PHOTONICS RESEARCH GROUP

Novel degrees of freedom for design of silicon microrings

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Promotor: Prof. Wim Bogaerts

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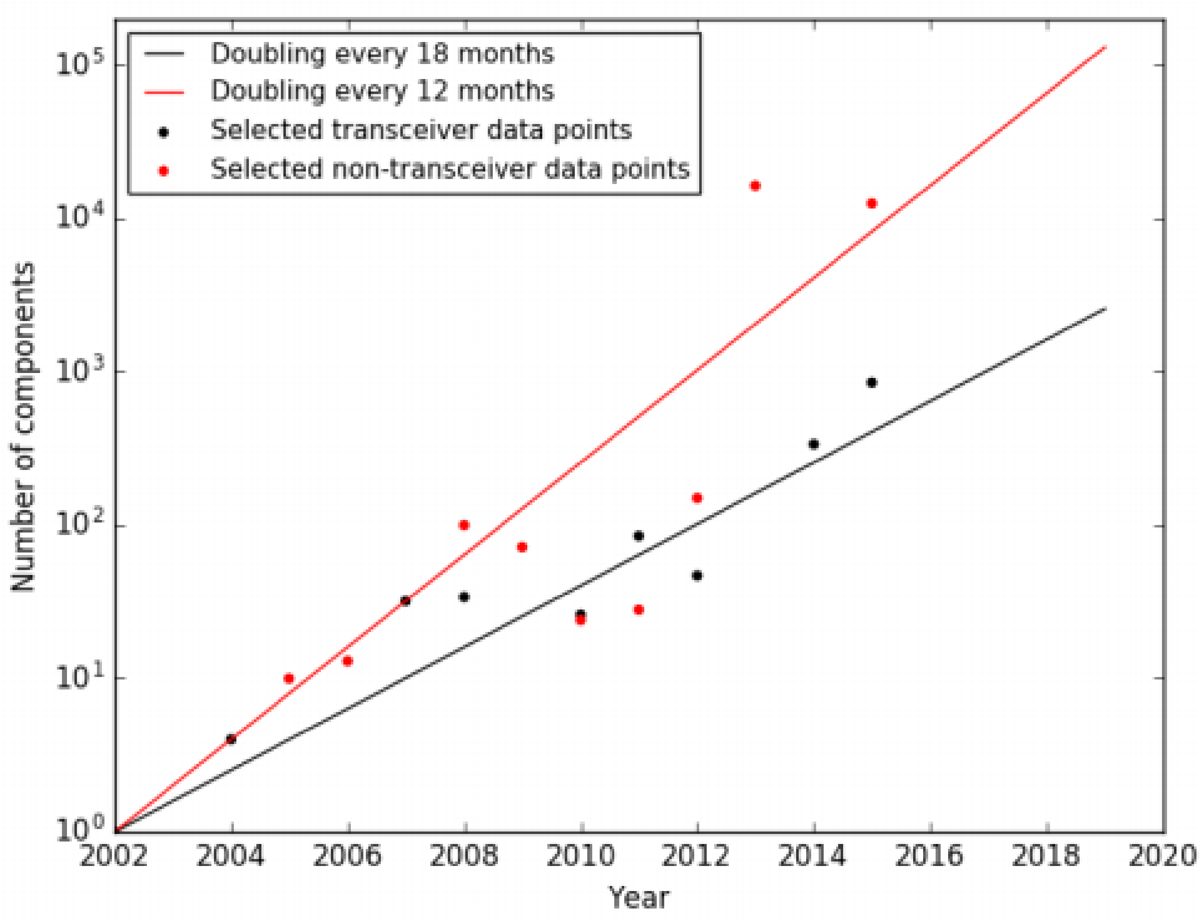
imec embracing a better life

BACKGROUND

- At the stage of maturation of silicon photonics



A. Khanna, OFC, Th1B.3, 2017

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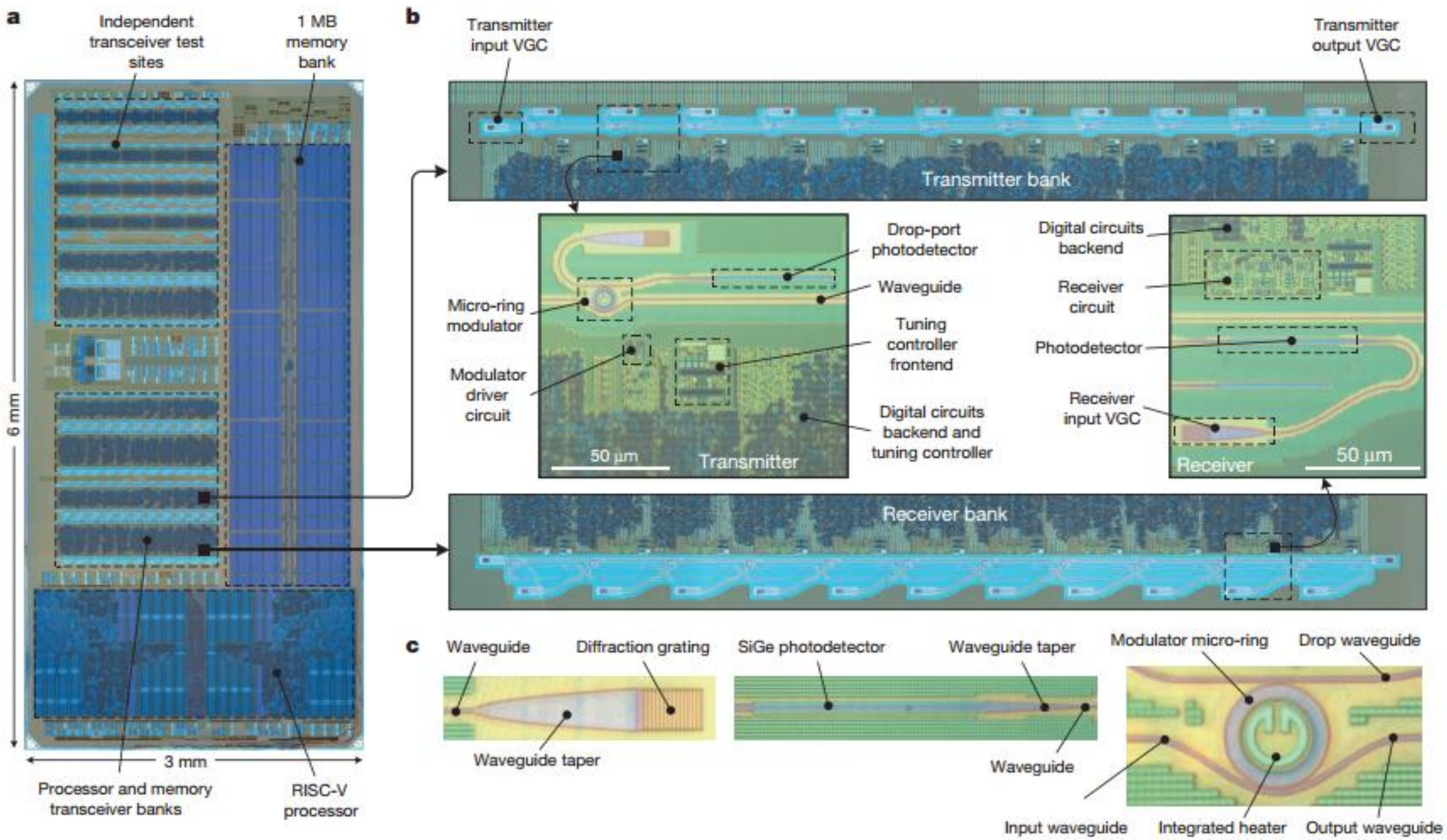
BACKGROUND

- Large scale PICs around corner
- State of the art silicon PIC contains >1000 optical components



C. Sun, Nature volume 528, pages 534–538, 2015

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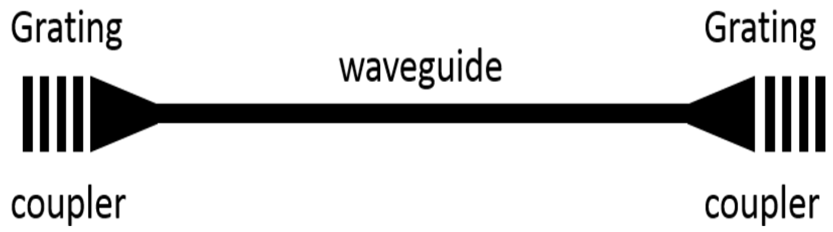
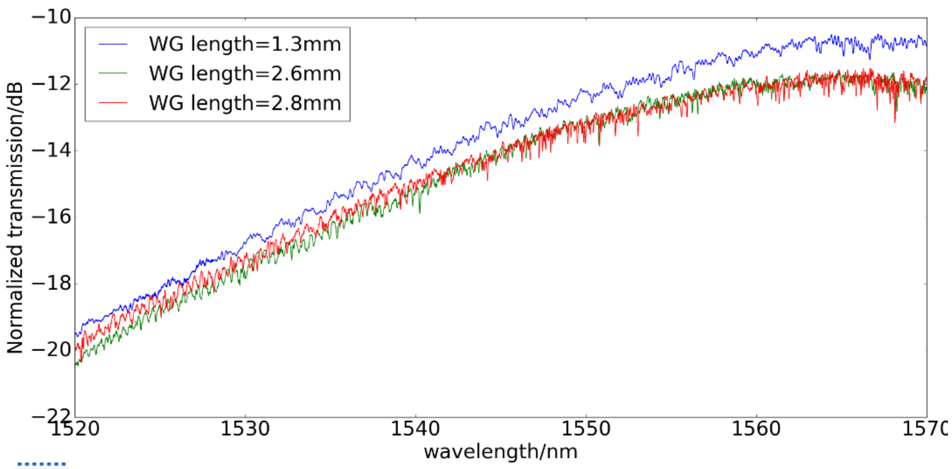
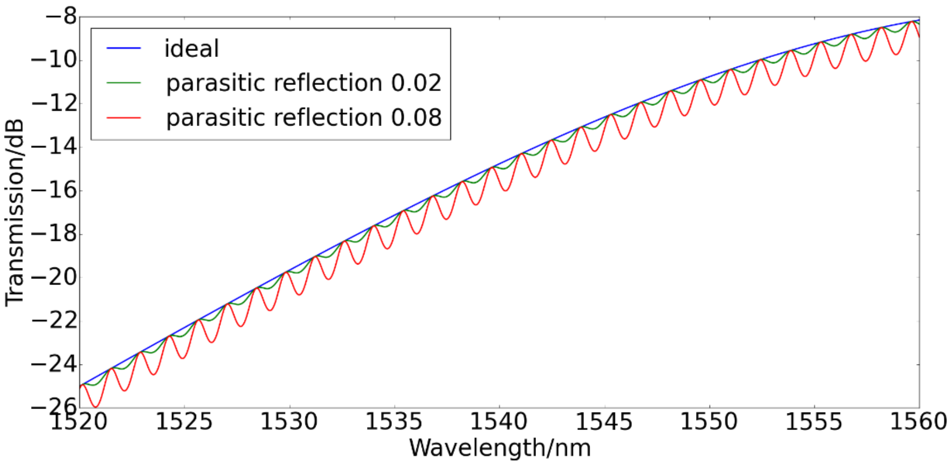
PARASITICS IN SILICON PIC

- Emerging issues
  - Variability
  - Parasitics
    - Unwanted effects
    - Substrate coupling, radiations, reflections etc.
    - Severe in high integration density







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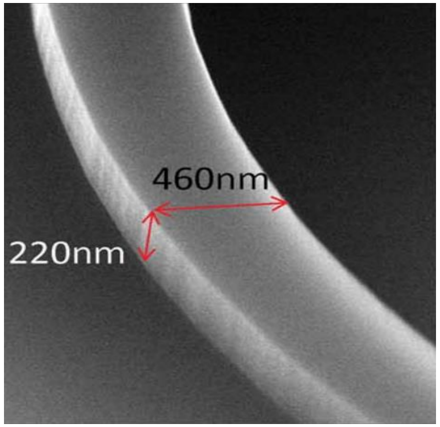
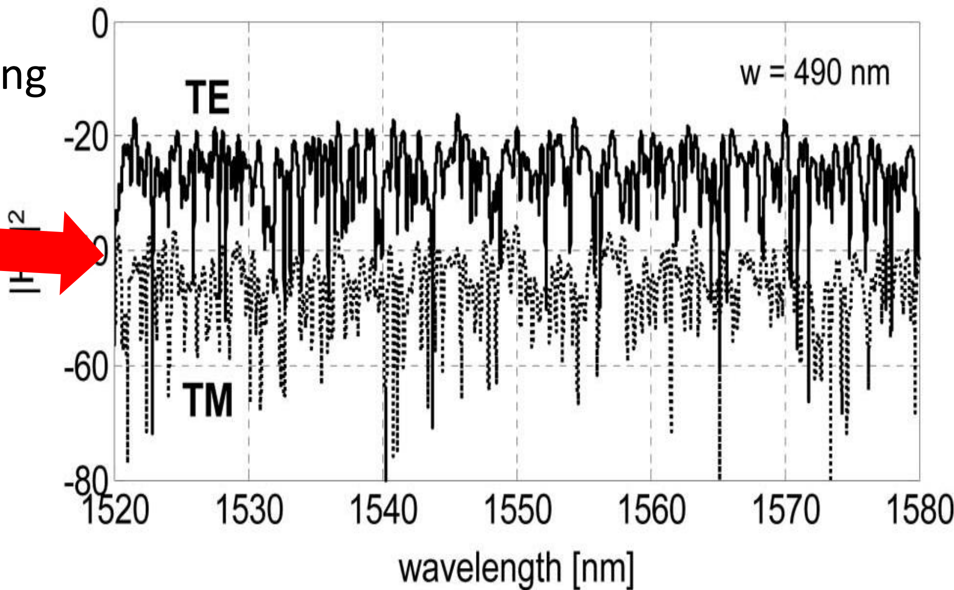
Backscattering in silicon waveguide

- Roughness
  - Lithography and etching leads to sidewall roughness
  - loss and backscattering



- Backscattering
  - Numerous distributed reflections along propagation
  - Induce stochastic reflections
  - also influence transmission



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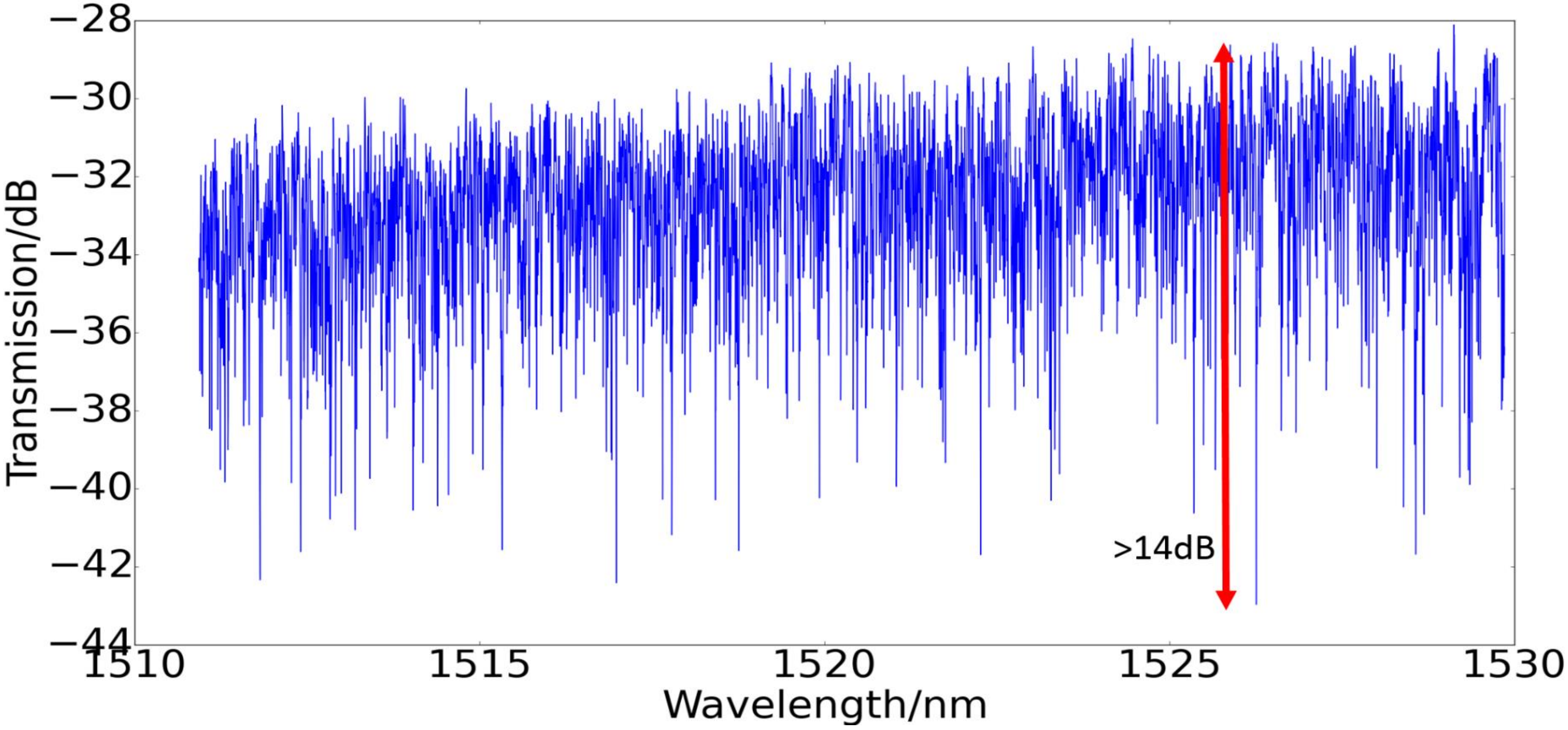
Backscattering in silicon waveguide

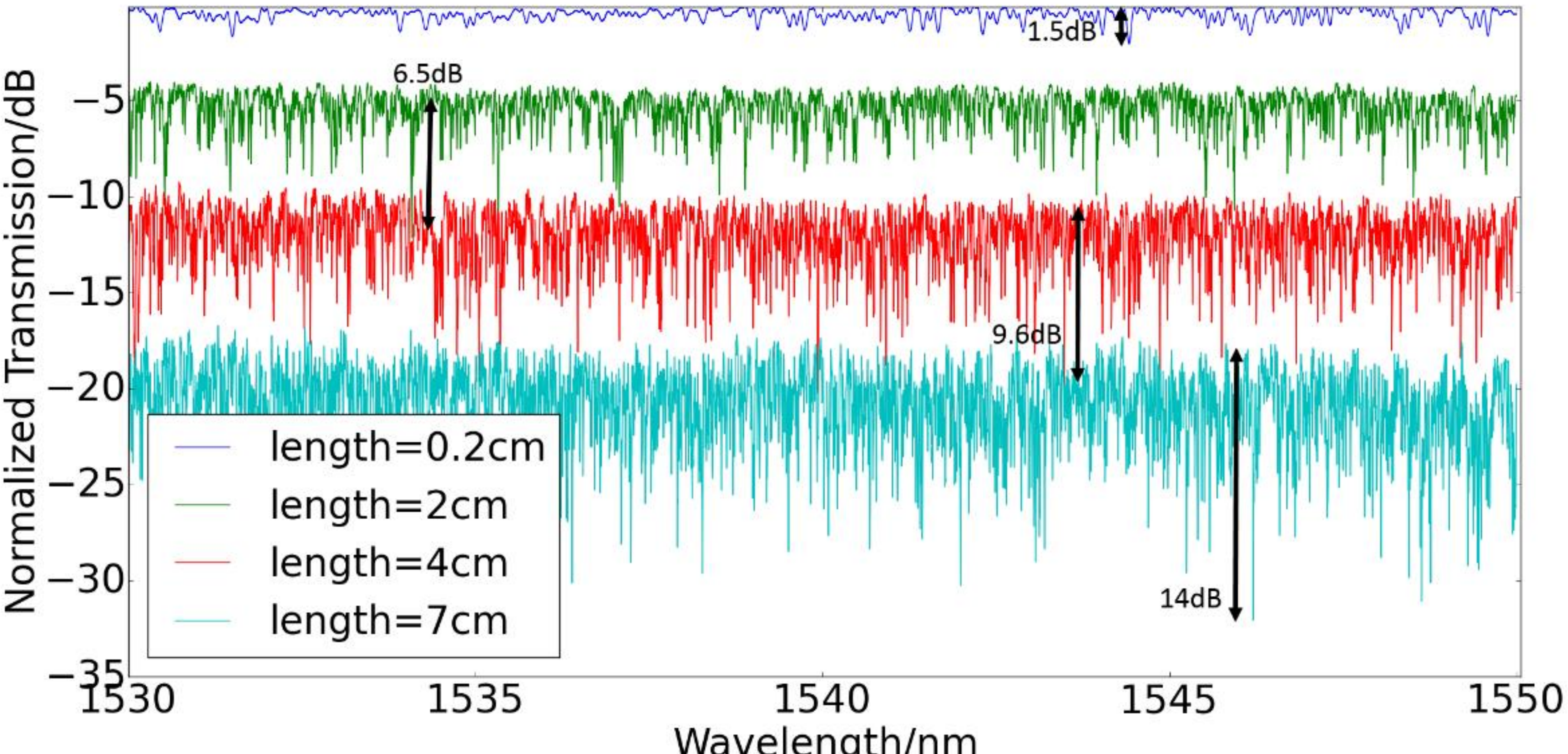
- Fluctuations in transmission spectral
  - Unacceptable for sensors, reservoir computing, chip scale interconnect etc.



7cm long strip WG fabricated at IMEC 200mm pilotline

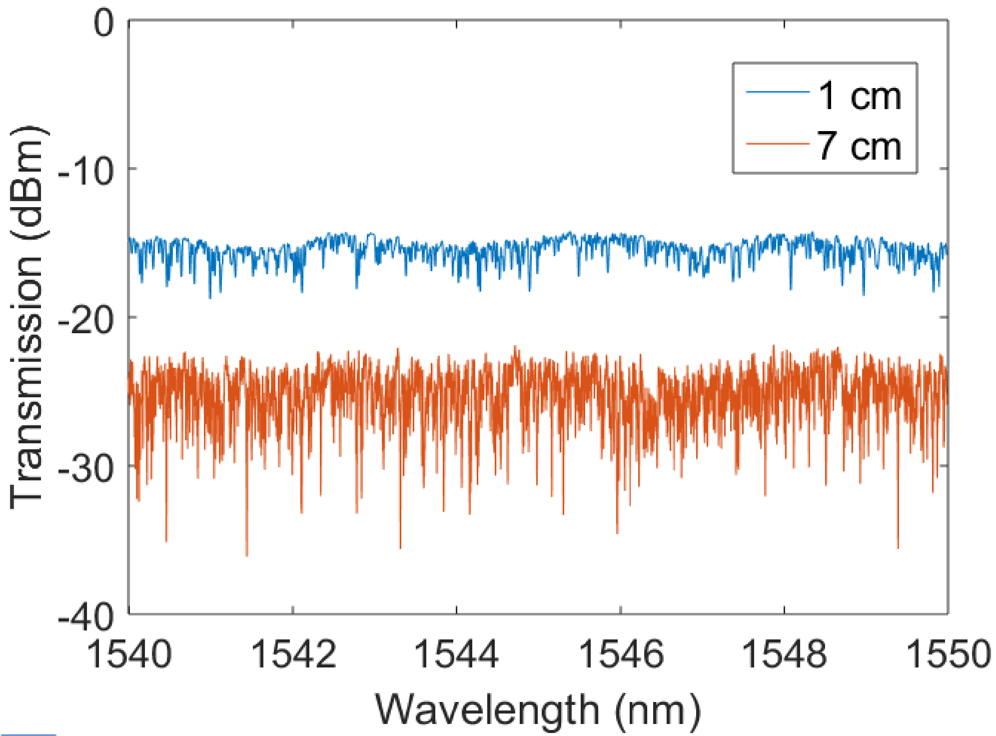
BACKSCATTERING IN SILICON WAVEGUIDE

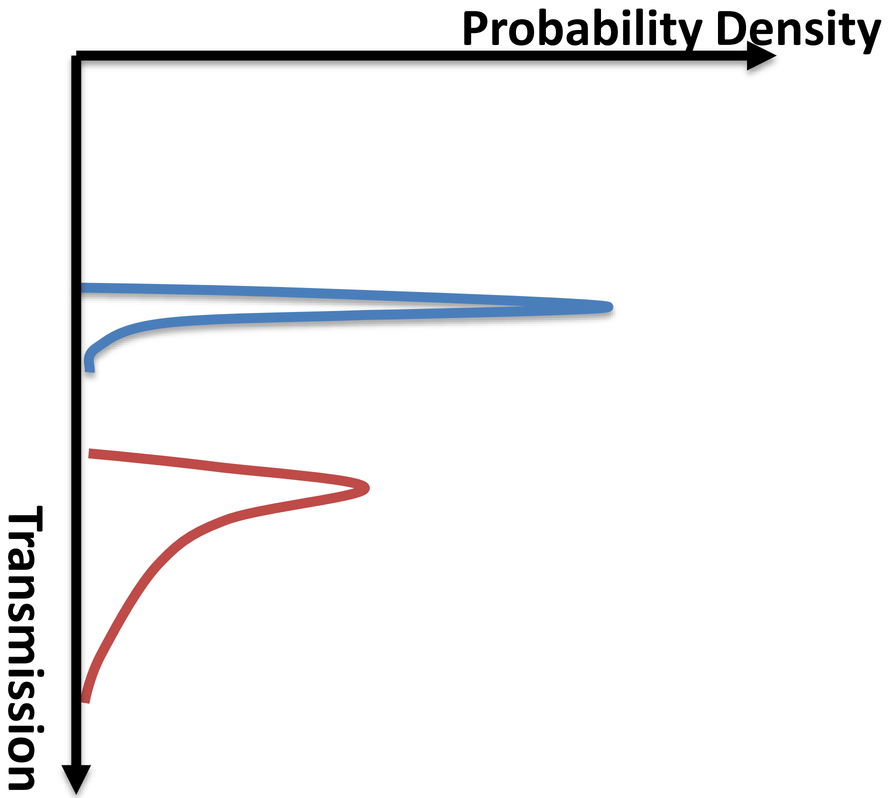
- Fluctuations in transmission spectral
  - Appears universally in air-clad strip WG
  - Waveguide length dependent



