Impact of High-Speed Modulation on the Scalability of Silicon Photonic Interconnects

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Outline

- Introduction – context – Silicon Photonics (SiP)
- Review of ring resonator
  - Low level metrics
  - High level metrics and models for obtaining them
- Design space exploration and pruning
  - For filtering (modulation), for dropping
  - Power penalties evaluation
  - Identification of ideal ring designs
  - Comparison with existing rings
- Proposed methodology
- Conclusion

Context

- Ever larger bandwidths required at all scales
  - From CPU-to-CPU to continent-to-continent
- Transition to larger bandwidths may occasion shifts to alternative technologies
  - Long distance-link have shifted year ago from copper to optics
  - Such a transition to optics has yet to occur for short distances (1-10cm)
    - Mainly for practical (=cost) issues: exotic materials required by optical components, unconventional and potentially bulky packages, etc.
- Silicon photonics can potentially offer a solution to most (many?) of these practical issues
  - Mass and cheap production through CMOS compatibility
  - Close integration with digital logic
- This does not necessarily mean that shift to silicon photonics will occur
  - Will SiP outperform competing technologies, at “bandwidth scale”?
  - Is there (semi-hidden) threats to SiP functionality, at “architecture scale”?

Outperforming competitors' cost and power

- Cost:
  - Silicon photonics needs
    - An external laser (array)
    - Edge coupling with external world (at least for laser)
    - Area for driver circuitries (one per wavelength!)
  - To be compared with new cabling solutions, novel signaling schemes used in electronic transceivers
- Power:
  - Elec. transceivers for intra-chip communication (1cm) achieve 0.1 pJ/bit [1]
  - Elec. transceivers for inter-chip communication achieve 65 fJ/bit [2]
  - These figures will probably improve by the time silicon photonics reaches maturity

  → We need to target such figures at least

→ Need for a in-depth optimization of device parameters and process

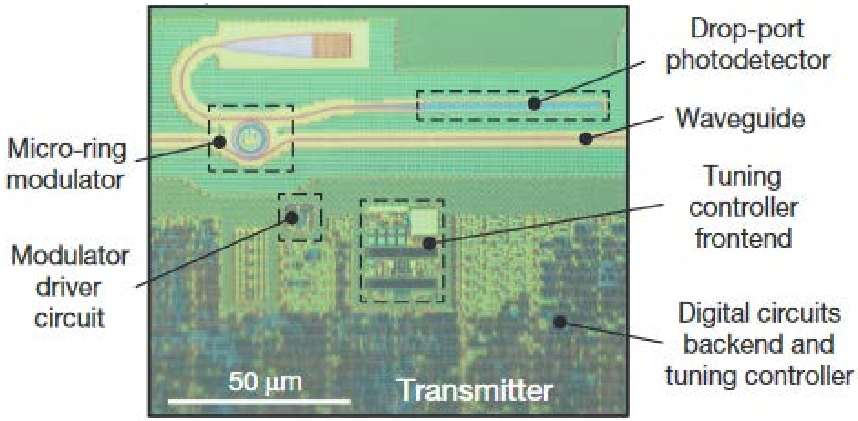
  → Especially at high data-rates

[1] Wary et al. "High-speed energy-efficient bi-directional transceiver for on-chip global interconnects", 2015
[2] Niitsu, et al. IEEE Trans. On VLSI 20 (7), 2012

Ensuring functionality at scale

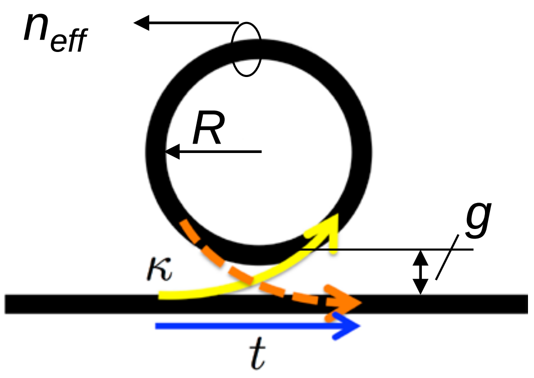
- Very few end-to-end demonstration of silicon photonic systems so far
- Demonstrations often include “tricks”
  - Optical amplifiers
  - Piecewise demonstration
  - Loss normalization
  - Device control with sophisticated lab equipment
- Multiple threats to correct functioning still remain
  - Fabrication variability, susceptibility of components to this variability
    - Insertion losses must be pushed to the minimal and no “surprise” 5dB can be tolerated
  - Integrated control (i.e. on chip) of devices, area and power it consumes
  - Underestimation of optical impairments as crosstalk
    - Especially at high-rate and at scale

→ Need for comprehensive models taking into account all these aspects



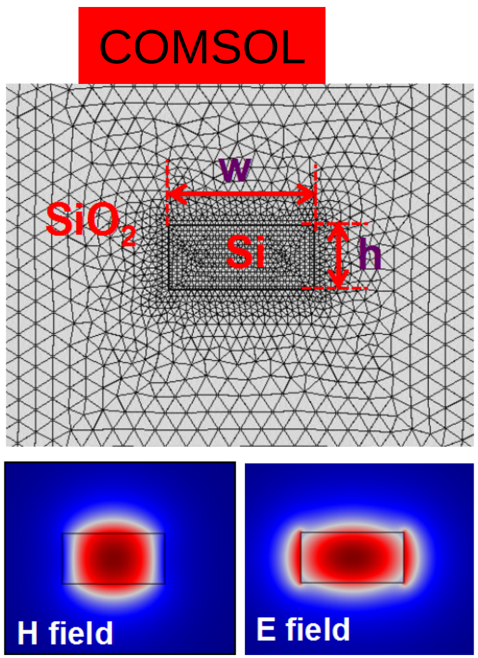
[C. Sun *et al.*, Nature 528, 2015]

Review of ring resonator



- Ring:
  - A circular waveguide with properties:
    - Effective refractive index n_{eff}
    - Waveguide loss $\alpha_{waveguide}$ (1/m or 1/cm or dB/cm)

    → Obtained by numerical methods (FDTD or FEM)



  - Radius R affecting:
    - Resonance

$$\lambda_m = \frac{2\pi R n_{eff}}{m}$$

Mode number

    - Loss in the ring

$$L = \exp(-2\pi R\alpha_{\text{ring}}(R))$$

Function of radius (1/m or 1/cm)

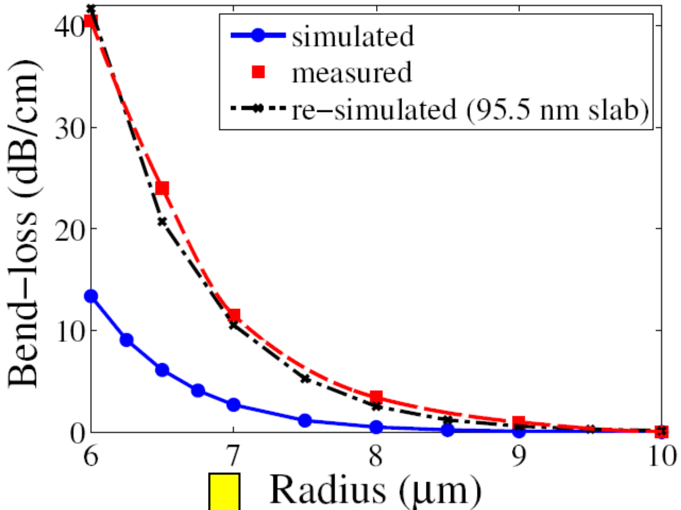
$$L \approx 1 - 2\pi R\alpha$$

Approx.

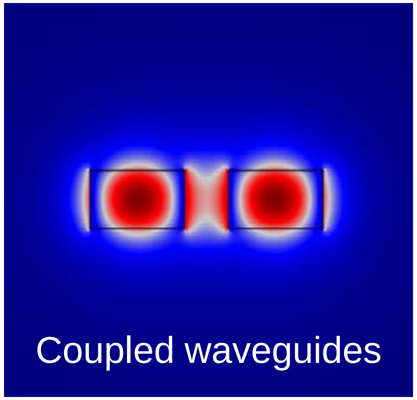
  - Gap size affecting:
    - Coupling coefficient

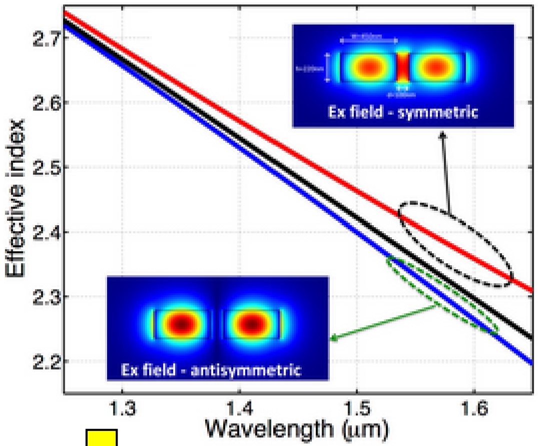
$$|\kappa| \sim \frac{1}{\text{Gap Size}}$$

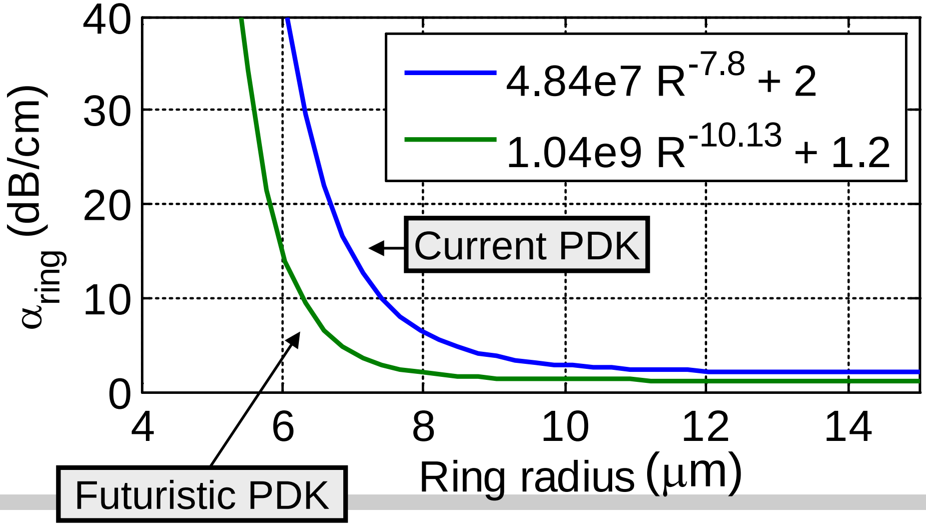
Investigating ring loss and coupling coefficients

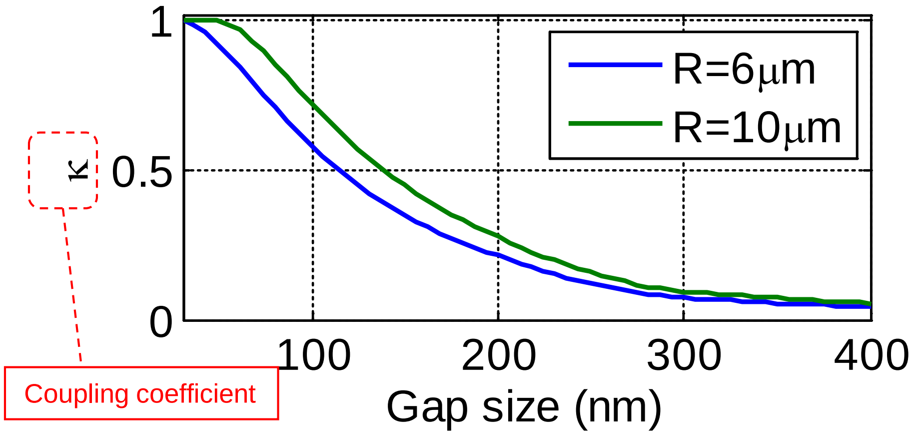


[H. Jayatilleka *et al.*, JLT, 2016]









High level metrics for ring resonators

- Ring bandwidth (a.k.a FWHM)
  - Range of filtered frequenties
  - Related to Q-factor

$$FWHM \approx \frac{1+\frac{\kappa^2}{2\pi R\alpha}}{\pi\frac{2n_g}{c\alpha}} = \frac{f_0}{Q}$$

- Free spectral range (FSR)

