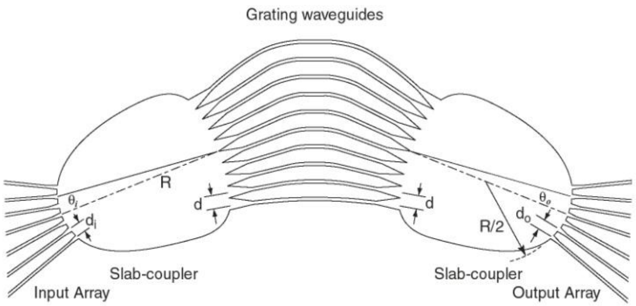
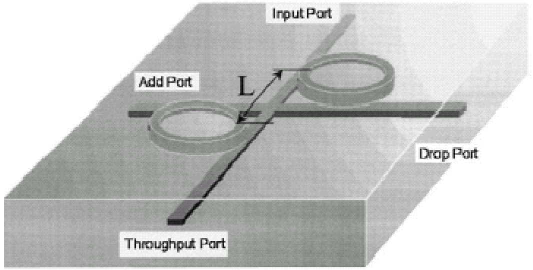




Passive Optical Components and Filtering Technologies

Christi Madsen

Texas A&M University

cmadsen@tamu.edu

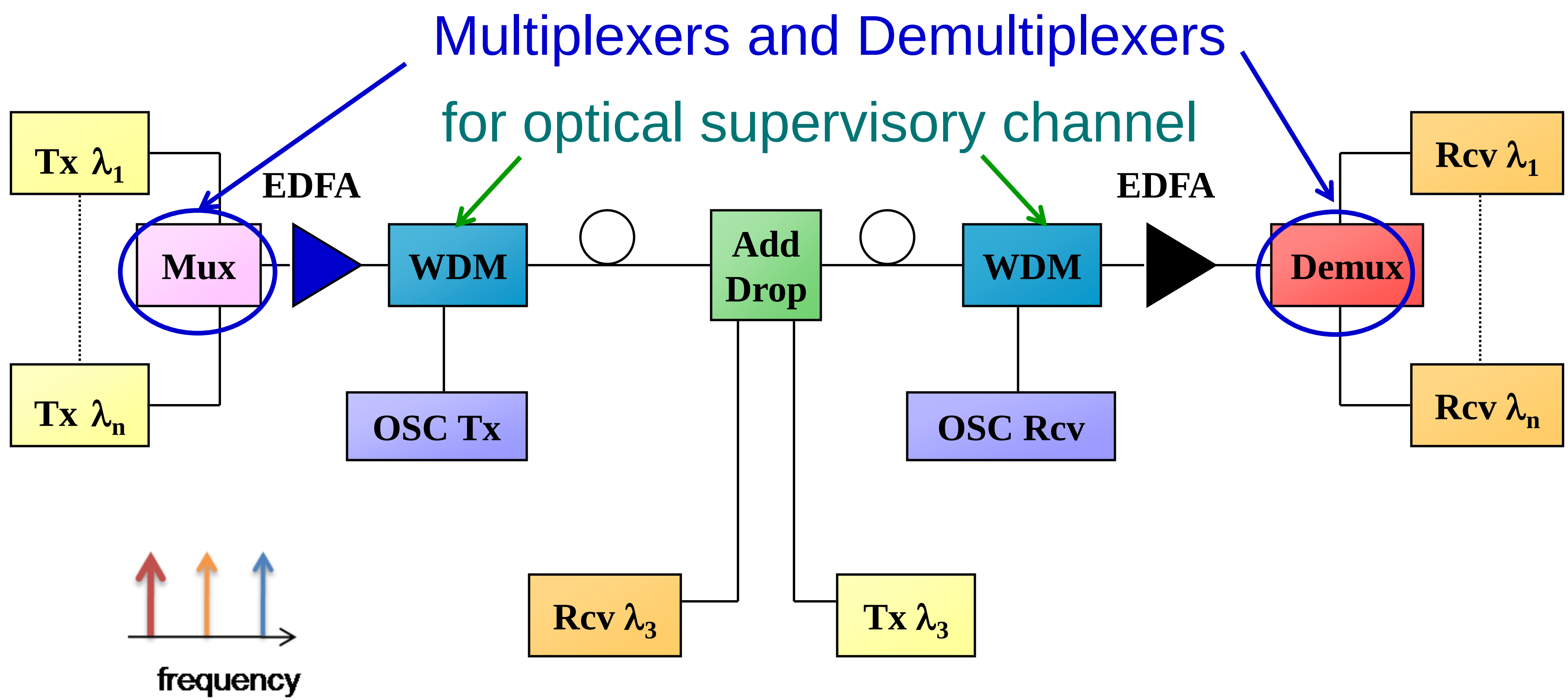
http://photonics.tamu.edu

Bruce Nyman

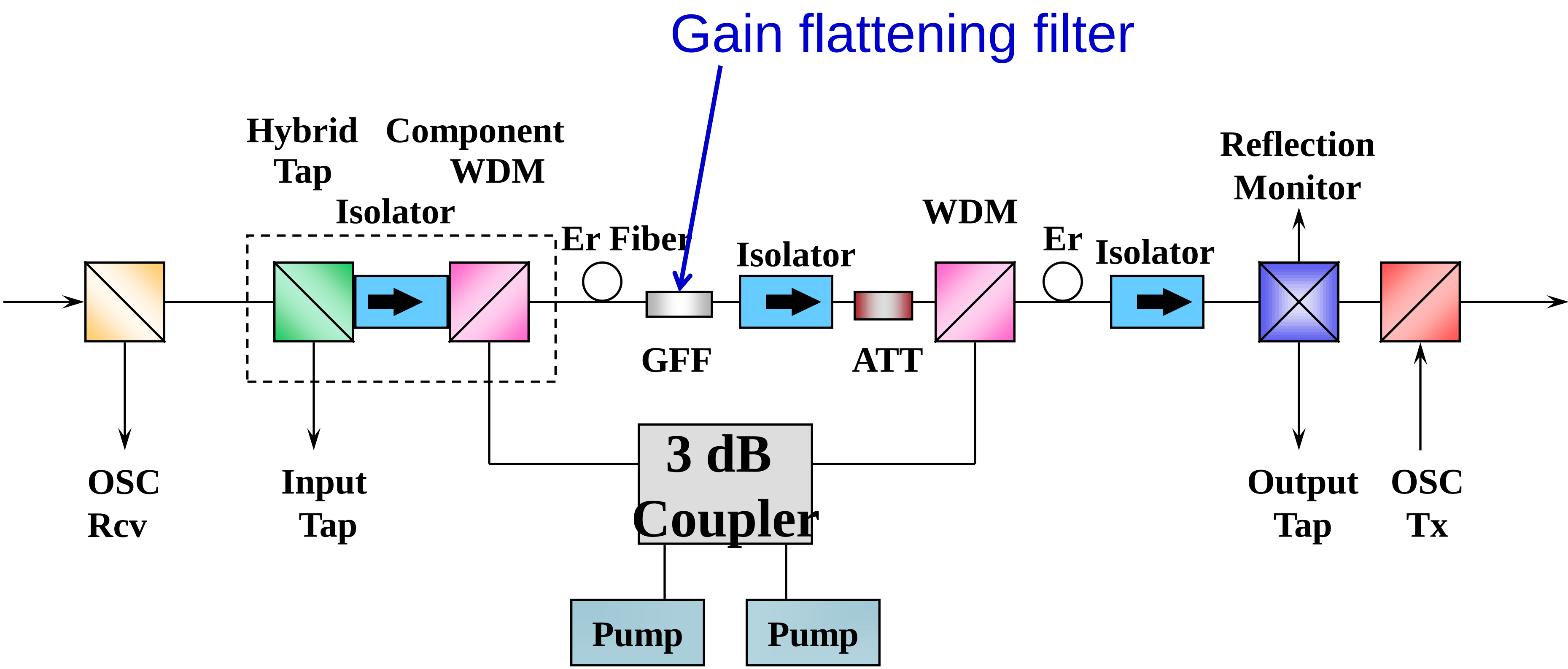
Outline

- Introduction
- Optical Filter Technologies
- Parameters and Measurements
- Component technologies
- Devices

Wavelength Division Multiplexed (WDM) System Architecture



EDFA Architecture



Optical Filters

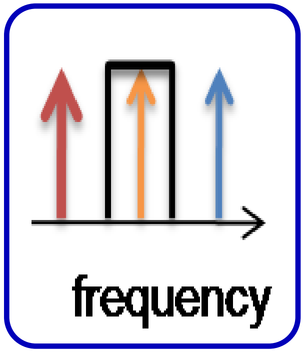
What makes them work?

- **Interference**
- (Most are coherent)

How do we use them?

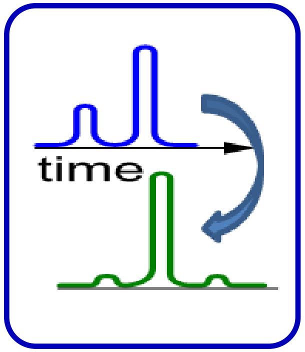
- **Optical communications**
  - **Wavelength division multiplexing**
  - **Dispersion & distortion compensation**
- **Optical Sensors**

Operations in Frequency & Time



Attenuate some frequencies relative to others

e.g. bandpass (and bandstop) filters



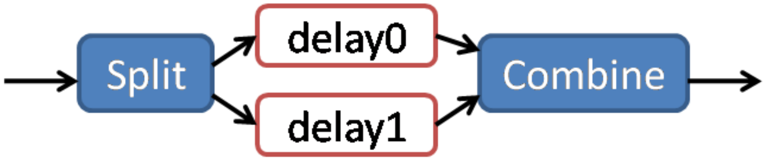
Delay a portion of the signal and subtract it

e.g. echo cancellers (electronic) dispersion compensators (optical)

Interferometers are Basic Optical Filters

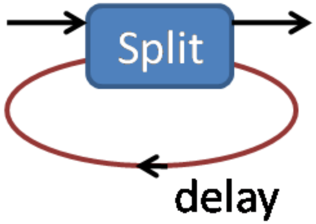
Feedforward Interference

- Mach-Zehnder Interferometer
- Michelson Interferometer
- Diffraction grating
- Arrayed waveguide grating



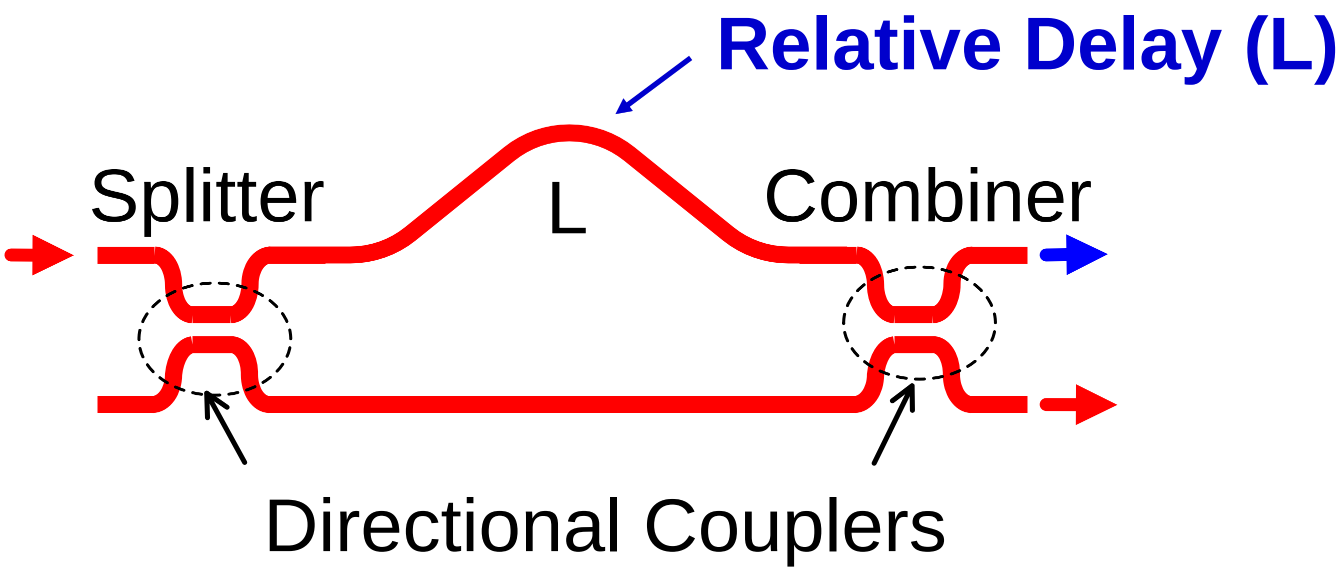
Feedback Interference

- Ring Resonator
- Fabry-Perot etalon
- Fiber Bragg gratings
- Dielectric (thin film) filters



Optical Interference Filters

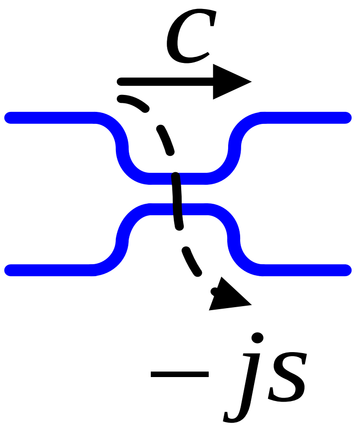
Split → Delay → Combine



Feedforward Interference

A Simple (Optical Waveguide) Splitter

Directional Coupler



coupling strength

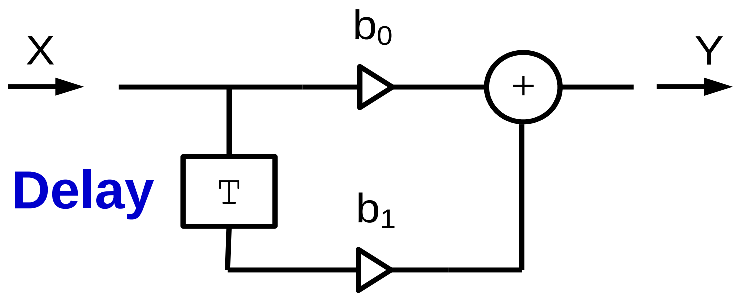
where c= $\cos(\theta)$, s= $\sin(\theta)$ and $\theta = \kappa_c L_c$

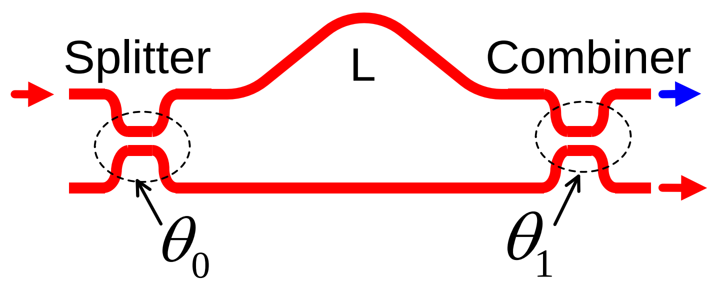
Coherent Interference, so operations are on electric-field

Comparison to a Digital Filter

Split → Delay → Weight → Combine

Digital filter (feedforward)





Splitter and Combiner Provide Weighting Function and ΔL ⇔ T is delay.

