Advanced Micro Ring Resonator Filter Technology

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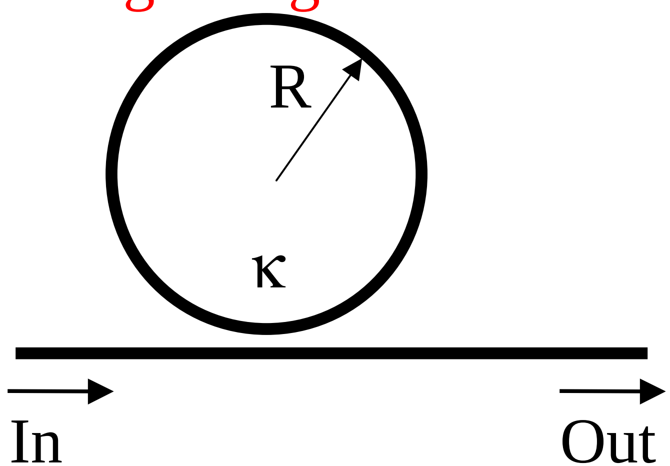
All-Pass Filters

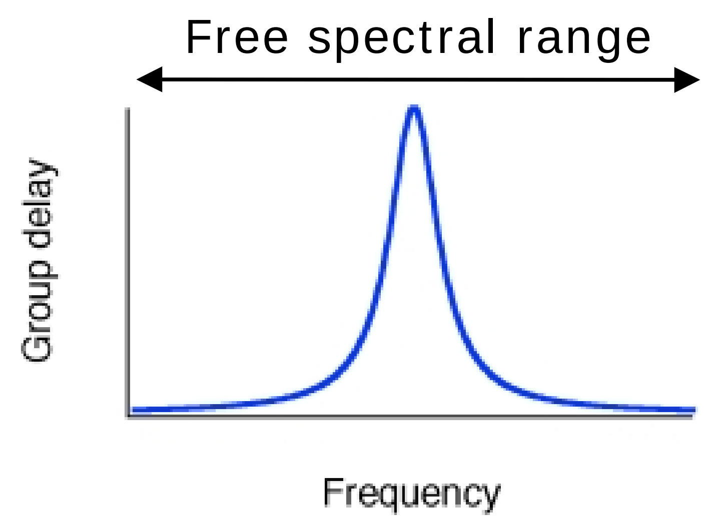
$$|H(\omega)| = 1$$

$$\phi(\omega) = arbitrary$$

- *Phase equalization*
- *Dispersion compensation*
- *Optical delay line*

Single stage APF





Mathematical Form

$$H(\omega) = \prod_{n=0}^{N-1} \frac{e^{j\omega} - z_n}{e^{j\omega} z_n^* - 1} = \prod_{n=0}^{N-1} \frac{e^{j\omega} - r_n e^{j\theta_n}}{e^{j\omega} r_n e^{-j\theta_n} - 1}$$

$$\boxed{|H(\omega)| = 1}$$

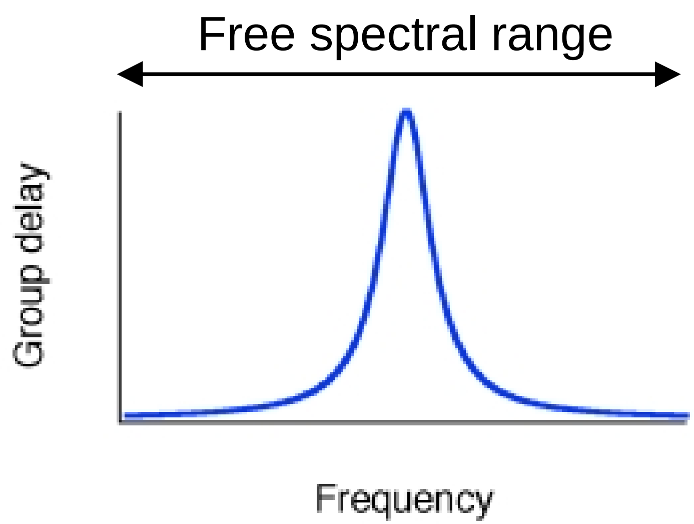
$$\boxed{\phi(\omega) = \sum_{n=0}^{N-1} Arg\left[\frac{e^{j\omega} - z_n}{e^{j\omega} z_n^* - 1}\right]}$$

Phase equalization without amplitude distortion

Group Delay

$$\tau(\omega) = \sum_{n=0}^{N-1} \frac{\sinh \chi_n}{\cosh \chi_n - \cos(\omega - \theta_n)}$$

