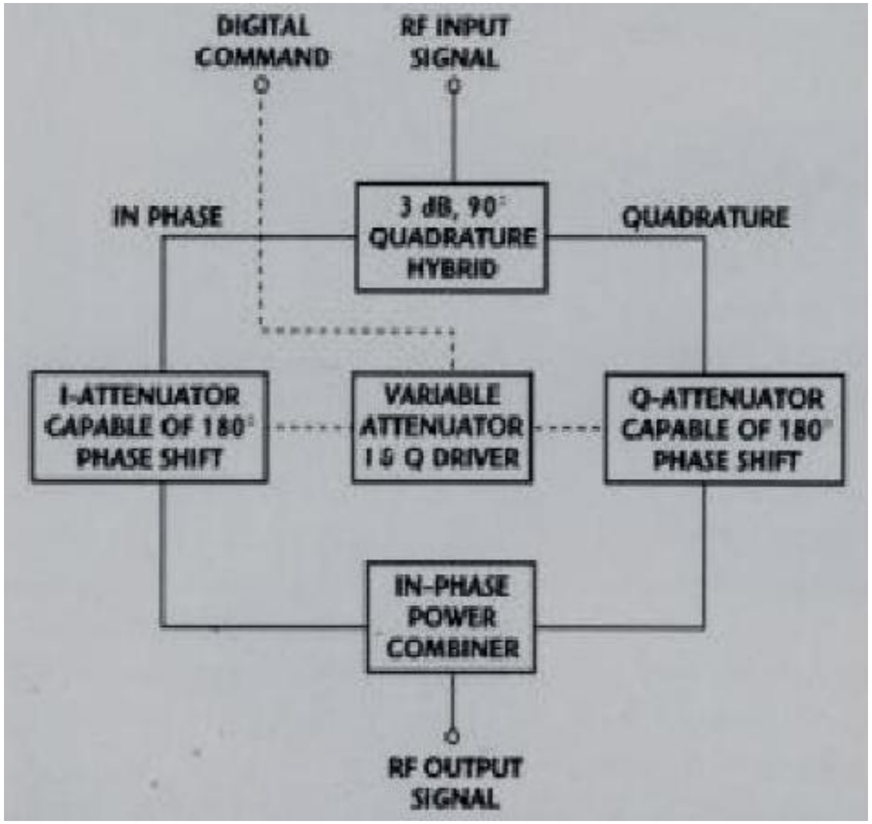


MODULATOR	SMF-28 FIBER
Operational Wavelengths	1260 to 1625 nm
Modulation Constant [low frequency]	27 radians/V @ 1.3 µm 23 radians/V @ 1.55 µm
Fiber Stretch / Optical Delay	3.8 µm/V, 0.028 ps/V
Linearity	3% at full scale drive
Frequency Range	See chart page 2
Optical Loss	≤ 0.5 dB, typical 0.2 dB
Extinction Ratio	n/a
Maximum Voltage Range [low frequency]	± 400V [800V P-P]
Impedance [off resonance]	Capacitance 0.1 µF, floating
Wire Lead	18 inches, flying leads, #30
Operational Temperature Range	0° to 70° C
Fiber Type	SMF-28e, 250 um acrylate jacket
Fiber Length	40 meters [includes 1 m bare fiber leads]

RF in-phase and quadrature (I&Q) modulator

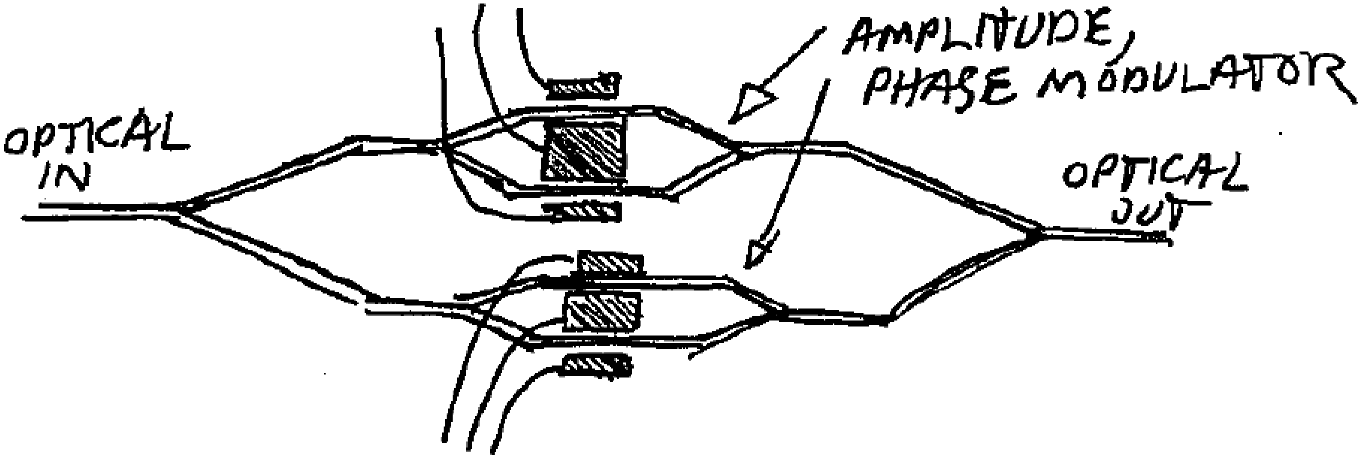
- **Input wave separated into two components, one shifted π/2 in phase**
- **Both components can be multiplied by [-1 to 1]**
- **They are added at the output to produce a phase shifted wave**
    - **If the control input is a continuous frequency, the modulator becomes a frequency shifter**





