Quantum Transducers on Integrated Photonic Platforms

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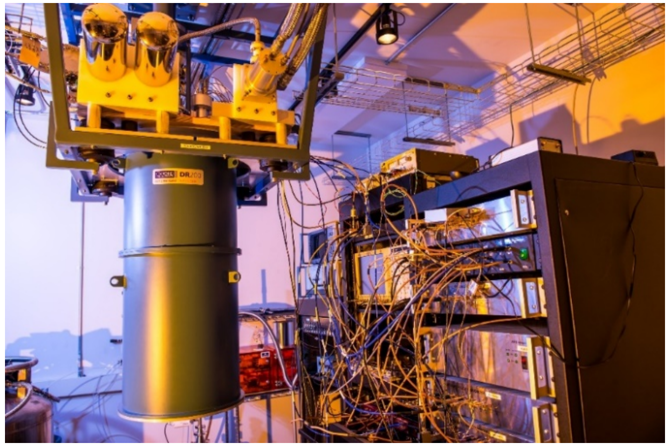
Physical Sciences & Systems Department

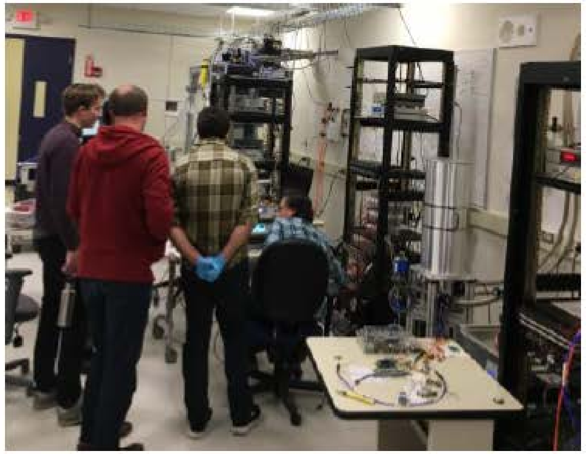
Raytheon BBN Technologies

Space & Airborne Systems

Photonics and Superconducting Quantum Technologies at Raytheon BBN

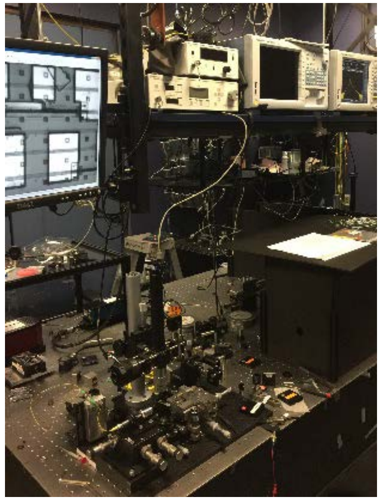
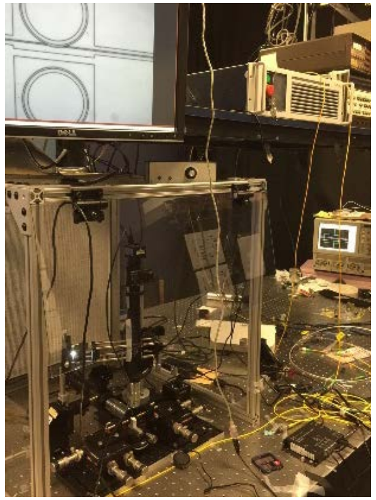
Cryogenic/Superconducting Electronics Labs



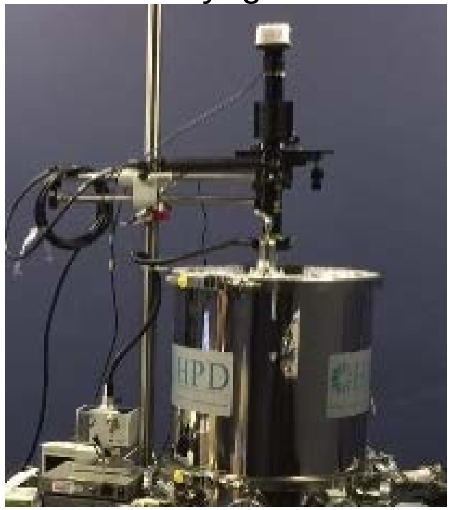



Optics & Integrated Photonics Testbeds

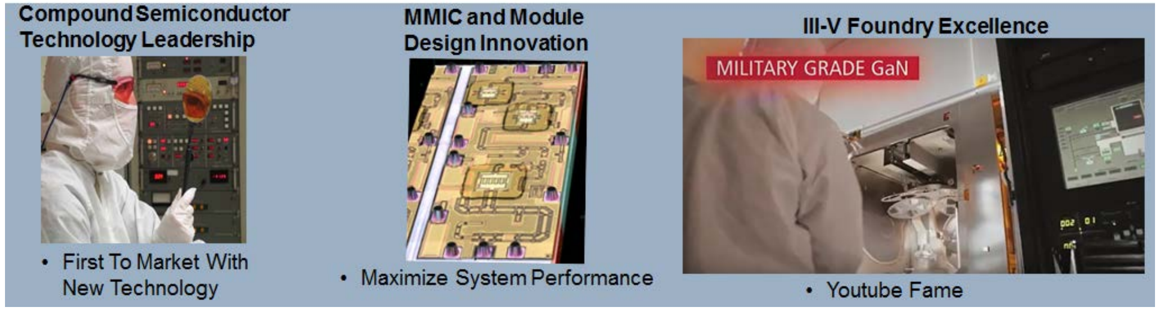
UV/Visible/Telecom Range

Cryogenics



III-Nitride (GaN) foundry at Andover MA



Access to Harvard Nanofabrication Facility

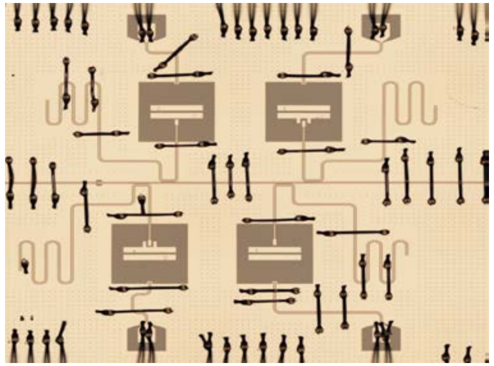

Raytheon

Quantum Engineering and Computing @Raytheon BBN

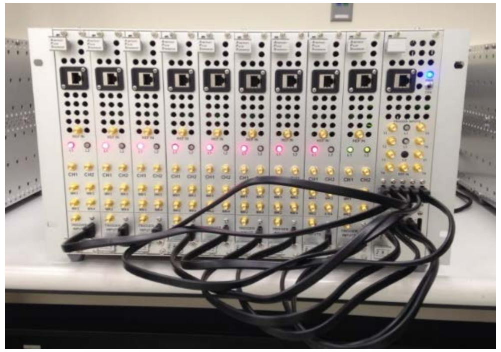
- ❑ **Algorithms**
  - *Novel uses of quantum walks for optimization problems*
  - *Randomized methods for characterizing circuits*
- ❑ **Programming Languages**
  - *Quantum Gate Language*
  - *Extensive research in higher-level language design*
- ❑ **Classical Control**
  - *Custom AWGs and Digitizers*
  - *Cryogenic digital and microwave circuits*
- ❑ **Devices**
  - *Photonic Integrated Circuits*
  - *Novel quantum-limited amplifiers*
  - *Multi-qubit circuits*

First demonstration of metro area QKD in Cambridge, MA
(DARPA Quantum Network Program, 2000-2005)

