Dark Matter Search on Chips

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arXiv: to appear soon

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

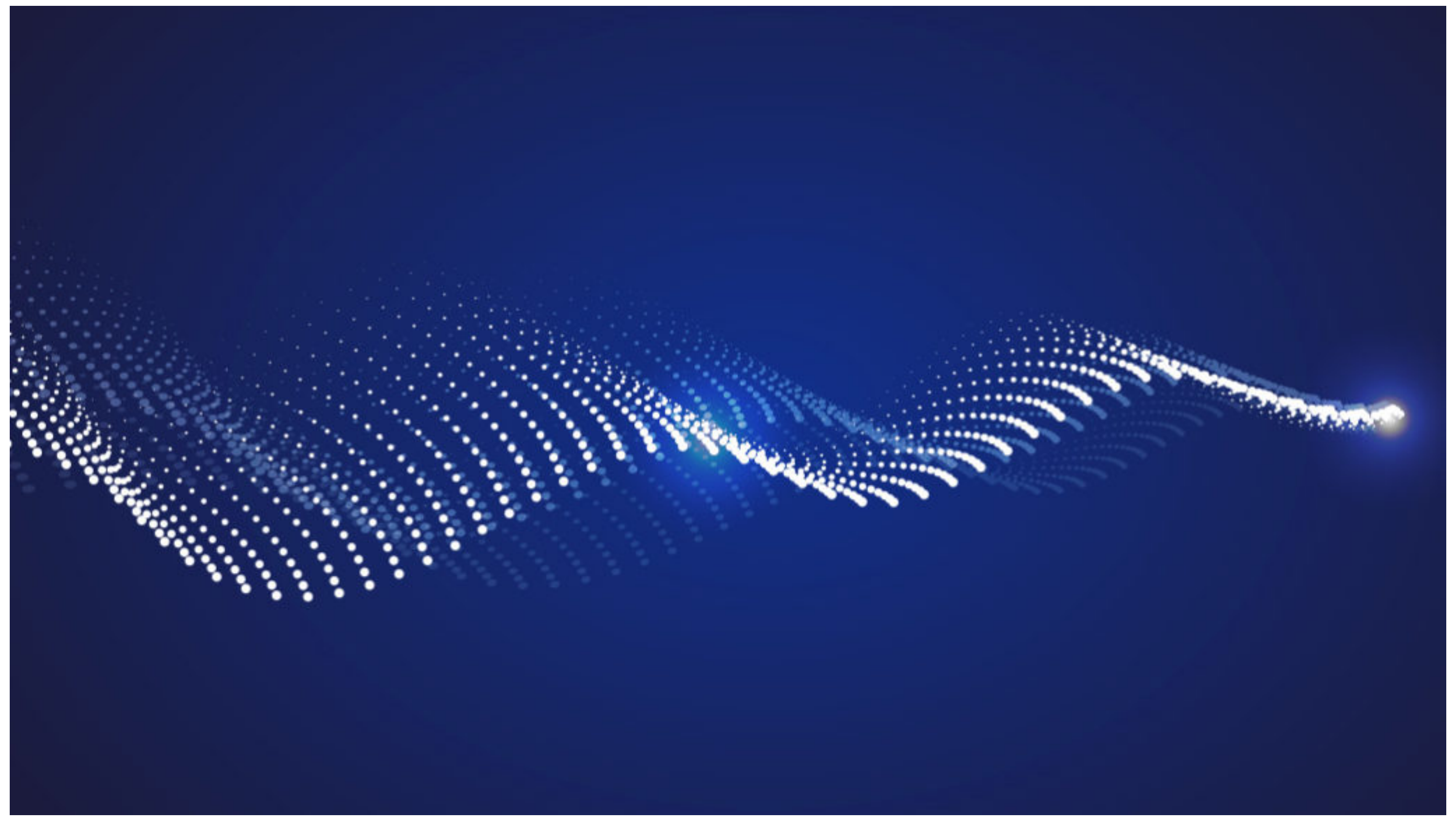
Fermilab

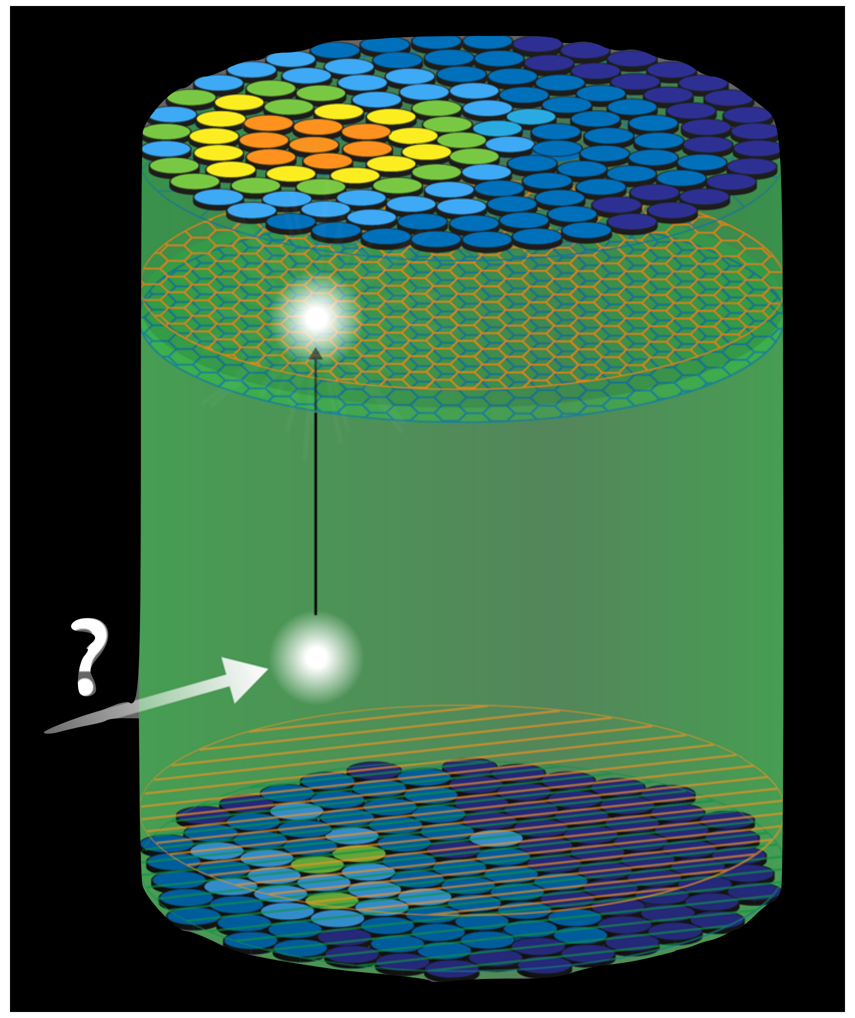
