Coupled Micro disk Resonators For Efficient Electro-Optic Quantum Frequency Conversion

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Introduction: Background and Theory

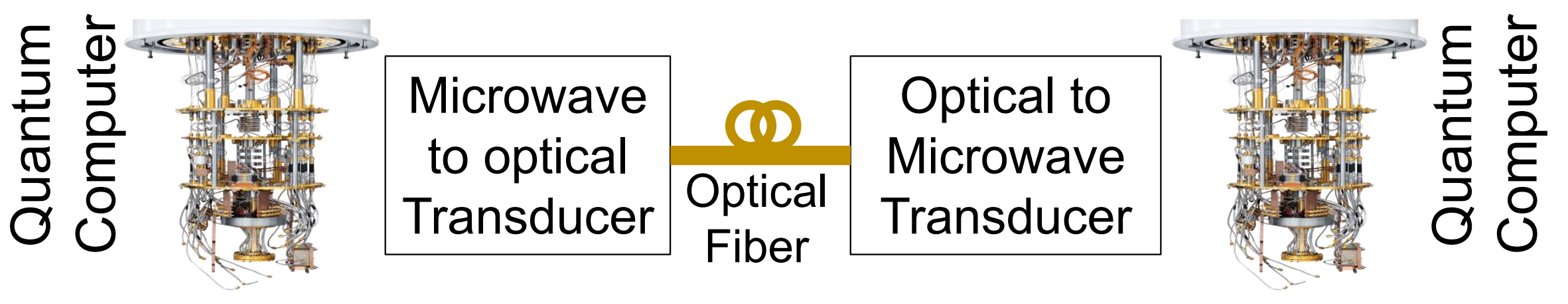
Interfacing Cryogenic Quantum Technology & Optics

Superconducting qubits

- Operate at sub-mk
- 10^9 Hz
- Short coherence time

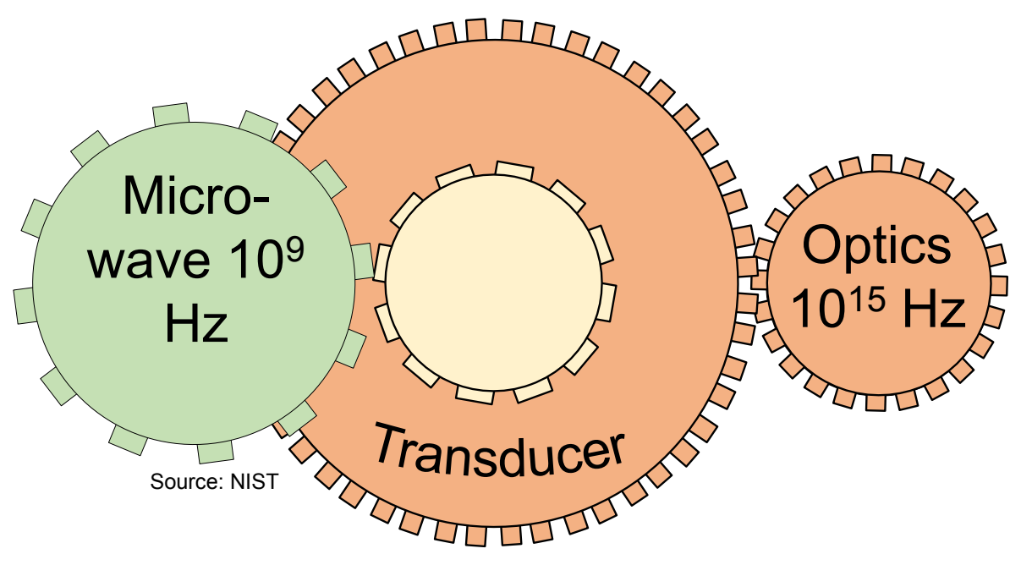
Optical quantum communication

- No temperature requirement
- 10^{15} Hz
- Long coherence time



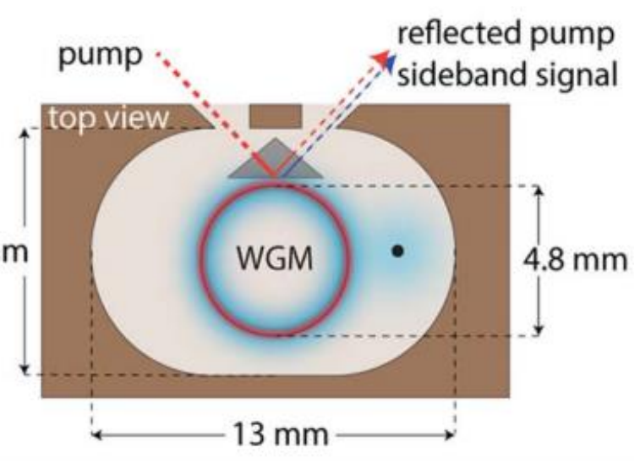
Quantum Frequency Transduction

- ❑ Opto-Mechanical (OM)
- ❑ Electro-Mechanical (EM)
- ❑ Magneto-Optical (MO)
- ❑ Electro-Optic (EO)
  - Direct conversion
  - High thermal stability
  - Scalable and tunable

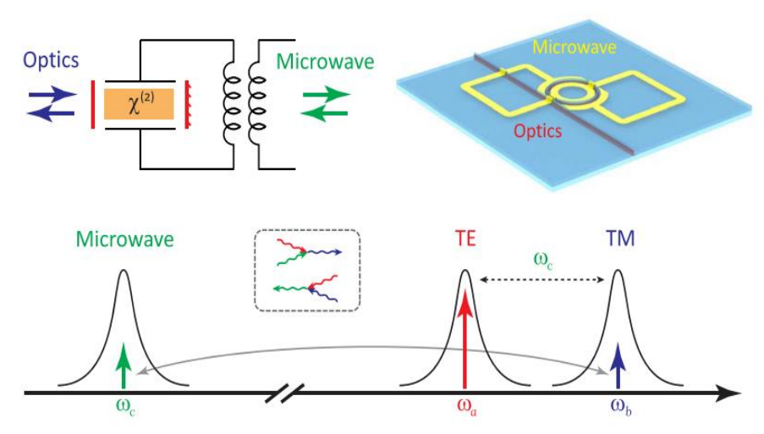


Common Approaches of EO Quantum Transducers

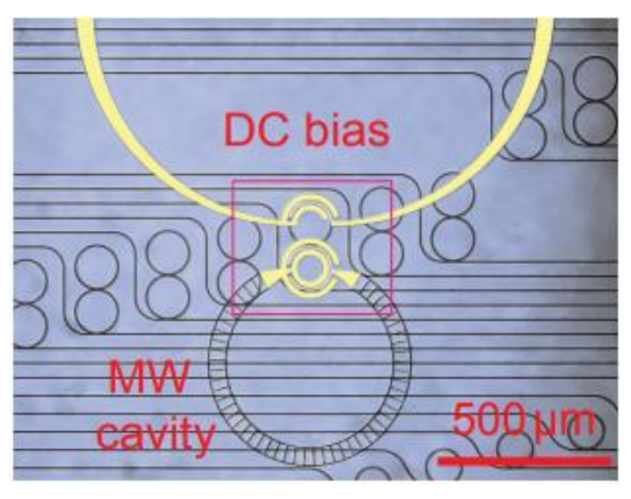
WGM resonator (LN based) [1]