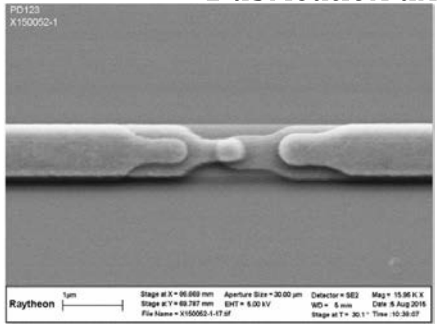
Multiqubit and amplifier chips

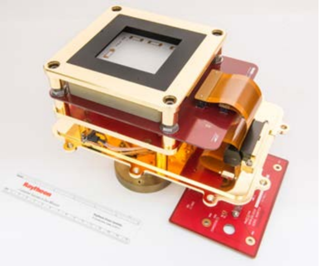


Quantum control circuits



Fabrication and packaging





Qubit specs:
T1 and T2 from 15-25 us
Resonant frequency = 7.1-7.4GHz

Interfacing Superconducting and Optical Technology

Cryogenic Classical/Quantum Computing

I/O via Optical MUXING, analog field generation CryoCMOS, limited DSP

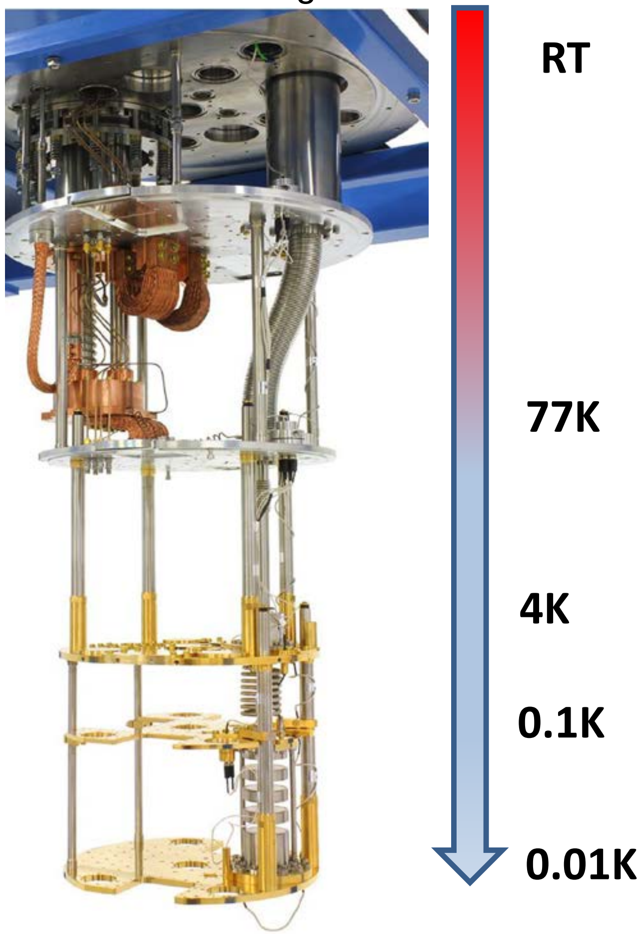
Cryomemory

Digital SFQ (logic/ADC) MMIC

Quantum Packaging

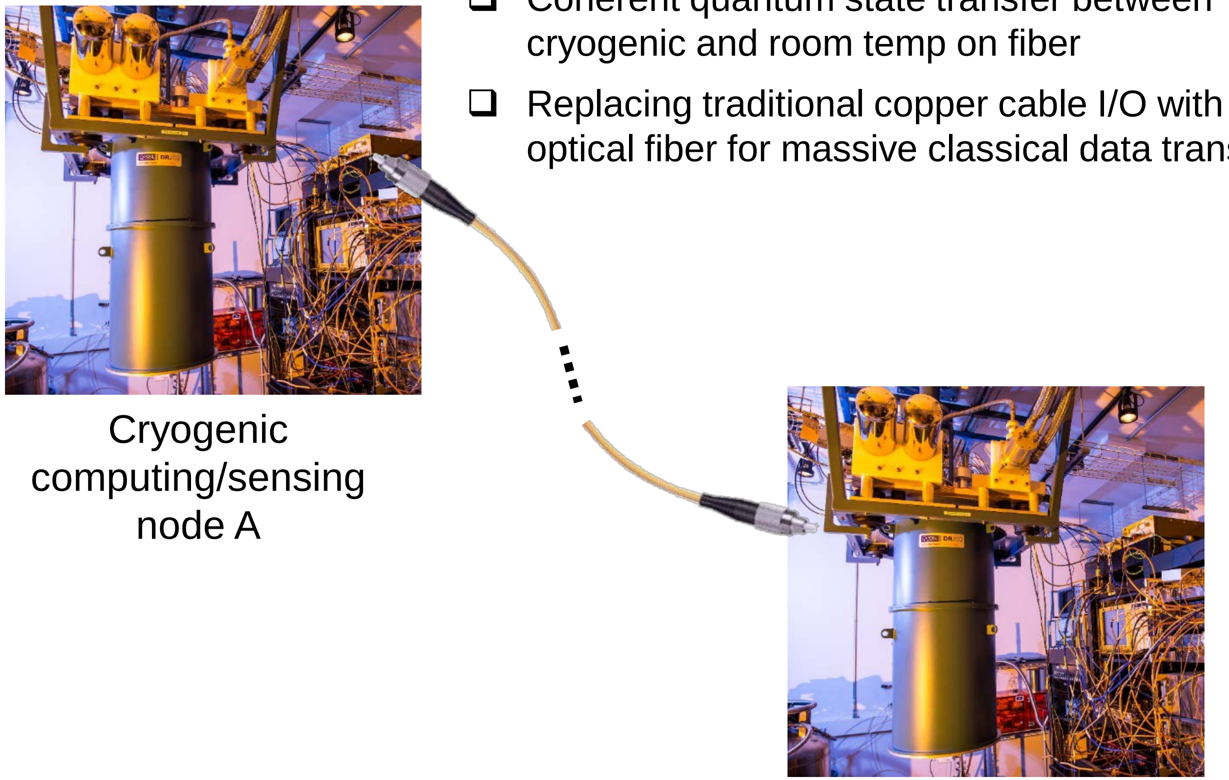
Quantum Devices

Dilution fridge



Optical comm for classical/quantum data transfer to remote distance

- ❑ Coherent quantum state transfer between cryogenic and room temp on fiber
- ❑ Replacing traditional copper cable I/O with optical fiber for massive classical data transfer



Cryogenic computing/sensing node A

Cryogenic computing/sensing node B

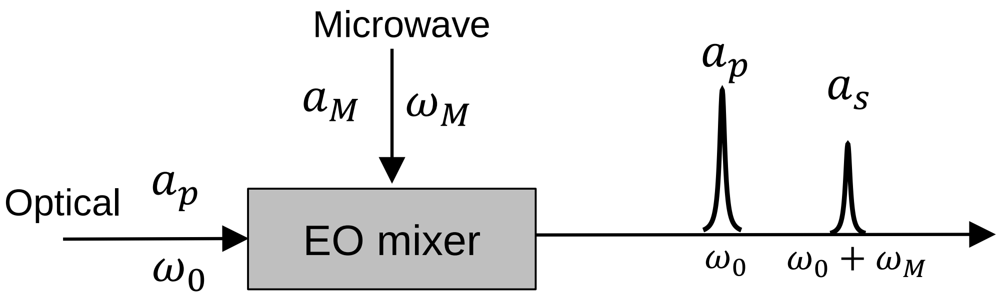
Raytheon

Quantum Technologies: Superconducting vs. Optical

	SC Quantum Technology	Optical Quantum Technology
Qubit operation frequency	5-10 GHz	193 THz
Operation Temperature	10 mK	Room temperature
Single photon nonlinearity	Strong (enables high fidelity gates)	Weak
Quantum memory	Yes (tens of microseconds and more)	No
Long distance comm/interconnect	No (stationary qubit)	Yes (flying qubit)
	Strong candidate for computing	Strong candidate for comm. (~km travel with no need for quantum repeater)

Pursued Transduction Schemes

Technology	g/2π	Thermal & Mechanical stability	Scalability	Tunability	Comment
Optomechanics	Hz-100 KHz	Low	Low	Low	Suspended, hard to scale
Piezo-mechanics	50 KHz	Low	Low	Low	Similar to optomechanics
Magnon	10 Hz	High	Low	Low	Small g < 10 Hz, suspended
Electro-optics	100 Hz-10 KHz	High	High	High	High g, ultrahigh optical Q (10^7), moderate microwave Q (10^3-10^5)



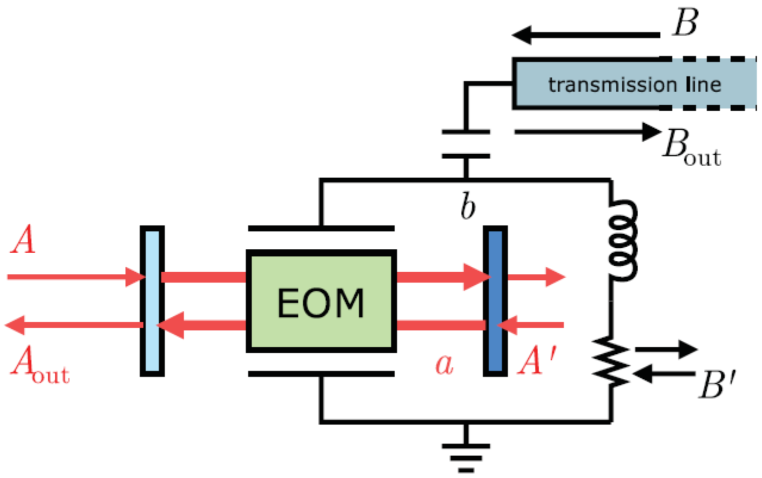
Quantum Electro-Optic Transduction

PHYSICAL REVIEW A **81**, 063837 (2010)

Cavity quantum electro-optics

Mankei Tsang*
Center for Quantum Information and Control, University of New Mexico, MSC07-4220, Albuquerque, New Mexico 87131-0001, USA
(Received 9 March 2010; published 30 June 2010)

The quantum dynamics of the coupling between a cavity optical field and a resonator microwave field via the electro-optic effect is studied. This coupling has the same form as the optomechanical coupling via radiation pressure, so all previously considered optomechanical effects can in principle be observed in electro-optic systems as well. In particular, I point out the possibilities of laser cooling of the microwave mode, entanglement between the optical mode and the microwave mode via electro-optic parametric amplification, and back-action-evading optical measurements of a microwave quadrature.



PHYSICAL REVIEW A **84**, 043845 (2011)

Cavity quantum electro-optics. II. Input-output relations between traveling optical and microwave fields

Mankei Tsang[1,2,3,*]

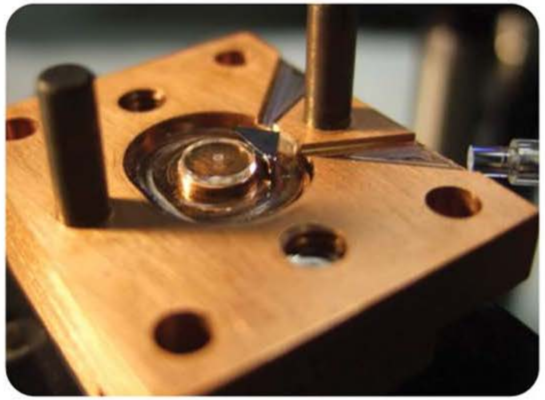
Vol. 20, No. 2/February 2003/J. Opt. Soc. Am. B 333

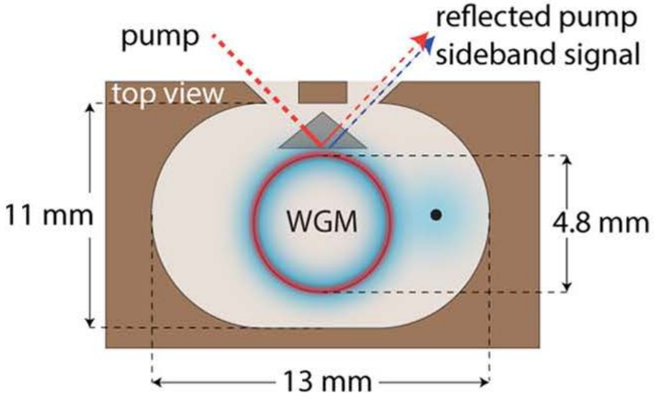
Whispering-gallery-mode electro-optic modulator and photonic microwave receiver

Vladimir S. Ilchenko, Anatoliy A. Savchenkov, Andrey B. Matsko, and Lute Maleki
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109-8099

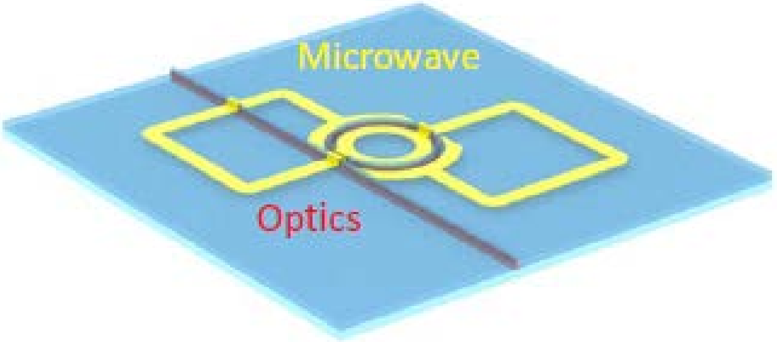
Example of EO Transduction Schemes

WGM EO Resonators, Harald Schwefel

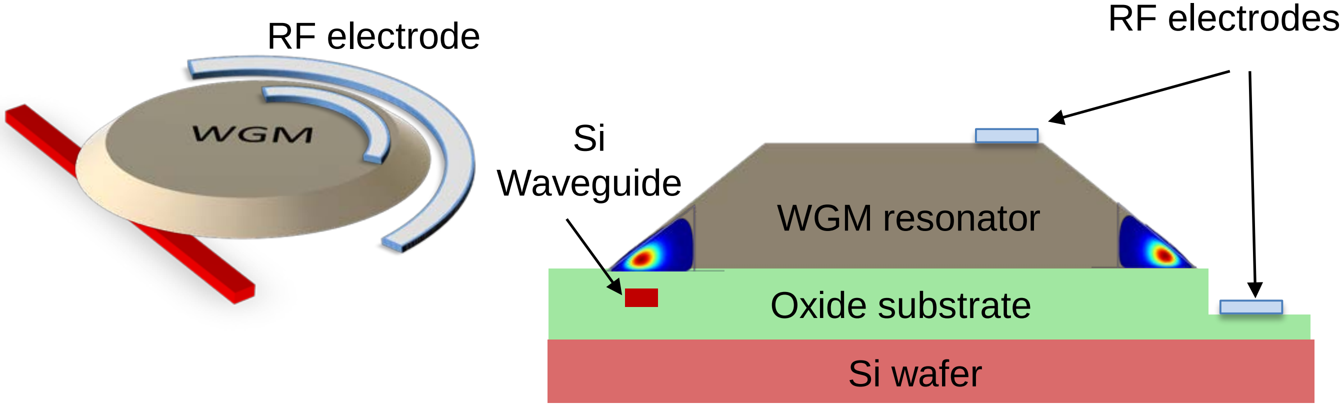




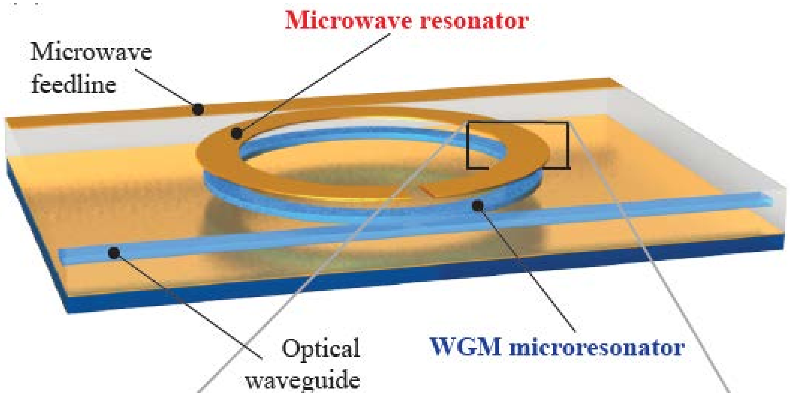
Integrated AlN resonators, Hong Tang (Yale)