Dark matter candidates

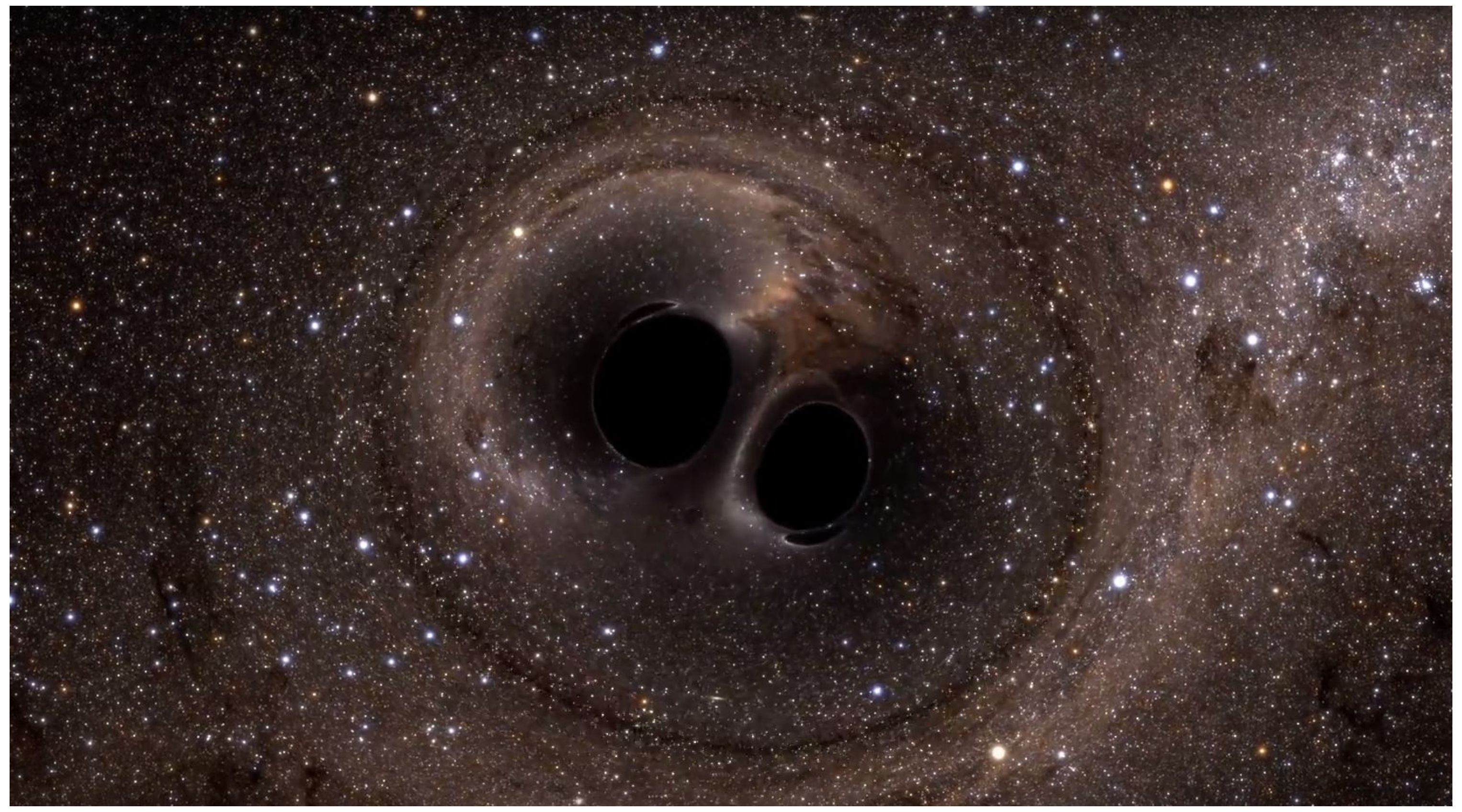
Ultralight dark matter (e.g. axion, dark photon)	Weakly interacting massive particles (WIMP)	Ultraheavy dark matter (e.g. black holes)
10^{-22} eV — 1 eV	10^{9} eV — 10^{13} eV	10^{50} eV — 10^{53} eV