BACKSCATTERING IN SILICON WAVEGUIDE

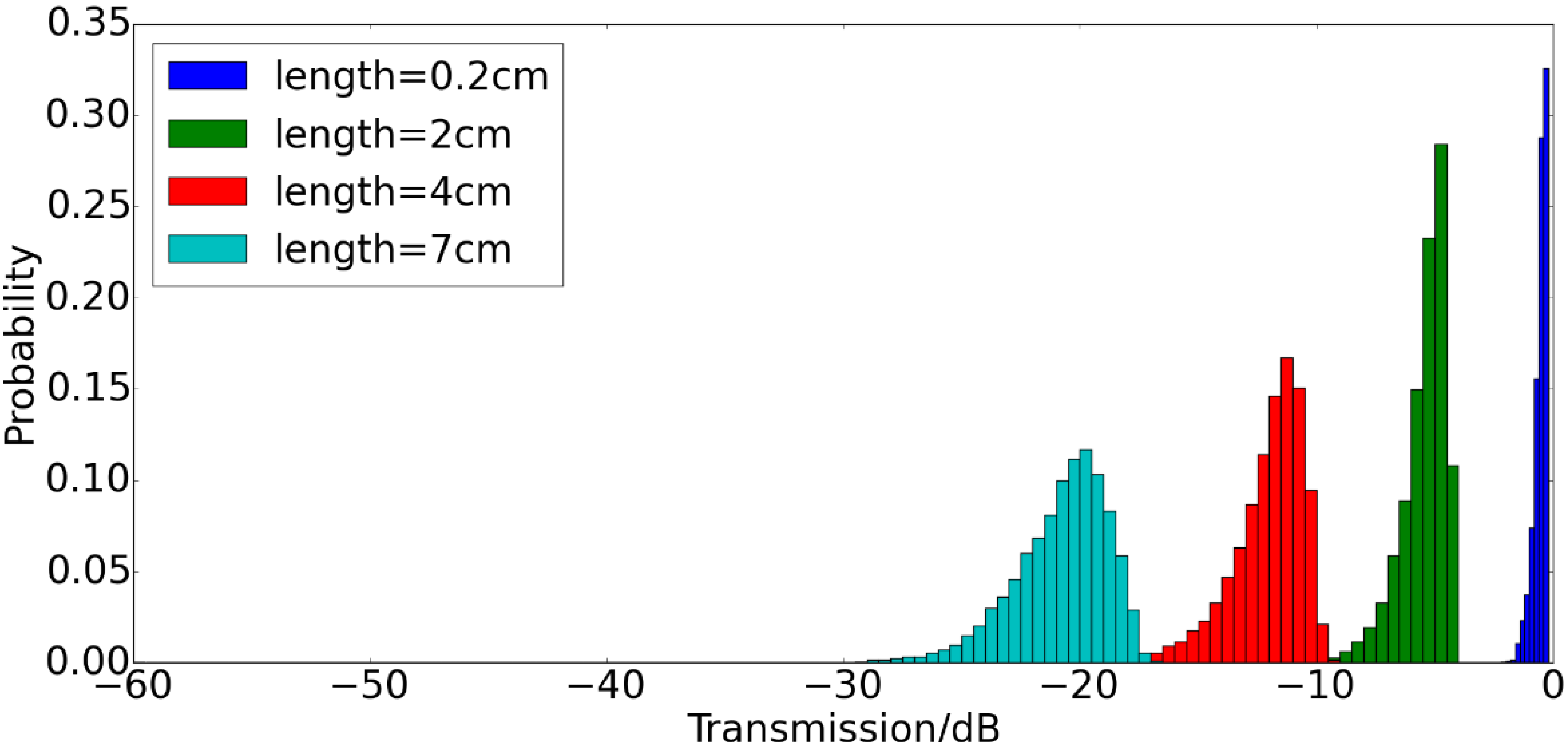
- PDF of the spectrum gets broader
    - WG transmission becomes non-deterministic
- WG Shall be characterized with a model instead of a loss factor
    - Yufei working on it





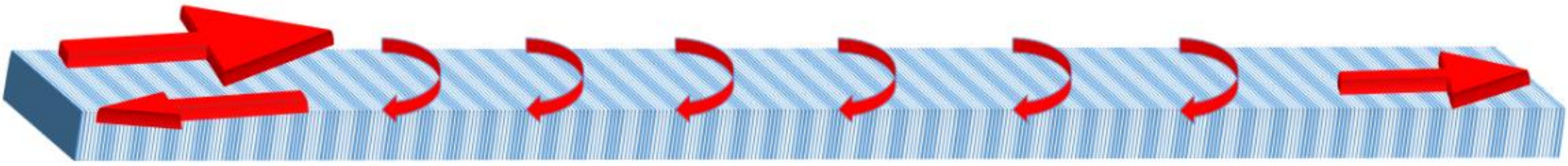
Backscattering in silicon waveguide

- Fluctuations in transmission spectral
  - Extreme value distribution fits well

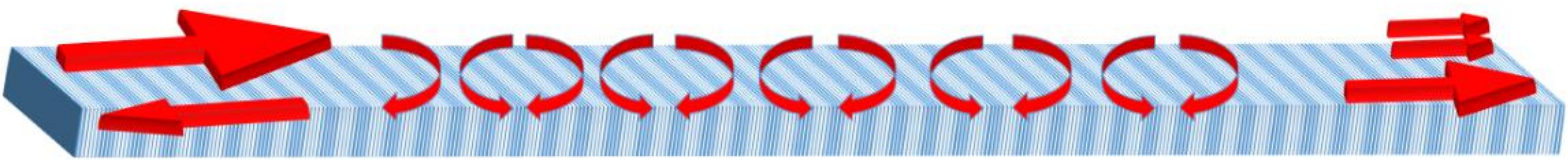


Backscattering in silicon waveguide

- Origin attributed to coherent multi-backscattering events
    - Numerous beams interfere at the output
    - Not new in photonics crystal WG. First reported in strip WG



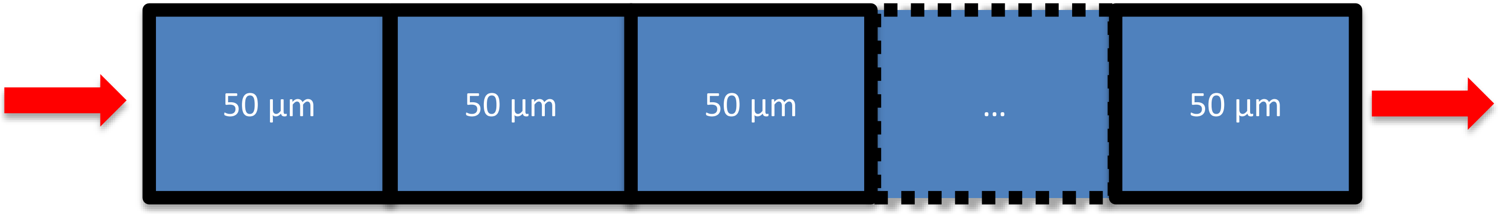
(a) Roughness: radiation loss + distributed backscattering



(b) Roughness: Coherent multi-scattering; Transmission influenced

Backscattering in Silicon Waveguide

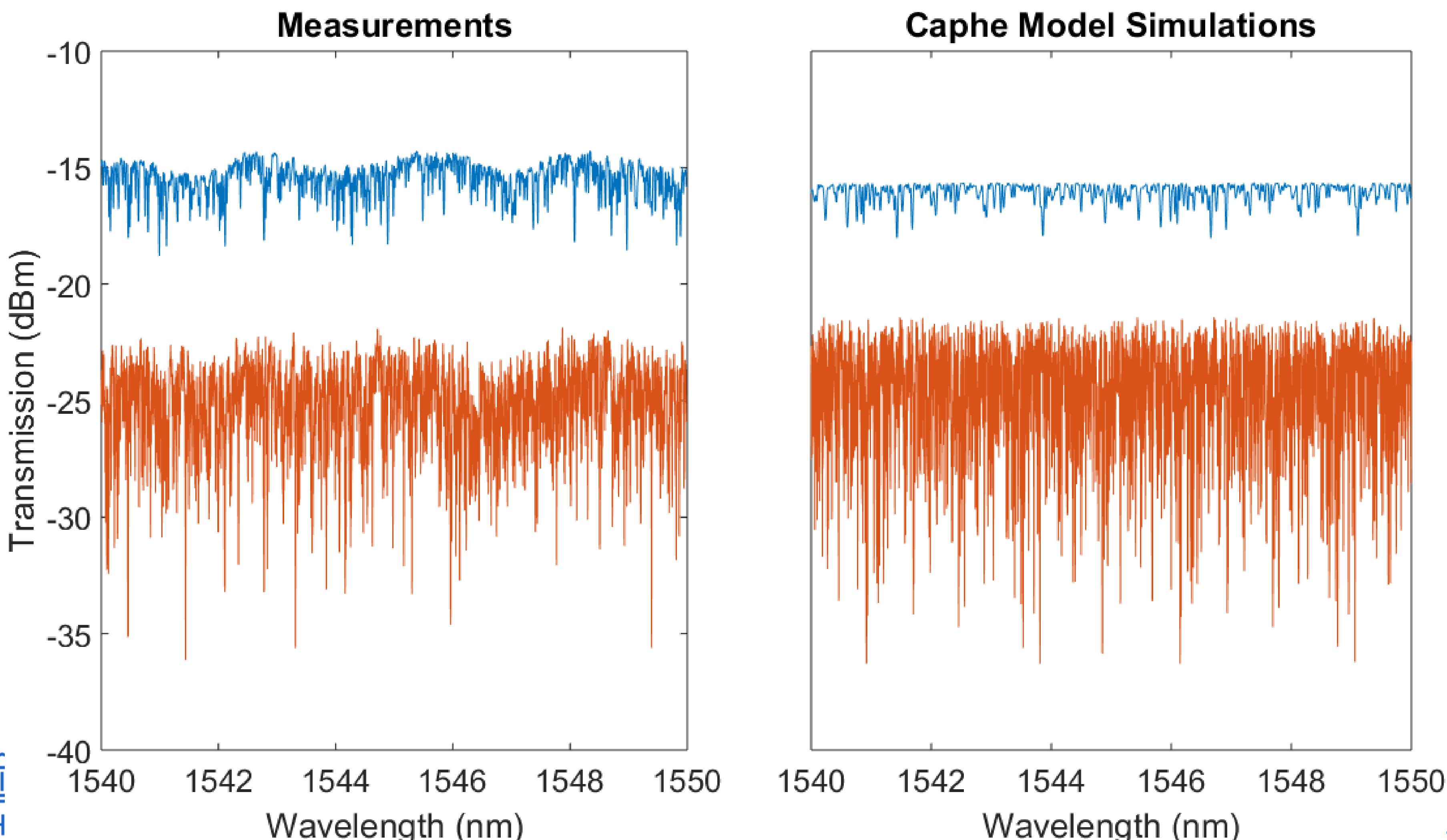
- Optical circuit model
  - Sectionize a WG into segments with reflector in between
  - Parameters :
    - Loss α
    - Reflectivity r → constant
    - Reflection phase ϕ → random



Y. Xing et al. OWTNM 2016, Poland

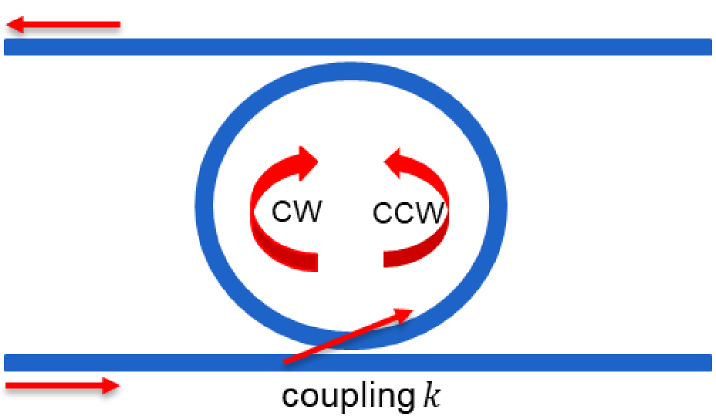
BACKSCATTERING IN SILICON WAVEGUIDE

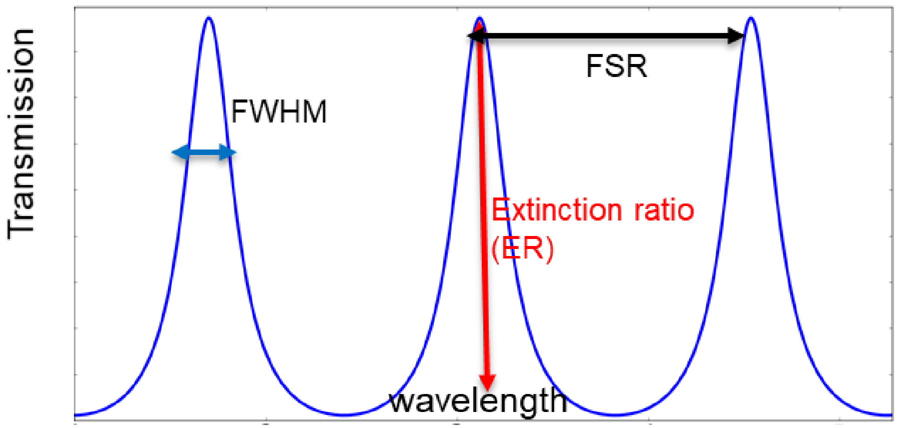
- Optical circuit model



PARASITICS IN SILICON MICRORING

- Parasitics in resonator are more severe, as light travels multiple rounds
- Two degenerate circulating modes (CW and CCW)
- Only two parameters to be manipulated for a ring resonator
  - Total roundtrip length L
  - Coupling coefficient κ

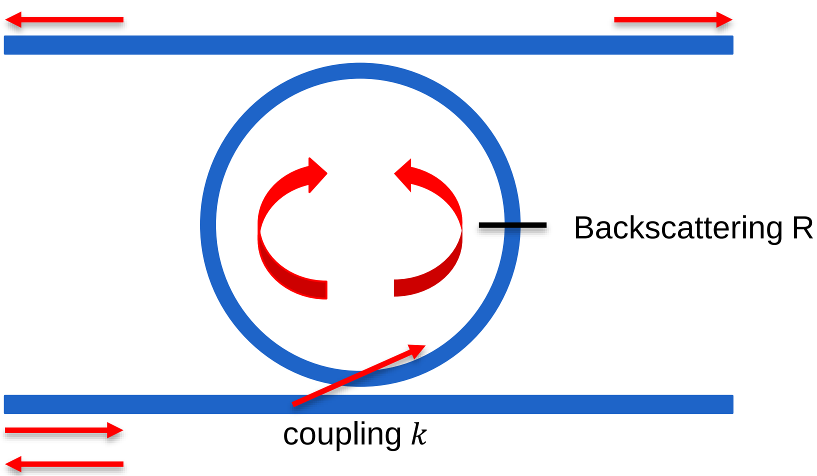


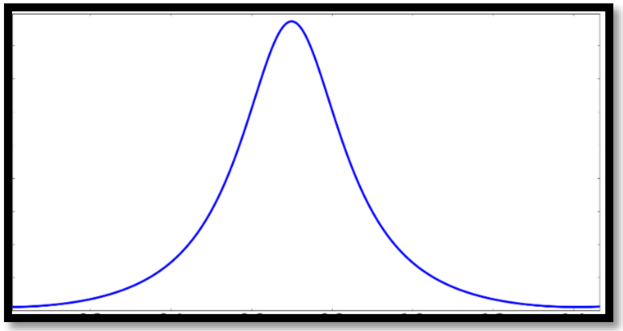


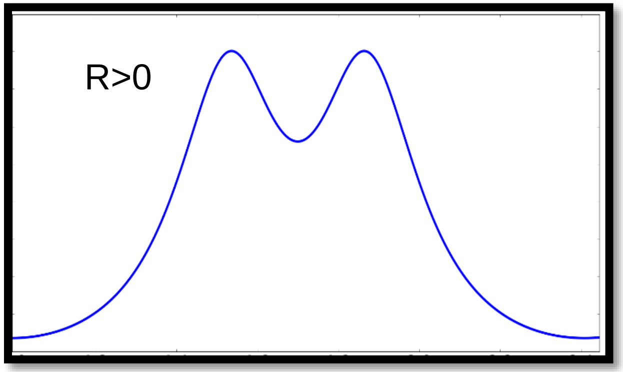
$$Q = \frac{\lambda}{FWHM}$$

PARASITICS IN SILICON MICRORING

- Backscattering/reflections
  - couples two modes and break degeneracy → splitting

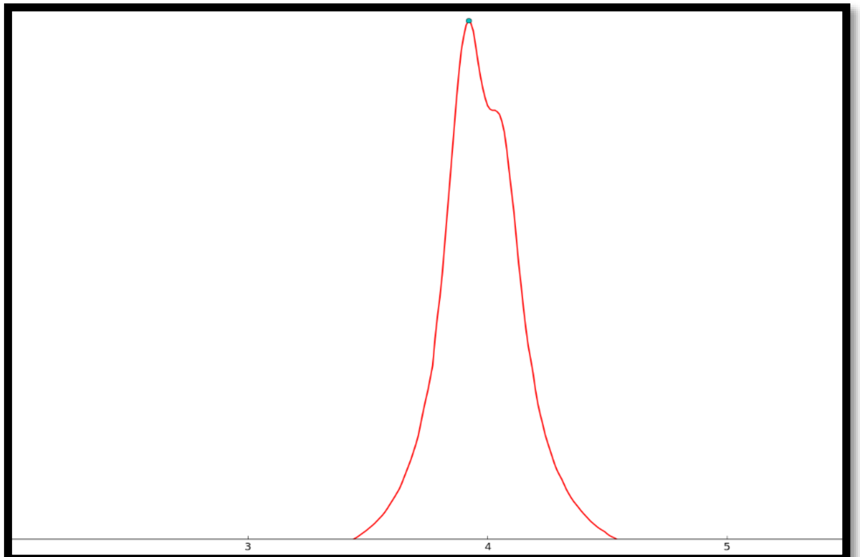


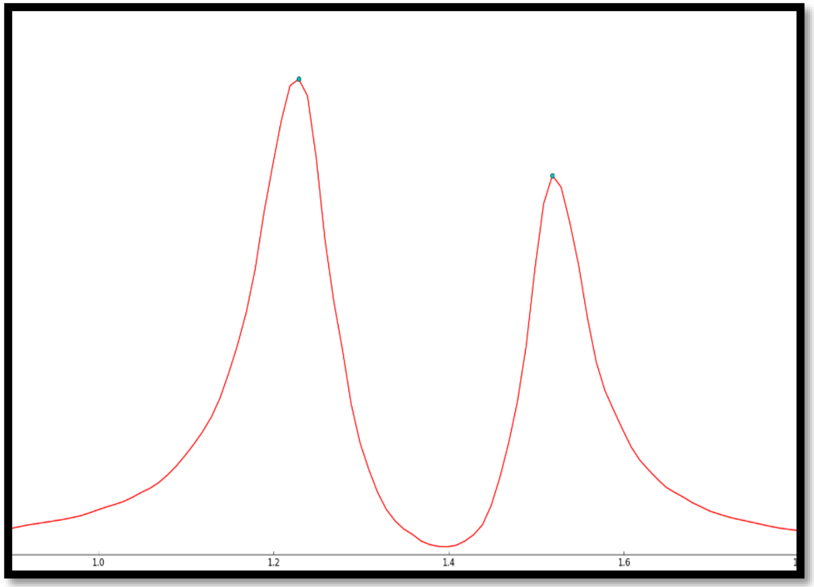


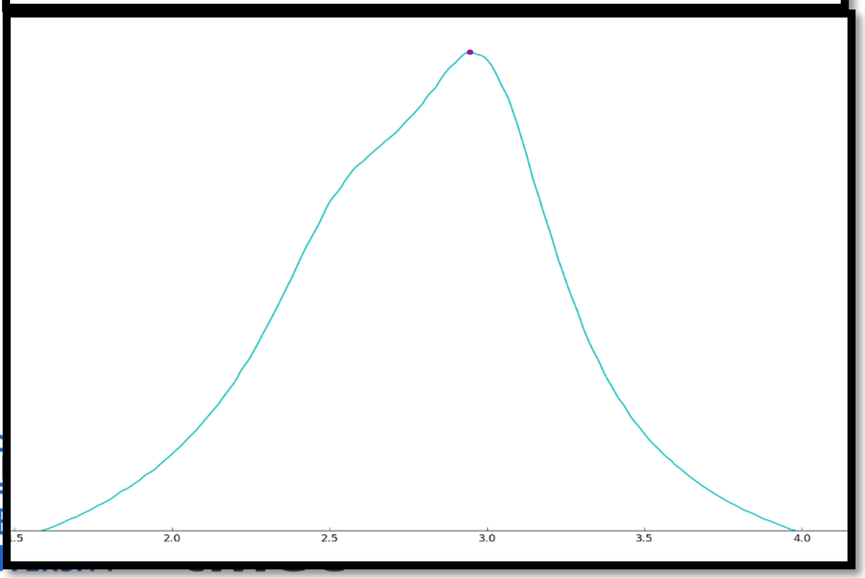


PARASITICS IN SILICON MICRORING

- Real examples







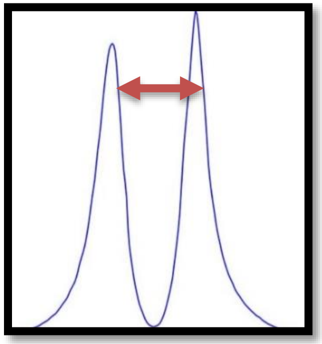
Real world gives resonance splitting!

PARASITICS IN SILICON MICRORING

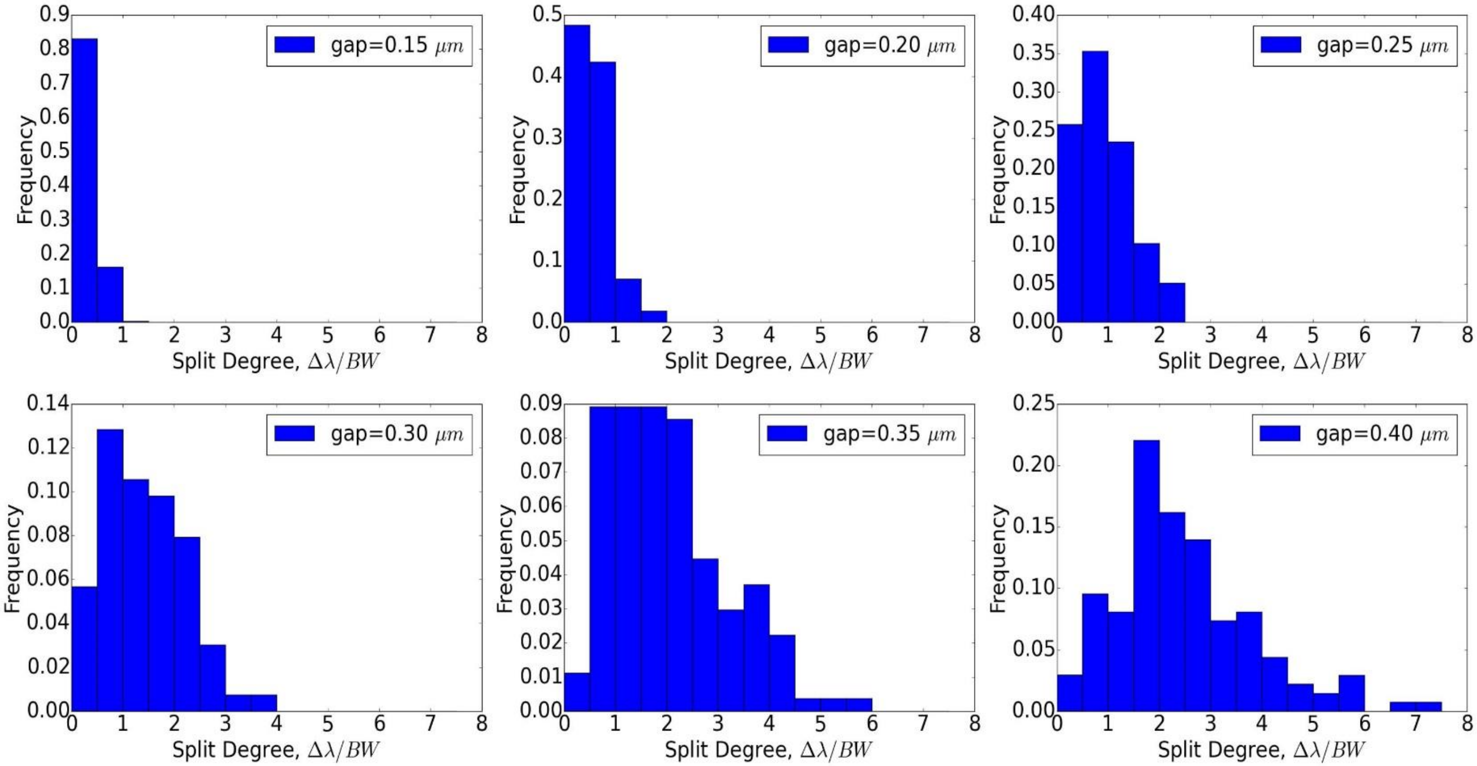
Split distance : $\Delta\lambda$

Bandwidth :BW

Split degree: $\Delta\lambda$/BW



- Statistics
  - Measured 50+ rings with 1000+ resonances
  - 550 show splitting



Split degree under different coupling gaps

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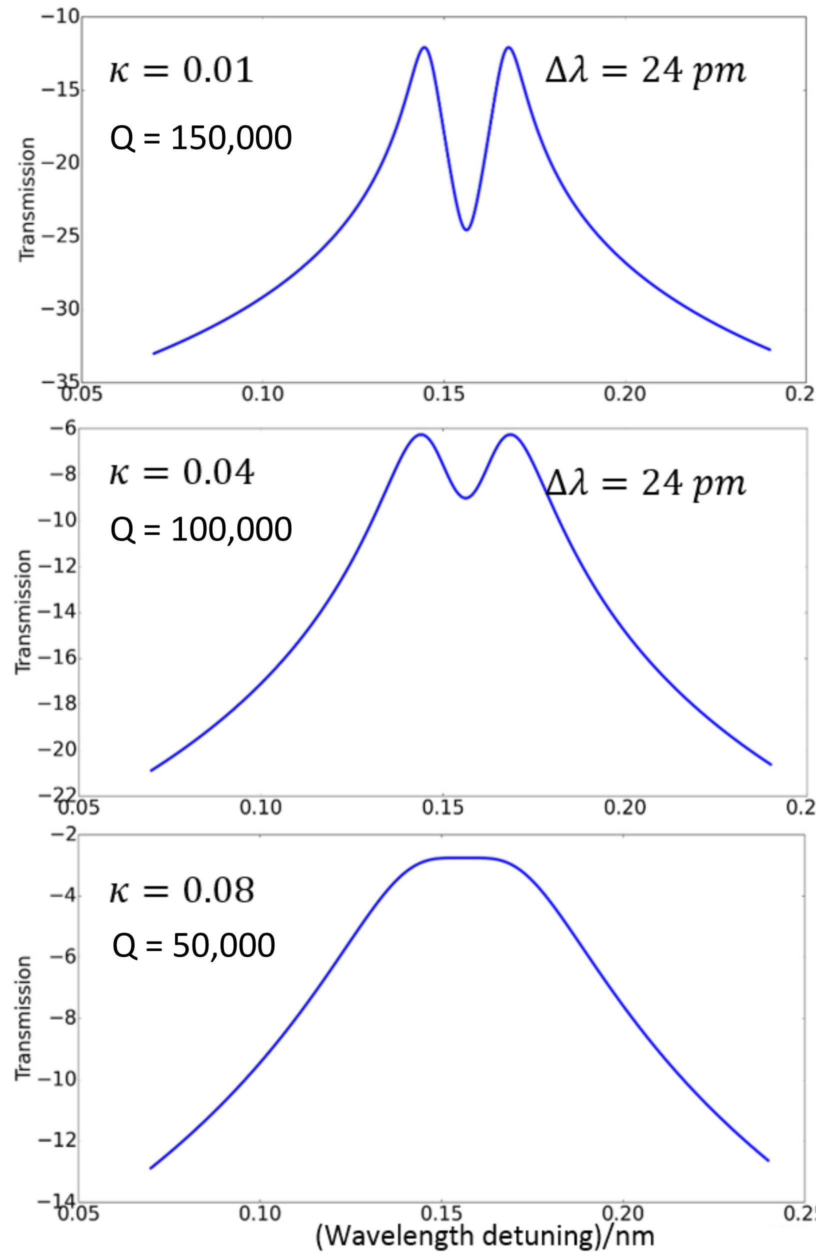
PARASITICS IN SILICON MICRORING