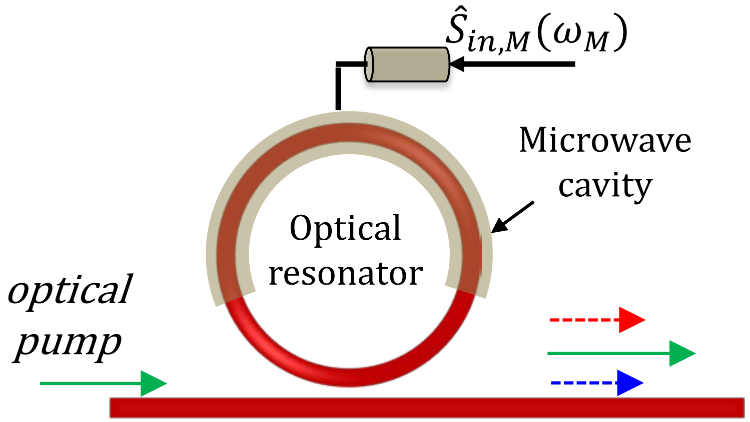
Early work of our group in collaboration with OEWaves and IBM

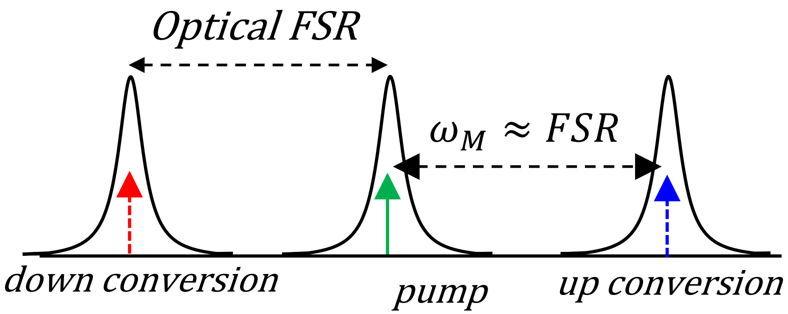


Integrated $LiNbO_3$ resonators, Kippenberg (EPFL)



Transduction using Single WGM Electro-Optic Resonators





$$P_{pump,opt} \approx \left(\frac{\hbar\omega_M}{Q_M}\right)\left(\frac{\omega_{opt}^3}{16Q_{opt}^2}\right)\left(\frac{1}{g^2}\right)$$ (*)

1476 OPTICS LETTERS / Vol. 15, No. 24 / December 15, 1990

Quantum frequency conversion

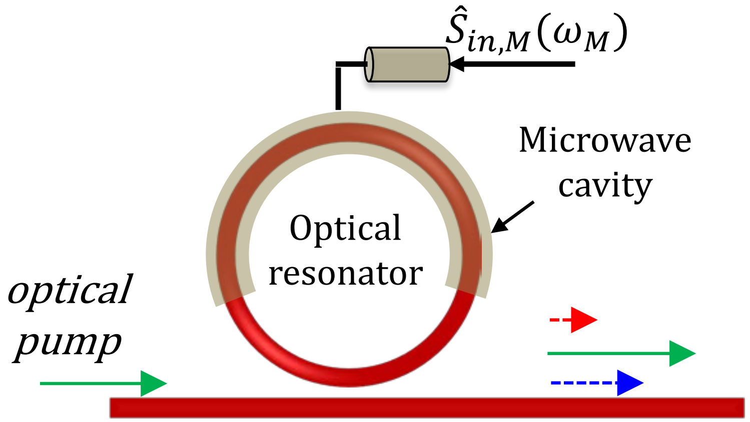
Prem Kumar

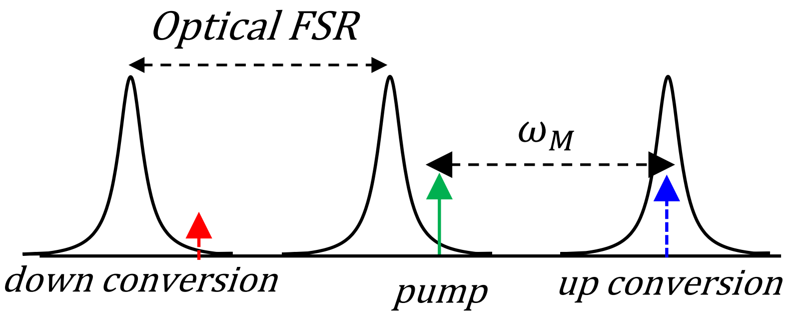
An experimental scheme is proposed by which the quantum states of two light beams of different frequencies can be interchanged. With this scheme it is possible to generate frequency-tunable squeezed light for spectroscopic applications.

The down-conversion sideband is undesired and a noise term

*: A. Matsko, et. al. "On fundamental noise of whispering gallery resonators," Optics Express 15, 17401 (2007).
*: M. Soltani, et. al. "Efficient quantum microwave-to-optical conversion using electro-optic nanophotonic coupled-resonators," PRA 96, 043808 (2017).

Transduction using Single WGM Electro-Optic Resonators



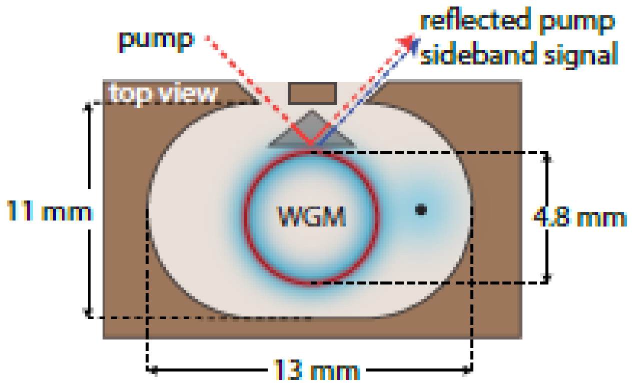


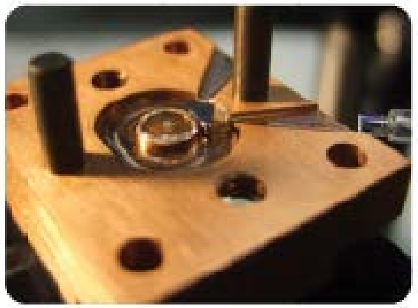
Optical Q	Microwave Q	g/2π	Pump power (on-resonance)	Pump power (off-resonance)
10^6	10^5	10 kHz	~3 µW	~9 mW