$$\chi_n = \ln r_n$$

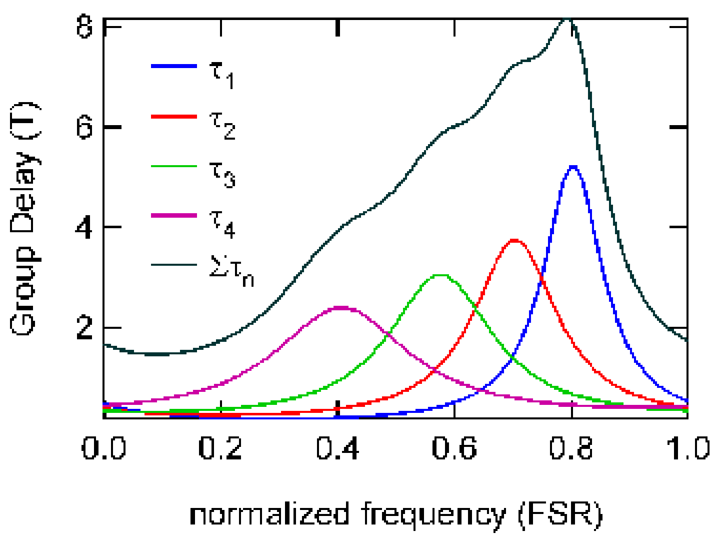


$$D(\omega) = \frac{d\tau(\omega)}{d\omega} \propto \frac{1}{FSR^2}$$

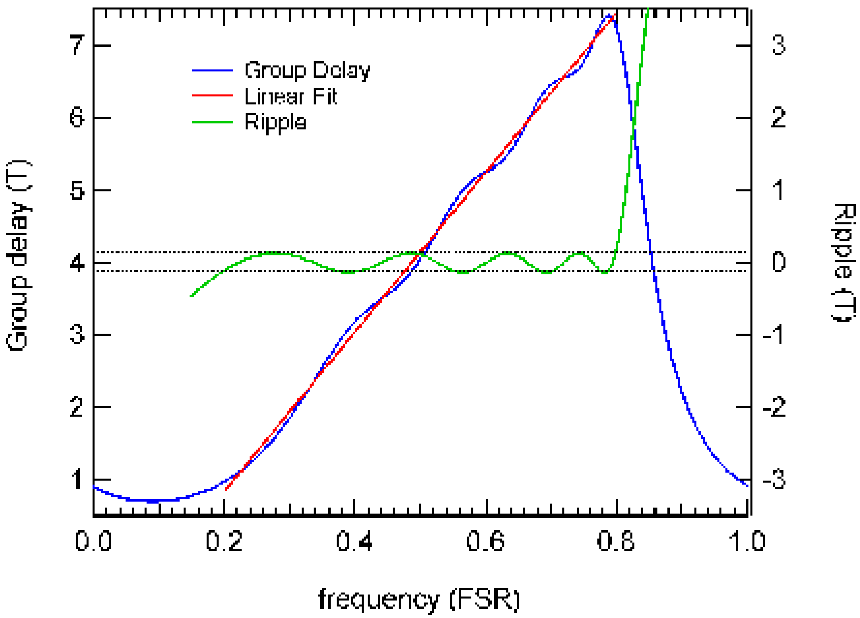
Larger FSR ⇒ smaller dispersion; More stages ⇒ more dispersion

Four-Stage All-Pass Filter

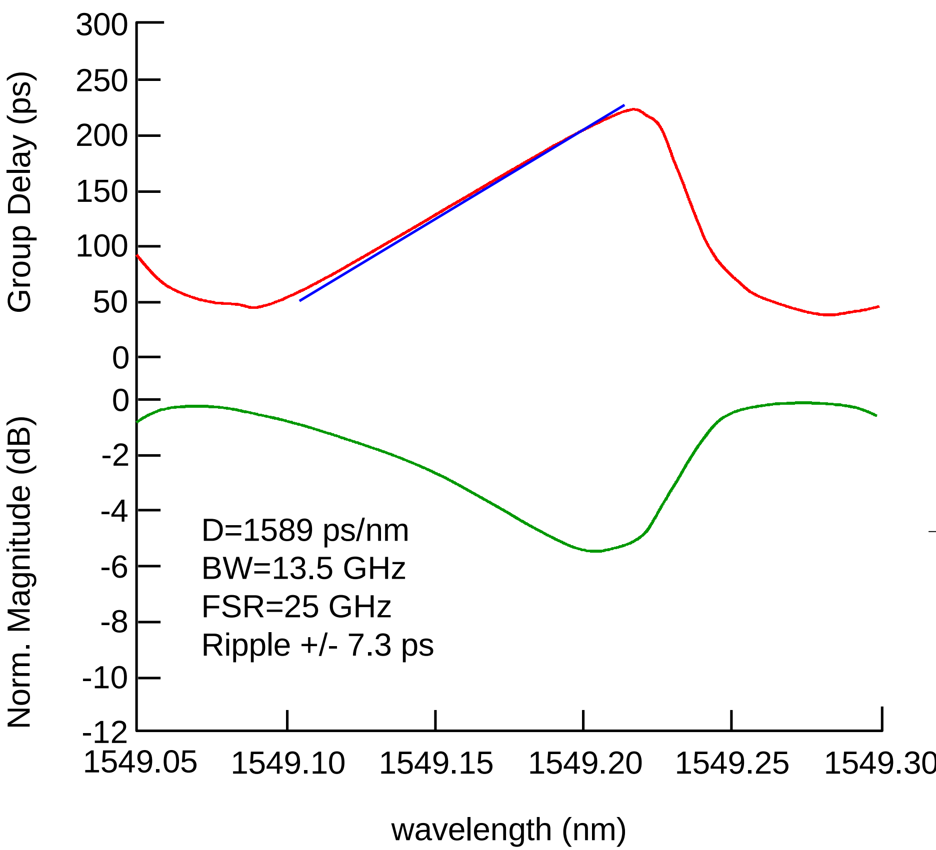
Approximation of Linear group delay across pass band