- Low Q → less splitting

- Low Q → invisible splitting



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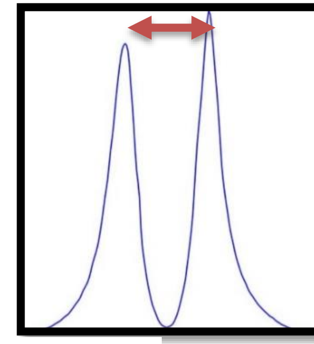
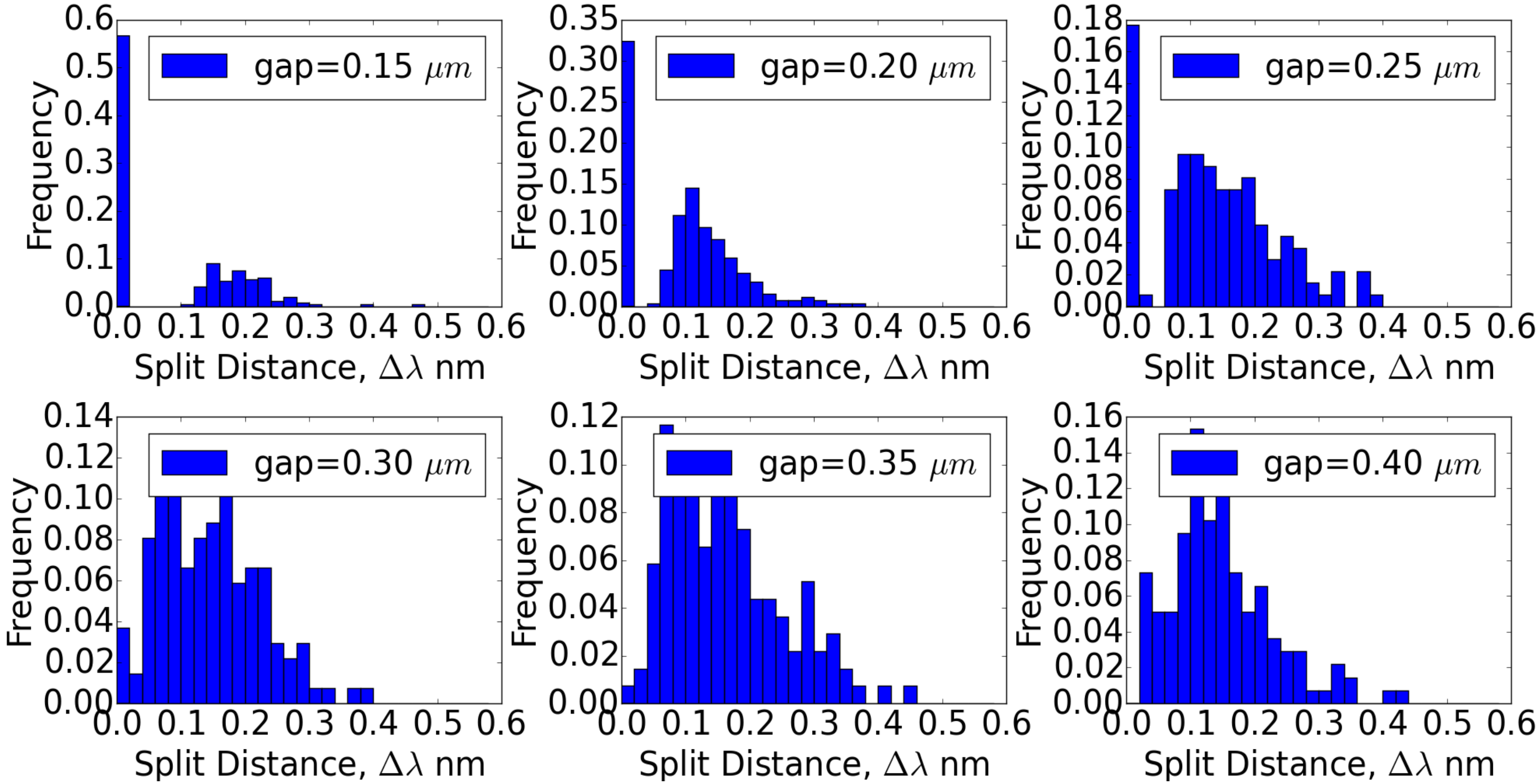
Parasitics in silicon Microring

- Statistics
  - Absolute split distance

Split distance : $\Delta\lambda$

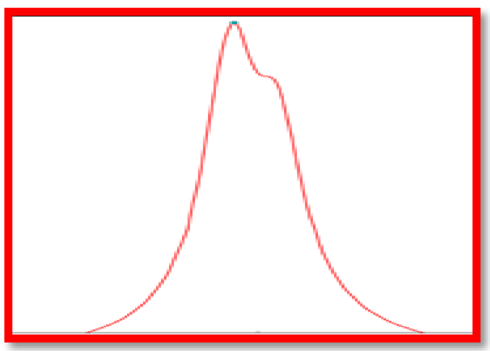


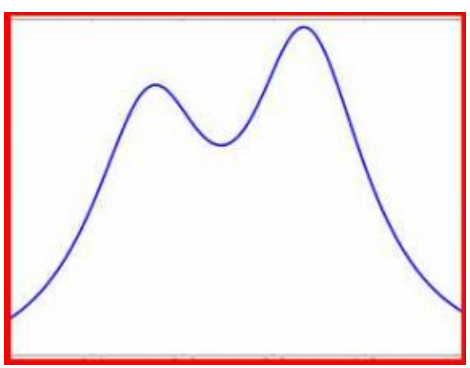


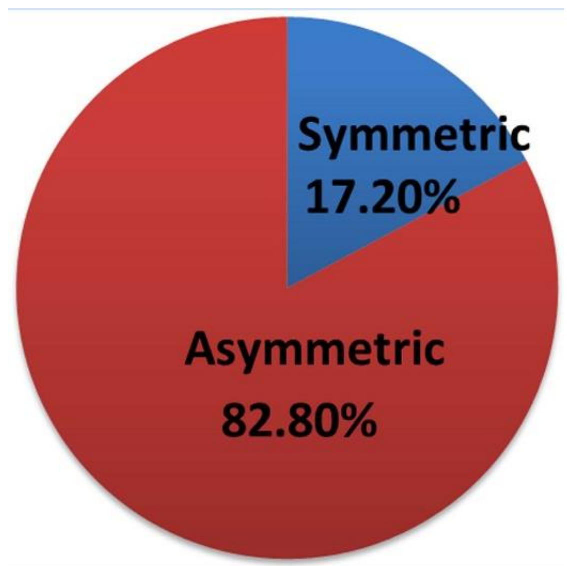
Split distance under different coupling gaps

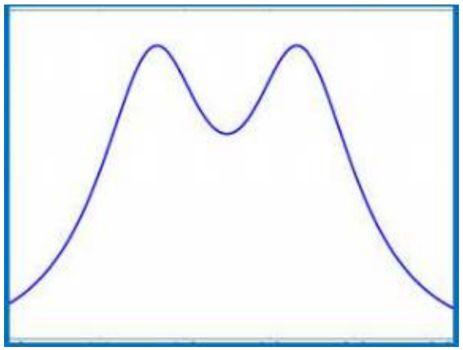
PARASITICS IN SILICON MICRORING

- Statistics
  - 80% of the 550+ split resonances are asymmetric









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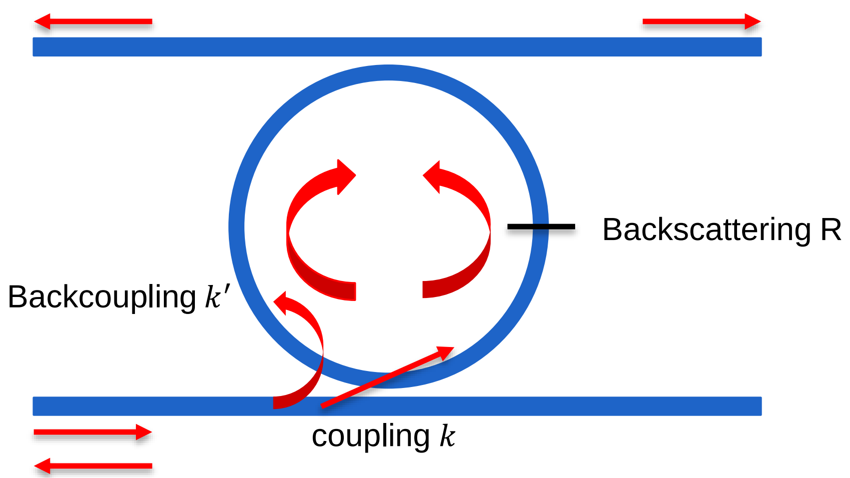
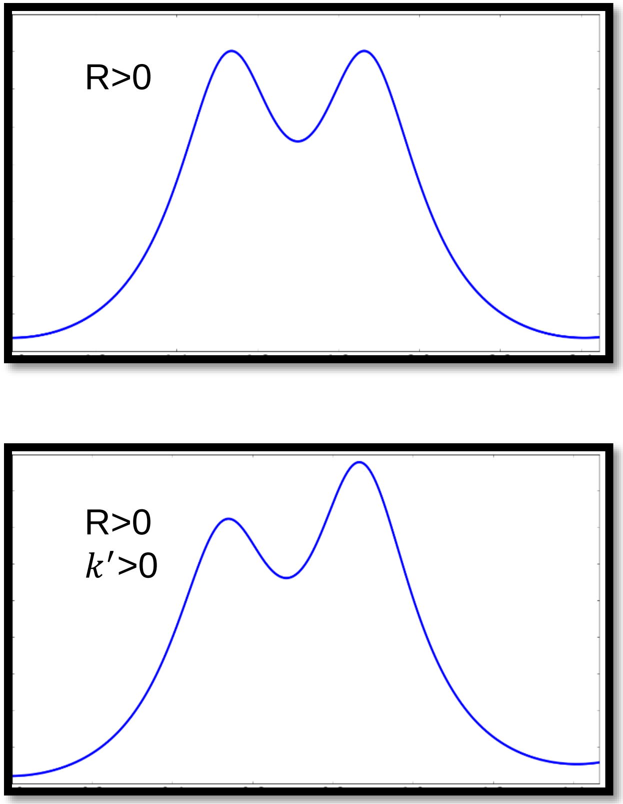
Parasitics in silicon Microring

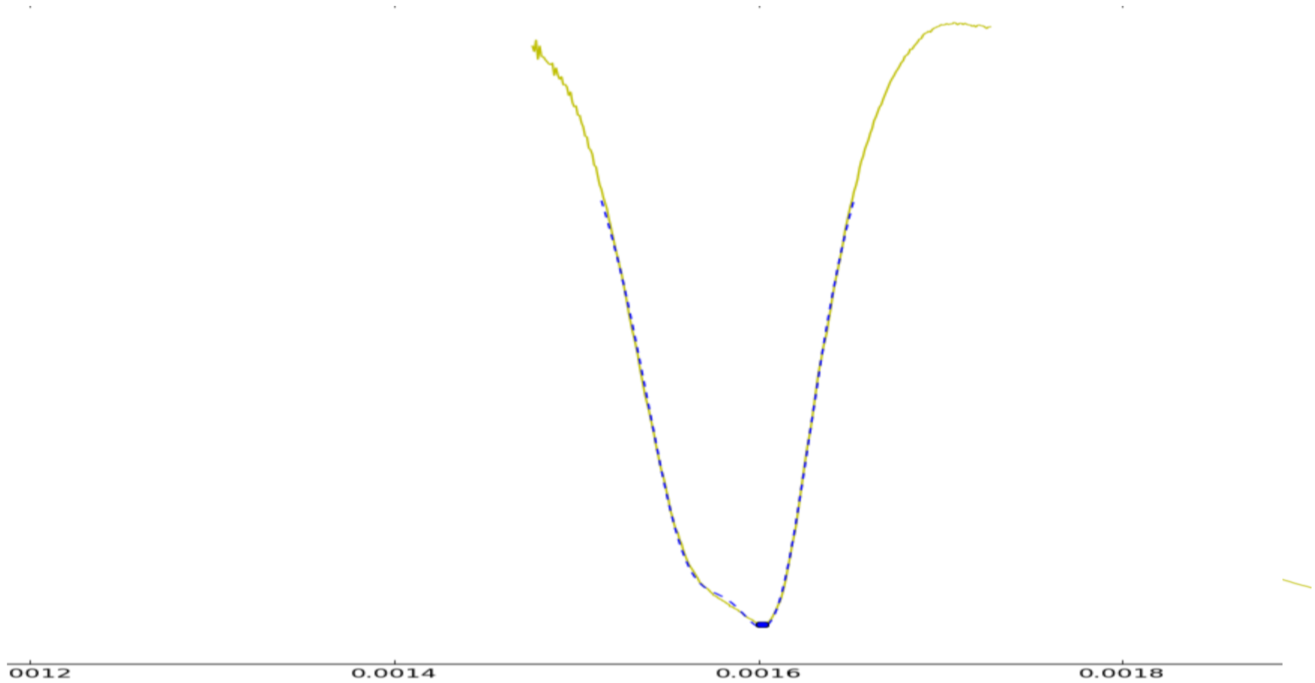
- Backcoupling
  - Affects peak asymmetry





Parasitics in silicon Microring

- Model
  - Based on temporal coupled mode theory (tCMT)
  - Incorporate the backcoupling
  - All kinds of resonance can be fitted well, in a automatic way

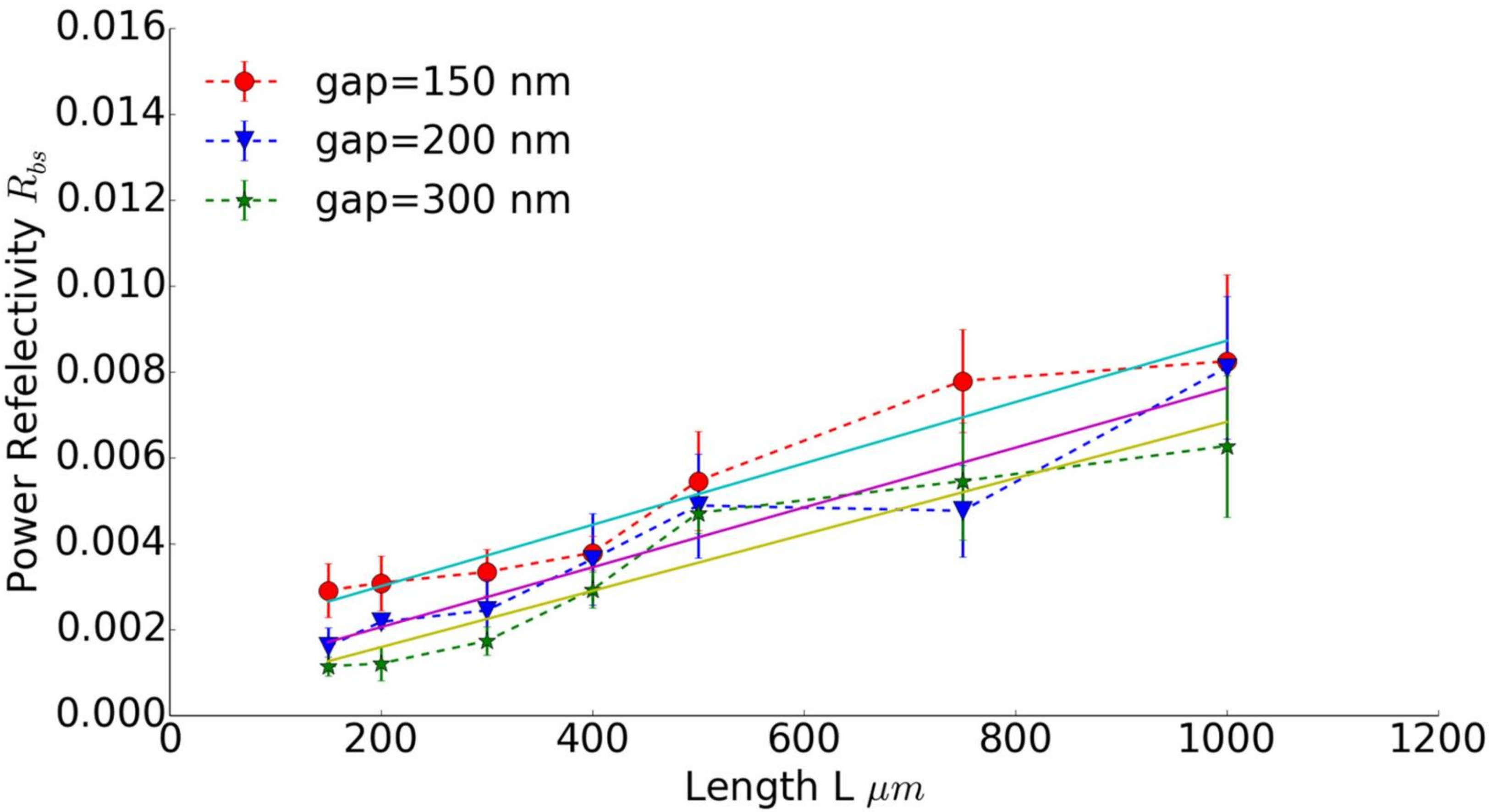


Parasitics in silicon Microring

- Quantitative analysis
  - Use the model to extract parameters
    - Backscattering strength (Rbs)
  - Perform a quantitative analysis of backscattering vs physical parameters (length L, coupling gap g, coupling length Lc)

Parasitics in silicon Microring

- Quantitative analysis
  - Rbs grows with ring length L
  - Rbs grows with decreasing gap g



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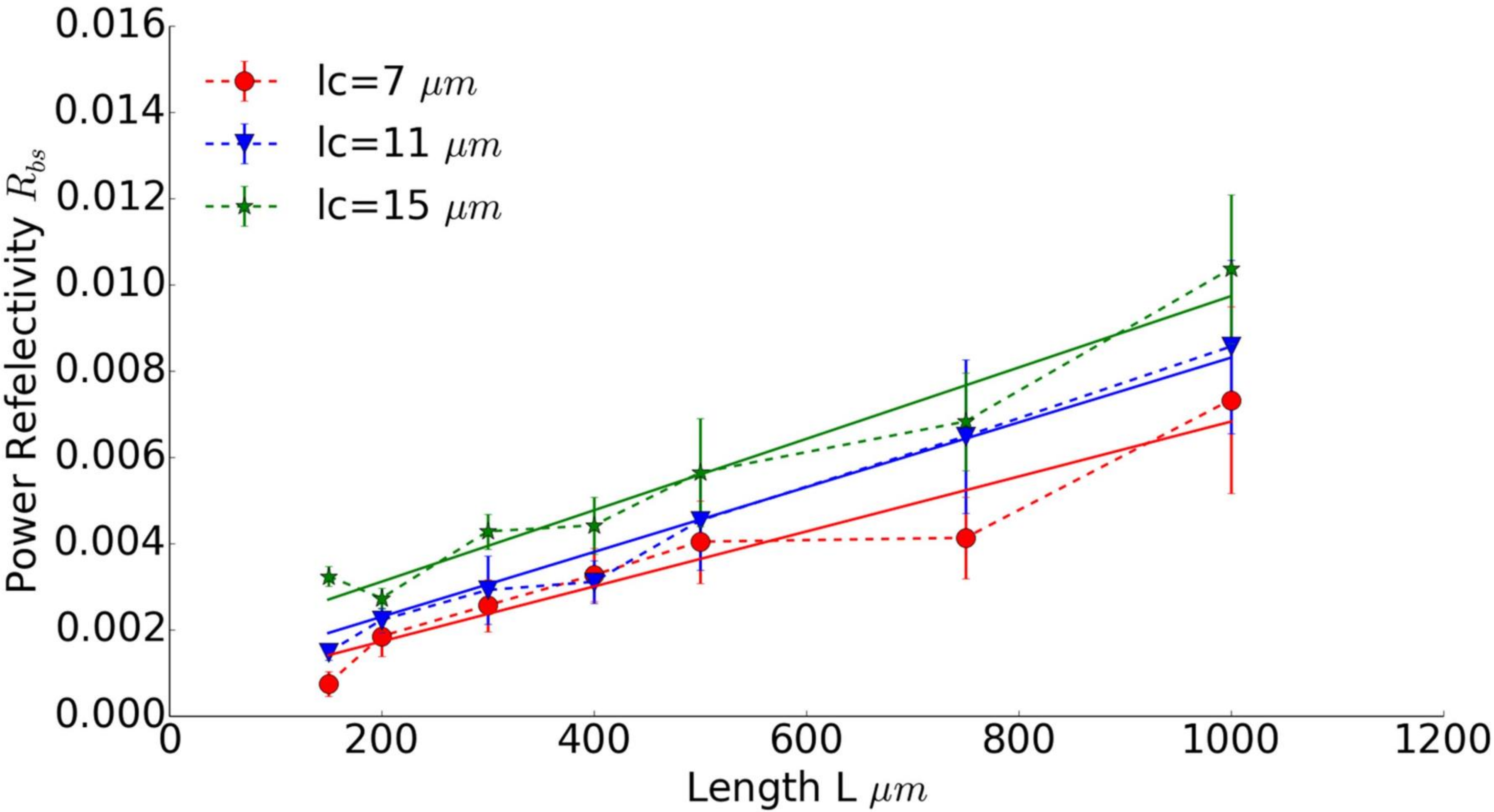
PARASITICS IN SILICON MICRORING

- Quantitative analysis
  - Rbs grows with coupling length Lc

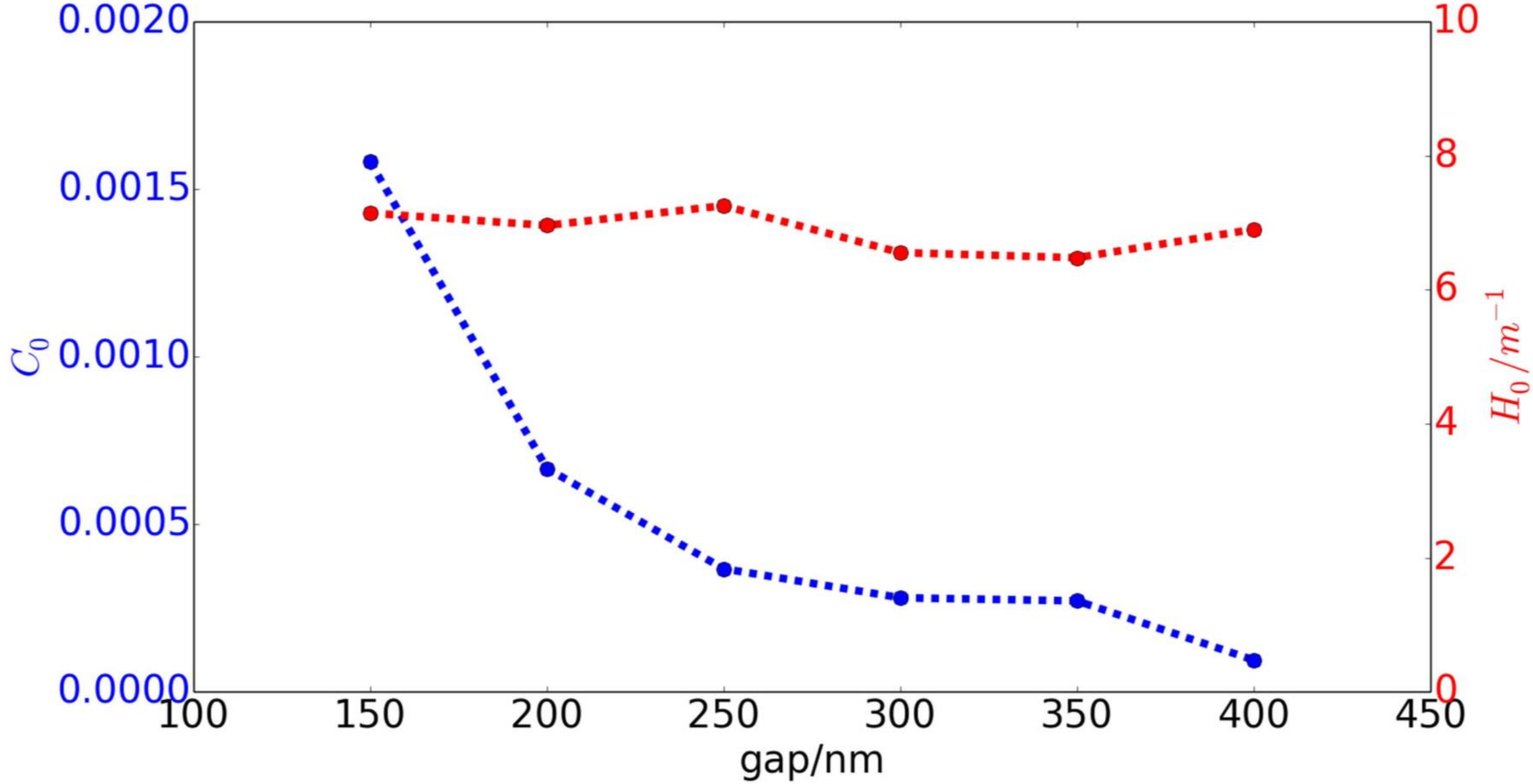


PARASITICS IN SILICON MICRORING

- Quantitative analysis
  - Simple predictive model for Rbs
  - Rbs = $H_0 L + C_0$, covers both the contributions from waveguide and couplers
  - H_0 depends on the cross-section of the WG and the quality of the roughness
  - C_0 determined by the couplers

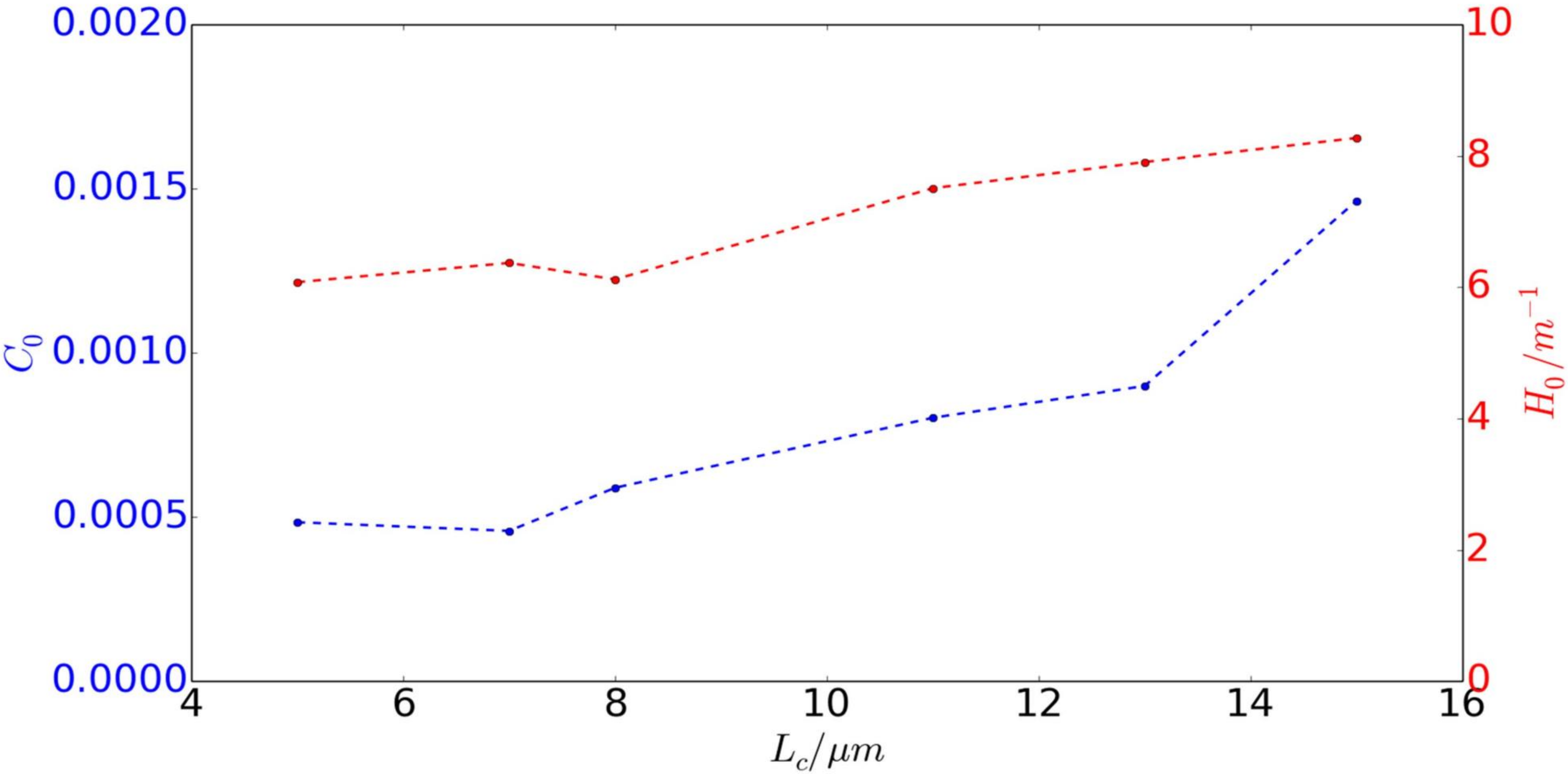
PARASITICS IN SILICON MICRORING

- Quantitative analysis
  - H_0, C_0 vs coupling gap
  - H_0 constant, C_0 decreases



