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

OPTICS 2016, March 18th, Dresden, Germany

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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

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
Review of ring resonator

- **Ring:**
  - A circular waveguide with properties:
    - Effective refractive index $n_{\text{eff}}$
    - Waveguide loss $\alpha_{\text{waveguide}}$ (1/m or 1/cm or dB/cm)
    → Obtained by numerical methods (FDTD or FEM)
  
  - Radius $R$ affecting:
    - Resonance
    - Loss in the ring
    \[ L \approx 1 - 2\pi R \alpha \]
  
  - Gap size affecting:
    - Coupling coefficient
    \[ |\kappa| \sim \frac{1}{\text{Gap Size}} \]
Investigating ring loss and coupling coefficients

- Bend-loss (dB/cm) vs. Radius (µm)
- Coupled waveguides
- Current PDK
- Futuristic PDK
- Coupling coefficient

Equations:
- $4.84 \times 10^7 R^{-7.8} + 2$
- $1.04 \times 10^9 R^{-10.13} + 1.2$

[Jayatilleka et al., JLT, 2016]
High level metrics for ring resonators

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

- Free spectral range (FSR)

- Transmission at resonant frequency
  - vestiges from filtering

- Transmission at detuning of FSR/2
  - exactly between resonances
Ring resonator filter – desired properties

- Good signal suppression (at resonance)
  \[ L = 1 - k^2 \rightarrow 2\pi R\alpha \approx k^2 \]

- Critical coupling: \( TR_{\text{res}} \sim 0 \)

- FSR large enough to maximize WDM capabilities

- Low suppression outside resonance
  \( TR_{\text{max}} > -0.05 \text{ dB} \) (cascading 20 \( \rightarrow \) 1dB, cascading 100 \( \rightarrow \) 5dB)

- Bandwidth large enough to support signal
  \( \text{FWHM}_{\text{GHz}} > \sim \text{Bitrate}_{\text{Gbit}} \text{ OOK} \)
Ring resonator filter – reducing design space

- Attenuation at resonance
- Minimal attenuation
- Ring bandwidth

Graphs showing the relationship between gap size (nm) and ring radius (µm) for different parameters.
Impact of high-speed signals

Ring bandwidth @ 10Gbps

Ring bandwidth @ 25Gbps
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
    - $\text{IL}((\text{detuning} = 50\text{nm}/\#\text{channels} - \text{bitrate})) < 0.05\text{dB}$
Ring diameter limitation

- Selection of designs leading to signal suppression of -15dB at least

- Below 4\(\mu\)m, 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:

\[ L = \frac{1 - \kappa_{\text{out}}^2}{1 - \kappa_{\text{in}}^2} = \frac{t_{\text{in}}^2}{t_{\text{out}}^2} \]

- Transmission (thru) at resonance:

\[ TR_{\text{res}} \approx \left( 1 + \frac{\kappa_{\text{out}}^2}{2\pi R\alpha} - \frac{\kappa_{\text{in}}^2}{2\pi R\alpha} \right)^2 \]

- Transmission (drop) at resonance

\[ DR_{\text{max}} \approx \left( 1 + \frac{\kappa_{\text{out}}^2}{2\pi R\alpha} + \frac{\kappa_{\text{in}}^2}{2\pi R\alpha} \right)^2 \]

- Transmission (thru) out of resonance (at FSR/2):

\[ TR_{\text{max}} \approx \frac{\left( \frac{\lambda Q}{2\pi Rn_g} \right)^2}{\left( \frac{\lambda Q}{2\pi Rn_g} \right)^2 + TR_{\text{res}}} \]
Design space pruning

How to choose? Depend on the architecture (number of thru, drop) • number of channels • channel rate

Ideal drop loss (0.1 dB) But high thru loss (0.05 dB)

Thru loss limited

Ideal thru loss (0.002 dB) but high drop loss (0.5 dB)

Drop loss limited

Min attenuation (thru) out of resonance

Truncation limited
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

[Graph showing bandwidth and Q factor as functions of ring radius and input gap size]