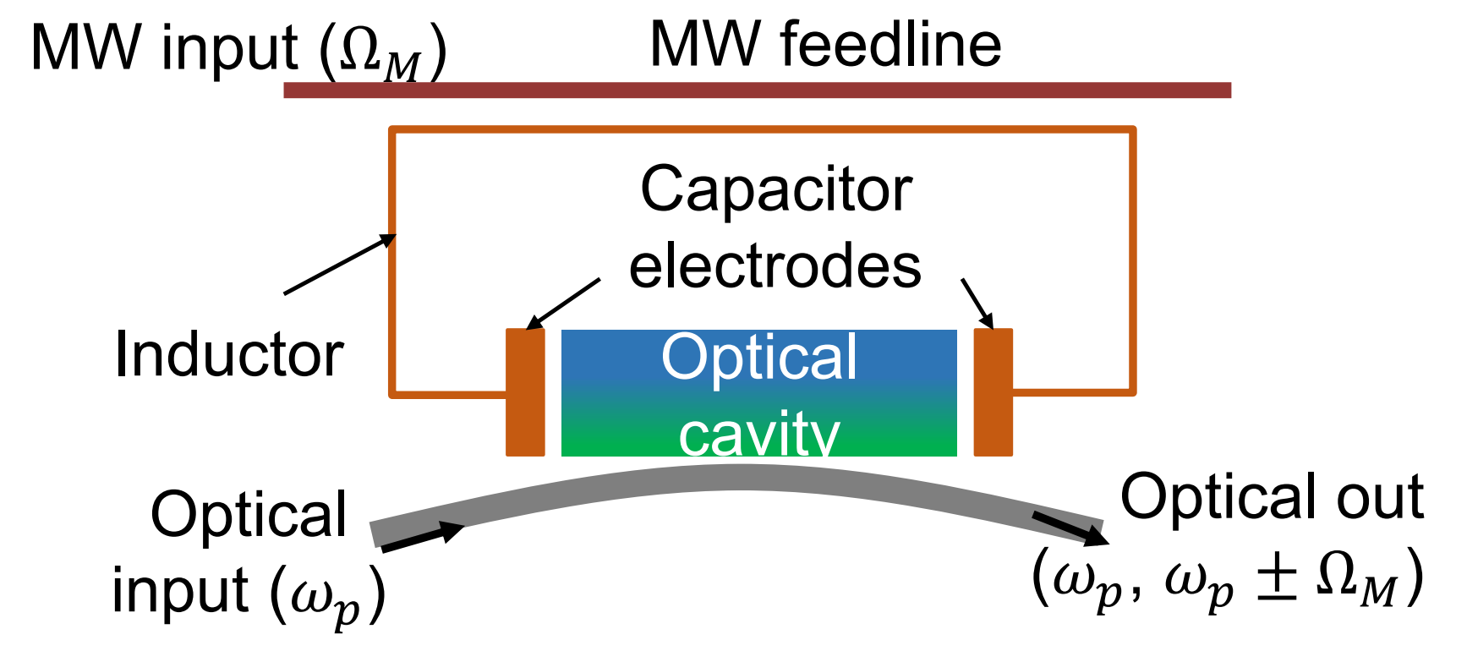
Hybrid-mode Resonator (AlN based)[2]



Coupled Resonator (LN[3] or AlN[4] based)



Electro-Optic Transduction – Theory and Equations



Microwave annihilation➔ $\omega_{s+} = \omega_p + \Omega_M$
Microwave generation➔ $\omega_{s-} = \omega_p - \Omega_M$

Single Photon Conversion rate

$$g = \frac{r\epsilon_p\omega_l}{V_p}\sqrt{\frac{\hbar\Omega_M}{8\epsilon_0\epsilon_M V_M}}\int_V \psi_M|\psi_p^2|dV$$

Cooperativity

$$C = \frac{4g^2\overline{n_p}}{\gamma_{opt}\gamma_M}$$

Mean photon number

$$\overline{n_p} = \frac{4\gamma_{opt}^{ext}}{\gamma_{opt}^2}\frac{P_{in,opt}}{\hbar\omega_p^2}$$