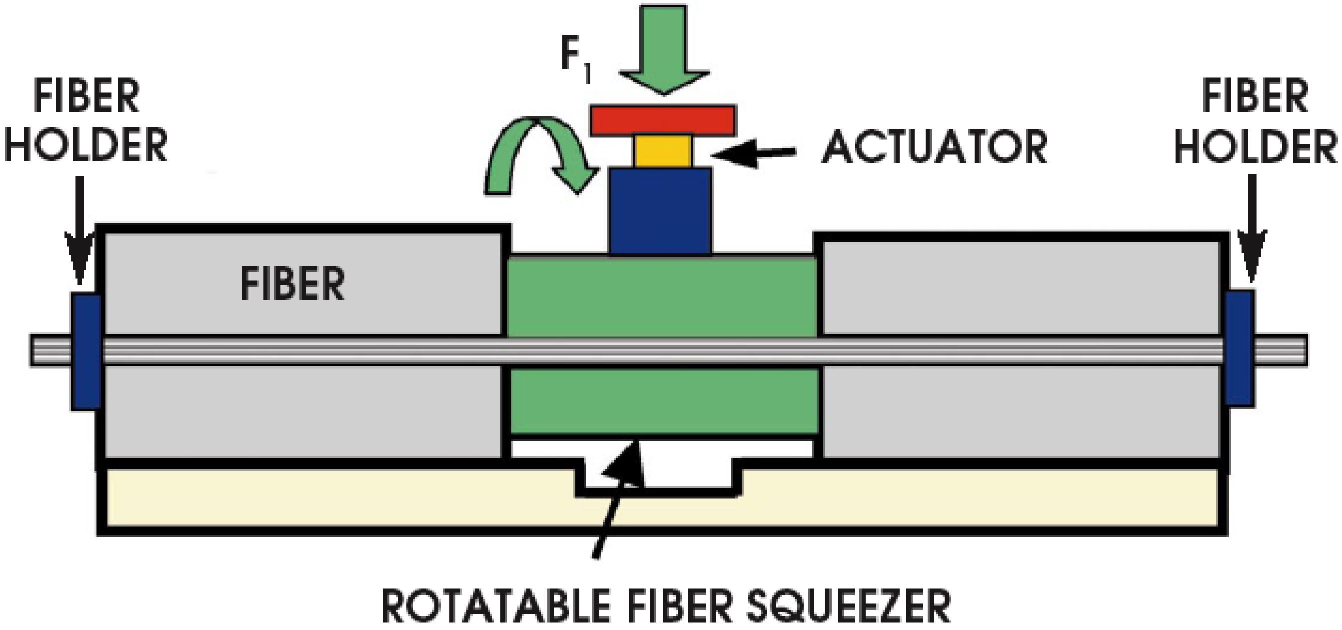
Optical I and Q modulator

- Input signal is split equally in two arms
- Amplitude and phase can be controlled in both arms
  - Note that if both arms of a Mach-Zehnder modulator are driven together, the device becomes a pure phase modulator
- When recombined, the resultant output wave has controllable phase
- Used in Differential Phase Shift Keying (DPSK) telecommunications
  - Populate the complex plane with a ring of bit values (4 or 8)



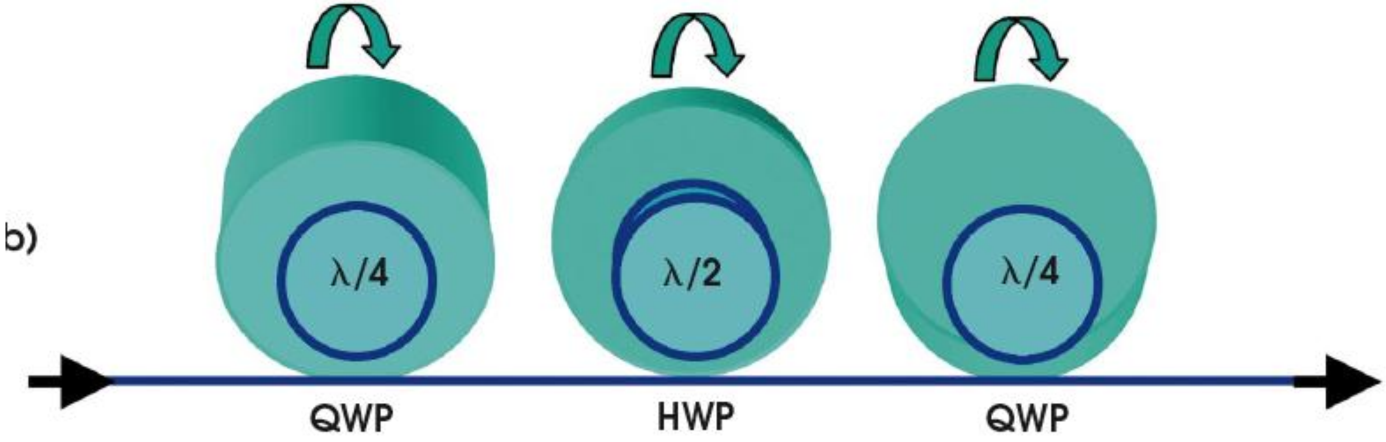
Stress birefringence polarization controller

- **Variable stress causes variable relative retardation parallel and perpendicular**
- **Rotation of the retarder with respect to the input polarization**
  - **Free space optic embodiment is Babinet compensator**



Loop polarization controller

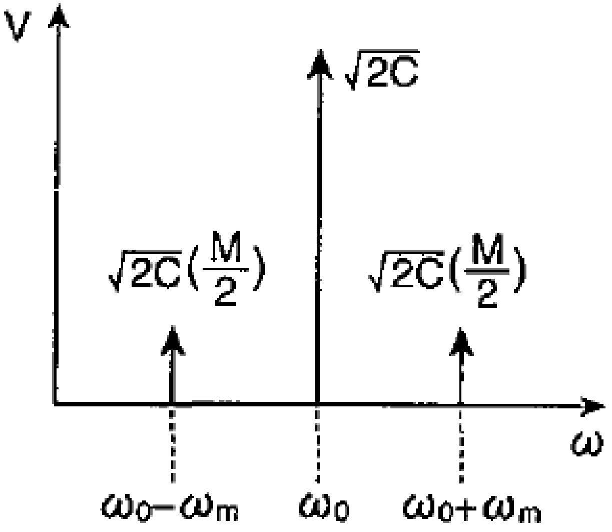
- Looping of fibers induces stress birefringence
- Loops (“paddles”) are rotated with respect to the input and each other
- Arrangement allows access to any part of the Poincare sphere from any other part
- H. C. Lefevre, Electronics Letters 16, 778 (1980)

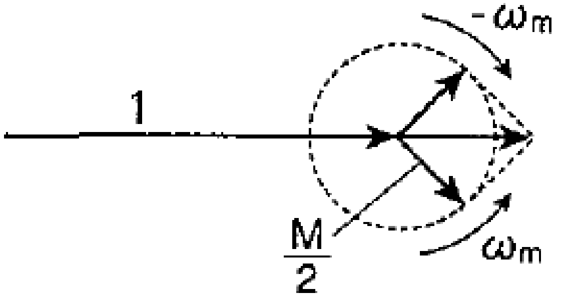


Amplitude modulation

- **M is modulation depth**
- **Note that spectrum analyzer will detect sideband power, so squaring carrier/sideband ratios**

$$\begin{aligned} V(t) &= \sqrt{2C}\left[1 + M\cos\omega_m t\right]\sin\omega_0 t \\ &= \sqrt{2C}\left[\sin\omega_0 t + \frac{M}{2}\sin(\omega_0+\omega_m)t + \frac{M}{2}\sin(\omega_0-\omega_m)t\right] \end{aligned}$$





