Ultra-high-Q resonator on a chip and its applications

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Graduate School of Nanoscience and Technology, KAIST

with Vahala group at Caltech
hQphotonics

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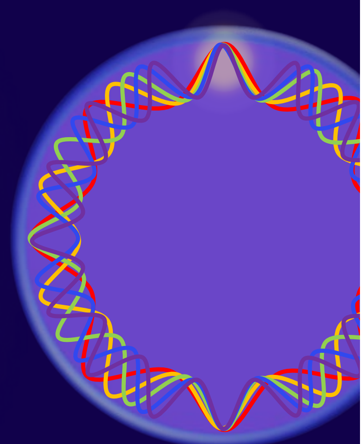
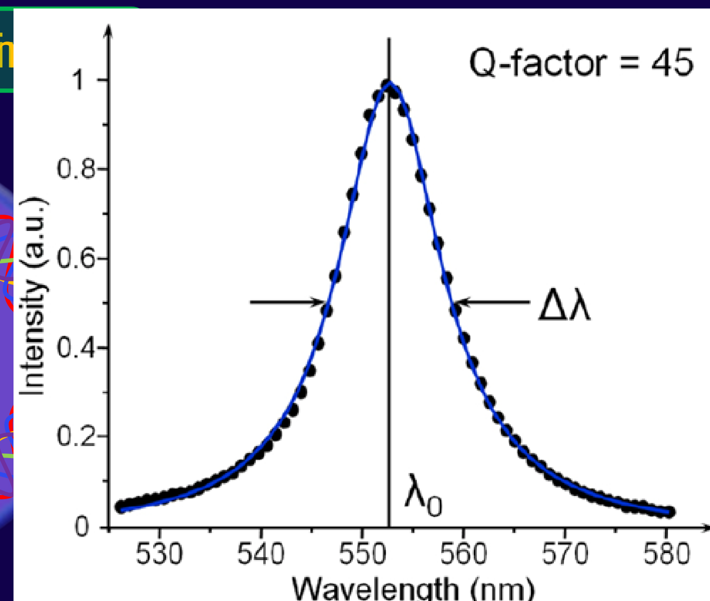
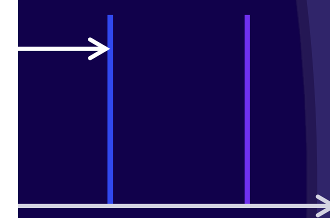
General Introduction

- Ultra-high-Q optical micro-resonators





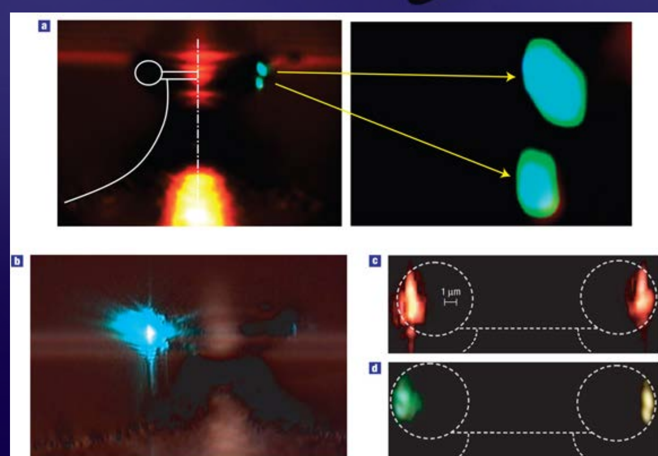


General Introduction

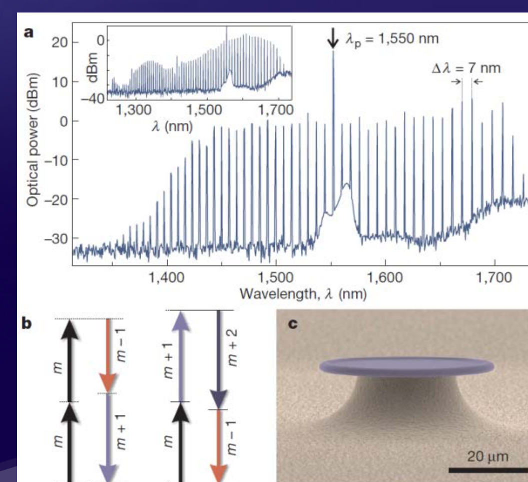
- Ultra-high-Q optical micro-resonators

I_{cavity} ⨳ $I_{threshold}$

Nature 2002



Nature Physics 2007



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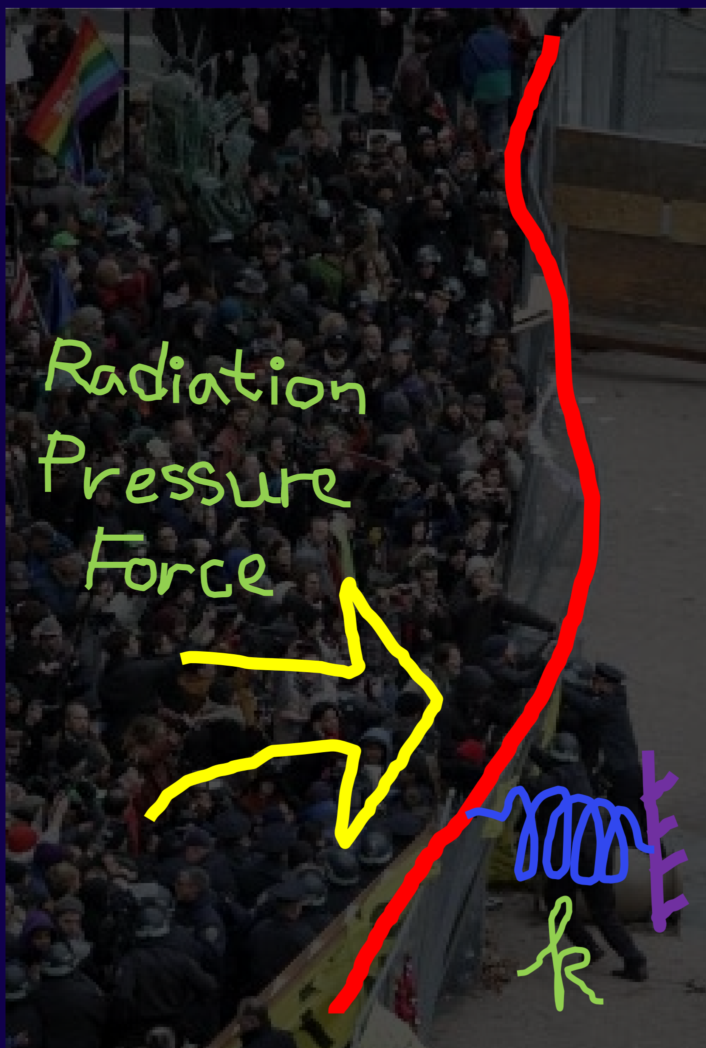
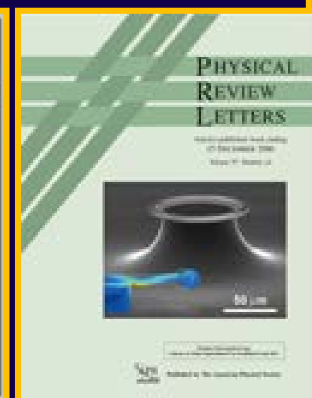
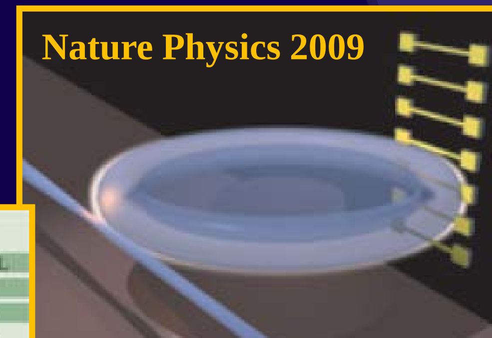


PRL 2007

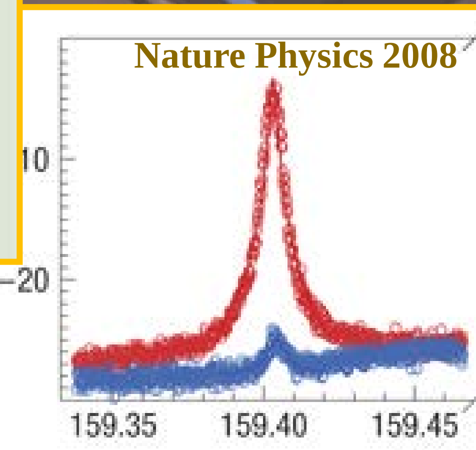
PRL 2006

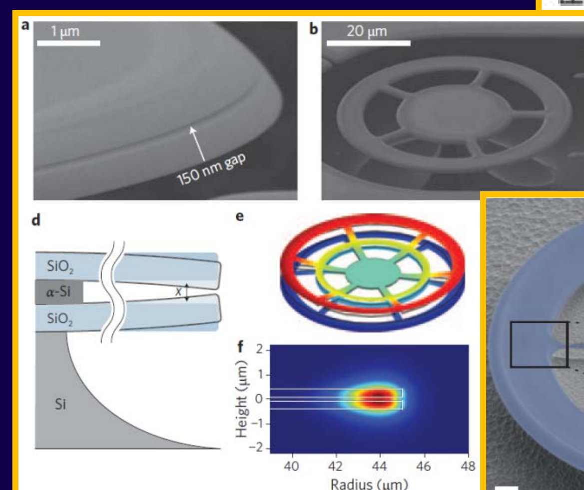


Nature Physics 2009

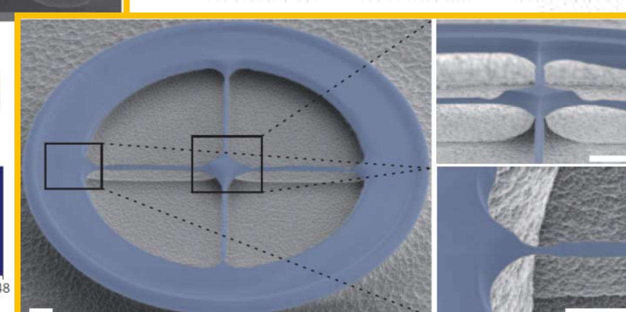


Nature Physics 2008





Nature Photonics 2007



Nature Photonics 2009

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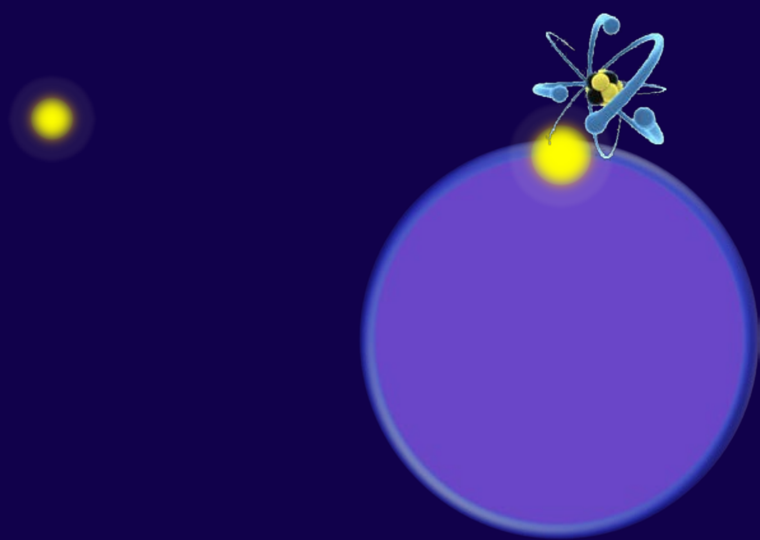
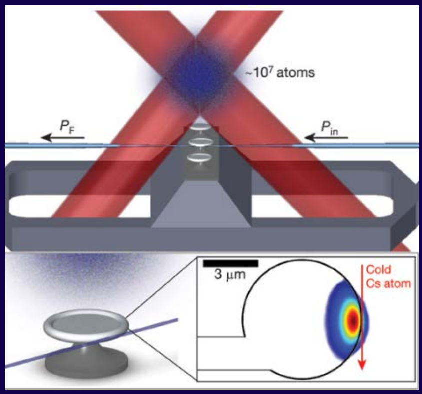
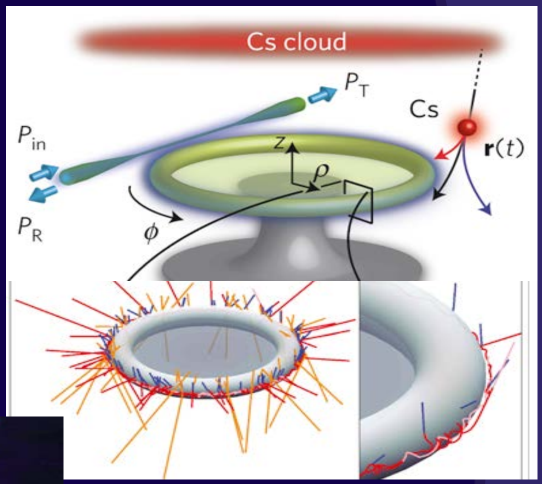
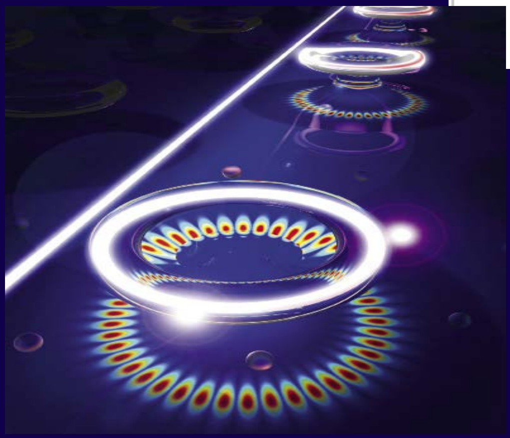


Nature 2006

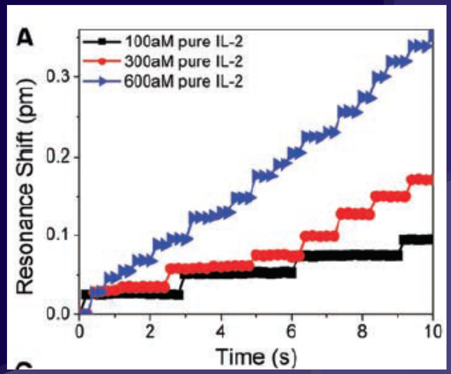


Nature Physics 2011





Nature Photonics 2009



Science 2007

General Introduction

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Nature 2003

Cited over 1500 times

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Part I

Part I

Ultra-high-Q Wedge resonator

Record Q on a Si chip

Standard semiconductor fabrication process

Precise size control

Reference cavity

First reference cavity on a chip

Longest resonator on a chip

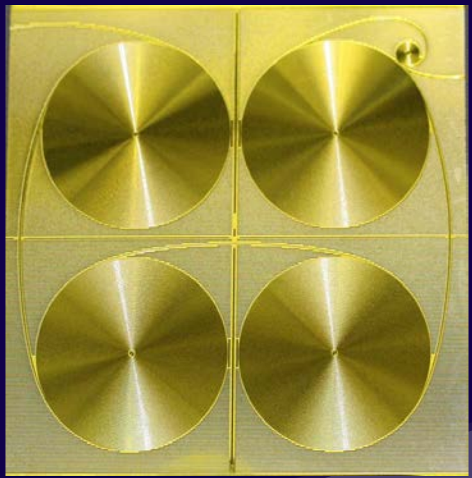
Part2

Ultra-low-loss Waveguide

Record loss

Record length

Wide bandwidth

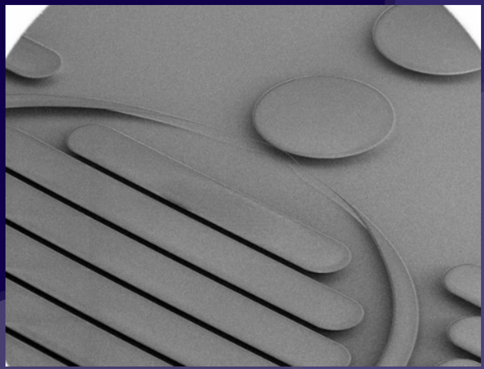


Part3

Toward integrated photonic circuits

Goal: implementation of simple photonic circuits monolithically on a silicon chip

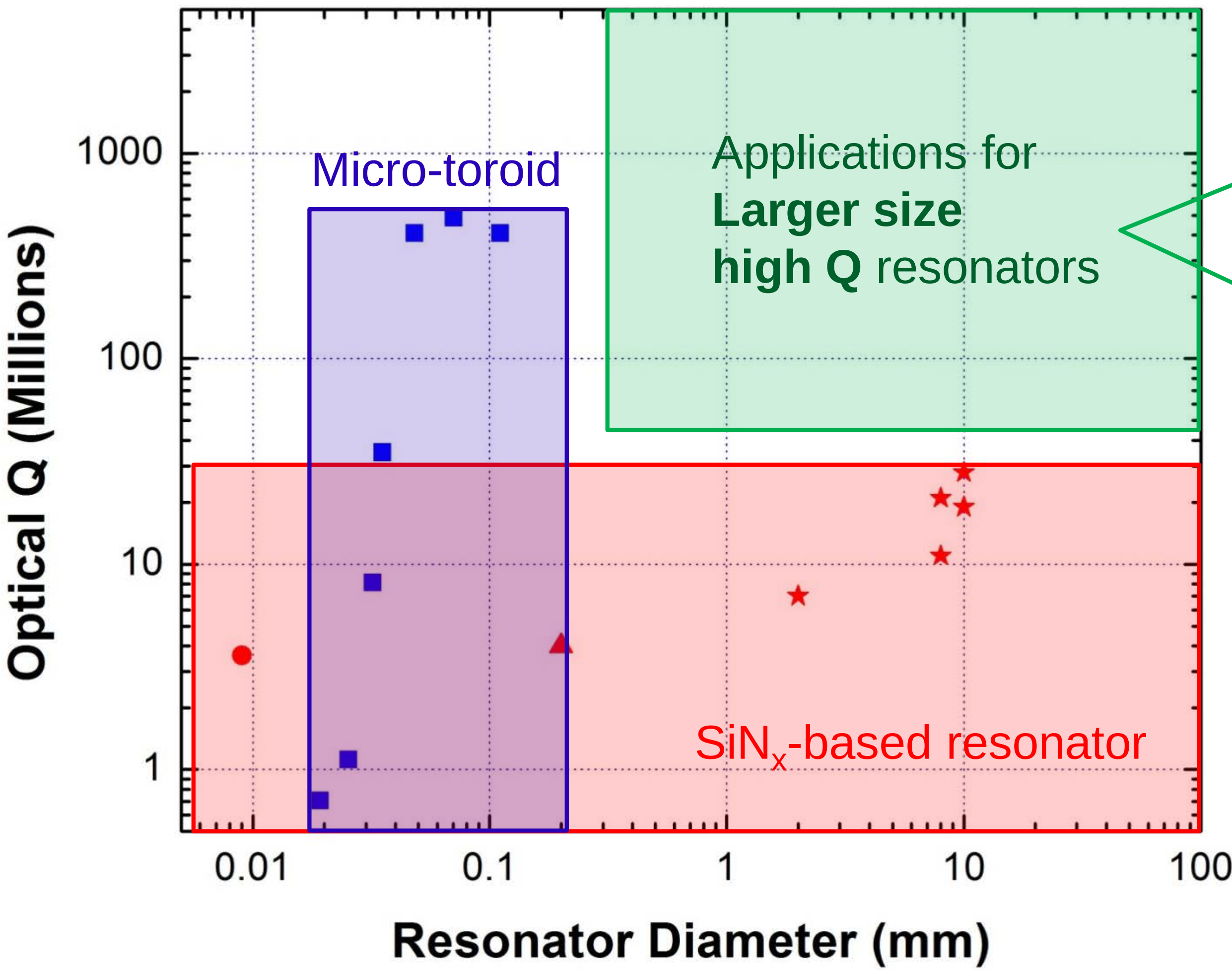
Miniaturization
Mass production
Robustness