Calculating a Filter's Impact on a Signal

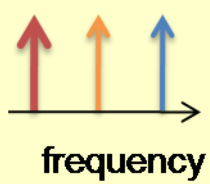
A filter is characterized by its **Frequency** (or Impulse) **Response**.

impulse response

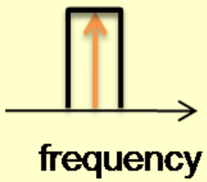
$x(t)$ $h(t)$ $y(t) = x(t) * h(t)$

Signal In → filter → Signal Out

$X(f)$



$H(f)$ $Y(f) = X(f)H(f)$



frequency response

$f \approx 193\text{THz}$

$\lambda \approx 1550\text{nm}$

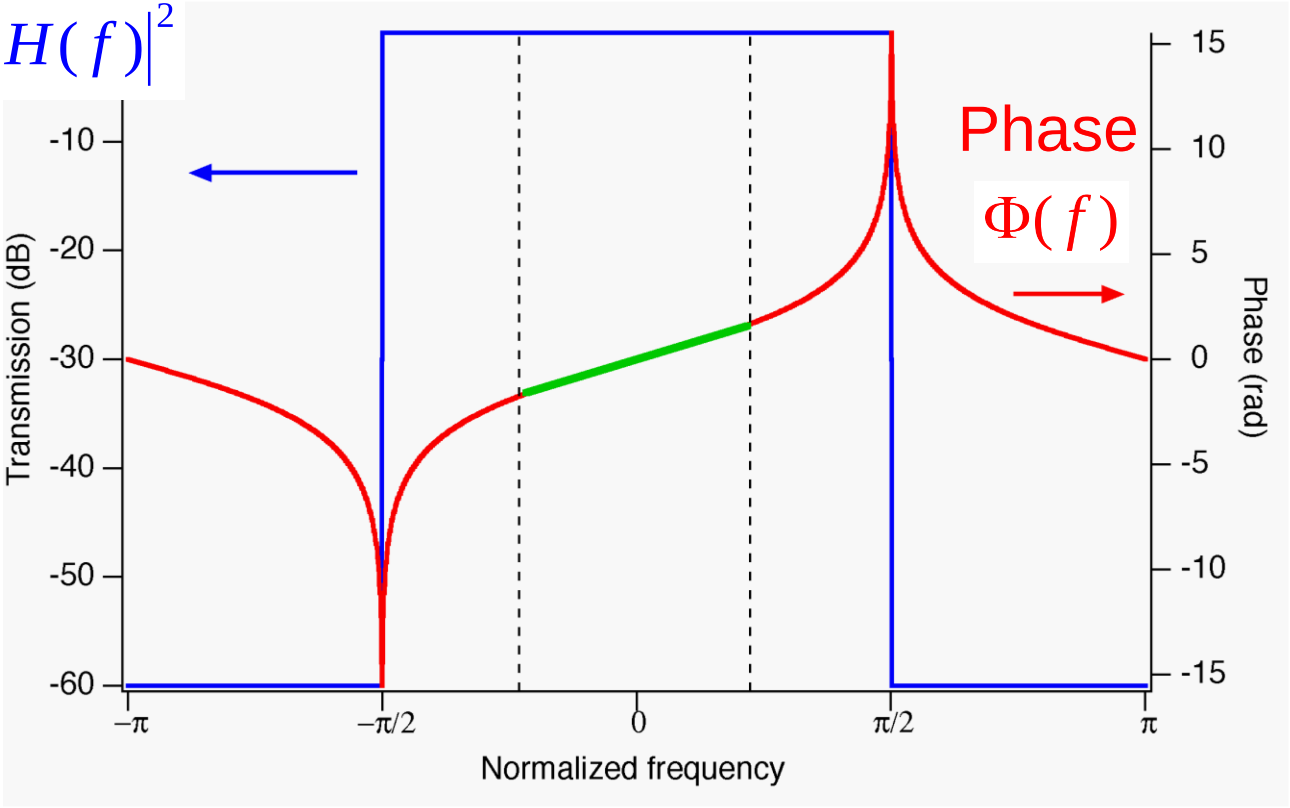
Fourier transform relates time and frequency domains for a linear time-invariant system

Magnitude and Phase Response are Important

Magnitude

$10\log_{10}|H(f)|^2$

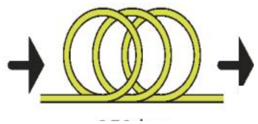
Idealized Boxlike Response



$$H(f) = |H(f)|e^{j\Phi(f)}$$

Frequency Response of a Simple Delay Line

Consider a lossless optical delay line of length L:

E_{in}  $E_{in} e^{-j\beta L}$

Delay-line frequency response

$$H(\omega) = e^{-j\beta L} = e^{-j\omega T} \qquad \text{where } T = \frac{n_e L}{c}$$

Phase Response

$$\Phi = -\omega T$$

Linear with respect to frequency:
Linear-phase response

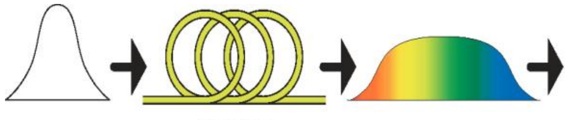
How about Group Delay and Dispersion?

Group Delay $\tau_g(\omega) \equiv -\frac{d\Phi(\omega)}{d\omega}$

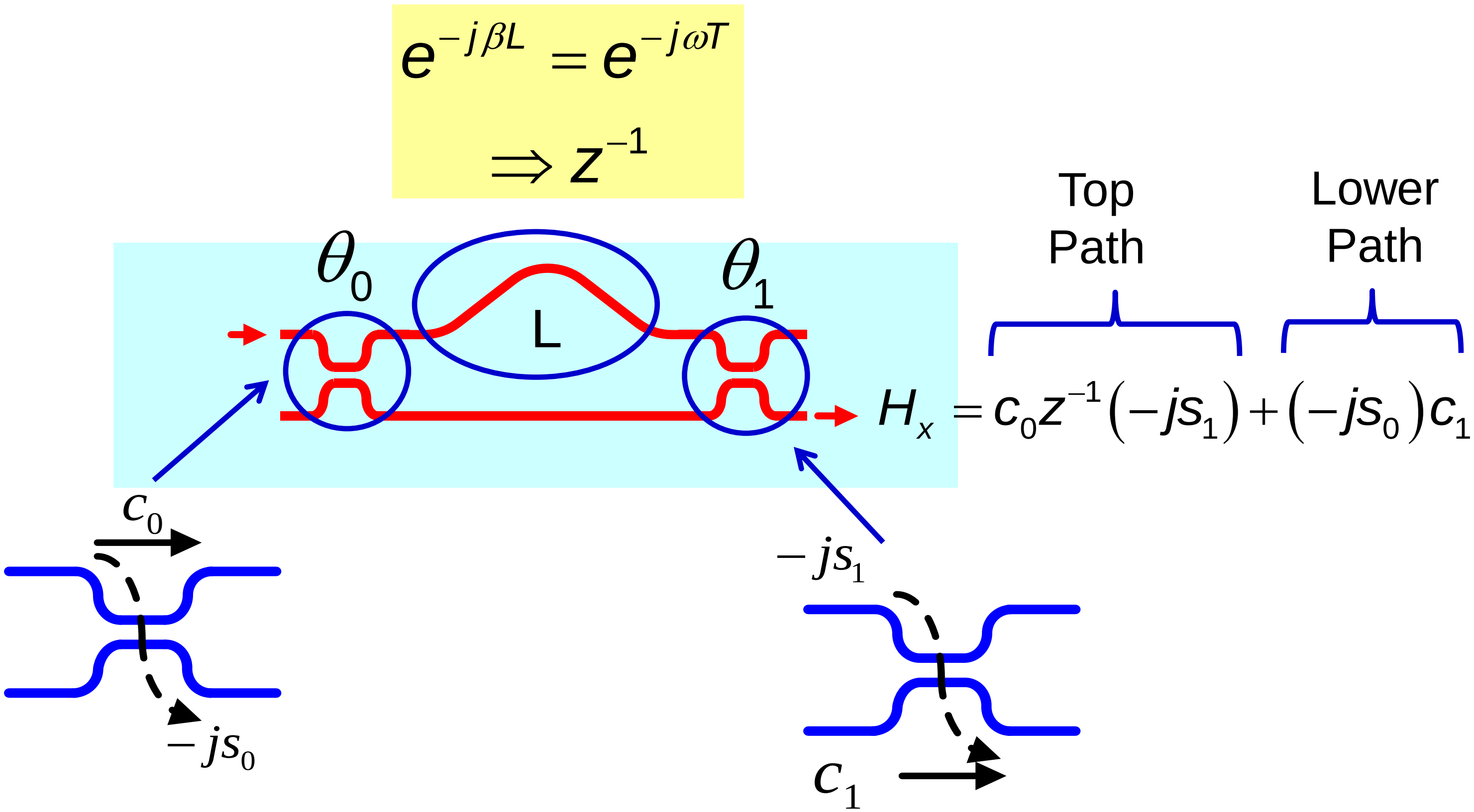
The change in phase with frequency gives the delay.

Dispersion $D = \frac{d\tau_g}{d\lambda}$ (ps/nm)

If group delay is wavelength-dependent, then device/filter is Dispersive!



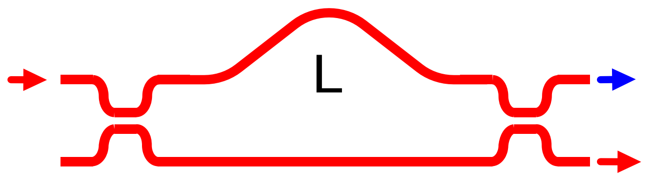
Frequency Response for a Mach Zehnder Interferometer



Frequency response can be obtained by inspection!

Mach-Zehnder Interferometer

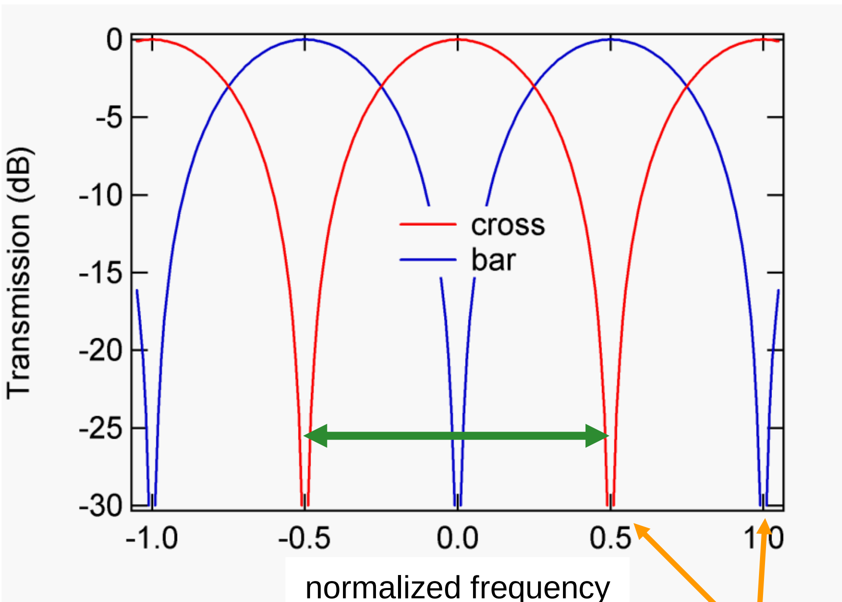
Feed-forward interference (with identical couplers)



$$H_{=} = c^2 z^{-1} - s^2$$

$$H_x = -jcs\left(z^{-1} + 1\right)$$

All-zero transfer functions



Free Spectral Range

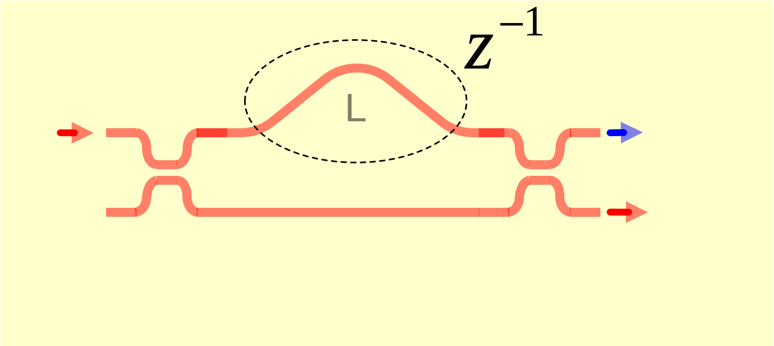
$$FSR = \frac{c}{n_g L}$$

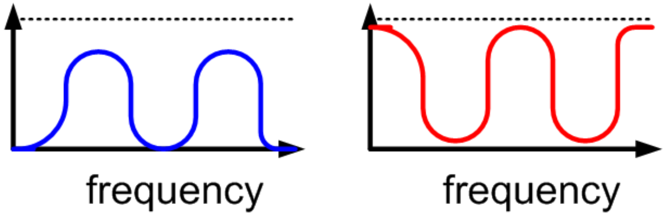
path length difference

$$z^{-1} \Rightarrow e^{-j2\pi f/FSR}$$

Frequencies of zeros

Feedforward Interference Filters



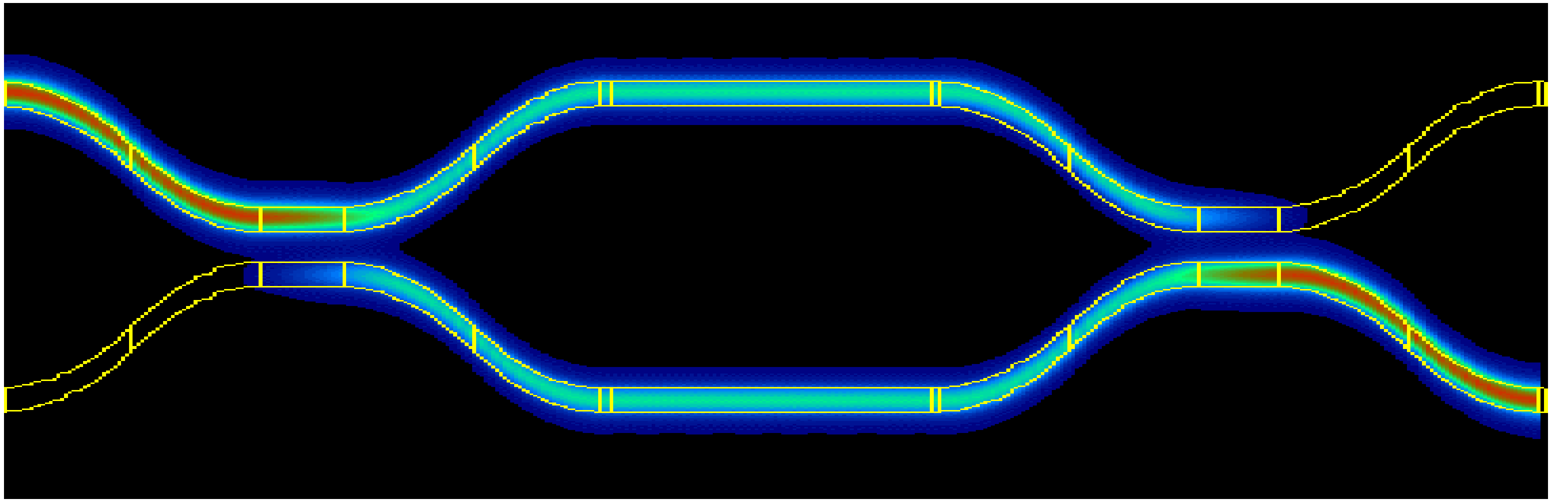


$b_1 z^{-1}$

Frequencies of

- The Z-transform description yie... ...al in z.
- The roots (called zeros) tell us the transmission minima!
- Change the coefficients to change the filter response

Symmetric Mach-Zehnder interferometer



Waveguide layout: Vary phase in one arm relative to the other

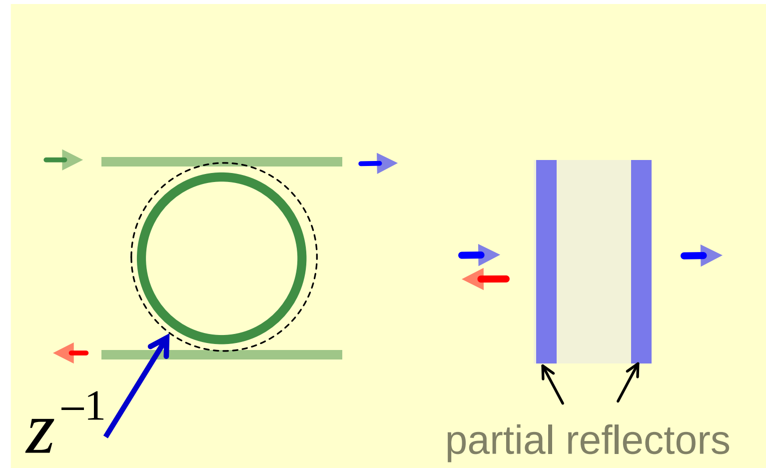
Variable coupler

Variable attenuator

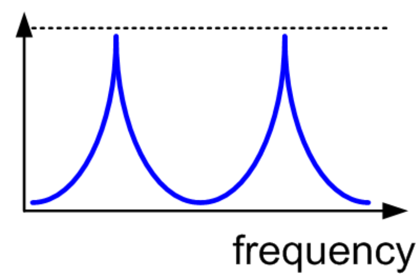
1x2 and 2x2 switch

Arms the same length → wavelength independent

Feedback Interference Filters

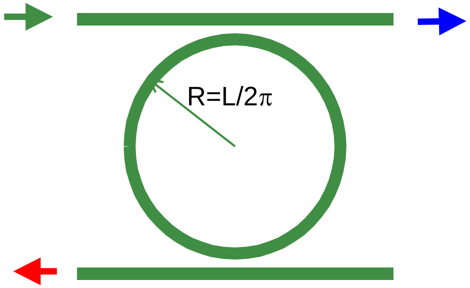


z^{-1}



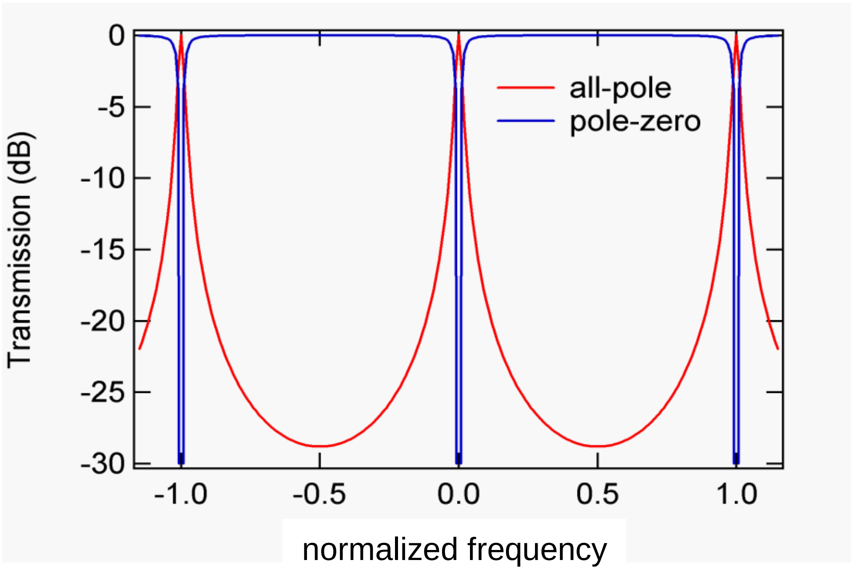
A denominator polynomial in z results due to feedback.
The roots (called poles) tell us the transmission maxima!