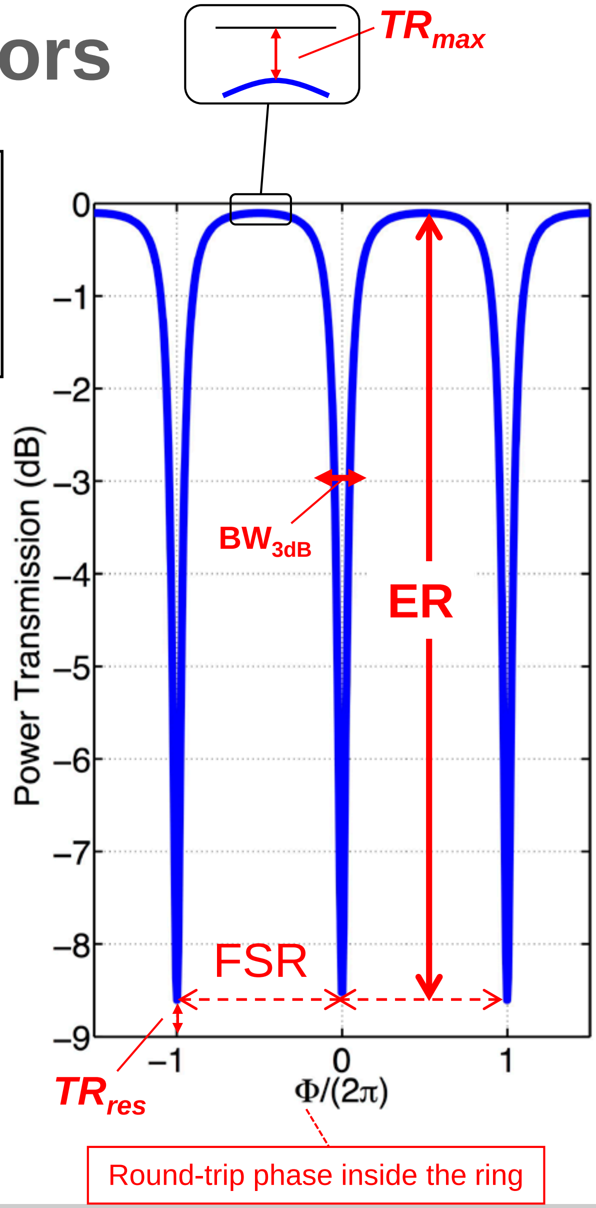
$$FSR_{nm} = \frac{\lambda^2}{2\pi R n_g}$$

- Transmission at resonant frequency
  - vestiges from filtering

$$TR_{res} = \frac{\left(1-\frac{\kappa^2}{2\pi R\alpha}\right)^2}{\left(1+\frac{\kappa^2}{2\pi R\alpha}\right)^2}$$

- Transmission at detuning of FSR/2
  - exactly between resonances

$$TR_{max} = \frac{\left(\frac{\lambda Q}{2\pi R n_g}\right)^2 + \frac{\left(1-\frac{\kappa^2}{2\pi R\alpha}\right)^2}{\left(1+\frac{\kappa^2}{2\pi R\alpha}\right)^2}}{\left(\frac{\lambda Q}{2\pi R n_g}\right)^2 + 1}$$



Ring resonator filter – desired properties

- Good signal suppression (at resonance)

  → Critical coupling: $L = 1 - \kappa^2 \longrightarrow$ $2\pi R\alpha \approx \kappa^2$

  → TR_{res} ~ 0

- FSR large enough to maximize WDM capabilities

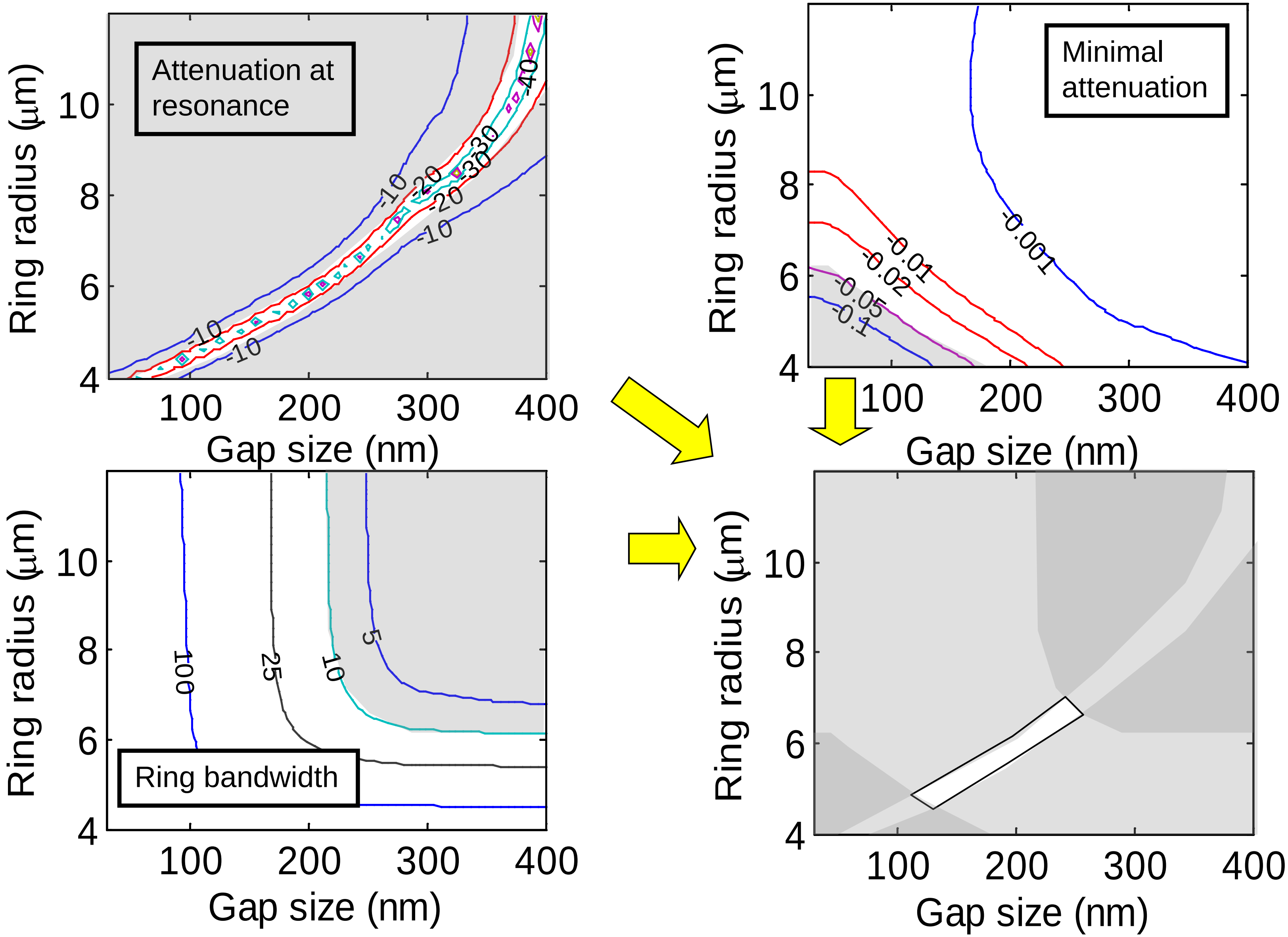
- Low suppression outside resonance

  → TR_{max} > -0.05 dB (cascading 20 → 1dB, cascading 100 → 5dB)

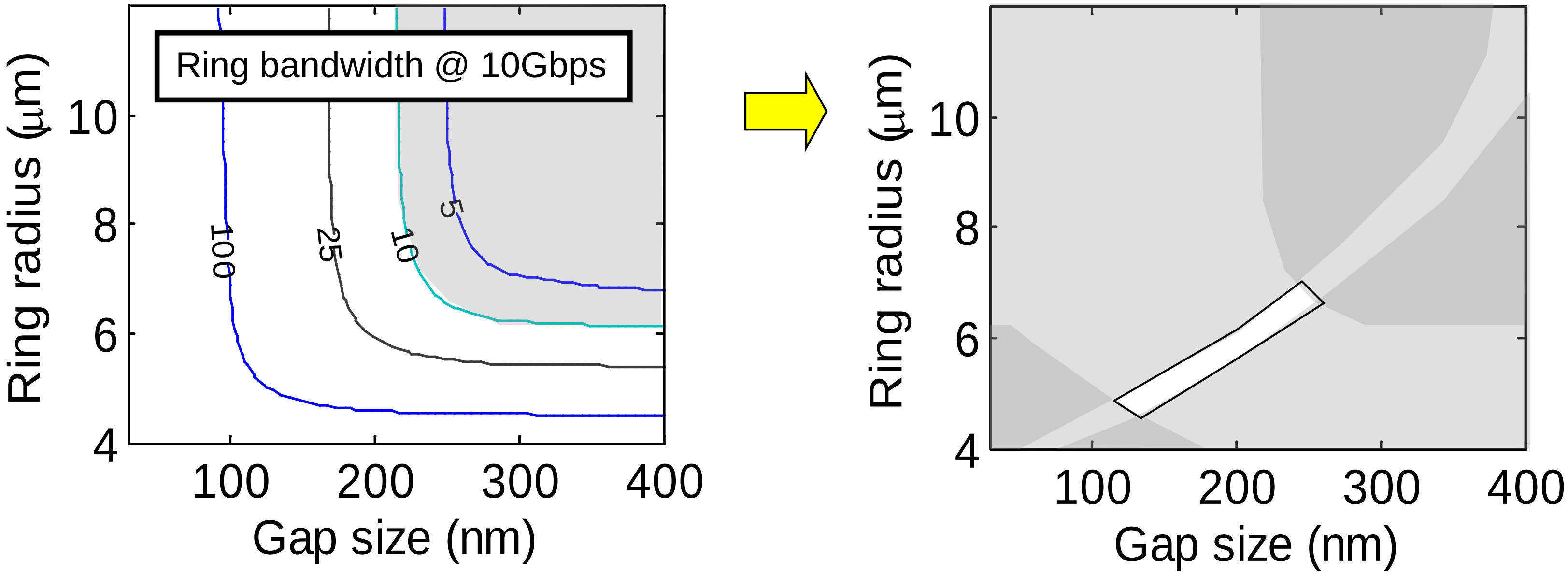
- Bandwidth large enough to support signal

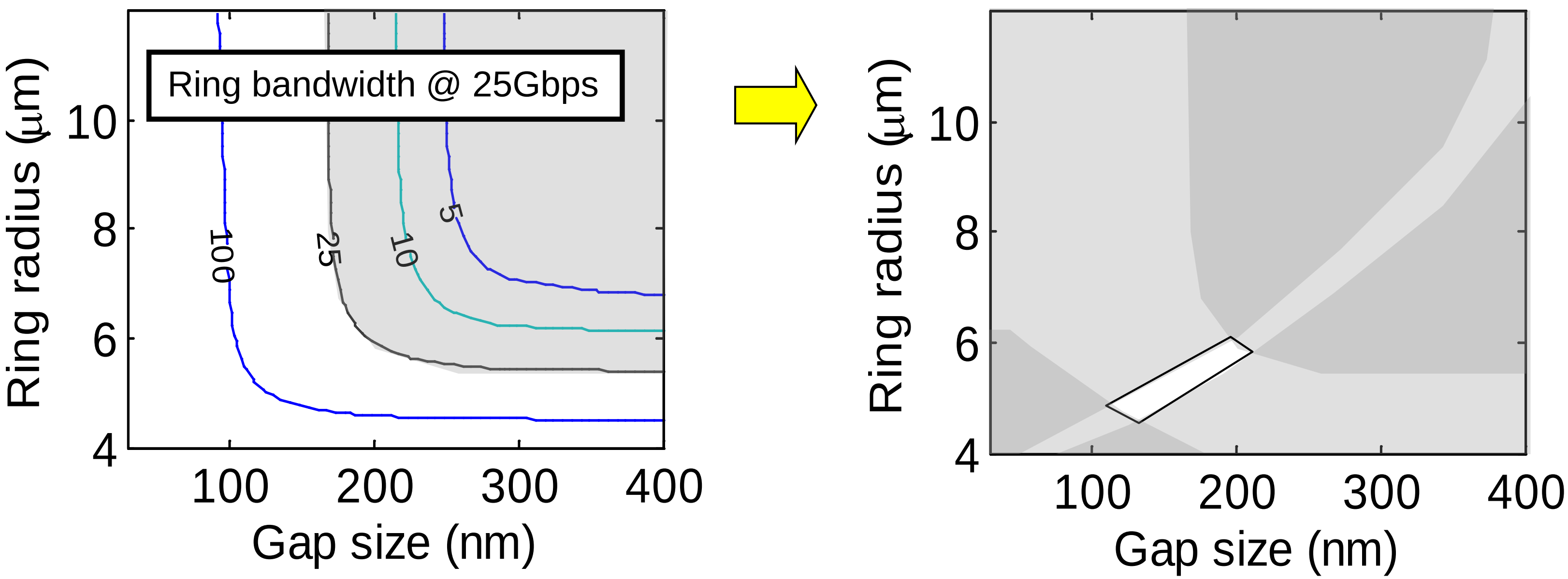
  → $FWHM_{Ghz}$ > ~$Bitrate_{Gbit}$ OOK