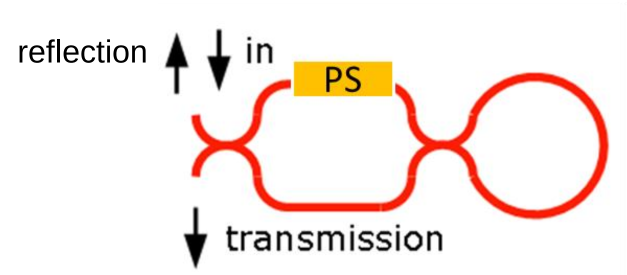
Parasitics in silicon Microring

- Quantitative analysis
  - H_0, C_0 vs coupling length
  - H_0 constant, C_0 increases

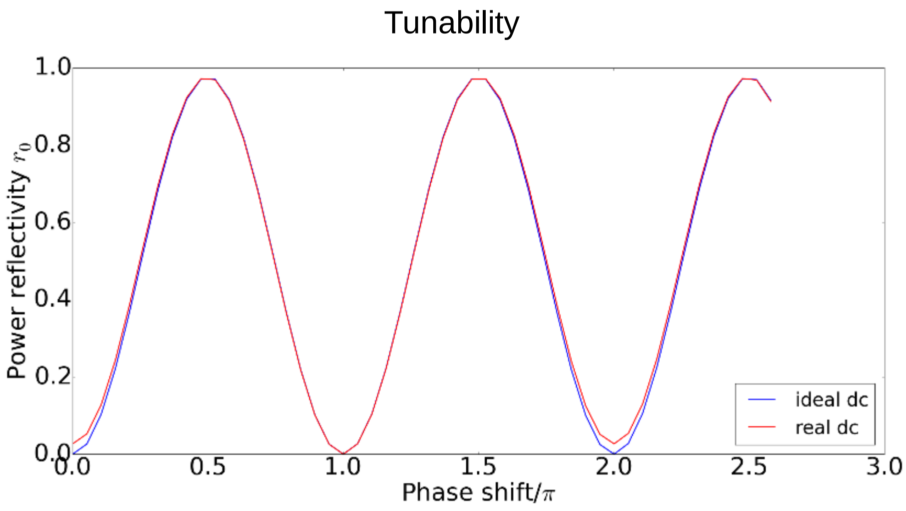


SUPPRESS BACKSCATTERING IN MICRORING

- Fabrication hardly changes → BS always there
- Design methods to suppress backscattering
  - Take control of total internal reflections
- Integrated, tunable, low loss CMOS compatible reflector

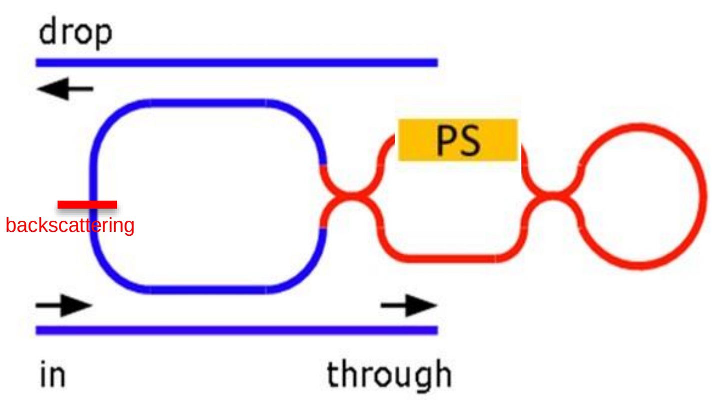


- 0.5*pi → 100% change in reflectivity

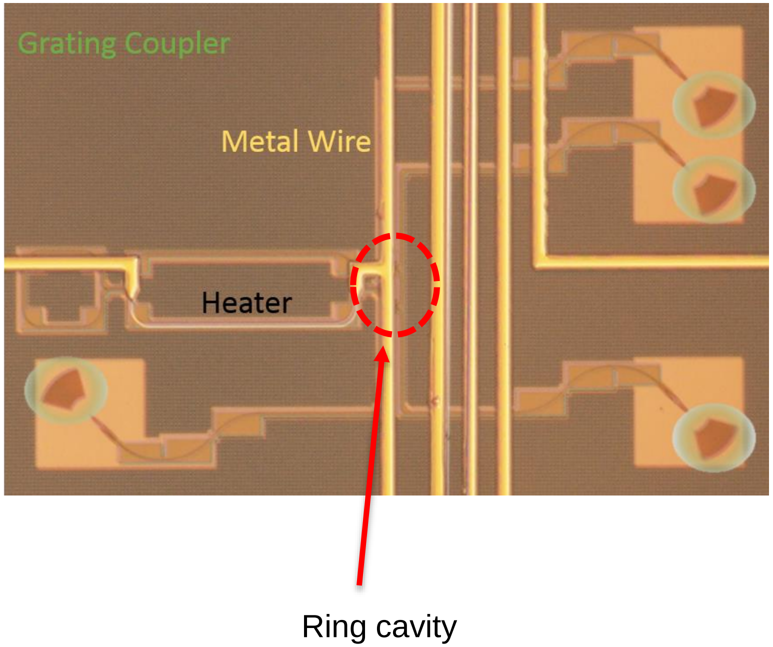


Suppress backscattering in Microring

- Schematic

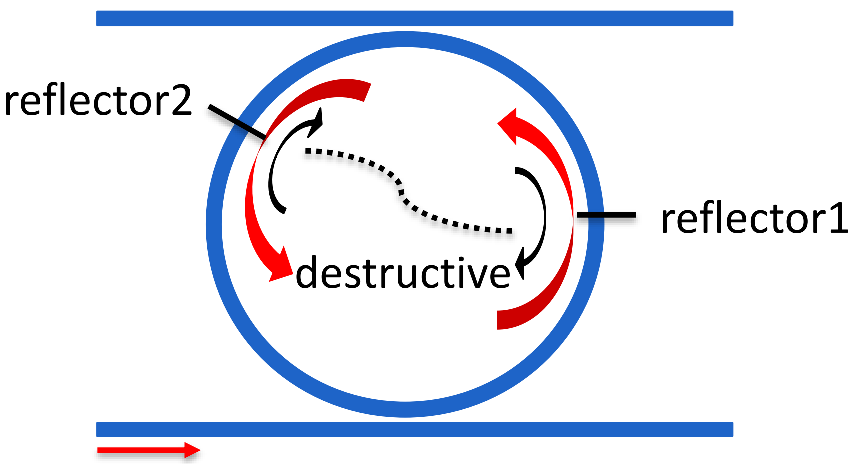


- Device



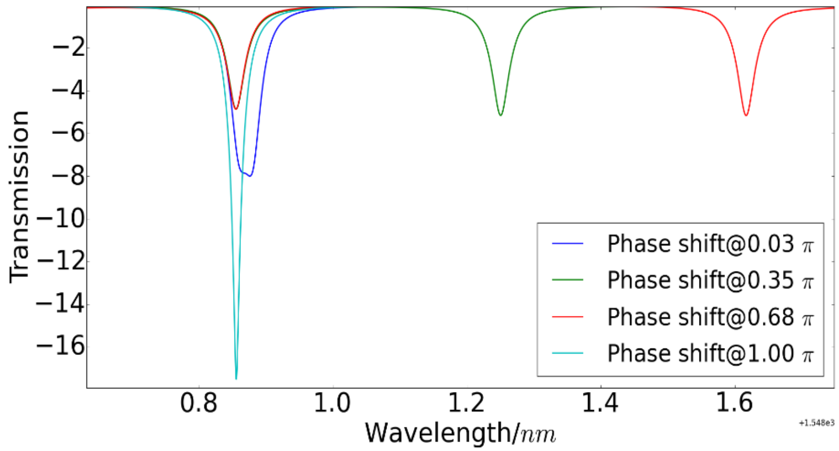
SUPPRESS BACKSCATTERING IN MICRORING

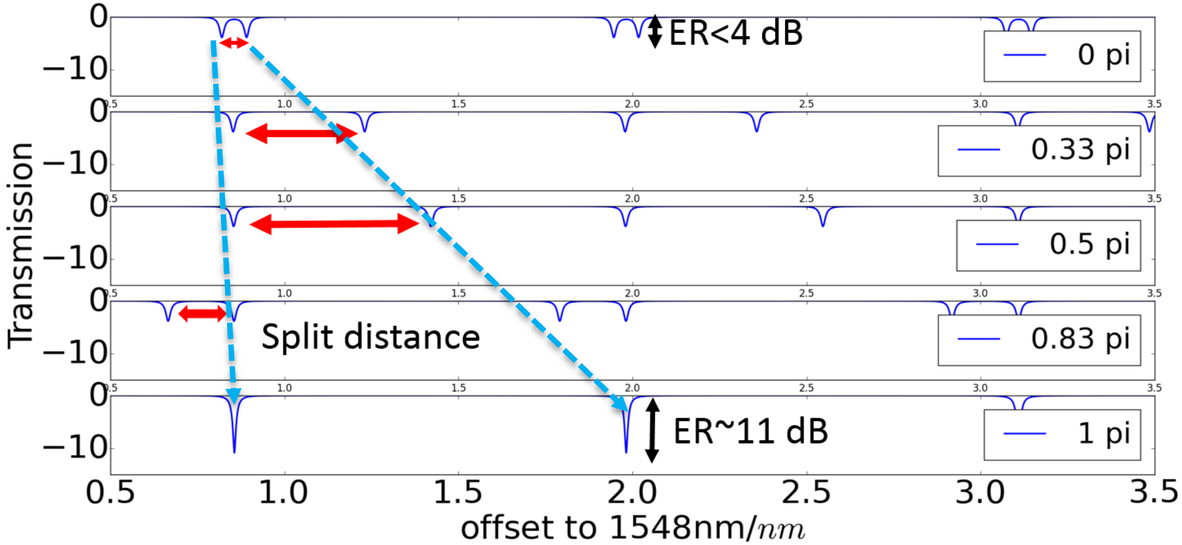
- principle



Suppress backscattering in Microring

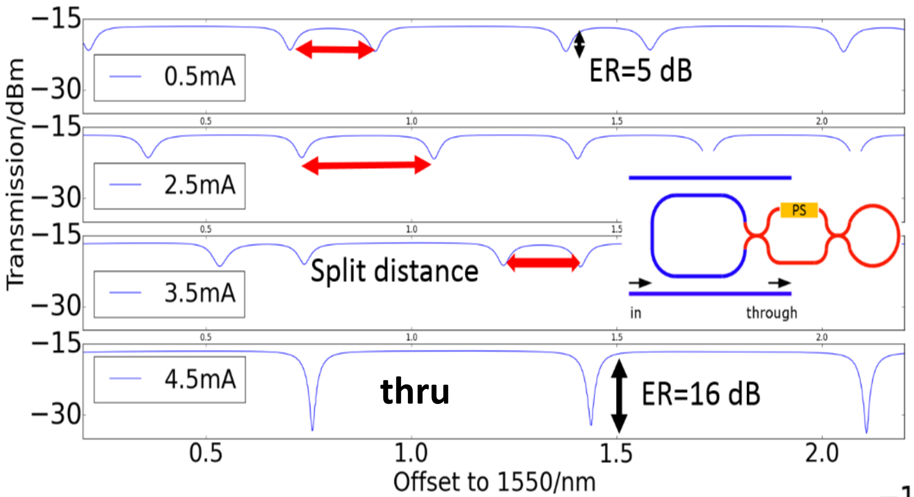
- Simulation – Full control of the resonance



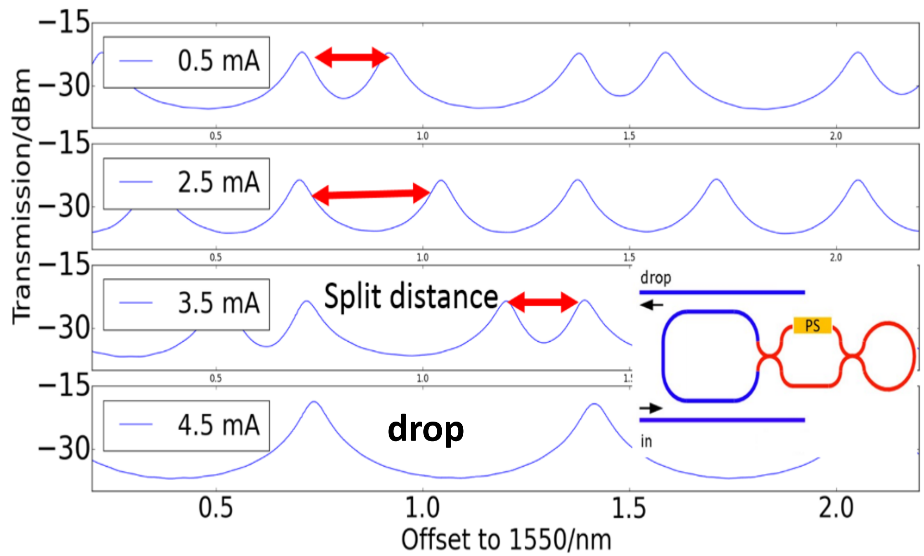


Suppress backscattering in Microring

- Measurement - cancel splitting in thru and drop ports with an improved ER

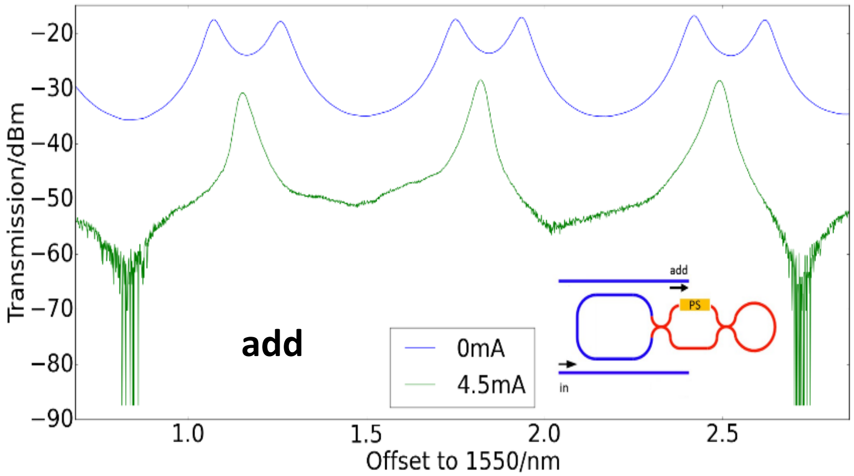


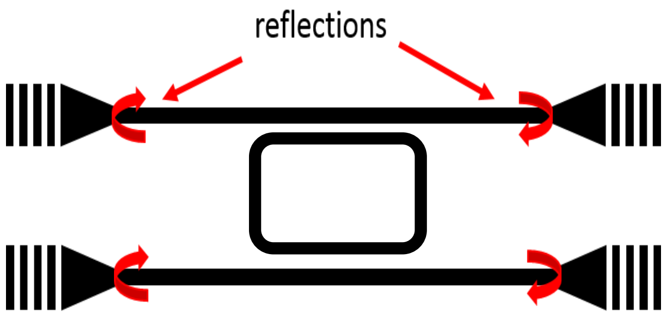
Note how the ER gets recovered



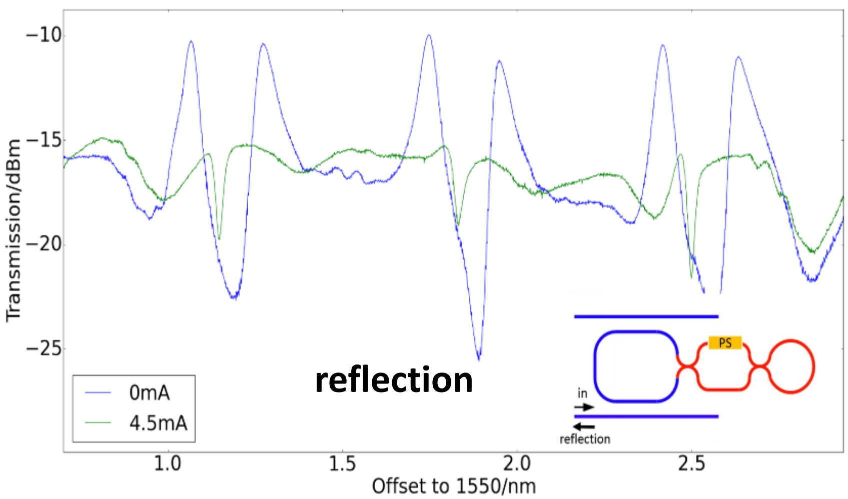
Suppress backscattering in Microring

- Measurement - suppress leakage to add port and reflection to in port





1. Still some leakage due to parasitic reflections
2. Power suppressed and no splitting any more



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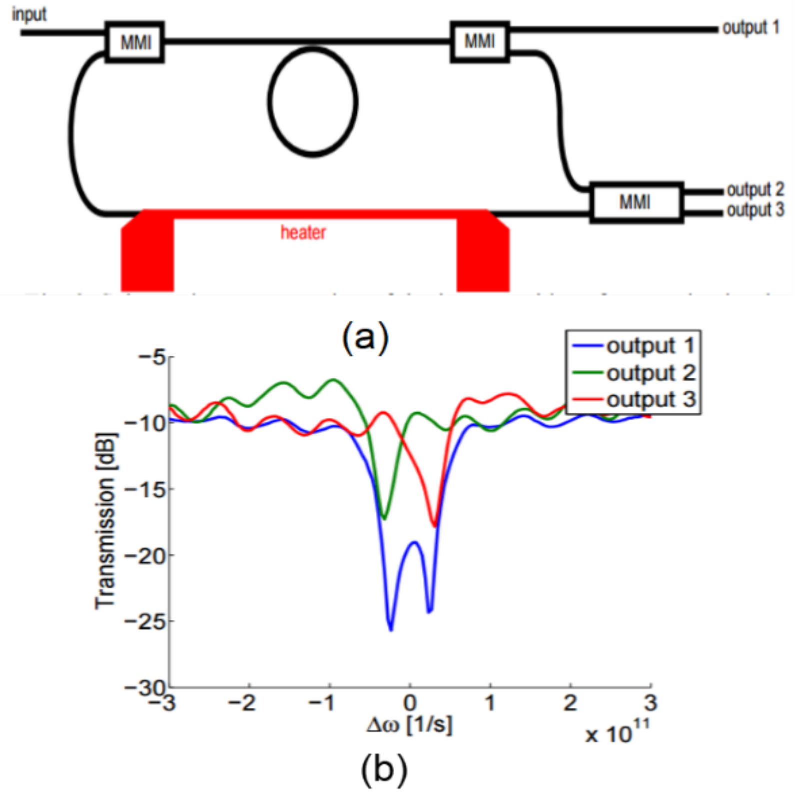
SUPPRESS BACKSCATTERING IN MICRORING

- Other approaches for this problem – post-processing
  - Introduce loss
  - Only solves splitting
  - Quality sacrificed (ER)
  - Single port (thru) solution



S. Werquin, Optics Express Vol. 21, No. 14, 2013

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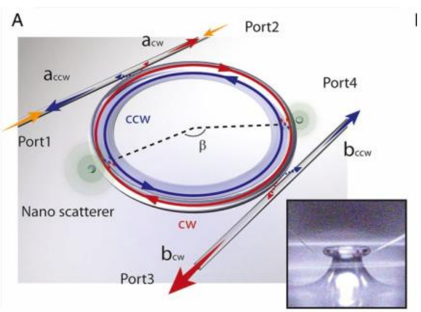
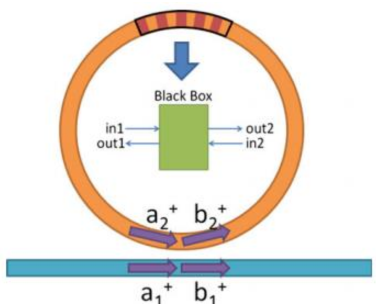
Suppress backscattering in Microring

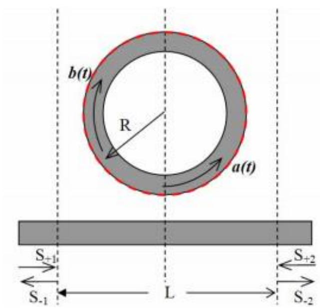
- Other approaches for internal reflections
    - Uncontrollable



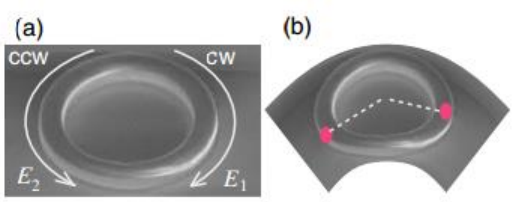
B. Peng, PNAS, 2016, 113(25)



Y. M. Kang, Opt Quant Electron, 2009, 41



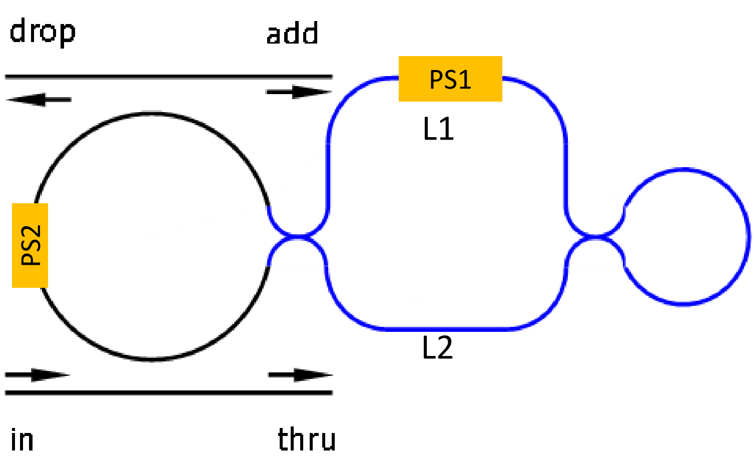
Z. Zhang, Optics Express, 2008, 16(7)

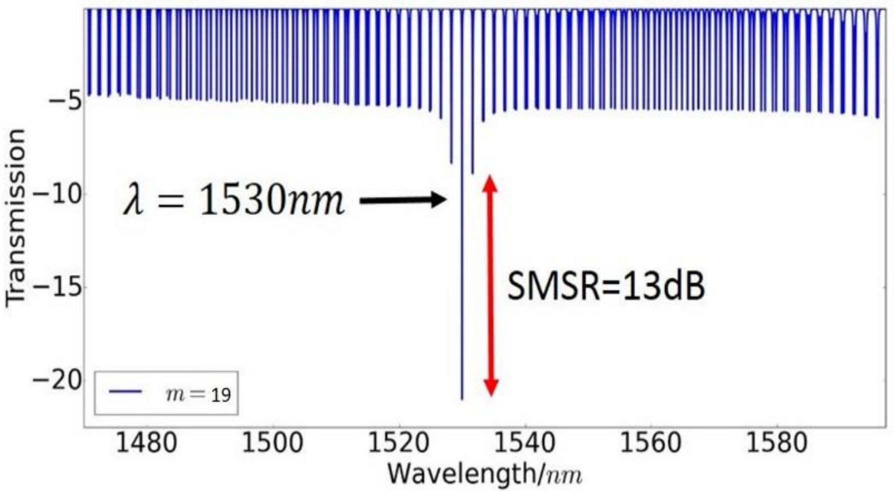


S. Longhi, Photonics Research, 2017, 5(6)

REFLECTIONS ENGINEERING – SINGLE MODE RING

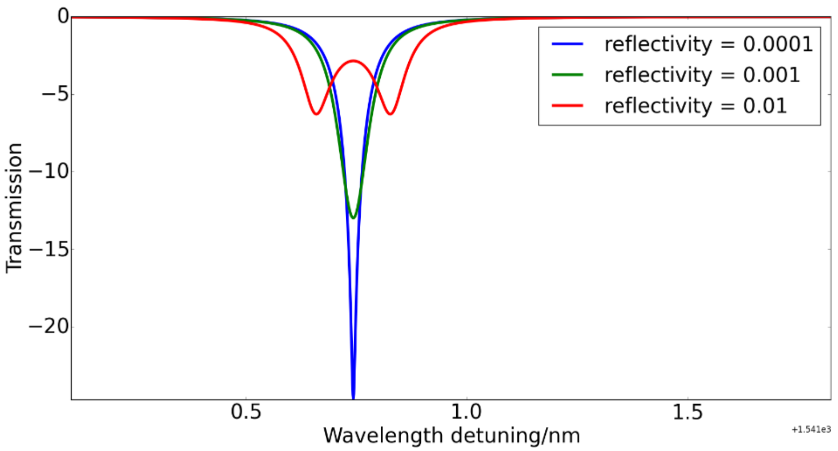
- Suppression of BS is a result of reflections engineering
- Other applications → pseudo single mode filter, ultra wide FSR and tuning range
- Large FSR is desired to sensors, single mode laser cavities etc.