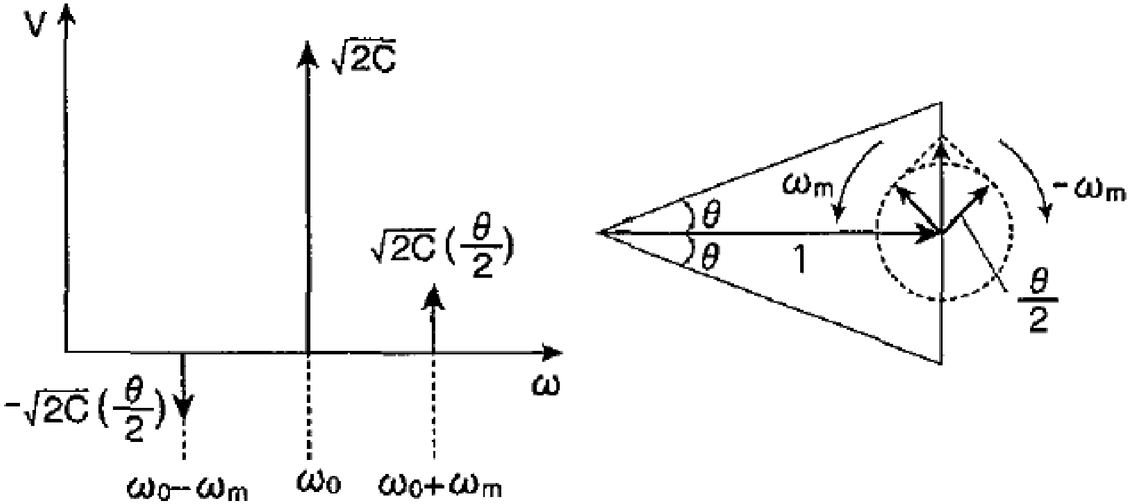
Phase modulation

$$V(t) = \sqrt{2C}\sin\left[\omega_0 t + \theta\sin\omega_m t\right],$$

- **Theta is the modulation depth, which is the peak phase deviation in radians**
- **If the “pi phase shift” voltage is Vp, the modulation depth is π*V/Vp**

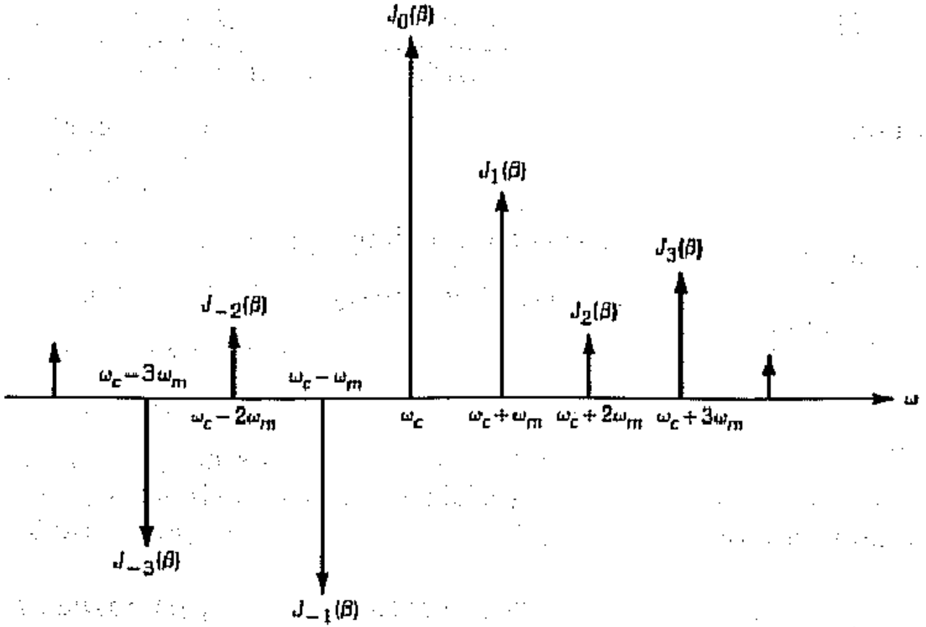
$$V(t) = \sqrt{2C}\,J_0(\theta)\sin\omega_0 t + \sqrt{2C}\sum_{n=1}^{\infty} J_n(\theta)\sin\left(\omega_0 + n\omega_m\right)t$$

$$+ \sqrt{2C}\sum_{n=1}^{\infty} (-1)^n J_n(\theta)\sin\left(\omega_0 - n\omega_m\right)t\,.$$

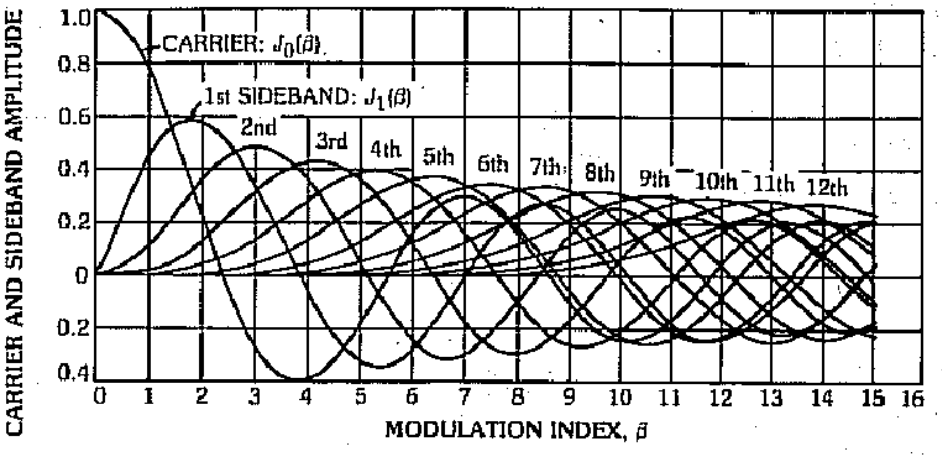


High-index phase modulation

- **Sideband amplitudes are the Bessel functions**
- **One can observe the sideband power, the square of the amplitudes, with a tunable filter**
- **Mod index is easily determined by noting the relative sideband heights**



$$
\begin{aligned}
e(t) = A_c\{&J_0(\beta)\cos\omega_c t \\
&- J_1(\beta)[\cos(\omega_c - \omega_m)t - \cos(\omega_c + \omega_m)t] \\
&+ J_2(\beta)[\cos(\omega_c - 2\omega_m)t + \cos(\omega_c + 2\omega_m)t] \\
&- J_3(\beta)[\cos(\omega_c - 3\omega_m)t - \cos(\omega_c + 3\omega_m)t] + \cdots\} \\
= A_c &\sum_{n=-\infty}^{\infty} J_n(\beta)\cos(\omega_c + n\omega_m)t
\end{aligned}
$$