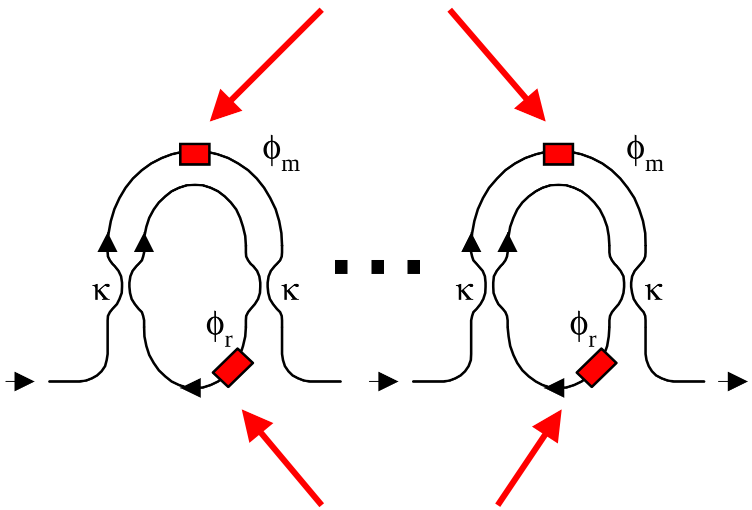
Equi-ripple design



Four-Stage All-Pass Filter Experimental



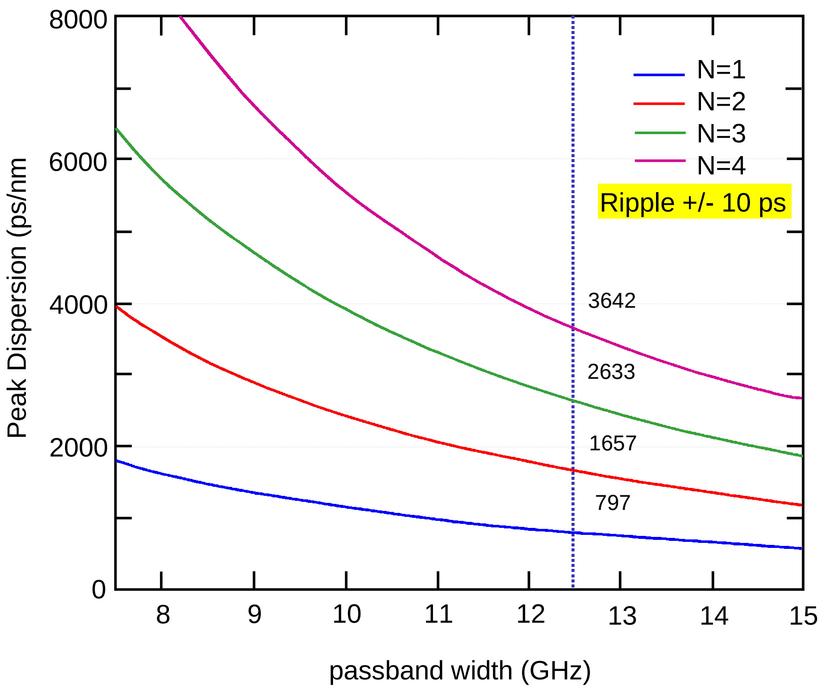
Heaters → phase shift
(tunable coupling)



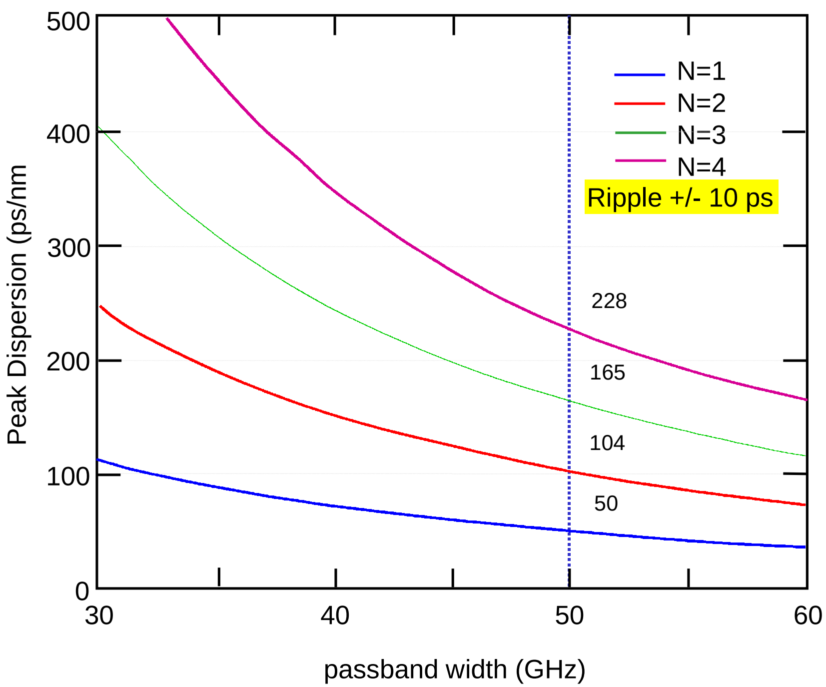
Heaters → phase shift
(tunable peak position)