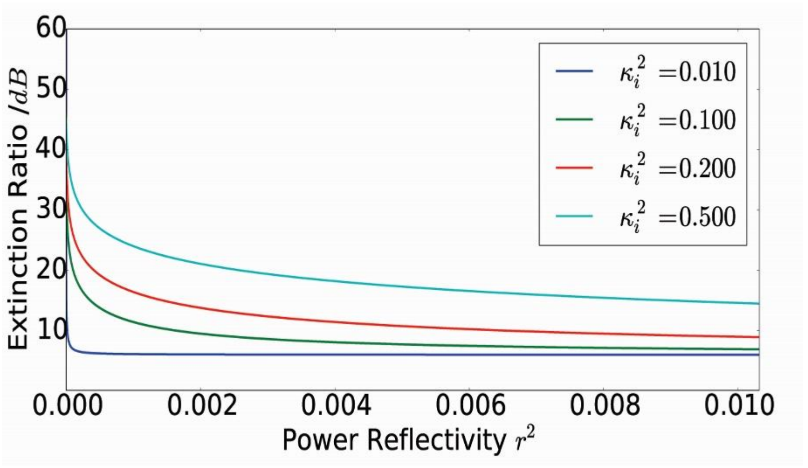




REFLECTIONS ENGINEERING – SINGLE MODE RING

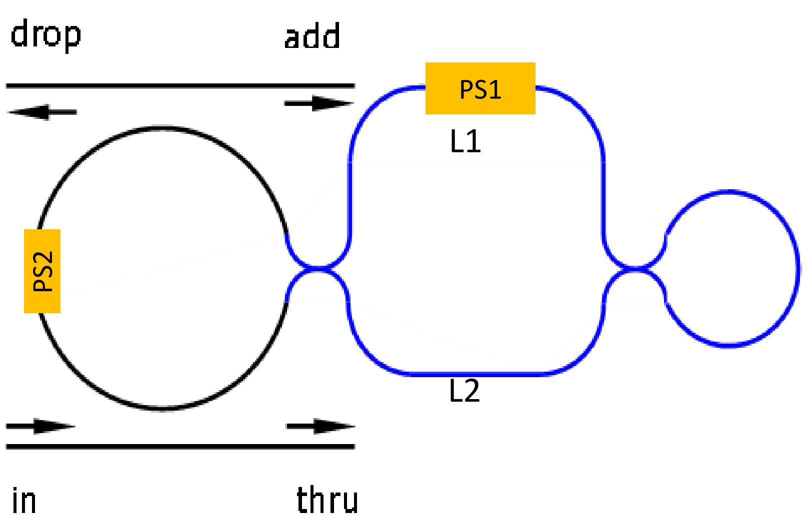
- Principle for wide FSR
  - Ring: Internal reflection → splitting + extinction ratio degradation

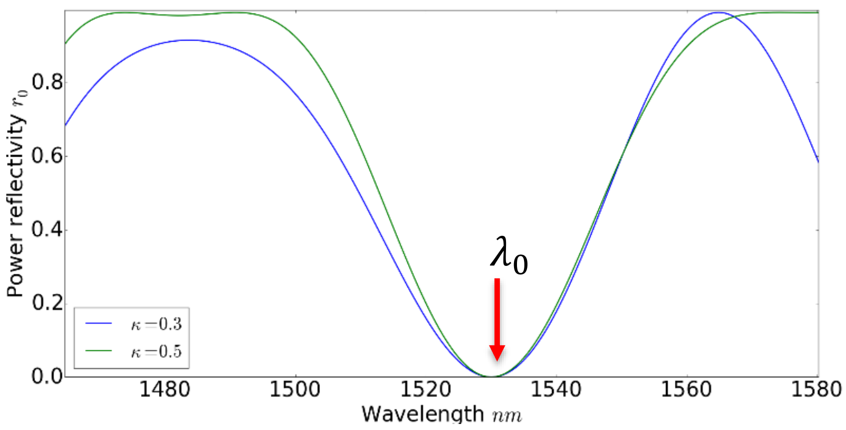




Reflections engineering – single mode ring

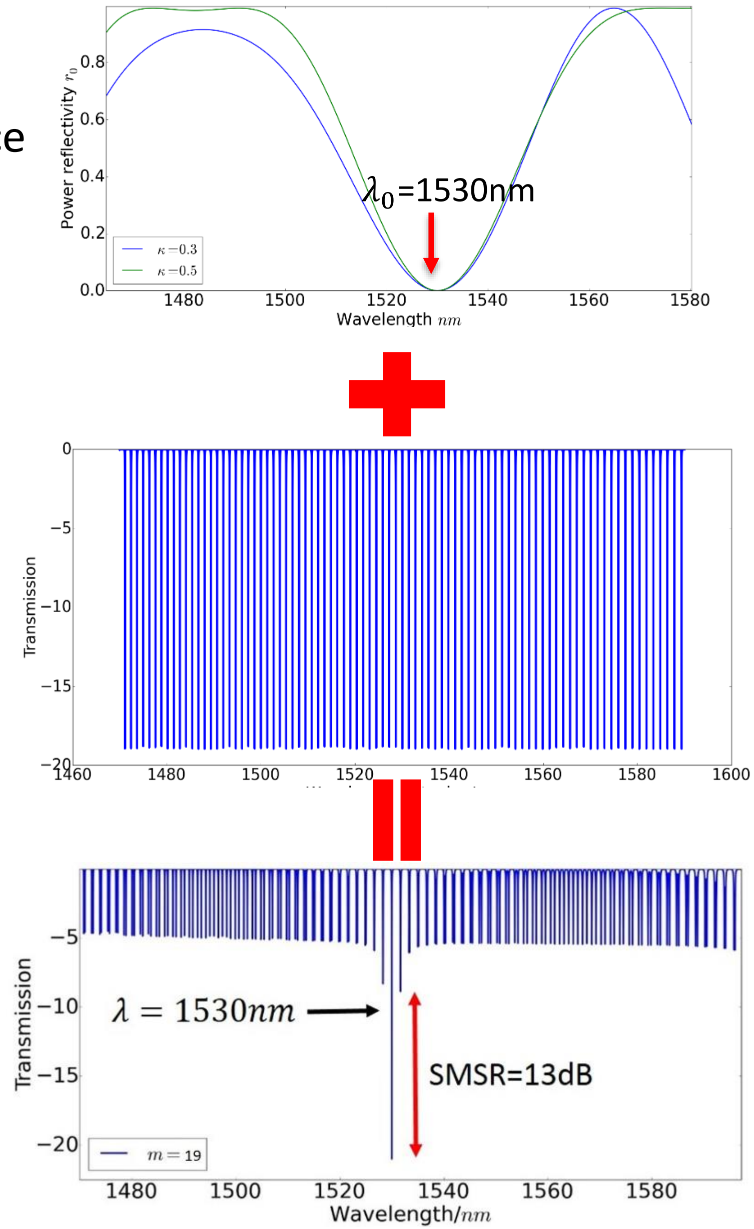
- Principle for wide FSR
  - Reflector: provides a special spectrum
  - $L1 \neq L2$, unbalanced MZI
  - $\frac{2\pi\Delta L}{\lambda_0} = m\pi$, m is the interference order of the MZI
  - Only one wavelength in a very broad range has 0 reflection





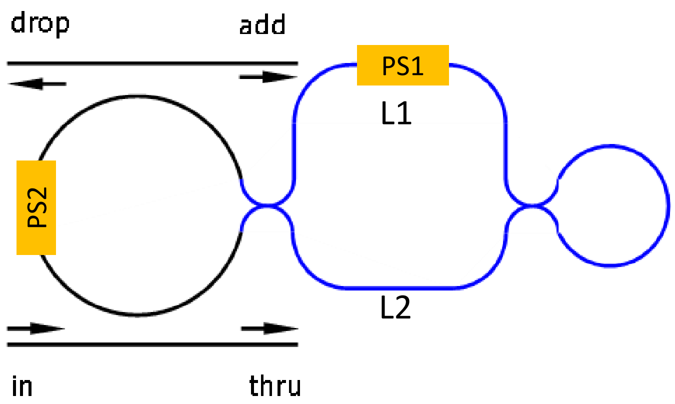
REFLECTIONS ENGINEERING – SINGLE MODE RING

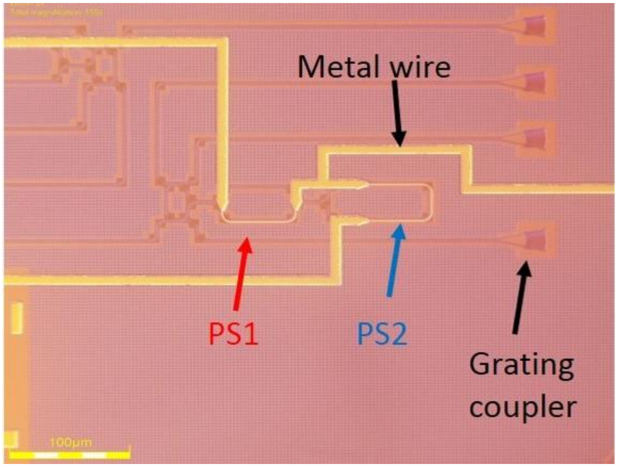
- Principle for wide FSR
- Alignment between Zero-reflection and resonance
- Like a Vernier effect between reflector + ring

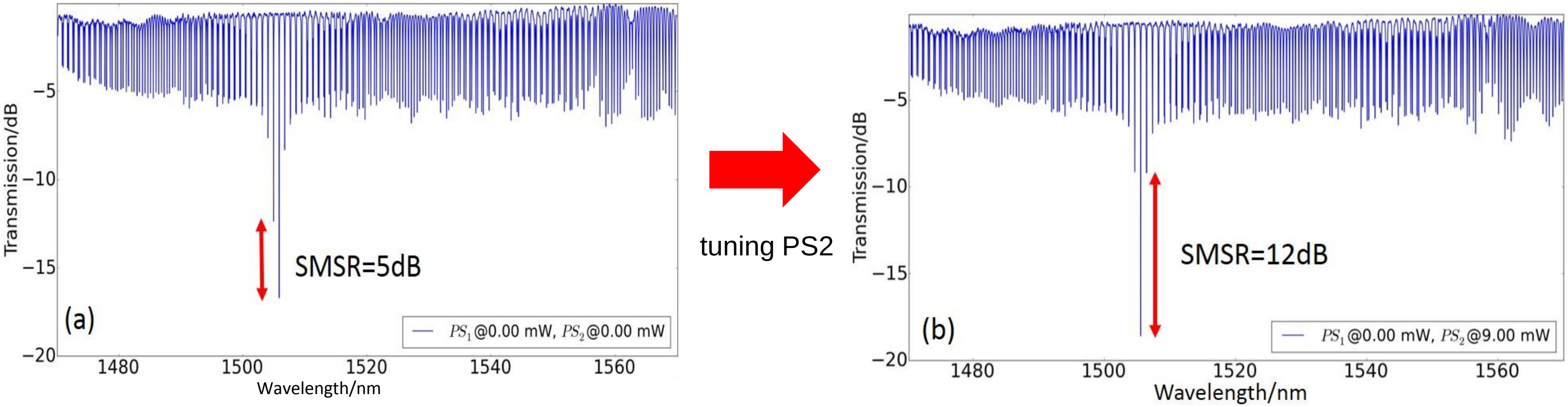


Reflections engineering – single mode ring

- Measurements of wide FSR







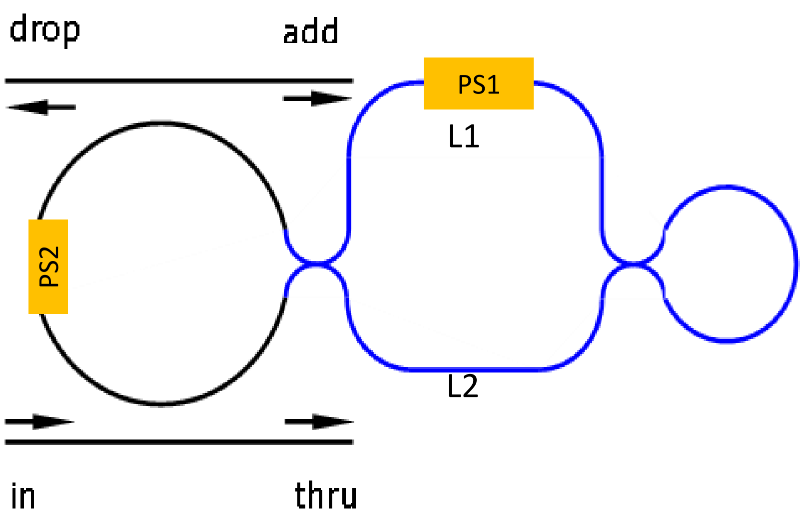
Reflections engineering – single mode ring

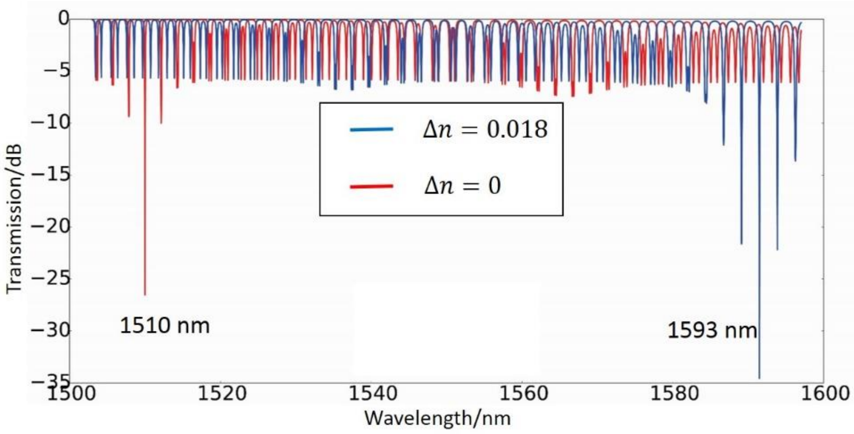
- Principle for ultra wide tuning range
  - PS1: shift the zero reflection wavelength. Fast!
  - PS2: shift the complete ring spectrum. Slow!

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\Delta n}{n_g}\frac{L_{ps1}}{\Delta L}$$

Amplification factor

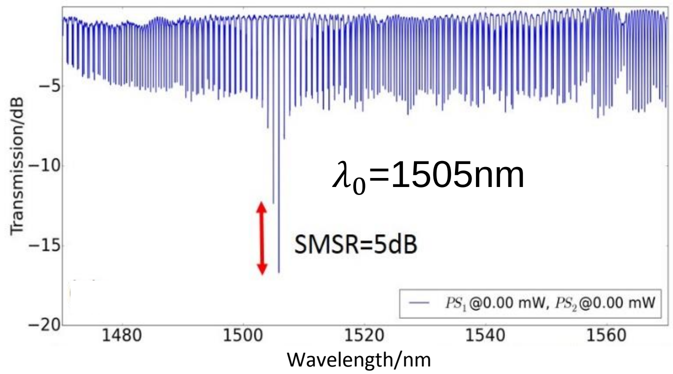
$$\frac{\Delta\lambda}{\lambda_0} = \frac{\Delta n}{n_g}$$

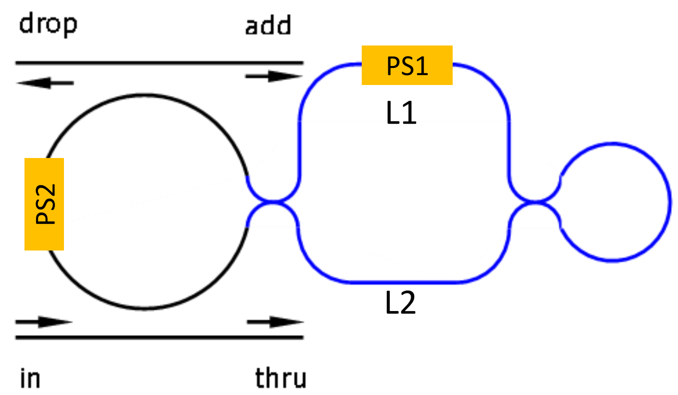




REFLECTIONS ENGINEERING – SINGLE MODE RING

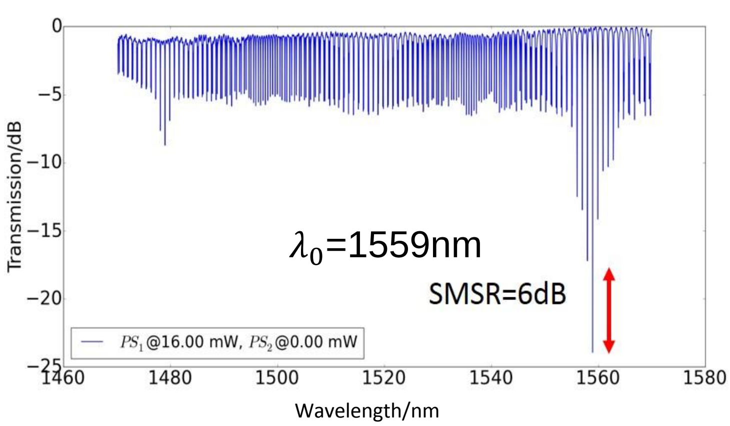
- Measurements of wide tuning range



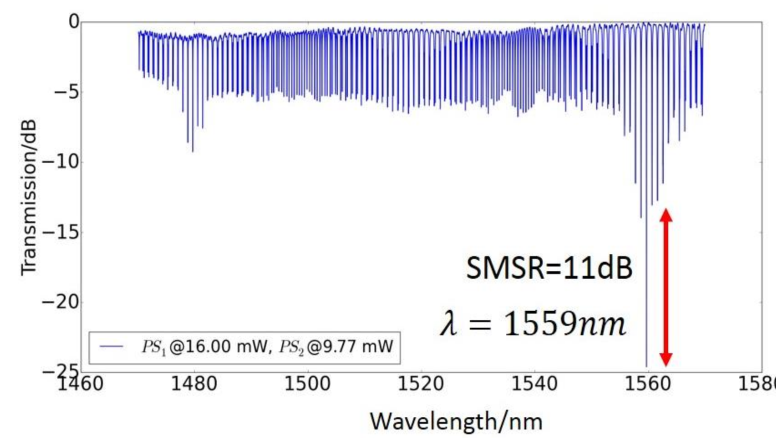


tuning PS1 16mW, Δn=0.014

11 times wider tuning range !



tuning PS2



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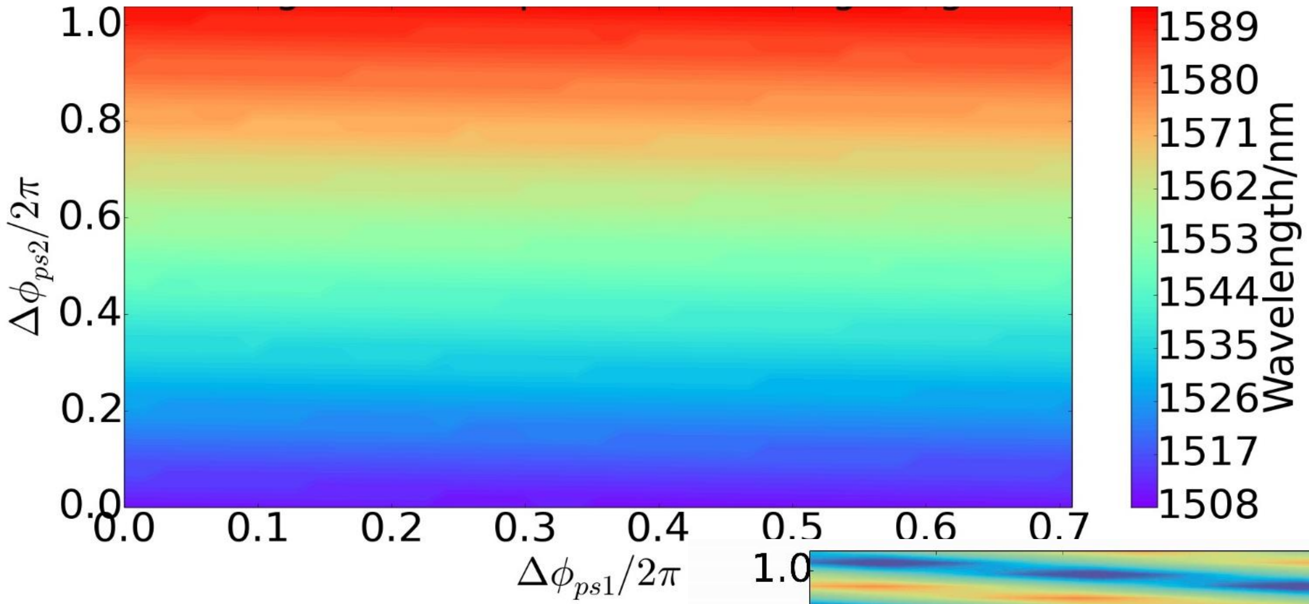
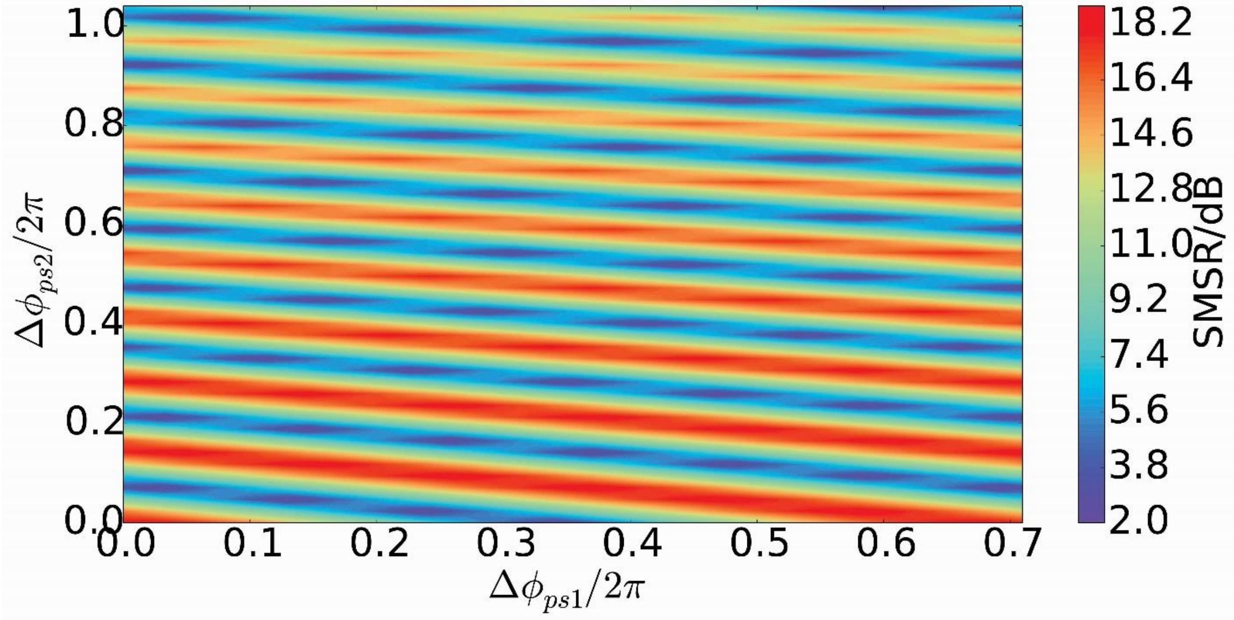
Reflections engineering – single mode ring

- Contour plots

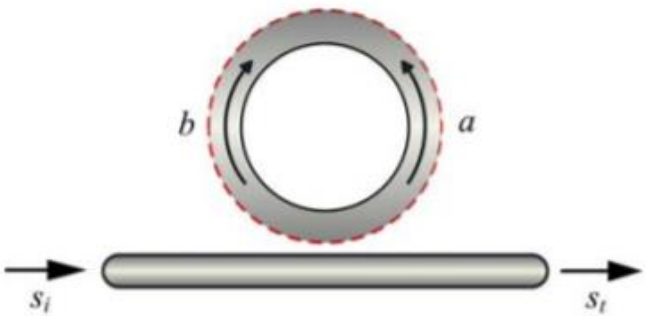




REFLECTIONS ENGINEERING – OTHERS

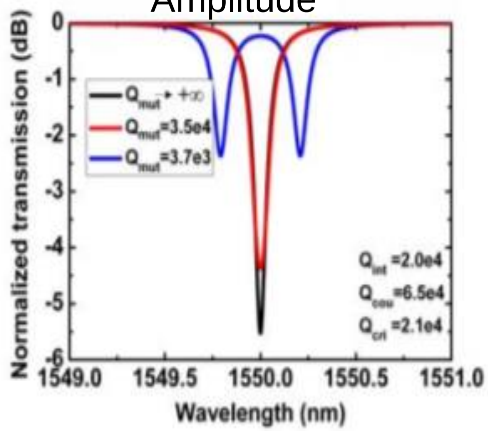
- Tunable fast light
- Resonance splitting → anomalous dispersion → pulse advancement

$$v_g = \left.\frac{c}{n(\omega) + \omega \frac{dn(\omega)}{d\omega}}\right|_{\omega=\omega_c} = \frac{c}{n_g}$$

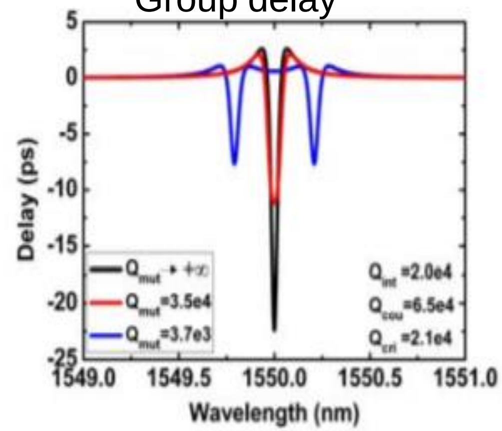


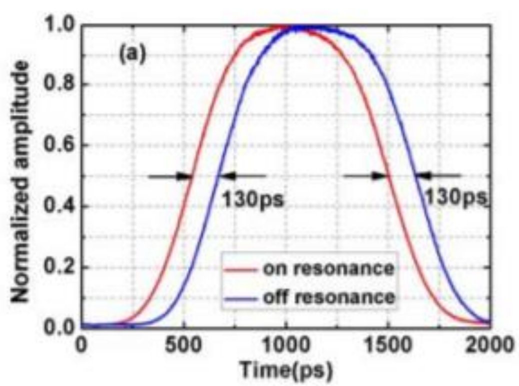
Q. Li et al., Optics express, 17(2), 2008

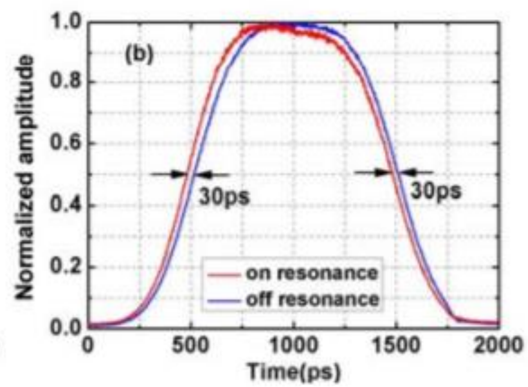
Amplitude



Group delay

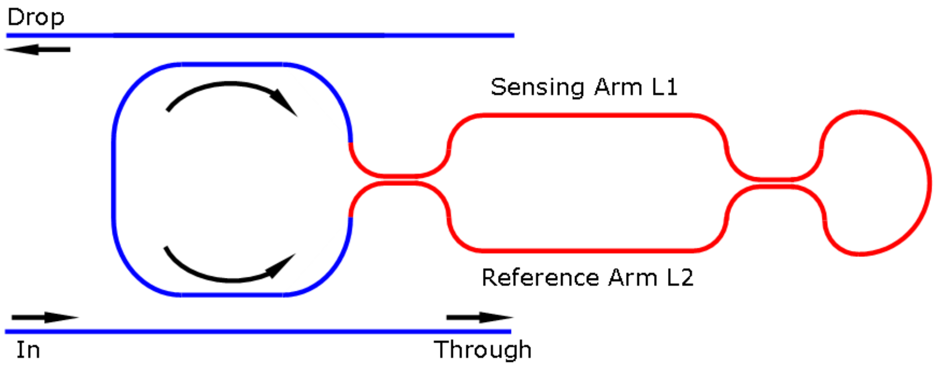


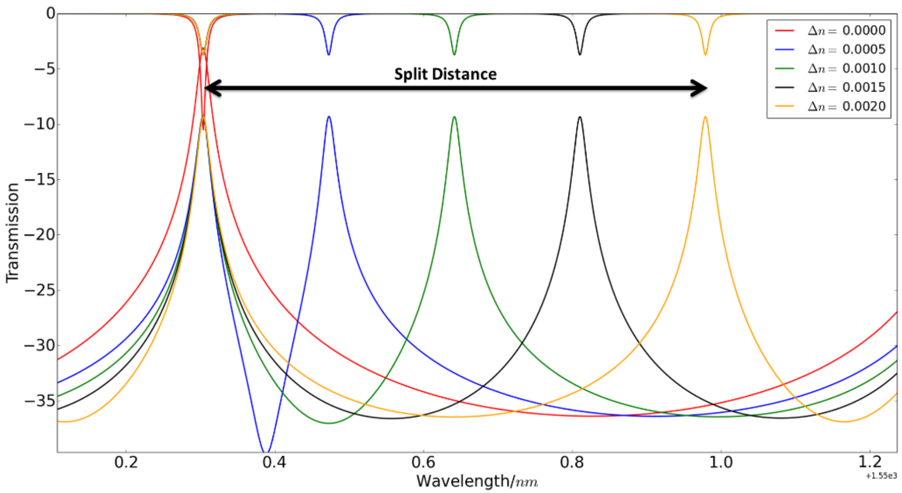




REFLECTIONS ENGINEERING – OTHERS

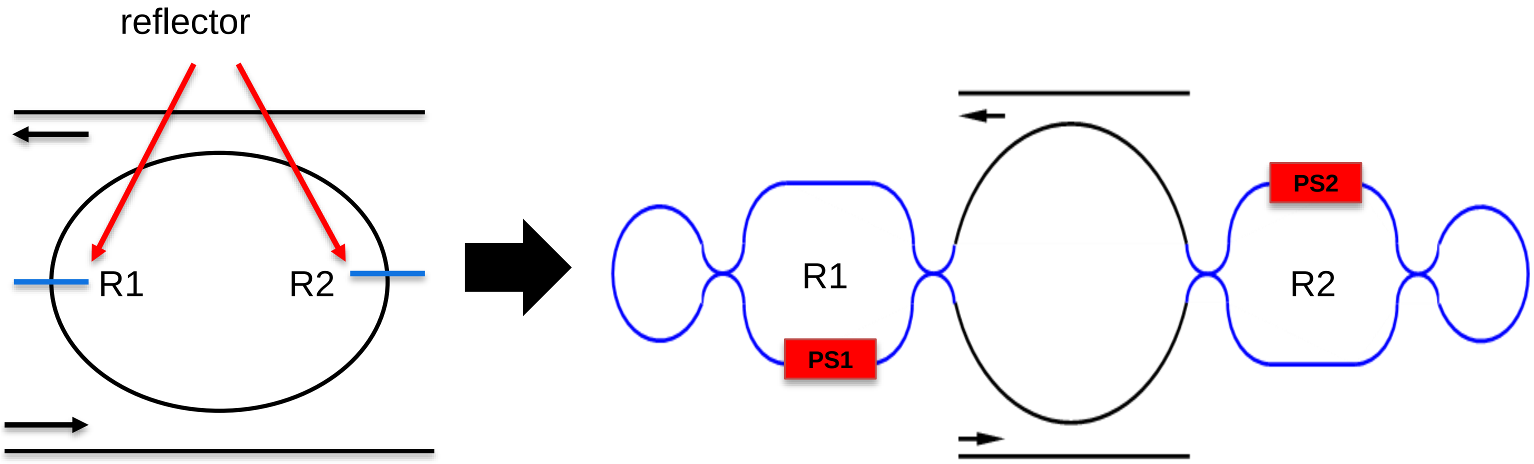
- Sensing scheme
- Resonance splitting → index change
- combines the advantage of MZI sensor and ring sensor
  - Temperature insensitive
  - High resolution





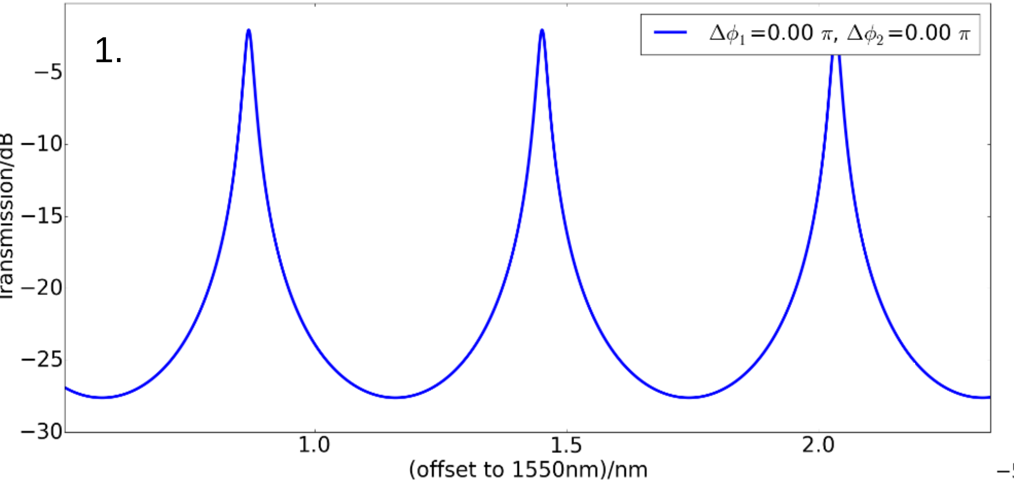
REFLECTIONS ENGINEERING – TWO REFLECTORS

- Two embedded Fabry-Perot cavities will be formed
- Output is an interference pattern of the ring and FP cavities.