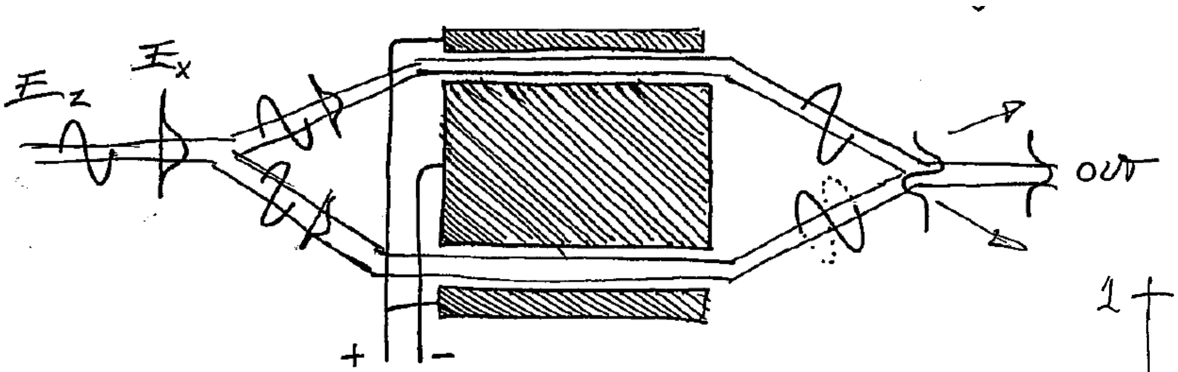


Modulators, electro-optic

- **Waveguide on electro-optic substrate (RWV p. 768)**
  - **Phase**
    - **Waveguide sort of like a fiber**
    - **Waveguide material changes index as a function of external field**
    - **Field applied over a few microns, so low voltage**
    - **Phase match RF and light for high speed (~100GHz)**
  - **Amplitude**
    - **Turns phase modulation into amplitude modulation, by putting phase modulator in an interferometer**
    - **When phase difference is pi, light is extinguished because field at output looks like higher order mode, doesn’t propagate**
    - **Note: not an amplitude modulator but a power modulator, thus AM sidebands are different**
- **RWV page 709, 710**

EO amplitude (power) modulator

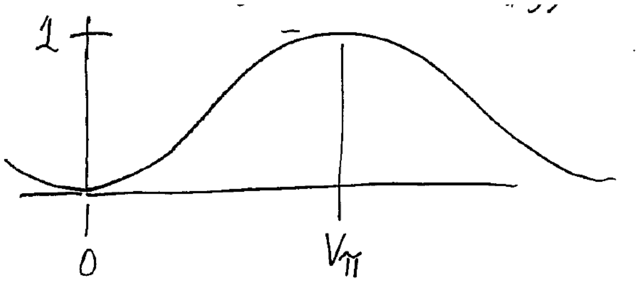
- **Phase**

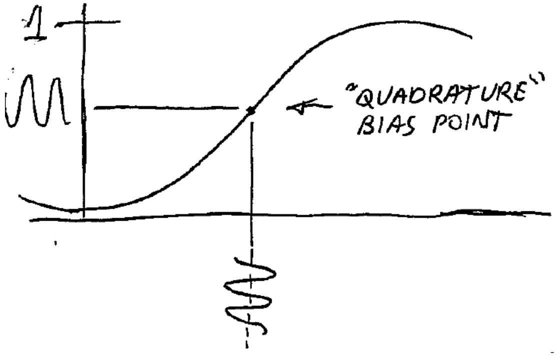


$$P(t) = P_0 \sin^2 \frac{1}{2}\left(\pi \frac{V(t)}{V_\pi} + \phi_B\right)$$

$$= P_0 \frac{1}{2}\left(1 - \cos\left(\pi \frac{V(t)}{V_\pi} + \phi_B\right)\right)$$

$$\sin^2\theta = \frac{1}{2}(1 - \cos 2\theta)$$



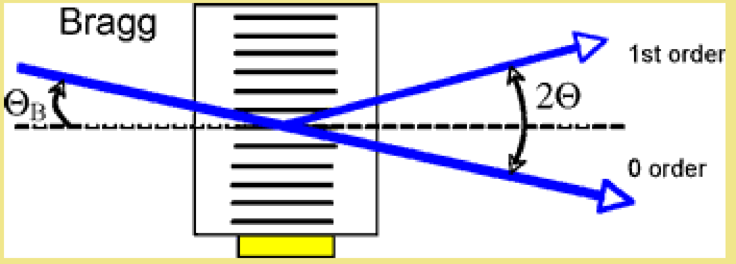


Modulators, acousto-optic

- **Bragg diffraction interacts acoustic wave with optical wave**
- **Periodic index modulation can be created by acoustic wave (stress-optic effect), launched by RF (piezoelectric effect)**
- **Index modulation is moving at acoustic velocity, Doppler shifting the optical wave up or down depending on geometry**
  - **The frequency shift is the RF frequency**
  - **The added phase shift is the RF phase**
- **Diffraction efficiency depends on index wave amplitude and interaction length**
  - **Diffraction efficiency can be modulated by changing RF amplitude, resulting in amplitude modulator**
- **Other functions such as tunable filters and scanners can be realized using swept RF sources**