Dispersion vs. Bandwidth Tradeoff

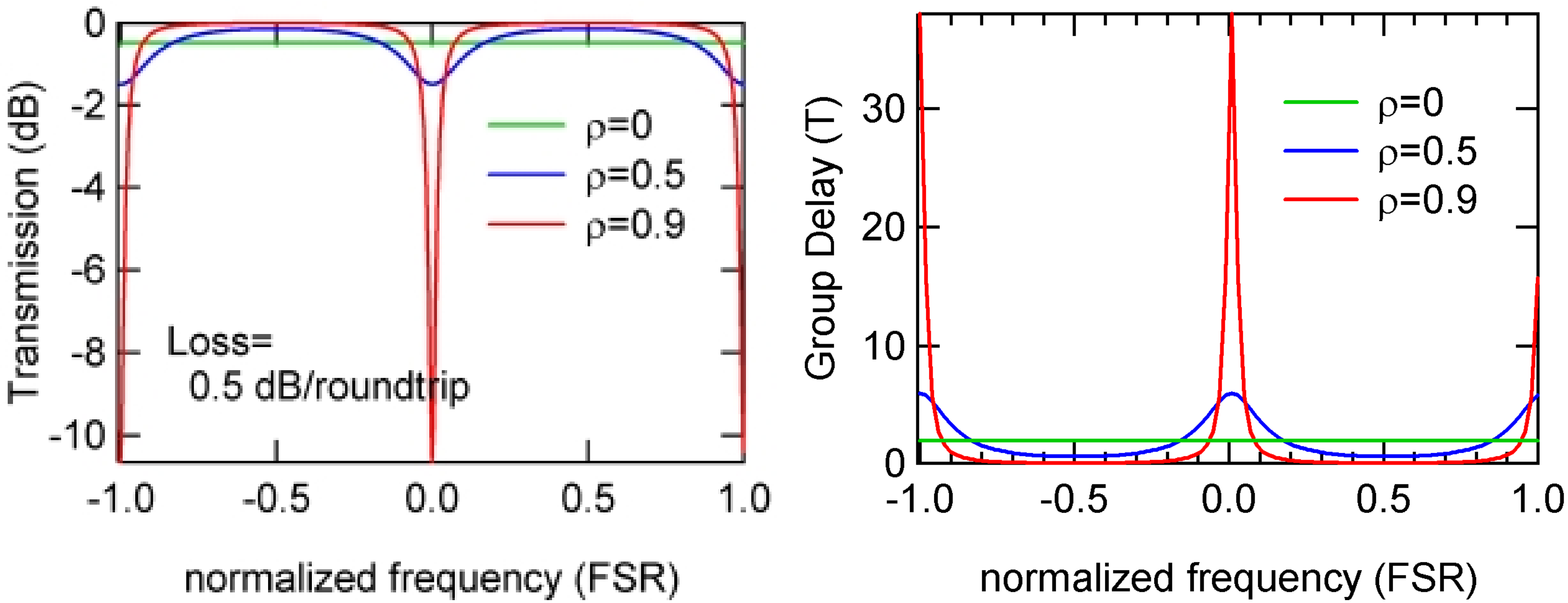
25 GHz Channel Spacing



100 GHz Channel Spacing

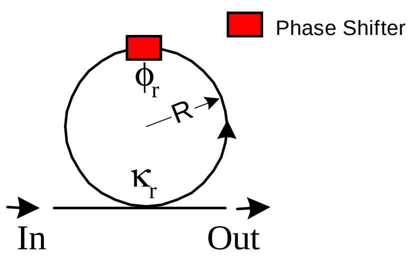


All-Pass Filter - Effect of Finite Loss



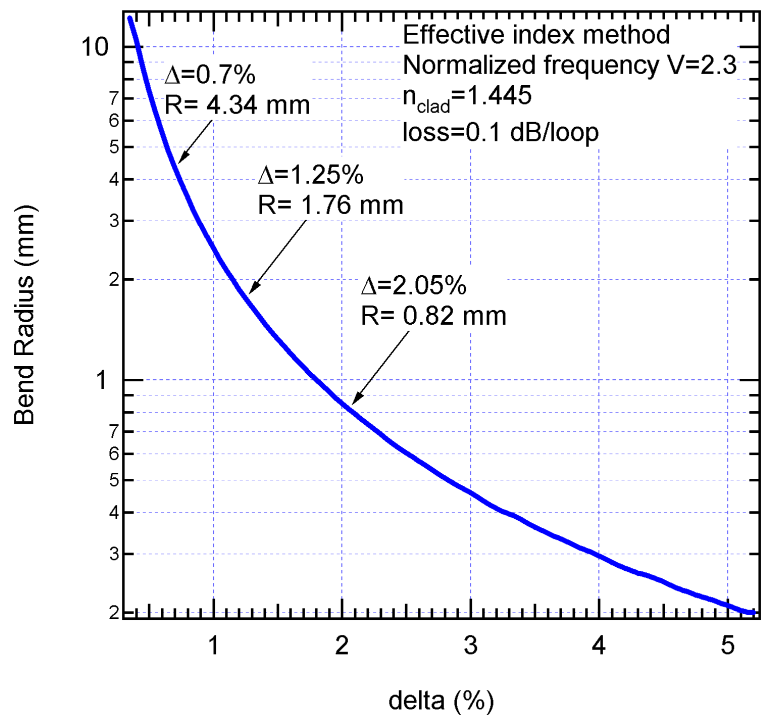