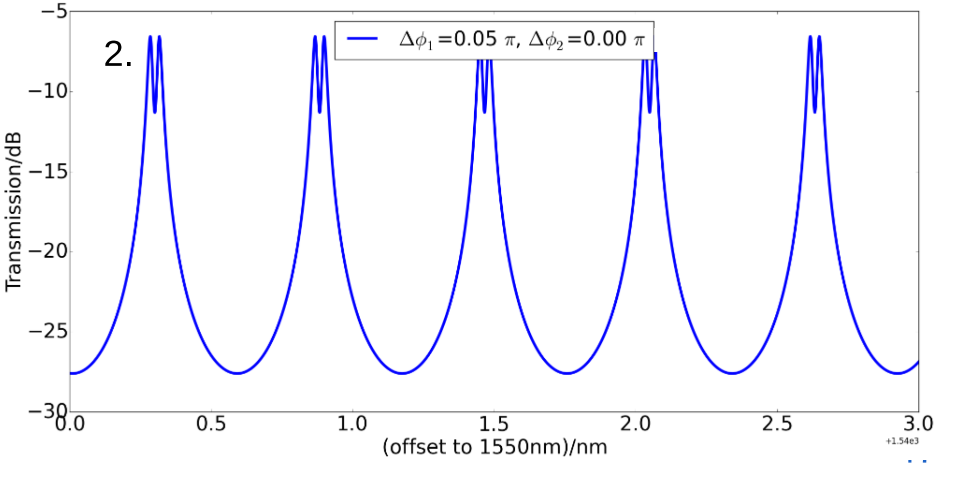
REFLECTIONS ENGINEERING – TWO REFLECTORS

- Simulation - 4 categories
  1. Pure Lorentzian resonance (R1=R2=0)
  2. Normal resonance splitting (R1>0, R=0)



R1=R2=0

R1>0, R2=0



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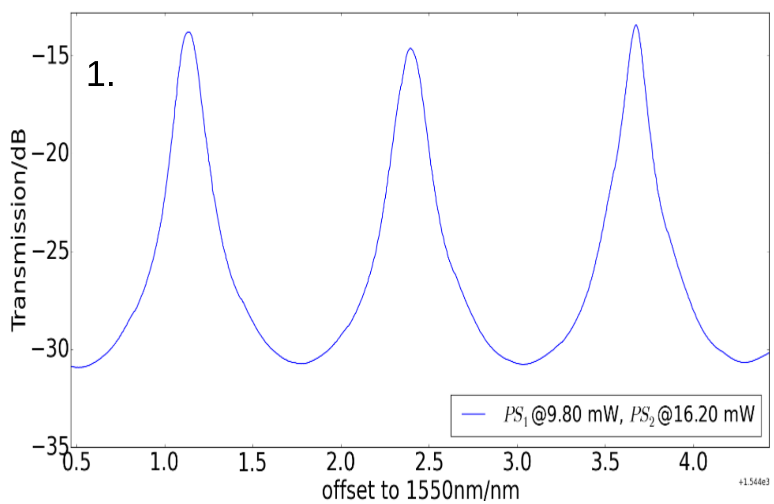
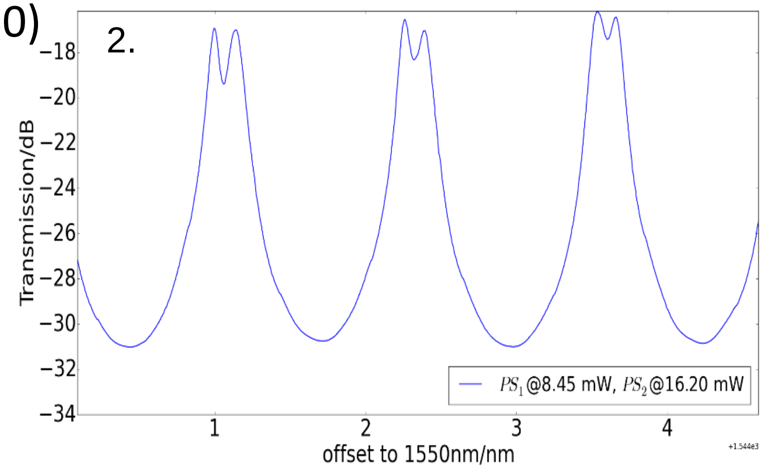
REFLECTIONS ENGINEERING – TWO REFLECTORS

- Measurement
  1. Pure Lorentzian resonance (R1=R2=0)
  2. Normal resonance splitting (R1>0, R=0)

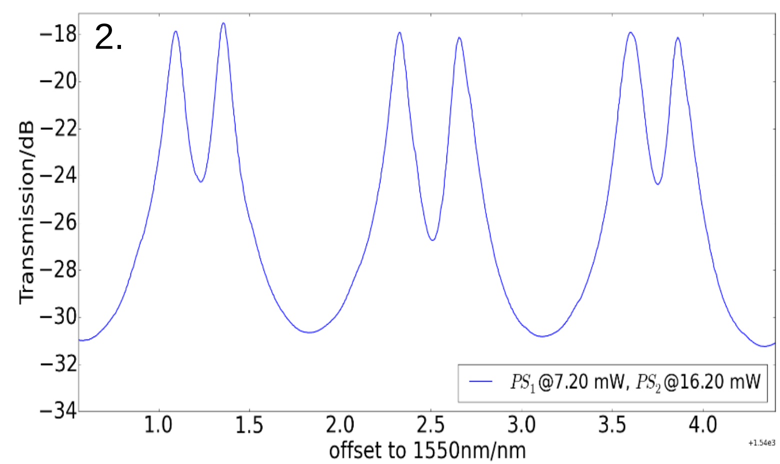
R1=0, R2=0



R1>0, R2=0

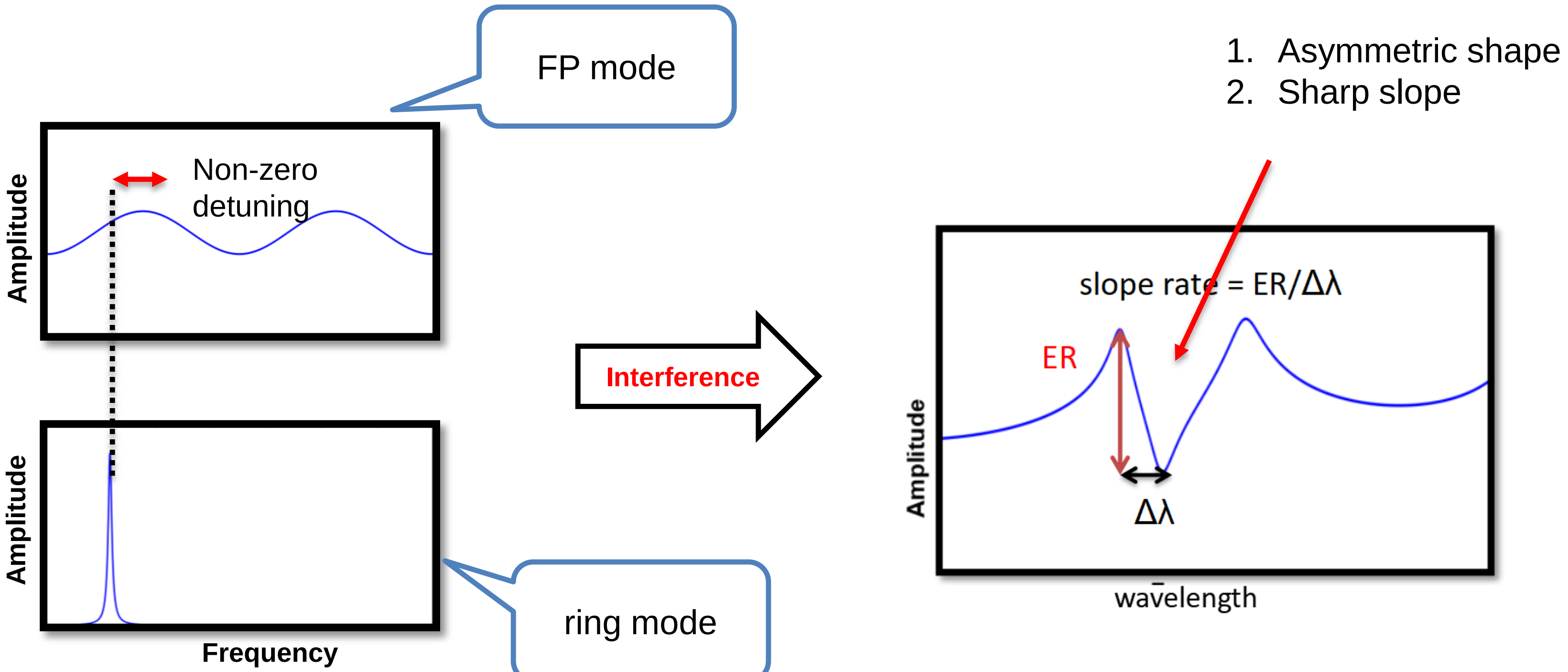


R1↑, R2=0



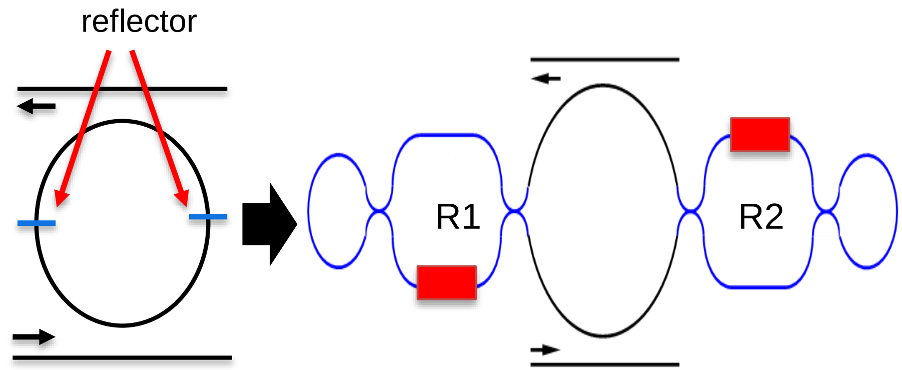
REFLECTIONS ENGINEERING – TWO REFLECTORS

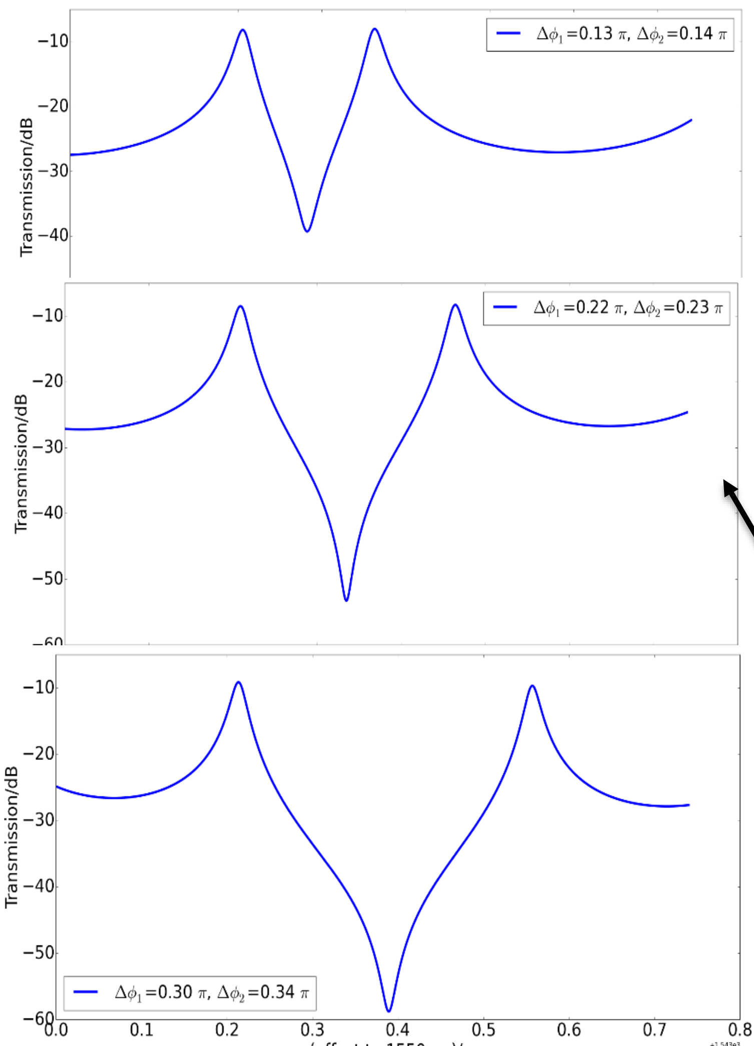
3. Fano resonance (R1>0, R2>0) -- Principle
   - Principle: Interference between a continuous mode (low Q) and a discrete mode (high Q) with non-zero detuning



Reflections engineering – two reflectors

3. Fano resonance – simulation
   - Dynamic tuning

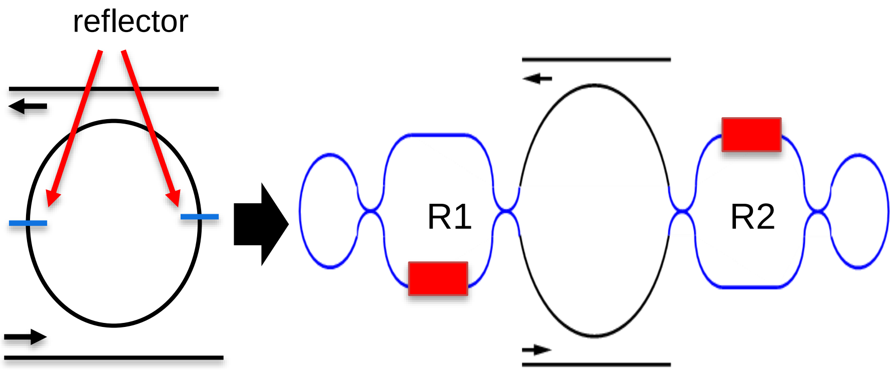


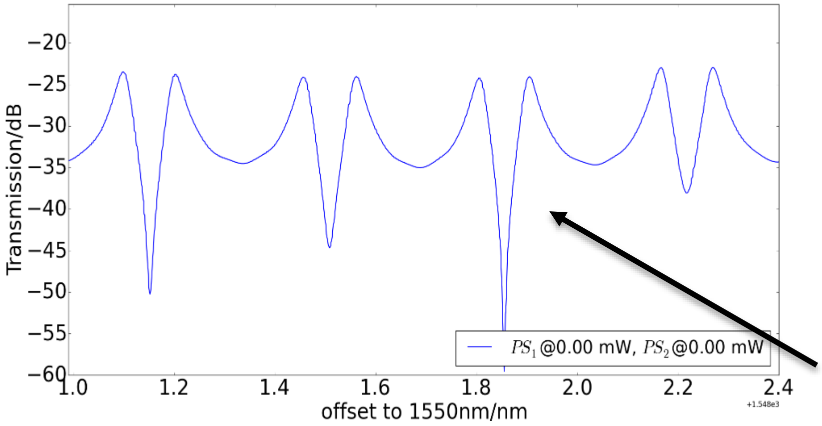


Tunability of Fano resonance

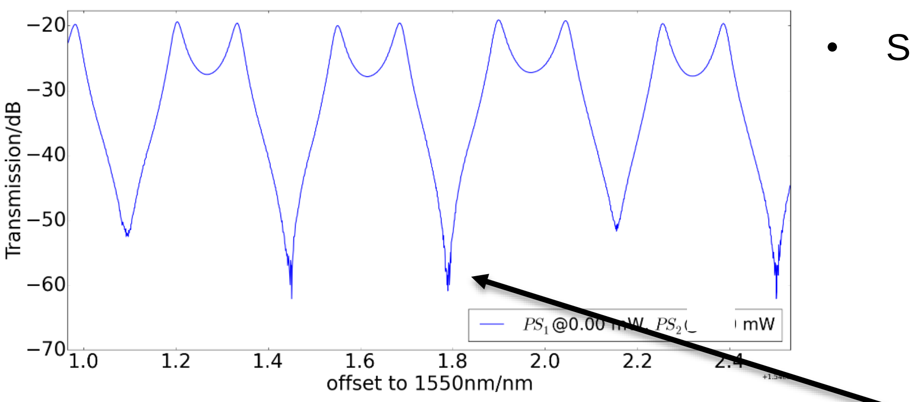
REFLECTIONS ENGINEERING – TWO REFLECTORS

3. Fano resonance – measurements





- Max. slope rate > 700dB/nm, with ER~36dB
- Slope rate of a normal silicon ring resonance ~ 60dB/nm



- Max. ER=40dB, with slope rate~400dB/nm

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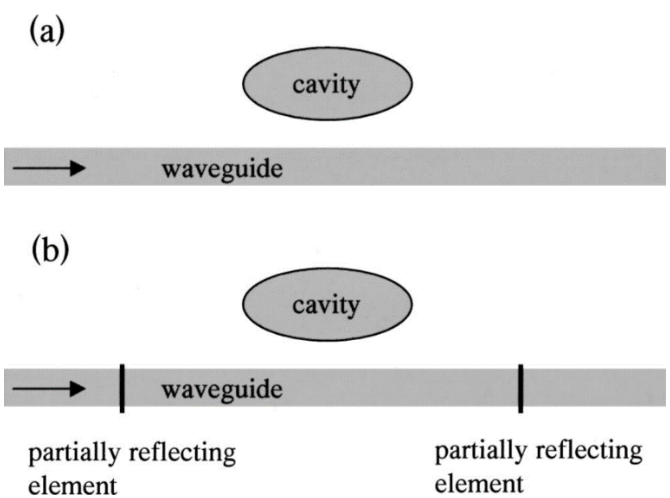
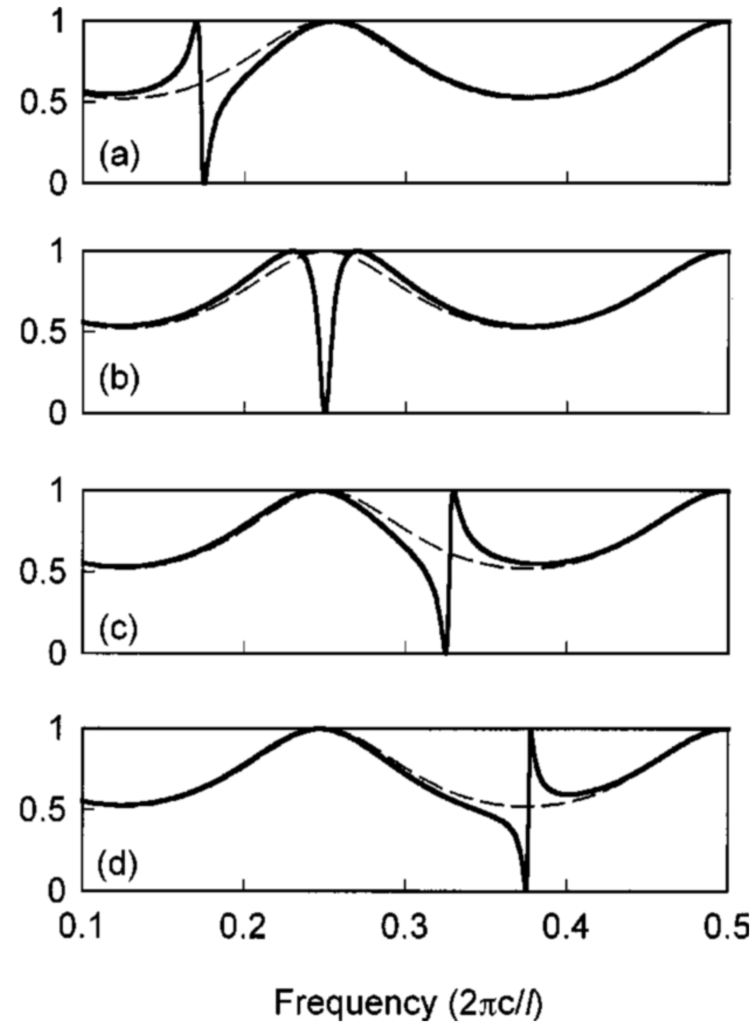
REFLECTIONS ENGINEERING – TWO REFLECTORS

3. Fano resonance – other approaches

   - Standing wave cavity + travelling wave cavity

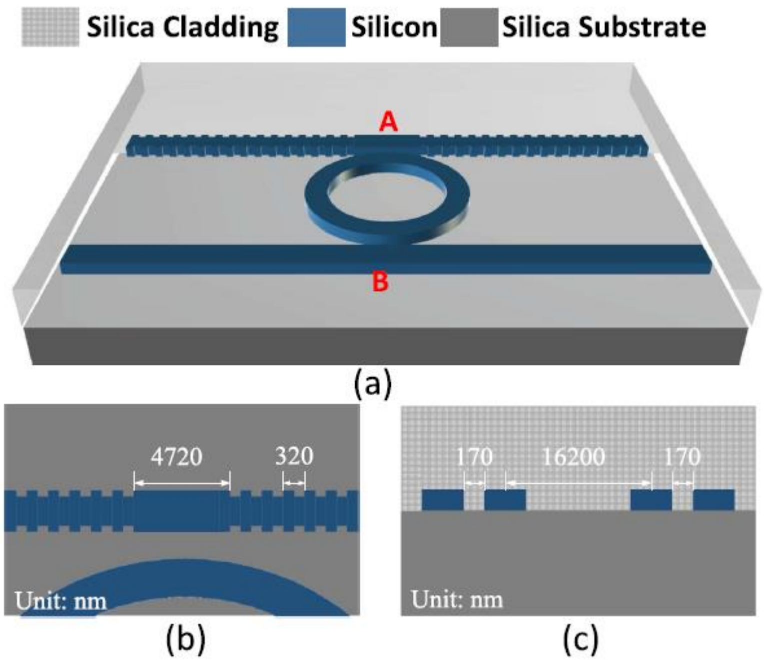


S. Fan et al.,, APL 80 (6), 908-910, 2002

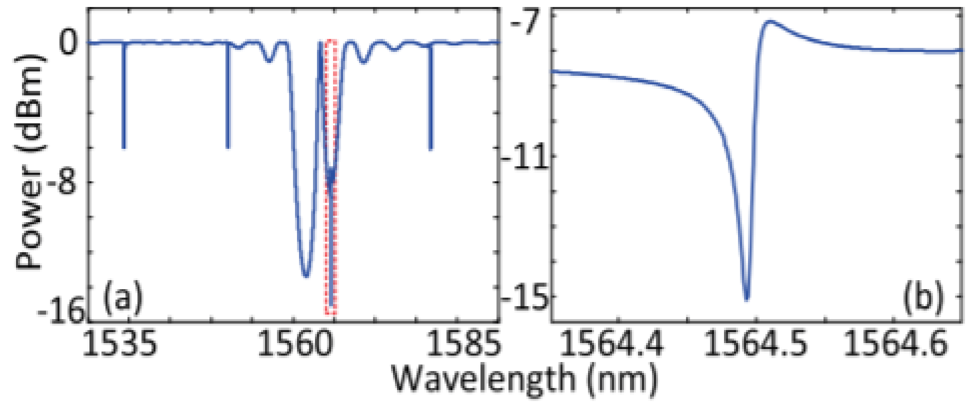


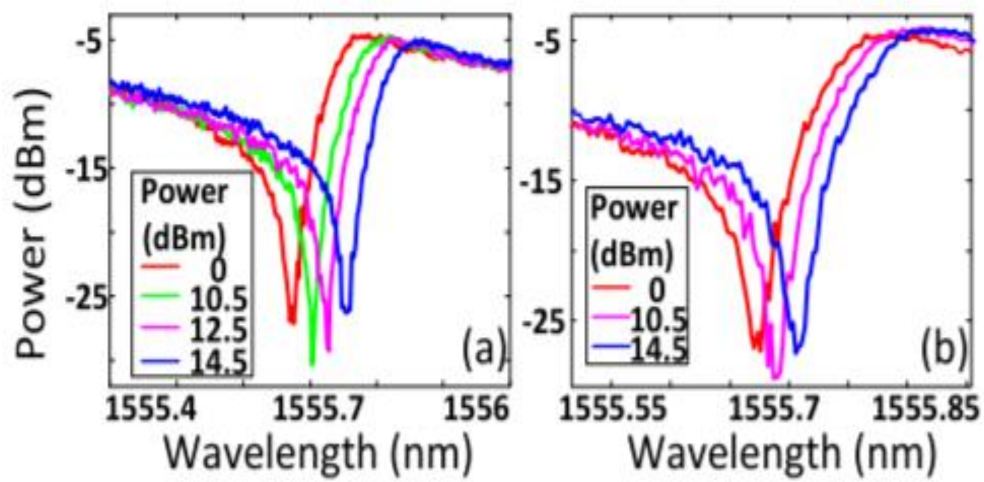
Reflections engineering – two reflectors

3. Fano resonance – other approaches
   - Bragg formed FP cavity with ring cavity
     - Optical tuning
     - Low performance