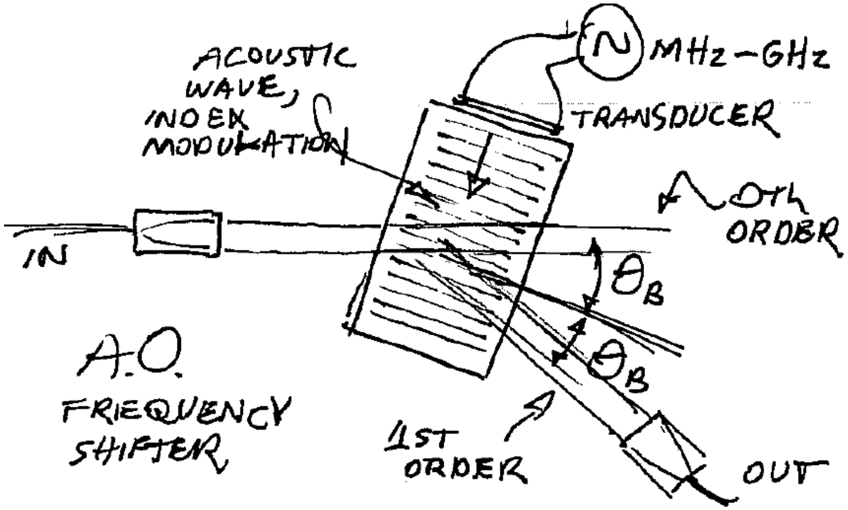
$$n(z,t) = n + \Delta n \cos(\omega t - kz),$$

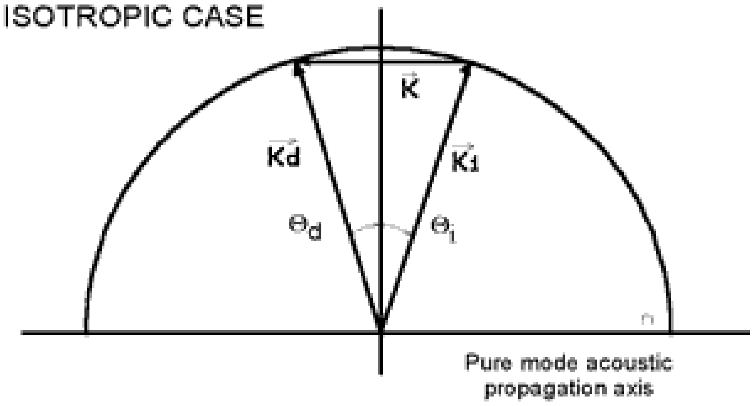
$$\Delta n = -\frac{1}{3} n^3 p_{ij} a_j,$$



AO frequency shifter

- **Constant amplitude RF applied to modulator**
- **Frequency shift is RF frequency**
- **Efficiency of diffraction into first order ~60%**
- **Couple light out of fiber and back in after diffraction**



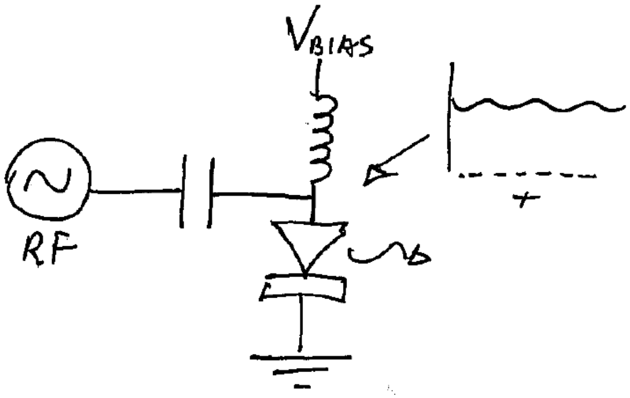


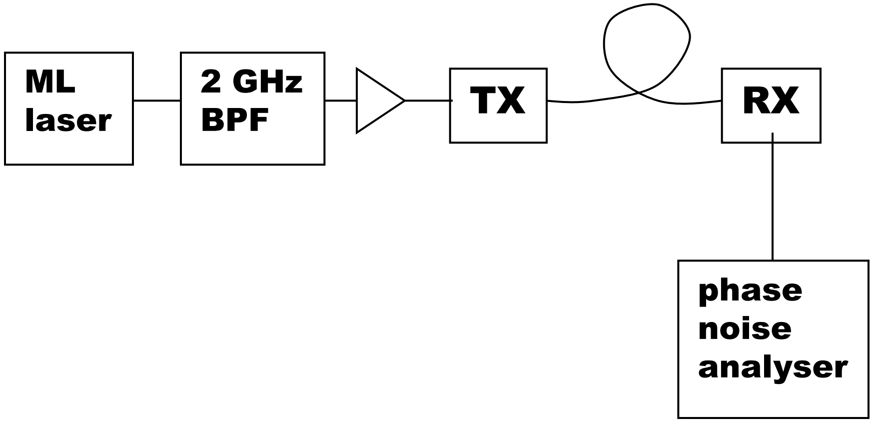
$$\vec{K}_d = \vec{K}_i +/- \vec{K}$$

$K_i = 2\pi n_i/\lambda_o$ - wave vector of the incident beam.
$K_d = 2\pi n_i/\lambda_d$ - wave vector of the diffracted beam.
$K = 2\pi F/v$ - wave vector of the acoustic wave.