Internal, extraction and Net Conversion Efficiency

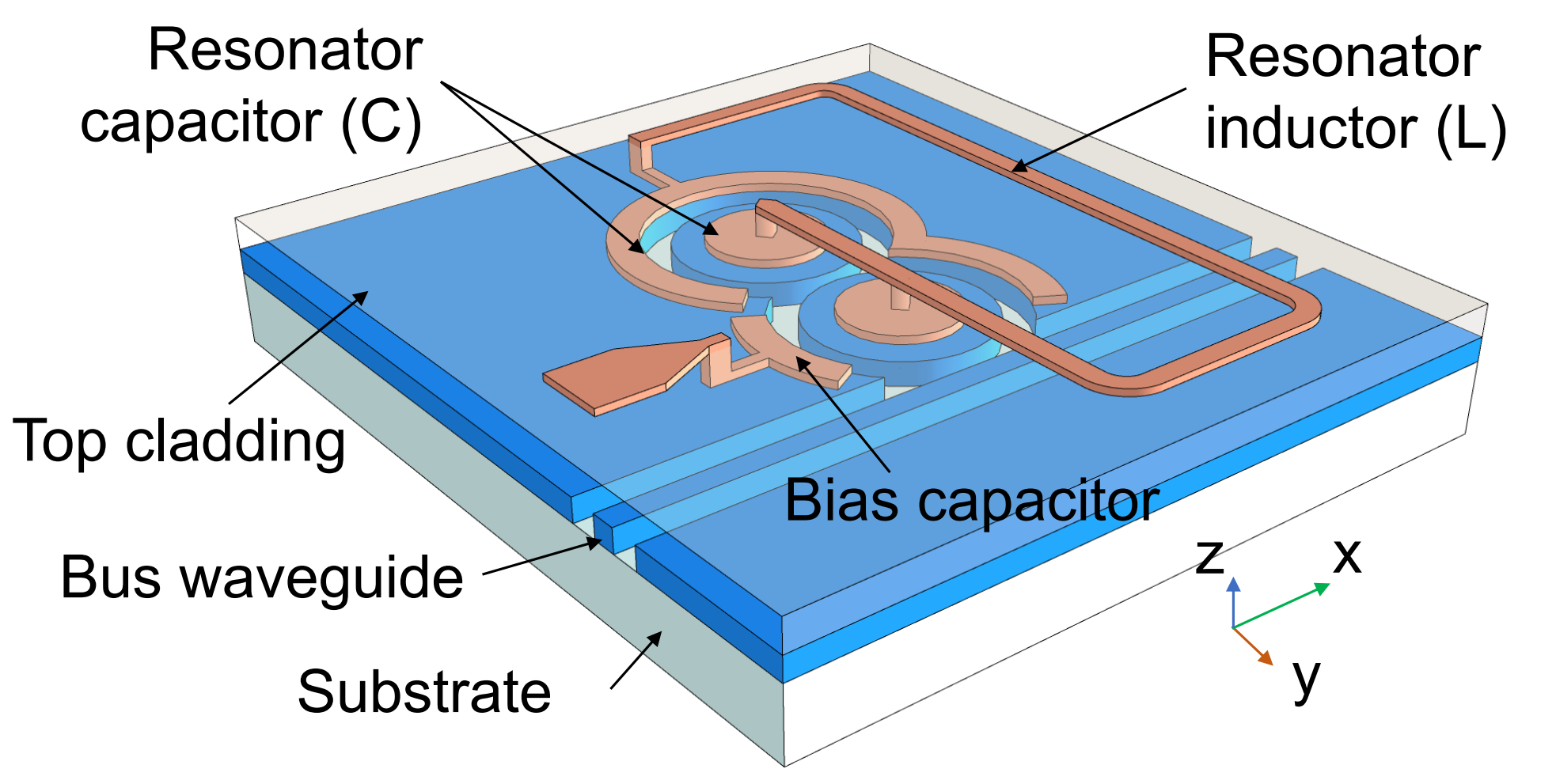
$$\eta_i = \frac{4C}{(1+C)^2}$$

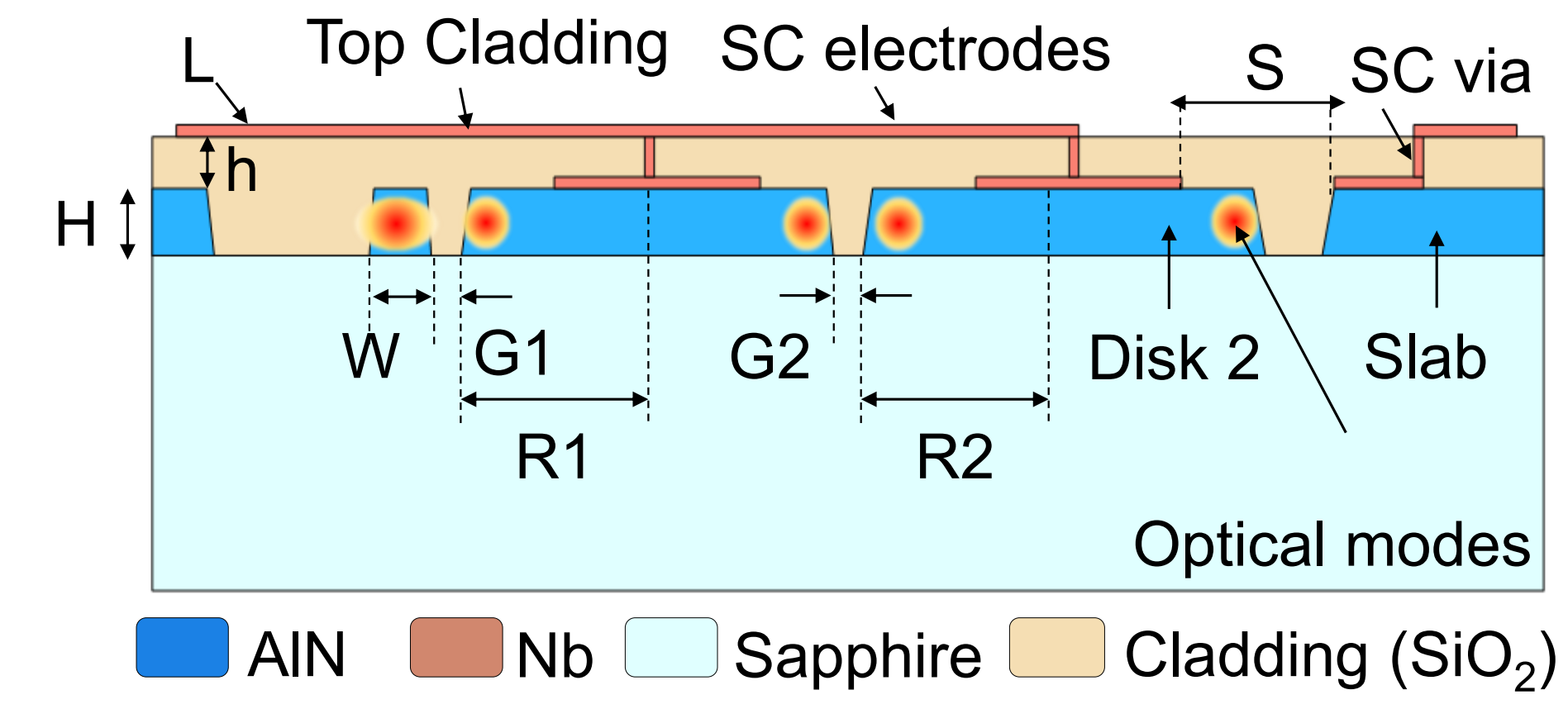
$$\eta_e = \frac{\gamma_{opt}^{ex}\gamma_M^{ex}}{\gamma_{opt}\gamma_M} = \frac{Q_{opt}Q_M}{Q_{opt}^{ext}Q_M^{ext}}$$

$$\eta = \eta_i\eta_e$$

r	Nonlinear EO coefficient
ω_p, Ω_M	Optical pump and microwave frequencies
ψ_p, ψ_M	Normalized field distribution at ω_p and Ω_M
V_p, V_M	Mode volume at ω_p and Ω_M
ϵ_l, ϵ_M	Dielectric partitivity of EO material at ω_p and Ω_M
$\gamma_{opt}^{ext}, \gamma_M^{ext}$	Extrinsic loss rate at ω_p and Ω_M
γ_{opt}, γ_M	Net loss rate at ω_p and Ω_M
Q_{opt}^{ext}, Q_M^{ext}	Extrinsic quality rate at ω_pv and Ω_M
Q_{opt}, Q_M	Loaded quality factor at ω_p and Ω_M