Ring resonator filter – reducing design space

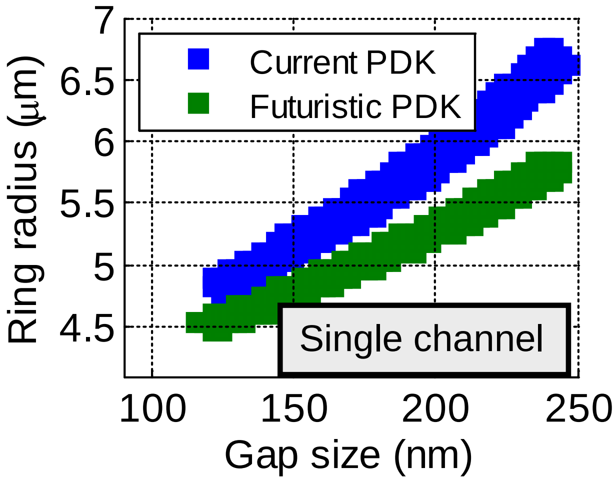


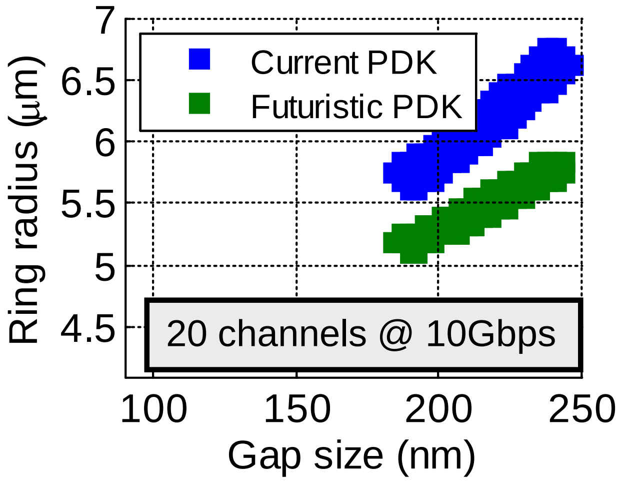
Impact of high-speed signals

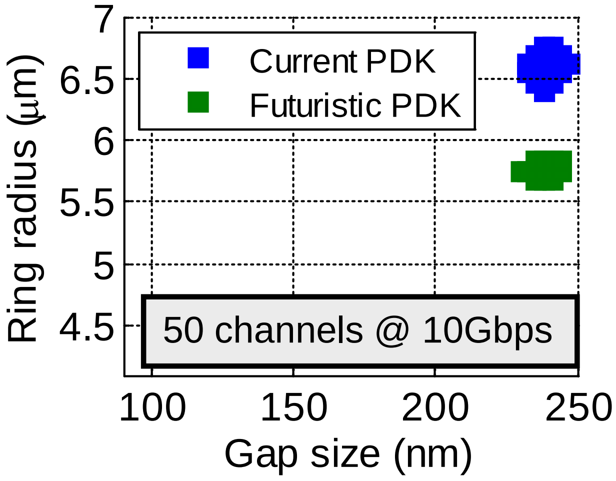




Impact of WDM and fab PDK



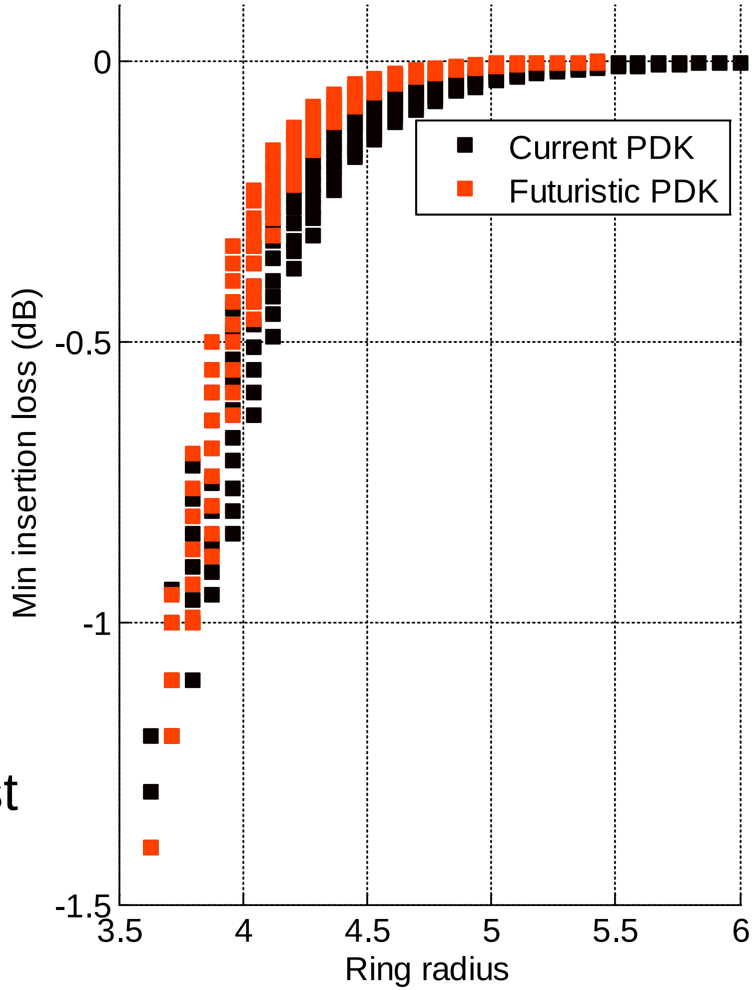




- Zones of feasibility for simple filters
  - Multiple channels: impose additional restriction on insertion loss
  - Insertion loss must stay low (here <0.05dB) around neighboring channel
    - IL(detuning = 50nm/#channels – bitrate) < 0.05dB

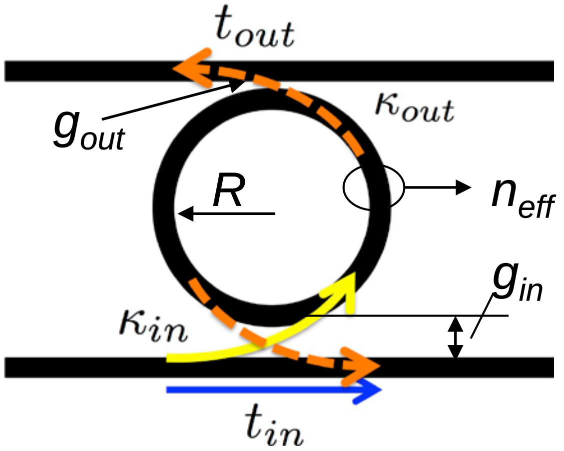
Ring diameter limitation

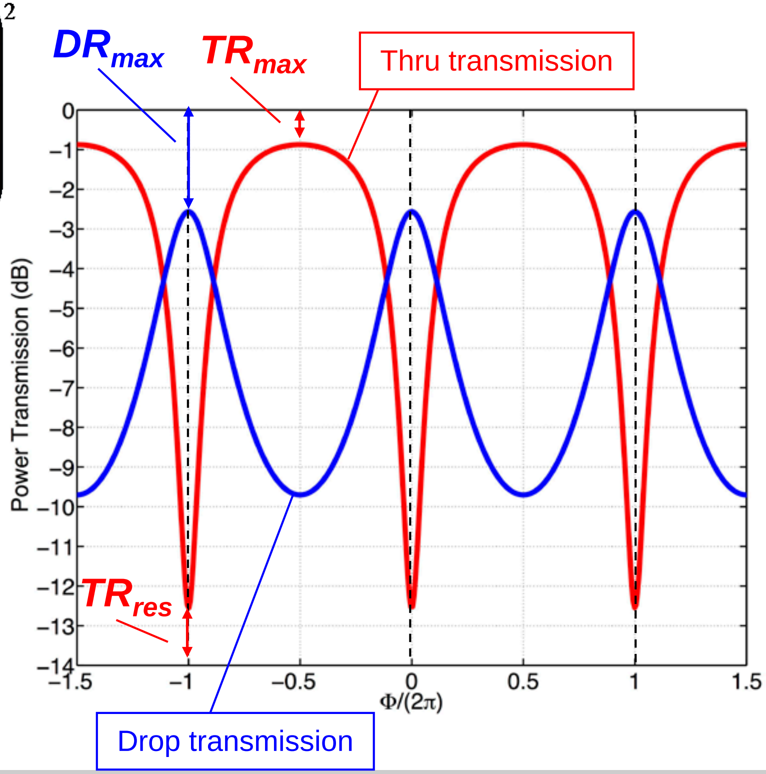
- Selection of designs leading to signal suppression of -15dB at least
- Below 4μm, loss inflicted to other channels increases sharply
- Progress on PDK do not provide much help.
- Result in small FSRs of 22 nm at most
  - To be compared with the ~200nm exploited in the fiber world



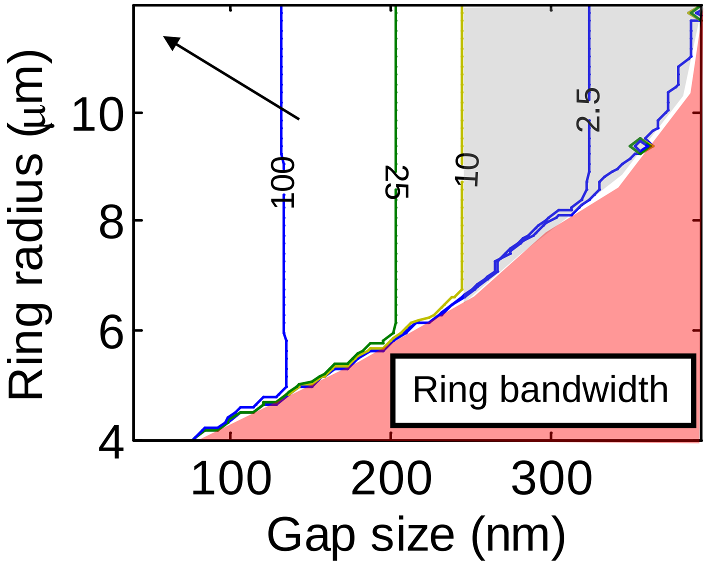
Ring resonator drop

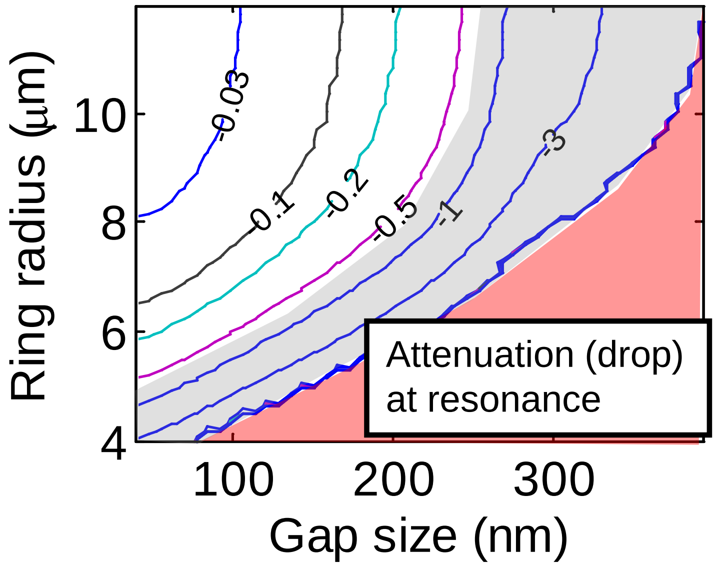
- Third design parameter: **output gap size**
- Critical coupling condition: $L = \frac{1-\kappa_{in}^2}{1-\kappa_{out}^2} = \frac{t_{in}^2}{t_{out}^2}$
- Transmission (thru) at resonance: $TR_{res} \approx \left(\frac{1 + \frac{\kappa_{out}^2}{2\pi R\alpha} - \frac{\kappa_{in}^2}{2\pi R\alpha}}{1 + \frac{\kappa_{out}^2}{2\pi R\alpha} + \frac{\kappa_{in}^2}{2\pi R\alpha}} \right)^2$
- Transmission (drop) at resonance $DR_{max} \approx \left(\frac{2\frac{\kappa_{out}\kappa_{in}}{2\pi R\alpha}}{1 + \frac{\kappa_{out}^2}{2\pi R\alpha} + \frac{\kappa_{in}^2}{2\pi R\alpha}} \right)^2$
- Transmission (thru) out of resonance (at FSR/2): $TR_{max} \approx \frac{\left(\frac{\lambda Q}{2\pi R n_g}\right)^2 + TR_{res}}{\left(\frac{\lambda Q}{2\pi R n_g}\right)^2 + 1}$