Direct modulation of laser diode

- Common in telecom, cable TV
- Capable of very low noise





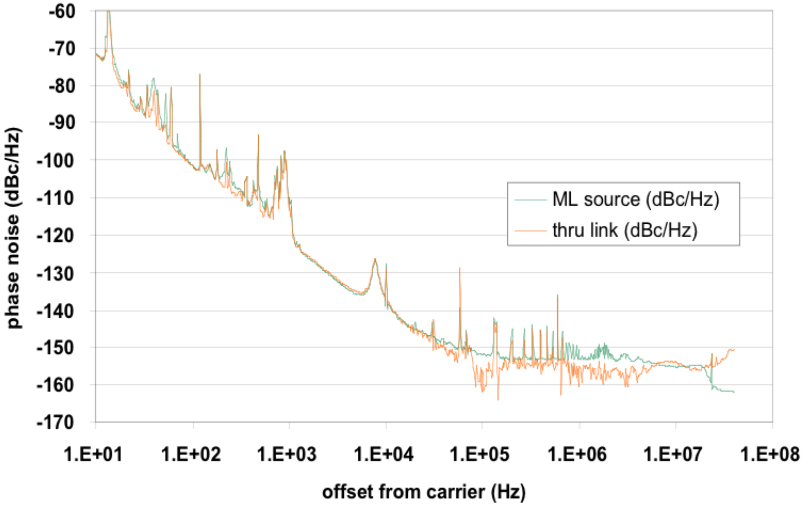
ML laser

2 GHz BPF

TX

RX

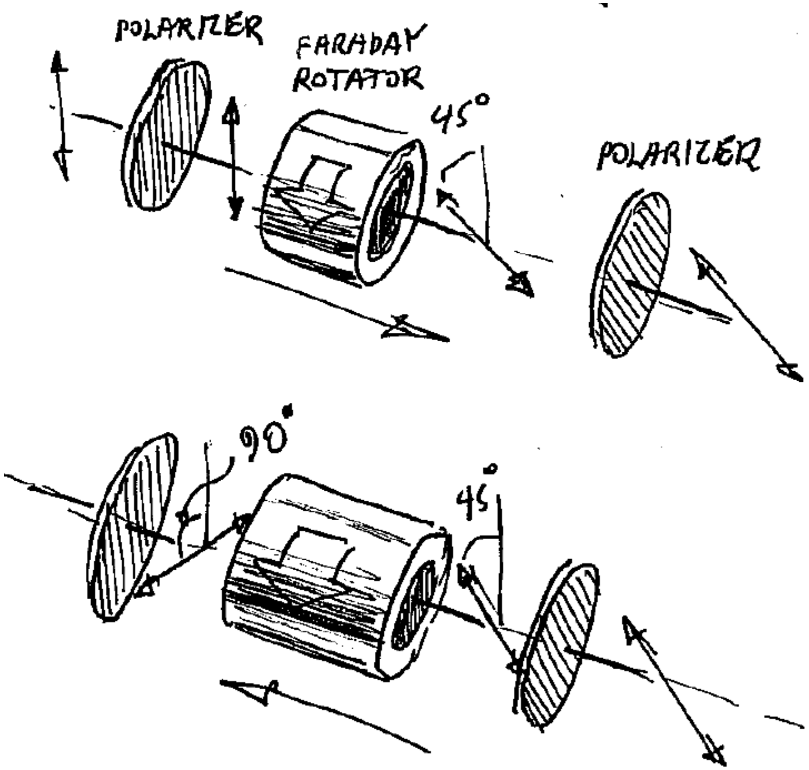
phase noise analyser



- Low noise RF source: modelocked laser pulse train on photodiode, bandpass filter at 2GHz
- Source jitter of 11 fsec RMS from 1kHz to 40MHz limited by photodiode shot noise at –155dBc
- Noise after link is 15fsec RMS, 1kHz to 40MHz
- No phase noise added by the link from 10Hz to 10kHz

Isolator

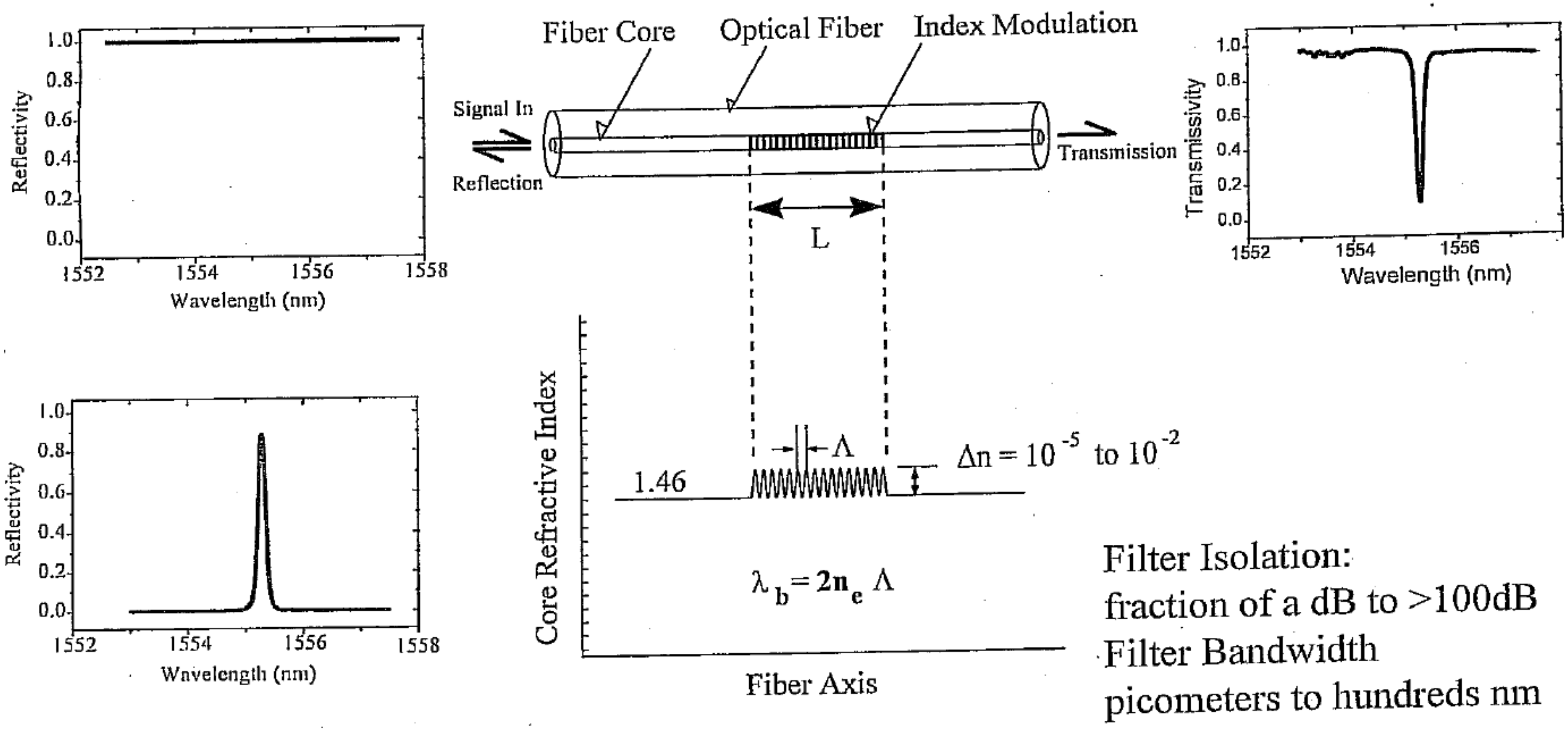
- **Based on Faraday effect (RWV page 721)**
- **Non-reciprocal polarization rotation makes optical “diode” function**
- **Can be extended to make circulator**
- **Input polarization-independent versions created by splitting input into two arms, isolating each and then recombining**



Filters

- **Dielectric bandpass or notch filter**
  - **Stack of transparent layers with alternating indices of refraction (RWV p. 295)**
  - **Direct analogy with periodic microwave filter designs**
- **Fiber Bragg grating**
  - **Periodic index modulation in fiber itself, very narrow band notch filter**
- **Birefringent filter (Lyot and Solc filters)**
  - **Based on wavelength dependence of polarization state after birefringent element**
- **Fabry-Perot resonator**
  - **Two-mirror resonator, tunable by varying spacing**
  - **Essentially one-dimensional fiber implementation has near ideal characteristics**