Proposed EO Transducer using coupled Micro-disk resonators



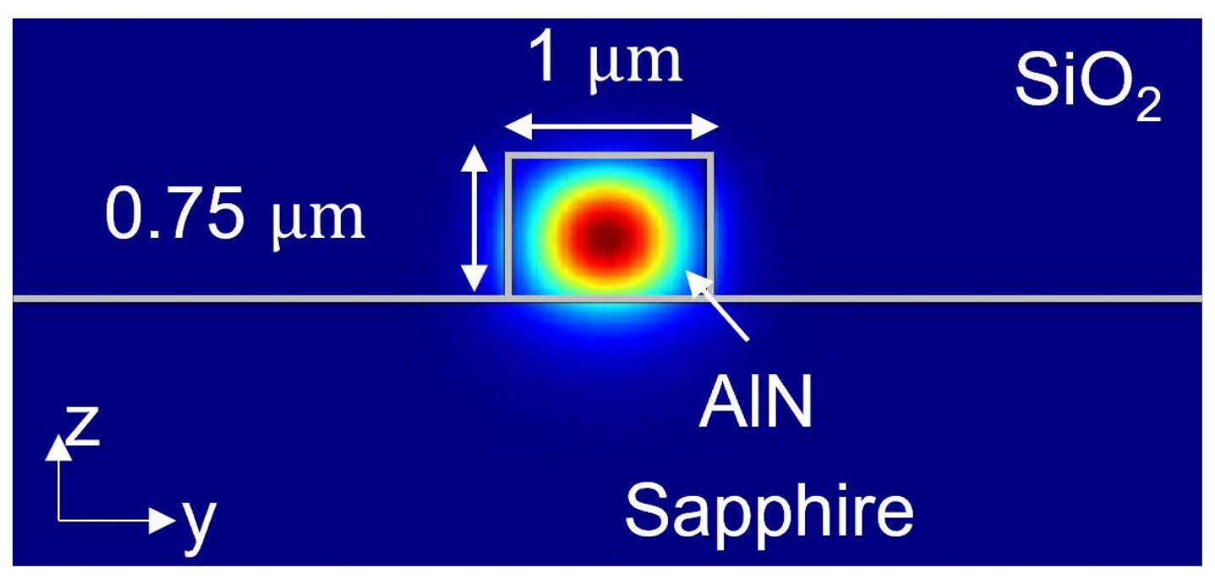


Advantages over Conventional Approaches

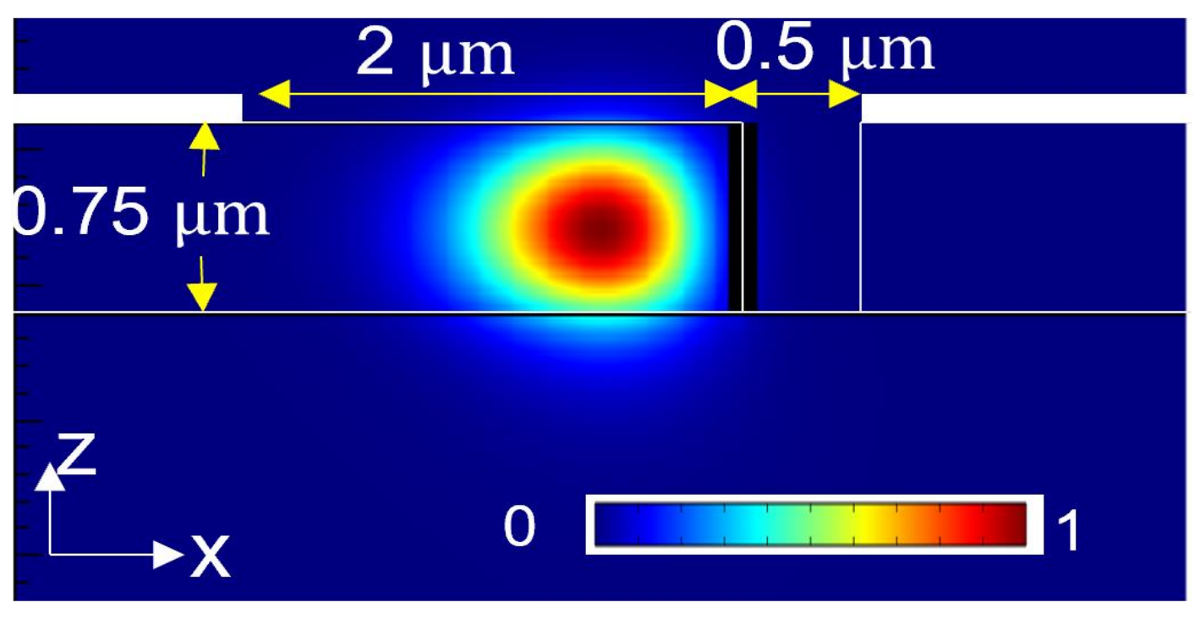
- ❑ Microwave electrodes are more closer to the cavity
  - Large optical-microwave mode overlap
  - improves conversion rate
- ❑ Autler-Townes resonance splitting (ATS)
  - High Q split resonances
  - Optical free spectral range ≈ the microwave frequency
- ❑ Improved sideband suppression
  - No sidebands present at the down converted frequency
- ❑ Low optical insertion loss
- ❑ Smaller footprint