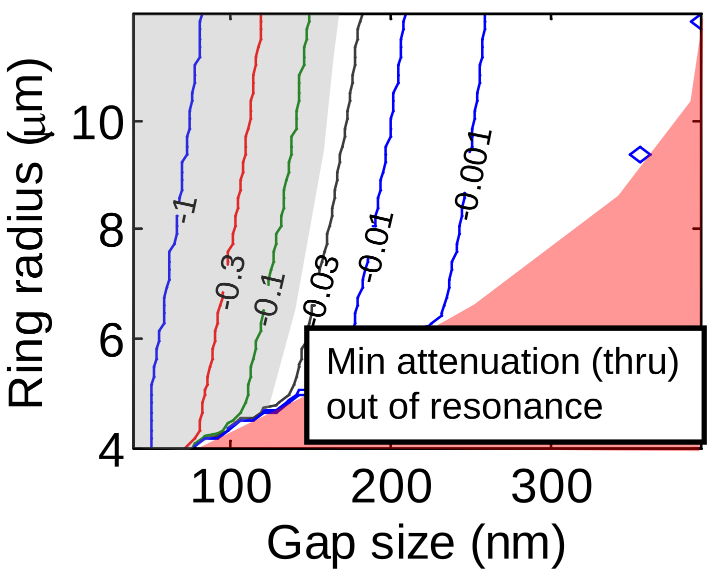


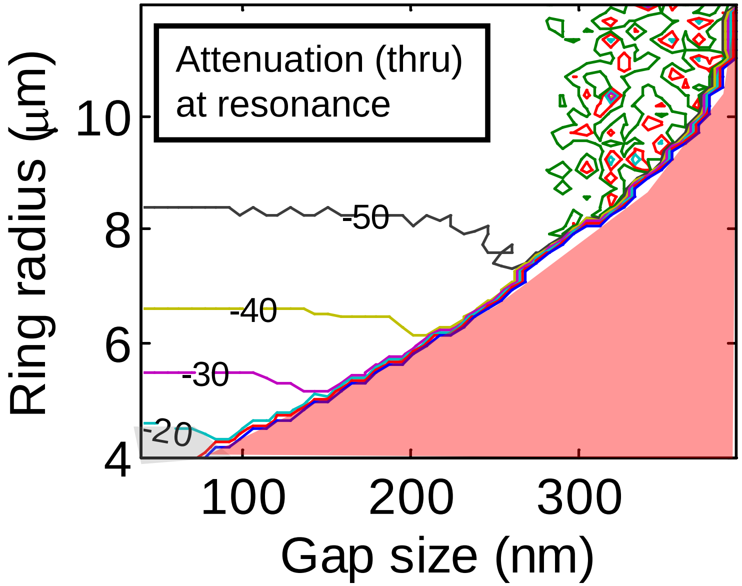


Ring drop – parameter space

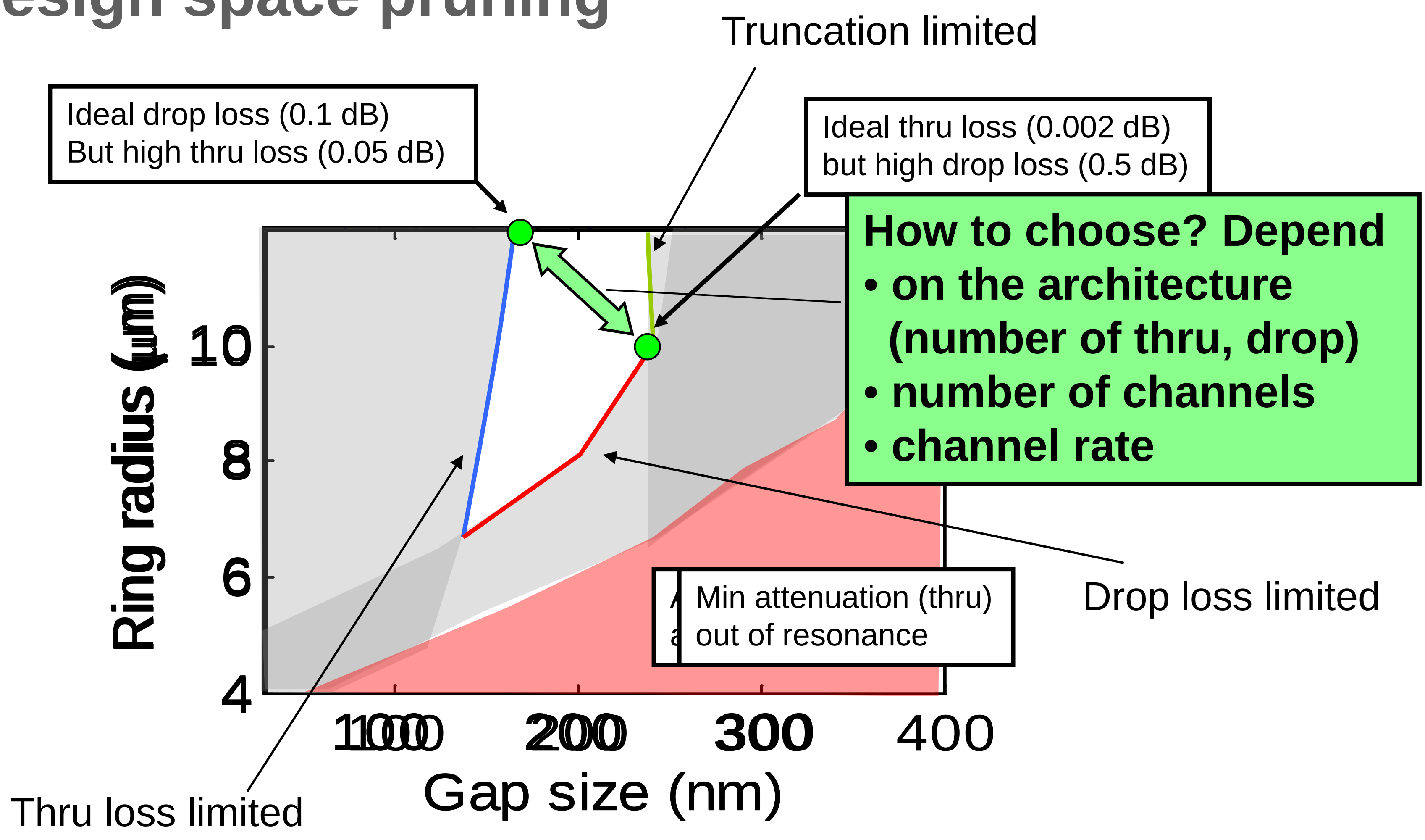




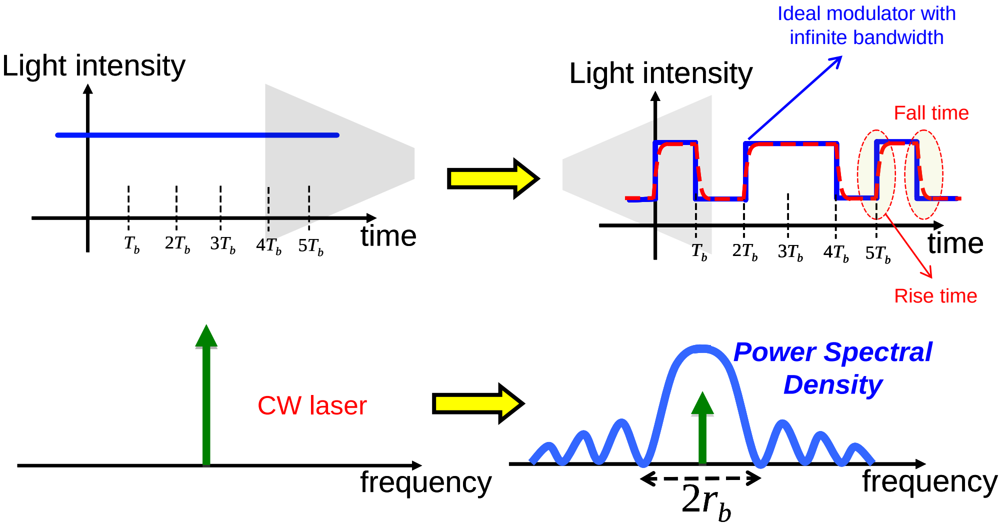




Design space pruning

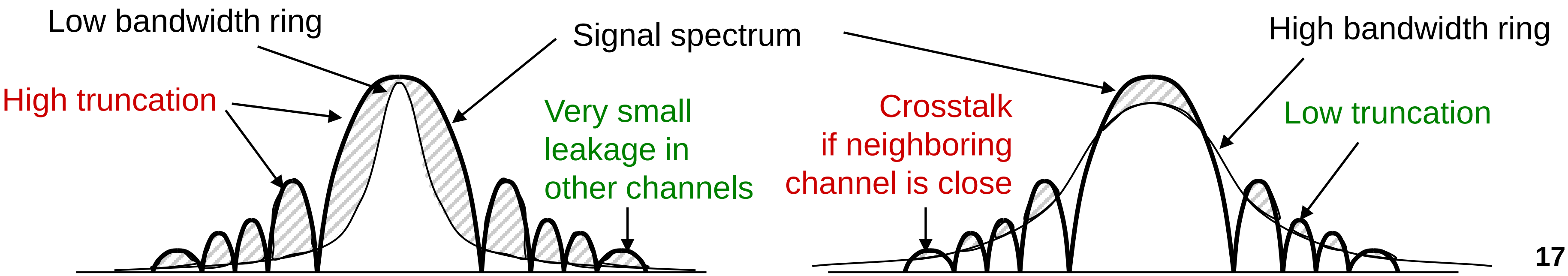


Balancing truncation and crosstalk

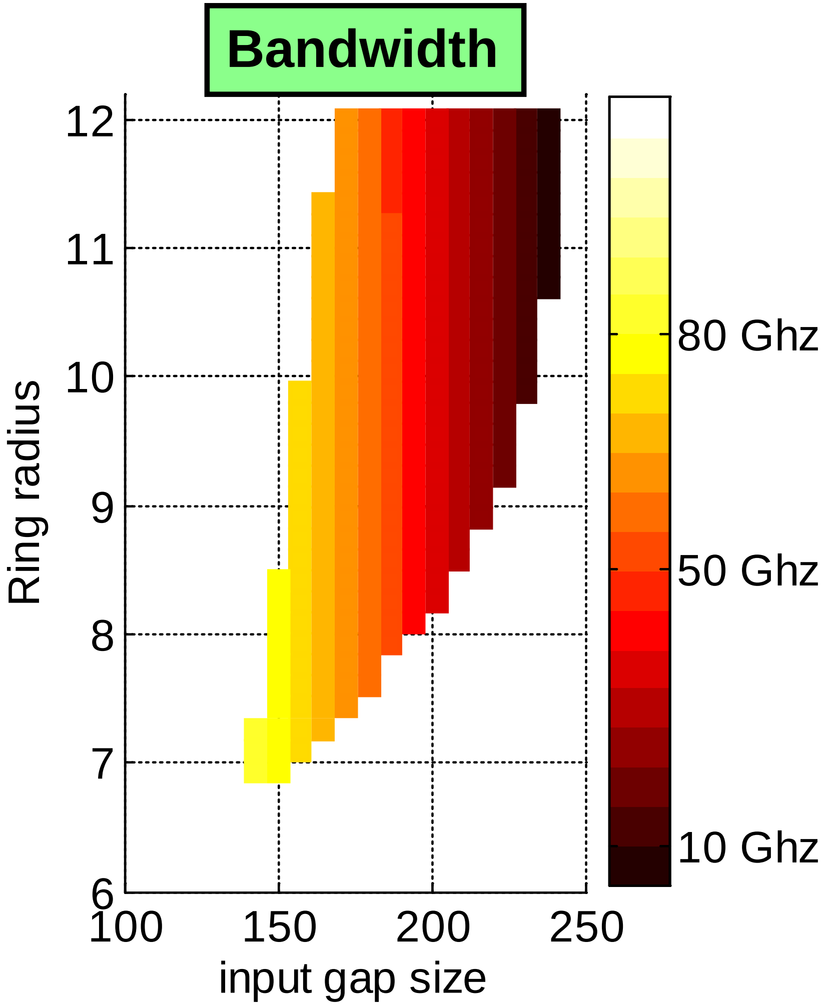


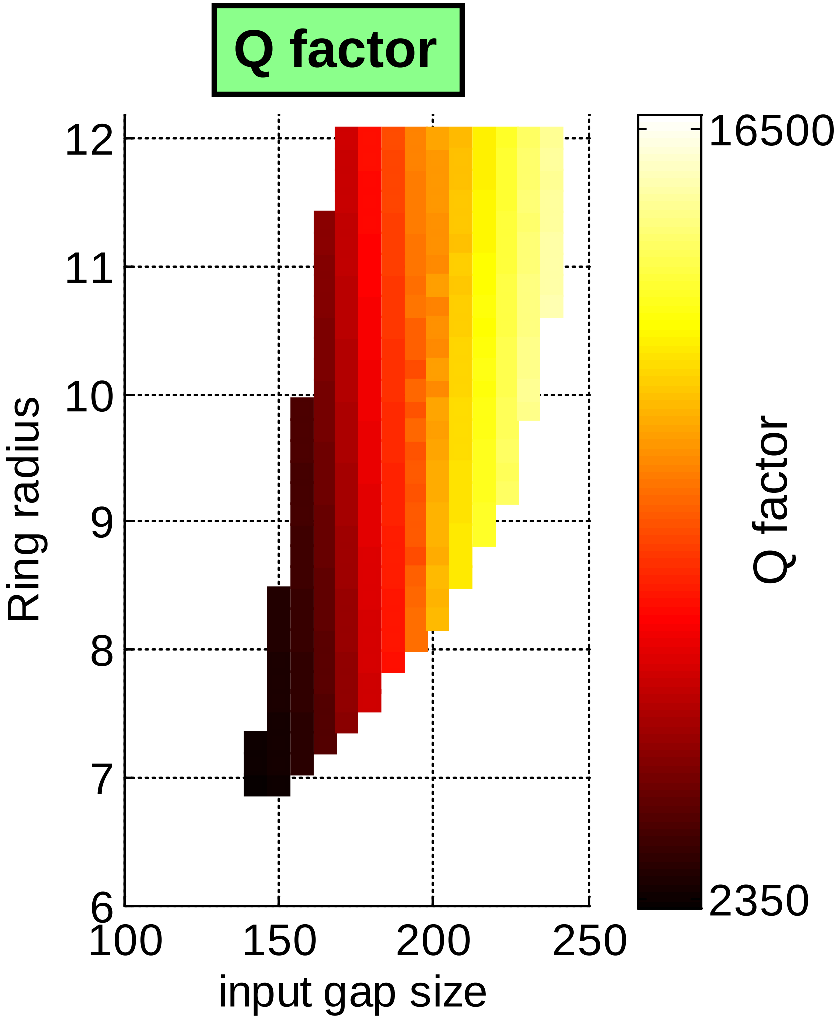
- Modulated signals occupy a broader range of bandwidth
  - Relevant part proportional to the bitrate
  - → Signal truncation: some of the relevant part is **not** dropped
  - Occupied spectrum potentially infinite
  - → Filtering cross-talk: some of the infinite part of the *other channels* is dropped **as well**

→ Truncation comes at the expense of cross-talk and vice-versa



Bandwidth/Q factor picking

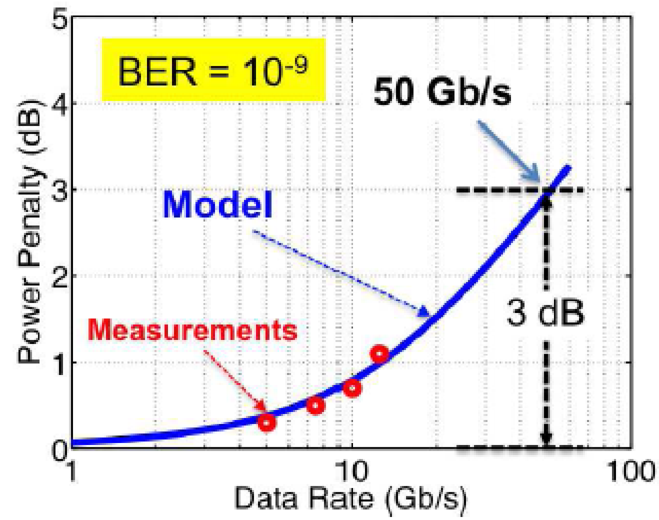




Impact of BW/Q: Truncation of the Spectrum

- Depends on the *modulation speed* (rate)
- Depends on the Q of the ring

- Truncation penalty reflects how much the **strength** of the information is reduced by the narrow-bend optical filter



(dB)

$$\text{TPP} = -5\log_{10}\left(1 - \frac{1+\beta^2}{2\pi\nu}\text{Real}\left(\frac{1-e^{-2\pi\nu(1-j\beta)}}{(1-j\beta)^2}\right)\right)$$

Power Penalty due to the high Q

$$\nu = \frac{f_0}{2Q \times r_b}$$