Bragg gratings in fiber



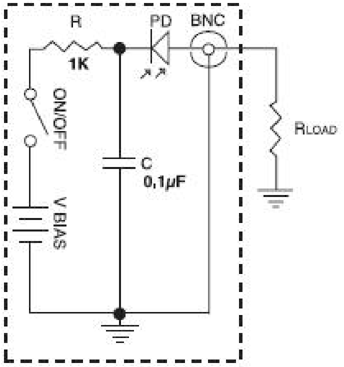
Filter Isolation:
fraction of a dB to >100dB
Filter Bandwidth
picometers to hundreds nm

- **William Morey**

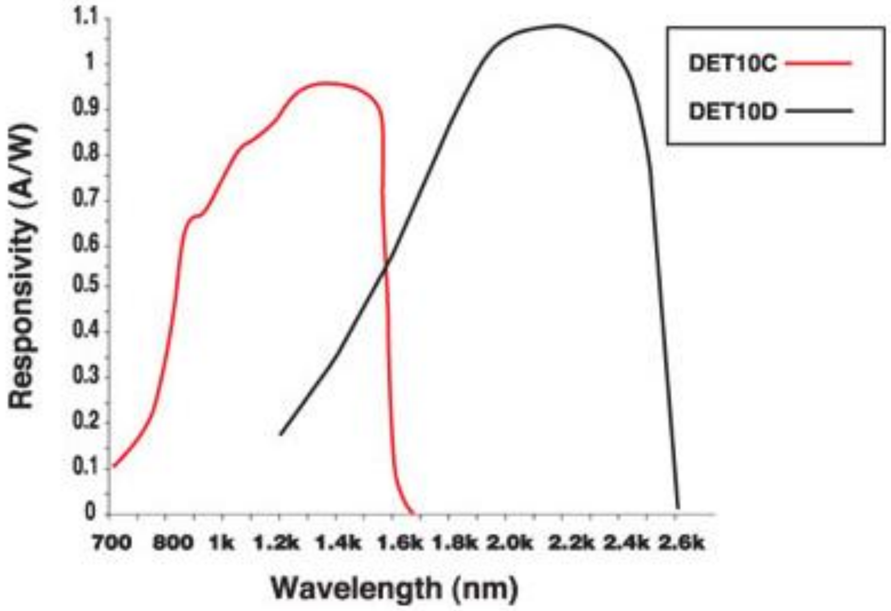
Detectors

- PIN junction photodiode is most common fast detector (~100GHz)
  - Bandwidth ~ 0.35/risetime for simple RC
  - Bandwidth ~0.44/pulse width for Gaussian
- Bandgap determines spectral sensitivity

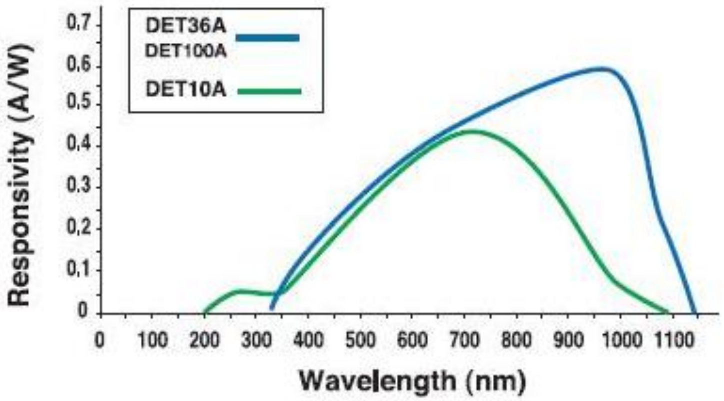
Operating Circuit



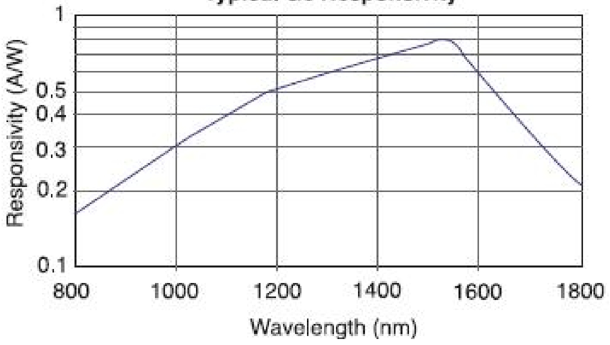
InGaAs Responsivity Curves



Silicon Responsivity Curves

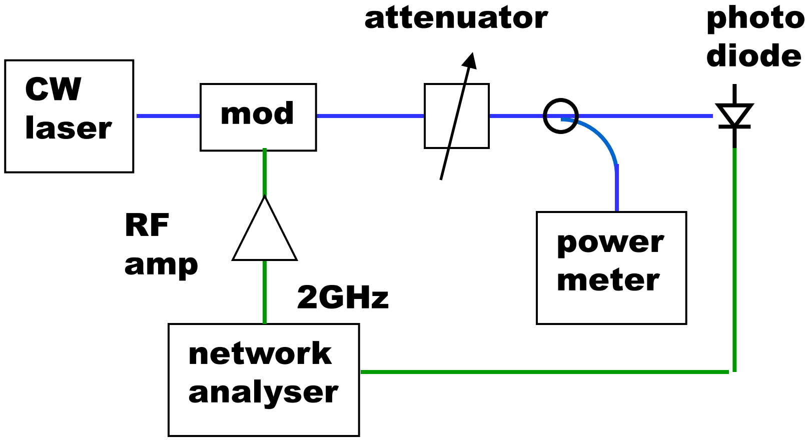


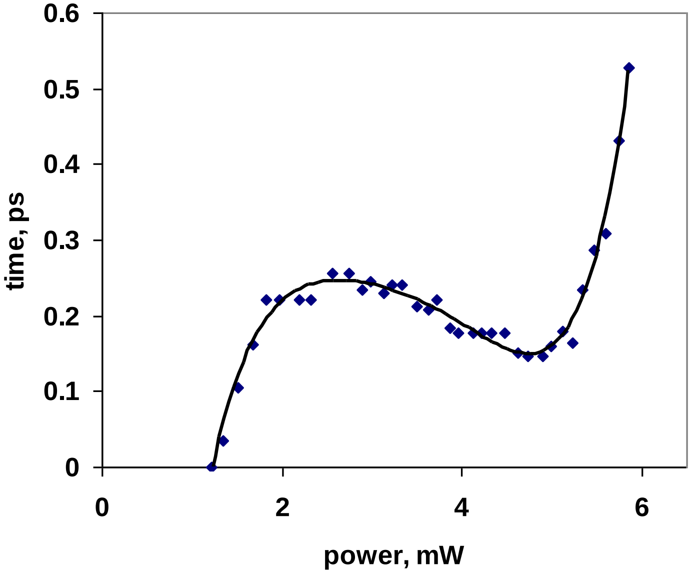
Typical Ge Responsivity



Measuring AM-to-PM characteristic

- **Saturation occurs when photocarrier density is high enough to diminish intrinsic electric field**
  - **Efficiency decreases, ultimately limiting signal amplitude**
  - **Junction capacitance is modulated, changing phase transfer function**
    - **"AM-to-PM"**
    - **Bandwidth decreases**
  - **Time domain response shows "tail"**
  - **Most diodes saturate at around 100-200mV into 50 Ohms, though higher sat power models are available**