Previous high Q resonators

	Optical Q	Typical Size (diameter) 1um 10um 1mm 10mm	on-chip	Integration on chip	Size controllability
CaF_2 resonator	10^{11}		No	Not easy	Not easy
SiO_2 micro-sphere	10^{10}		No	Not easy	No
SiO_2 micro-toroid	$5x10^8$		**Yes**	Not easy	No
SiN_x - based resonator	$5x10^6$		**Yes**	**Easy**	**Yes**

Previous on-chip resonators



Micro-toroids: ■ [1] D. K. Armani, et al, Nature, 2004

SiNx-based resonators: ● [2] Paul E. Barclay, et al, App. Phys. L., 89, 131108, 2006

▲ [3] Shah Hosseini, et al, IEEE/LEOS meeting, 2009

★ [4] Daoxin Dai, et al, Optics Express, 2011

- Octave spanning frequency comb on a chip
- SBS laser
- RF signal generation
- Low thermal noise reference cavity
- Optical Gyroscope on a chip

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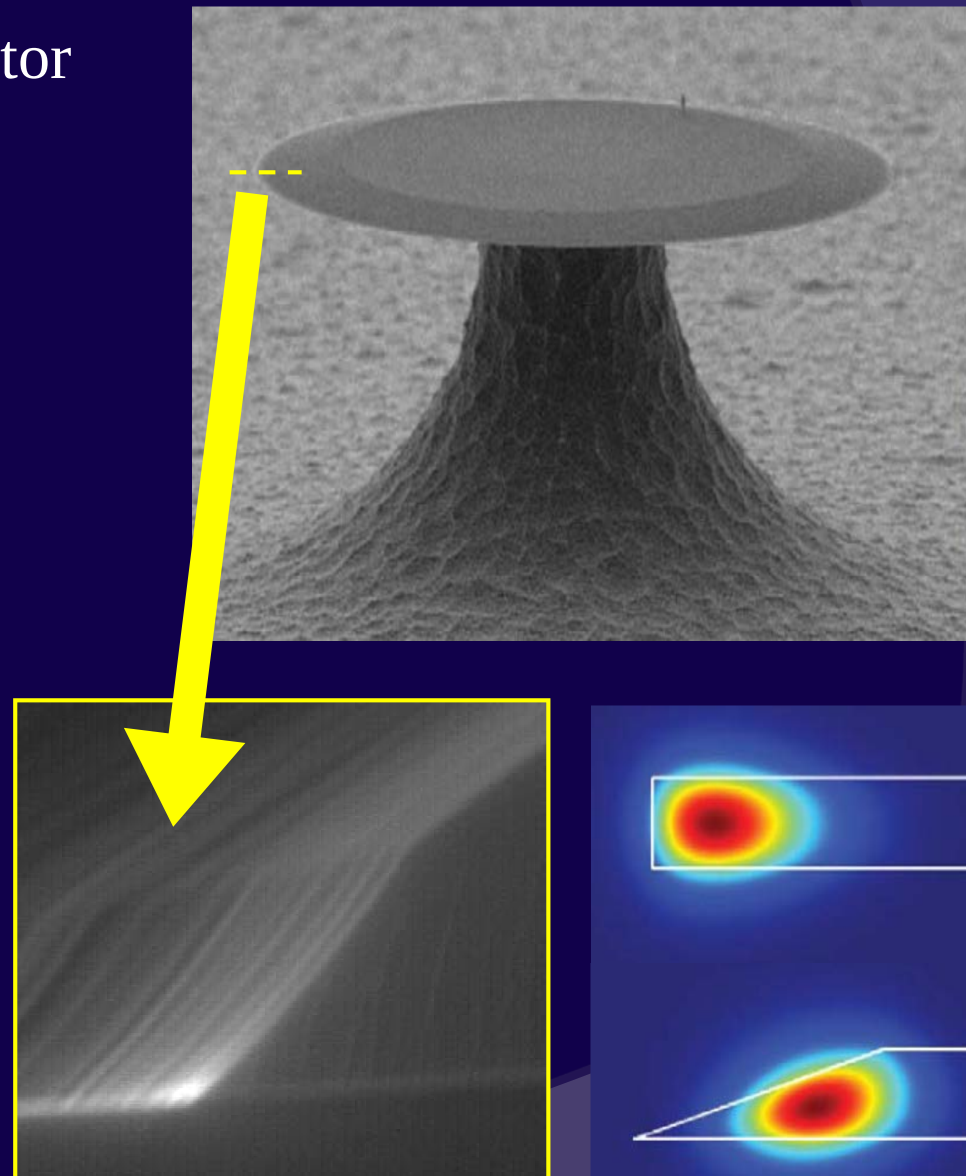
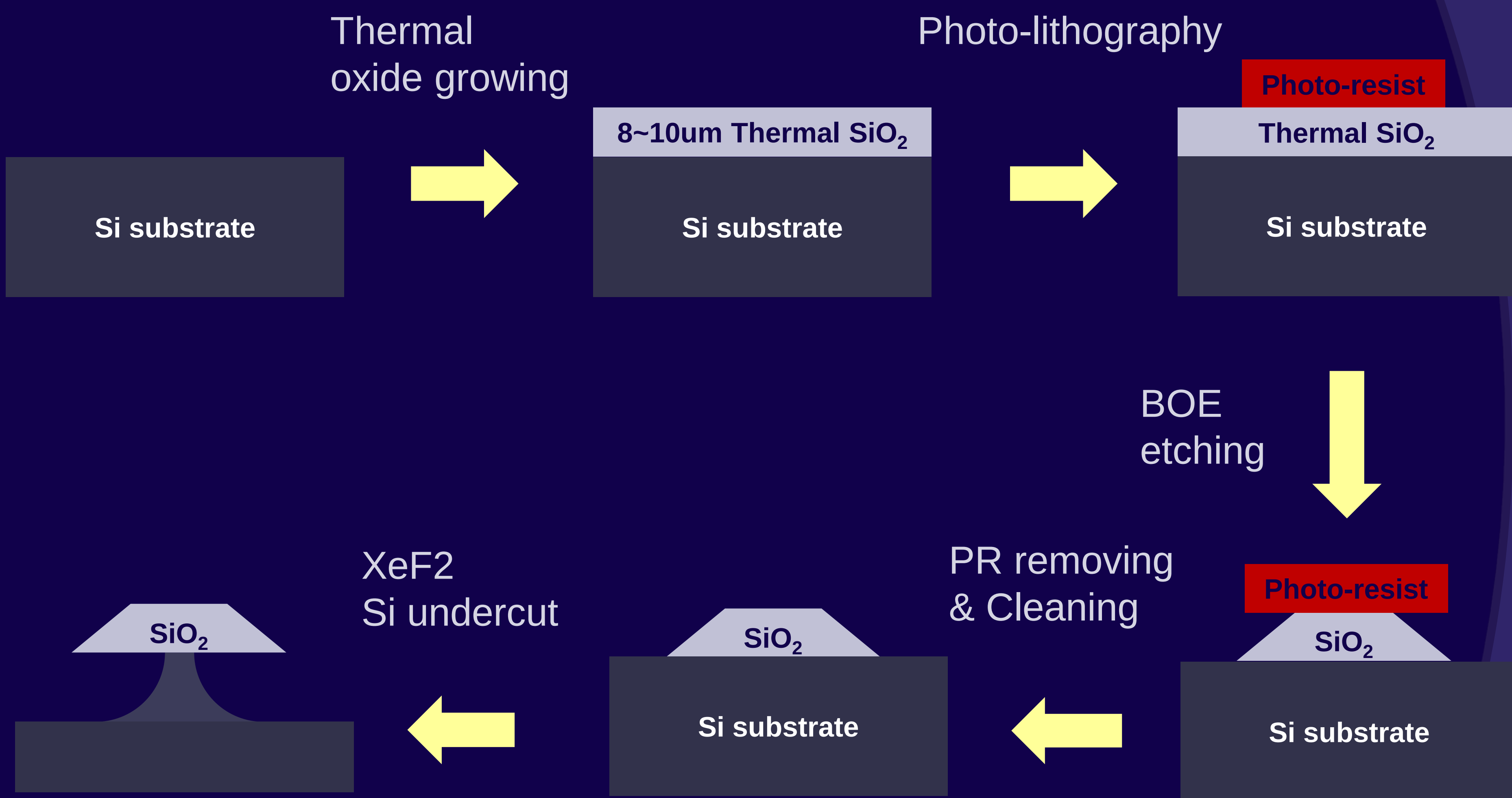
Resonator Design

- Previous SiO_2 wedge disk resonator
  - Vahala group
    Phys. Rev. A, 74, 051802, 2006
  - Optical Q: Tens of Millions
- To achieve higher Q
  - Removing discontinuity of the slope (Foot-region) around the edge area
  - Smoother etched surface
  - Thicker oxide to put optical modes into the cavity
    → To decrease interference with surface roughness



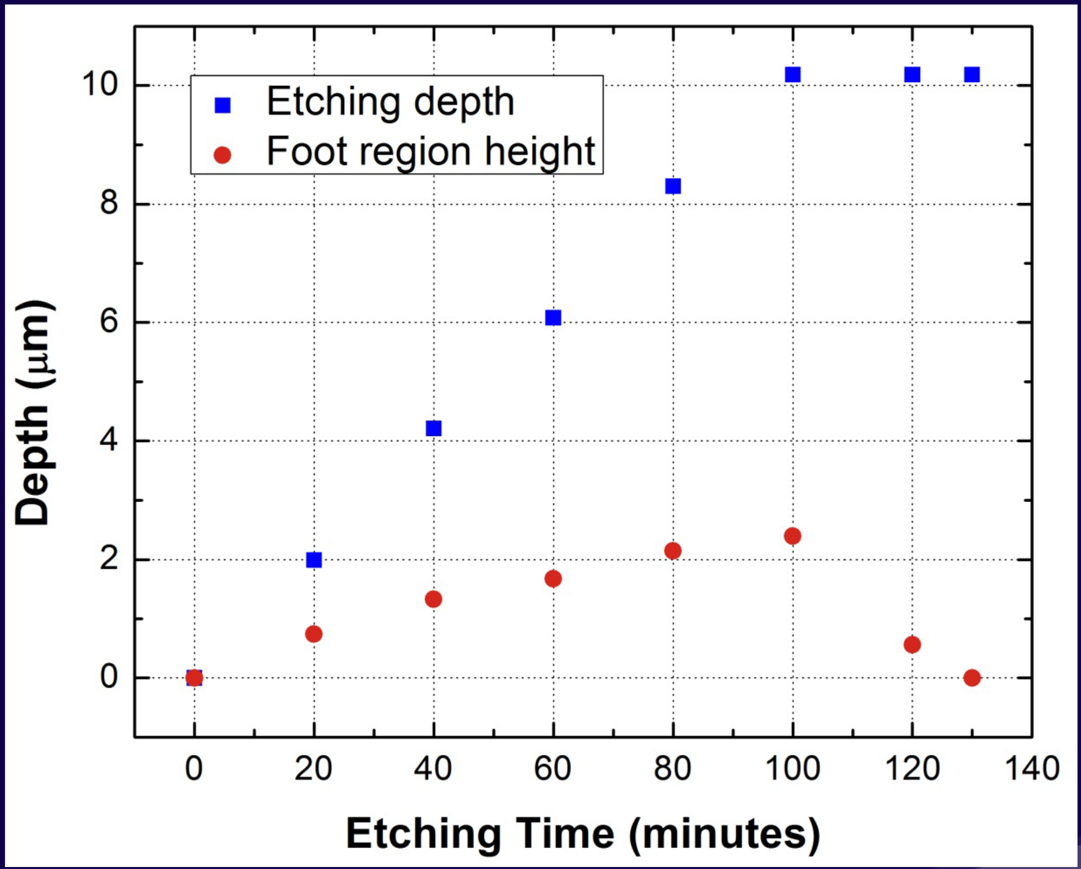
Fabrication procedure

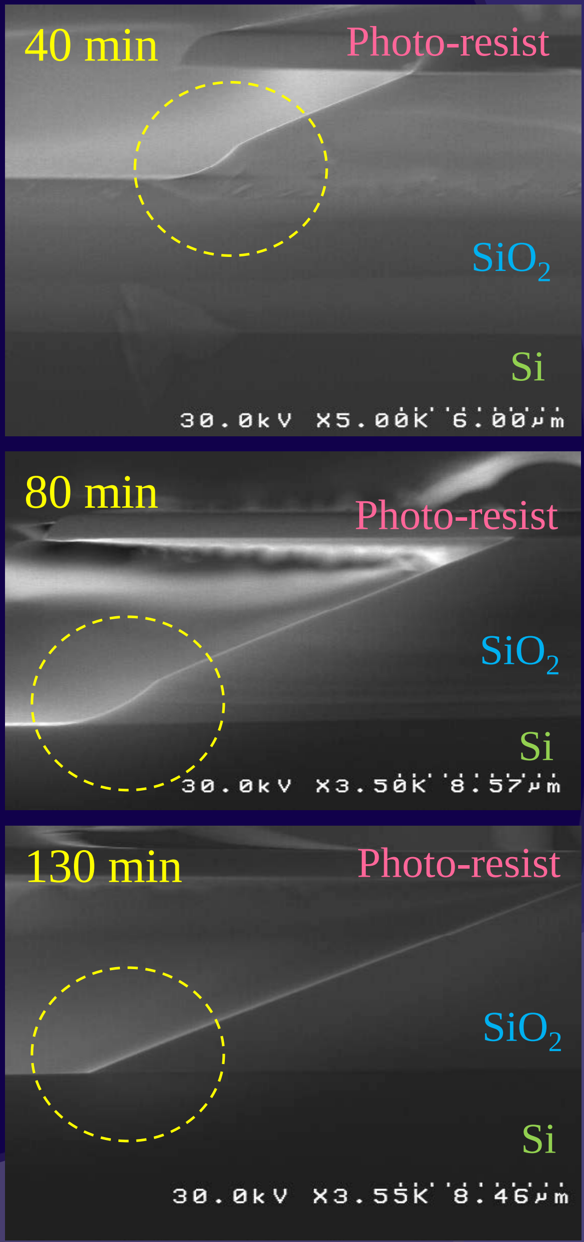


Elimination of discontinuity on side wall

Foot-region on side wall

- Increasing additional etching time
  ➔ decreasing foot-region size





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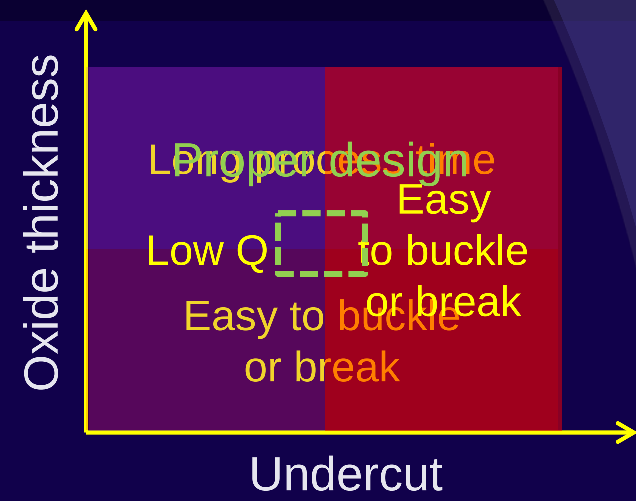
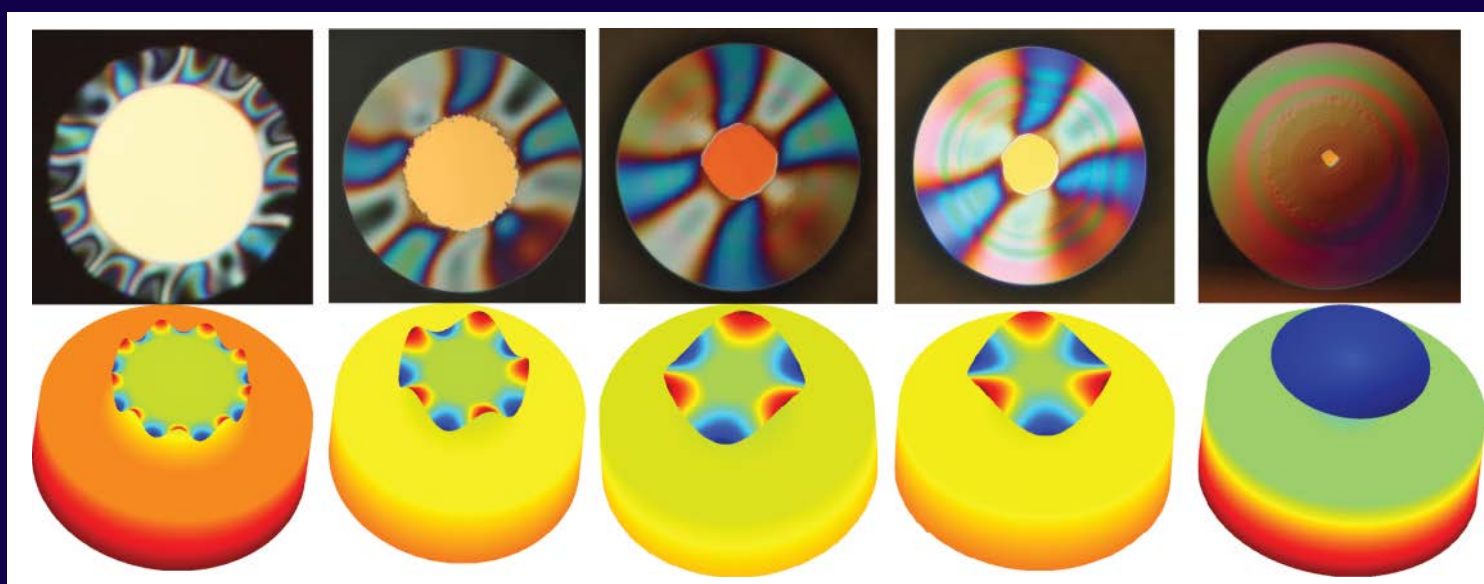
Mechanically stable structure

- Deformation of silica disk structure
  - Origin: thermally grown SiO_2 @ 1000˚C

$$\boldsymbol{\alpha_{silica}(0.5 \times 10^{-6}) < \alpha_{silicon}(3 \times 10^{-6})}$$



Buckling patterns for various Si undercut (2 μm thickness, 500 μm diameter disk)