Taking into account Bandwidth of ring and DATA RATE

Resonance freq. of ring ($f_0 = c/\lambda_0$)

$$\beta = \frac{2Q}{f_0} f_\Delta$$

Taking into account possible detuning

Freq. detuning from f_0

- If Q → 0 (infinite bandwidth)
  - TPP → 0 (no filtering effect)

Impact of BW/Q: Reduction of the OOK Extinction

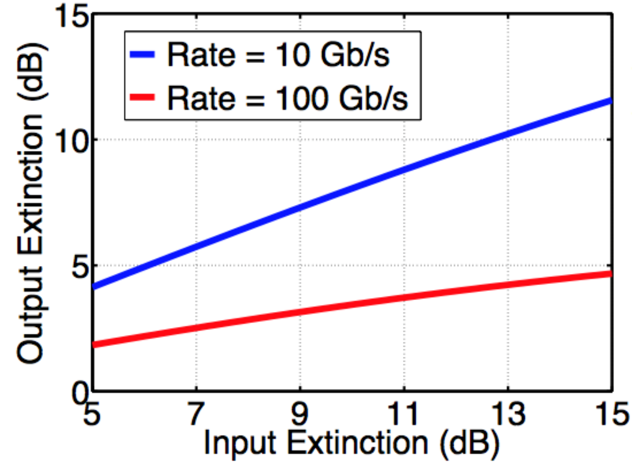
- Limited BW of ring reduces the ER of OOK modulation
- Impact on ER depends on the input ER (itself dependent on modulation)

$$\frac{\sqrt{er_{out}}-1}{\sqrt{er_{out}}+1} \approx \frac{\sqrt{er_{in}}-1}{\sqrt{er_{in}}+1} \times \sqrt{\gamma}$$

Taking into account Bandwidth of ring and DATA RATE

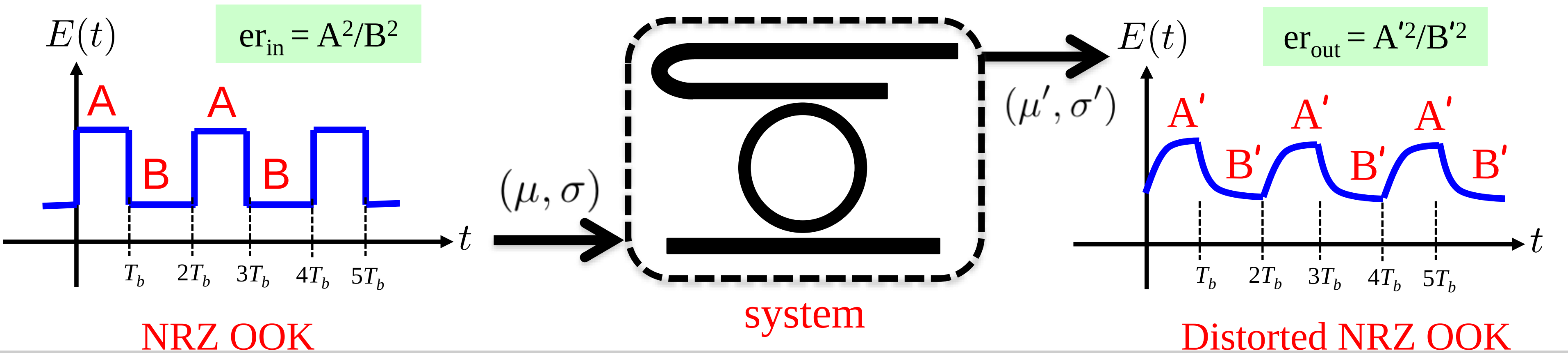
$$\gamma = 1 - \frac{1-\exp(-2\pi\nu)}{2\pi\nu}$$

$$\nu = \frac{f_0}{2Q \times r_b}$$



Q ≈ 20000

BW_{3dB} ≈ 10 GHz



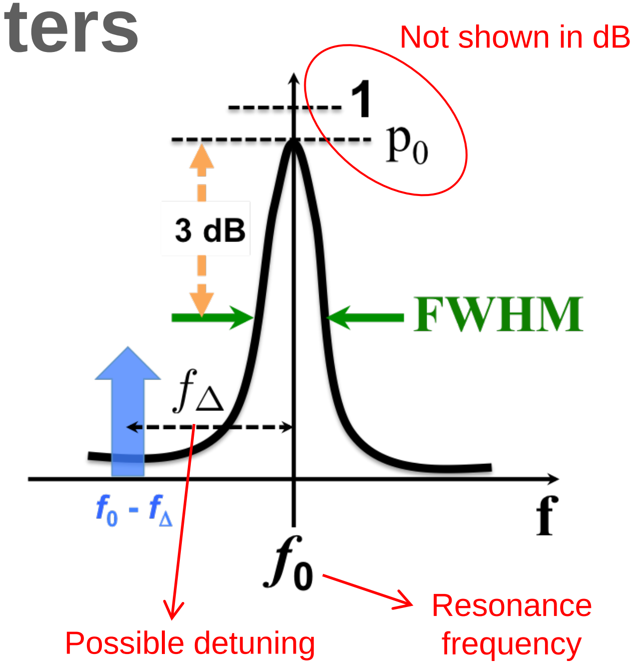
Impact of BW/Q: effect of other filters

- Attenuation of the Lorentzian tail for drop path
  - at critical coupling

$$\underset{\text{(drop)}}{\text{IL Penalty}} = -10\log_{10}\left(1 - Q\frac{\alpha\lambda_0}{\pi n_g}\right) - 10\log_{10}\left(\frac{1}{1+\left(\frac{2Q}{f_0}f_\Delta\right)^2}\right)$$

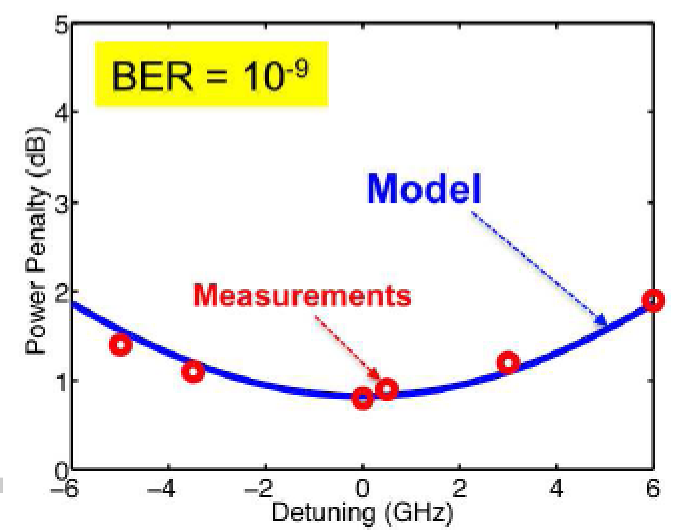
Insertion Loss at the resonance
(a function of *Q* factor)