Off-resonance pump though suppresses the down-conversion, heats up the fridge

Mechanically Polished WGM $LiNbO_3$ EO Resonators

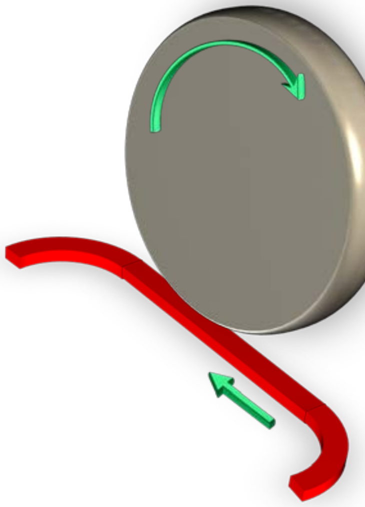
Discrete coupling

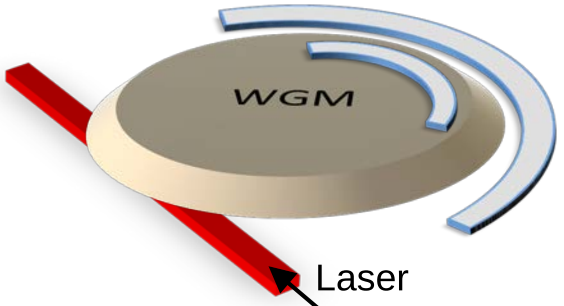


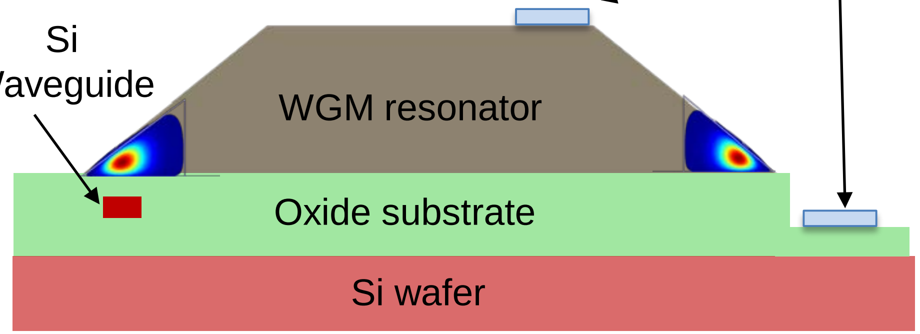


A. Rueda, et. al., Optica 3, 597 (2016)

Integrated coupling

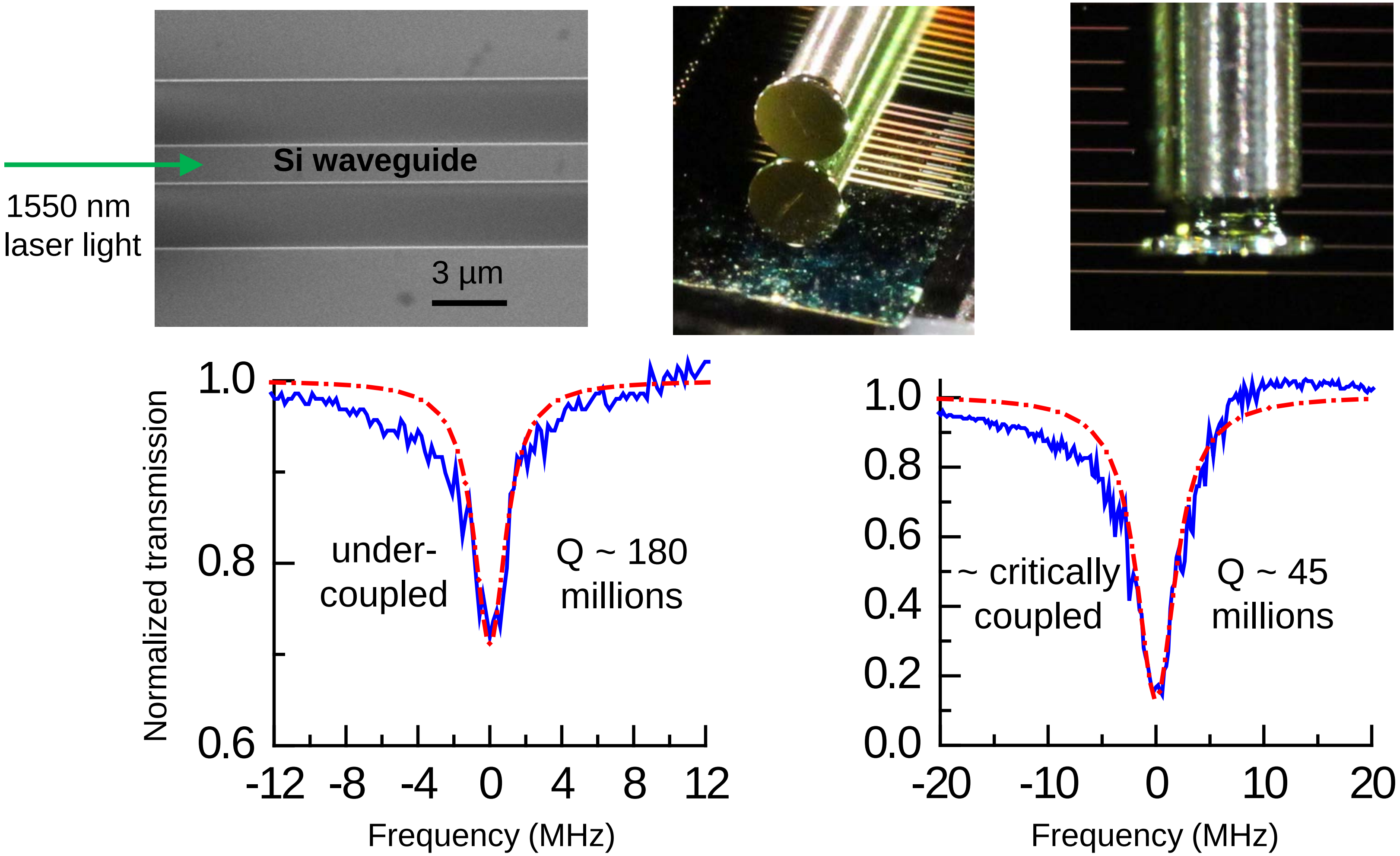






$$g\sim 100\ Hz, \qquad Optical\ Q\sim 108-109, \qquad Microwave\ Q?$$

Demonstration of Efficient Coupling between Si Waveguides and WGM LN Resonators

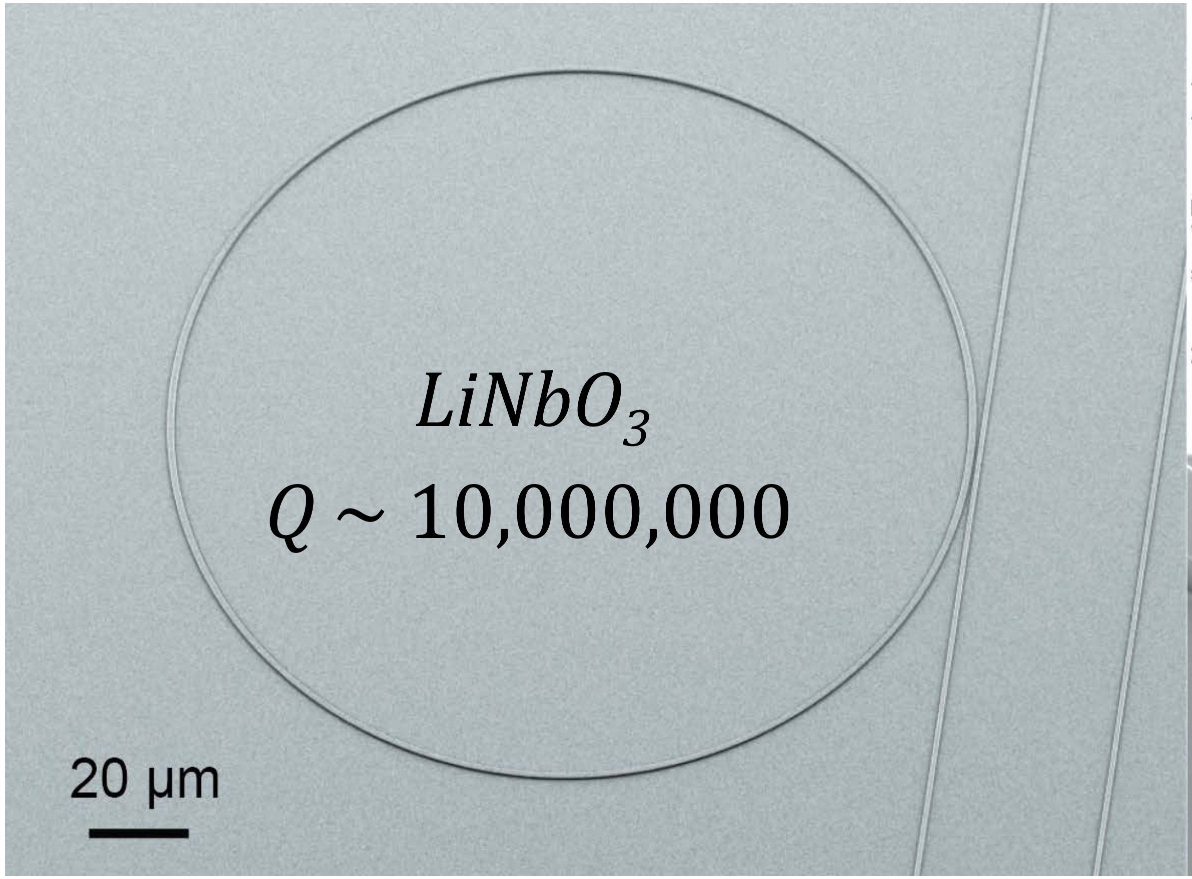


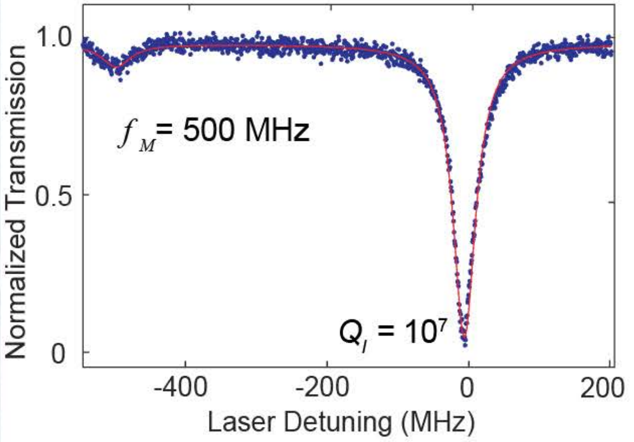
Efficient coupling demonstration between a Si waveguide and a WGM LN Resonator (Q~10^8)

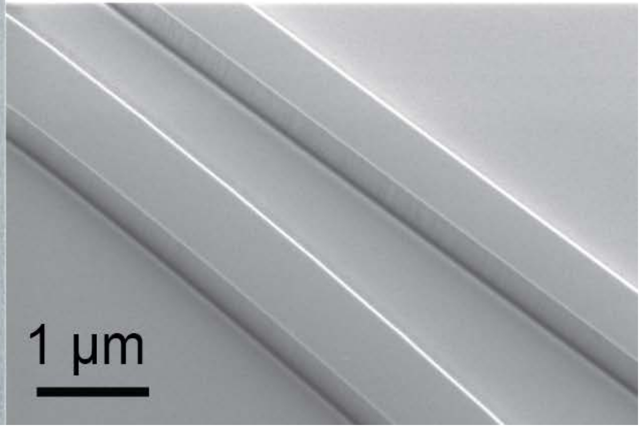
M. Soltani, et. al. “Ultra-high Q whispering gallery mode electro-optic resonators on a silicon photonic chip,” Opt. Letters 41, 4375 (2016)

Migrating to Integrated Nanophotonic EO Resonators

Work of Loncar’s group (Harvard) M. Zhang, et al., Optica **4** (12), 1536–1537 (2017)



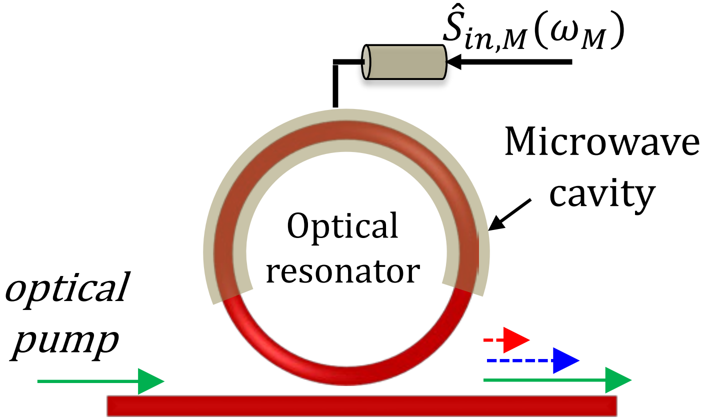


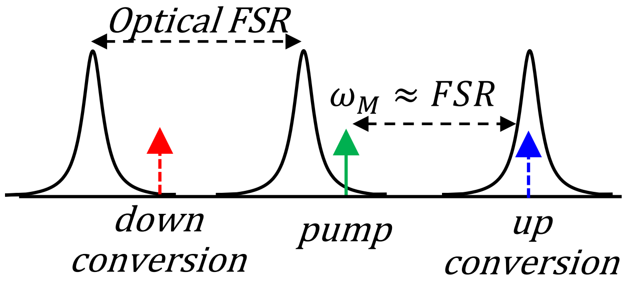


Integrated Ultra-high Q Nanophotonic EO Resonators Results in much higher g factors

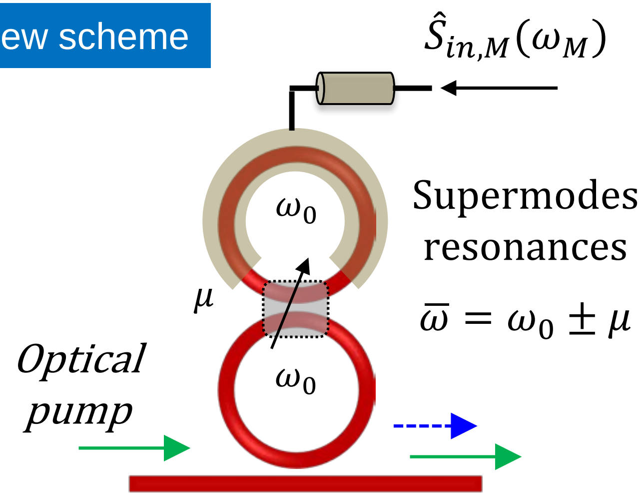
Coupled Nanophotonic EO Resonators

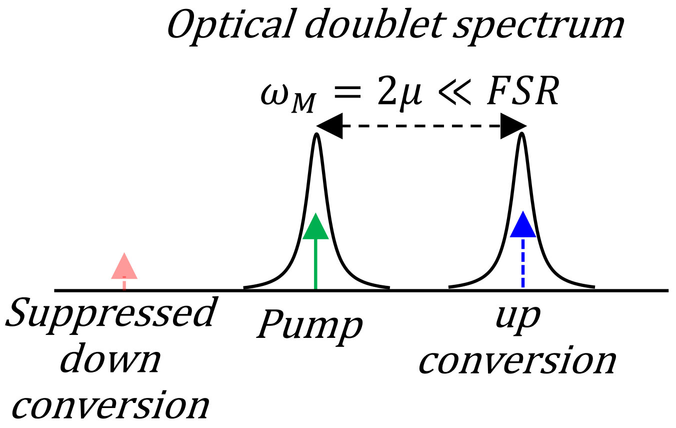
Conventional scheme





Our new scheme





$$\hat{H}_0 = \hbar\omega_+ \hat{a}_+^\dagger \hat{a}_+ + \hbar\omega_M \hat{a}_M^\dagger \hat{a}_M$$