Device Design and Simulations

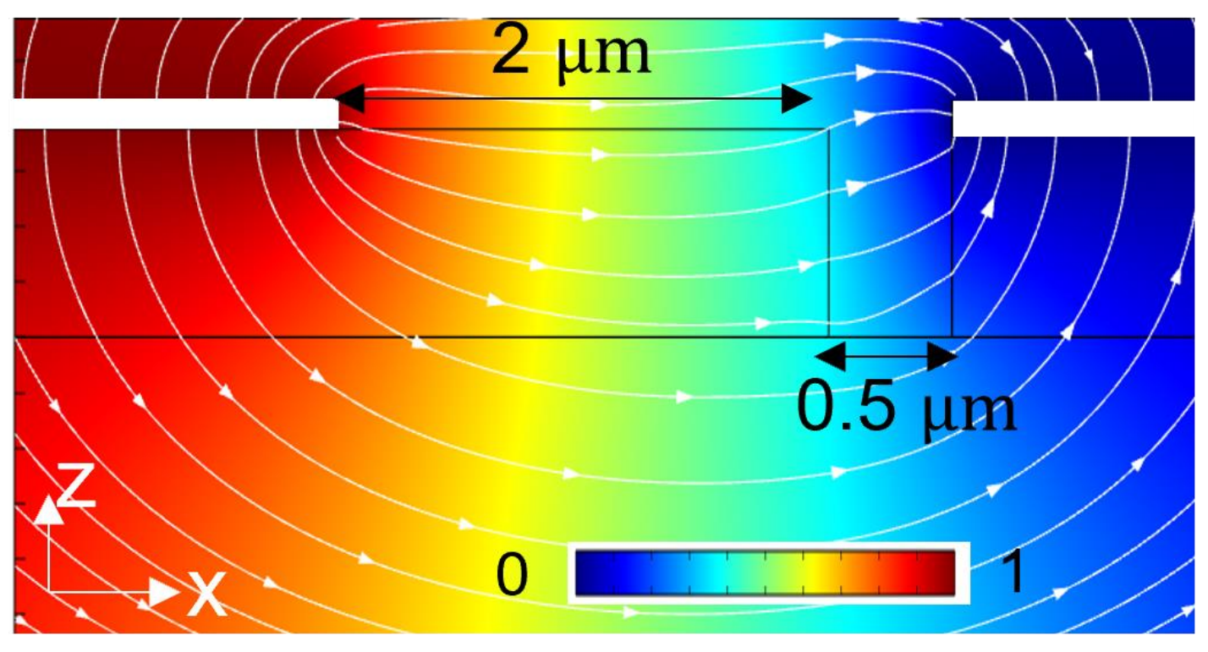
Modes and Transmission Characteristics



(a) TE mode profile

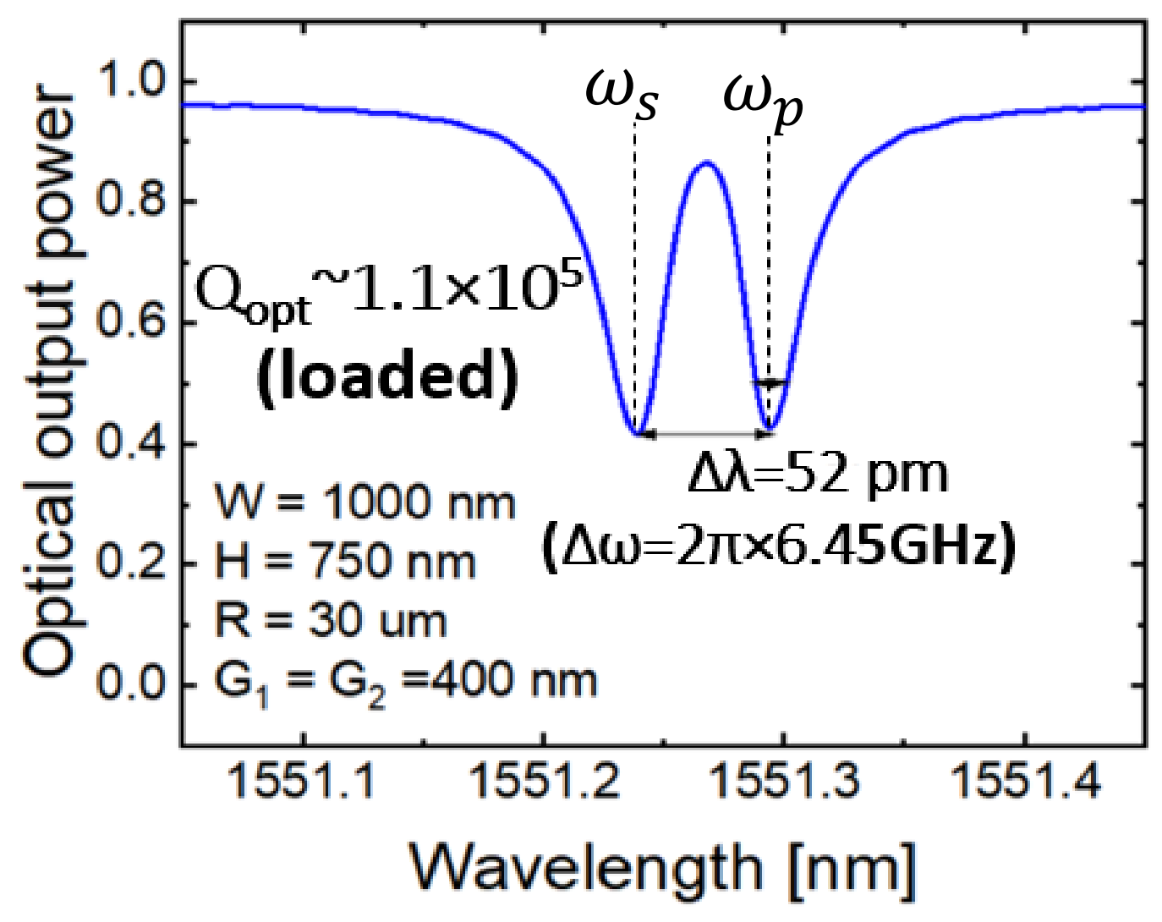


(b) WGM profile



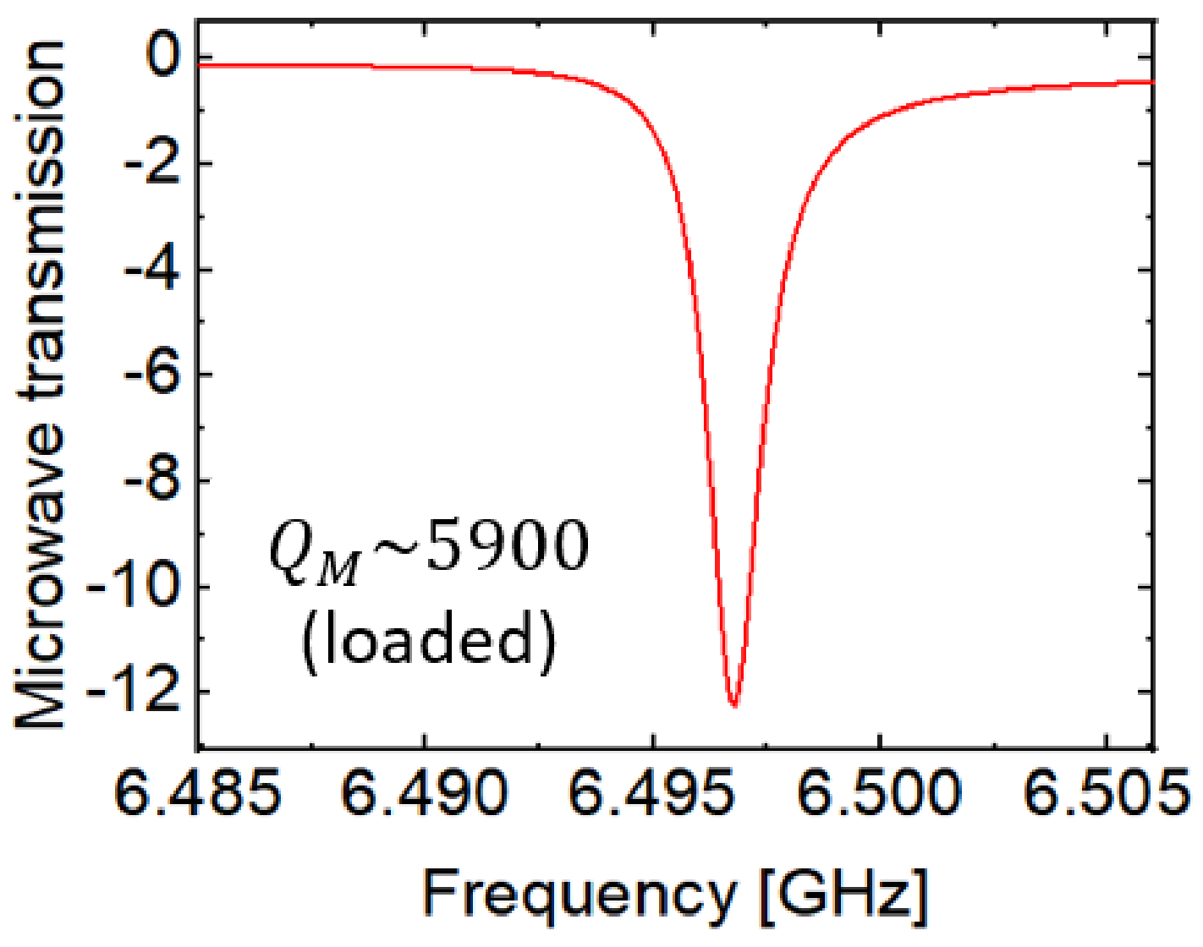
(c) Microwave Electric potential