Wavelength fits in a galaxy ⟼

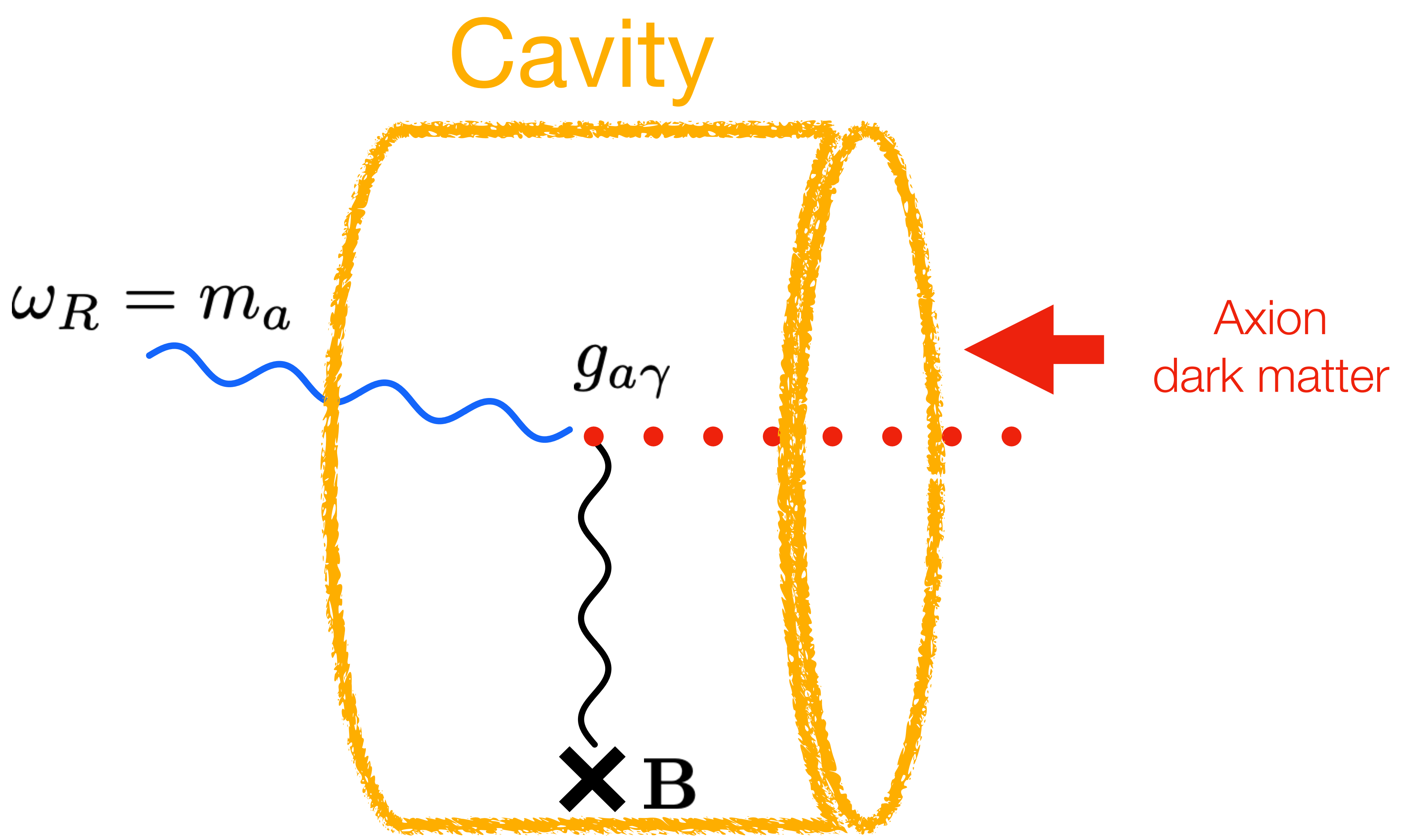
Planck mass







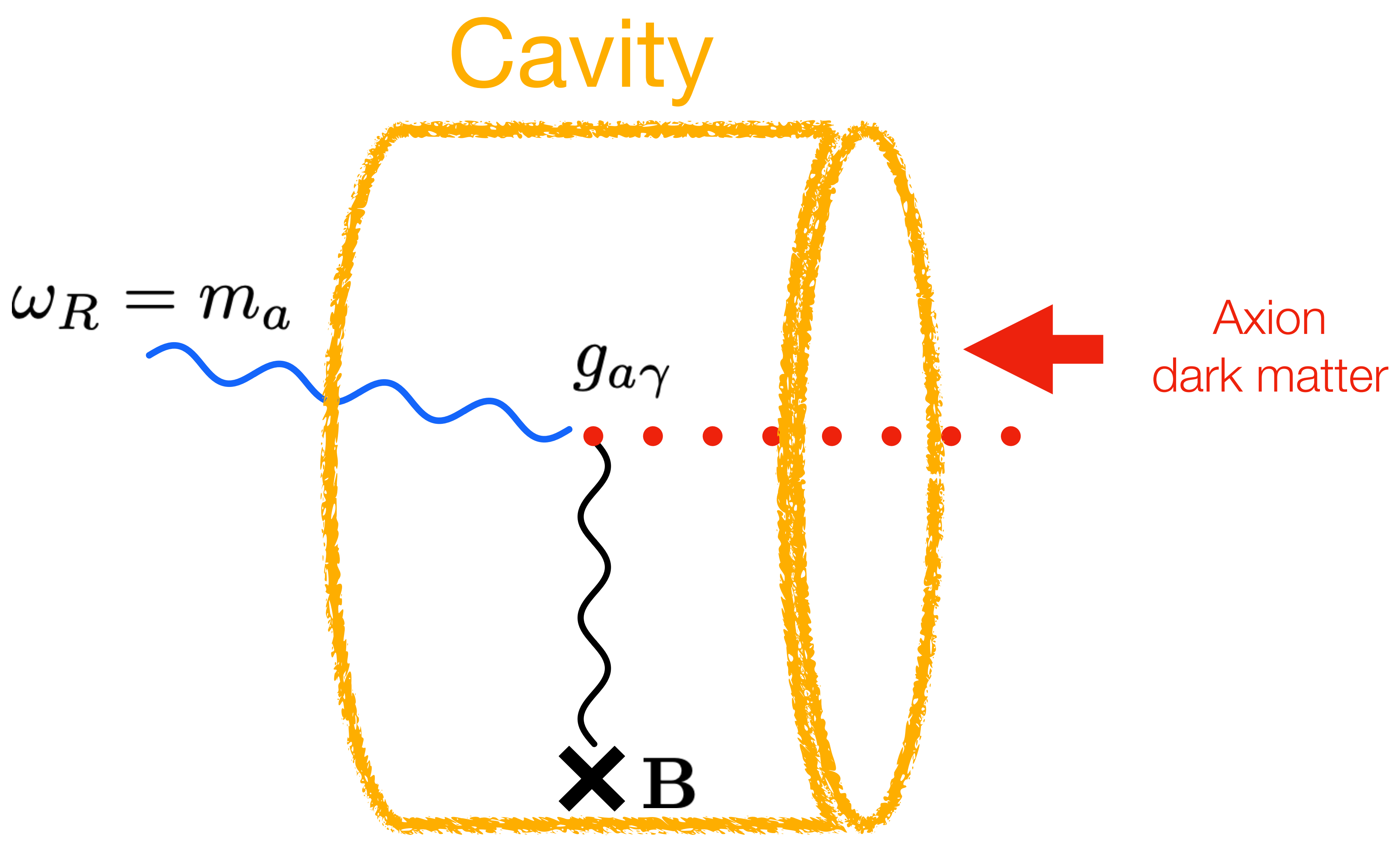
Dark Matter Detection using Cavities



Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

Dark photon $\frac{1}{2} \chi F'_{\mu\nu} F_{\mu\nu}$

Dark Matter Detection using Cavities



Usually target μeV axion/DP

Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

Dark photon $\frac{1}{2} \chi F'_{\mu\nu} F_{\mu\nu}$

$$P_{\rm sig} = P_{\rm D} Q C_i^2 |\eta|^2$$

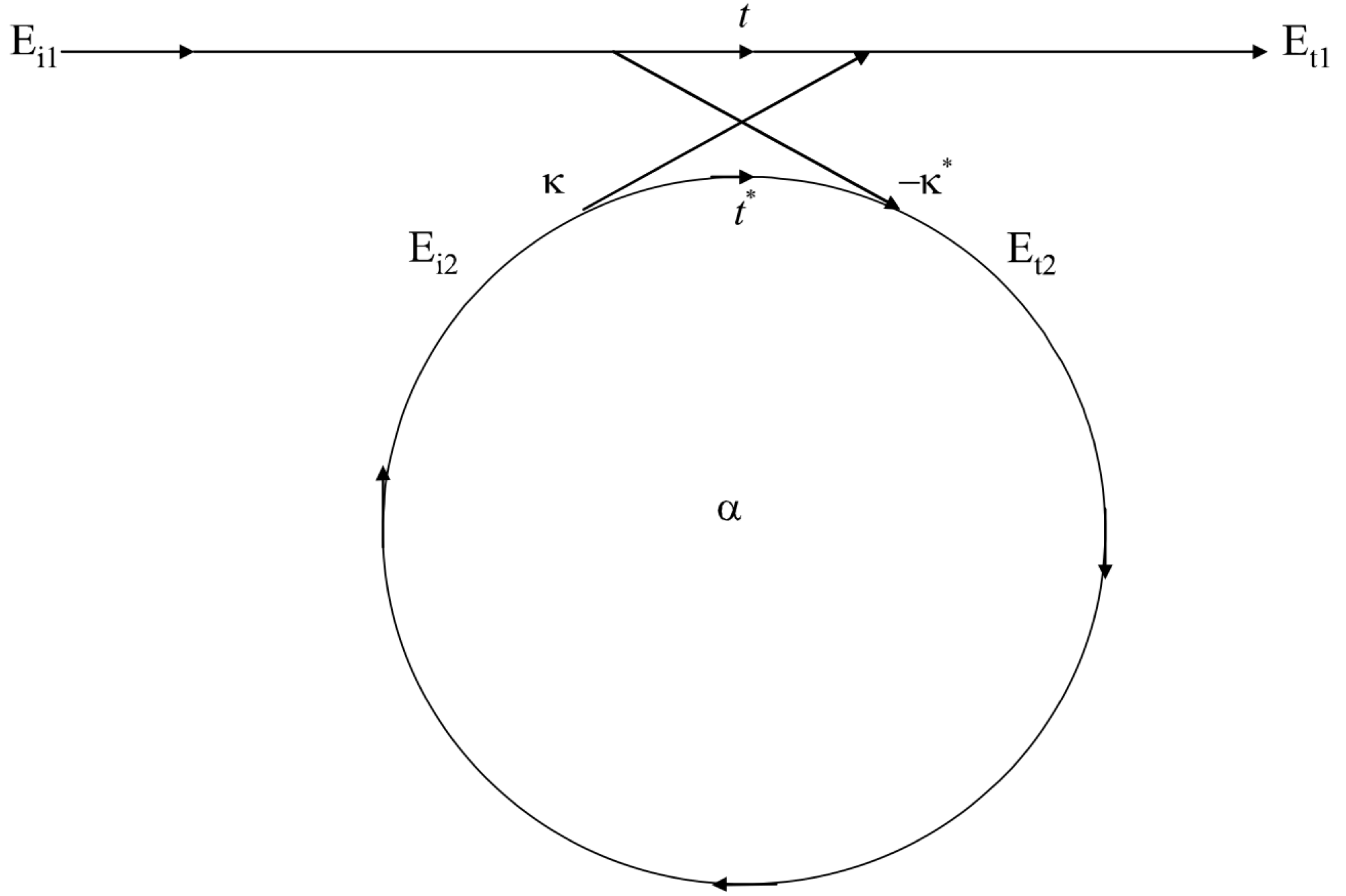
$|\eta|^2$: momentum conservation

Q : quality factor

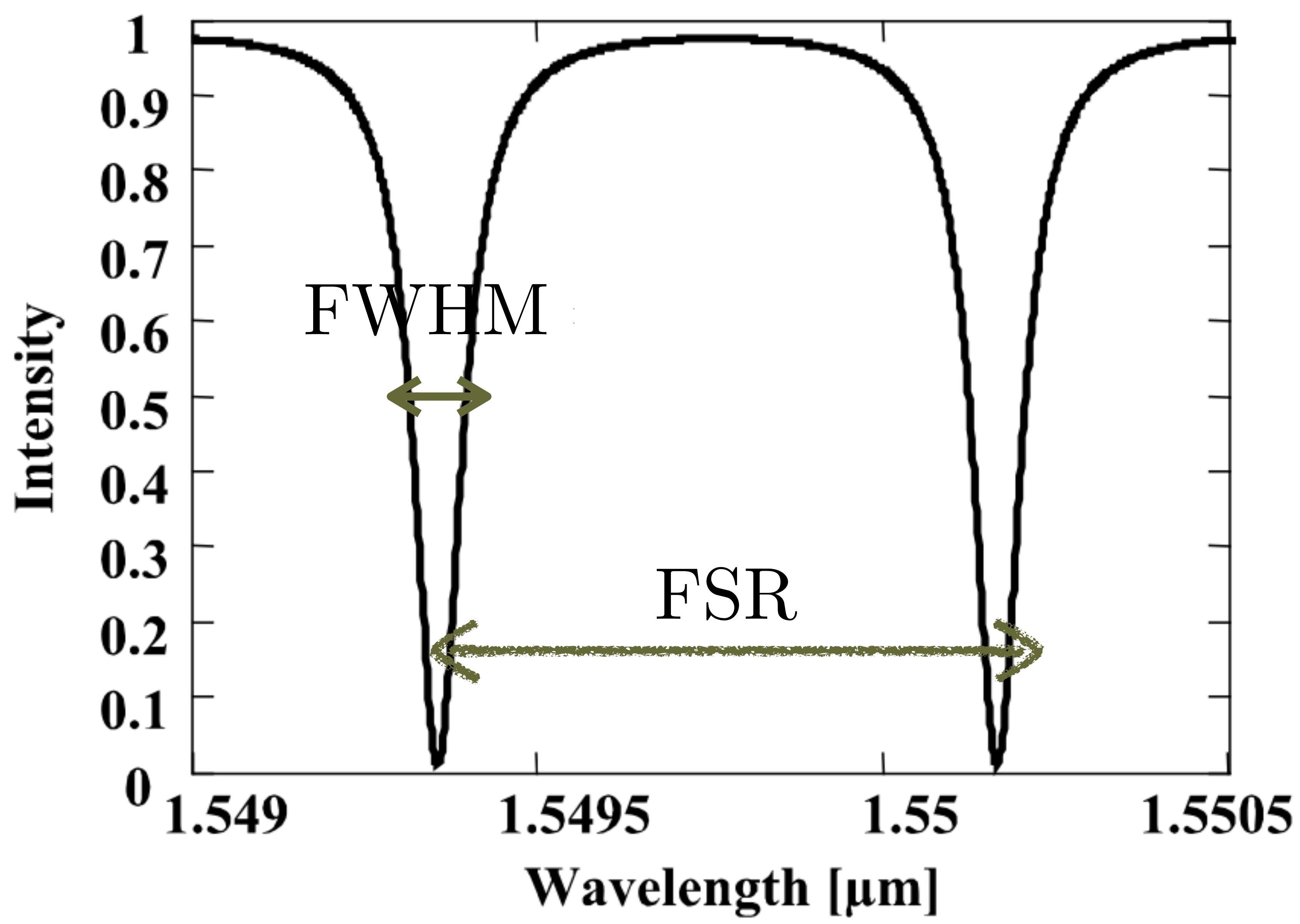
$P_D \propto \rho_D V$

$$C_i^2 = \begin{cases} g_{a\gamma}^2 \mathbf{B}^2 \omega_R^{-2} & i = a \\ \chi^2/3 & i = \mathbf{A}' \end{cases}$$

Ring Resonator: eV axion/DP



$$L \sim 100\mu\text{m} \qquad \lambda \sim \mu\text{m} \sim {m_a}^{-1}$$



$$Finesse = \frac{\text{FSR}}{\text{FWHM}}$$

$$Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}} L}{\lambda} finesse$$

Ring Resonator: eV axion/DP

Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

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New Challenges:

- Phase matching
- Large Q
- Large V

$$P_{\text{sig}} = P_{\text{D}} Q C_i^2 |\eta|^2$$

$|\eta|^2$: momentum conservation

Q : quality factor

$P_D \propto \rho_D V$

$$C_i^2 = \begin{cases} g_{a\gamma}^2 \mathbf{B}^2 \omega_R^{-2} & i = a \\ \chi^2/3 & i = \mathbf{A}' \end{cases}$$