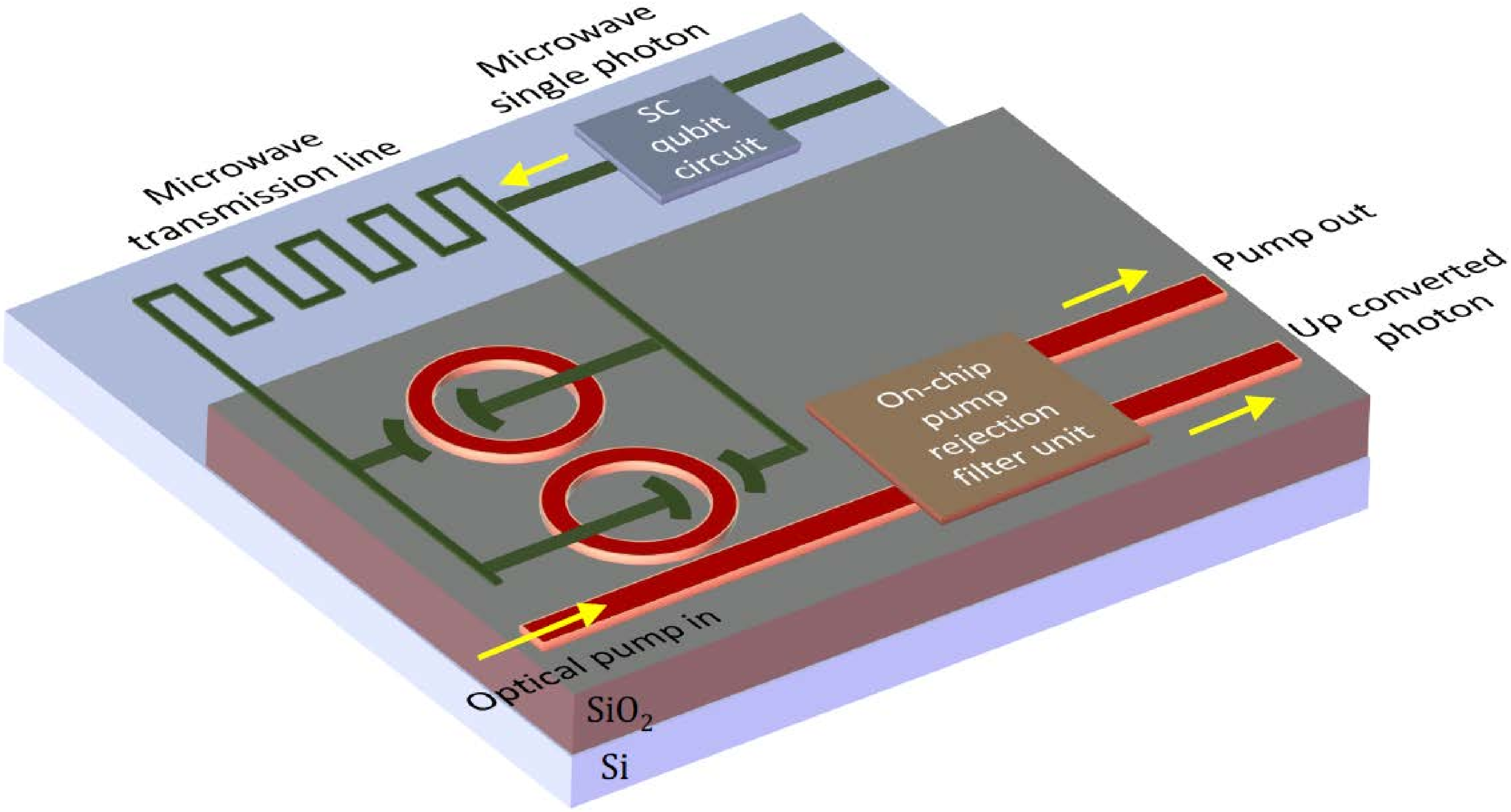
optical — microwave

$$\hat{V} = \hbar g \sqrt{N} \left(\hat{a}_+^\dagger \hat{a}_M + adjoint \right)$$

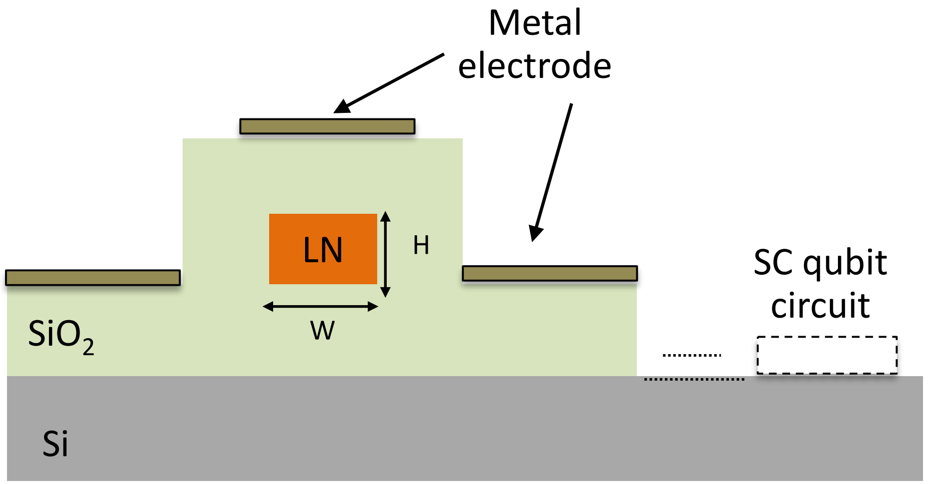
Coupled nanophotonic EO resonator with doublet resonance integrated with a microwave resonator provide an ultracompact triply-resonant system with enhanced g and suppressed down-conversion

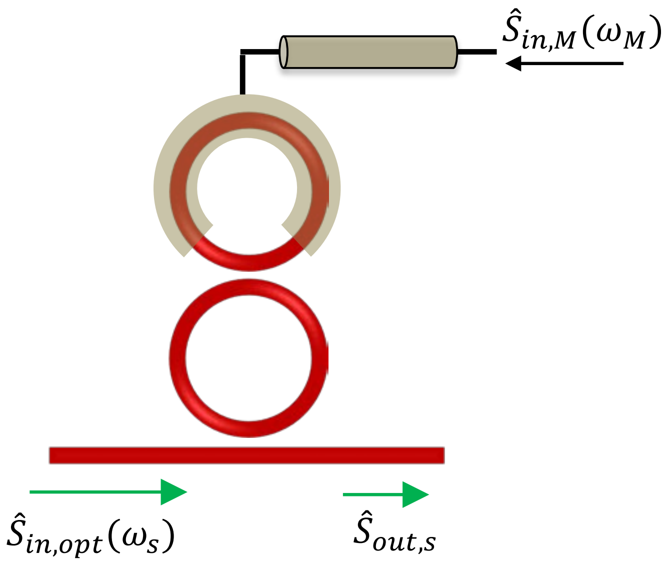
Monolithic Quantum Transduction on Chip

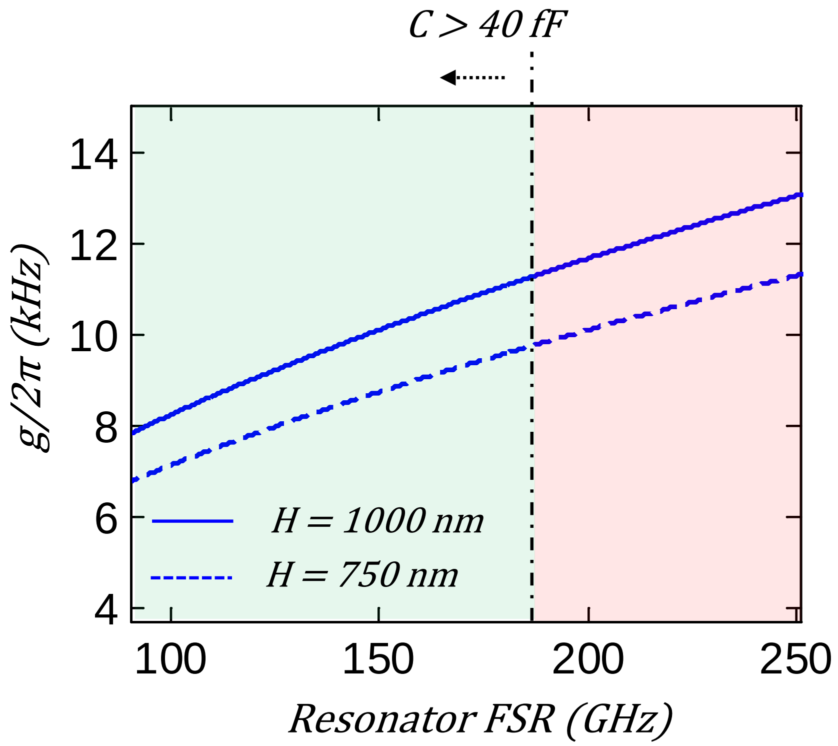
Collaboration with Harvard University (Marko Loncar)

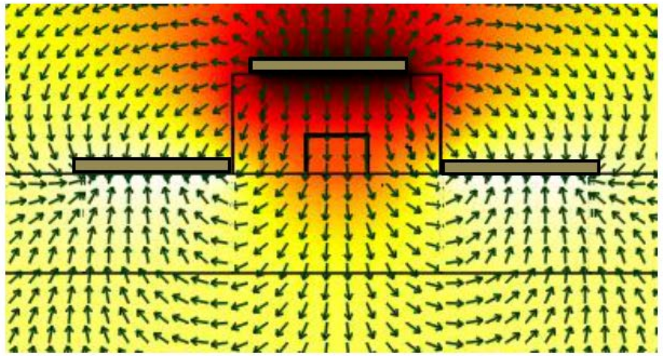


Calculation of g Factor for Nanophotonic Coupled Resonator





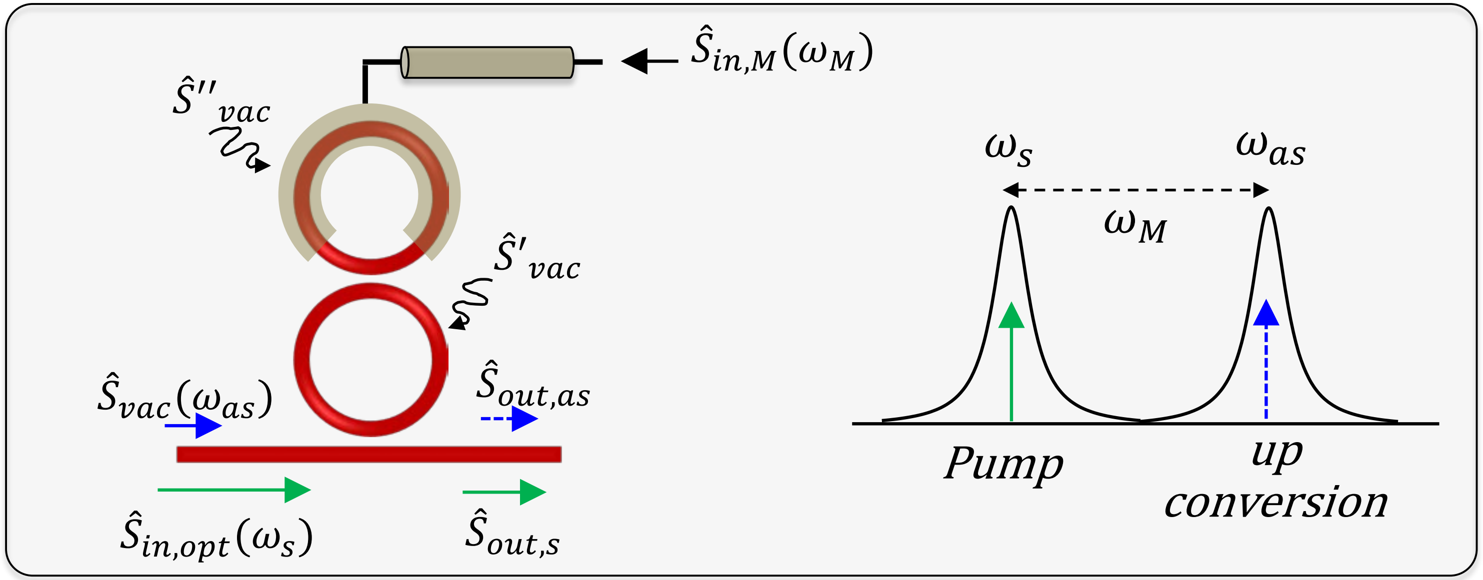




$$g \approx n_e^2 r_{33} \omega_0 \sqrt{(\hbar\omega_M / U_M)}\, \alpha E_M$$

Significant enhancement in *g* factor (~10 kHz)