Broadband All-Pass Filters

Basic Design

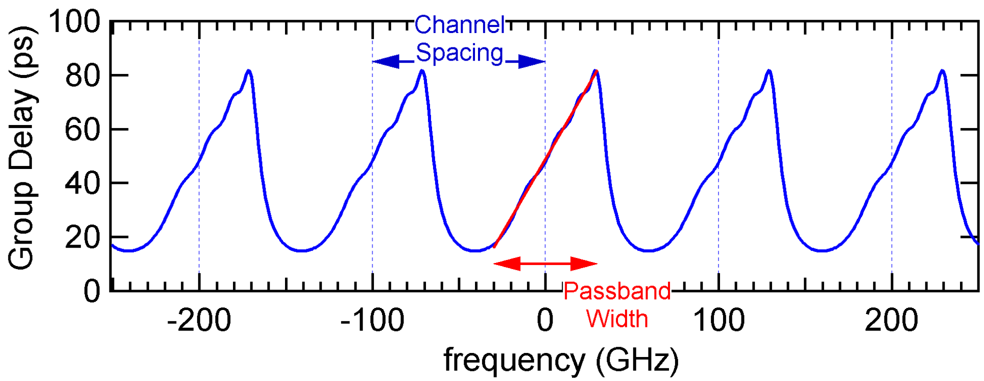


$FSR \uparrow \Rightarrow R \downarrow \Rightarrow \Delta \uparrow$

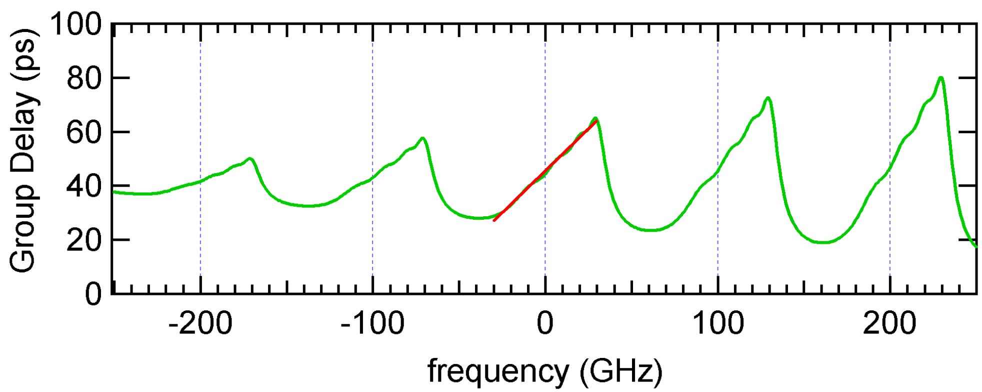
Achieving required coupling κ practically not feasible