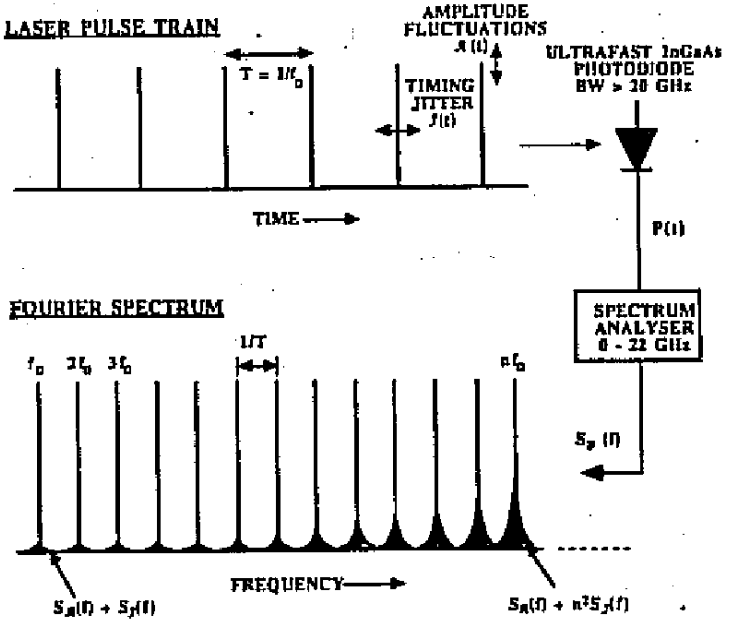


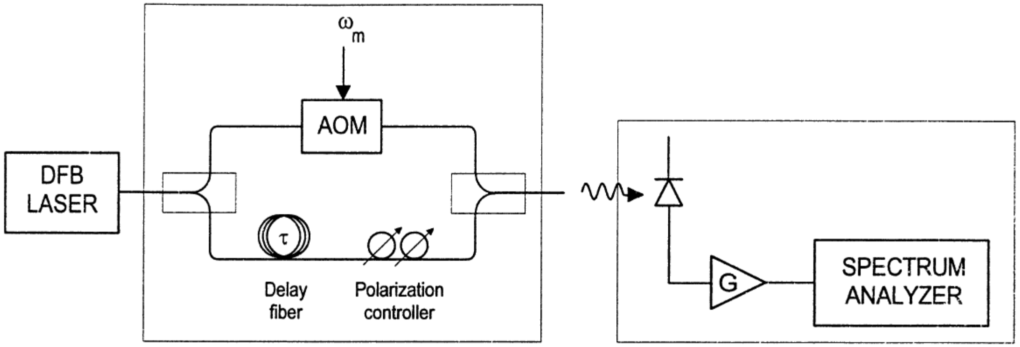


- **"Kink" in AM/PM curve provides zero-slope operating point**
  - **+/- 10% in power produces <10fs timing shift**
  - **Power is easily regulated to 1%**

Detection in frequency domain

- Note that photocurrent is proportional to optical power
  - Diode output is proportional to the square of the optical field (“square law detector”), thus can be used as a mixer to derive difference frequency (if it’s within detector bandwidth)
  - Observe beats between two optical signals
  - Detect envelope modulation of optical wave

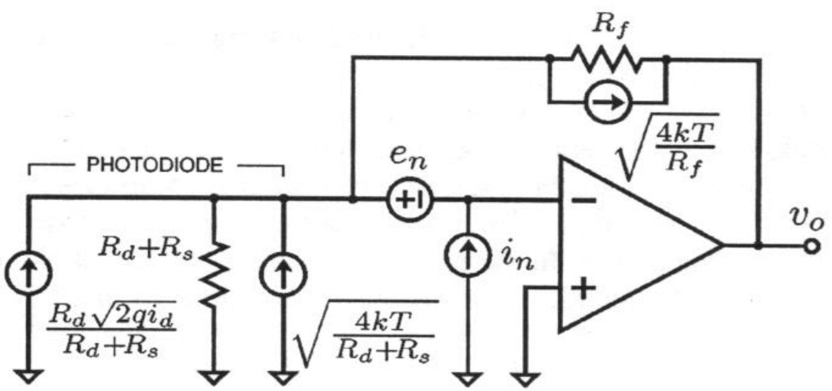




Delayed self-heterodyne interferometer

Optical detection

Noise sources in detection



$$\overline{v_o^2} = \Bigg[\underbrace{\frac{2qi_dR_d^2}{(R_s+R_d)^2}}_{\substack{\text{DARK}\\\text{CURRENT}\\\text{SHOT NOISE}}} + \underbrace{\frac{4kT}{R_s+R_d}}_{\substack{\text{PHOTODIODE}\\\text{JOHNSON}\\\text{NOISE}}} + \underbrace{\overline{i_n^2}}_{\substack{\text{OP-AMP}\\\text{CURRENT}\\\text{NOISE}}} + \underbrace{\frac{4kT}{R_f}}_{\substack{\text{FEEDBACK}\\\text{RESISTOR}\\\text{JOHNSON}\\\text{NOISE}}}\Bigg]R_f^2$$

$$+\underbrace{\overline{e_n^2}\left(1+\frac{R_f}{R_s+R_d}\right)^2}_{\substack{\text{OP-AMP}\\\text{VOLTAGE}\\\text{NOISE}}} \quad \mathrm{V^2/Hz} \qquad (28)$$

where

i_d	dark current;
i_n	op-amp input noise current spectral density;
e_n	op-amp input noise voltage spectral density;
R_d	photodiode dynamic resistance;
R_s	photodiode series resistance.