Figure of Merits for Efficient Conversion



Optimal conversion occurs at *C=1*

$$N = \frac{\gamma_{opt}\gamma_M}{4g^2} = \frac{\omega_{opt}\omega_M}{4Q_{opt}Q_M g^2}$$

$$P_{pump,opt} = \left(\frac{\hbar\omega_M}{Q_M}\right)\left(\frac{\omega_{opt}^3 Q_{ex,opt}}{16Q_{opt}^3}\right)\left(\frac{1}{g^2}\right)$$

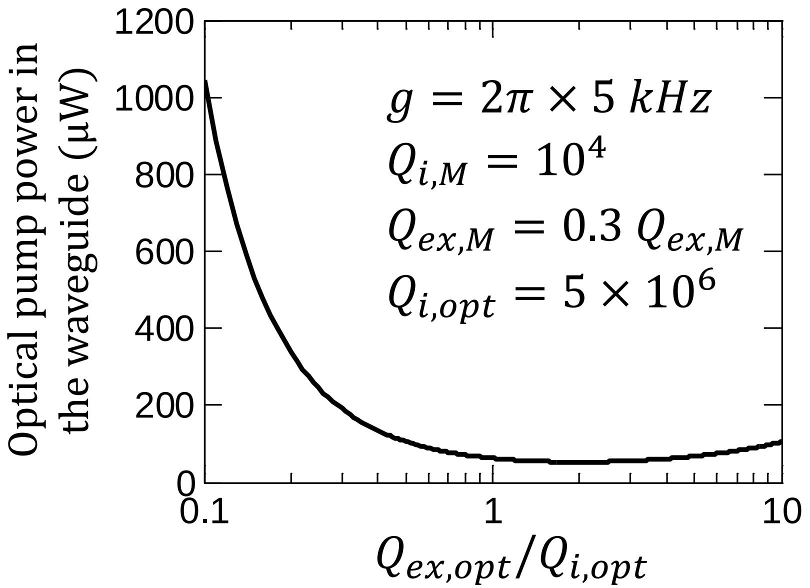
Microwave-to-Optical Quantum Transduction

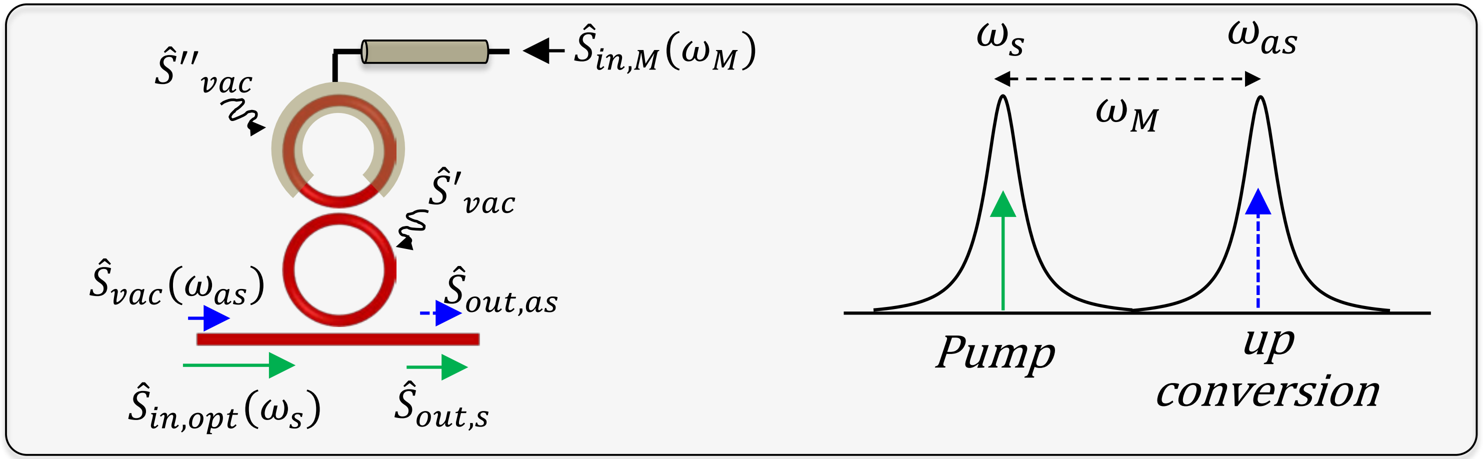
$$\hat{S}_{out,as} = i\sqrt{\frac{Q_{opt}\,Q_M}{Q_{ex,opt}\,Q_{ex,M}}}\hat{S}_{in,M} + \frac{Q_{opt}}{Q_{i,opt}}\hat{S}_{vac} - \frac{Q_{opt}}{\sqrt{Q_{ex,opt}\,Q_{i,opt}}}\hat{S}'_{vac} + i\sqrt{\frac{Q_{opt}\,Q_M}{Q_{ex,opt}\,Q_{i,M}}}\hat{S}''_{vac}$$

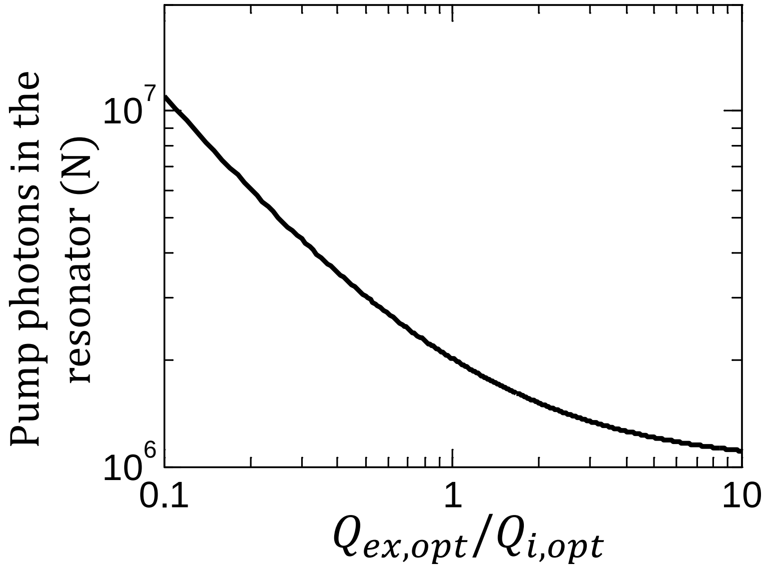
Efficient and low noise transduction requires the optical and the microwave resonators in overcoupled regime

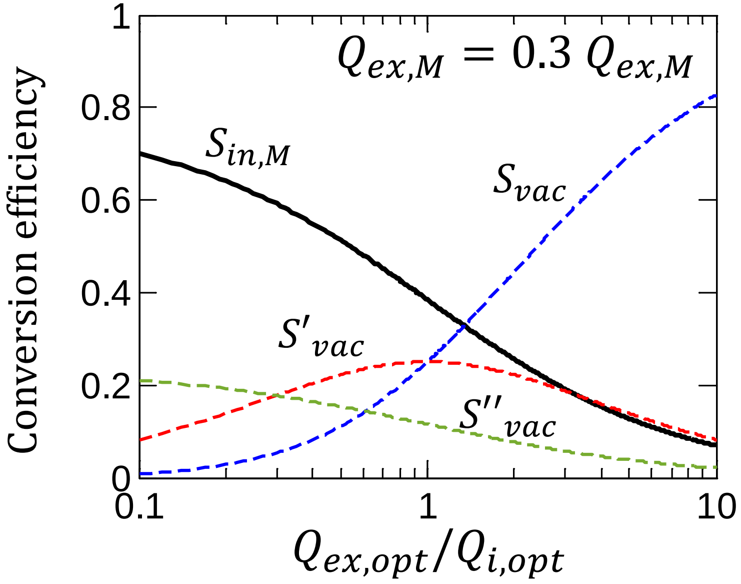
M. Soltani, et. al. "Efficient quantum microwave-to-optical conversion using electro-optic nanophotonic coupled-resonators," PRA 96, 043808 (2017)

Impact of Microwave and Optical Q Parameters on Pump Power, Conversion Factor, and Noise





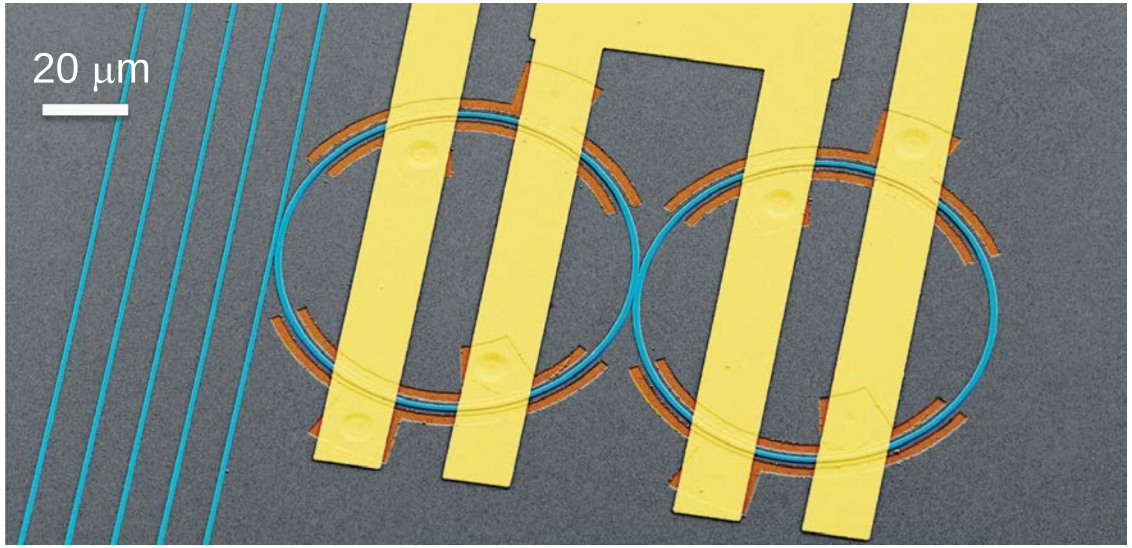


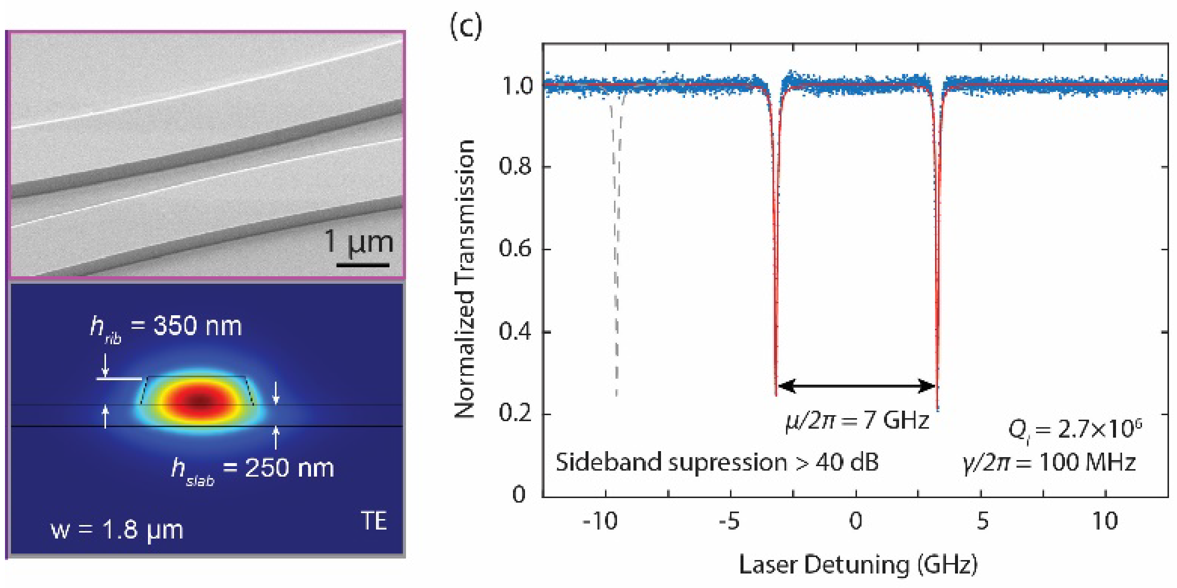


- We need optical Q (1-10 millions) and microwave Q (10-100 thousands) and in overcoupling regime:
  - ❑ To reduce optical pump power
  - ❑ To reduces the vacuum noise effects