W. Zhang et al., OL Vol. 41, No. 11, 2016





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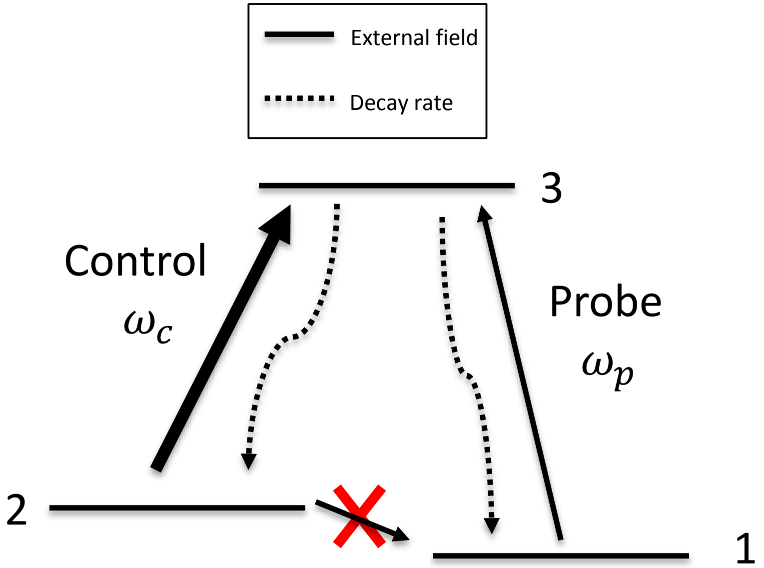
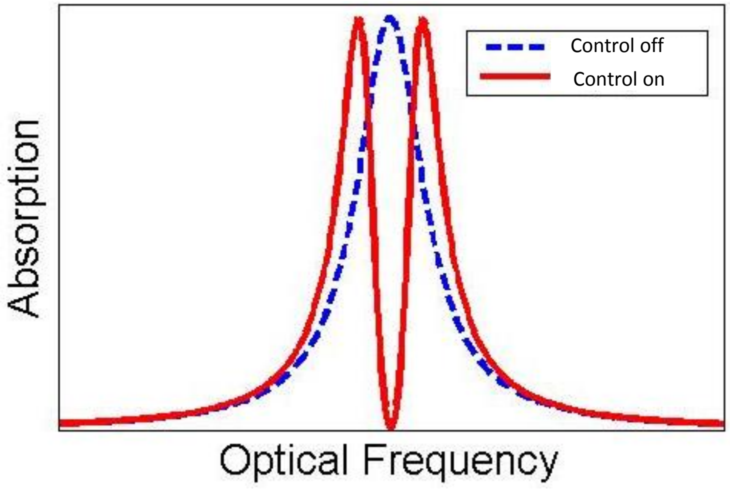
REFLECTIONS ENGINEERING – TWO REFLECTORS

4. Electromagnetically induced transparency (EIT) -- Principle

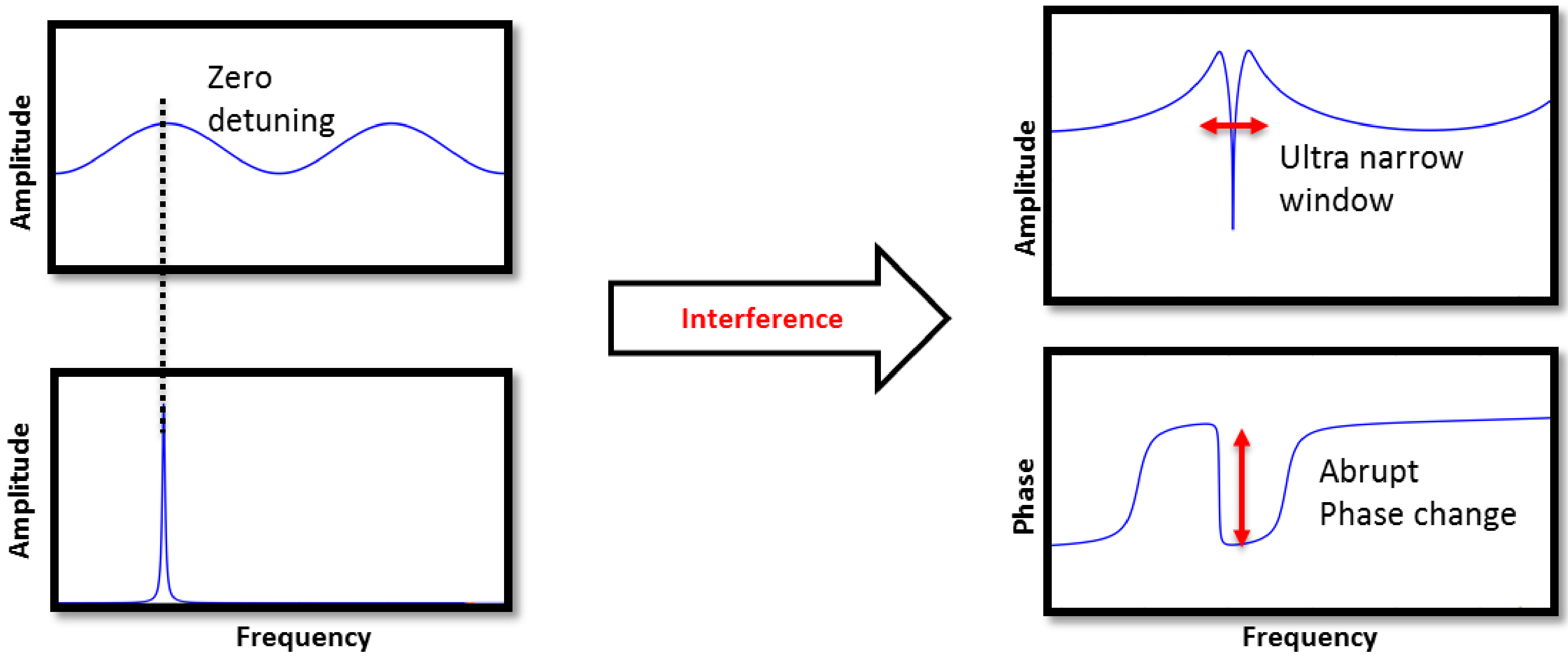
   - Principle: destructive interference between two excitation pathways in an atomic systems (from 2 to 3 and from 1 to 3).
   - Without control, the absorption of probe shows Lorentzian line, with control, a dip is induced.





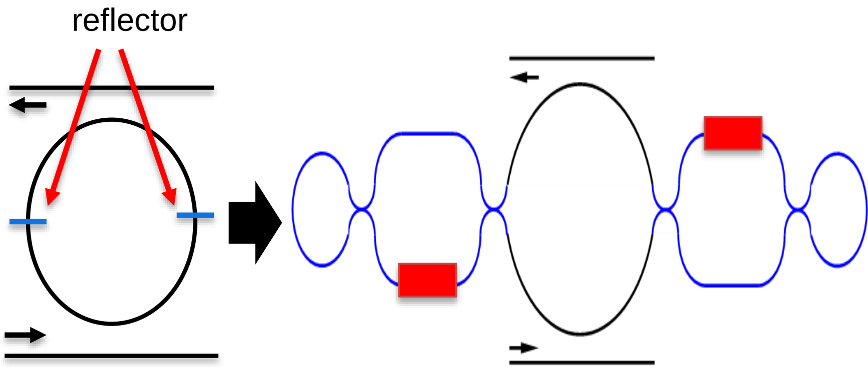
Reflections engineering – two reflectors

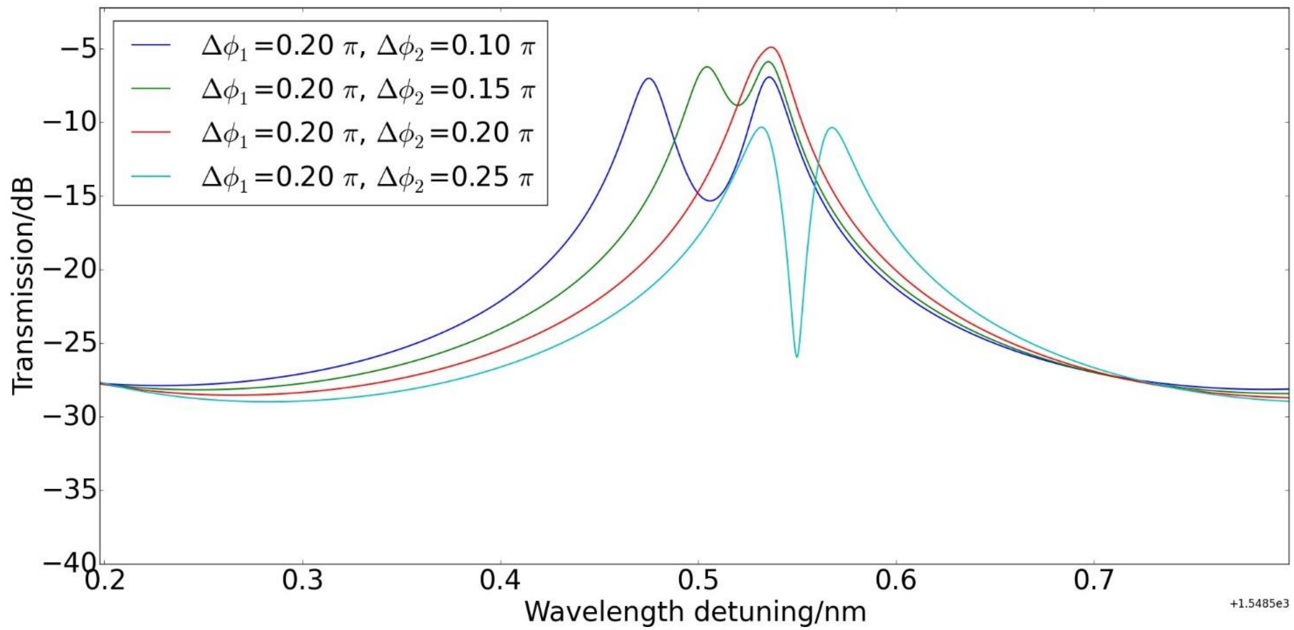
4. EIT – principle in optical field
   - Principle: fundamentally a Fano resonance, zero-detuning between the smooth mode and discrete mode



REFLECTIONS ENGINEERING – TWO REFLECTORS

4. EIT – simulation
   - On the basis of Fano, fine tune reflectors
   - First demonstration of transition between Fano and EIT in a single device

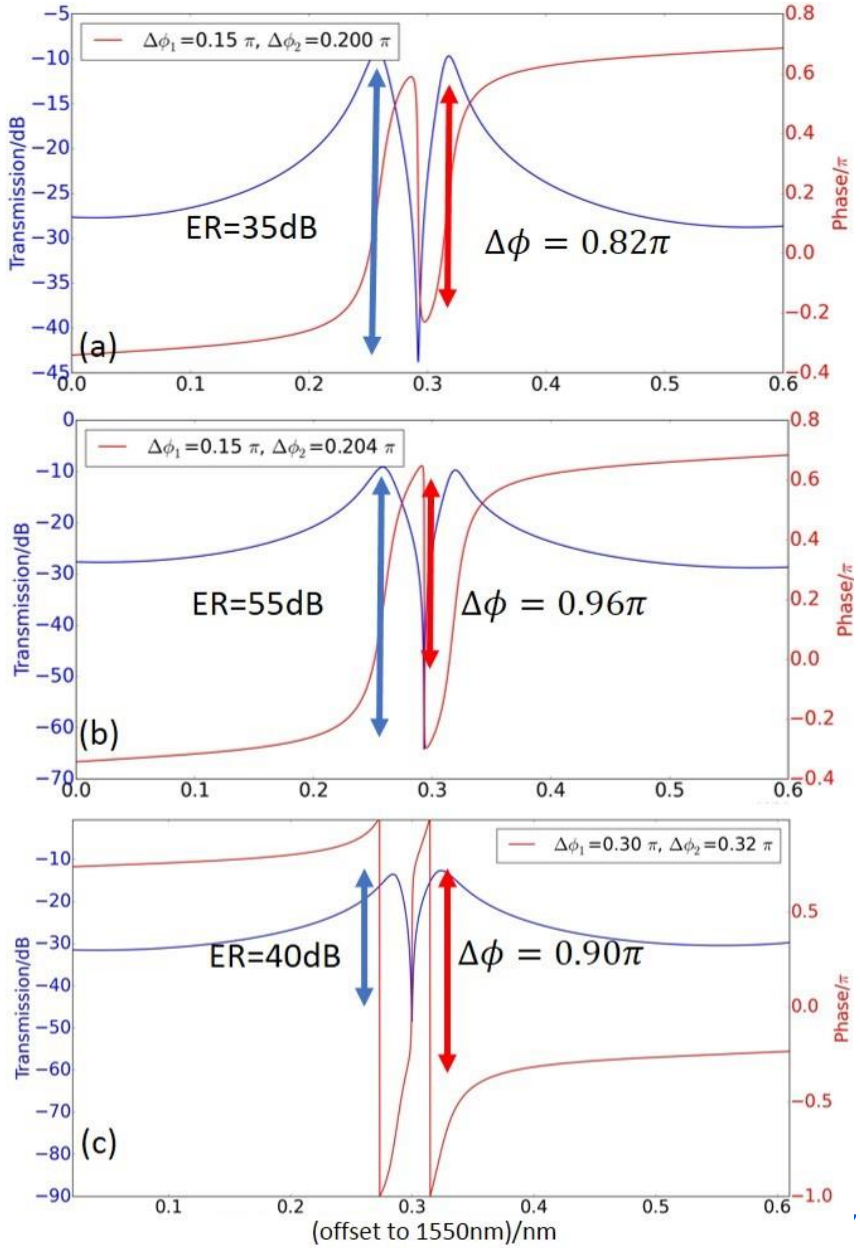




Reflections engineering – two reflectors

4. EIT – simulation

   - Key parameters can be further tuned



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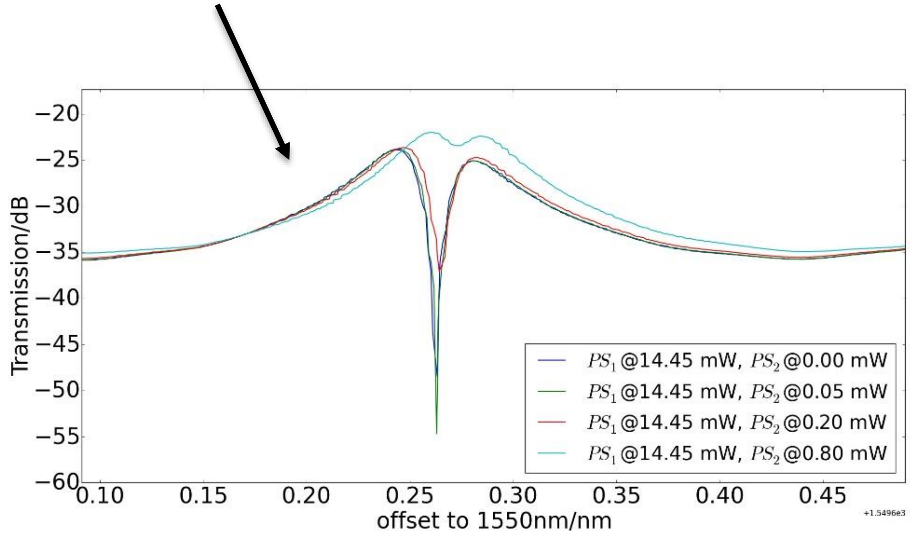
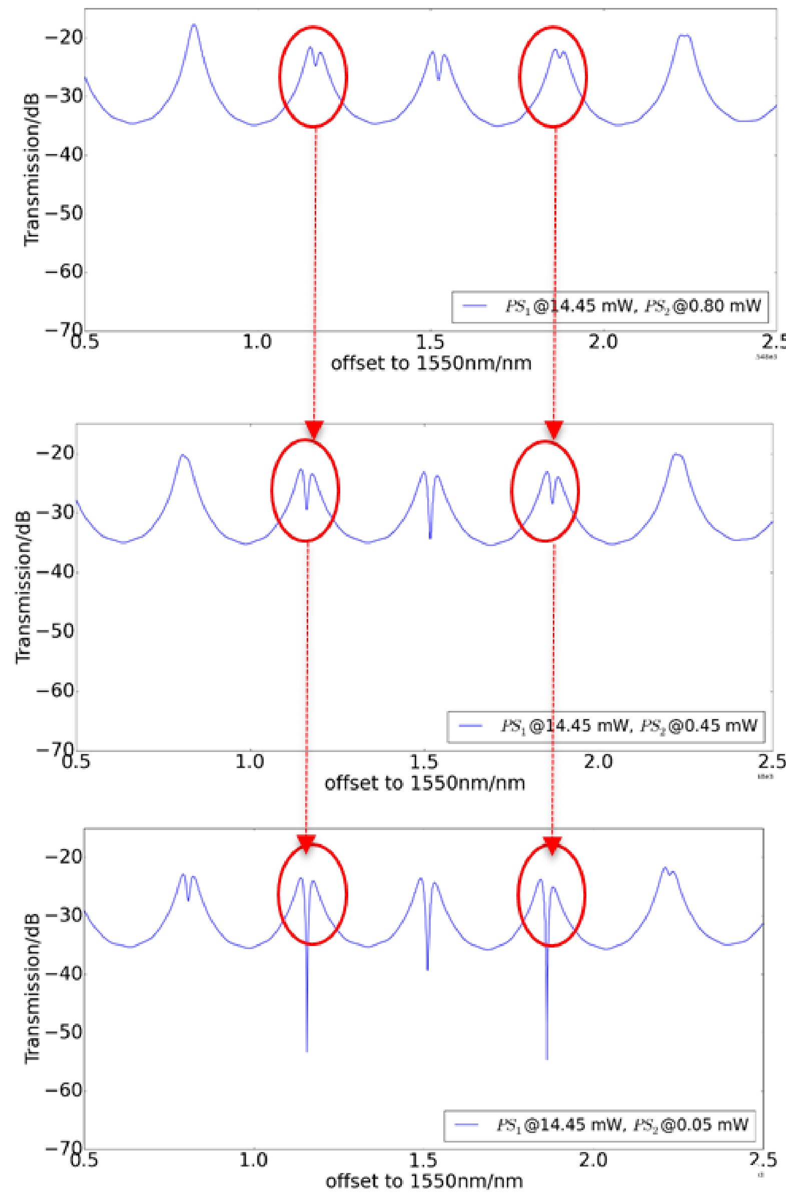
REFLECTIONS ENGINEERING – TWO REFLECTORS

4. EIT – measurements

Power only changes 0.4mW

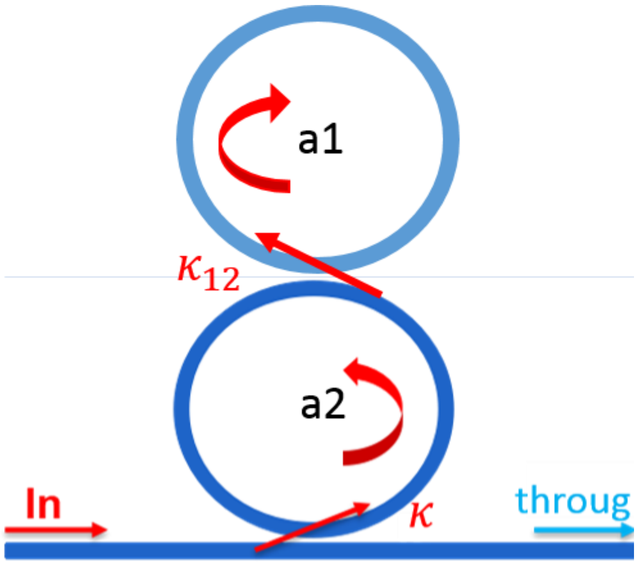
Peak evolves dramatically



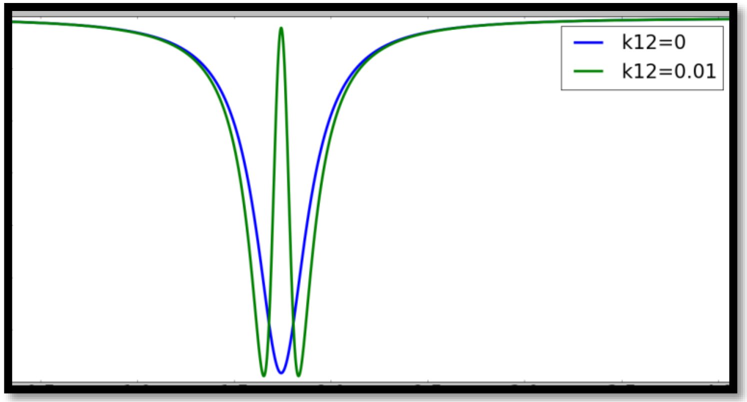


Reflections engineering – two reflectors

4. EIT – popular approach
    - Coupled ring cavities
    - Hard to guarantee and tune
    - Difficult to engineer loss in silicon photonics

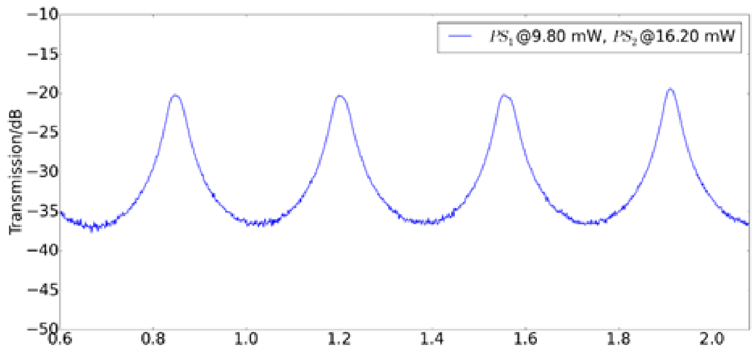


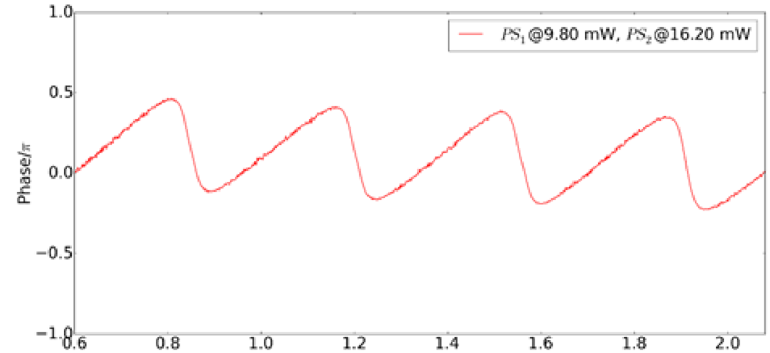
- Different Q factor
- Good alignment



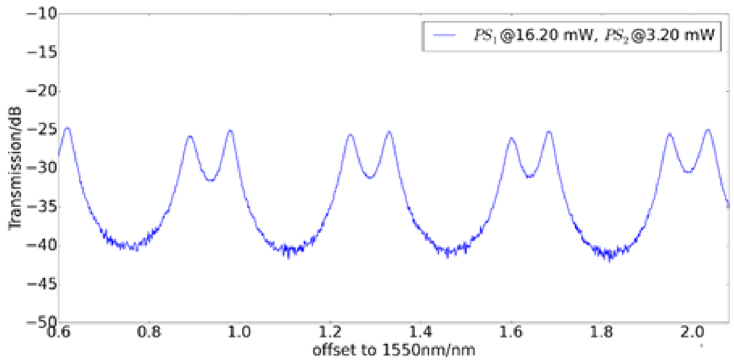
REFLECTIONS ENGINEERING – TWO REFLECTORS

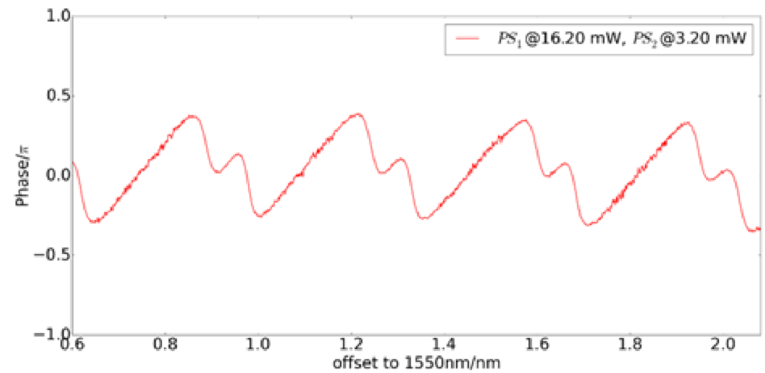
4. EIT – phase measurements



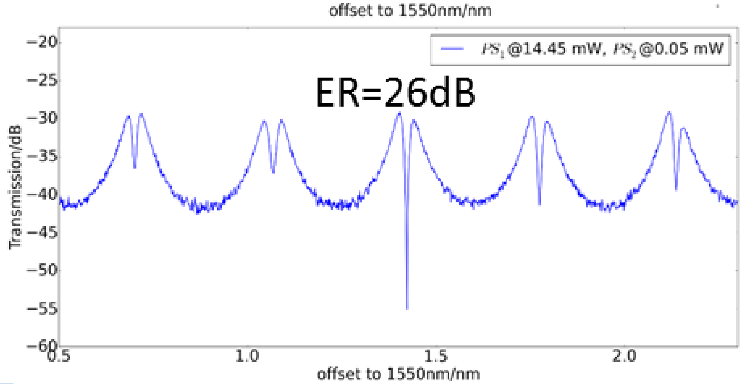


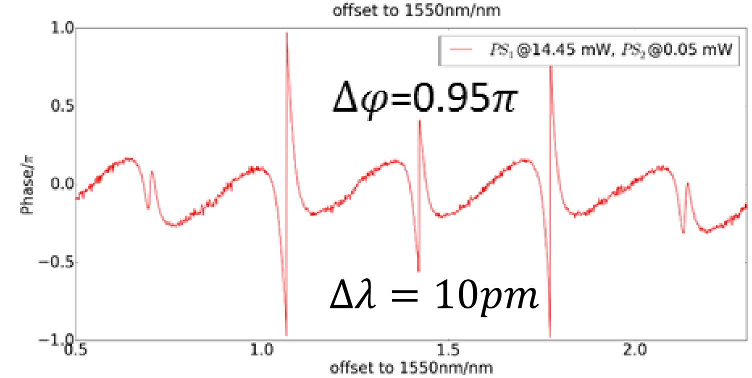
Lorentzian resonance





Resonance splitting





EIT

$n_g > 300$

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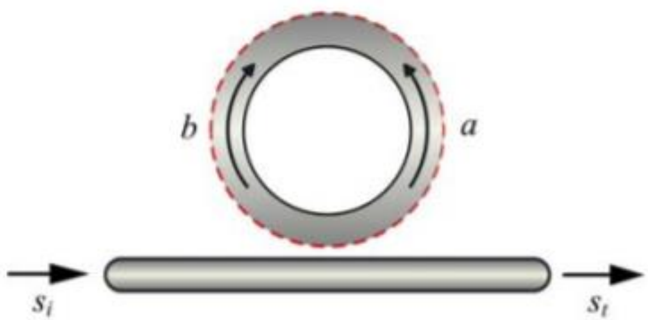
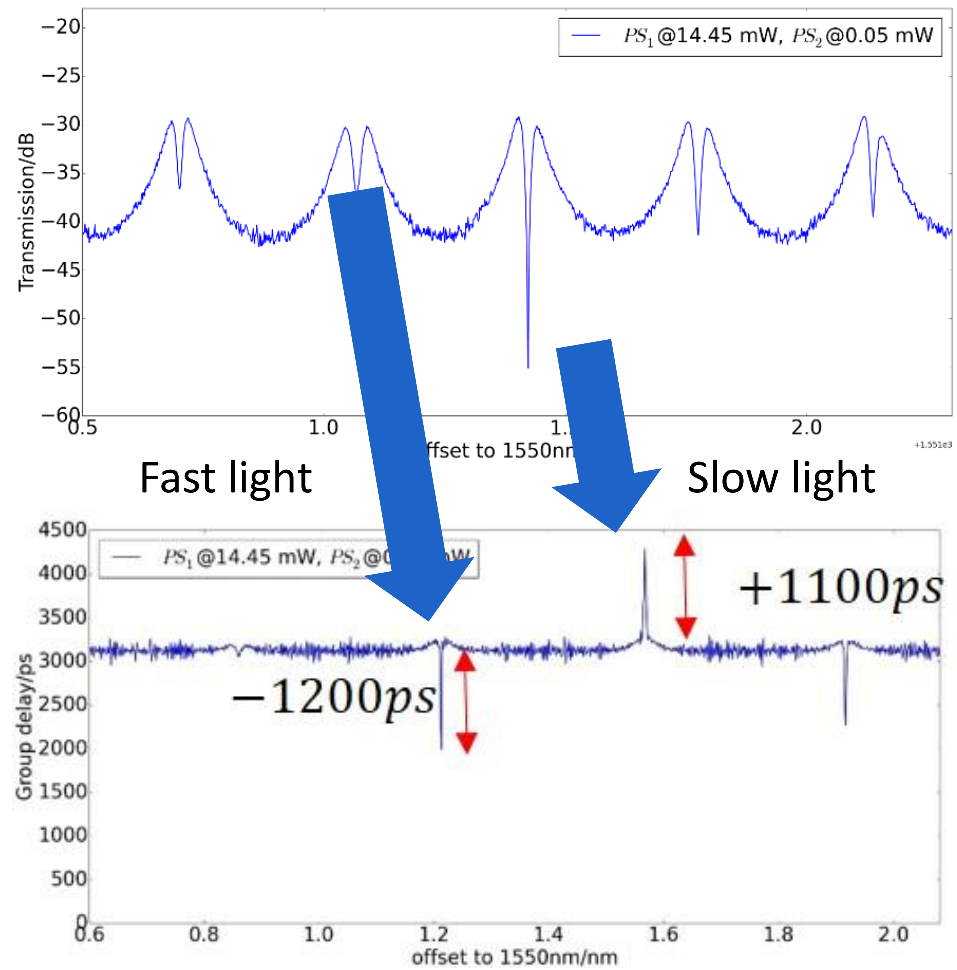
Reflections engineering – two reflectors