***Applied Physics Letters*, 102, 031113 (2013)**

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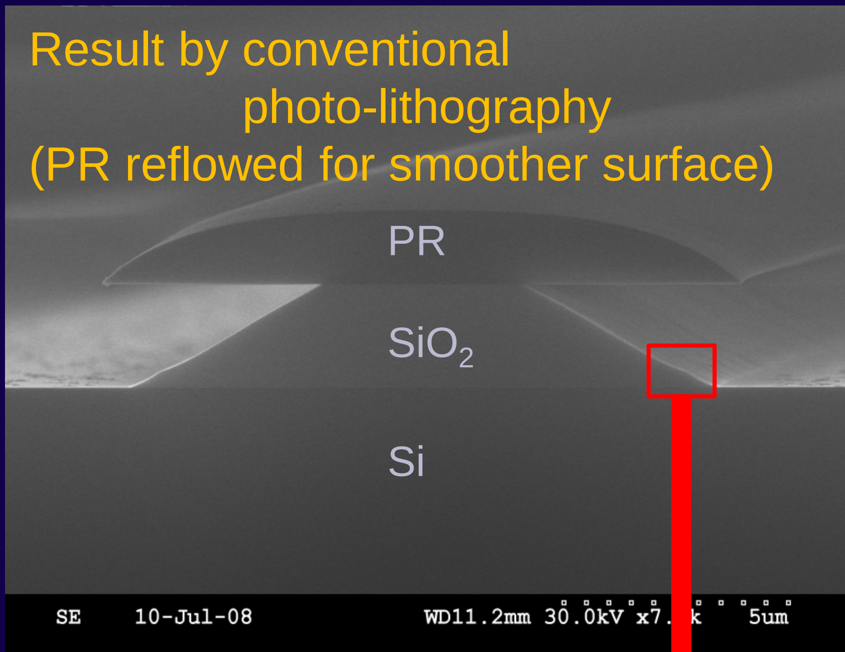
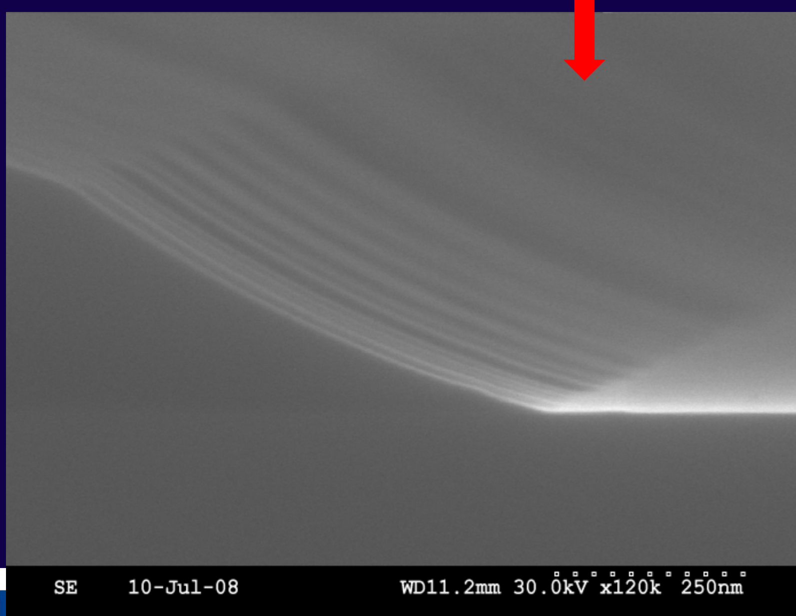
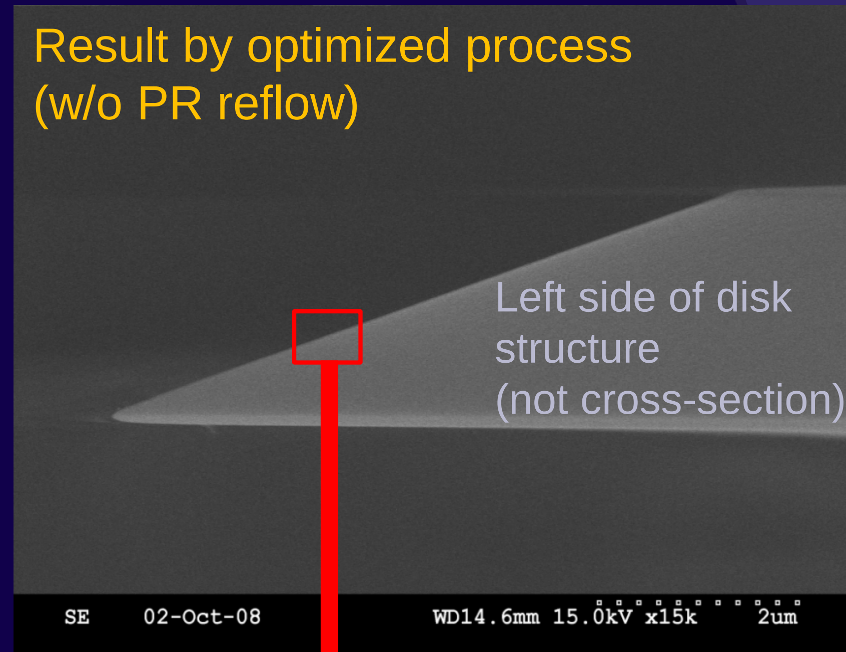
Resonator surface roughness

Result by conventional photo-lithography
(PR reflowed for smoother surface)

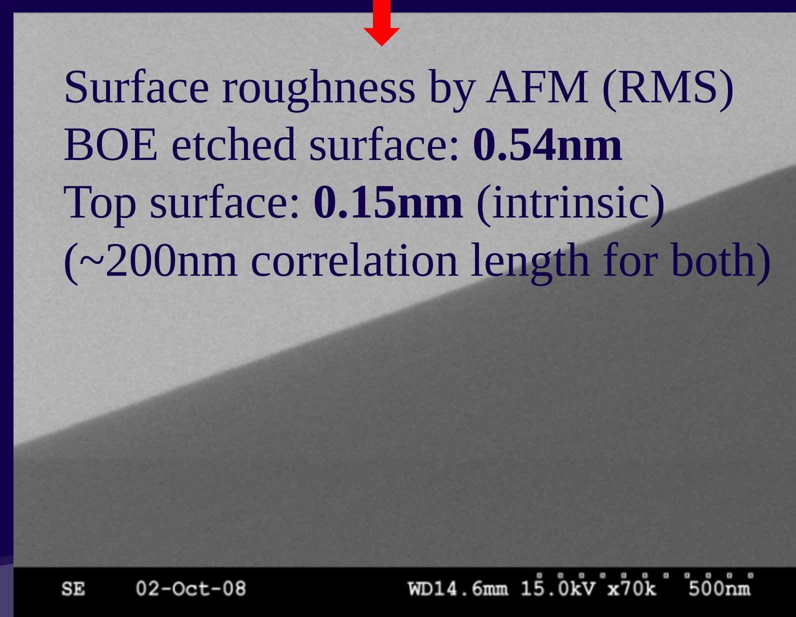




Result by optimized process
(w/o PR reflow)



Surface roughness by AFM (RMS)
BOE etched surface: **0.54nm**
Top surface: **0.15nm** (intrinsic)
(~200nm correlation length for both)

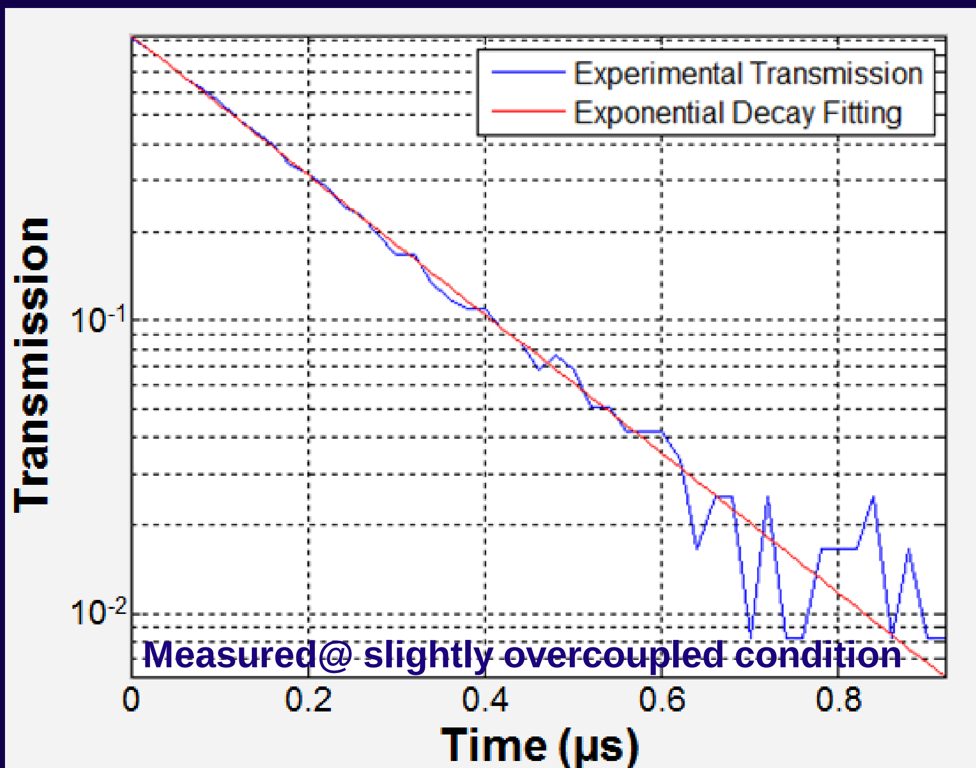


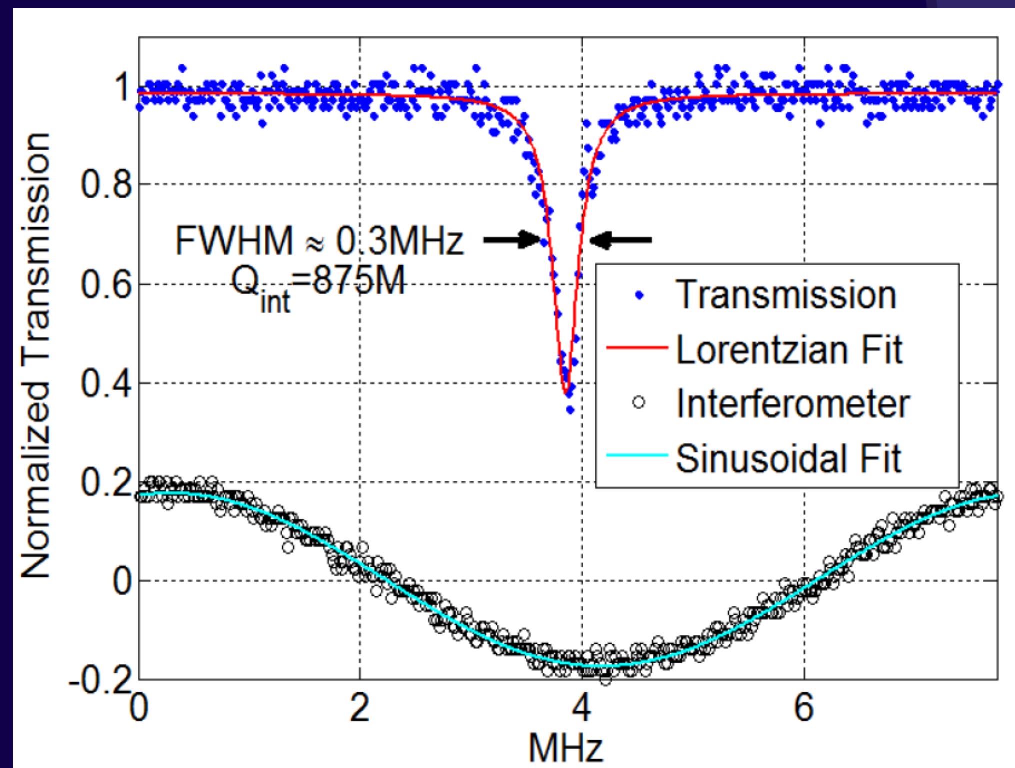
Nanoscience and Technology

Q measurement result

- Optical Q measurement
  - ~1550nm signal wavelength
  - Lorentzian transmission spectrum measurement
  - Ring-down measurement for cavity life time

Max. Q: ~875M





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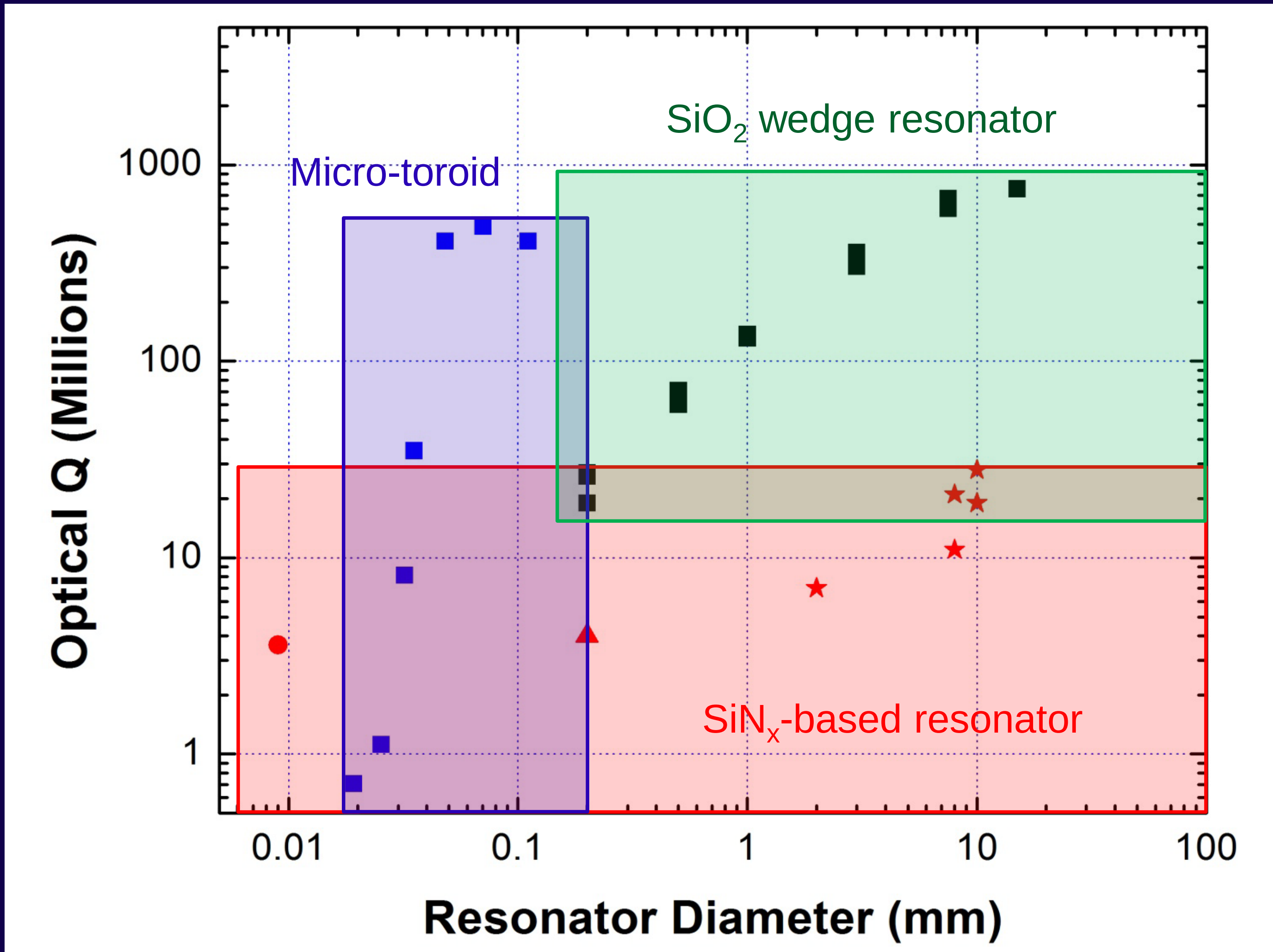
Optical Q vs disk diameter



Resonator Free Spectral Range control

Resonator size controllability

Size deviation in the fabrication steps:

Original pattern on CAD file

↓ < 1 μm (0.02 % for 6 mm disk)

Chrome pattern on the mask

↓ < 1 μm

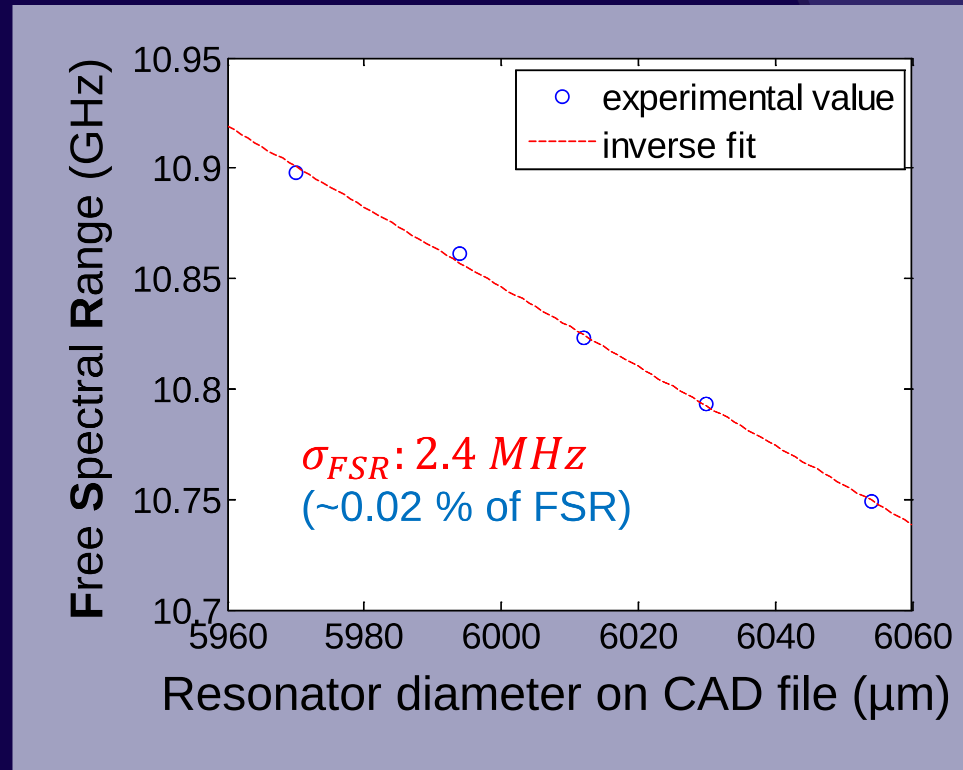
Photo-Resist pattern on the wafer

↓ ~ 0.5 μm (assuming 30 seconds etching time uncertainty)

BOE etched wedge oxide disk

↓ No significant size change

Wedge oxide disk after XeF_2 undercut



***Optics Express*, vol. 20, p. 26337, 2012**

~100 mins etching T for 25 μm **lateral** etching (0.2 μm diameter control for 10 s etching T)

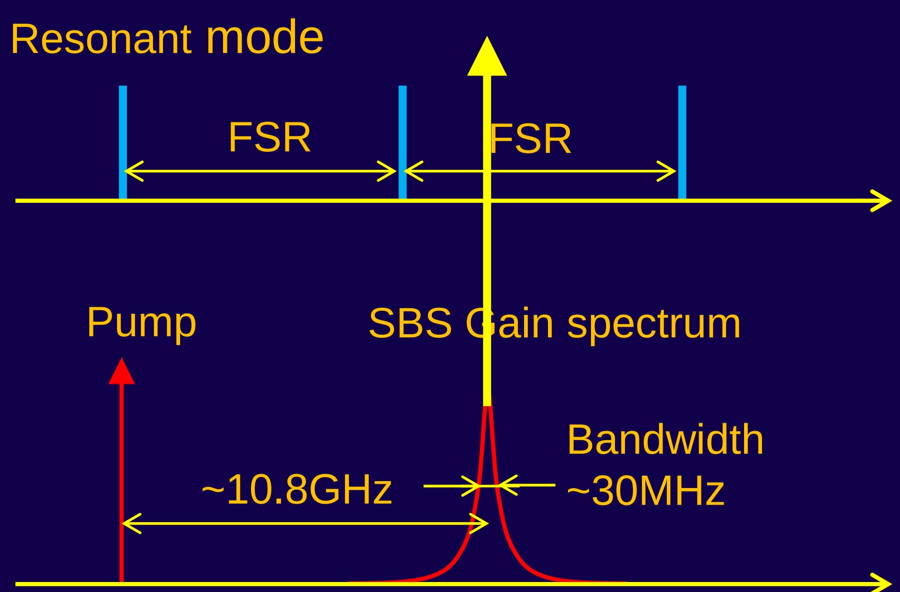
➔ Additional precise size control

SBS process in a cavity

- Stimulated Brillouin Scattering process in the high Q cavity

Resonator size control → Resonant mode FSR = SBS Frequency Shift (~10.8GHz @ SiO_2)