Phase Matching

Periodic Photonic Structure: Bloch Modes

$$\mathbf{E}_{\mathbf{K}} = \mathbf{u}_{\mathbf{K}}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}} \,, \quad \mathbf{u}_{\mathbf{K}}(\mathbf{r}) = \mathbf{u}_{\mathbf{K}}(\mathbf{r}+\mathbf{R})$$

$$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r}+\mathbf{R})$$

Bloch wavevector

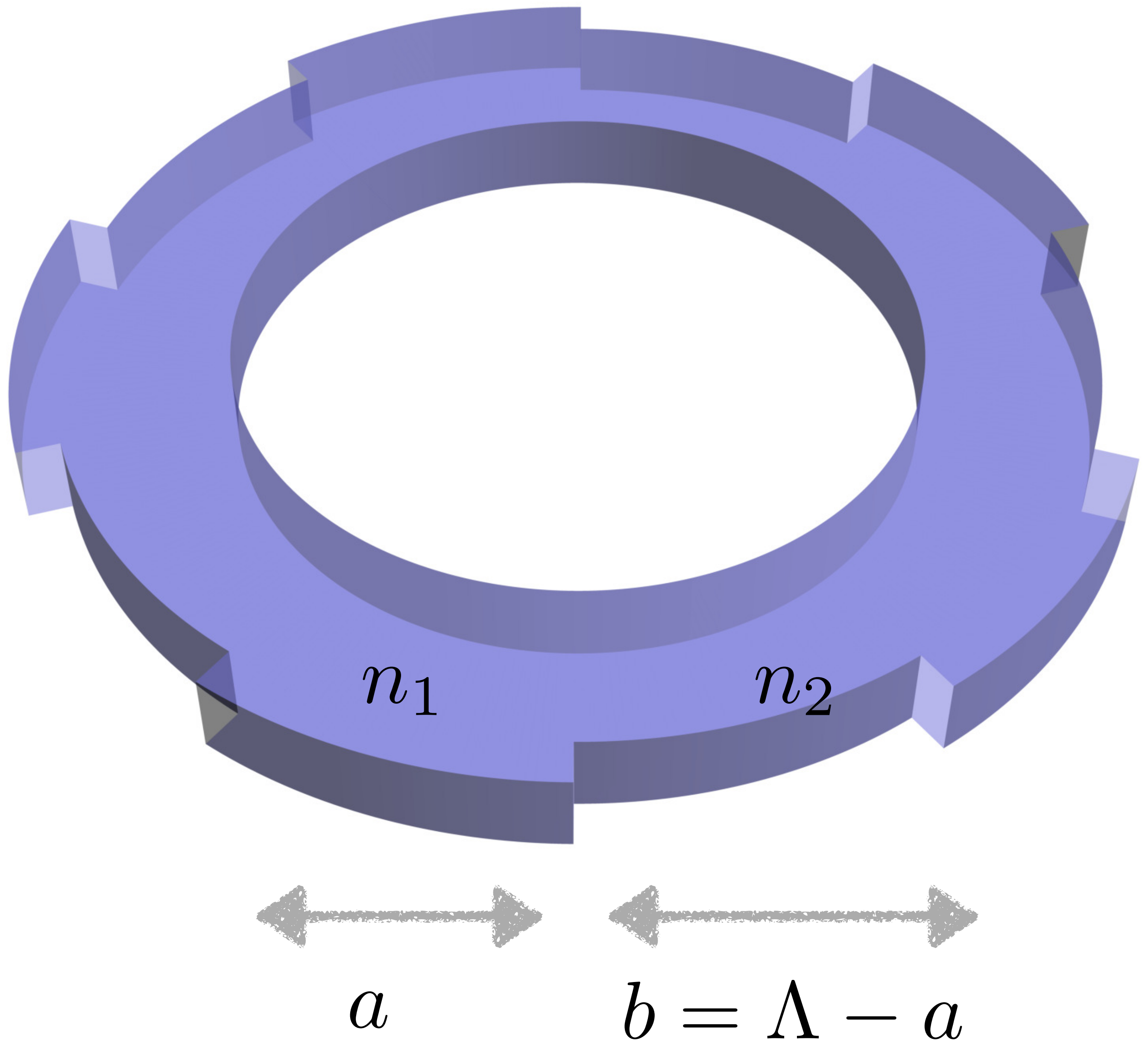
Lattice vector

$$|\eta|^2 \equiv \frac{V^{-2}\int d\mathbf{x}'d\mathbf{x}\ \mathbf{E}_1^*(\mathbf{x})\cdot\hat{\mathbf{n}}\mathbf{E}_1(\mathbf{x}')\cdot\hat{\mathbf{n}}e^{-(\mathbf{x}-\mathbf{x}')^2/\lambda_{\rm dB}^2}}{V^{-1}\int d\mathbf{x}\ \varepsilon(\mathbf{r})\,|\mathbf{E}_1(\mathbf{x})|^2}$$

$$|\eta|^2 = |\eta_u|^2 \frac{1}{N_u^2}\sum_{i,j} e^{-i\mathbf{K}\cdot(\mathbf{R}_i-\mathbf{R}_j)}$$