Extra attenuation by detuning from the resonance
(a function of *Q* factor)



- Attenuation for the through path
  - at critical coupling

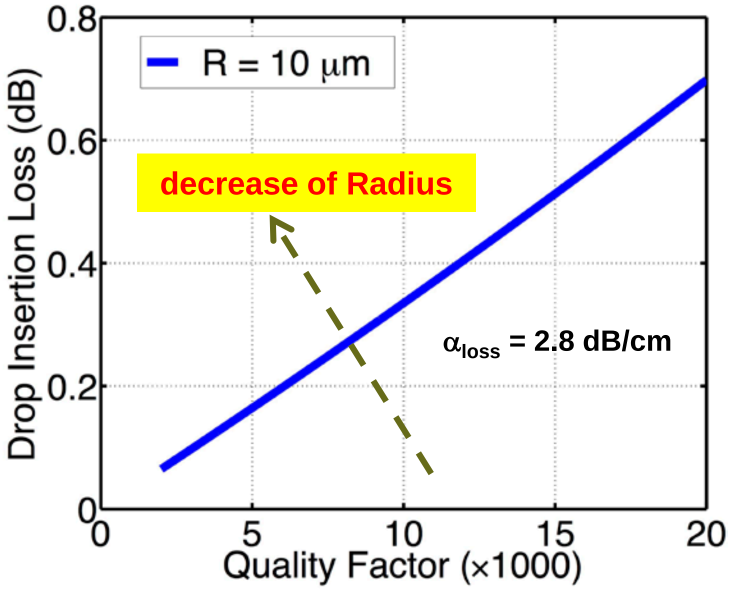
$$\underset{\text{(thru)}}{\text{IL Penalty}} = -10\log_{10}\left(\frac{\left(\frac{2Q}{f_0}f_\Delta\right)^2}{1+\left(\frac{2Q}{f_0}f_\Delta\right)^2}\right)$$



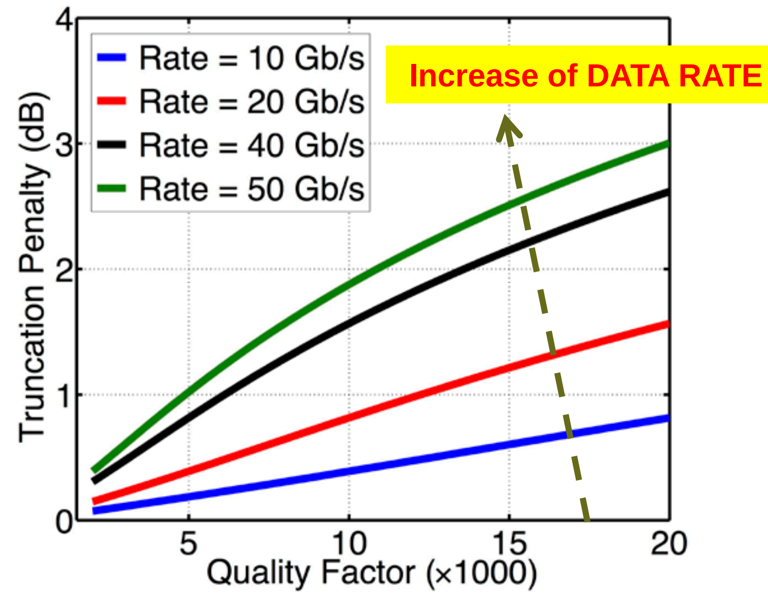
Total Penalty of a Single Add/Drop Ring Filter

Increasing Q will increase both the IL penalty and Truncation Penalty

R = 10 μm @ critical coupling (any rate)



R = 10 μm



Playing with the gap size

Impact of Q: Crosstalk in Ring Filters

- Optical Crosstalk as a noise mechanism

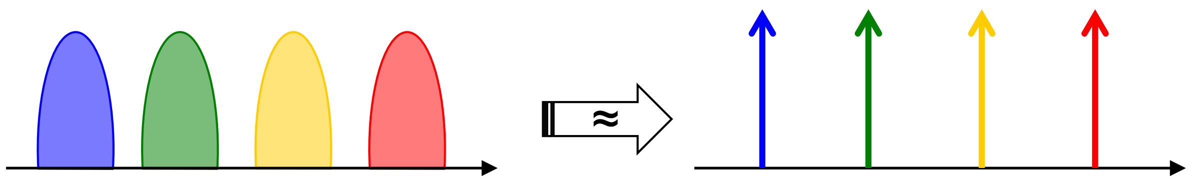
$$\mathrm{PP}_{\mathrm{XTalk}} \approx -10\log_{10}\left(1 - \frac{1}{2} q_{\mathrm{BER}} \frac{P_{\mathrm{XTalk}}}{P_{\mathrm{NRZ}}} \frac{er+1}{er-1}\right)$$

Target BER

Xtalk power (total)

Effect of ER of OOK (sensitivity to noise)

- **0th-order** Approximation
  - ignore the spectral bandwidth of modulation OOK light



  - Assume all the optical power is at the carrier (center) wavelength

$$S(E) \approx \mu^2\ \delta(f - f_c) + \sigma^2\ \delta(f - f_c)$$

NRZ optical power

  - Good approximation for LOW data rates and/or FLAT filters
  - This method has been widely used

✓ L. H. Duong *et al.*, “A case study of signal- to-noise ratio in ring-based optical networks-on-chip,” Design & Test, IEEE, vol. 31, no. 5, pp. 55–65, 2014.

✓ L. H. Duong *et al.*, “Coherent crosstalk noise analyses in ring-based optical interconnects,” in Proceedings of the 2015 Design, Automation & Test in Europe Conference & Exhibition, pp. 501–506, EDA Consortium, 2015.

✓ J. Chan *et al.*, “Physical-layer modeling and system-level design of chip-scale photonic interconnection networks,” Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on, vol. 30, no. 10, pp. 1507–1520, 2011.

Impact of Q: Crosstalk in Ring Filters

- **1st-order** Approximation
  - do not ignore the spectral shape of the OOK modulation

$$(P_{\text{XTalk}})_{i^{\text{th}}\ Ring} \approx P_{\text{NRZ}} \times \sum_{j=1, j\neq i}^{N} \Gamma_{i,j}$$

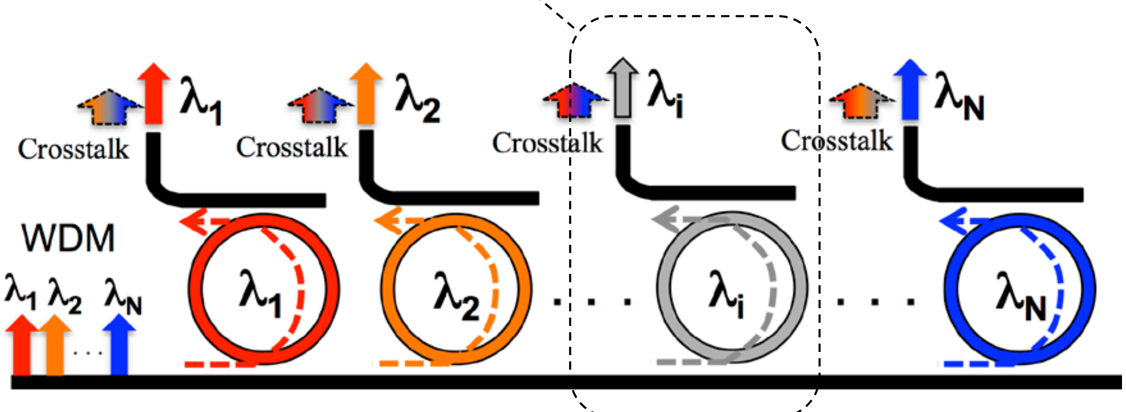
Fraction of crosstalk power from each NRZ channel

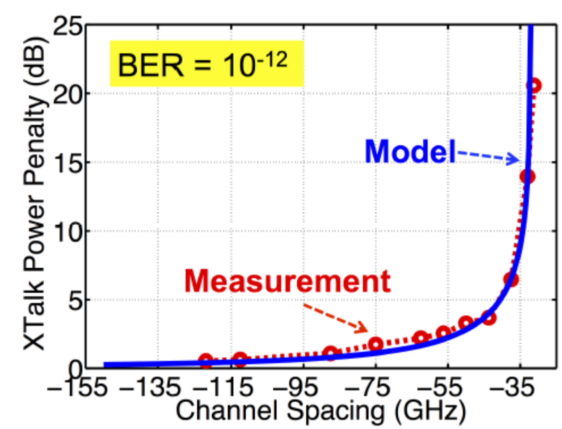
  - estimate the crosstalk power
    - ✓ based on the Lorentzian shape of the ring
    - ✓ based on the spectral shape of the NRZ OOK modulation
    - ✓ based on the DATA RATE

$F_\Delta = f_\Delta / r_b$ (data rate)

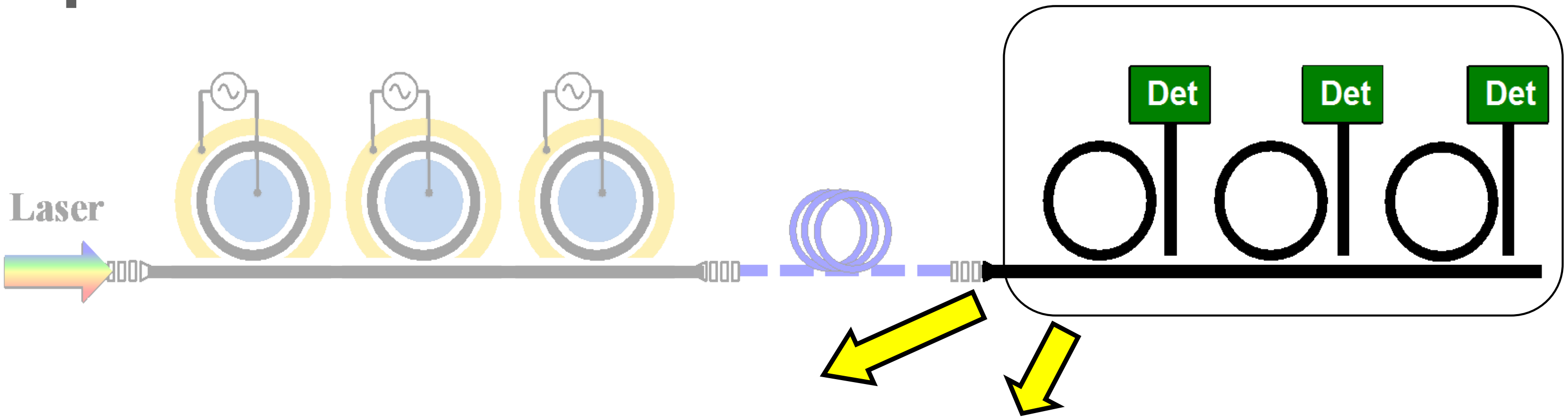
$$\Gamma_{i,j} = \int_{-\infty}^{\infty} \frac{\text{sinc}^2(F)\, dF}{1 + \left(\frac{F+(j-i)F_\Delta}{\xi_i}\right)^2} \left[\prod_{k=1}^{i-1} \frac{\left(\frac{F+(j-k)F_\Delta}{\xi_k}\right)^2}{1 + \left(\frac{F+(j-k)F_\Delta}{\xi_k}\right)^2} \right]$$