Resonant mode FSR ↓ SBS-induced gain & lasing

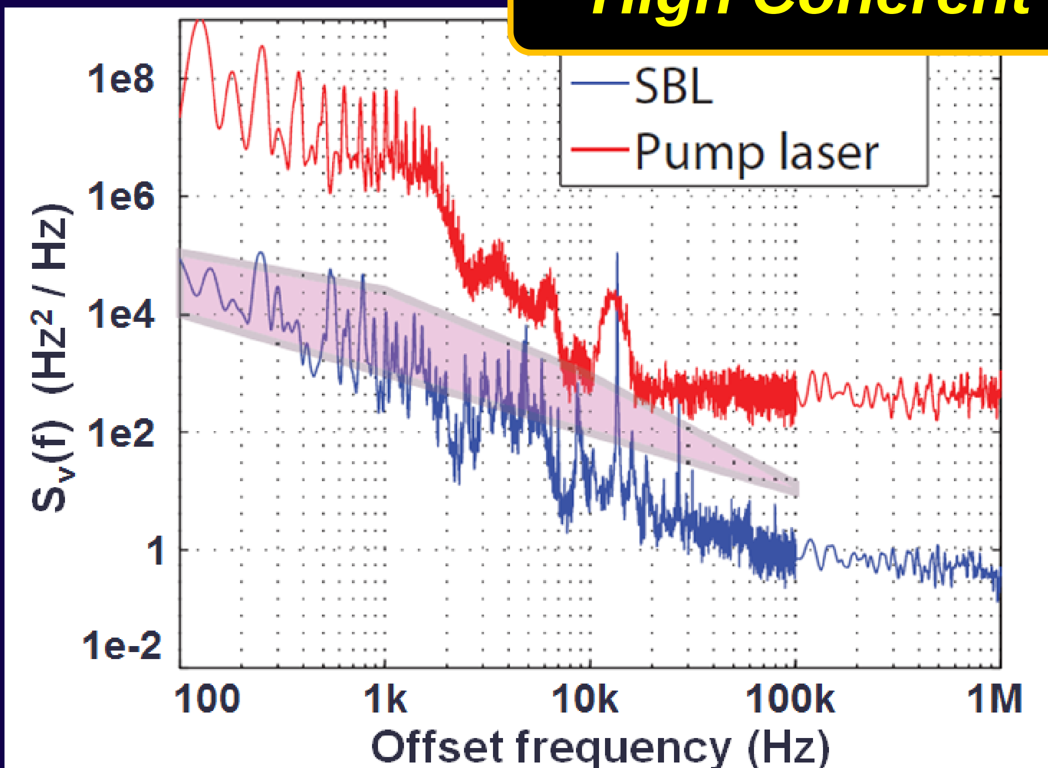


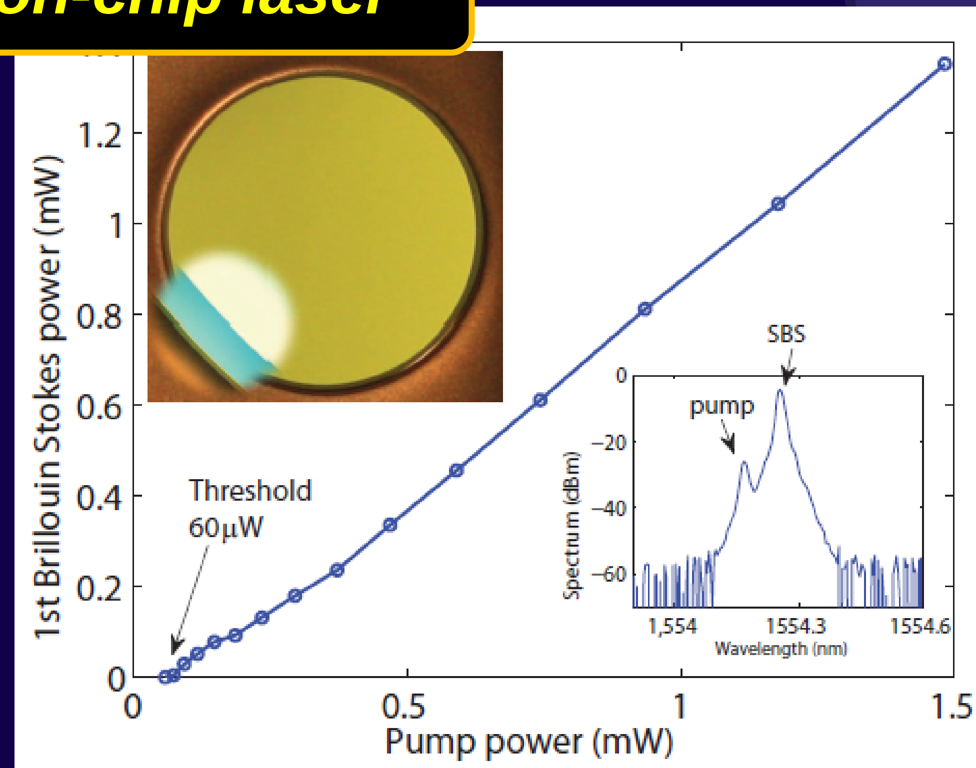
SBS gain Bandwidth **~30MHz** ≫ Wedge Resonator FSR controllability **~2.4MHz**

SBS laser on a chip

- Stimulated Brillouin Scattering laser

High Coherent on-chip laser

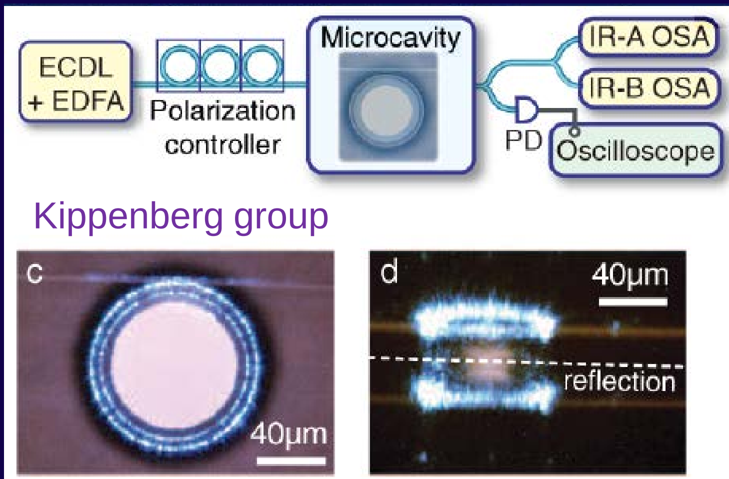




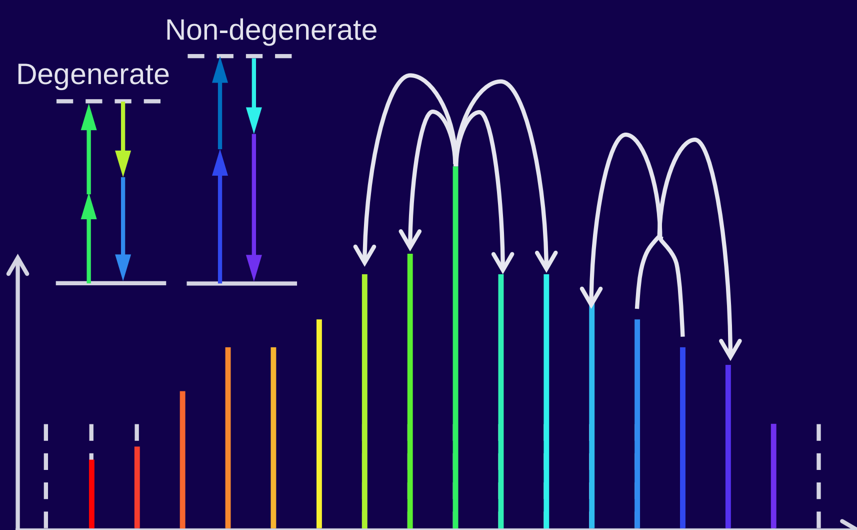
Nature Photonics, vol. 6, p. 369, 2012
Optics Express, vol. 20, p. 20170, 2012
Optics Express, vol. 39, p. 287, 2014

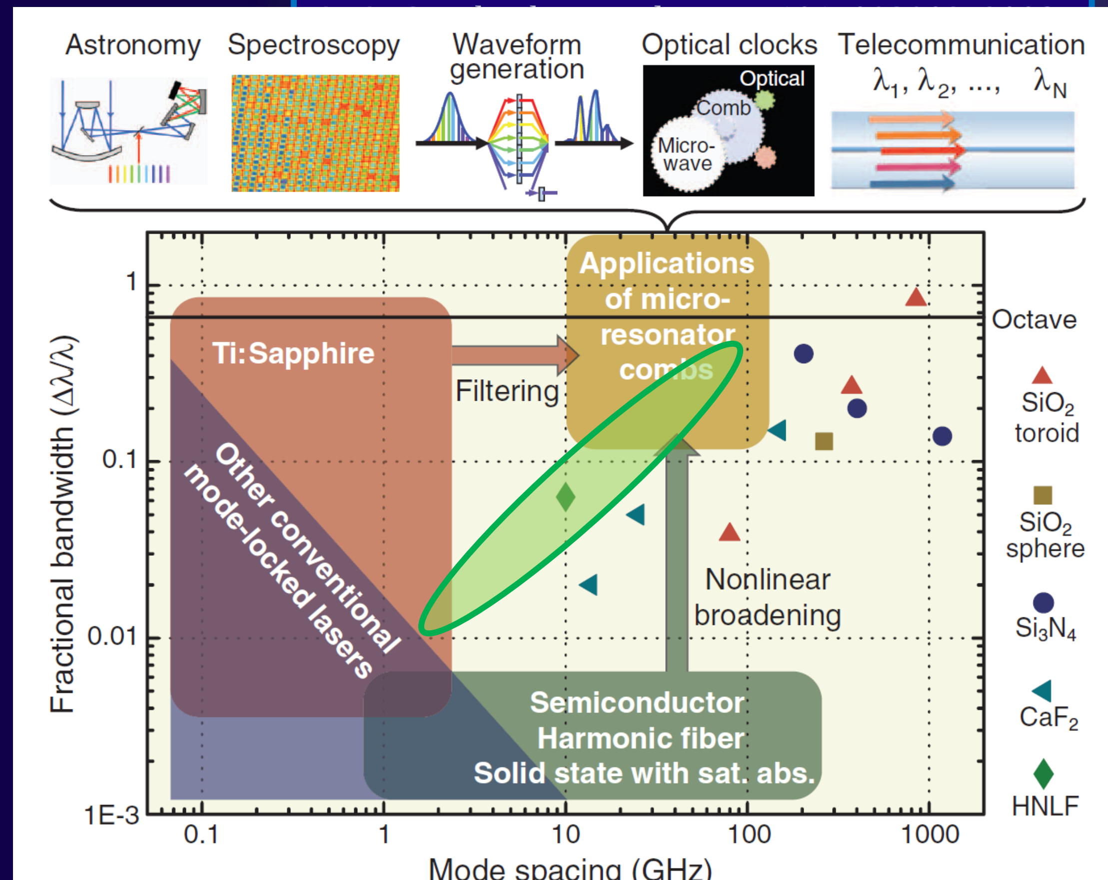
Applications - Frequency comb generation   previous work

- Frequency comb generation in a micro cavity



P. Del Haye, et al., **Nature** 450, 1214, 2007
I. H. Agha, et al., **Phys. Rev. A** 76, 043837, 2007
P. Del Haye, et al., **PRL** 101, 053903, 2008





T. J. Kippenberg, et al., Science 332, 555, 2011

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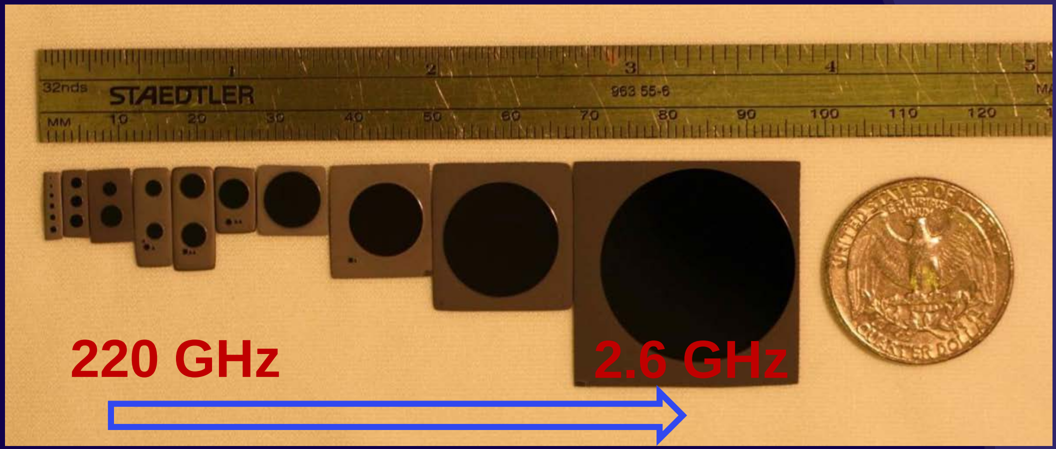
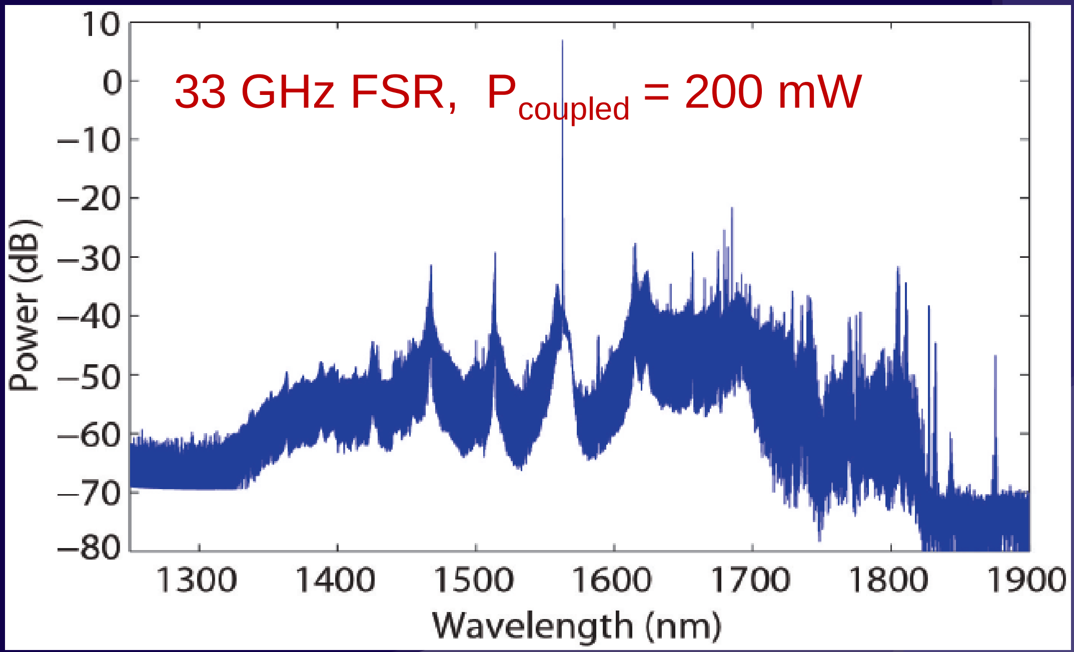
Applications - Frequency comb generation our work

- Frequency comb generation in a micro cavity
  - Generation of smaller FSR comb
  - Larger resonator in high Q
    - Lower threshold for pump power

$$P_{th} \propto \frac{n}{n_2}\frac{\omega}{FSR}\frac{A_{eff}}{Q_0^2}$$

  - Precise control of FSR





Physical Review Letters, vol. 109, p. 233901, 2012

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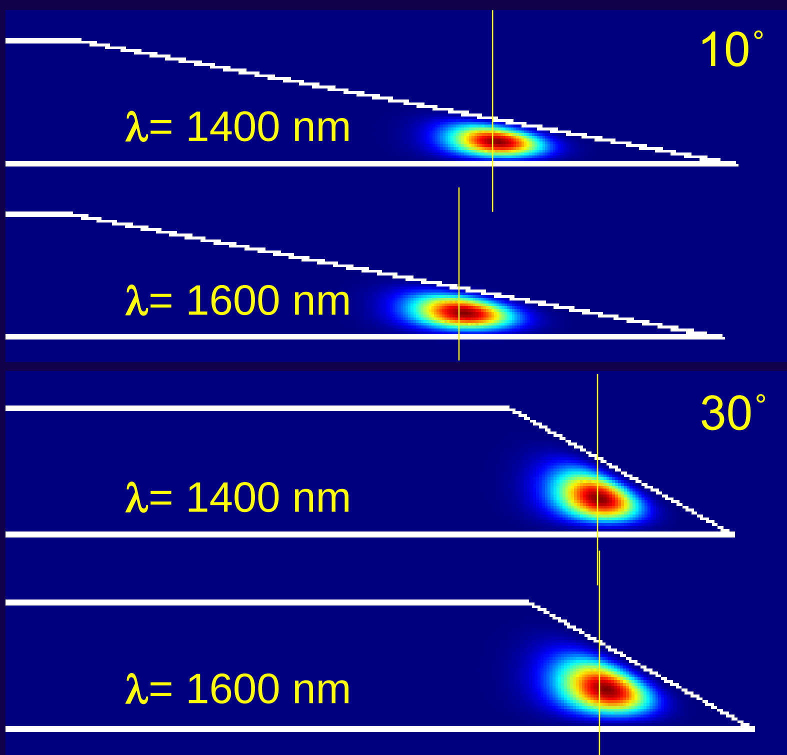
Resonator dispersion control