Multi-channel Dispersion Compensation



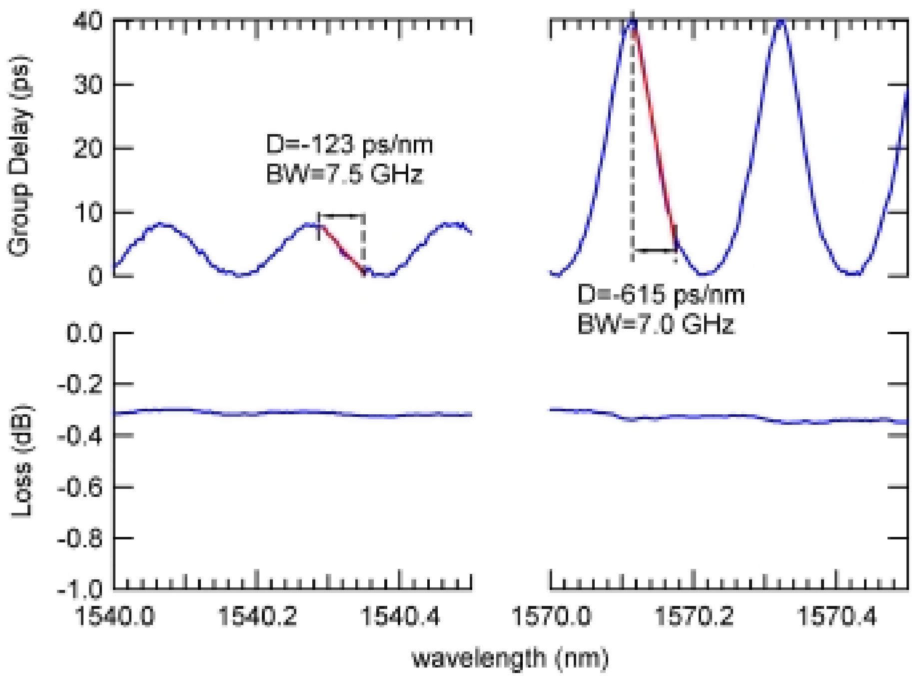
Constant dispersion compensation



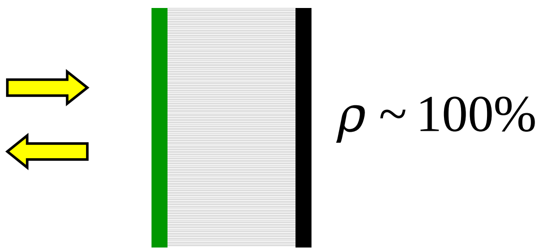
Dispersion slope compensation

Thin-film All-Pass Filter

Single-stage Silica substrate (25 GHz FSR)

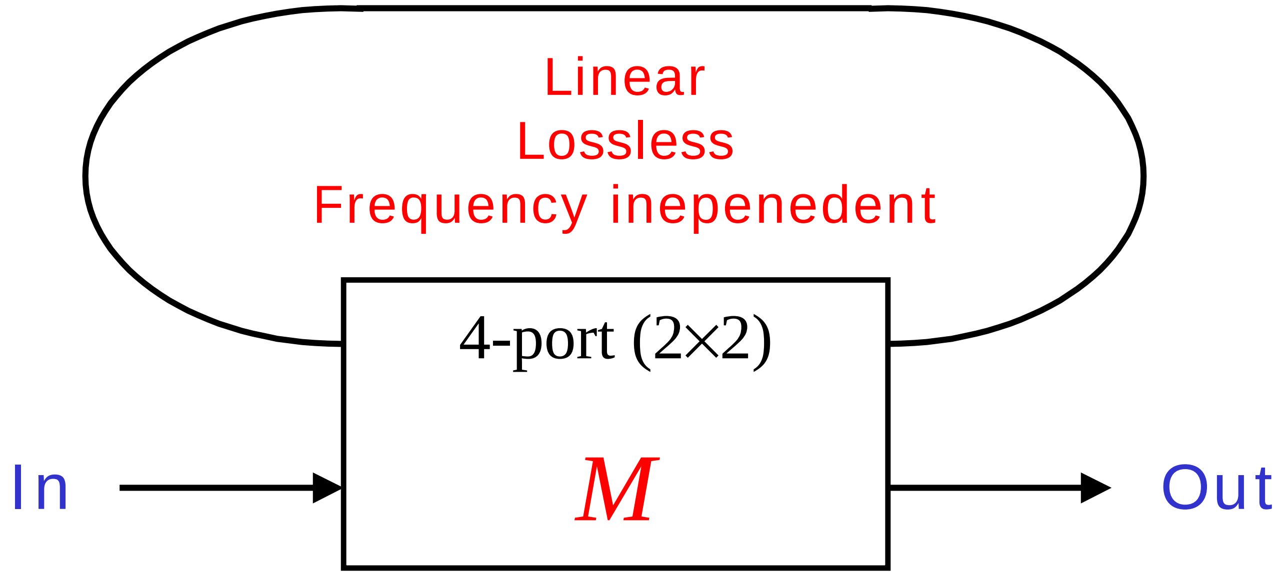


Package loss 0.3 dB



Gires-Tournois Interferometer (GTI)

General Construction of an All-Pass Filter

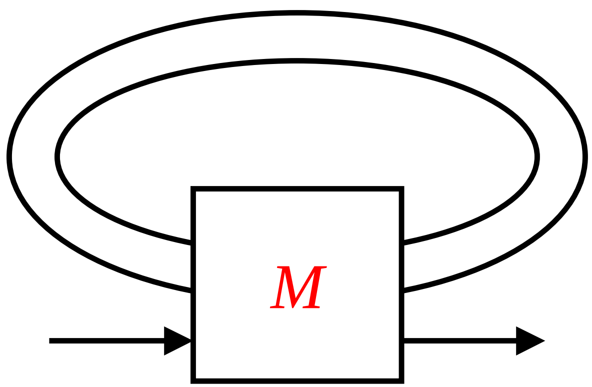


This is an all-pass filter if:

1. $\det(M) = 1$
2. $M_{22} = M_{11}^{*}$

FSR determined by feedback path delay

More General All-Pass Structures



$$\det(M) = 1$$

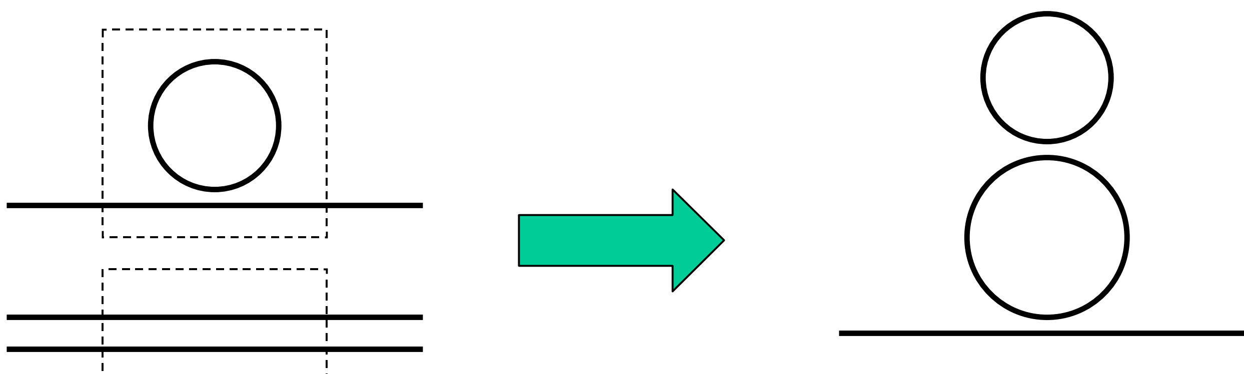
$$M_{11}^{*} = M_{22}M_{33} - M_{23}M_{32}$$

$$M_{22}^{*} = M_{11}M_{33} - M_{13}M_{31}$$

$$M_{33}^{*} = M_{22}M_{11} - M_{21}M_{12}$$

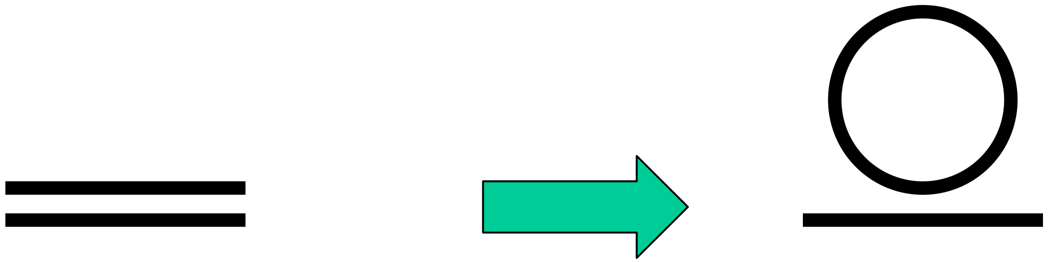
Single stage APF

Coupler



2-stage APF

Simple Case



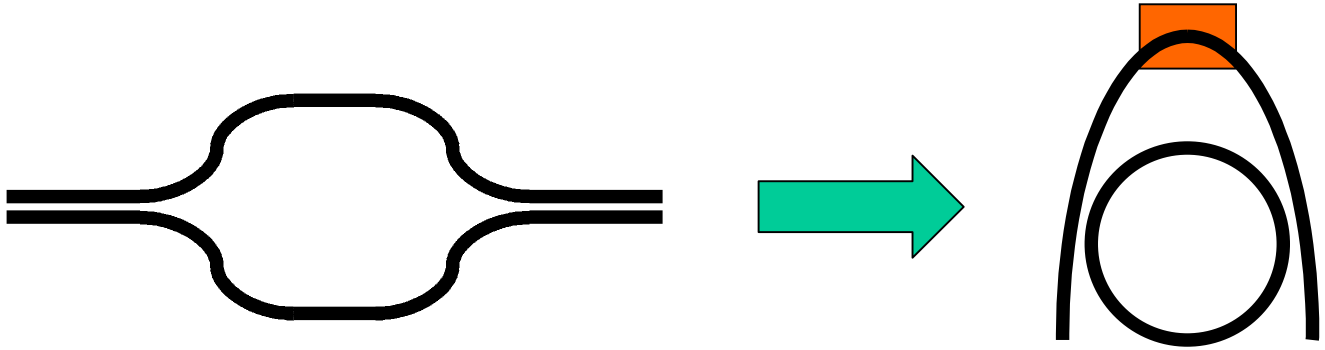
Directional coupler

Single stage all-pass filter

<u>Scaling problem:</u>

Larger FSR ⇒ Smaller rings ⇒ Larger bend loss ⇒ Larger Δ material ⇒ Coupler gap too small