Demonstration of Nanophotonic LN Coupled Resonators

M. Zhang, C. Wang, Y. Hu, A. Shams-Ansari, G. Ribeill, M. Soltani, M. Loncar, "Microwave-to-Optical Converter based on Integrated Lithium Niobate Coupled-Resonators," CLEO 2017





Loncar group (Harvard)

The experimental results show resonance doublet with intrinsic Q ~ 3 millions

Conclusion (Continued)

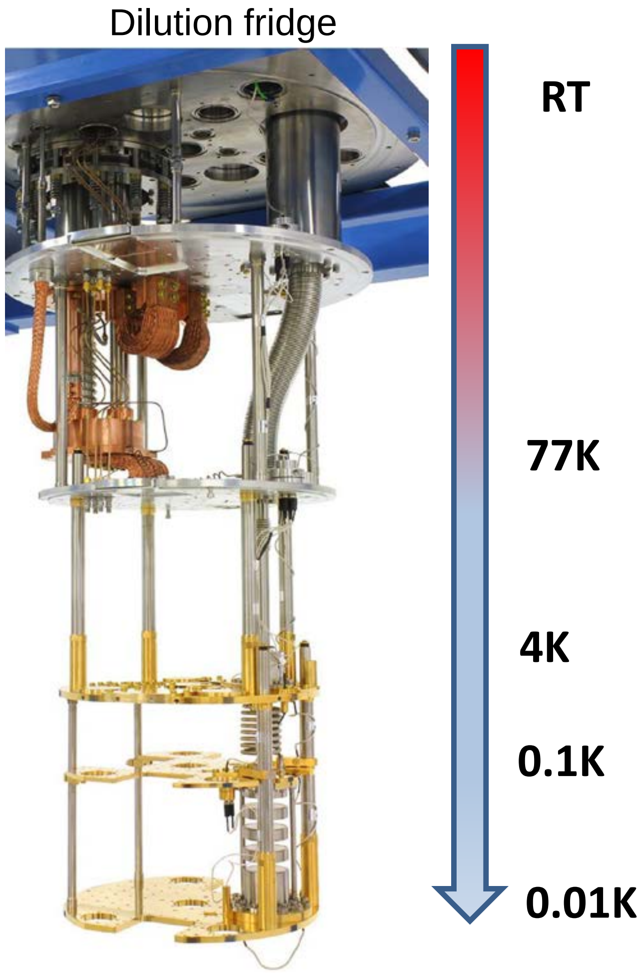
Quantum Electro-optic Transduction

What We Like to Achieve	
g/2π	~1-10 kHz
Thermal & Mech. stability	High
Scalability	High
Tunability	High
Any suspended component	No
Required optical resonator Q	10^6-10^7
Required microwave resonator Q	~10^4-10^5
Optical pump power	~ µW
Transduction efficiency	~>80 %
Fidelity of transferred Fock state	>80 %

Conclusion

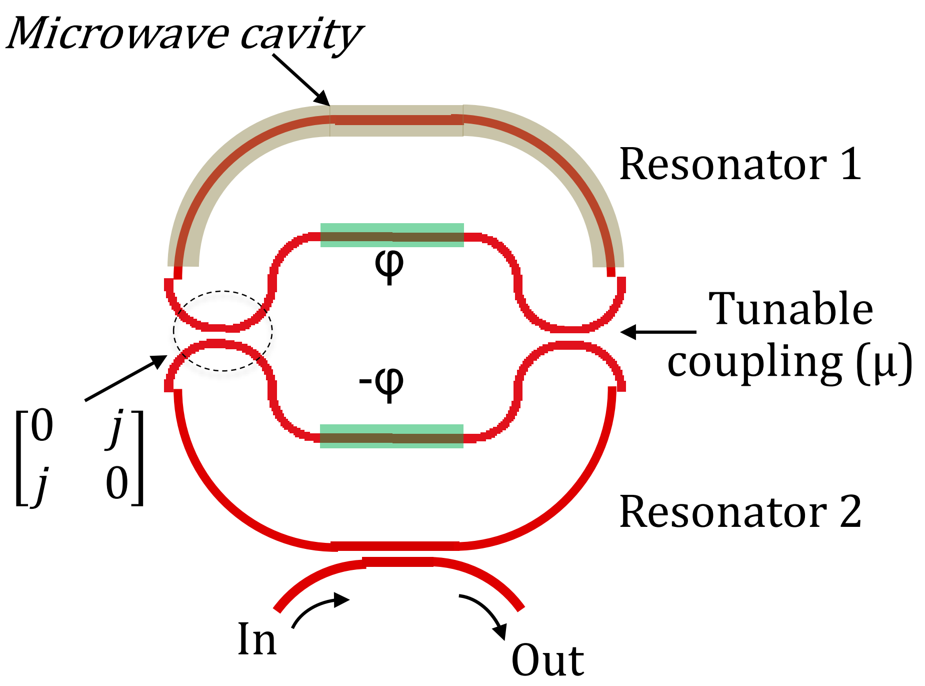
Developing Integrated Photonics at cryogenics is a key enabler for Quantum Technology

- **<u>Challenges:</u>**
  - Achieving low loss
  - Efficient coupling in-out to chip
  - Material properties: Optical, electronic, thermal, …
  - Efficient photonic and electronic functionalities at low temperatures
  - Efficient photonic filters with low insertion loss and high rejection needed
  - Photonic instrumentation and measurement at cryogenics



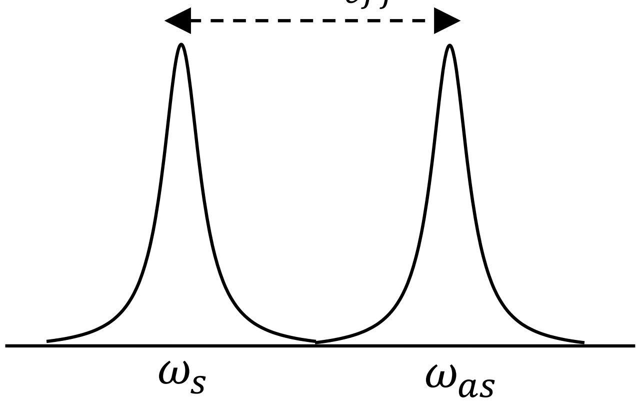
Backup

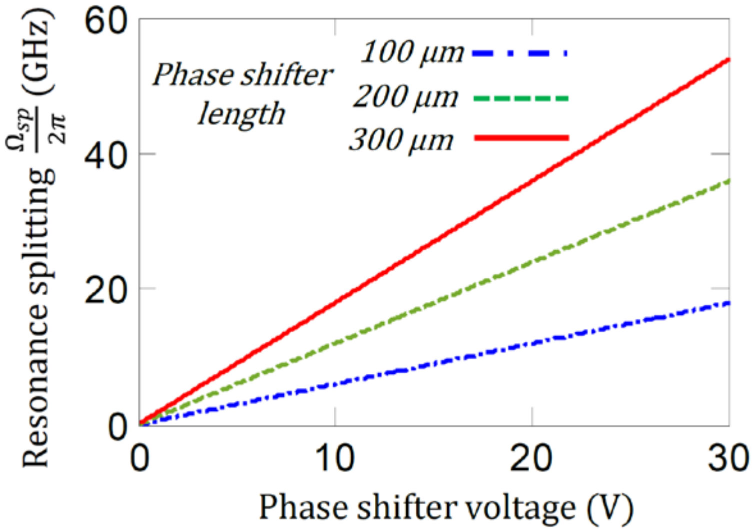
Coupled Resonator with Tunable Doublet Spacing