A Ring Resonator Optical Filter



Two outputs:

1. **Feed-back interference**
2. **Feedforward & Feedback**

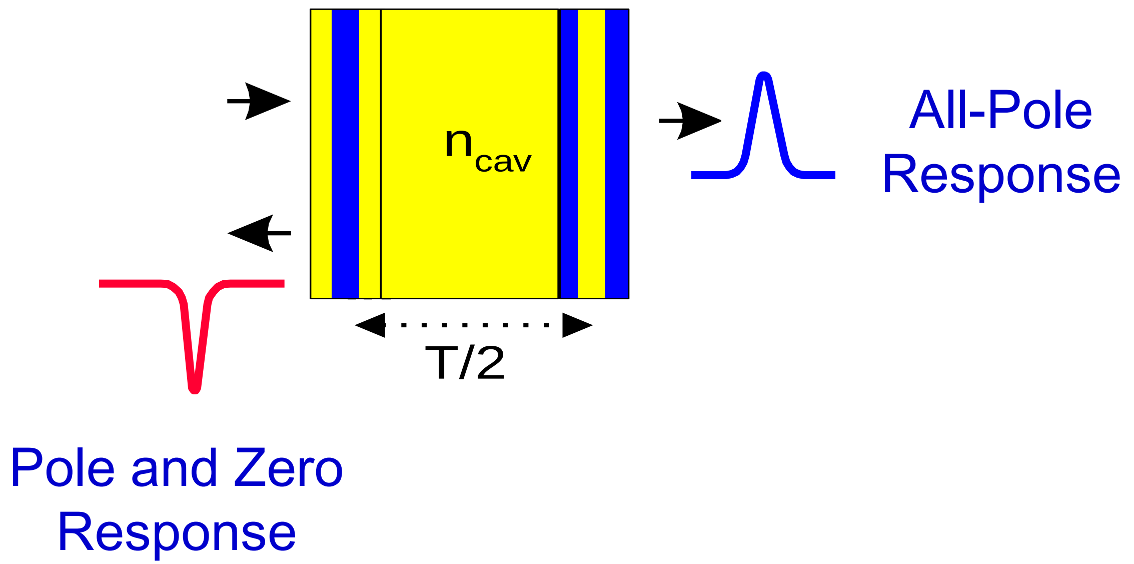


- **dispersive (all-pole=min-phase)**
- **large FSR ⇒ short feedback path!**

$$FSR = \frac{c}{n_g L}$$ ← Roundtrip

$$FSR = \frac{300(GHz)}{n_g L(mm)}$$ e.g. $100\text{GHz}=\frac{300}{1.5 \times 2\text{mm}}$

The Fabry-Perot Etalon

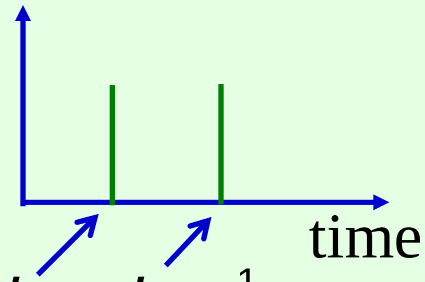


Power complementary outputs:
Transmission=All-pole, Reflection=Pole/zero

What about the time domain?

h(t)=

h(nT)



$b_0 + b_1 z^{-1}$

$h(n)$

Periodic! $H(\omega)$

Time (nT)

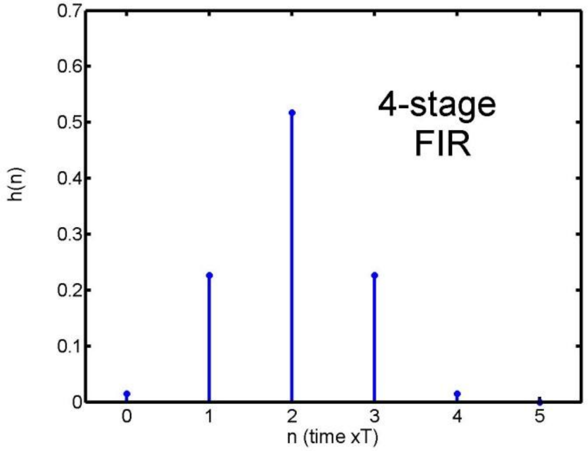
Normalized units

Frequency (1/T)

time: **unit delay (T)**
frequency: **period=Free Spectral Range=1/T**

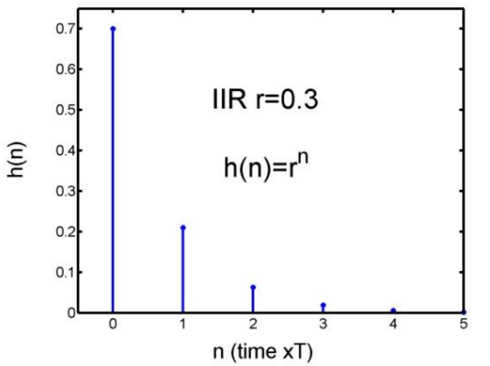
Impulse Response Classification

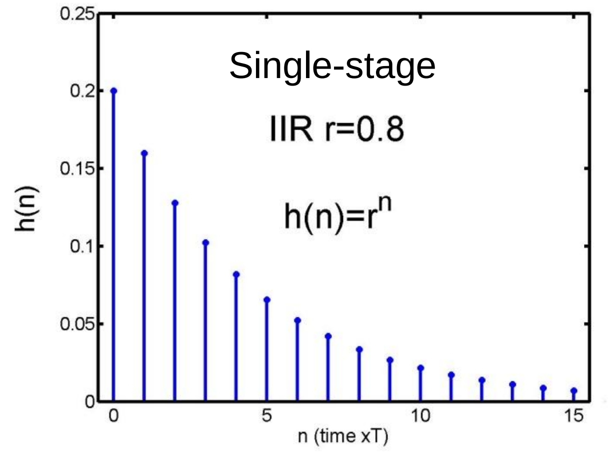
Finite impulse response (FIR)
– feedforward interference



Infinite impulse response (IIR)
- feedback interference
- feedforward and feedback interference

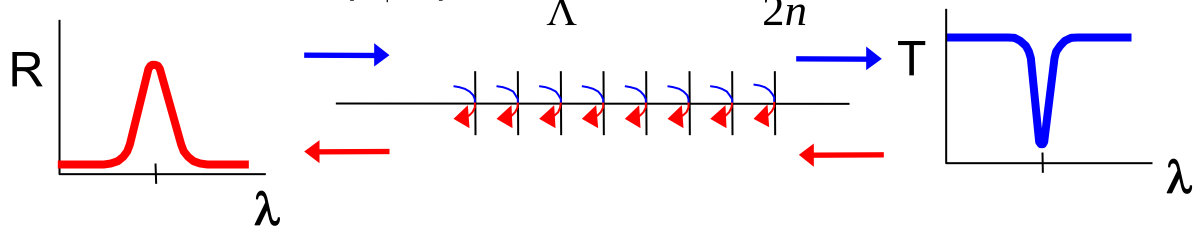
As r→0
IIR→FIR

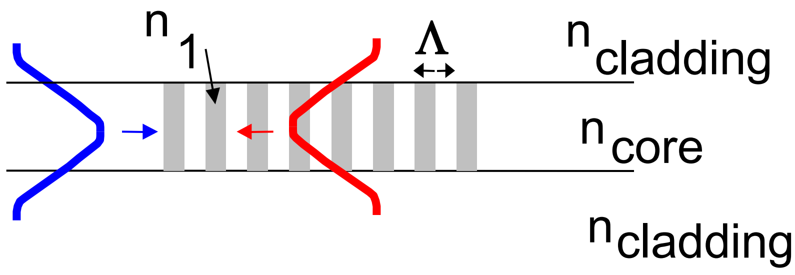




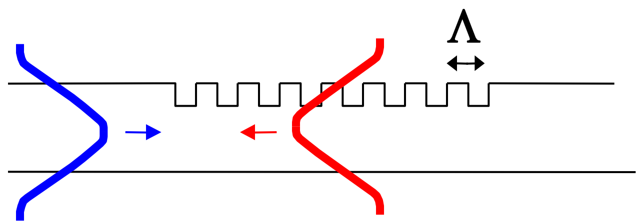
Bragg Gratings (1-D Photonic Bandgaps)

$$\beta_+ - \beta_- = \frac{2\pi}{\Lambda} \Rightarrow \Lambda = \frac{\lambda}{2n}$$





Photoinduced



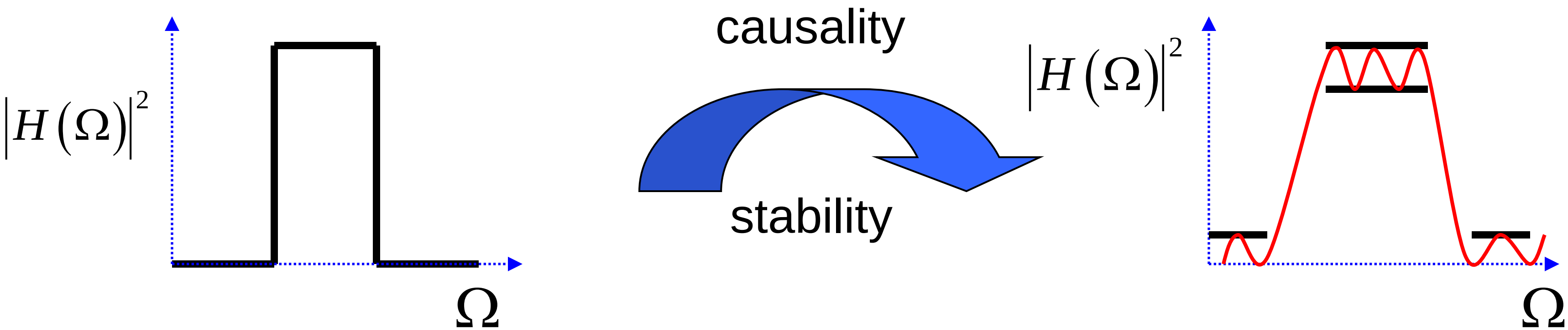
Etched

IIR filter: Transmission=All-pole, Reflection=Pole/zero

Ideal vs. Real Filters

Box-like Magnitude Response

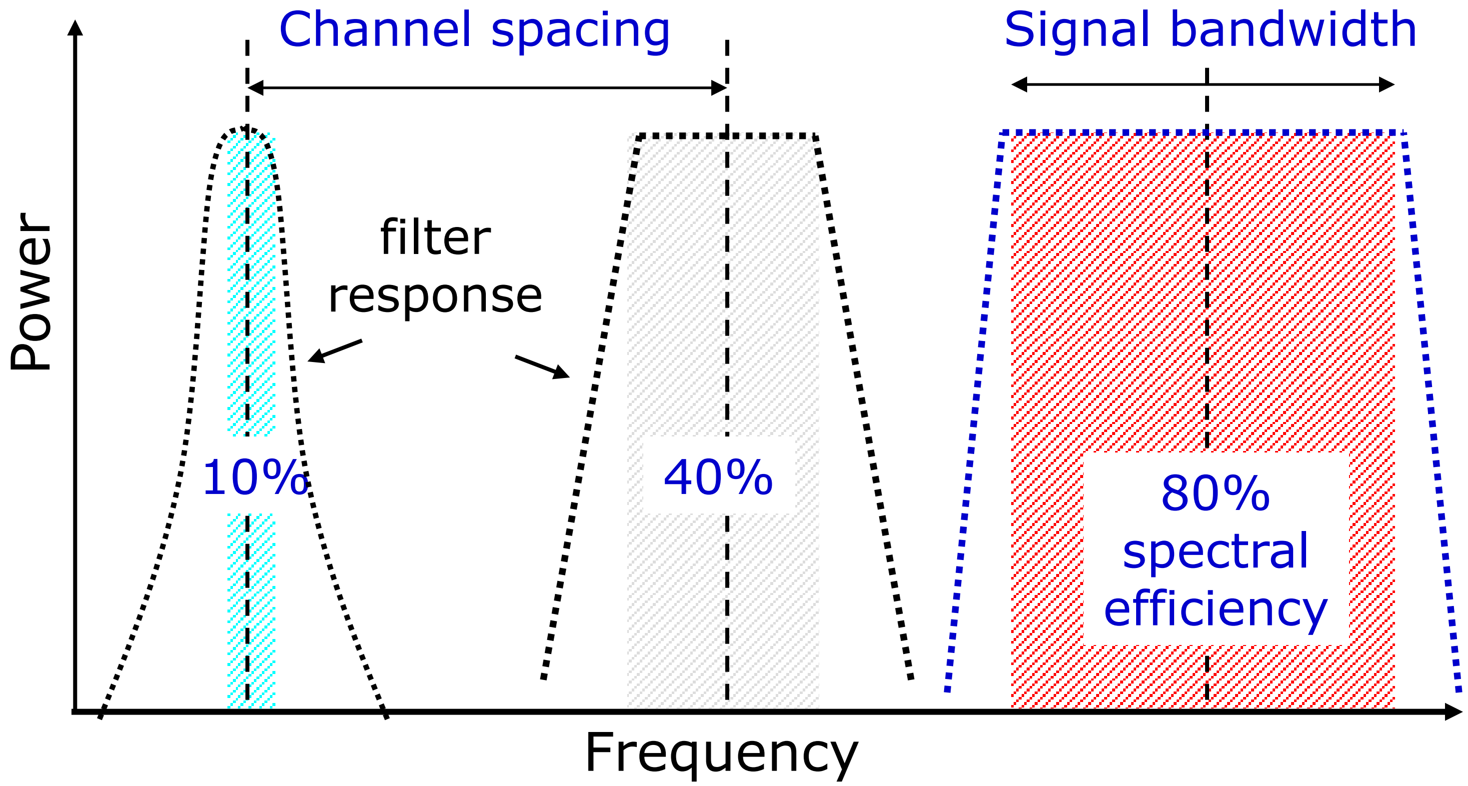
Realistic Specification



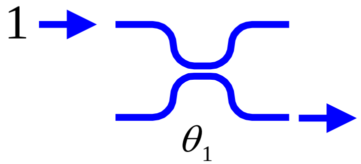
1. Zero at frequency points but not across a band
2. No infinitely steep transitions (Gibbs phenomenon)
3. Hilbert transform relationship between Real & Imag parts

Proakis & Manolakis, Digital Signal Processing, 1996, p.618

Multiplexing Filters & Spectral Efficiency



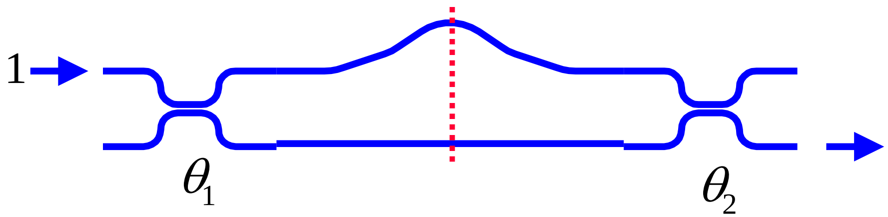
Optical FIR Lattice Filters



$$t_x = -js_1$$

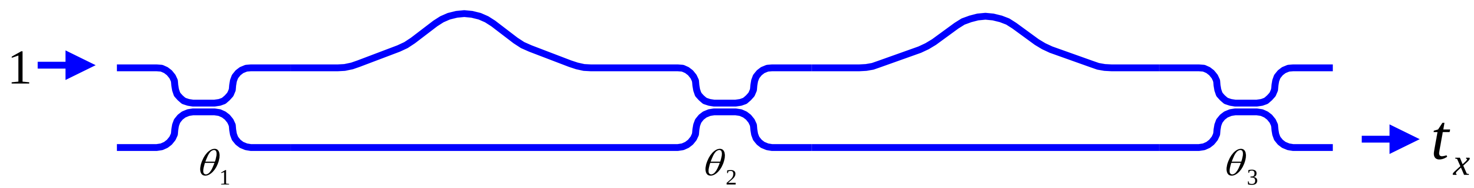
Sum of All Paths Principle

Mach-Zehnder Interferometer



$$t_x = -js_1c_2 - jc_1s_2z^{-1}$$

Two-Stage Lattice Filter

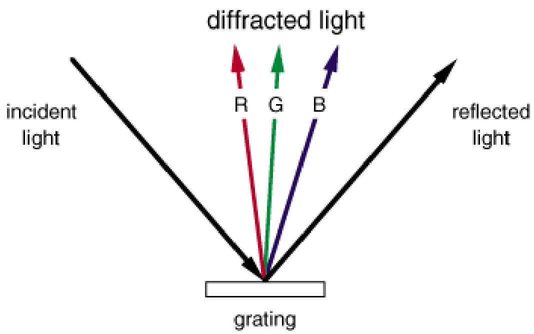


$$t_x = -js_1c_2c_3 - jc_1s_2c_3z^{-1} - js_1s_2s_3z^{-1} - jc_1c_2s_3z^{-2}$$

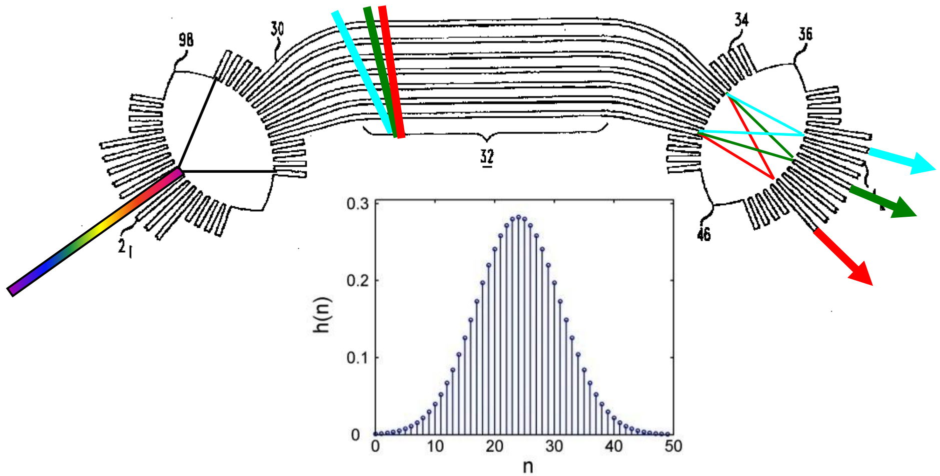
Analogous to birefringent crystal (Solc) filters