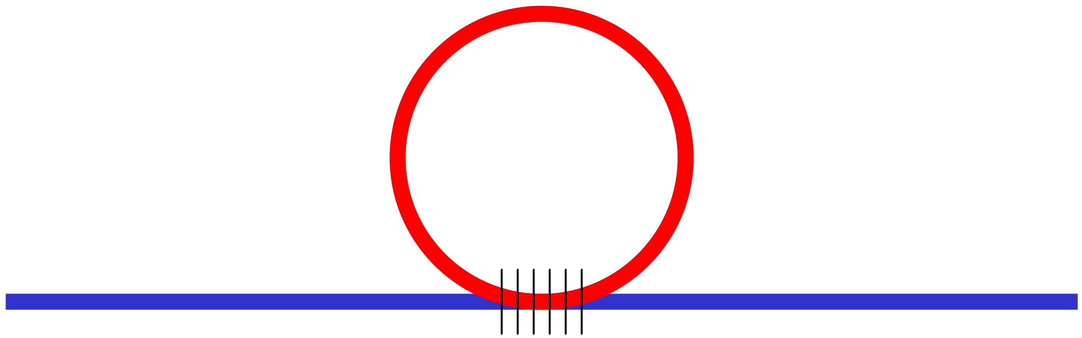
MZI-based APF



This design is <u>no longer sensitive</u> to the couplers

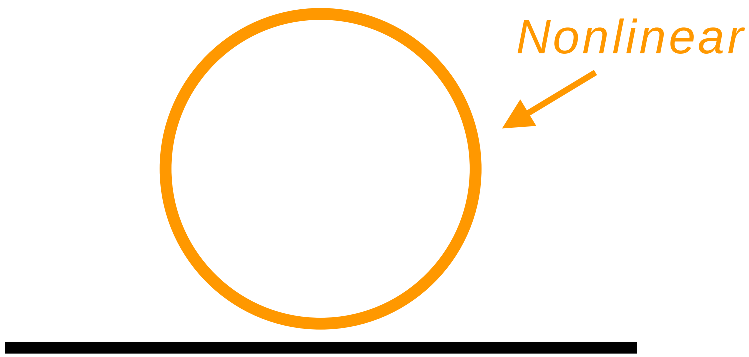
Equivalent to simple case, but with tunable coupling

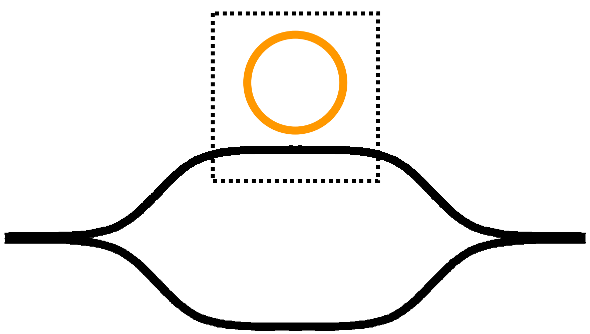
Another solution



Vertical grating-assisted coupling

Nonlinear all-pass filters





(Heebner and Boyd, *Opt. Lett.*, 1999)

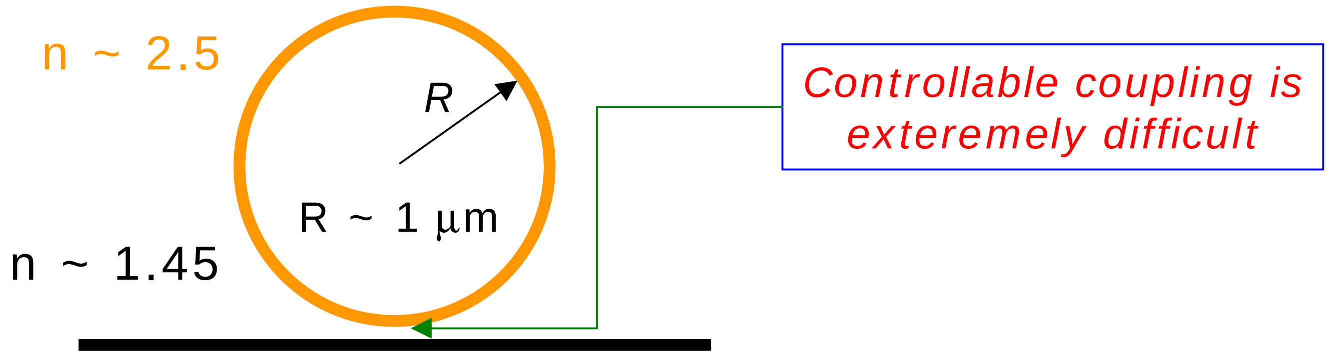
$$\Phi_{eff} \sim \left(\frac{2\pi}{\lambda} n_2 I L \right) 4\mathrm{F}^{\,2}$$

$$\mathrm{F} \sim \frac{\tau_{\max}}{T}$$

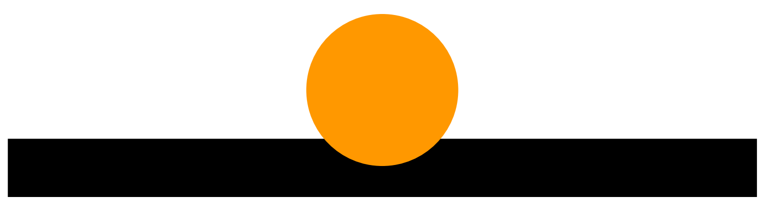
However, large F implies small bandwidth

For ~1 ps timescales requires very small rings or disks (~1 μm)

Practical considerations



Vertical coupling



R ~ 1 µm
F ~ 30
Cavity losses?

Summary

- *Ring resonators can be used as tunable optical phase equalizers*
- *Large bandwidth devices require many small rings*
- *Ring loss needs to be minimized*
- *Nonlinear micro rings may be used for fast all-optical switching*