- Bandwidth
  - 10 Ghz
  - 50 Ghz
  - 80 Ghz

- Q factor
  - 10 Ghz
  - 16500
  - 2350
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

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

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

\[
\nu = \frac{f_0}{2Q \times r_b}
\]

\[
\beta = \frac{2Q}{f_0} f_{\Delta}
\]

Taking into account possible detuning

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

Freq. detuning from \( f_0 \)
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)

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

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

\[ \nu = \frac{f_0}{2Q \times r_b} \]

Taking into account Bandwidth of ring and DATA RATE

\[ Q \approx 20000 \]
\[ BW_{3dB} \approx 10 \text{ GHz} \]
Impact of BW/Q: effect of other filters

• Attenuation of the Lorentzian tail for drop path
  – at critical coupling

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

- 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

\[
\text{IL Penalty}_{\text{(thru)}} = -10 \log_{10} \left( \frac{\left( \frac{2Q}{f_0} f_\Delta \right)^2}{1 + \left( \frac{2Q}{f_0} f_\Delta \right)^2} \right)
\]
Total Penalty of a **Single** Add/Drop Ring Filter

Increasing Q will **increase** both the IL penalty and Truncation Penalty

\[ R = 10 \, \mu m \] @ critical coupling (any rate)

- **Drop Insertion Loss (dB)**
  - \( \alpha_{loss} = 2.8 \, dB/cm \)

- **Truncation Penalty (dB)**
  - Increase of DATA RATE

Playing with the gap size
Impact of Q: Crosstalk in Ring Filters

- Optical Crosstalk as a noise mechanism
  \[ P_{P_{\text{XTalk}}} \approx -10 \log_{10} \left( 1 - \frac{1}{2} q_{\text{BER}} \right) \]

- **0th-order** Approximation
  - ignore the spectral bandwidth of modulation OOK light
  - Assume all the optical power is at the carrier (center) wavelength
    \[ S(E) \approx \mu^2 \delta(f - f_c) + \sigma^2 \delta(f - f_c) \]
  - Good approximation for LOW data rates and/or FLAT filters
  - This method has been widely used
Impact of Q: Crosstalk in Ring Filters

- **1st-order** Approximation
  - do not ignore the spectral shape of the OOK modulation
    \[(P_{XTalk})_{i}^{th \, Ring} \approx P_{NRZ} \times \sum_{j=1, j \neq i}^{N} \Gamma_{i,j}\]
  - 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

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

\[
F_{\Delta} = f_{\Delta}/r_b
\]

\[
\xi_k = \text{FWHM}/(2r_b)
\]
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
  - $t_{in} = t_{out} = 0.91$
  - $\kappa_{in} = \kappa_{out} = 0.44$
  - $Q = 1842$
  - $\alpha = 6 \text{ dB/cm}$
  - No critical coupling!

- Power penalties (measured):
  - Thru: $-0.1 - -0.8 \text{dB}$ (channel dependent)
  - Drop: $-0.4 - -1.8 \text{dB}$
    (10 Gbps signals)
Examples of fabricated ring: filter/modulator

- Q. Li et al., OFC (2014)
  
  Modulator: $R = 8 \ \mu m$, $Q = 4300$

  
  Modulator: $R = 5 \ \mu m$, $Q = 20000$
Methodology - Abstraction of Physical Devices

Input laser power, Number of wavelengths, Modulation rate

Explore both device and link parameters to optimize bandwidth or energy efficiency

Abstract Physical Models

Model the flow and characteristics of optical signal along the link
Methodology - Energy Analysis (pJ/bit)

Energy Analysis

Optical Loss

Required Laser Power

Electrical Circuits

Transmitter

Receiver

Receiver Sensitivity

FEC gain

Energy Circle

Thermal Tuning

Serialization

Modulators

FEC encoder

FEC decoder

Thermal Tuning

Amplifier

Deserialization
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]

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