Optical Phased-Array (FIR) Filters

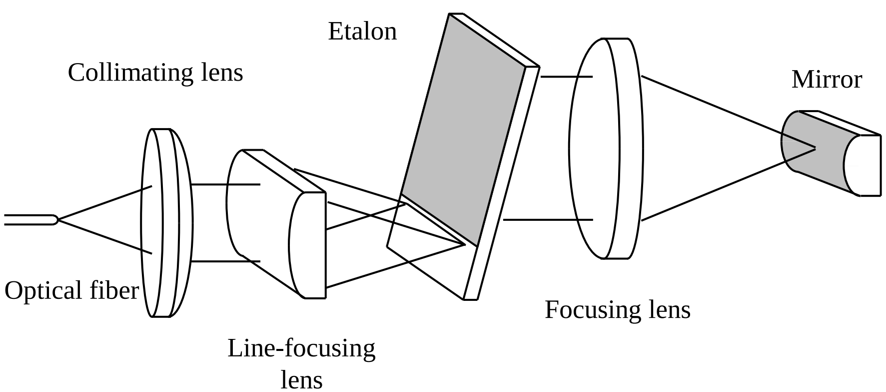
Diffraction Grating



Waveguide Grating Router



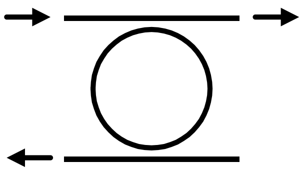
Virtual Image Phased Array



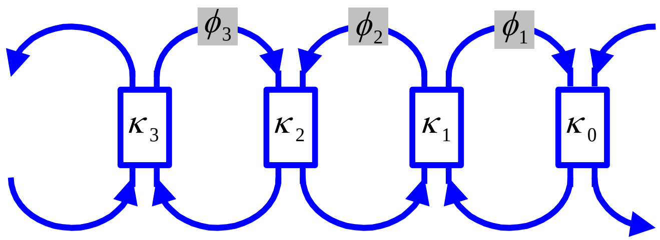
- **Multi-stage (100's)!**
- **Limited control on h(n) coefficients**

Shirasaki, *Opt. Lett.*, 1996.

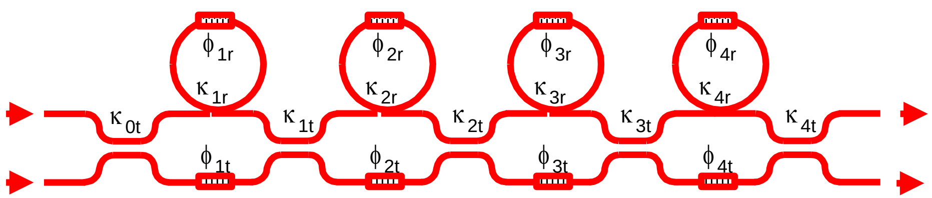
IIR Bandpass Filter Architectures



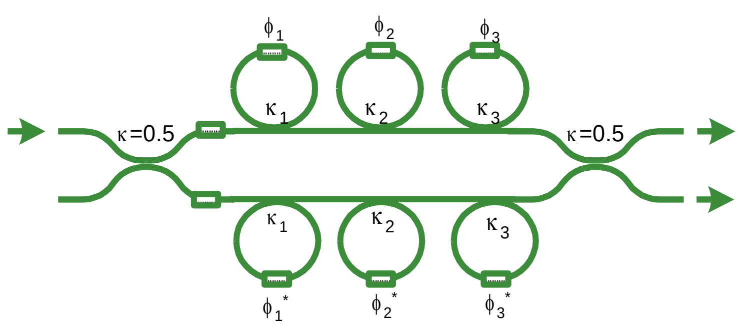
Single-pole filter
- Marcatili, BSTJ, p. 2103, 1969



Arbitrary pole locations
- Orta, et al., PTL, p.1447, 1995
- Madsen & Zhao, JLT, p. 437, 1996



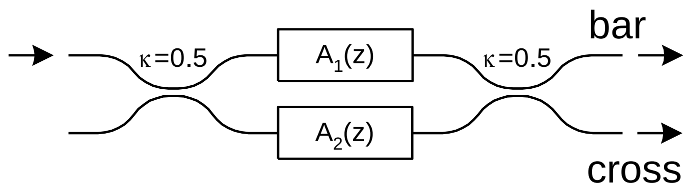
Arbitrary pole & zero locations
- Jinguji, JLT, p. 1882, 1996



Simplified pole/zero filter
- Madsen, PTL, 1998

Use allpass filter decomposition to realize <u>optimal</u> bandpass designs efficiently!

Comparison of Elliptic Filter to All-pole Filter

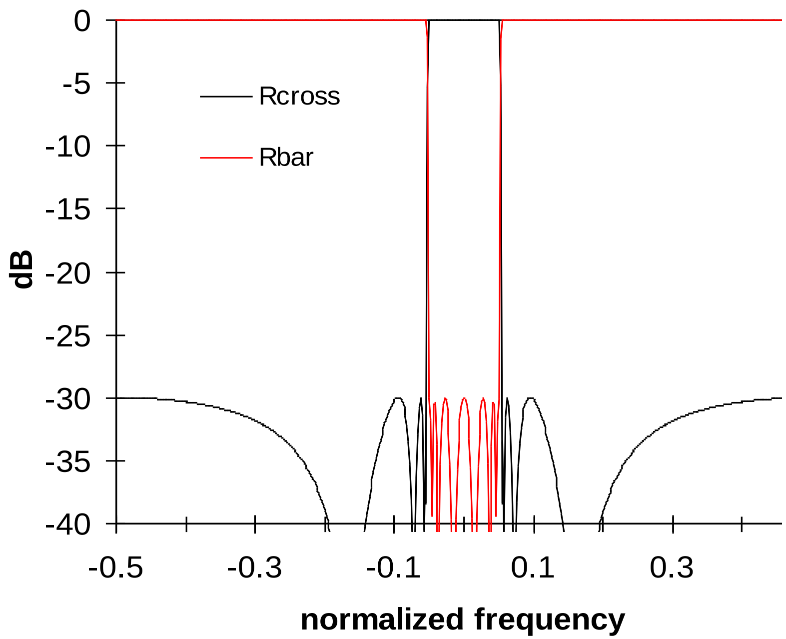


Example:

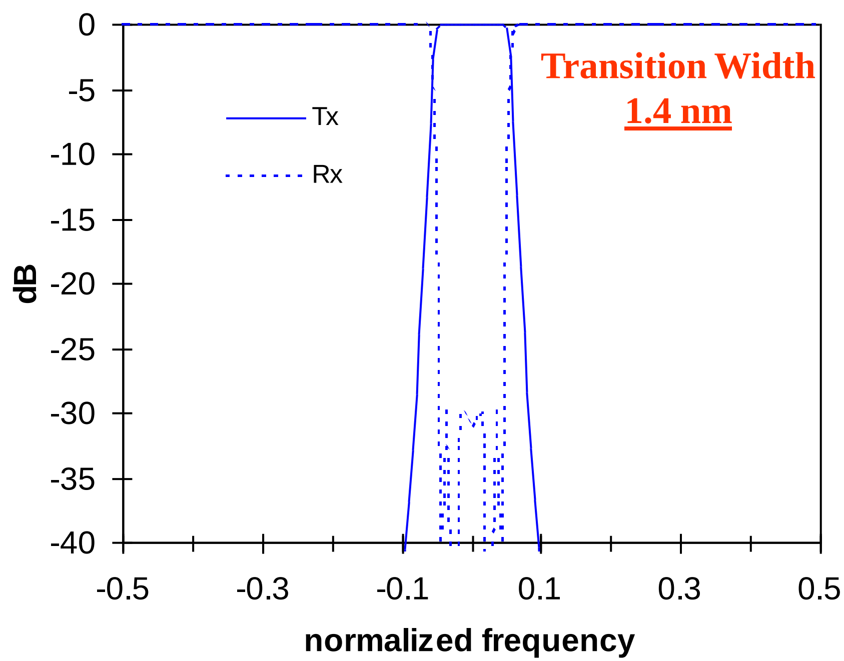
FSR=40 nm (L=40 μm for n_g=1.45)

FWHM=4 nm, 30 dB crosstalk rejection

8th Order Elliptic Filter



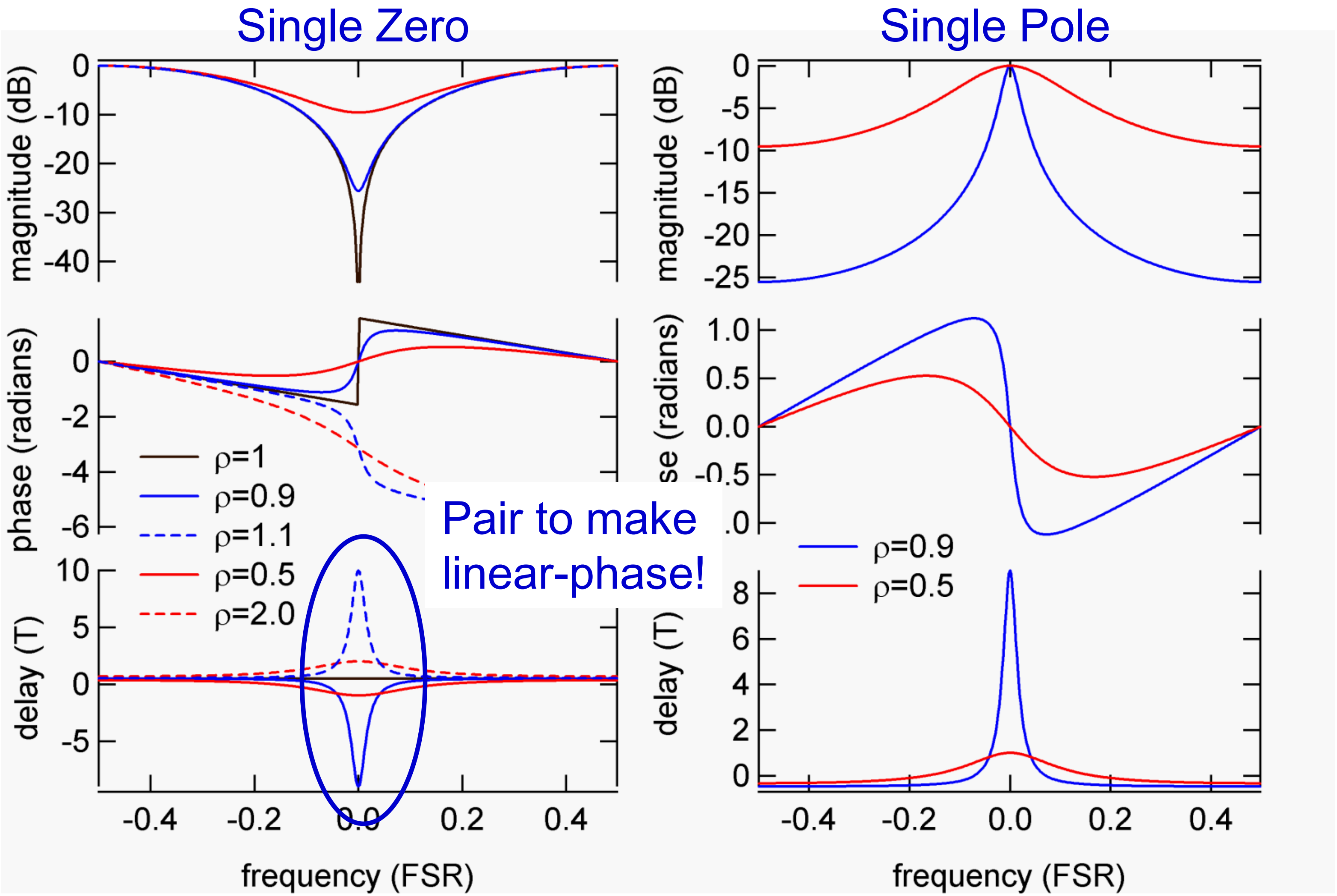
8-cavity Thin Film Filter



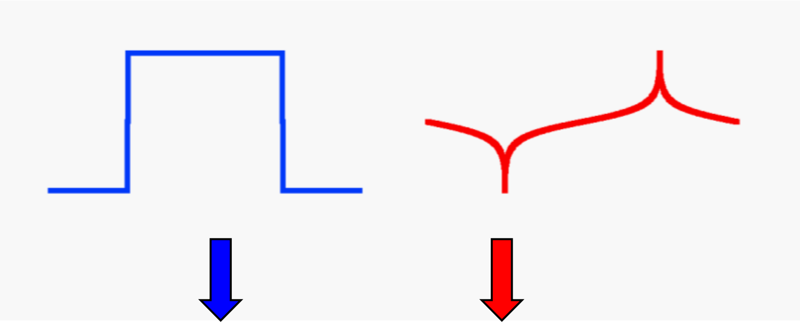
Transition width is 10x smaller for optimal pole/zero than all-pole filter!

Madsen, PTL, Aug. '98

Magnitude, Phase and Group Delay



Minimum-Phase Filters



$$\ln|H(\omega)| \Leftrightarrow \phi(\omega)$$

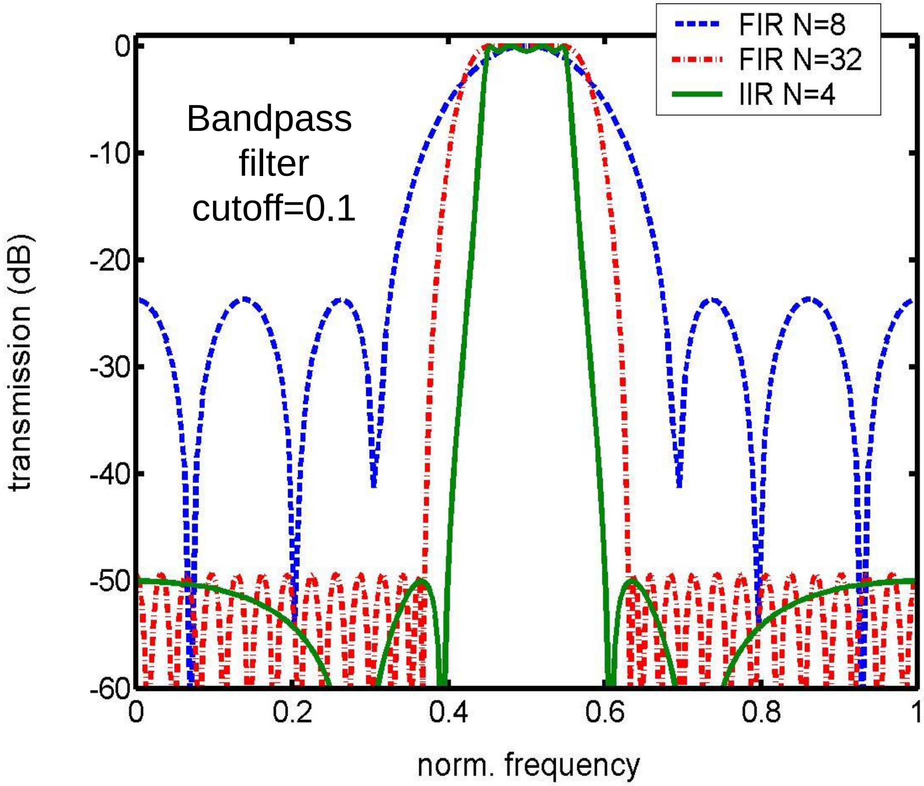
Hilbert transform pair - one *uniquely* determines the other