- (a) and (b) are calculated using Ansys Lumerical
- (c) is calculated in COMSOL Multiphysics
- (b) and (c) are calculated at the boundary of the disk.
- WGM: Whispering Gallery Mode



(d) Optical ATS Resonances

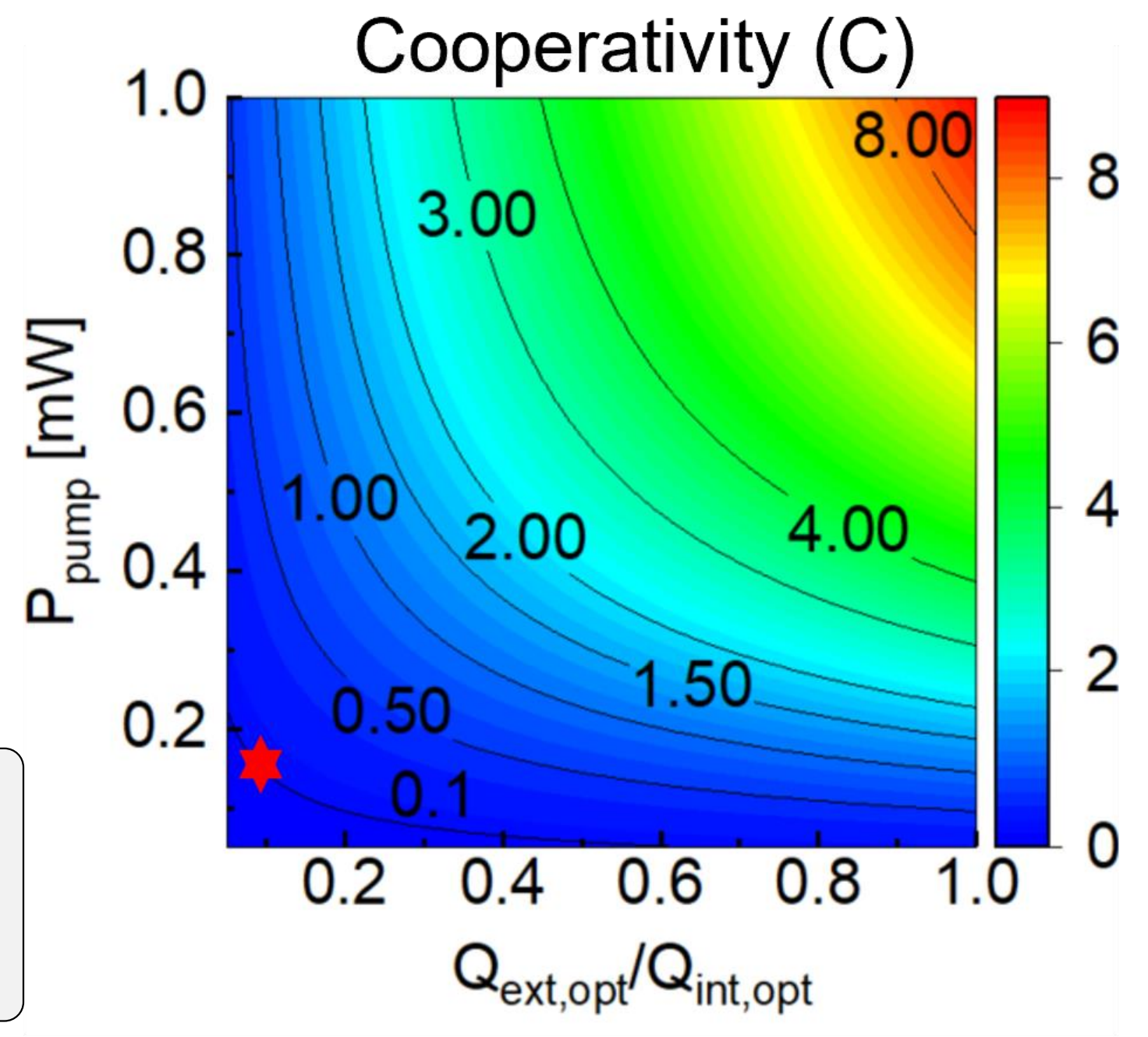
Calculated conversion rate
$g/2\pi = 1.17$ kHz