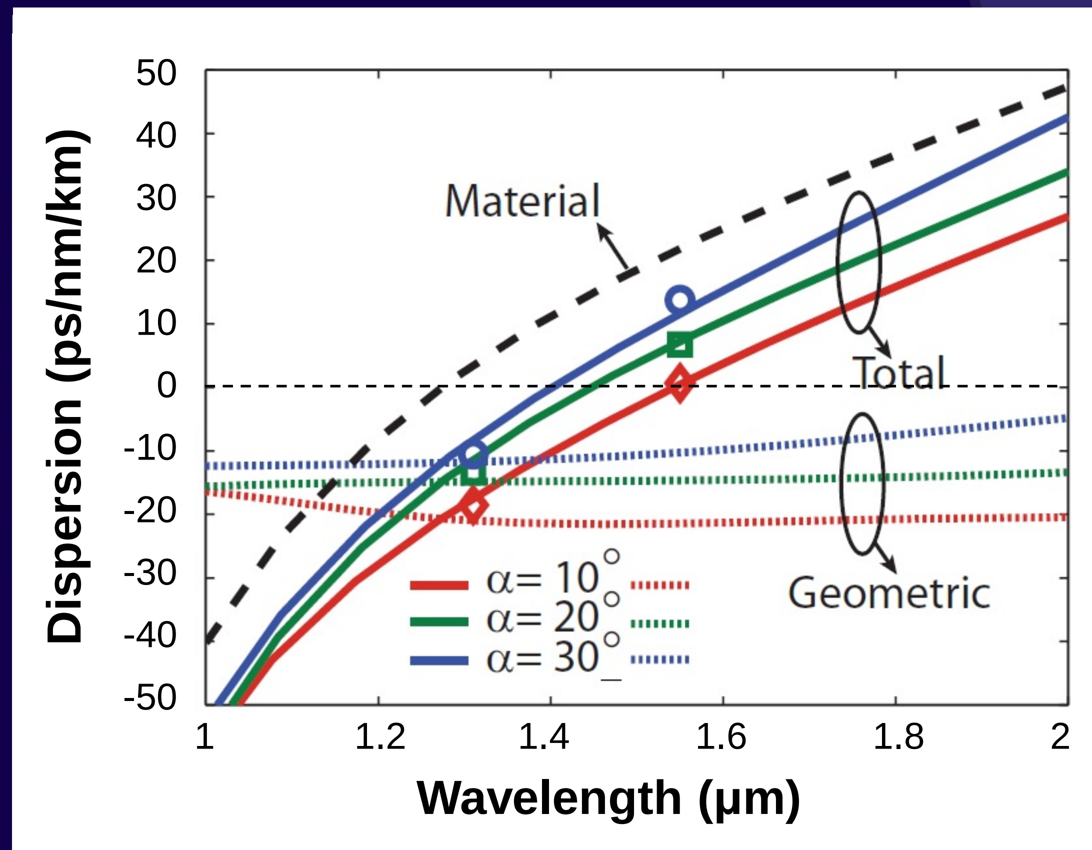
- Dispersion control by Wedge angle control

Adhesion control
between PR and thermal oxide

↓

Wedge angle control





Optics Express, vol. 20, p. 26337, 2012

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Part II

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Record Q on a Si chip

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Longest resonator on a chip

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Ultra-low-loss Waveguide

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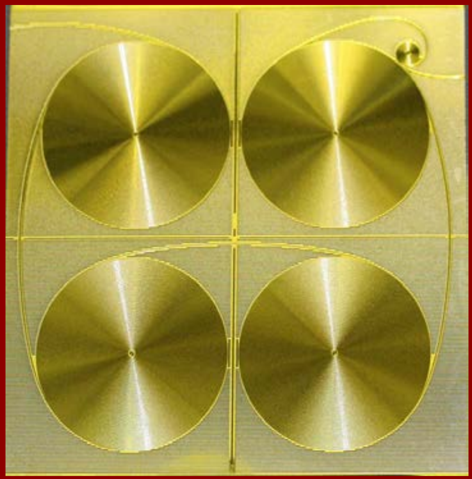
Record length

Wide bandwidth



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Toward integrated photonic circuits

Goal: implementation of simple photonic circuits monolithically on a silicon chip

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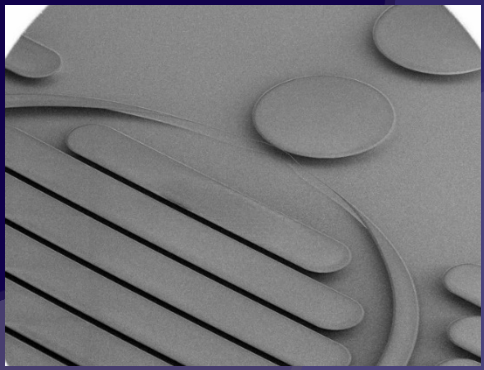
Mass production
Robustness



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Motivation: Fiber like losses on a chip

On-chip waveguide | **Optical fiber**

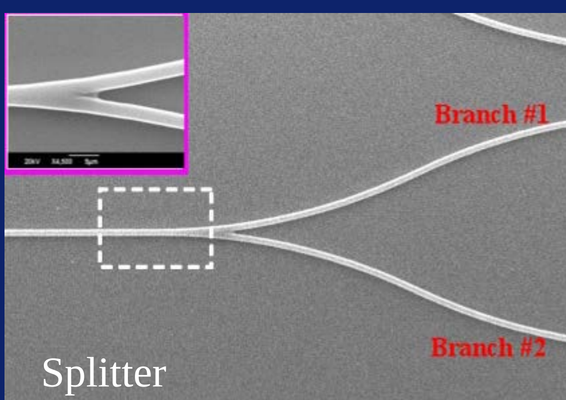
1µm — 1mm — 1m — 1km — 1,000km → Length of waveguide

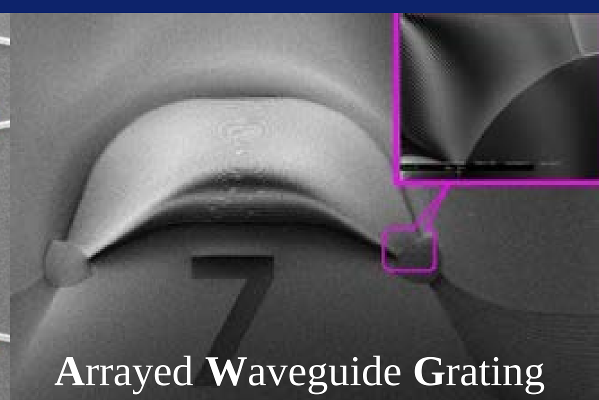
- **Loss: ~~0.1dB/cm~~**
- Integrability
- Precise control of dimension
- Mass-productivity
- Compact
- Shock resistance

- Non-linear signal process
- Supercontinuum generation
- RF filtering
- High-stability microwave oscillators
- Gyroscope

- **Loss: 0.2 dB/km**
- High bandwidth

On-chip photonics



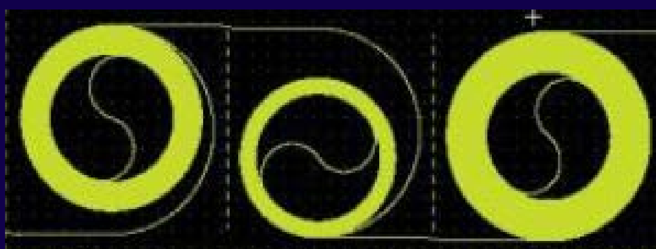


Optical telecommunication

Review: On Chip Waveguides

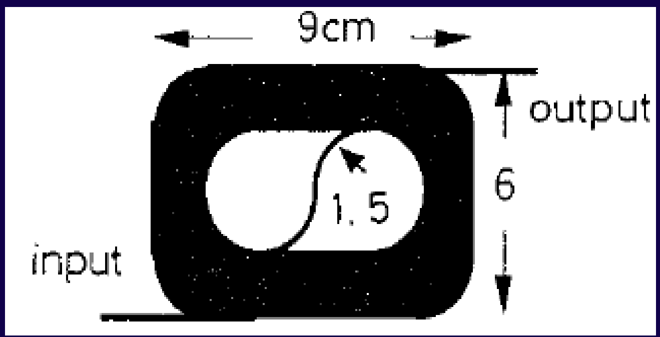
Towards longer length and smaller loss

Core Material	Cladding Material	Loss	Length	Ref.
Si_3N_4	SiO_2	2.9dB/m	6m	[1]
Si	SiO_2	27dB/m	0.64m	[2]
SiO_2	Air	1.7dB/m	10m	[3]



[1] Jared F. Bauters, et al, Optics Express, 19, p.3163, 2011

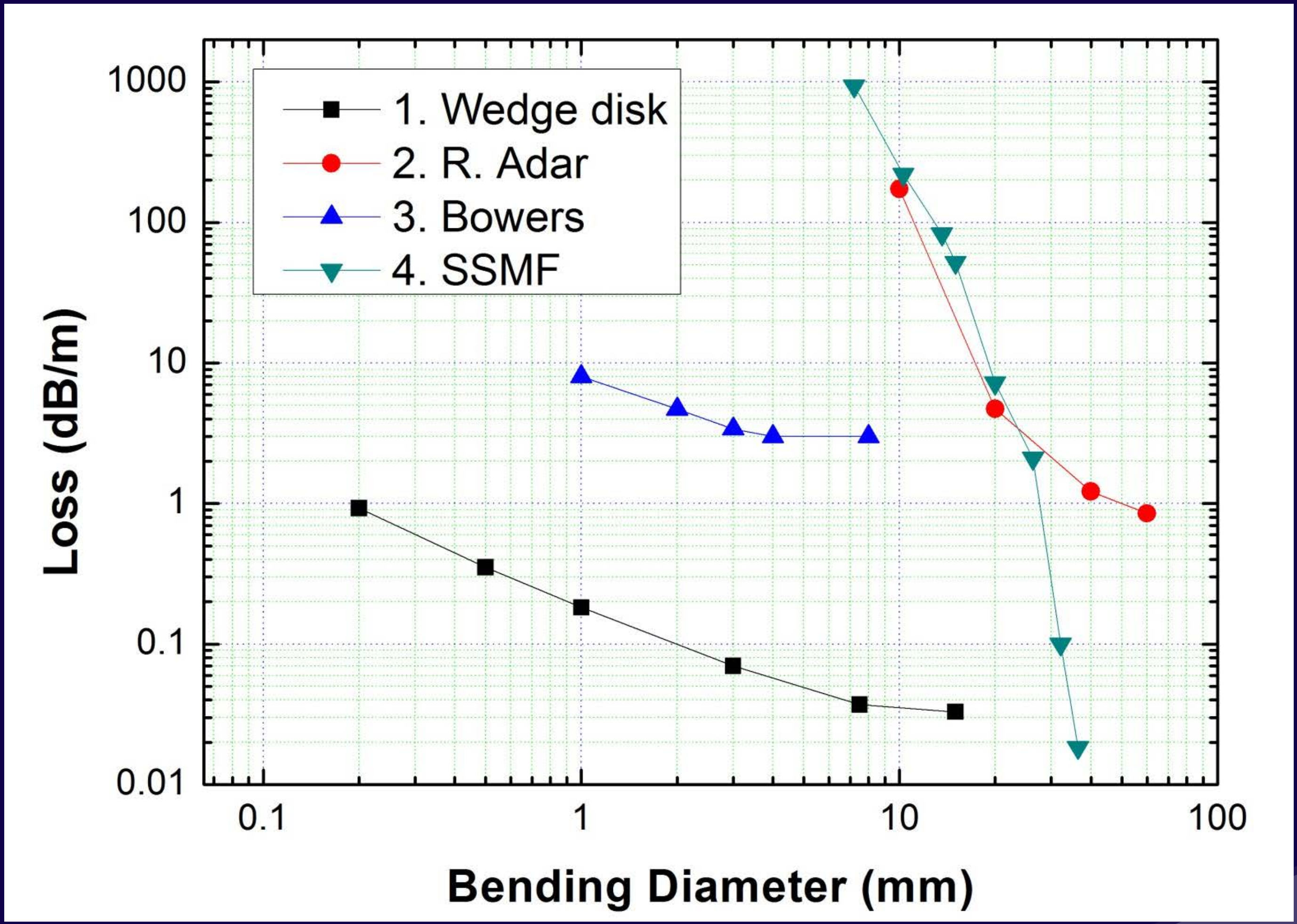
[2] Po Dong, et al, Optics Express, 18, p.14474, 2010



[3] K. Takada, et al, Electronics Letters, 32, p.1665, 1996

Optical loss of on-chip waveguide

- Waveguide loss estimated from wedge resonator Q



[1] Estimated from Wedge disk Q measurement result
[2] R. Adar, et al, Journal of Lightwave Technology, vol. 12, P. 1369, 1994
[3] J. Bauters, et al, Optics Express vol. 19, p. 3163, 2011
[4] from SSMF 28 fiber measured by OBR

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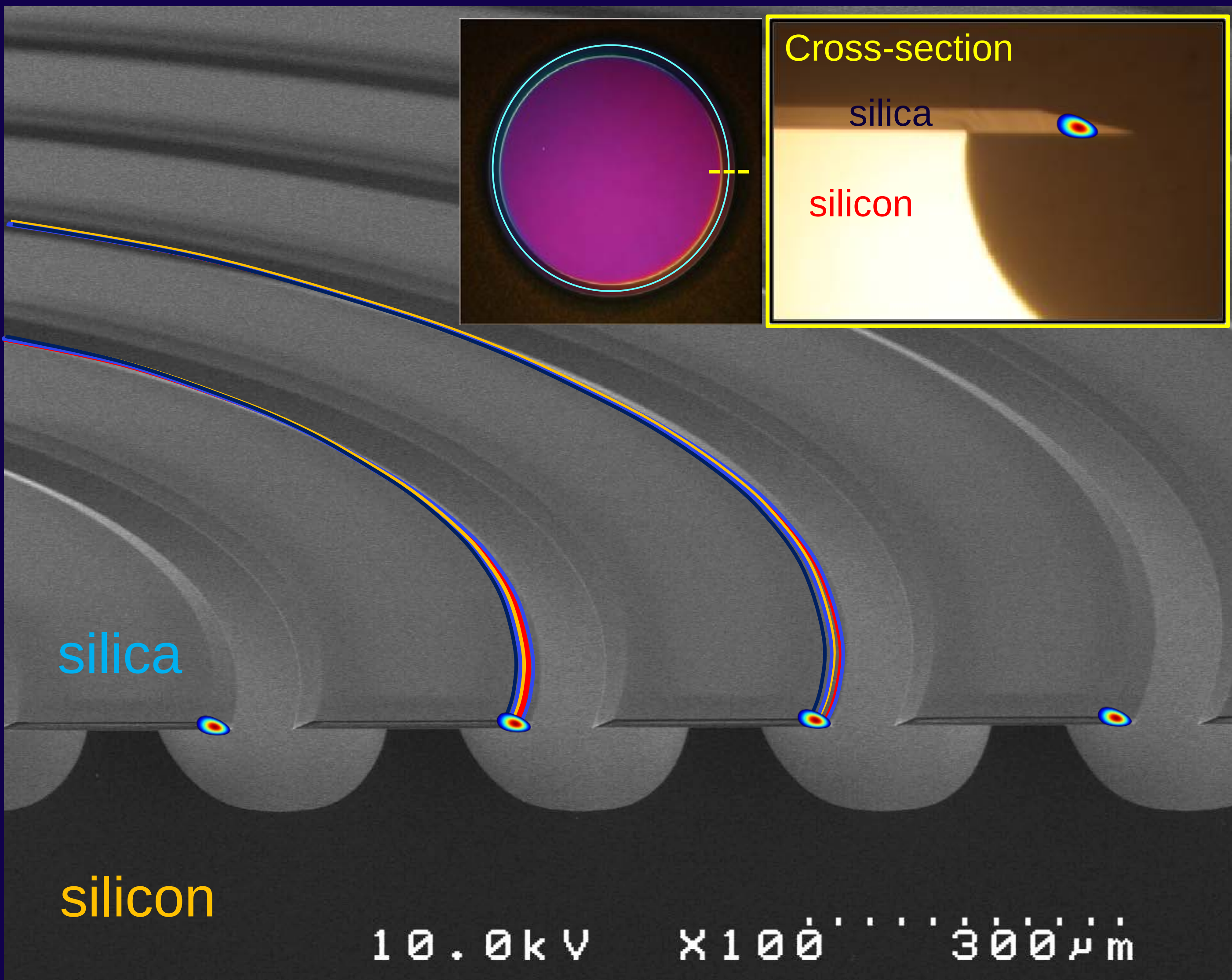
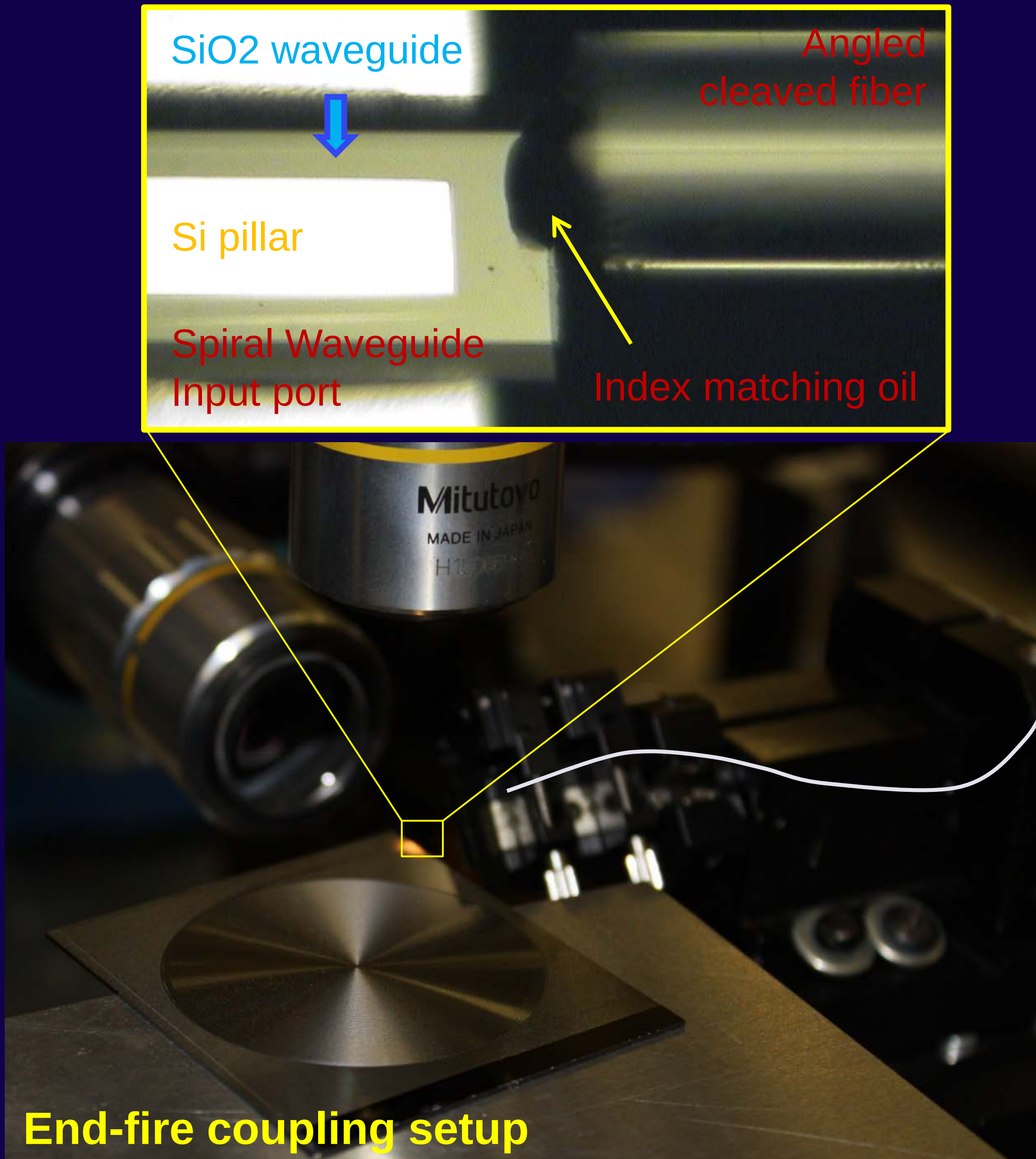
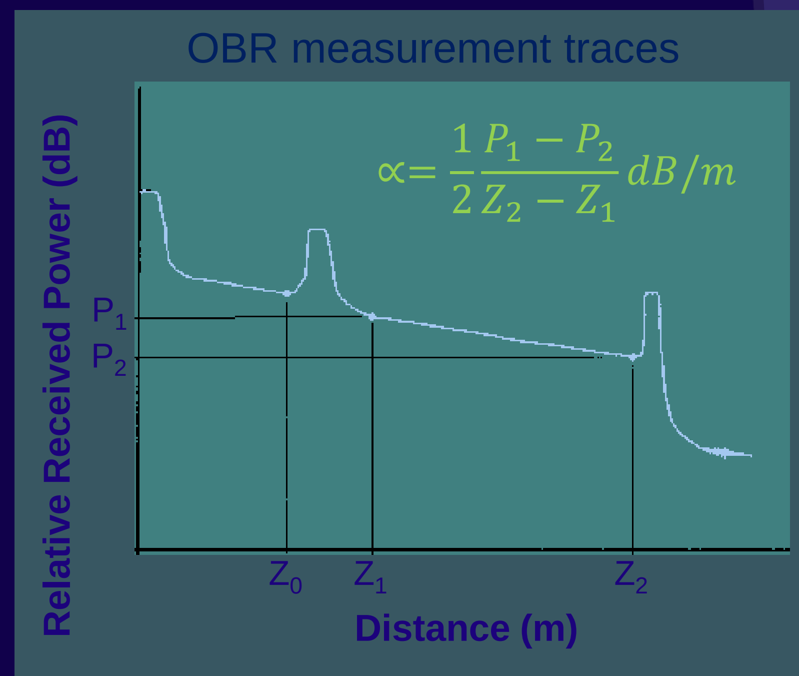
From Wedge Resonator to Spiral Waveguide