"Sharp corners" in $|H(\omega)|$ ➔ Nonlinear phase

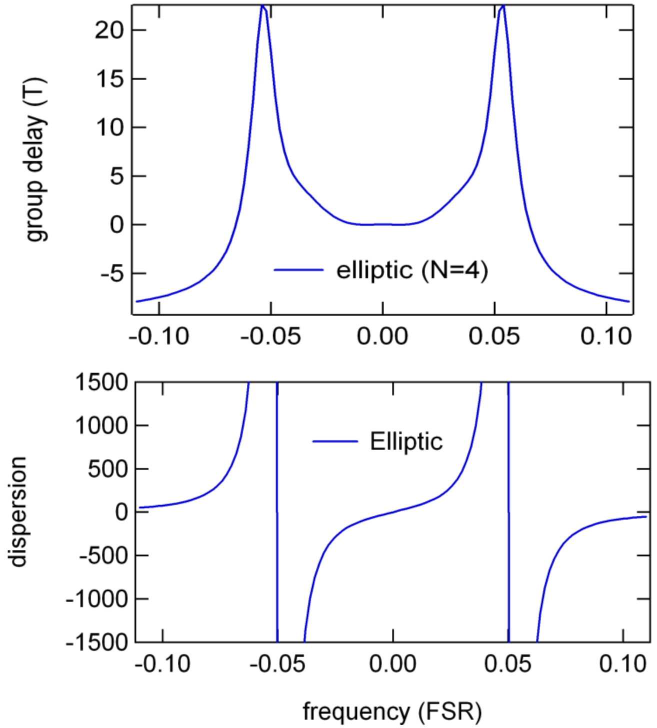
➔ Dispersion

Magnitude & phase satisfy Kramers-Kronig Relations

Comparison of FIR and IIR Bandpass Filters

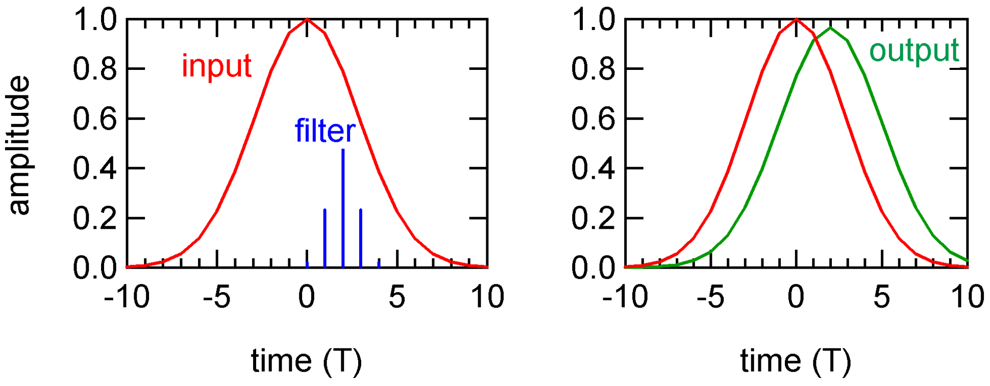


Nonlinear-phase response of IIR filter results in …



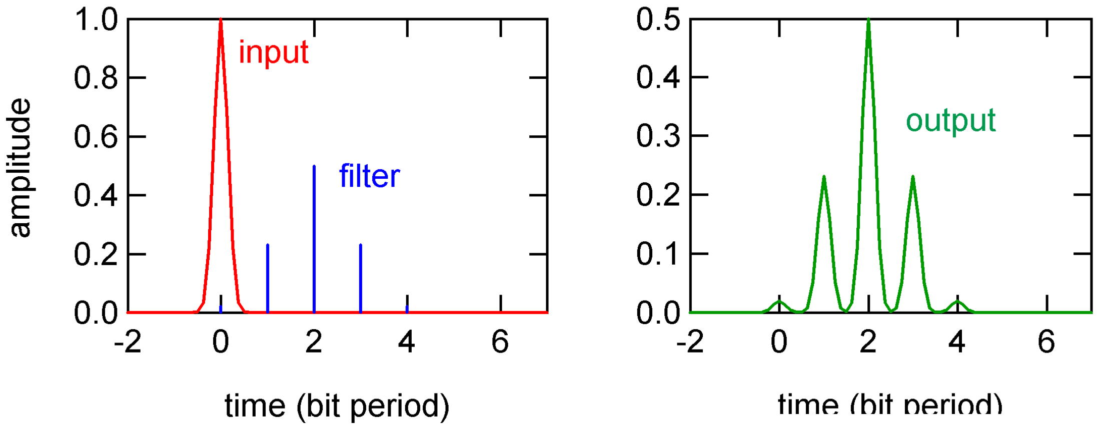
Feedback can produce sharp magnitude responses with only a few stages, but watch out for dispersion!

Input pulse width >> filter unit delay



Time Domain

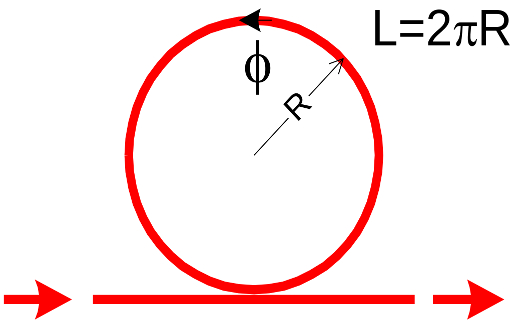
Filter unit delay >> Input pulse width

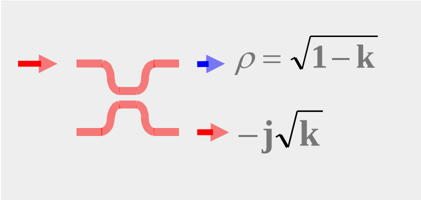


Time
Domain

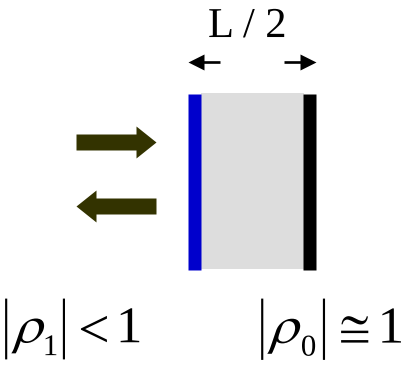
Optical Allpass Filters

Ring Resonator





Gires-Tournois Interferometer

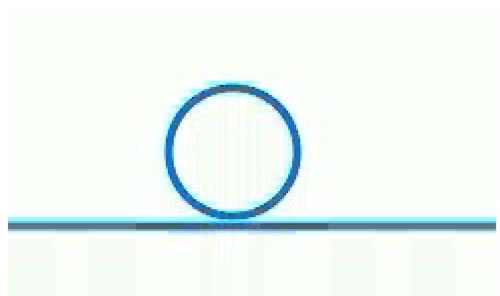


- Periodic frequency response (Free Spectral Range = one period)
- For a lossless filter, magnitude response = 1 (allpass!)

Filter unit delay : Input pulse width

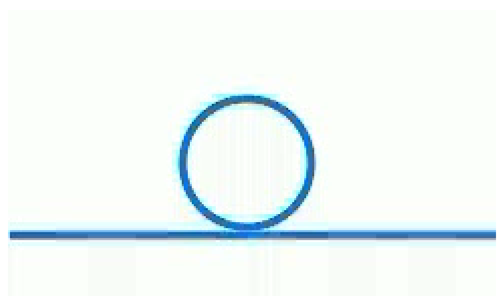
Allpass Filter Animation

Short pulse



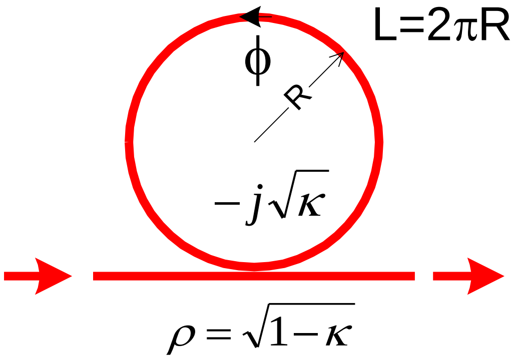
Interpulse filter

Long pulse



Intrapulse filter

Allpass Filter - Z Transform



Optical Transfer Function

$$A(z) \equiv \frac{Y(z)}{X(z)} = \frac{\rho - z^{-1}}{1-\rho\, z^{-1}}$$

⬅ zero

⬅ pole

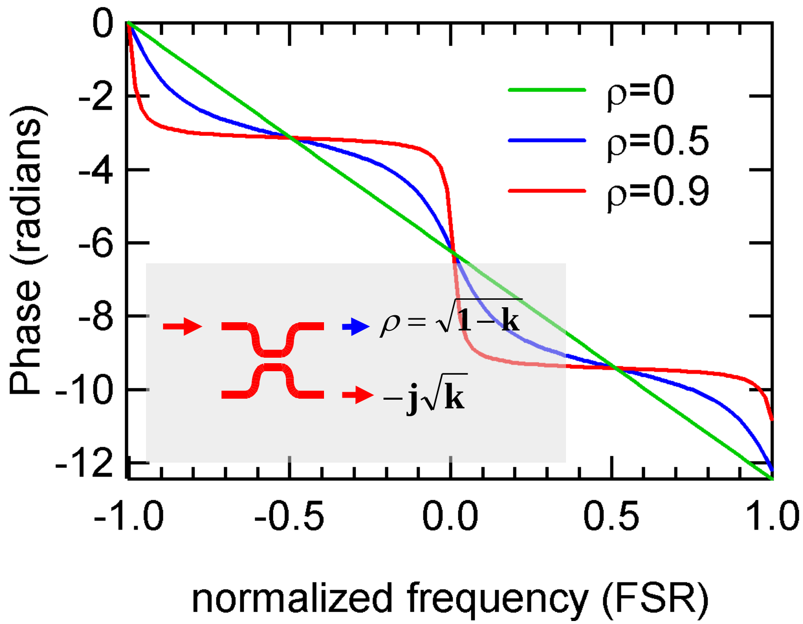
IIR Filter

Frequency Response

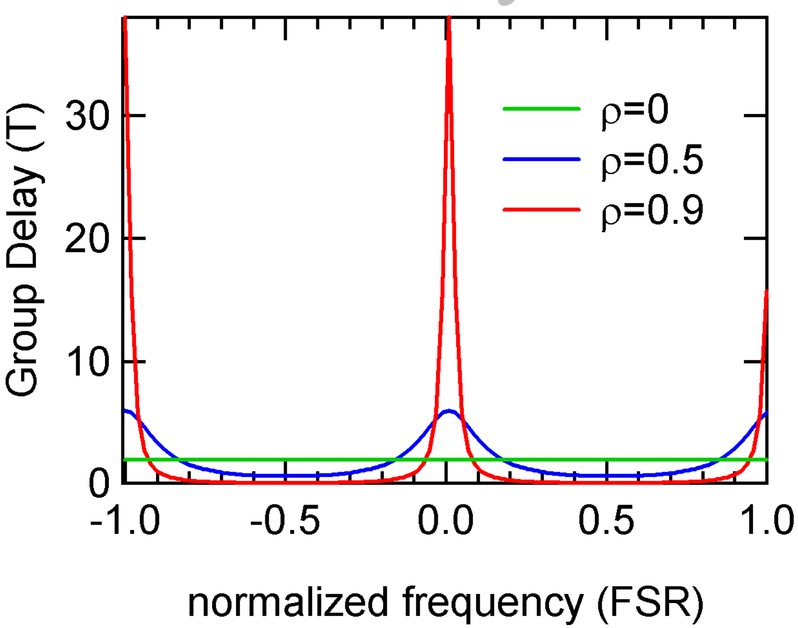
$$A(\omega) \equiv e^{j\Phi(\omega)}$$

Phase and Group Delay Response

Phase



Delay

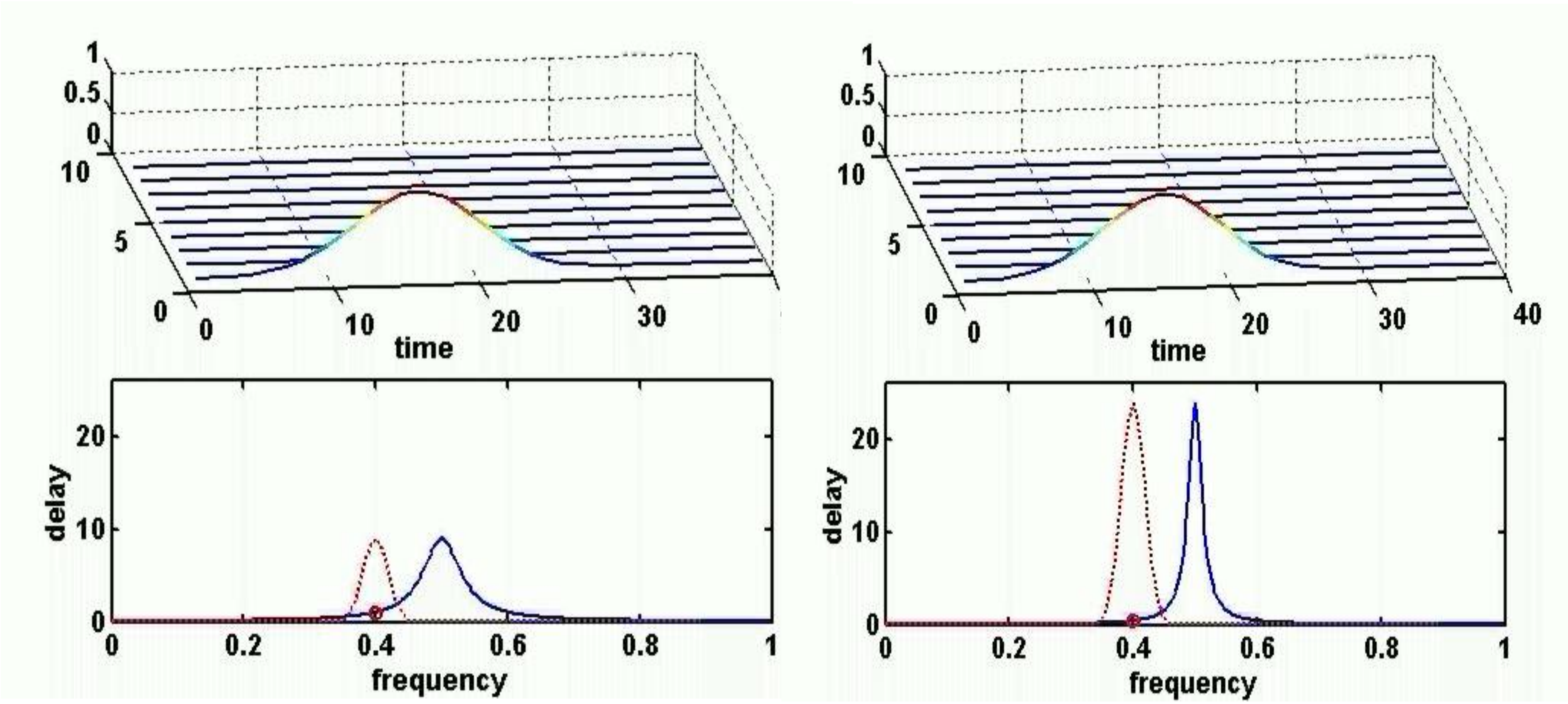


Group Delay $\tau_n = -\frac{d\Phi}{d\omega}$

Scaling: physical

Dispersion $D = \frac{d\tau_g}{d\lambda} = -c\left(\frac{T}{\lambda}\right)^2 D_n$ where $D_n = \frac{d\tau_n}{d\nu_n}$

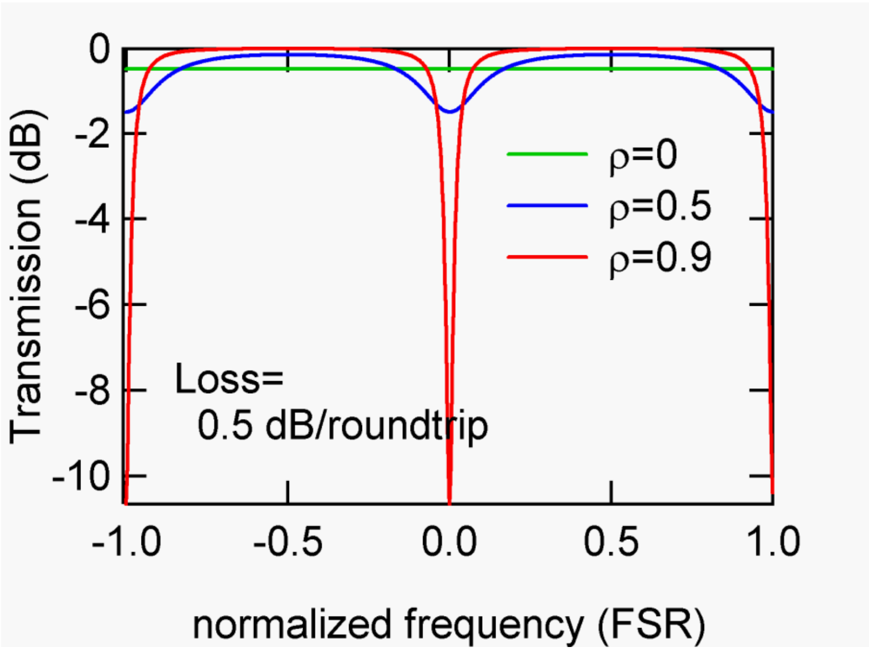
Gaussian Pulse Transmission

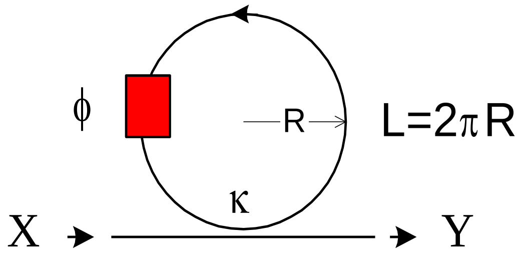


r=0.8 t_{fwhm}=10 r=0.92

Allpass Filter Magnitude Response

- For a <u>lossless</u> filter, magnitude response = 1 (allpass!)
- With loss, magnitude response depends on ρ