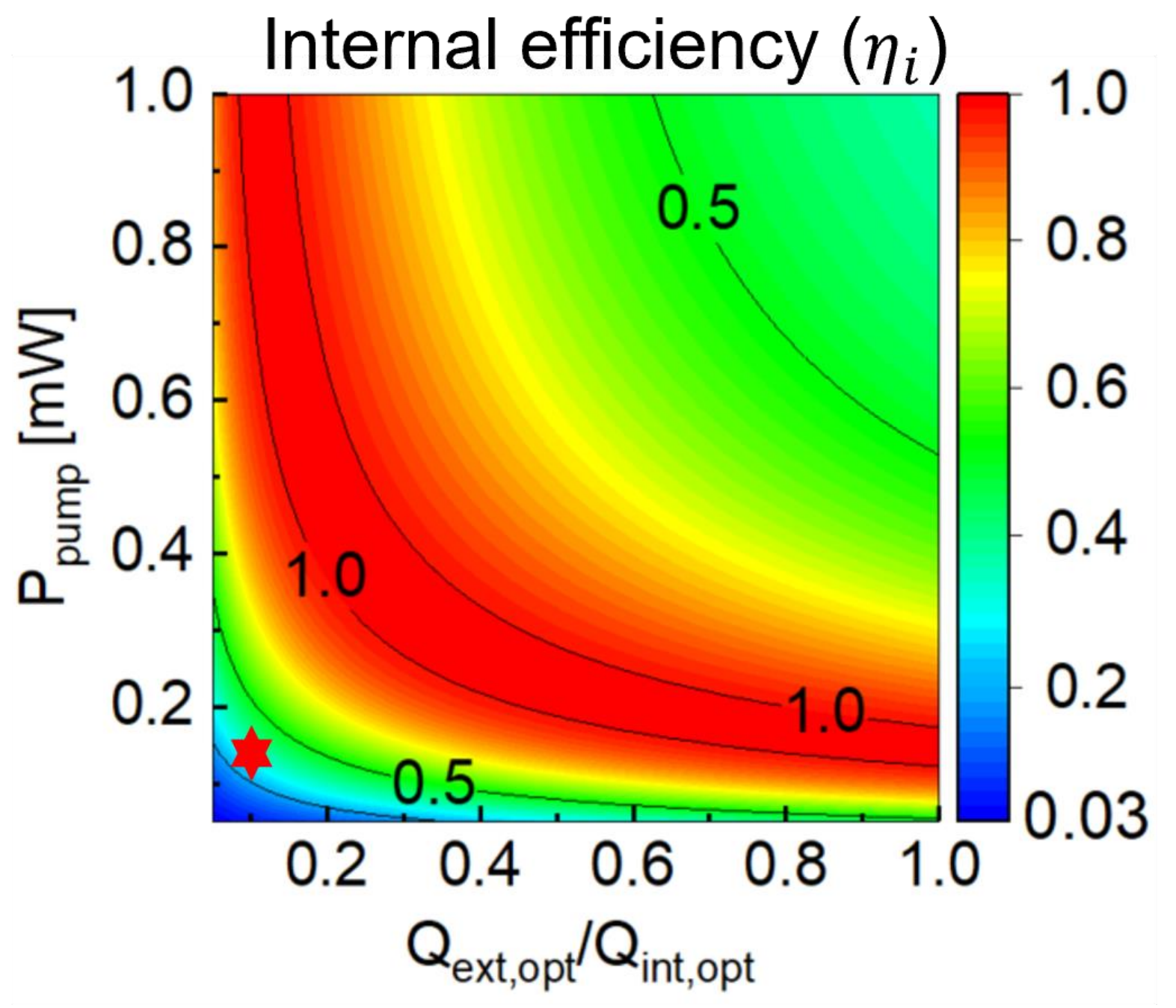
(e) Microwave Resonance

- (d) The calculated optical Q factor is limited by the FDTD simulation parameters
- (e) The Nb superconducting microwave resonator is simulated in SONNET assuming the microwave feed line 5μm above the resonator