4. EIT – delay measurements
   - Slow light at the EIT → 10cm silicon waveguide
   - Fast light at splitting → 10-fold improvement frompared to [1]

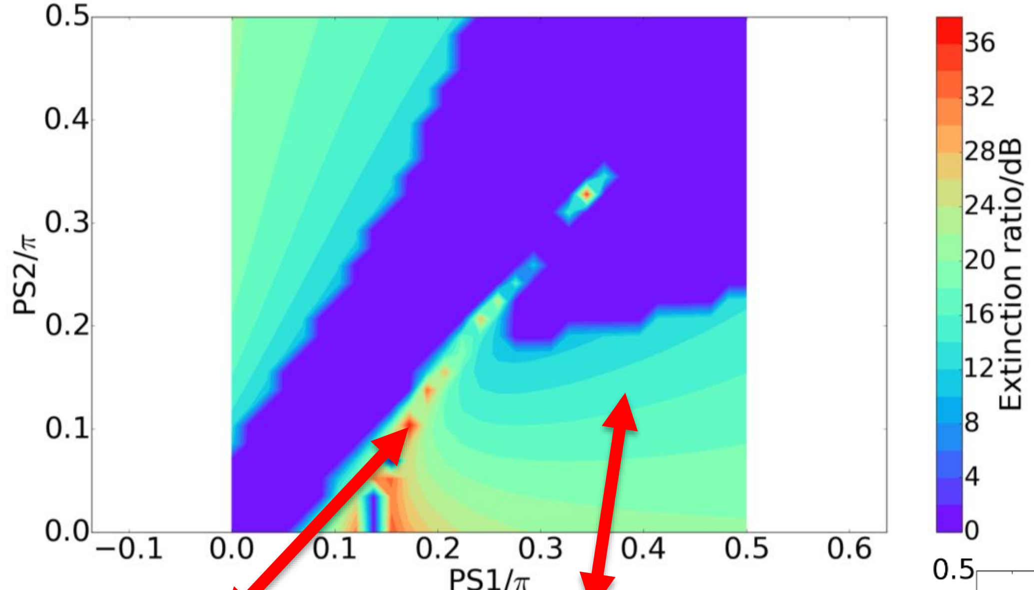


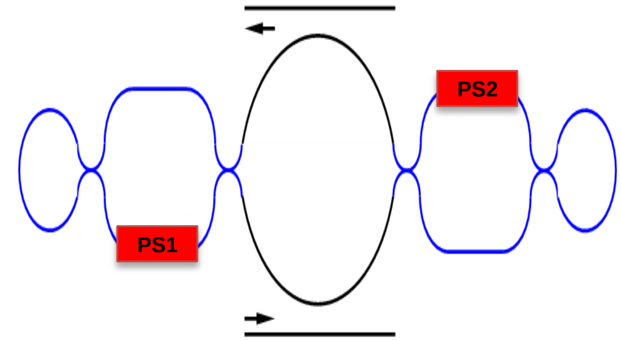
1. Q. Li et al., Optics express, 17(2), 2008

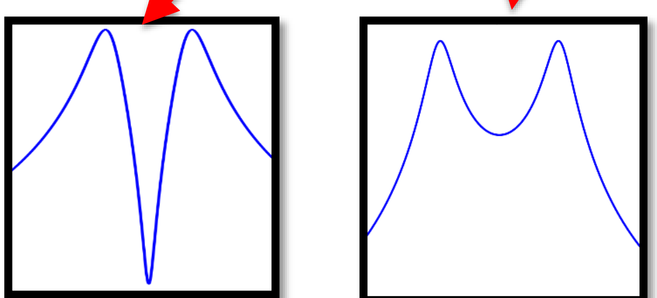


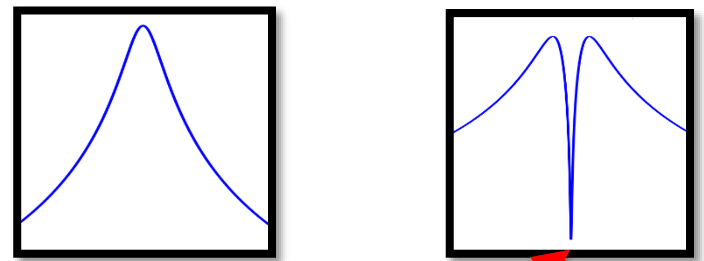
REFLECTIONS ENGINEERING – TWO REFLECTORS

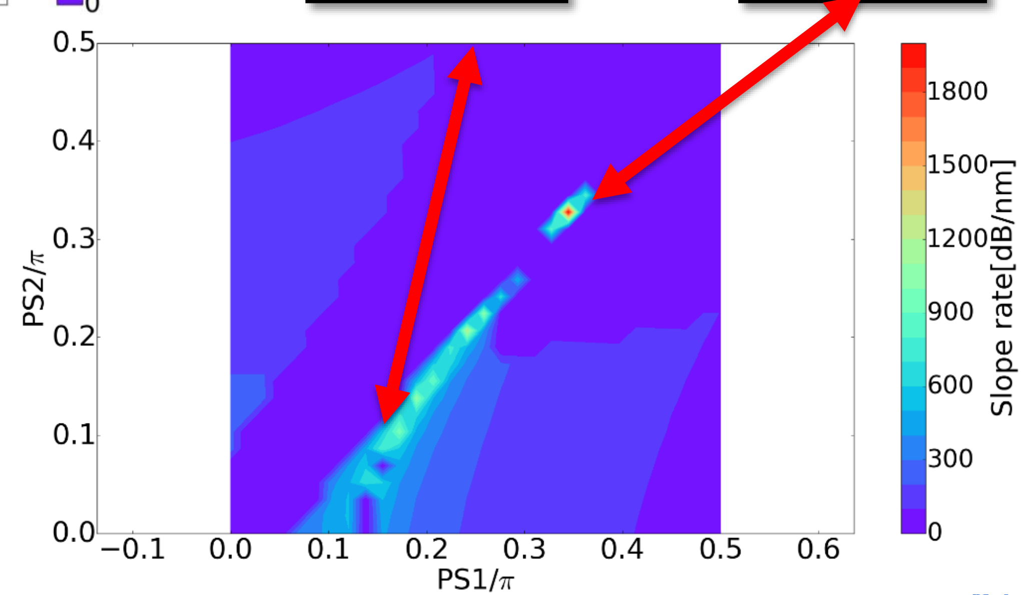
4. Contour plots





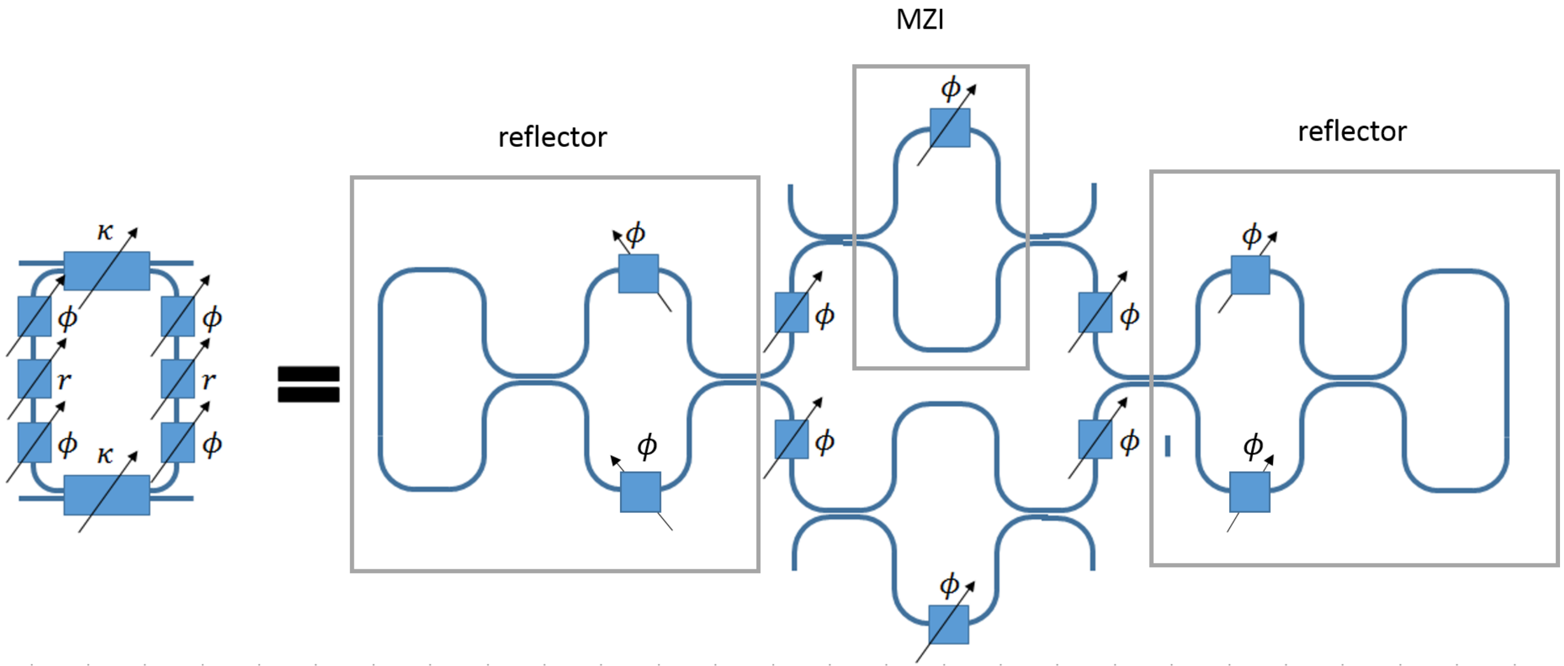


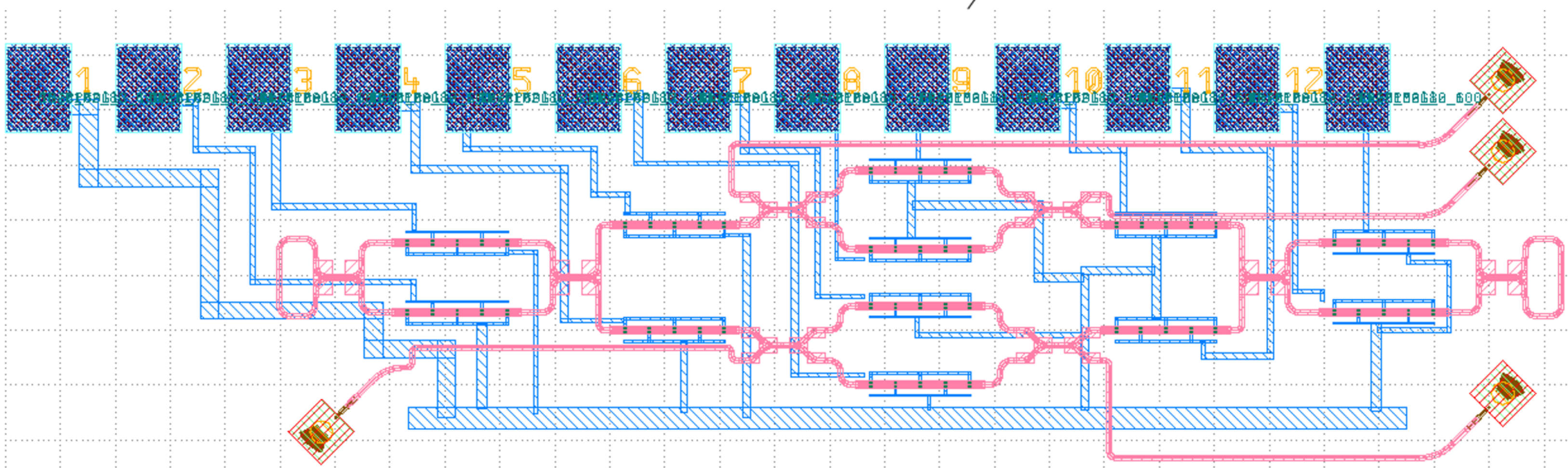




Generic programmable ring resonator

- A generic ring with many degrees of freedom





Conclusion & outlook

Conclusion

- Photonics parasitics study
- Model for various resonance splitting of ring resonator
- Turn two unwanted, non-deterministic effects into useful degrees of freedom
  - Internal reflections
  - Backcoupling

Outlook

- Programmable ring resonator
- Nonreciprocal transmission by reflections engineering in ring resonator

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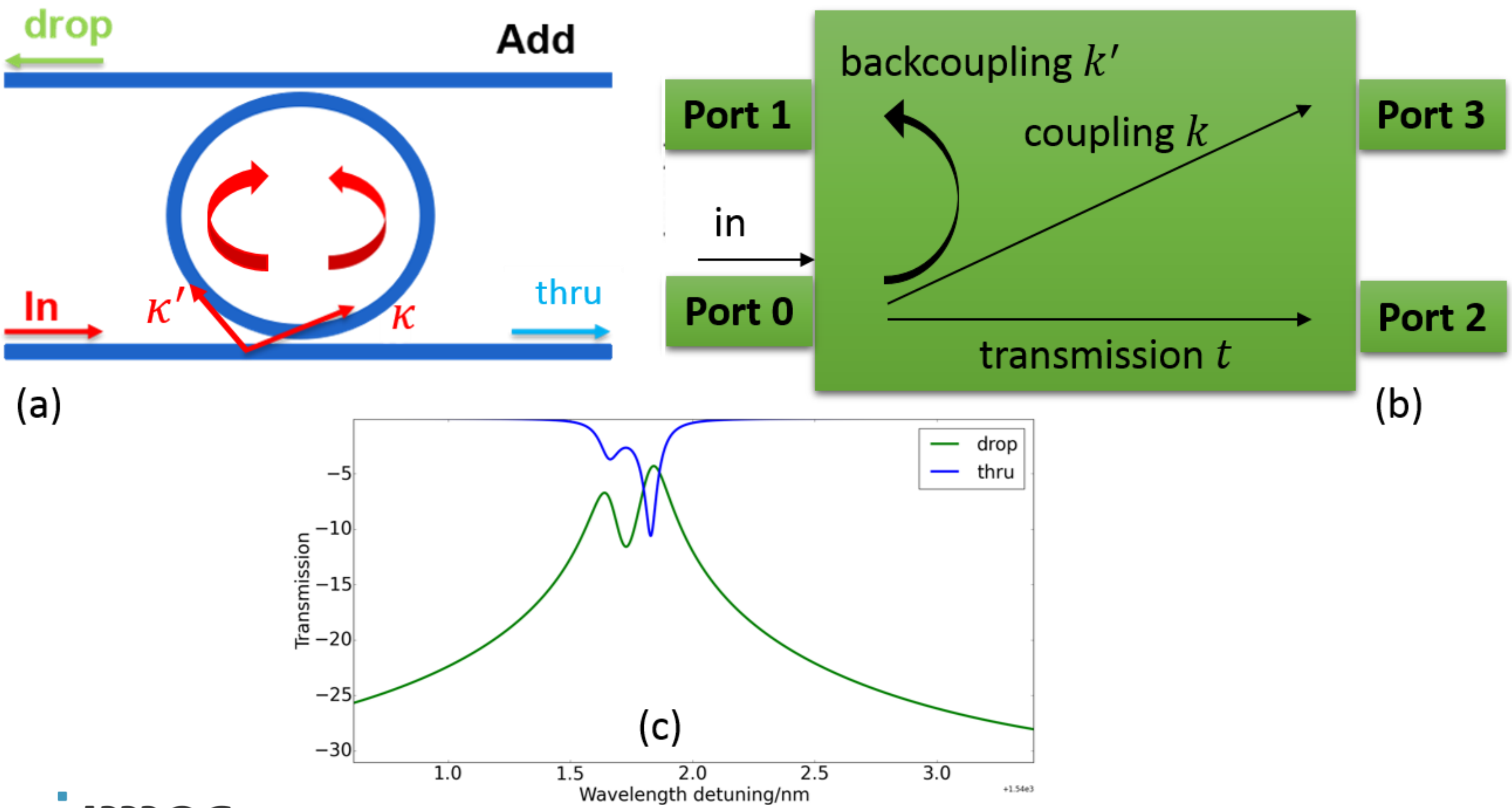
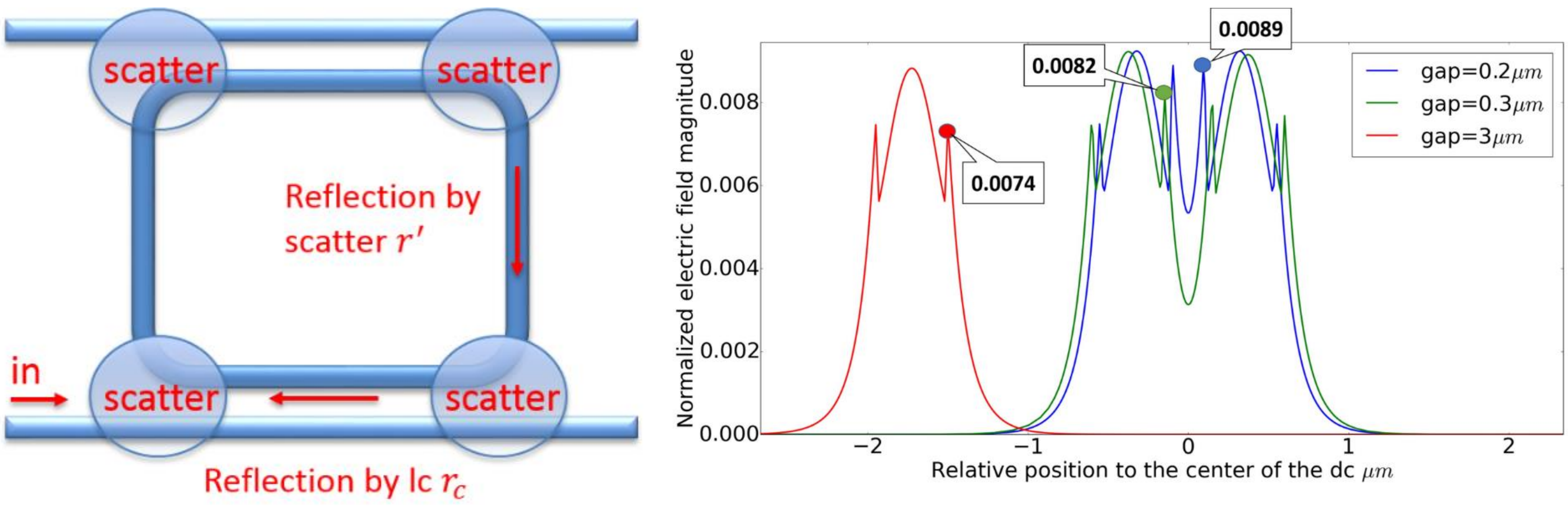
Parasitics in silicon Microring

- Origin for asymmetric resonance splitting
  - Backcoupling at the couplers
  - Contribution from input to both modes (CW and CCW)



Parasitics in silicon Microring

- Quantitative analysis
  - Couplers contribute to backscattering



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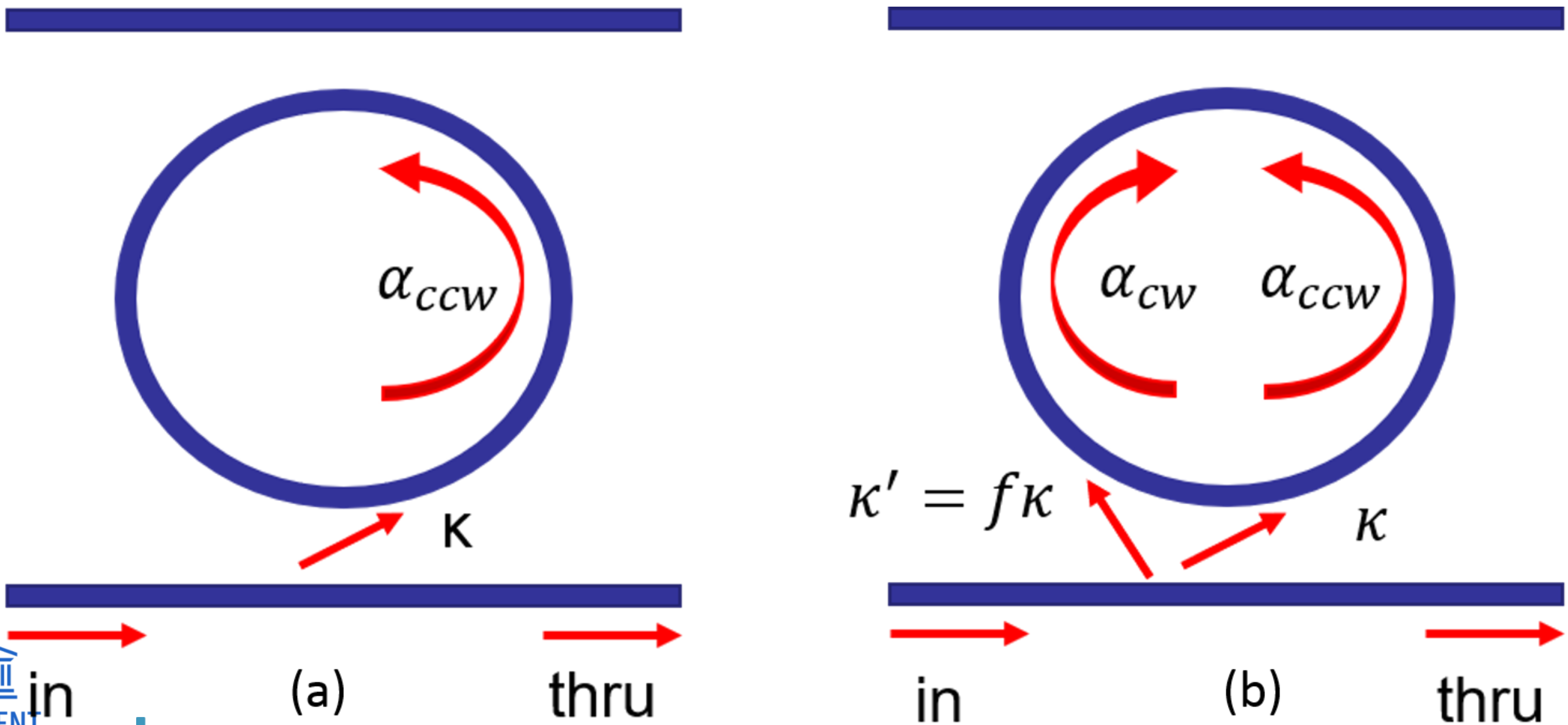
2ND DEGREE OF FREEDOM - BACKCOUPLING

- Two detrimental and non-deterministic parasitics in microrings
  - Internal reflections - affects splitting distance
  - Backcoupling - affects peak asymmetry
  - Need both to control a split resonance



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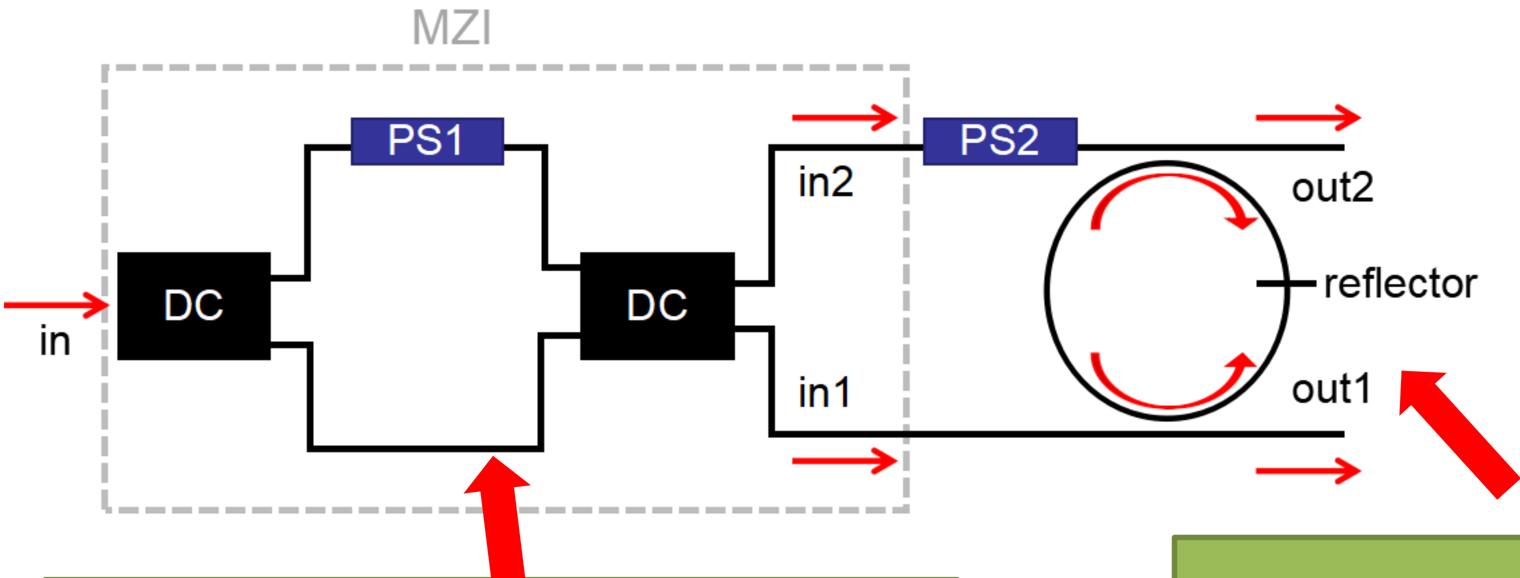
2ND DEGREE OF FREEDOM - BACKCOUPLING

- Unrealistic to directly control the backcoupling of a conventional DC
- PS1 changes backcoupling/coupling ratio; PS2 changes phase contrast



- MZI splits input into two beams, each couples to one of the two modes
- Tuning the split ratio of MZI is analogous to tune the backcoupling/forward coupling

- Two modes can be coupled through backscattering or intentional reflector