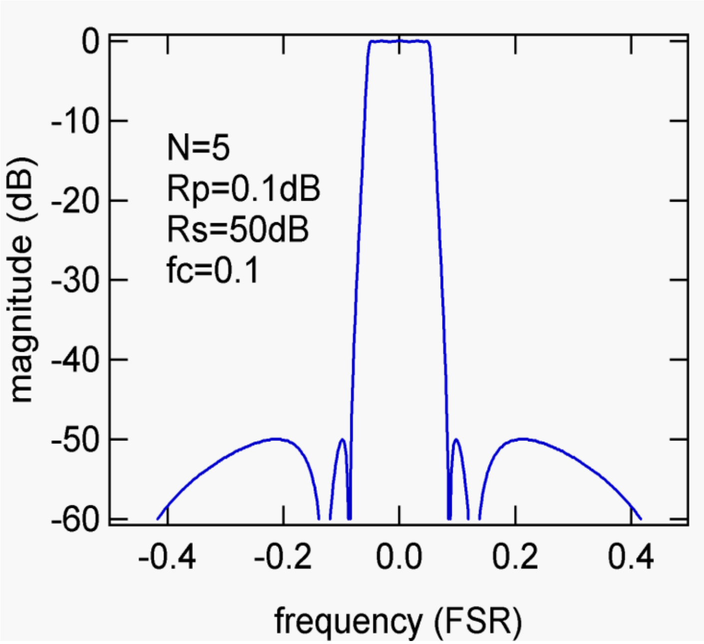
$$\rho = \sqrt{1-\kappa}$$

$$z^{-1} \rightarrow \gamma\, z^{-1}$$

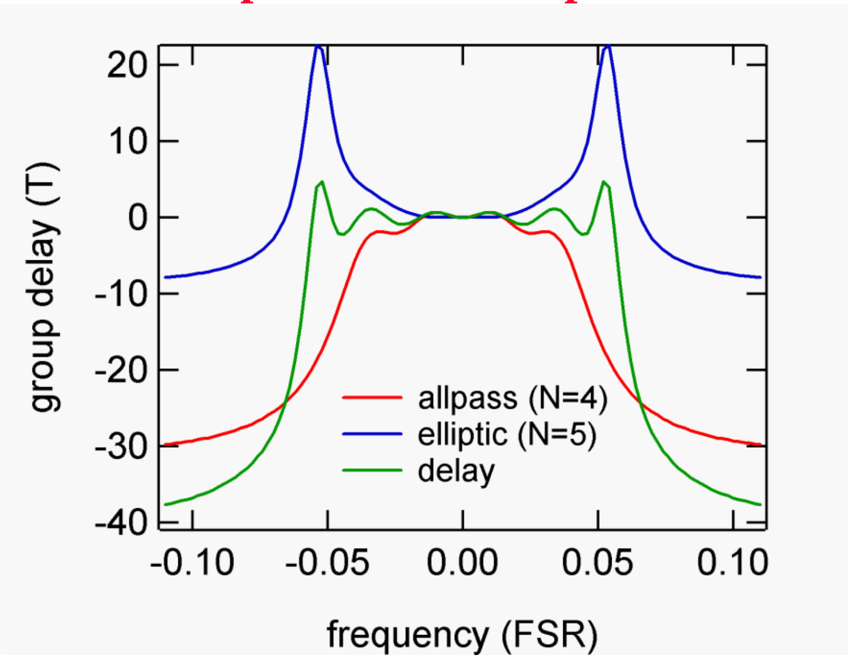
$$H(z) = \frac{\rho - \gamma z^{-1}}{1 - \rho\, \gamma z^{-1}}$$

Elliptic Filter with Dispersion Compensation

5th-Order Elliptic Filter Magnitude Response



Group Delay with & without Allpass Filter Compensator



Typically optimize for desired response (e.g. magnitude, delay), trading off with complexity (#stages)

Optical Filter Theory Concepts

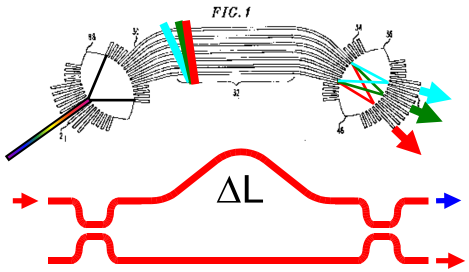
- Lumped element, normalized Z-transform design

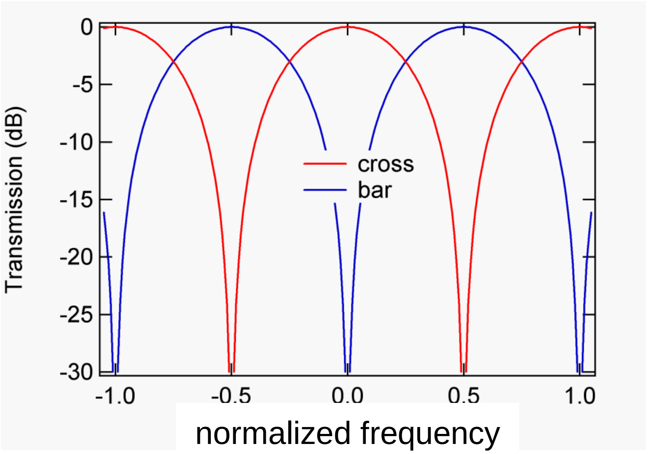
  easily calculate magnitude and phase response
- FIR versus IIR filters (weak IIR $\Rightarrow$ FIR)
- Min-, max- and linear-phase (uniqueness, dispersion)
- Causality: Hilbert transform relates Re and Imag parts

  min-phase: Hilbert transform relates mag and phase response
- Power complementary outputs if unitary (lossless)
- Filter synthesis $\Rightarrow$ nonlinear approximation problem

Optical Filter Toolbox (I)

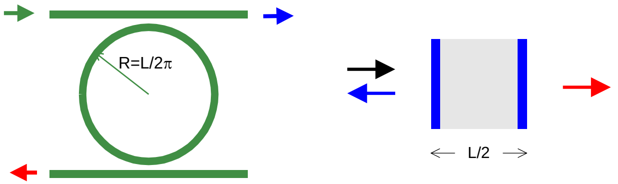
All-Zero (Mach-Zehnder)
Finite impulse response (FIR)
Feed-forward interference

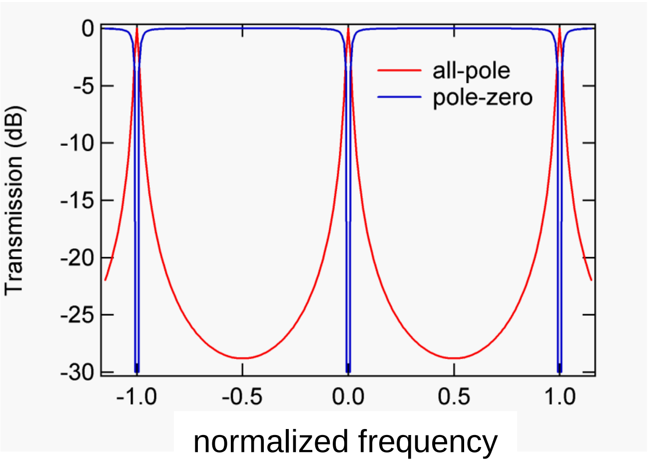




- symmetric ⇒ dispersionless
- path length difference ⇒ FSR

All-Pole (Fabry-Perot)
Infinite impulse response (IIR)
Feed-back interference

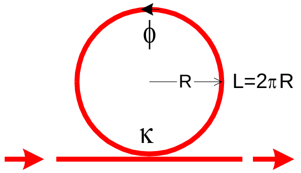


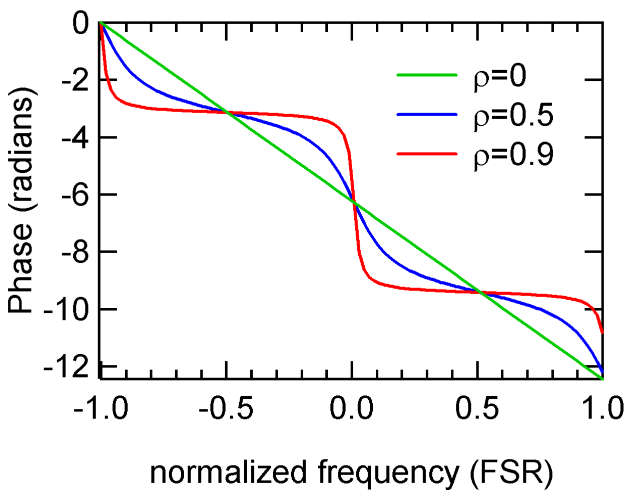


- dispersive (all-pole=min-phase)
- large FSR ⇒ short feedback path!

Optical Filter Toolbox (II)

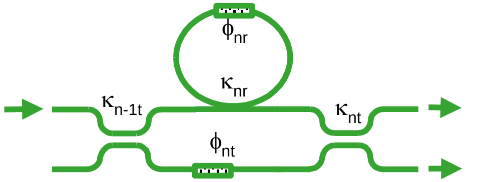
Feed-forward + feedback Allpass Filter

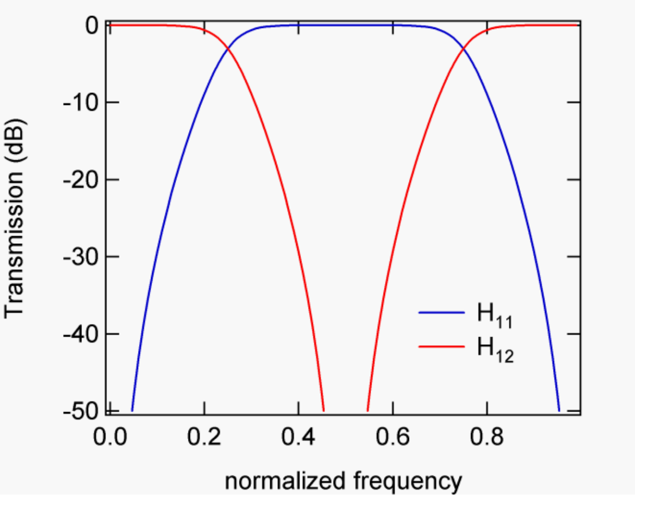




- phase engineering
- dispersion compensation

Feed-forward + feedback Pole-Zero Filter





- Chebyshev, elliptic, Butterworth
- PMD compensation

For an overview, see Madsen & Zhao, Optical Filter Design and Analysis, Wiley'99

Optical Filter Technologies

Temperature Dependence

Dispersion

Polarization Dependence

In theory, there is no difference between theory and practice. But, in practice, there is.

-- Jan L.A. van de Snepscheut

Loss

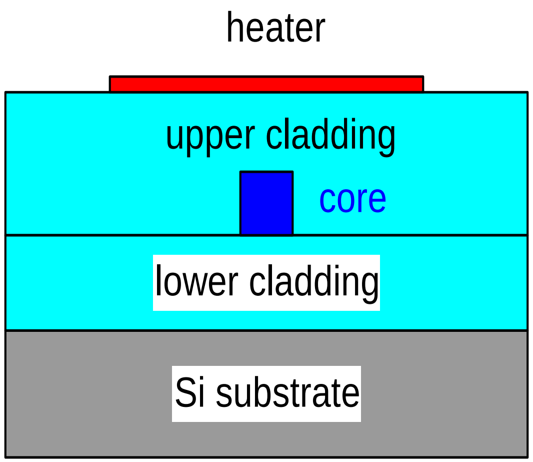
Manufacturability

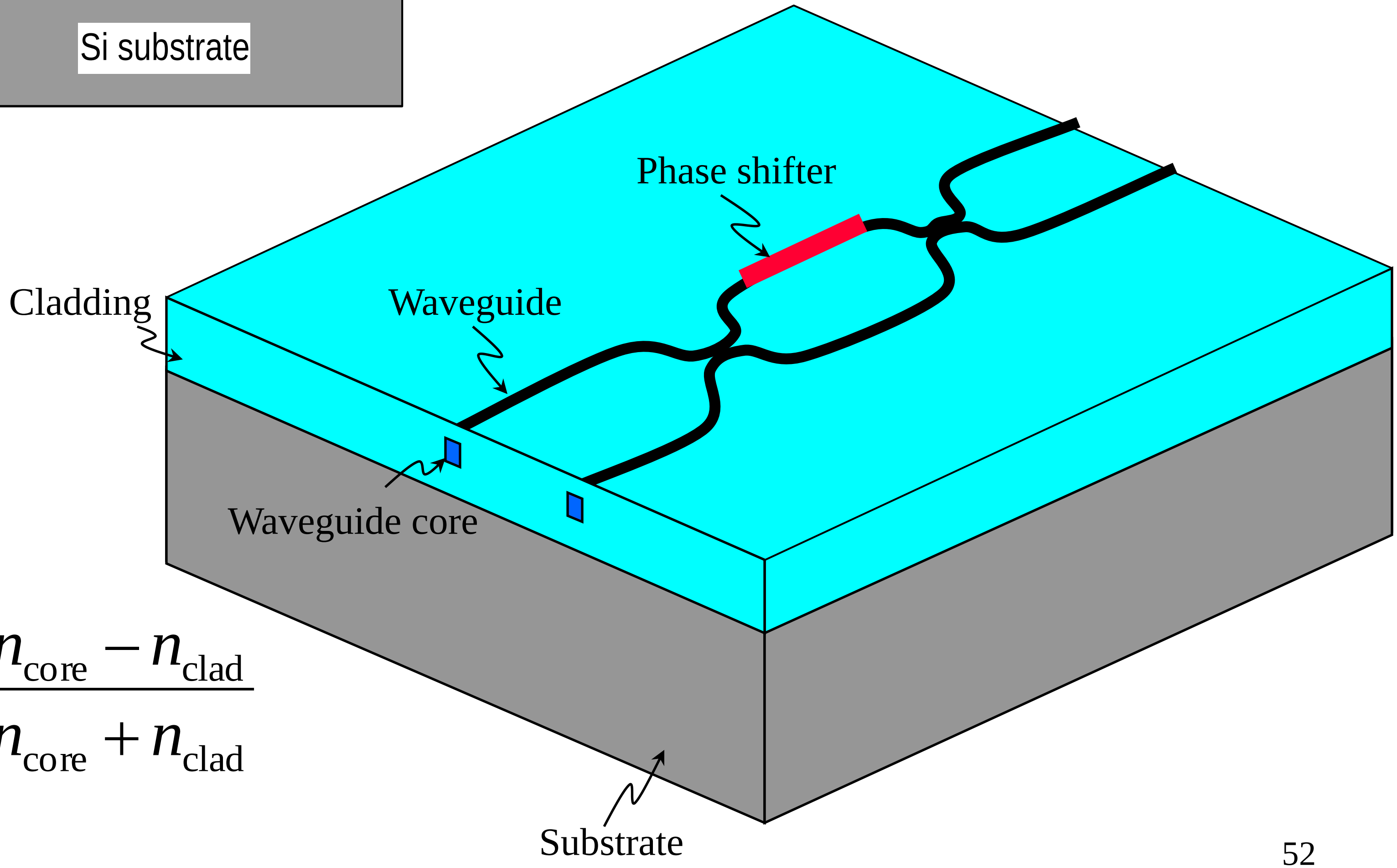
Scalable

Tunable

Integration

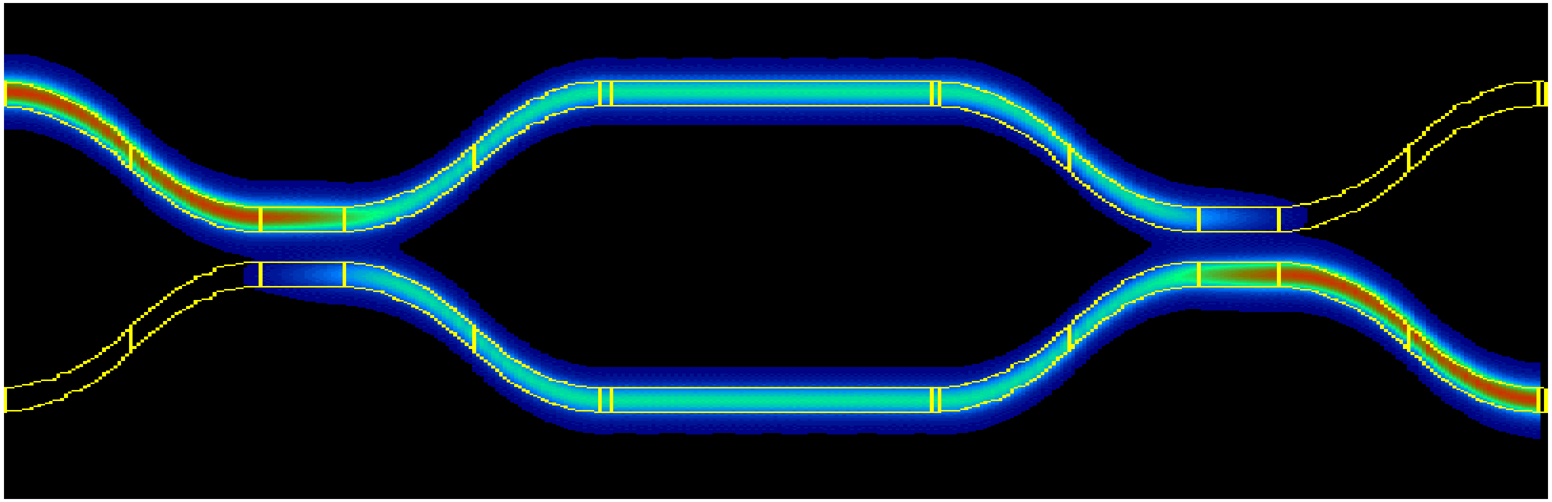
Integrated Optical Waveguides: Cross-Section





$$\Delta \equiv 2\frac{n_{\mathrm{core}} - n_{\mathrm{clad}}}{n_{\mathrm{core}} + n_{\mathrm{clad}}}$$