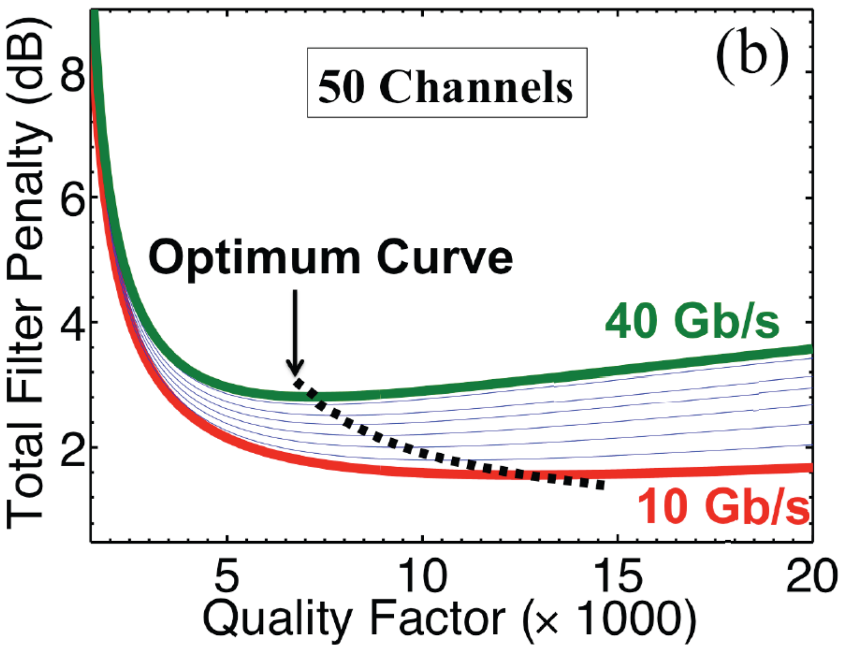
$\xi_k = \text{FWHM}/(2r_b)$



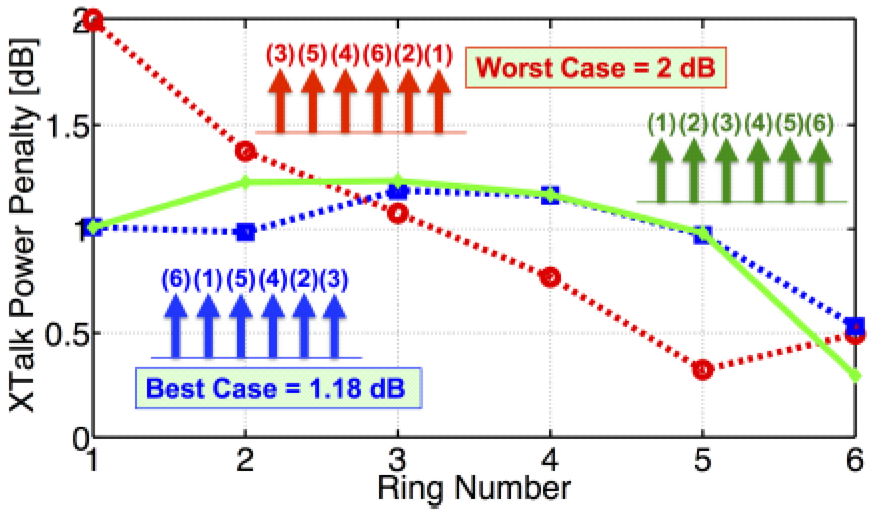


Optimization results





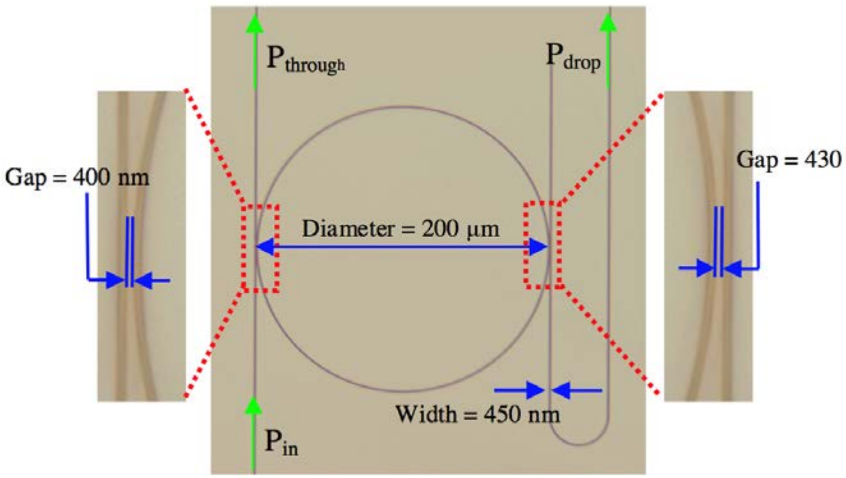
[Bahadori et al., Optical Interconnects, 2015]



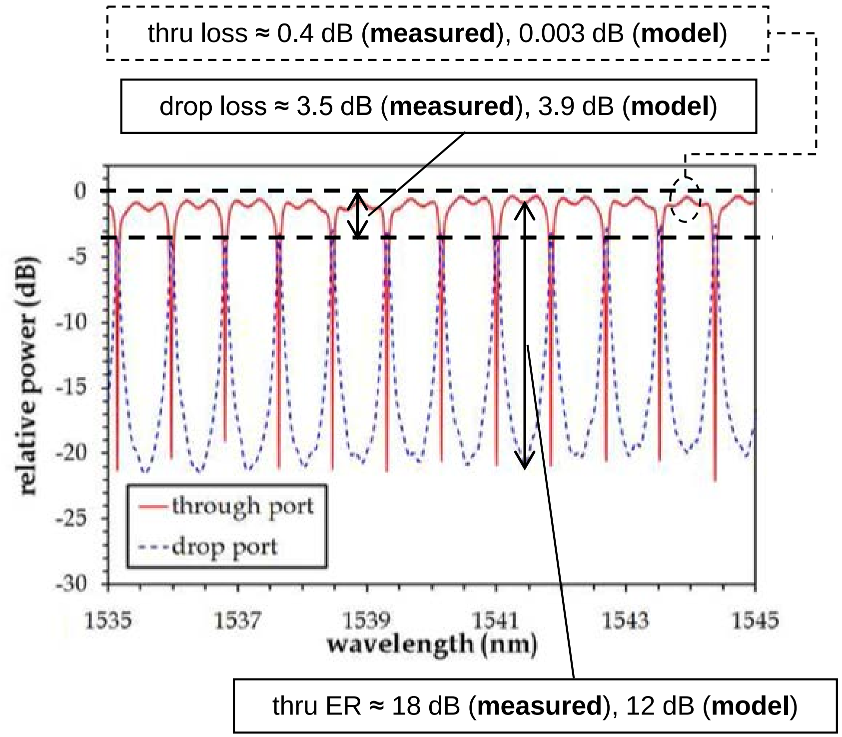
[Bahadori, et al. JLT, under revision]

Examples of Fabricated Rings

- P. Dong *et al.*, *Optics Express* (2007)



  - R = 100 μm (very big ring)
  - Q ≈ 19000 (measured),
  - Designed for critical coupling



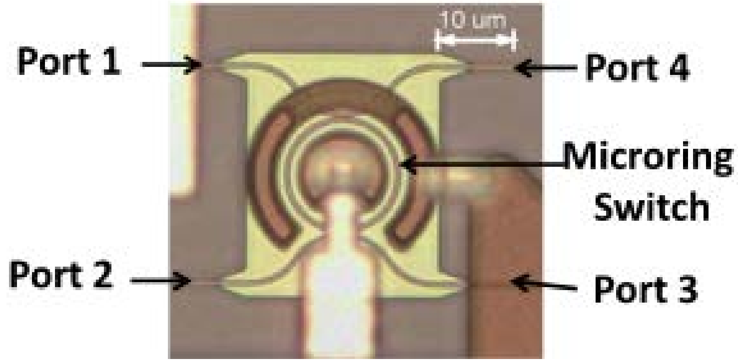
- Widely cited
  - But we could do better
    - Reduce drop loss
    - Pick the ideal BW for link

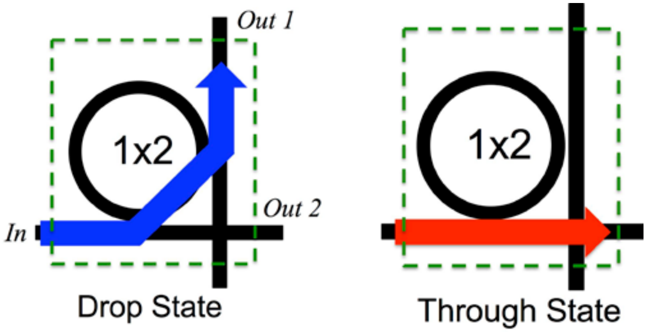
→ Measurements do not match model (higher loss in ring in 2007)

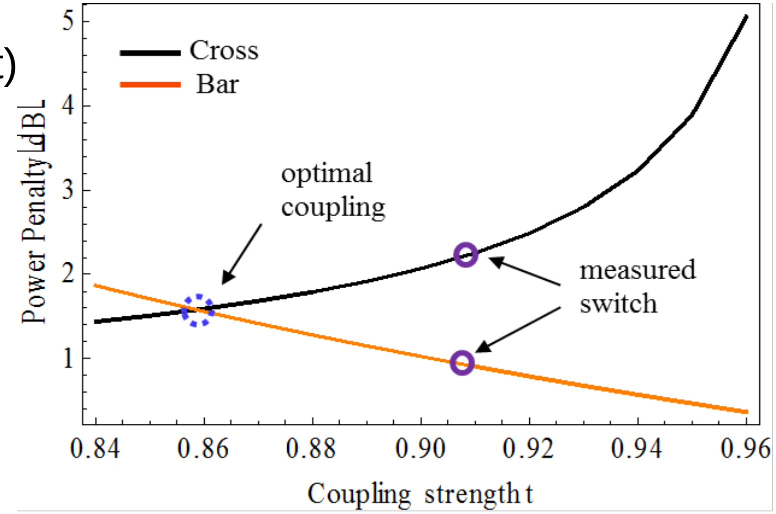
Another ring

- Analysed in Q. Li, PTL 27(18), 2015
  - t_{in} = t_{out} = 0.91
  - κ_{in} = κ_{out} = 0.44
  - Q = 1842
  - α = 6 dB/cm
  - No critical coupling!

  - Power penalties (measured):
    - Thru: -0.1 – -0.8dB (channel dependent)
    - Drop: -0.4 – -1.8dB
      (10 Gbps signals)

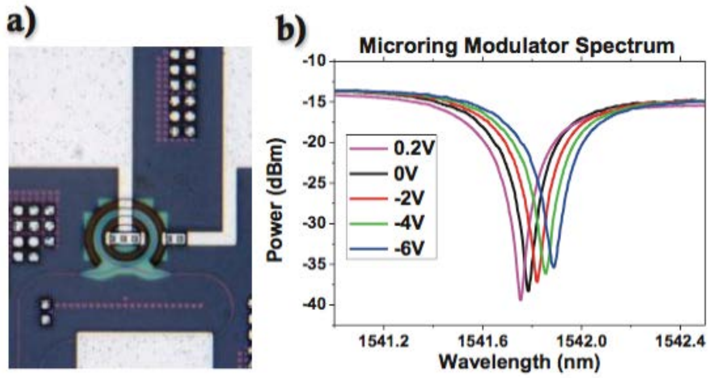






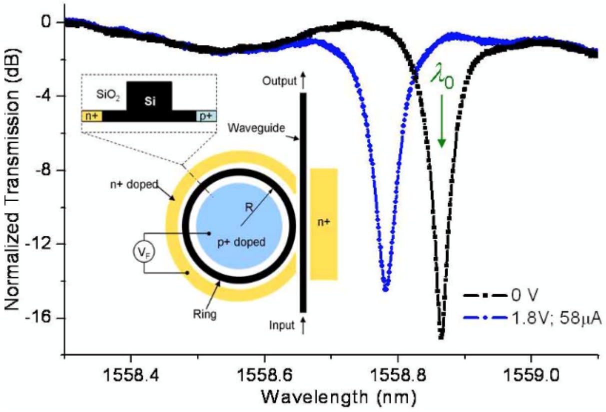
Examples of fabricated ring: filter/modulator

- Q. Li et al., OFC (2014)

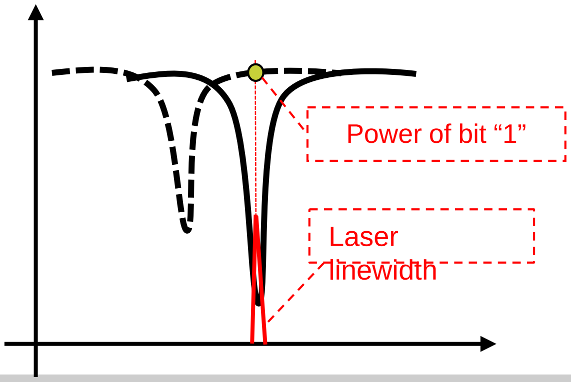


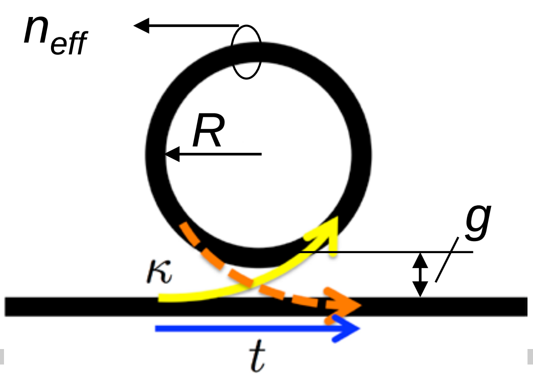
Modulator: R = 8 μm, Q = 4300

- Q. Xu et al., Opt. Express (2007)