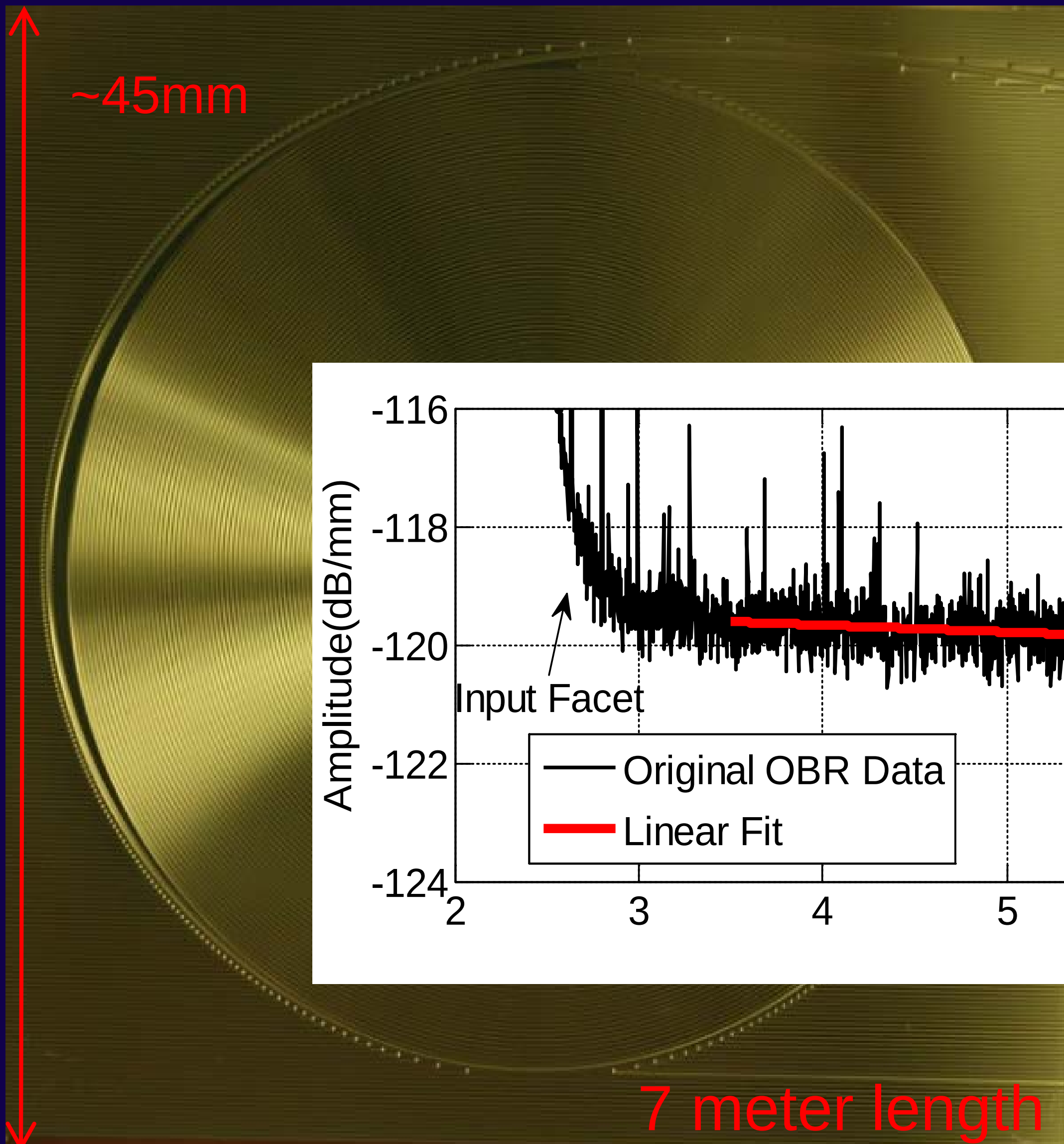


Loss measurement setup: Optical Backscatter Reflectometer

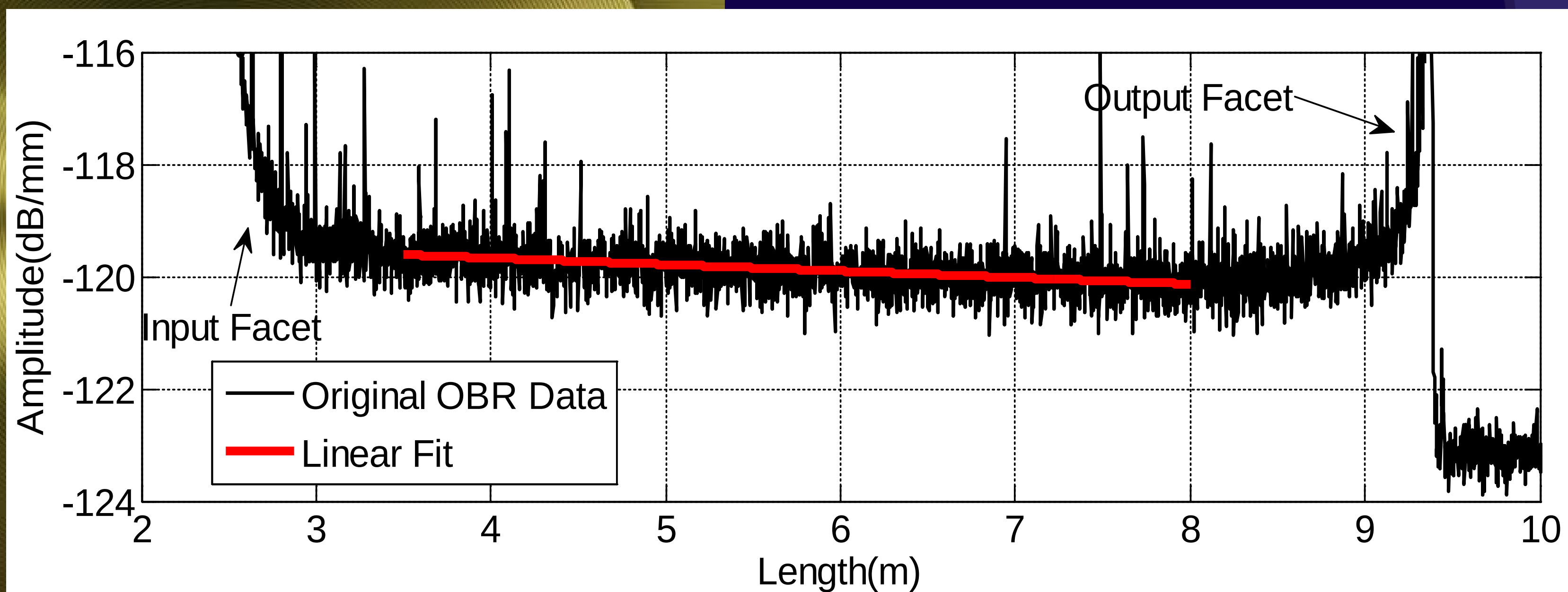




One Way Spiral Waveguide



Waveguide loss: 0.06dB/m



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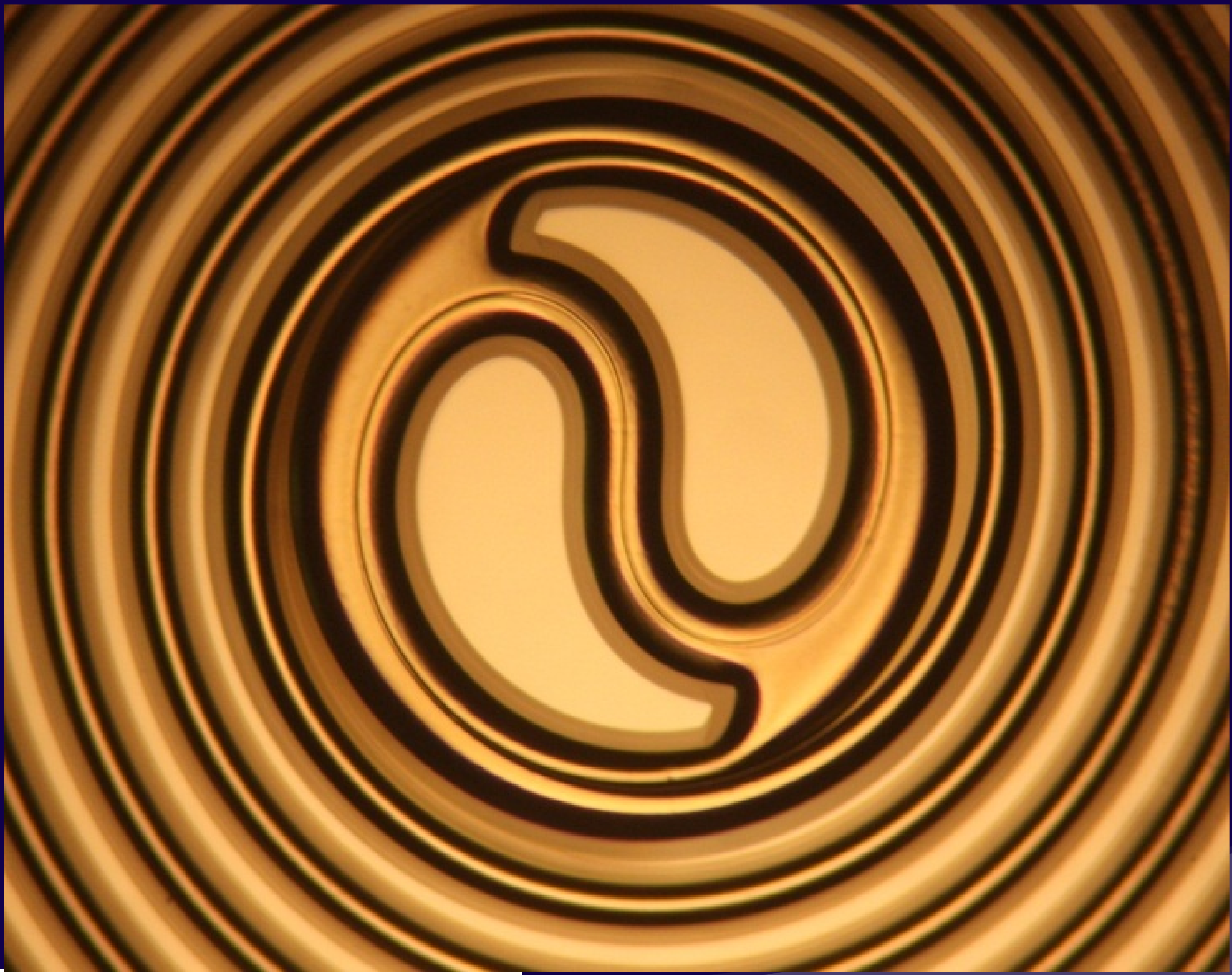
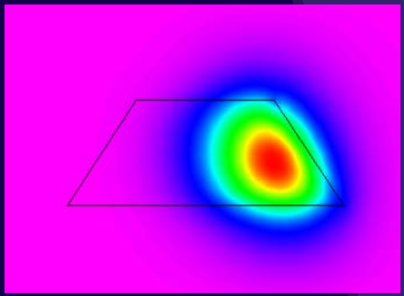
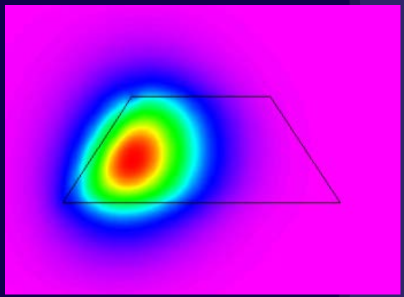
Hand-off Design: Adiabatic coupler



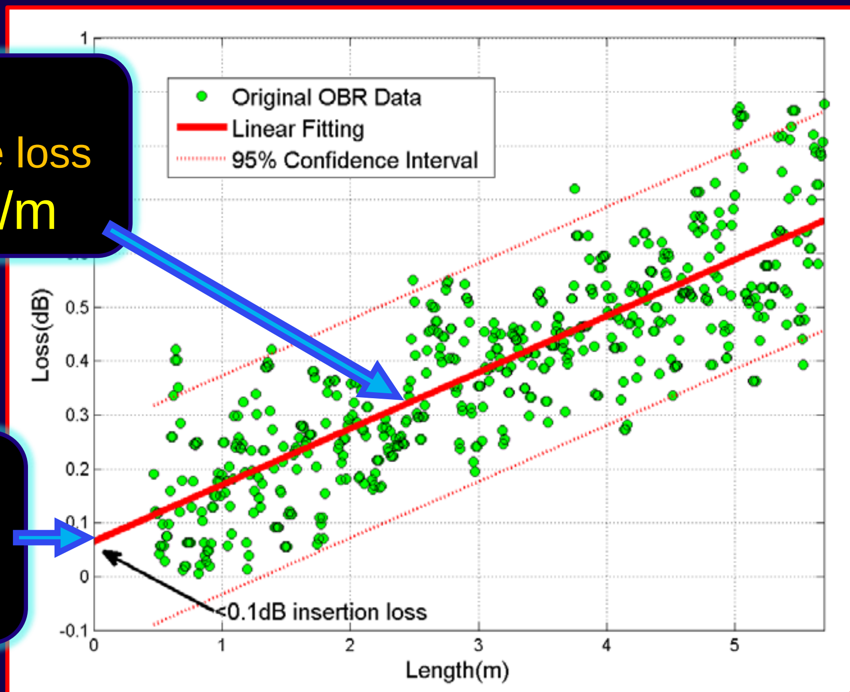


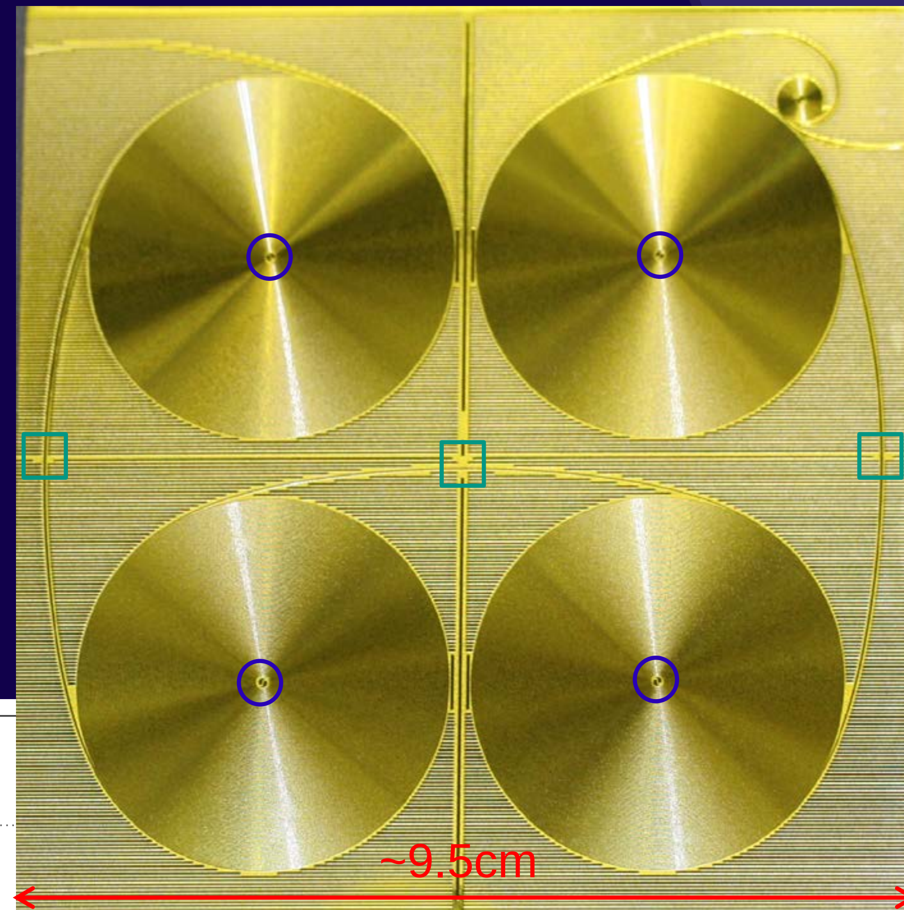


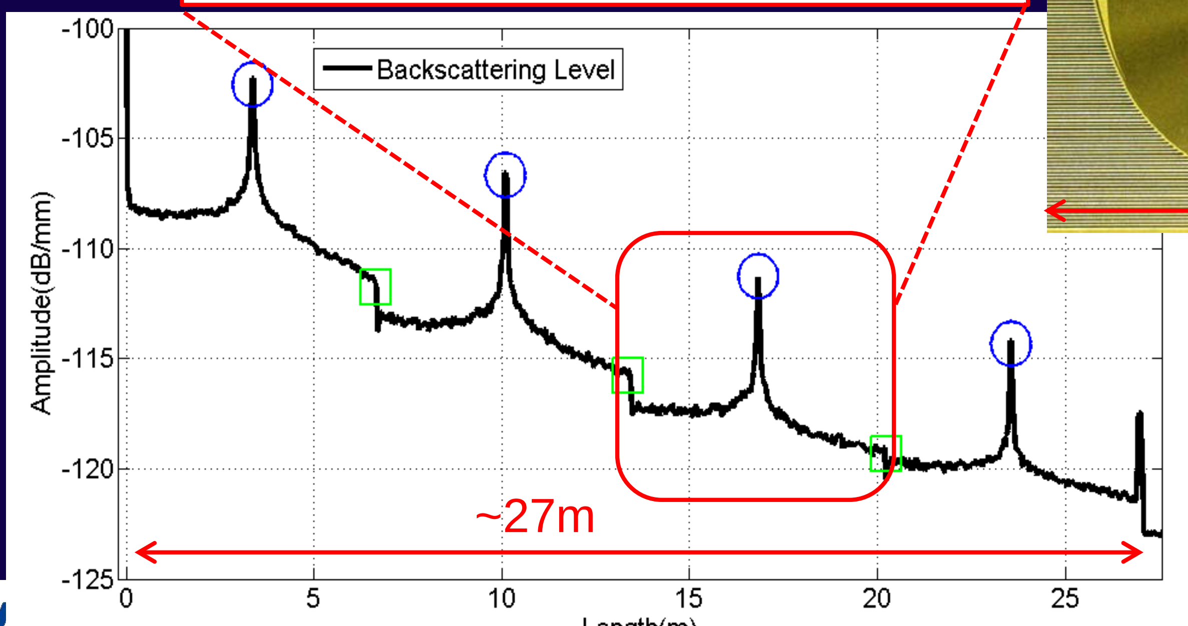
Cascade Spiral <0.1dB/m loss over 27m delay