Mach-Zehnder interferometer



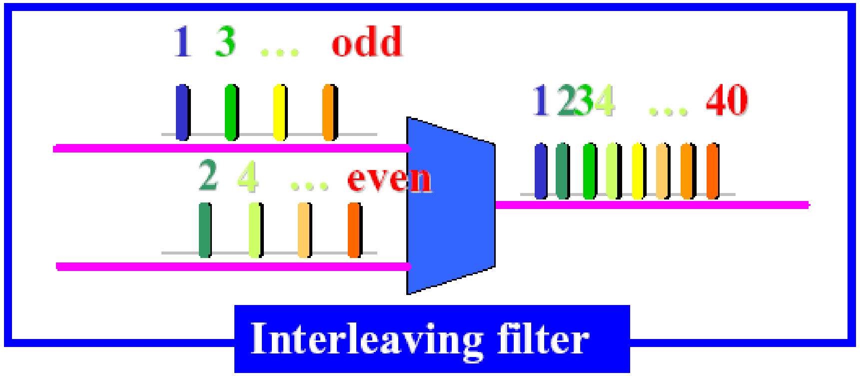
Vary phase in one arm relative to the other

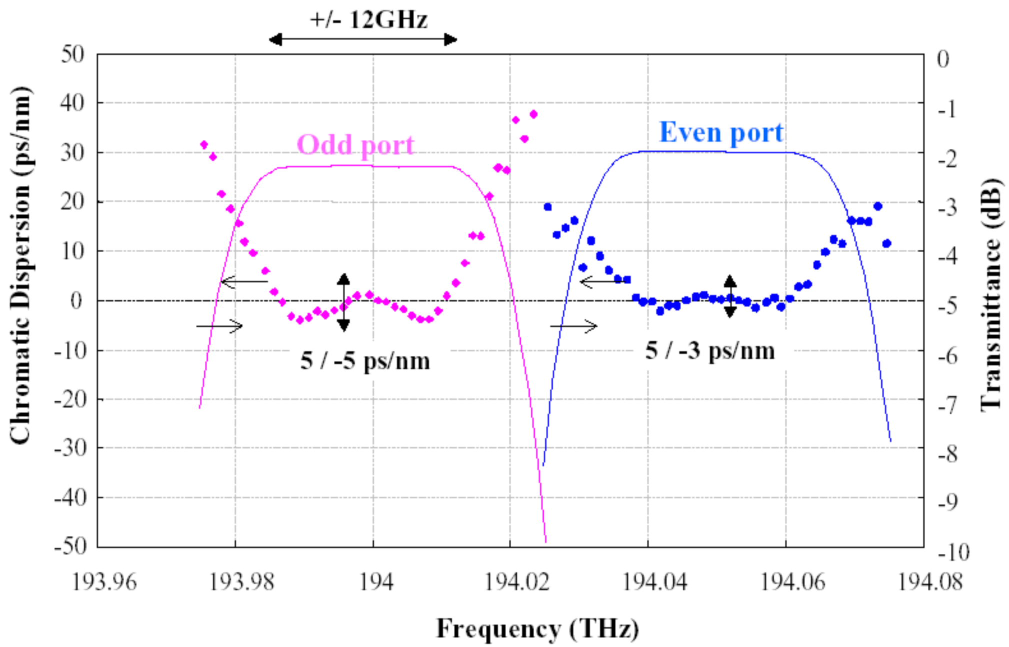
Variable coupler

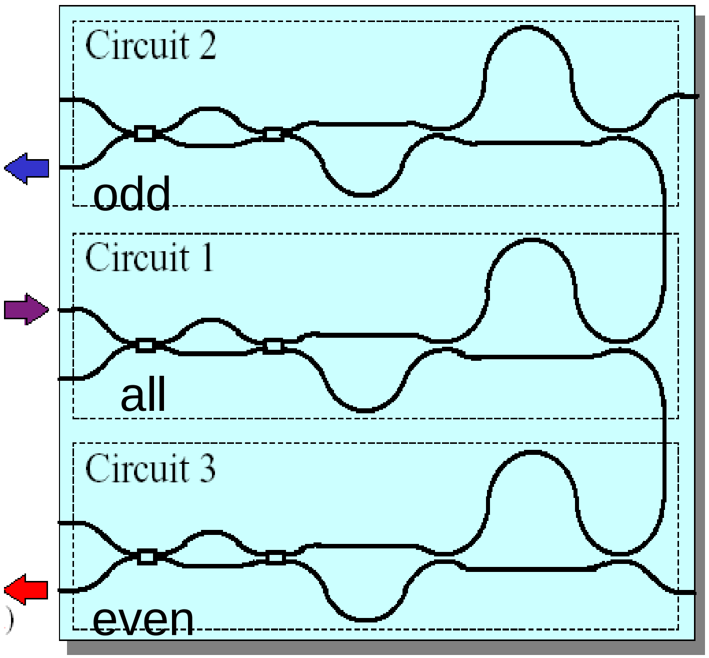
Variable attenuator

1x2 and 2x2 switch

“Fourier Filter” Low-dispersion Interleaver

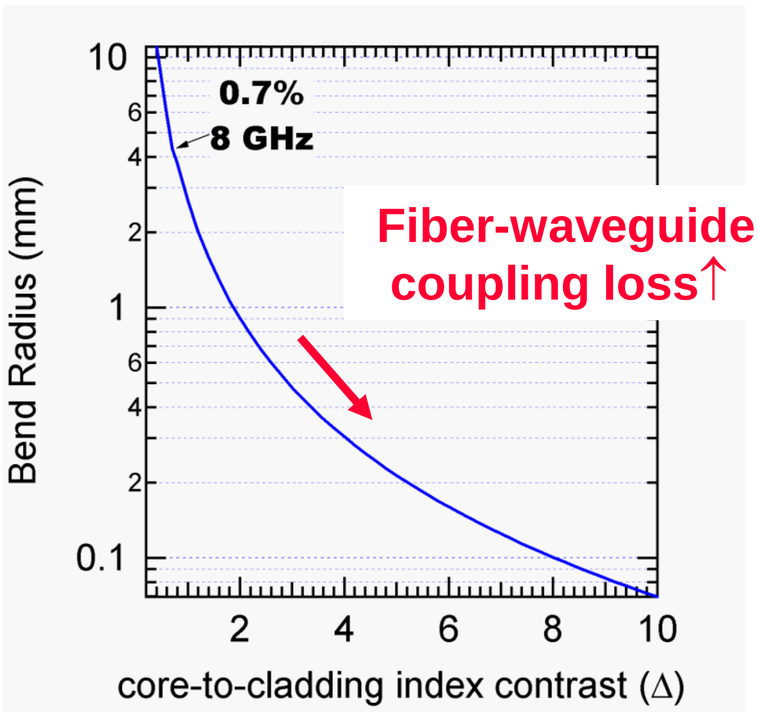


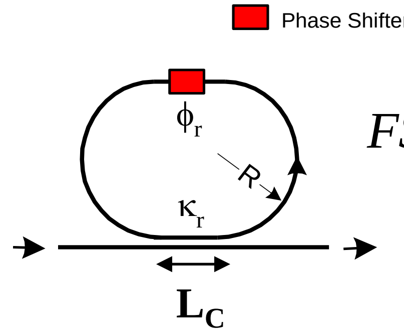




T. Chiba, et. al., OECC 2000. *Fourier Filter: Y. P. Li, et. al., Electron. Lett., 1995.*

Index Contrast and Bend Radius





$$FSR = \frac{c}{n_g L}$$

Rings

FSR (GHz)	L (mm)
8	25
12.5	16
25	8
50	4
100	2

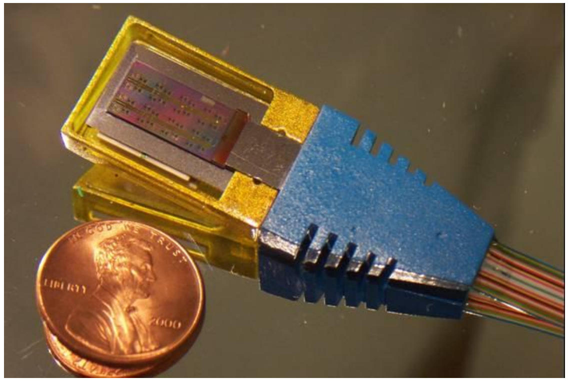
$$L = 2\pi R + 2 L_C$$

coupler lengths must shrink, too!

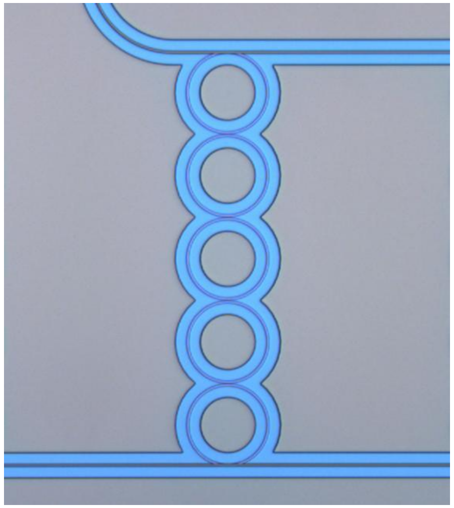
For large FSRs, rings need hi-index contrast

Micro-ring Resonator Filters

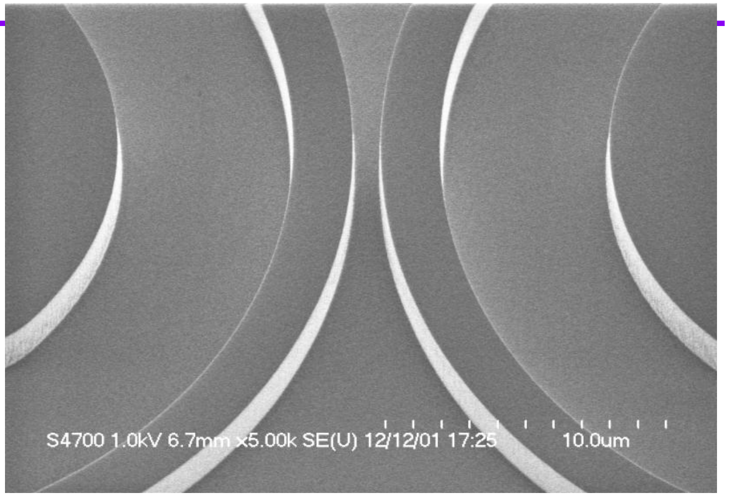
Higher Order Filters



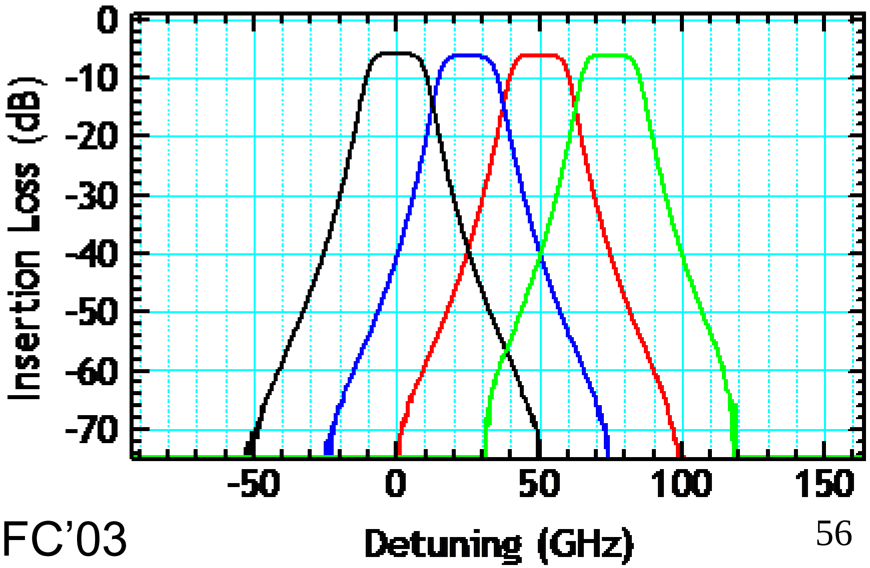
5th Order



SEM of Gap



Tunable 5th Order μring filter



Little, OFC'03

Dispersion via Taylor Series Expansion

$$\beta(\Omega_c + \Delta\Omega) \approx \beta(\Omega_c) + \beta'\Delta\Omega + \frac{1}{2!}\beta''\Delta\Omega^2 + \frac{1}{3!}\beta'''\Delta\Omega^3 + \cdots$$

Delay — Quadratic dispersion — Cubic dispersion

Phase

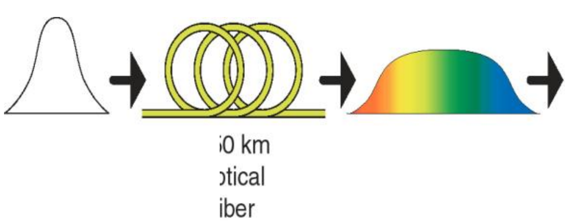
$$\Phi = -\beta L$$

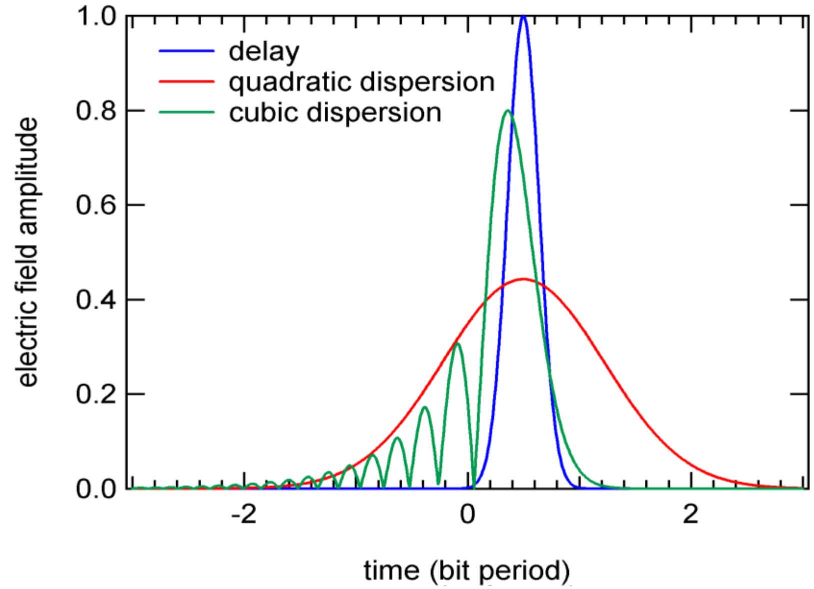
Delay

$$\tau_g \equiv -\frac{d\Phi}{d\Omega}$$

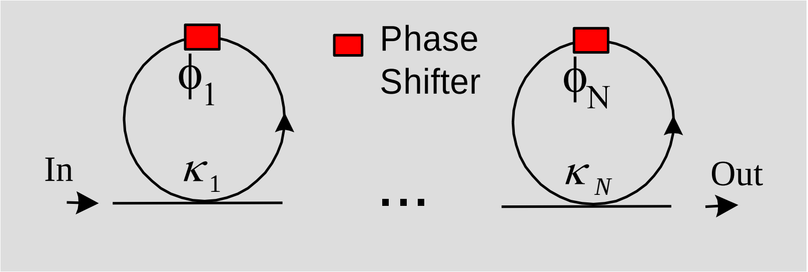
Dispersion (ps/nm)

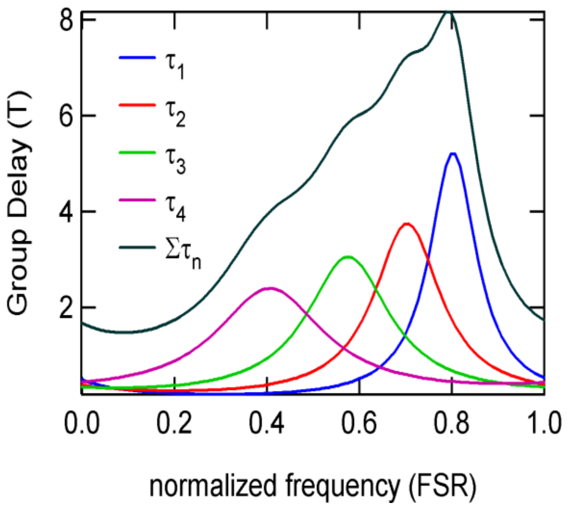
$$D \equiv \frac{d\tau_g}{d\lambda}$$





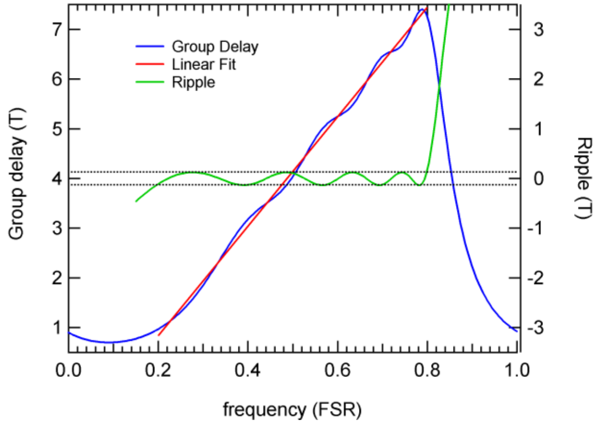
Multi-Stage Group Delay





Nonlinear design optimization

- bandwidth utilization
- dispersion
- group delay ripple



Favors High Spectral Efficiency!