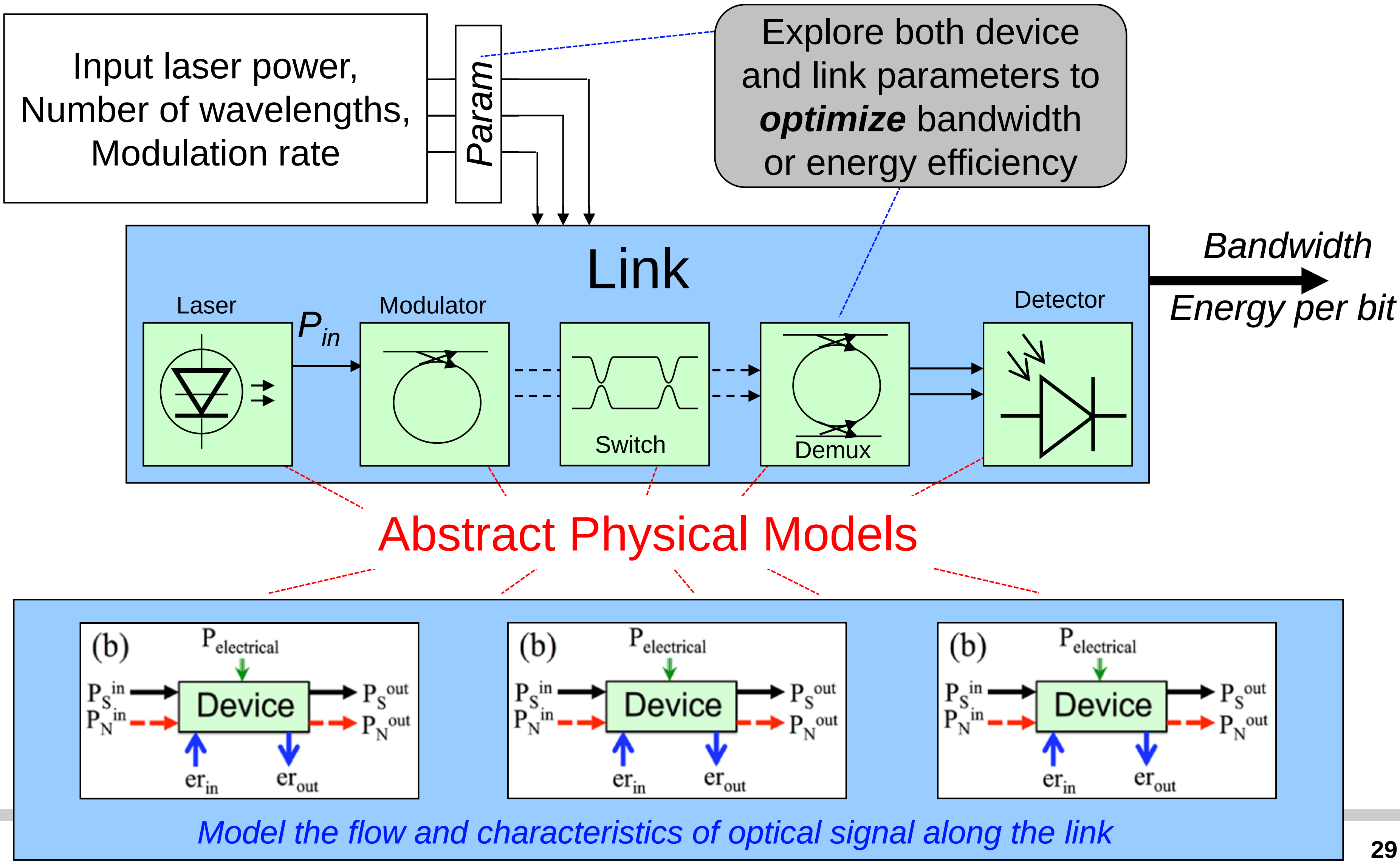


Modulator: R = 5 μm, Q = 20000 !

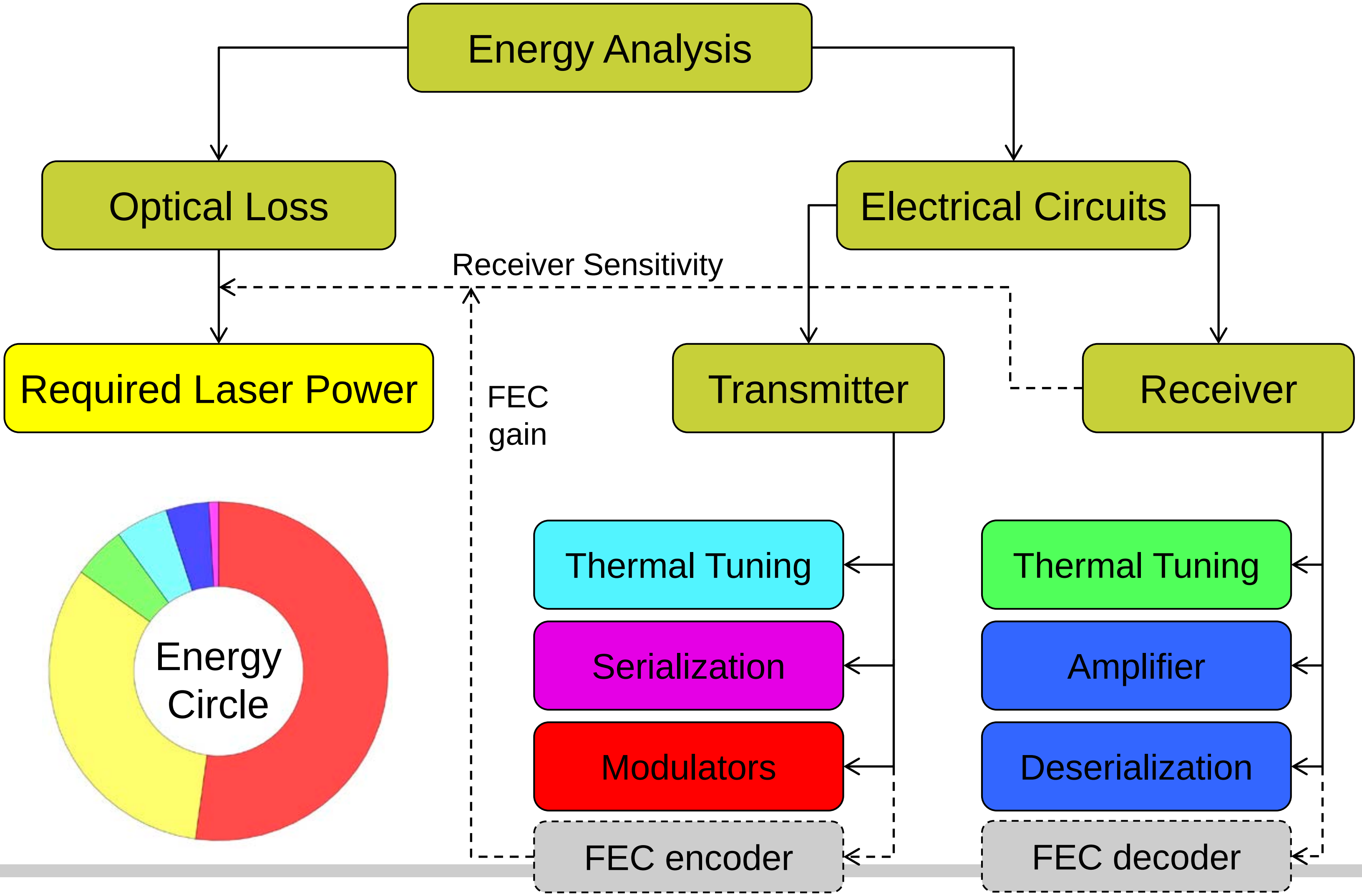




Methodology - Abstraction of Physical Devices

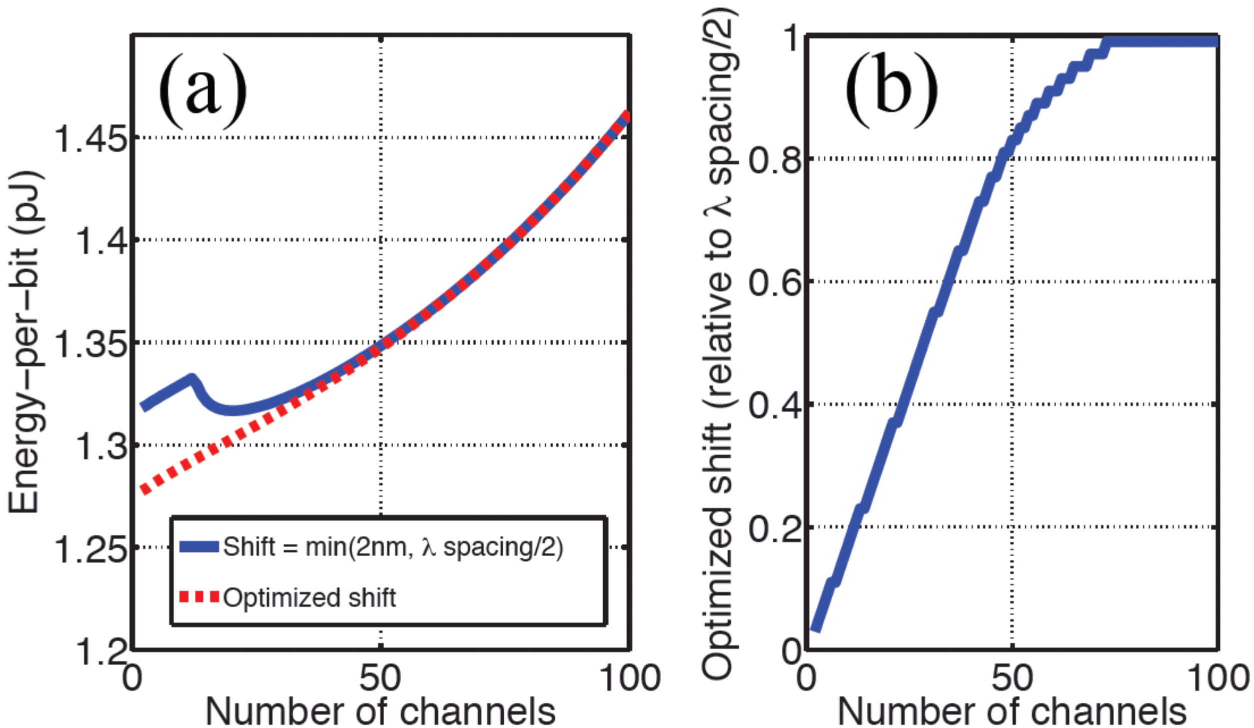


Methodology - Energy Analysis (pJ/bit)



Goal: conduct link wide optimizations

- E.g. extinction ratio (optical signal quality) vs. voltage (power consumption)
  → For low number of wavelengths, largest resonance shift not required [1,2]



[1] R. Wu, et al. "Compact modeling and system implications of microring modulators in nanophotonic interconnects", ACM SLIP 2015
[2] S. Rumley, et al. "PhoenixSim: Crosslayer Design and Modeling of Silicon Photonic Interconnects", AISTECS workshop, 2016

Conclusions

- Ring resonator based interconnects as very complex systems requiring fine tuning
  - Point I was thinking to make at this workshop: mind the ring bandwidth!
  - After making these slides: even more complex design space!
    For every ring:
    - Input gap, output gap, radius, (doping)
    - Find the right BW (depends on the architecture, bit-rate), align the wavelength, balance losses (also depends on the architecture), reach desired FSR…

  → Constant power penalty based approach questionable
    - Can be very conservative, or very optimistic, depending on the context
- Silicon photonics still lacks maturity
  - Well defined compact models, PDKs need to be defined
    - Previously proposed designs should be re-assessed against these definitions
  - Large scale modeling/design methodologies building on these PDKs to be developed
  - The (current) impossibility to realize small rings is a big concern