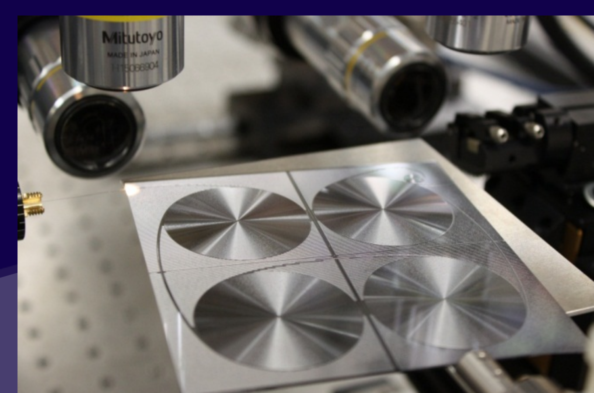
Slope
Waveguide loss
<0.1dB/m

Intersection
Hand-off loss
<0.1dB





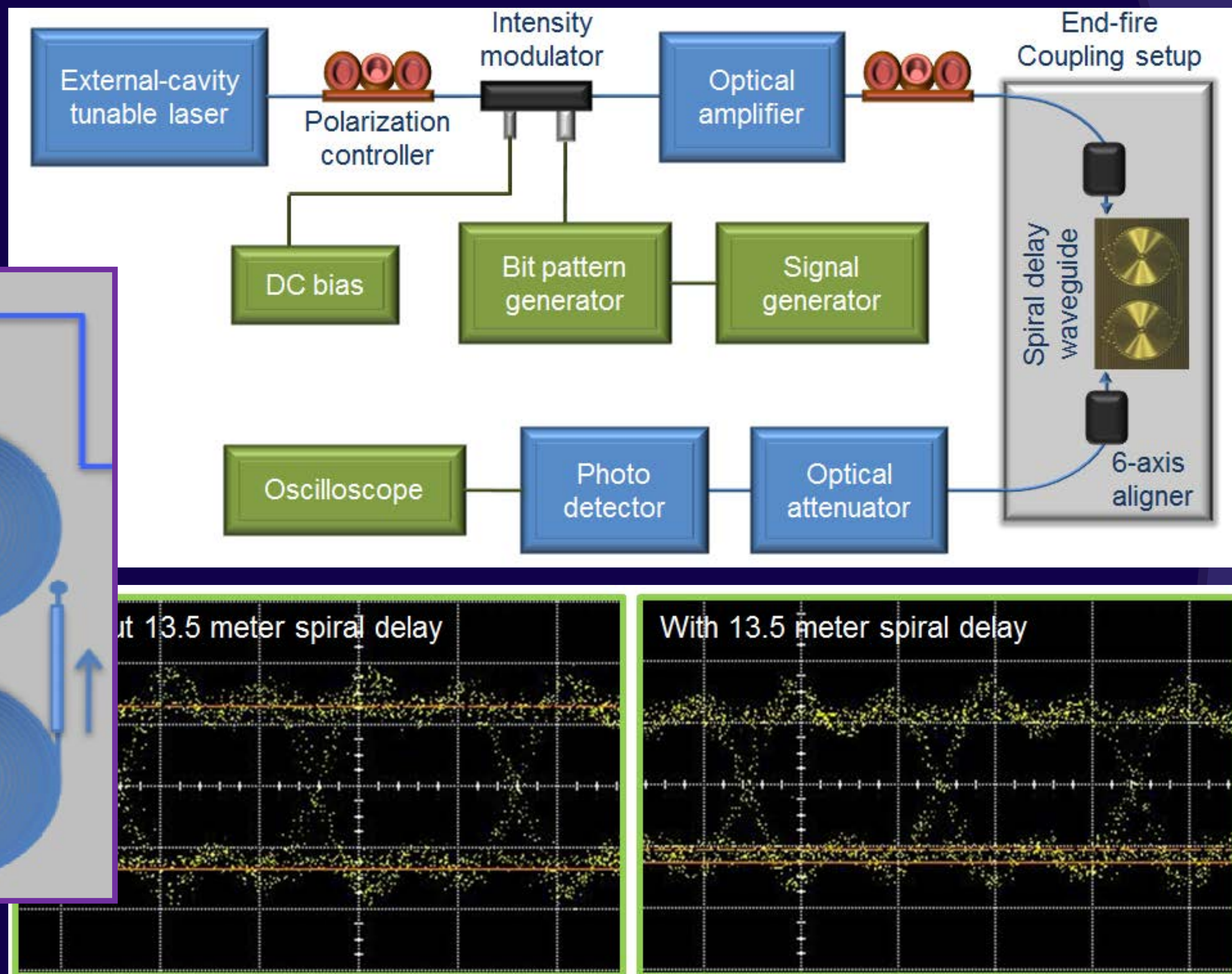




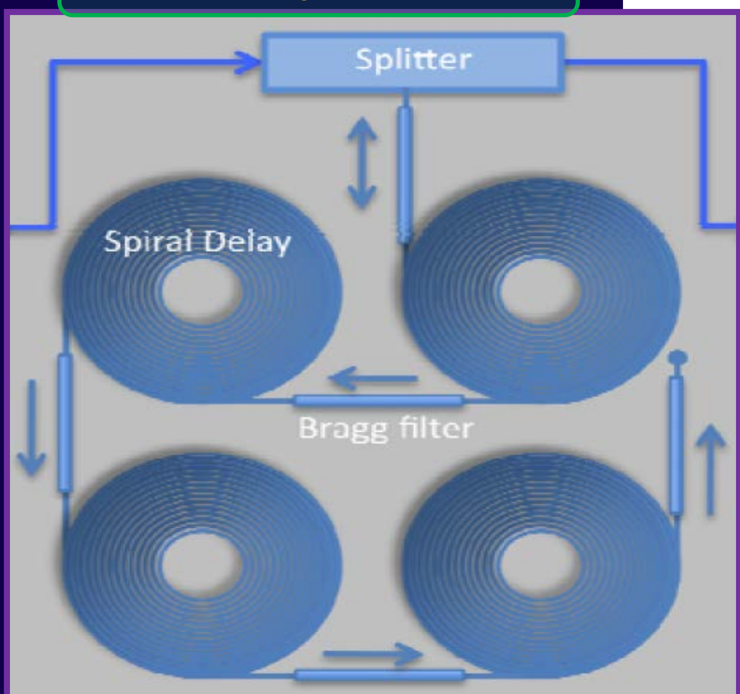
Nature Communications, 3:867 doi:10.1038/ncomms1876, 2012

Applications - Optical data buffer

- 2.5 G bit/s data buffer (~170 bits in buffer)

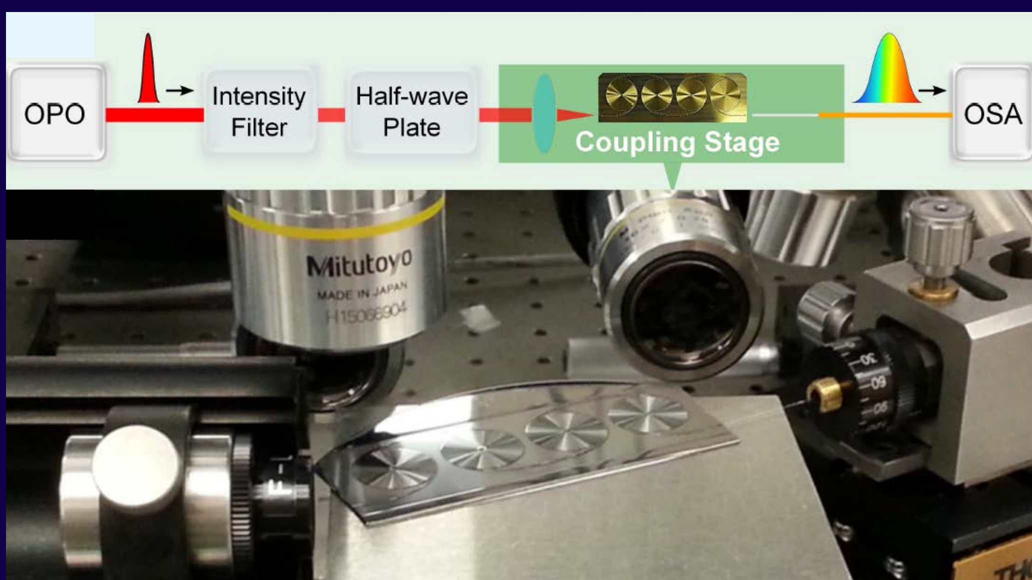


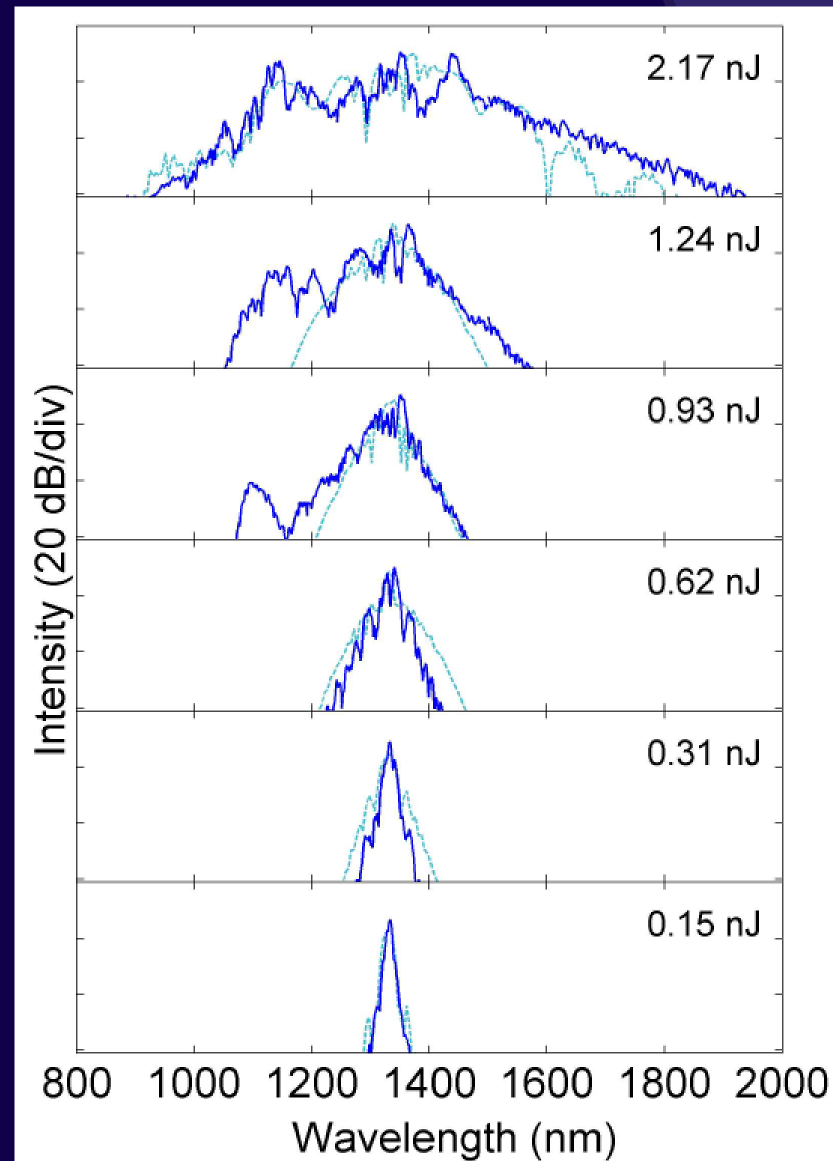
Microwave photonic filter



Applications - Super continuum

- Experimental result
  - Waveguide length : 3.5 m
  - Input : 180-fs pulses, 2.17 nJ coupled energy (from optical parametric oscillator)
  - Output : 936 ~ 1888 nm (162 THz)





Optics Letters, vol. 39, p. 1046, 2014

Part II

Part1

Ultra-high-Q Wedge resonator

Record Q on a Si chip

Standard semiconductor fabrication process

Precise size control

Reference cavity

First reference cavity on a chip

Longest resonator on a chip

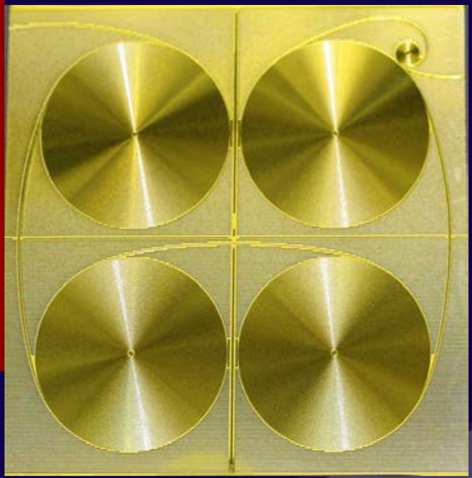
Part2

Ultra-low-loss Waveguide

Record loss

Record length

Wide bandwidth

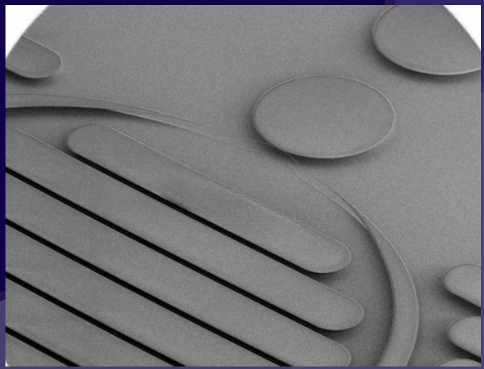


Part3

Toward integrated photonic circuits

Goal: implementation of simple photonic circuits monolithically on a silicon chip

Miniaturization
Mass production
Robustness



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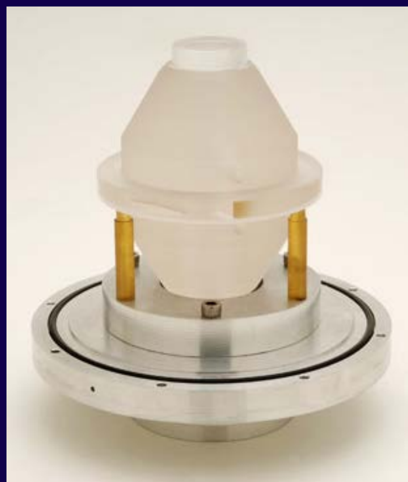
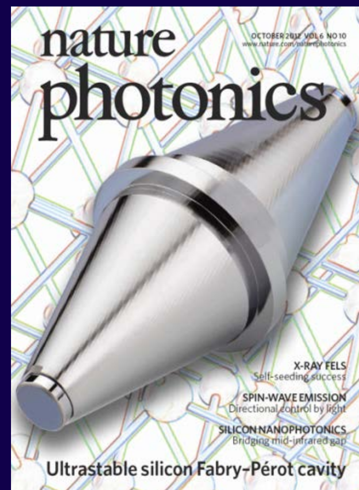
Motivation: Compact Reference Cavities



Stable Laser Systems



Jun Ye Group, JILA

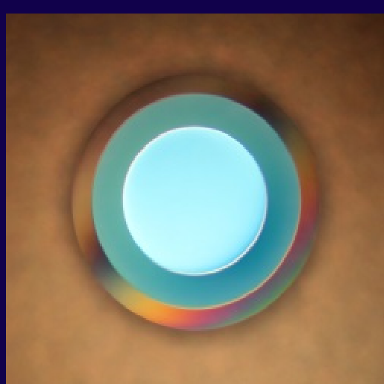
Fractional frequency instability:
$\sigma_y(\tau) \approx 1 \times 10^{-16}$ @ $\tau = 400\ ms$

Laser linewidth < 40 mHz at 1.5 μm

Dimesion:
20 cm x 10 cm (length x diameter)

T. Kessler, Nature Photonics 6, 687–692 (2012)

Can we make ***compact and integrable*** reference cavities **on a chip**?



Motivation: Compact Reference Cavities

Due to the thermodynamic fluctuation of temperature,

$$\frac{<(\Delta\omega_{TR})^2>}{\omega^2} = \alpha_n{}^2 \frac{k_B T^2}{C V_m \rho}$$: Thermo-refractive noise

$$\frac{<(\Delta\omega_{TE1})^2>}{\omega^2} = \alpha$$ ... ise

$$\frac{<(\Delta\omega_{TE2})^2>}{\omega^2} = k_l$$ ...

Mode volume

$= \boldsymbol{\sigma}$

$\boldsymbol{\alpha_n}$: Thermo-refractive coefficient

$\boldsymbol{\alpha_l}$: Linear thermal expansion coefficient

$\boldsymbol{\beta_T}$: Compressibility of the resonator

Frequency fluctuation

$$\propto \boldsymbol{\sigma} \frac{\sqrt{\rho V}}{V}$$

[1] Gorodetsky et a... ...04).

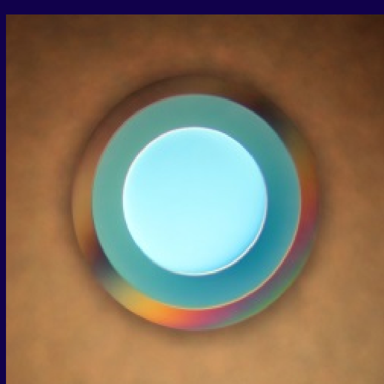
[2] A. B. Matsko et al., J. Opt. Soc. Am. B 24, 1324 (2007).

Compact and integrable reference cavities **on a chip** !

Higher **stability** (less frequency fluctuation) ?