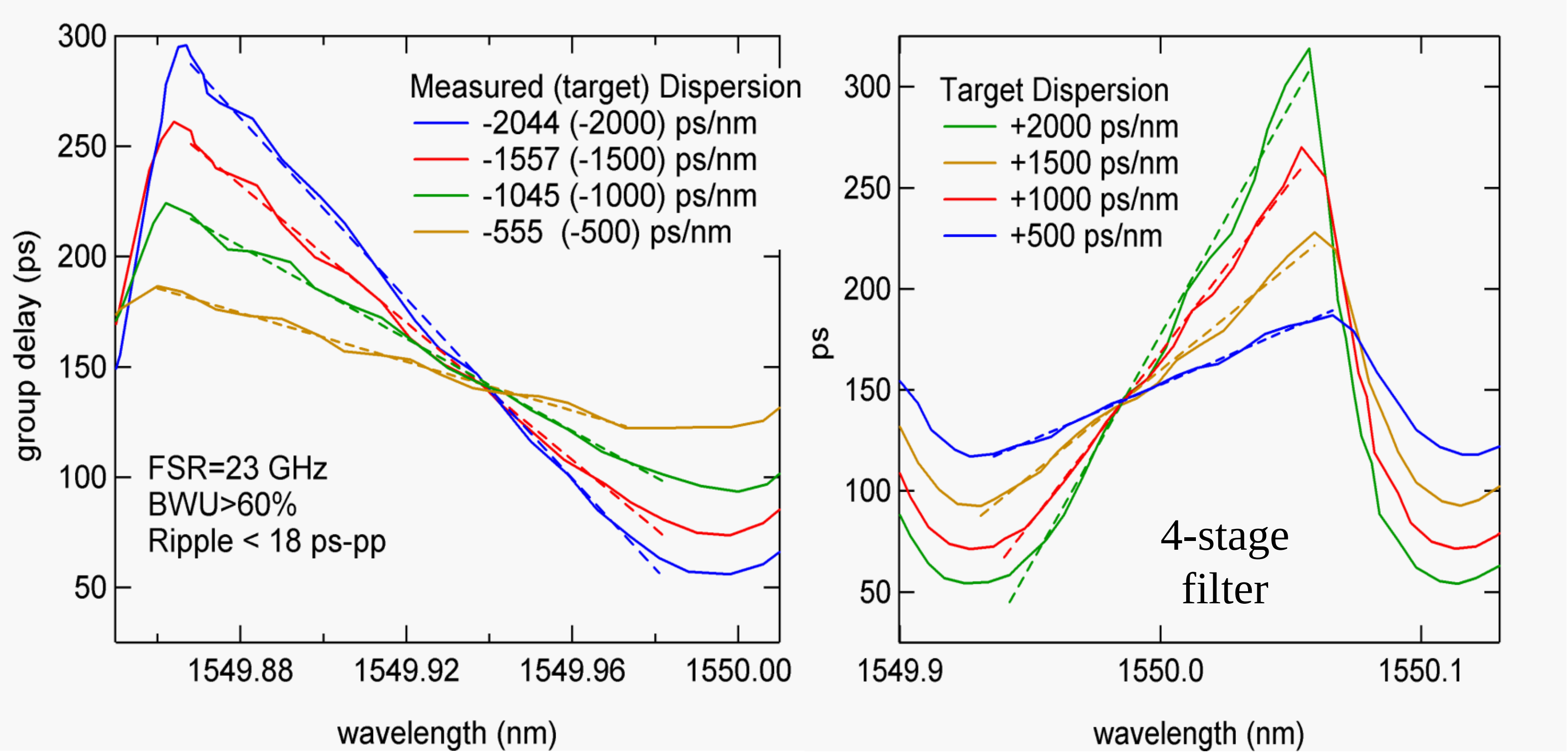
Theoretically lossless

Precisely tune two variables/stage

Madsen & Lenz, PTL '98

US Patent 6289151

Continuous Dispersion Tuning: Measurement Results



Δ=2% SiO_2 waveguides
bend radius~1 mm
2 thermo-optic phase shifters/stage

0.4 dB/feedback path
0.8 dB/facet coupling loss to SSMF
(without optimization)

Madsen, et al, OFC'01, PD9

Filters in Optical Sensing

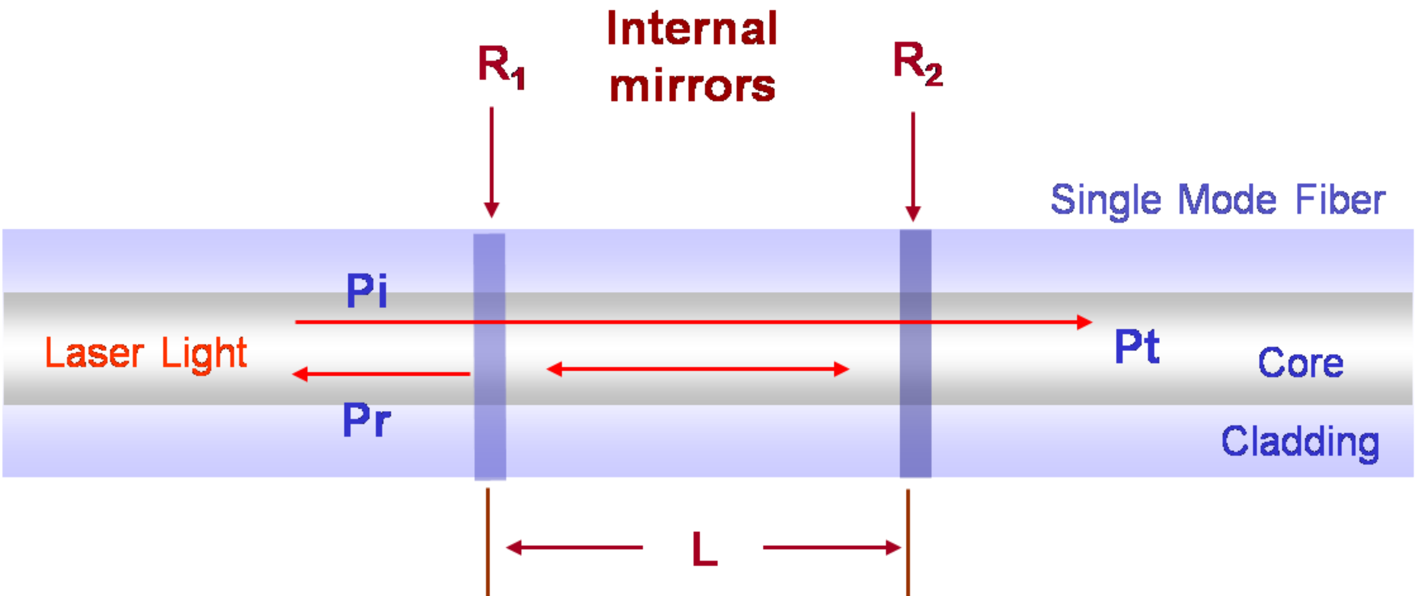
FIR Filters

- Weak reflectors in Fabry Perot
- Sensing applications

IIR Filters

- Thin film etalons
- Ring resonators

Fiber Fabry-Perot Interferometer (FFPI)



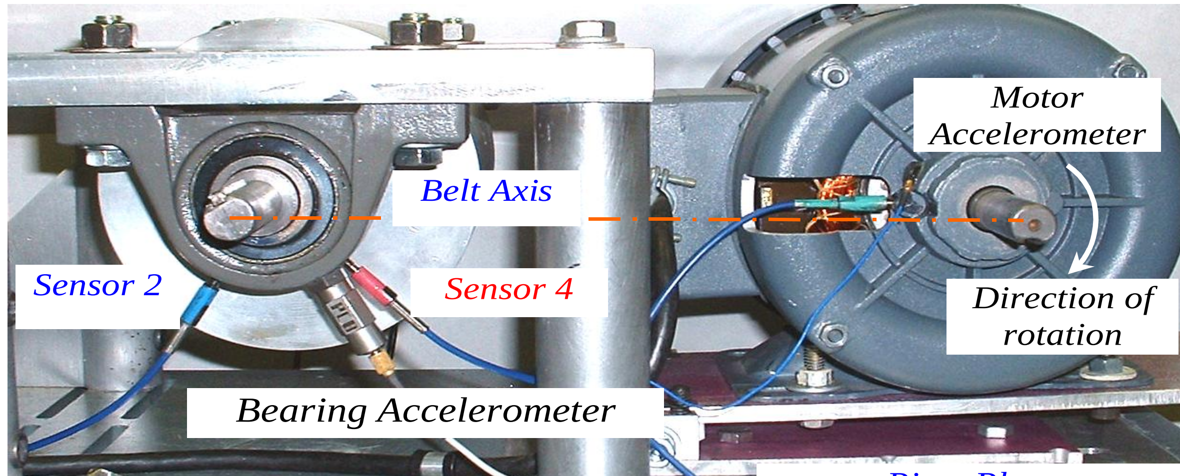
$$R_{FP} = \frac{P_r}{P_i} = R_1 + R_2 + 2\sqrt{R_1 R_2}\cos\phi \quad \text{where } \varphi = \frac{4\pi nL}{\lambda}$$

P_r: Reflected optical power, P_i: Incident optical power

ϕ: round-trip optical phase shift, mirror reflectance R_1, R_2 << 1.

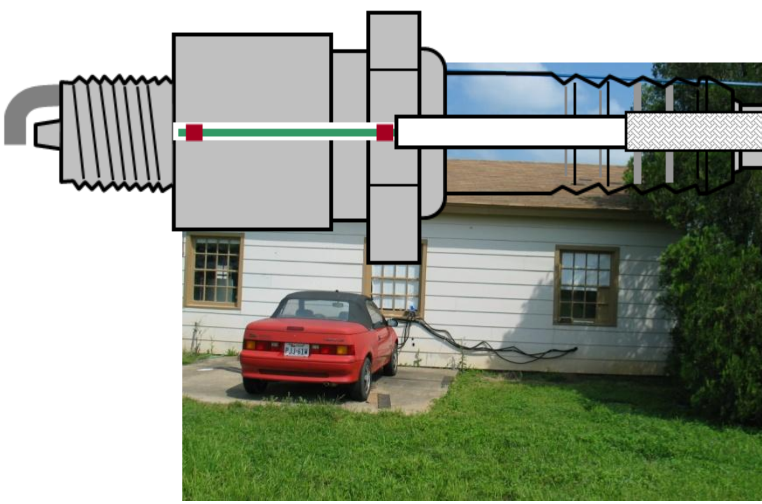
If $R = R_1 = R_2$, then $$R_{FP} = \frac{P_r}{P_i} = 2R(1+\cos\phi)$$

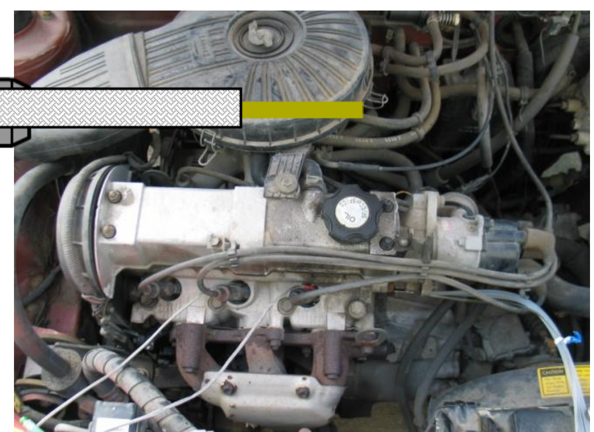
Applications of the FFPI



Test Set Up

Pivot Plate

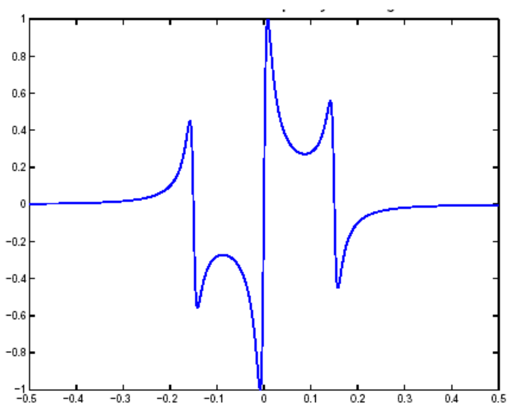


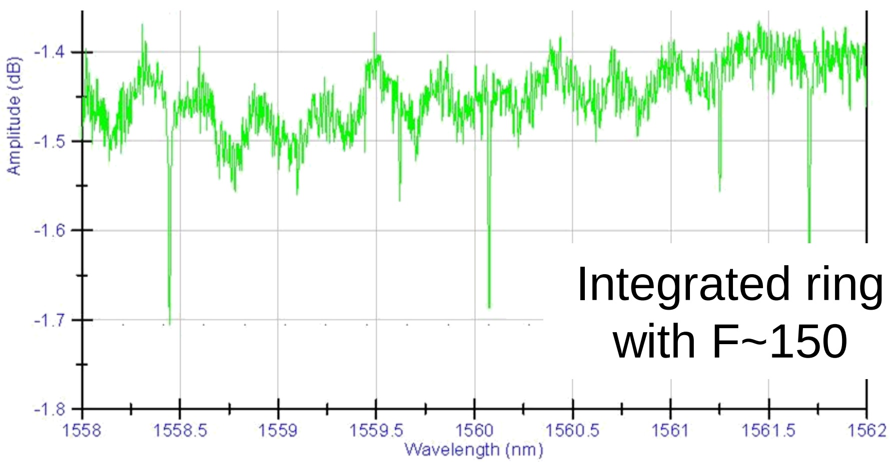


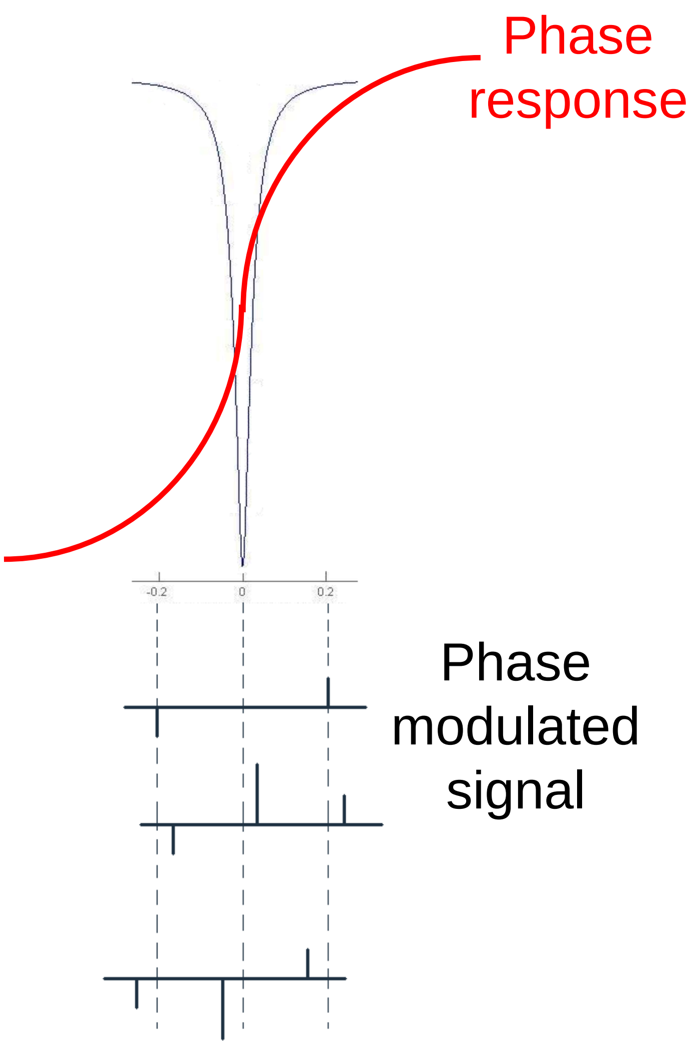
High-finesse (Narrow Bandwidth) Sensors

Pound-Drever-Hall Method

Error signal

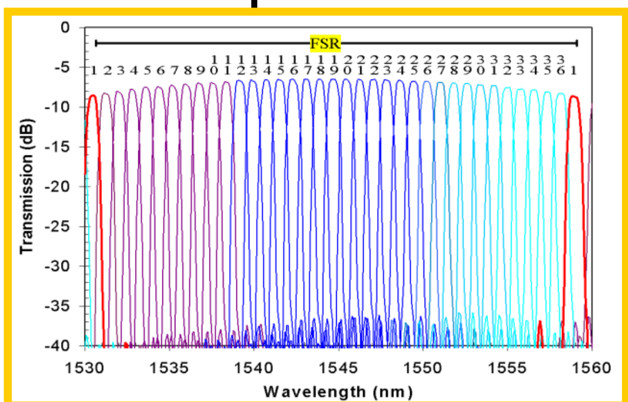




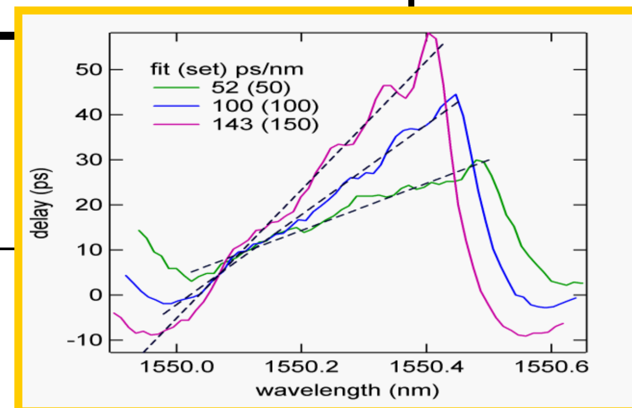


Bandwidth Processing Engines

Technology	Bandwidth	Tunable or Adaptive
	Baseband	
	Octave(s)	
Optical	Decades!	Low to Hi-speed



10-100's THz



Sub- to 10's GHz

Lots of potential!

References

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