$$\begin{bmatrix} 0 & j \\ j & 0 \end{bmatrix}$$

$$\Omega = 2\pi \frac{n_g FSR}{n_{eff}} \frac{\varphi}{\pi}$$

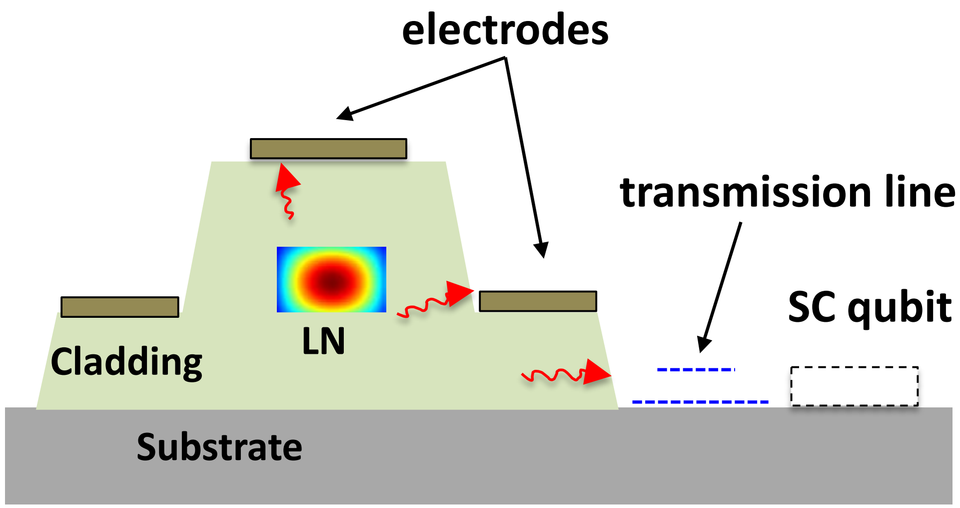


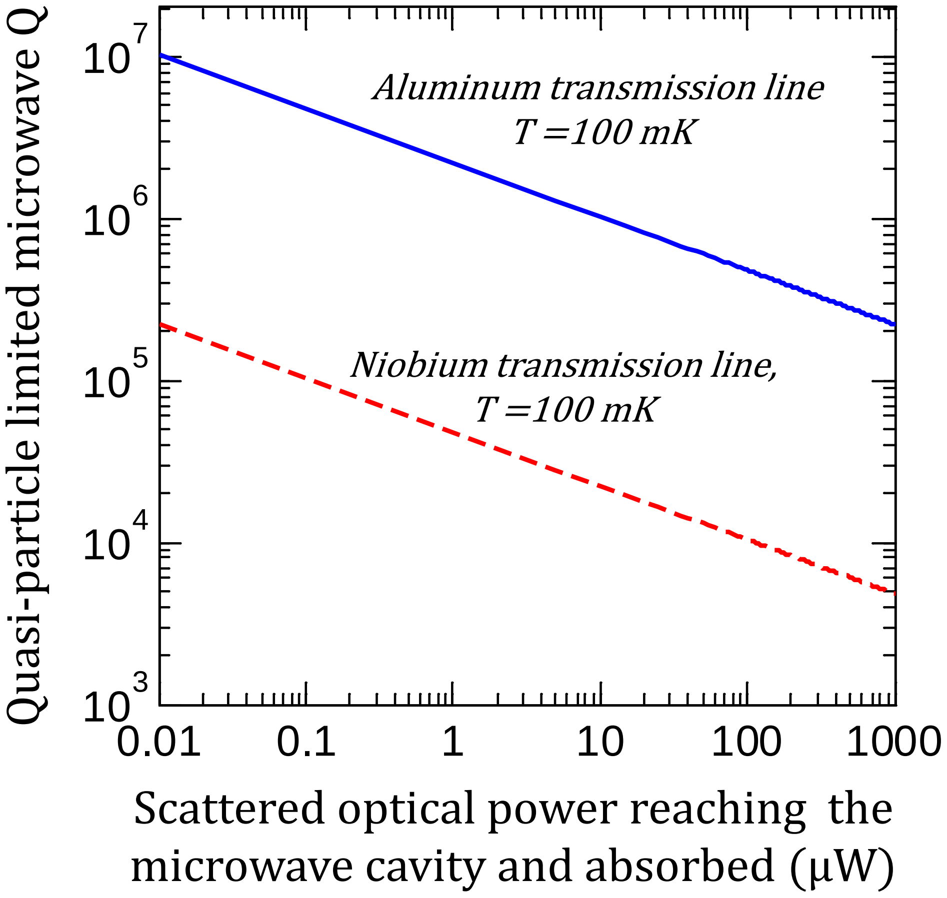


Tuning of doublet spacing allows perfect frequency matching to microwave resonance

Impact of Scattered Optical Photons on Generating Quasi-particles and Microwave Q

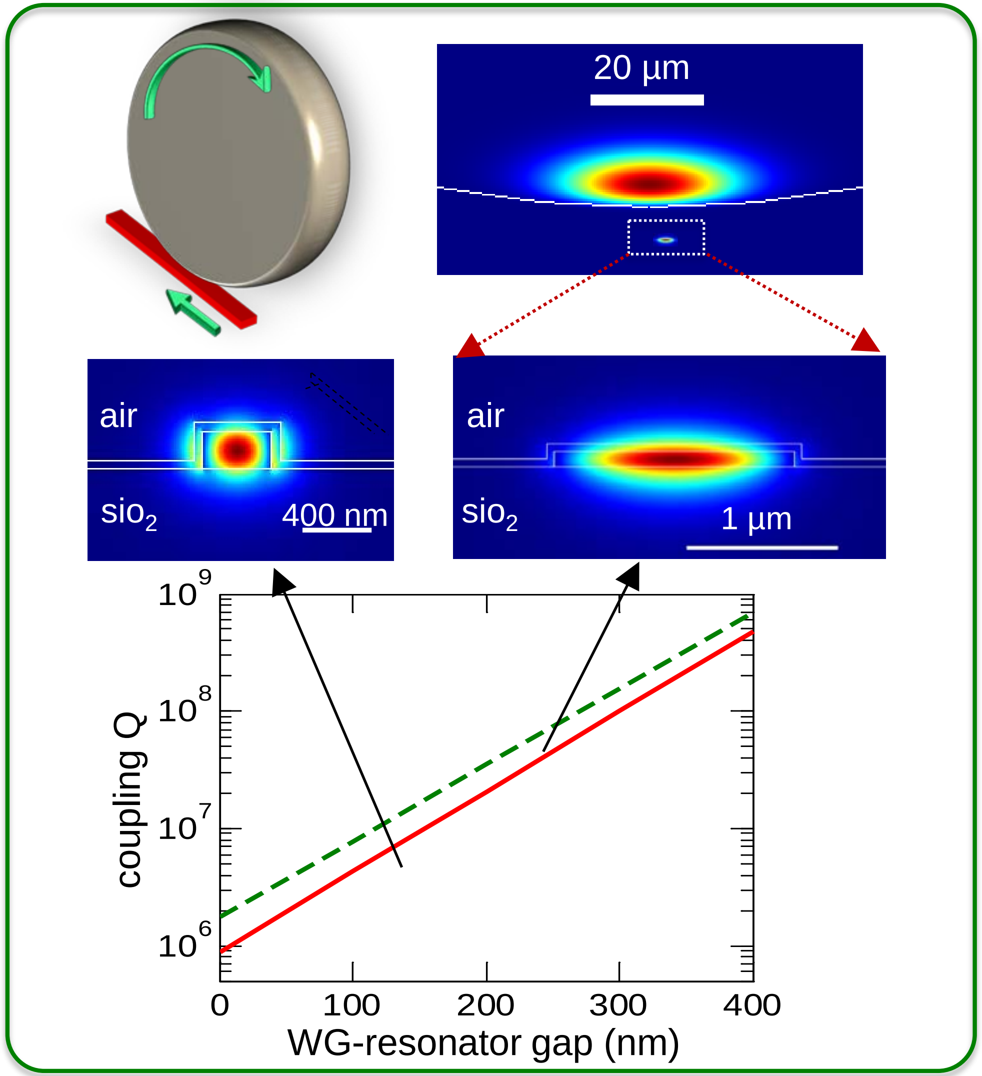
- ❑ Scattered optical photons reaching the SC microwave cavity can generate quasi-particles and limit the microwave Q.
- ❑ Not all optical photons reach the microwave cavity, and not all gets absorbed

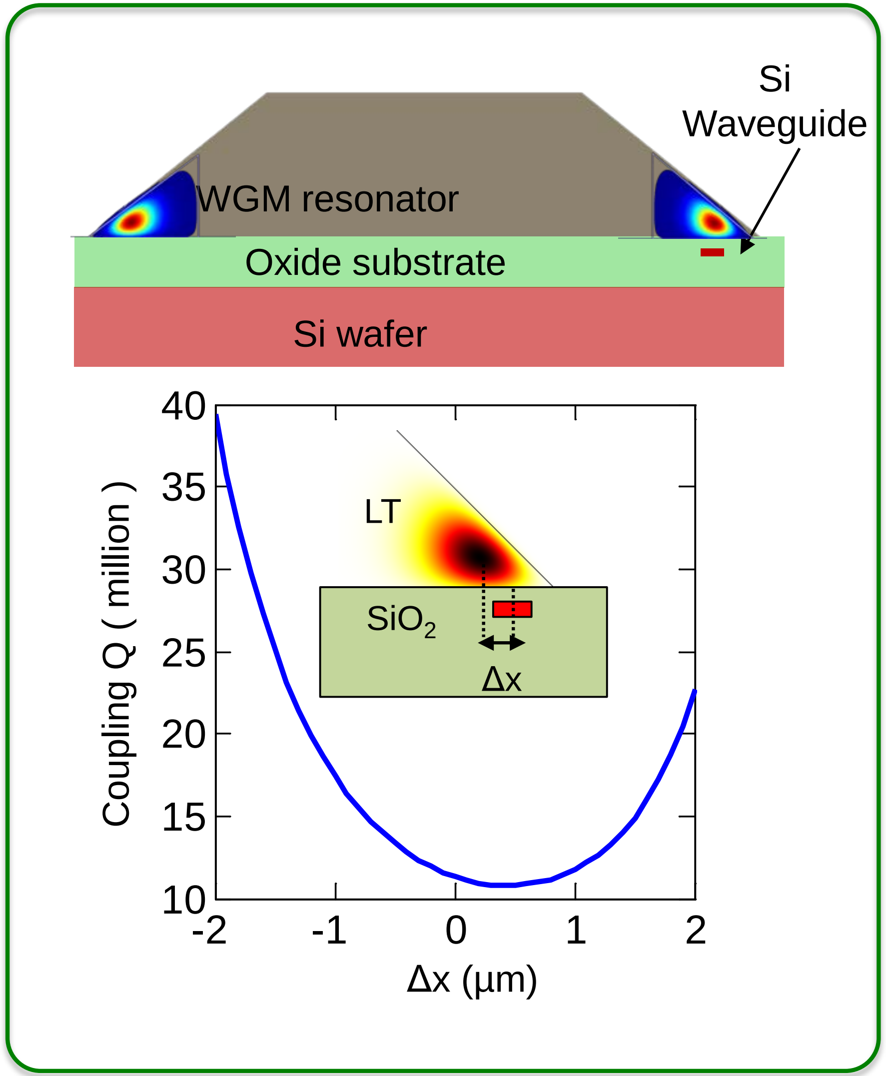




The calculated results show that the microwave Q stays high even with large scattered optical photons

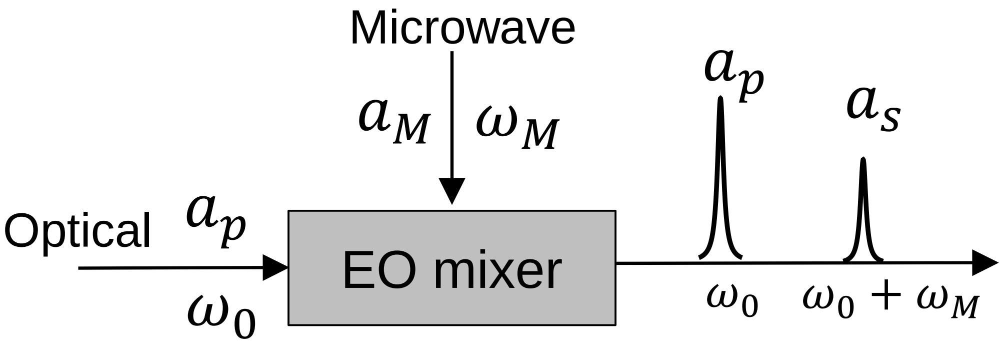
Efficient Coupling Design between Si Waveguide and WGM LN Resonators



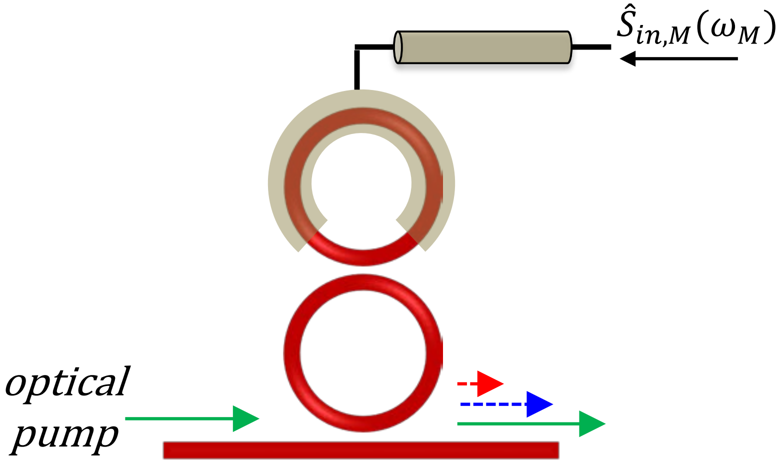


Simulation results showed phase matching and efficient coupling between a Si waveguide WGM Resonator

Figure of Merits for Efficient Conversion



$$\frac{da_s}{dt} = -iga_P a_M$$



Intrinsic conversation rate

$$g \approx n_e^2 r_{33} \omega_0 \sqrt{(\hbar\omega_M/U_M)}\, \alpha E_M$$

- Refractive index
- EO coeff.
- Microwave mode energy
- Overlap factor of microwave and optical mode
- Microwave E field

Cooperativity factor

$$C = 4g^2 N/(\gamma_{opt}\gamma_M)$$

- # pump optical photons in resonators
- Optical cavity decay rate
- Microwave cavity decay rate