$Q_{max} \sim 140\ million$

$FSR \sim 173\ MHz$



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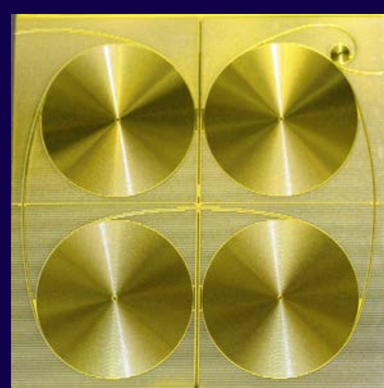

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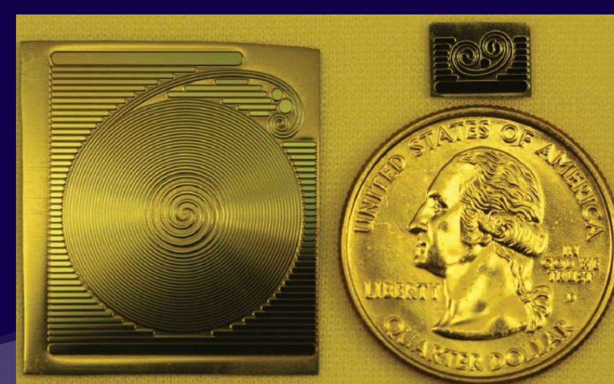

1.2 m length over 1 inch^2

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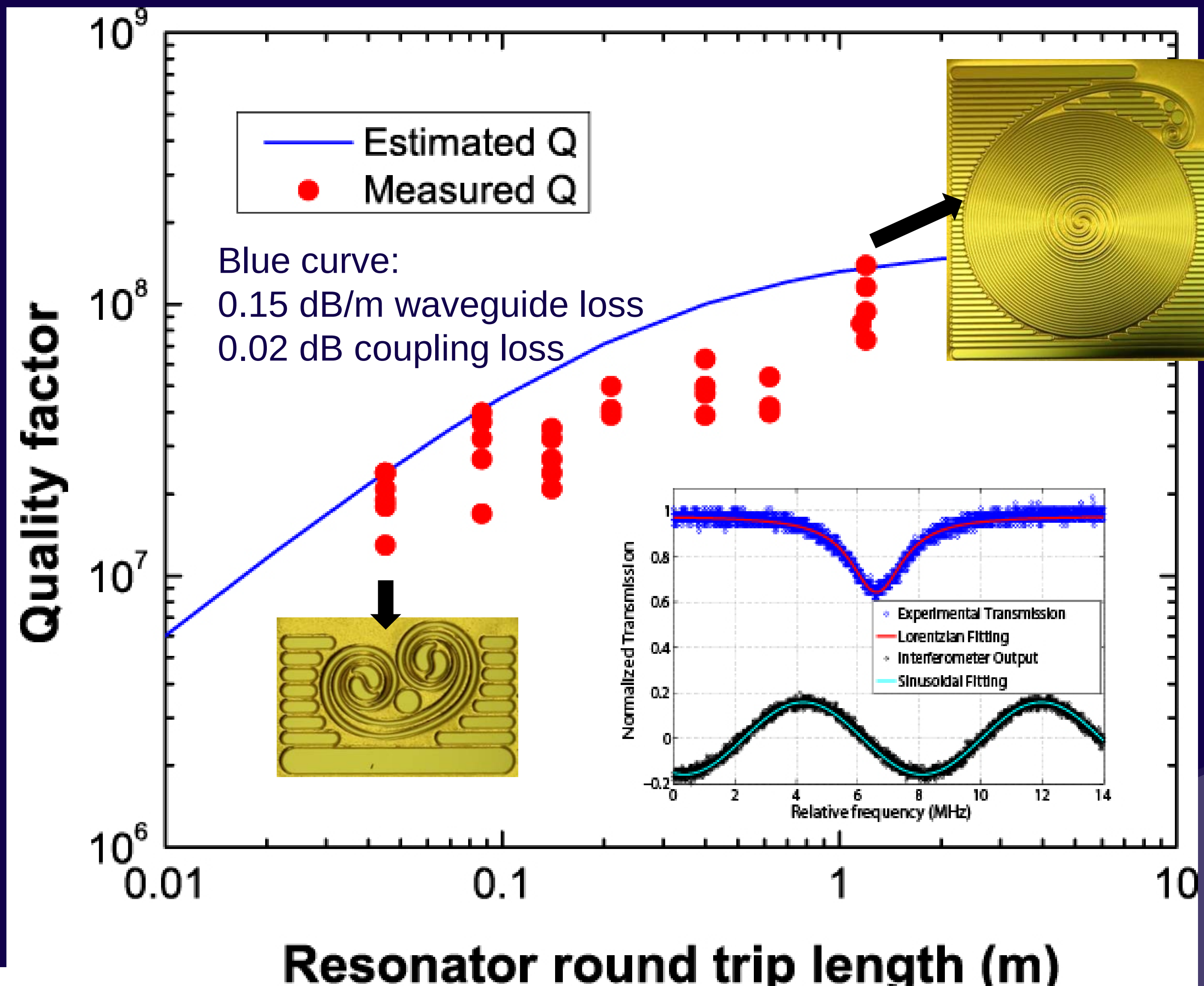
Q versus resonator length

Maximum Q of 140 million obtained with a 1.2m long resonator



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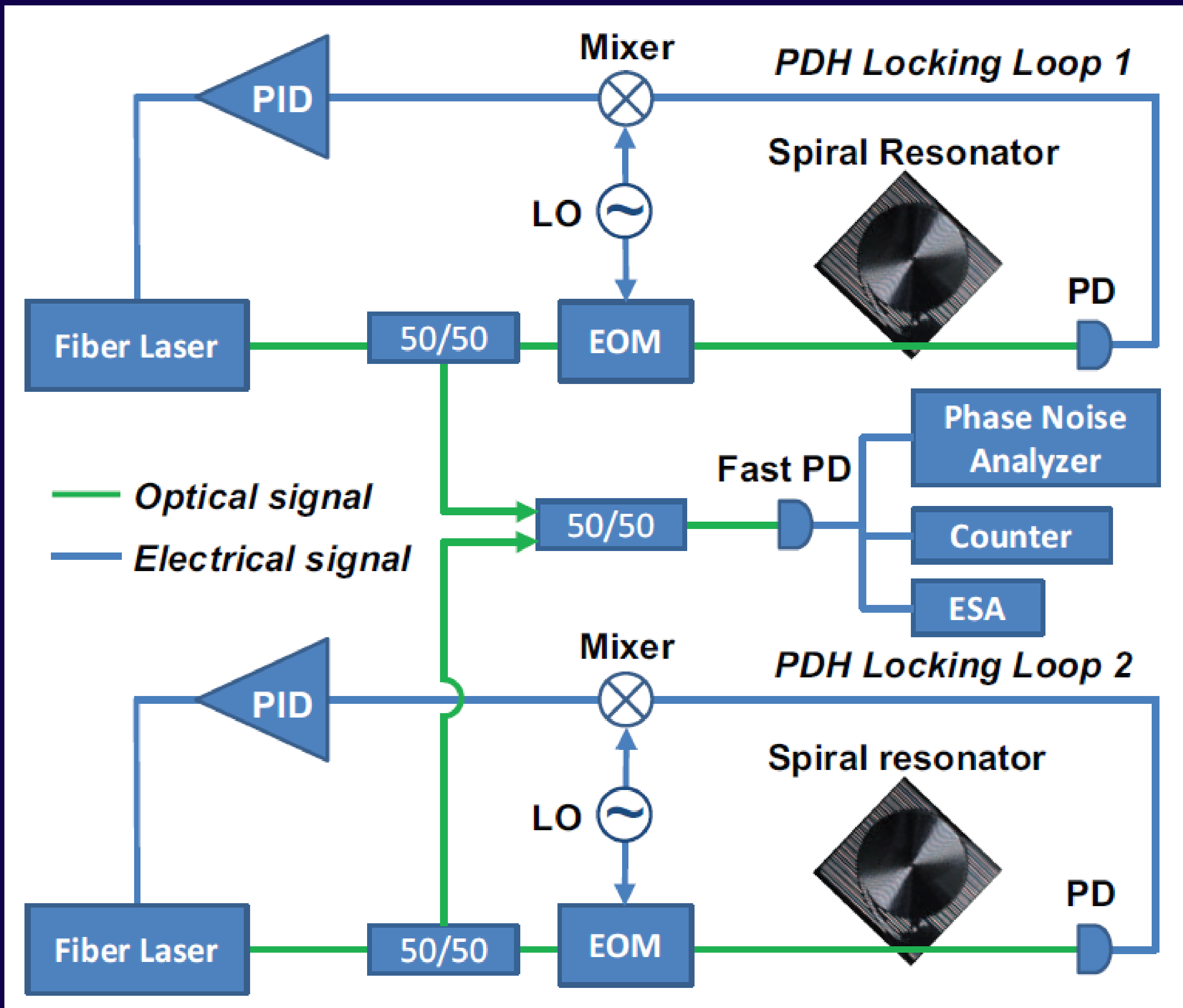
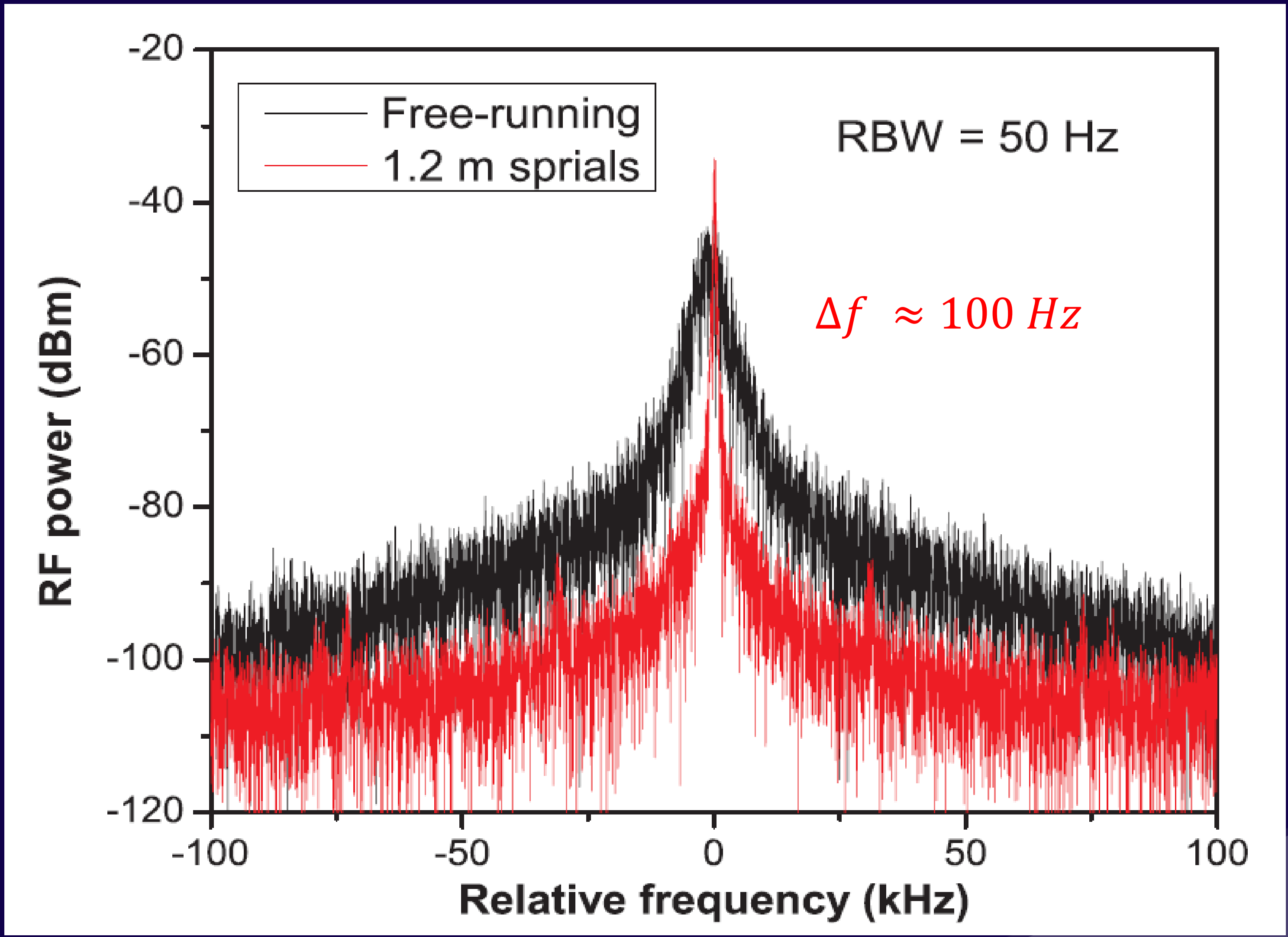
Experimental setup



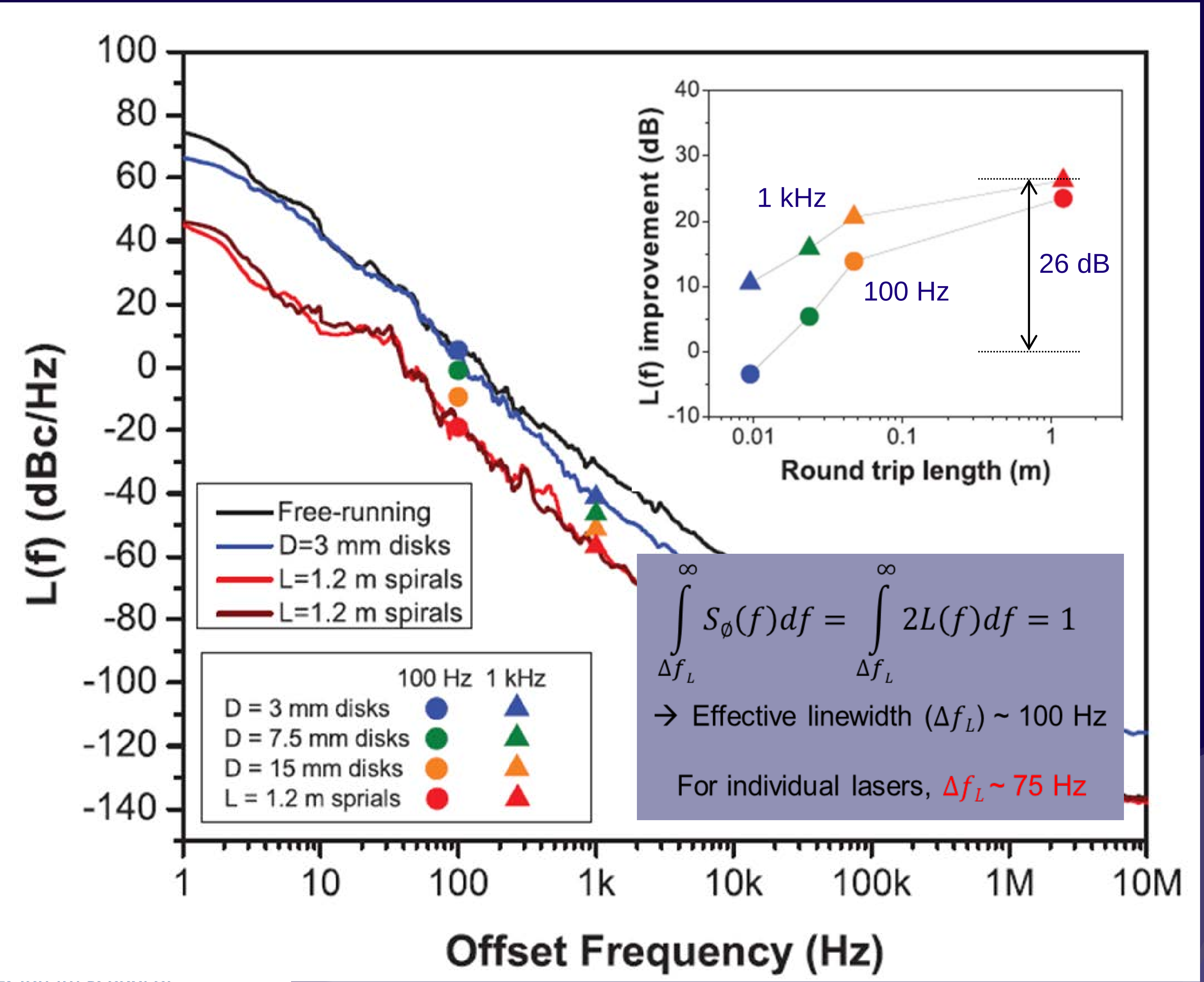
PDH : Pound-Drever-Hall
LO : Local Oscillator
PD : Photo-Detector
EOM : Electro-Optic Modulator
ESA : Electrical Spectrum Analyzer
PID : PID controller

Optical signal
Electrical signal

Electrical Spectra (L = 1.2 m spiral resonators)



Phase noise (L = 1.2 m spiral resonators)

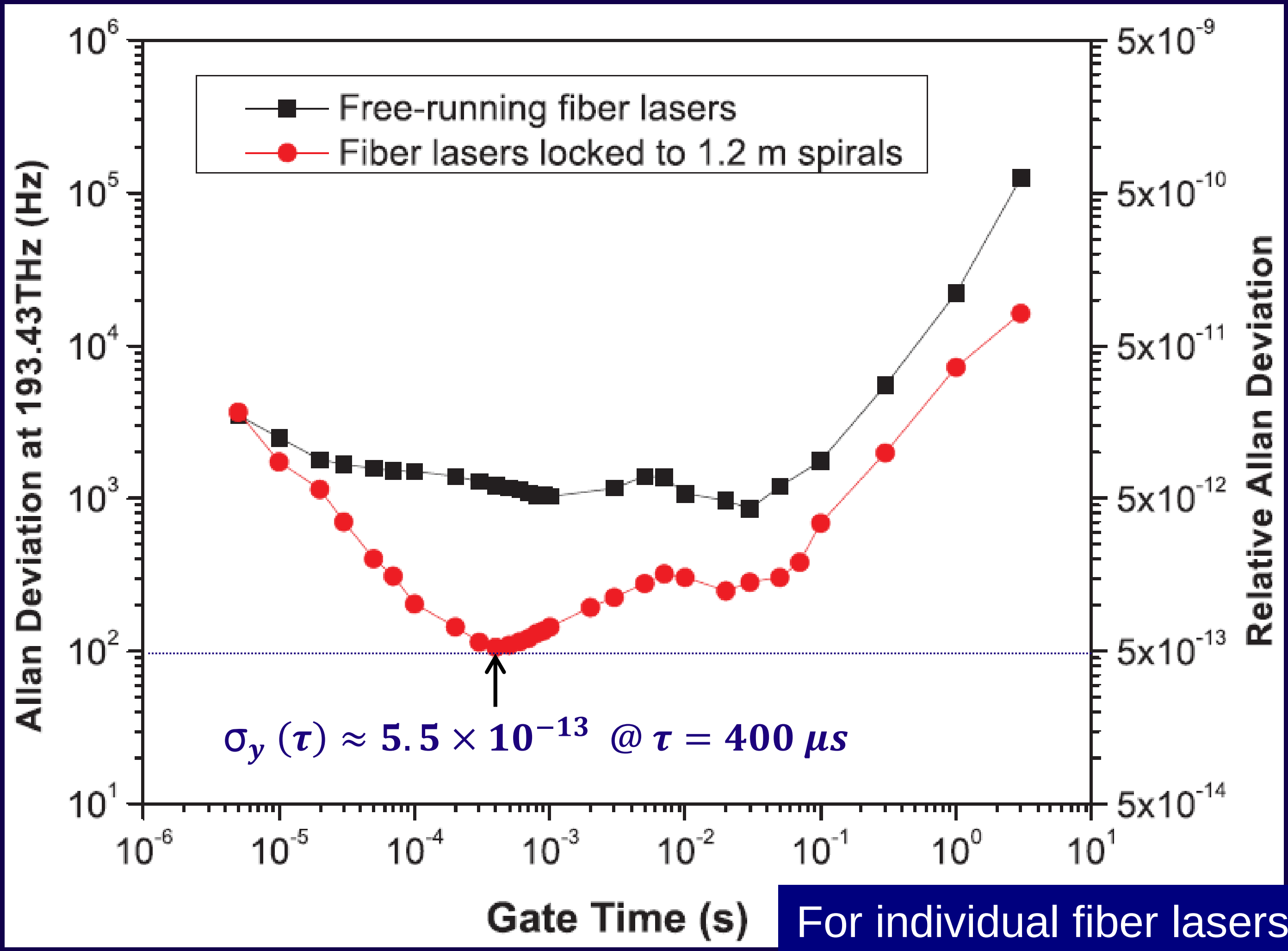


$$\int_{\Delta f_L}^{\infty} S_{\emptyset}(f)df = \int_{\Delta f_L}^{\infty} 2L(f)df = 1$$

→ Effective linewidth (Δf_L) ~ 100 Hz

For individual lasers, Δf_L ~ 75 Hz

Alan deviation measurement result



For individual fiber lasers,

$\sigma_y(\tau) \approx 4 \times 10^{-13}$ @ $\tau = 400\ \mu s$

Nature Communications, vol. 4, 2468, 2013

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