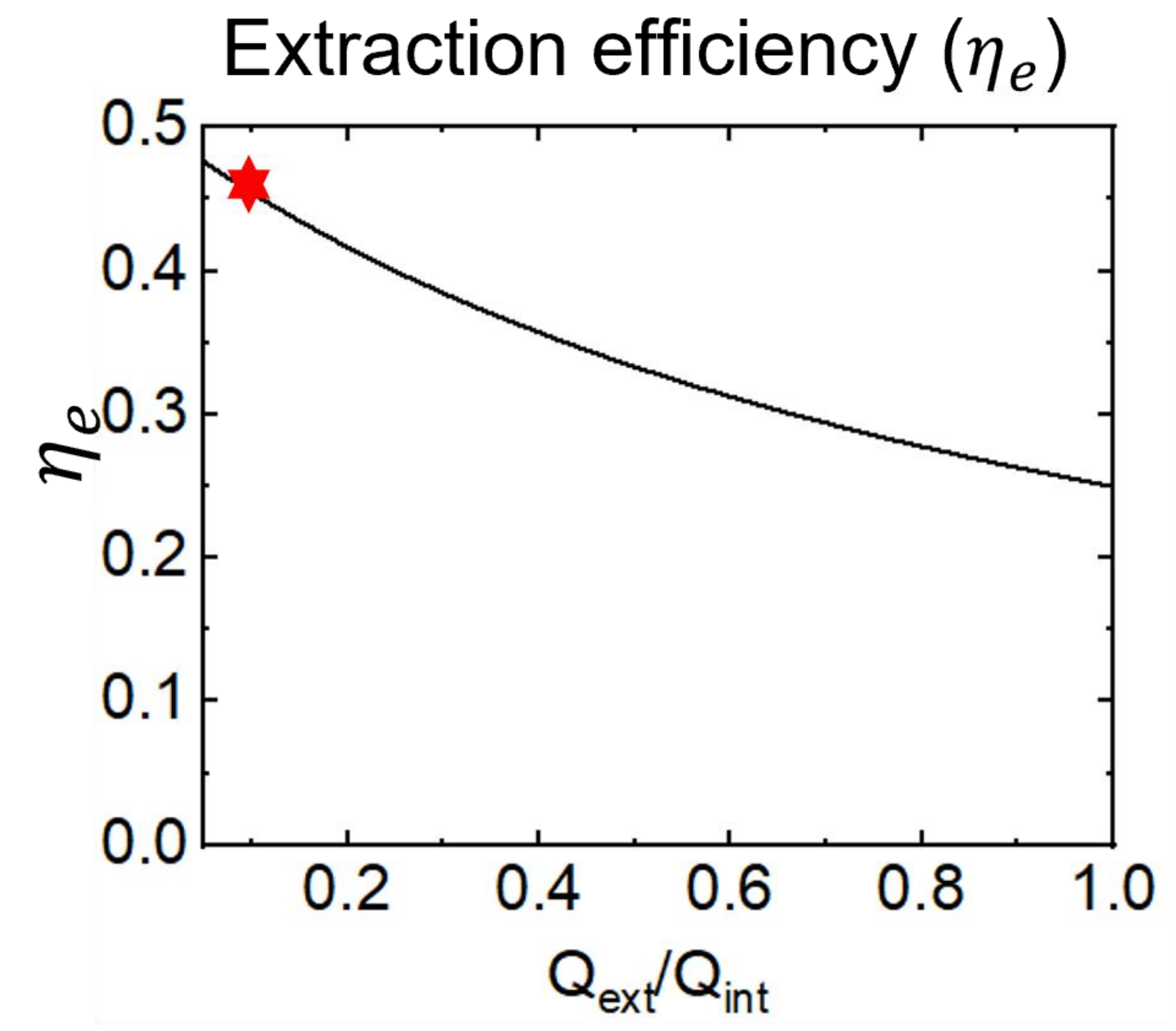
Efficiency Calculations



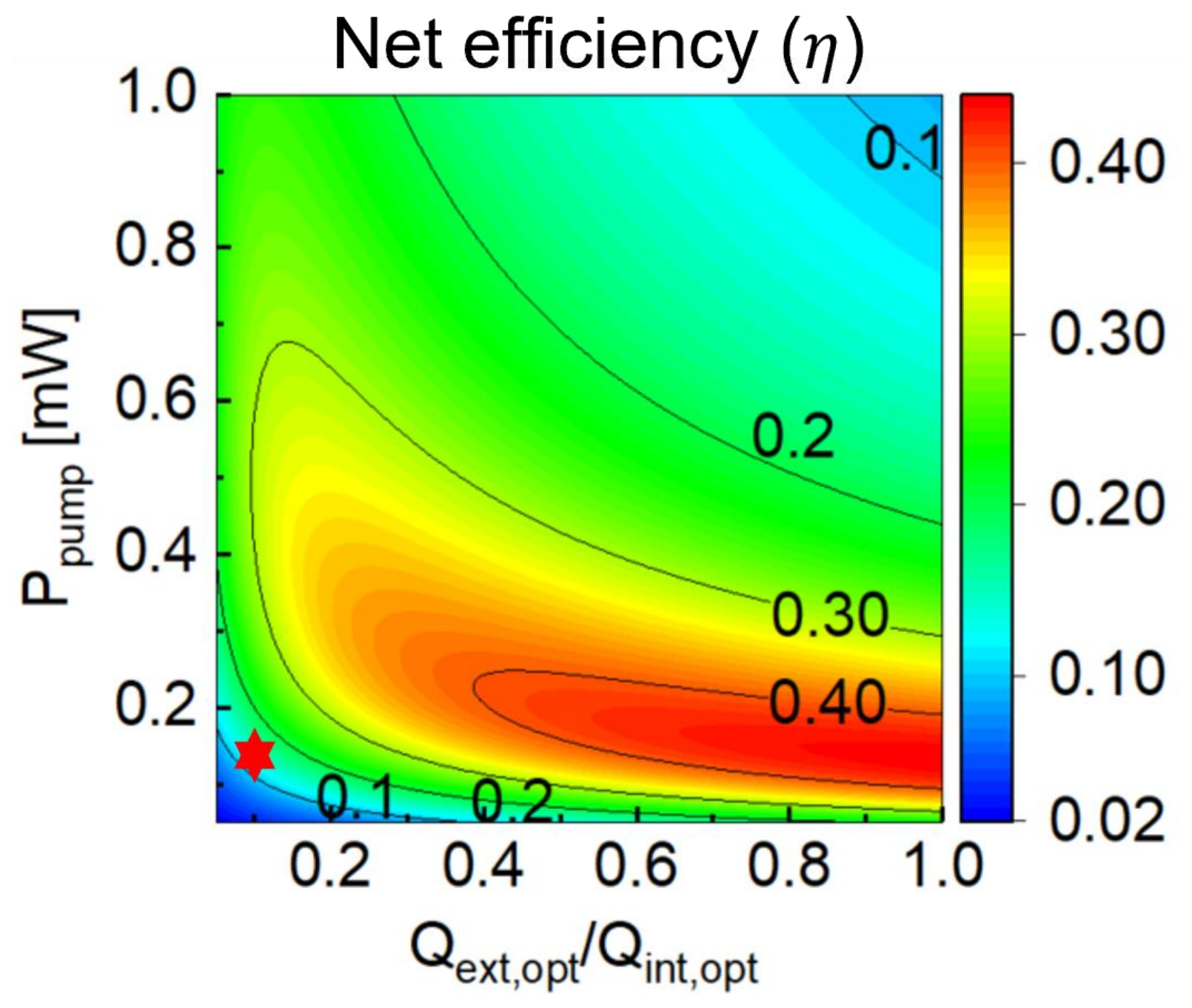
Cooperativity (C)



Internal efficiency (η_i)



Extraction efficiency (η_e)



Net efficiency (η)

Assumptions: $Q_{opt}^{ext} \le Q_{opt}^{int} = 10^7$ (Overcoupled), $Q_M^{ext} = Q_M^{opt} = 2 \times 10^4$ (Critically coupled)
* represents $Q_{opt}^{ext}/Q_{opt}^{int} = 0.1$, $Q_{opt} = 10^5$, $P_{pump} = 150$ μW

Summary and Discussions

Performance Comparison (*preliminary simulation results)

References	$g/2\pi$ (Hz)	Q_{opt}	P_{pump} (mW)	η_i (%)	η (%)	Footprint (μm²)
AlN single ring [2]	330	2×10^4	6.3	25	2	500 × 500
AlN double ring [3]	40	1.5×10^6	2.9	0.12	2.4×10^{-3}	250 × 500
AlN double disk [this work*]	1170	9×10^5	0.15	27	12.5	120 × 60

Outlook

- ➢ Optical simulation studies at cryogenic temperature
- ➢ Tunability of free spectral range
- ➢ Fabrication of high Q disk resonators (internal Q ~ 10^7)
- ➢ Experimental validation of transduction efficiency
- ➢ Loss estimation

Acknowledgement

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