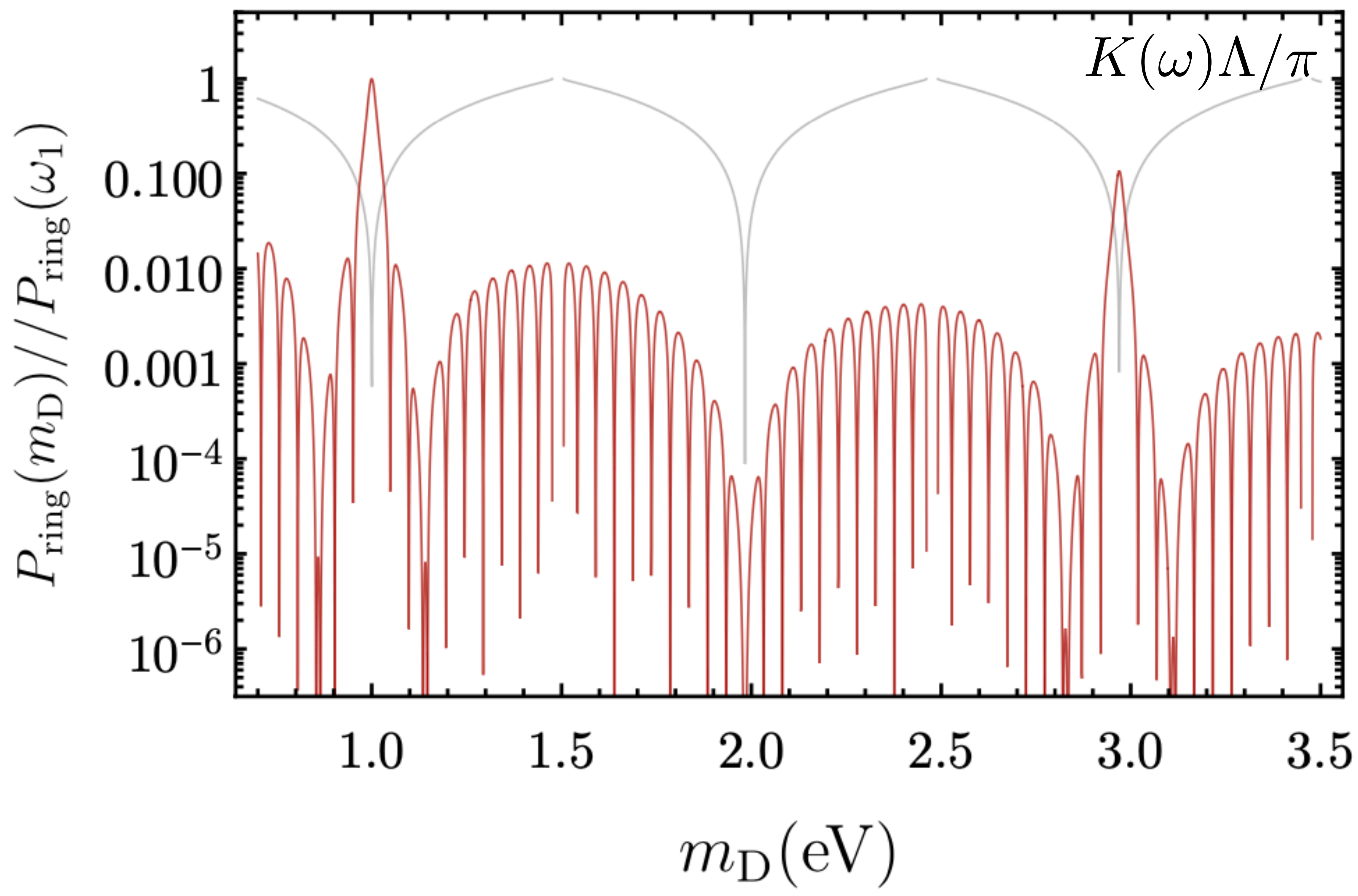
Resonator size << $\lambda_{\rm dB}$

1D Toy Model



$$\beta_{1,2} = n_{1,2}\omega$$

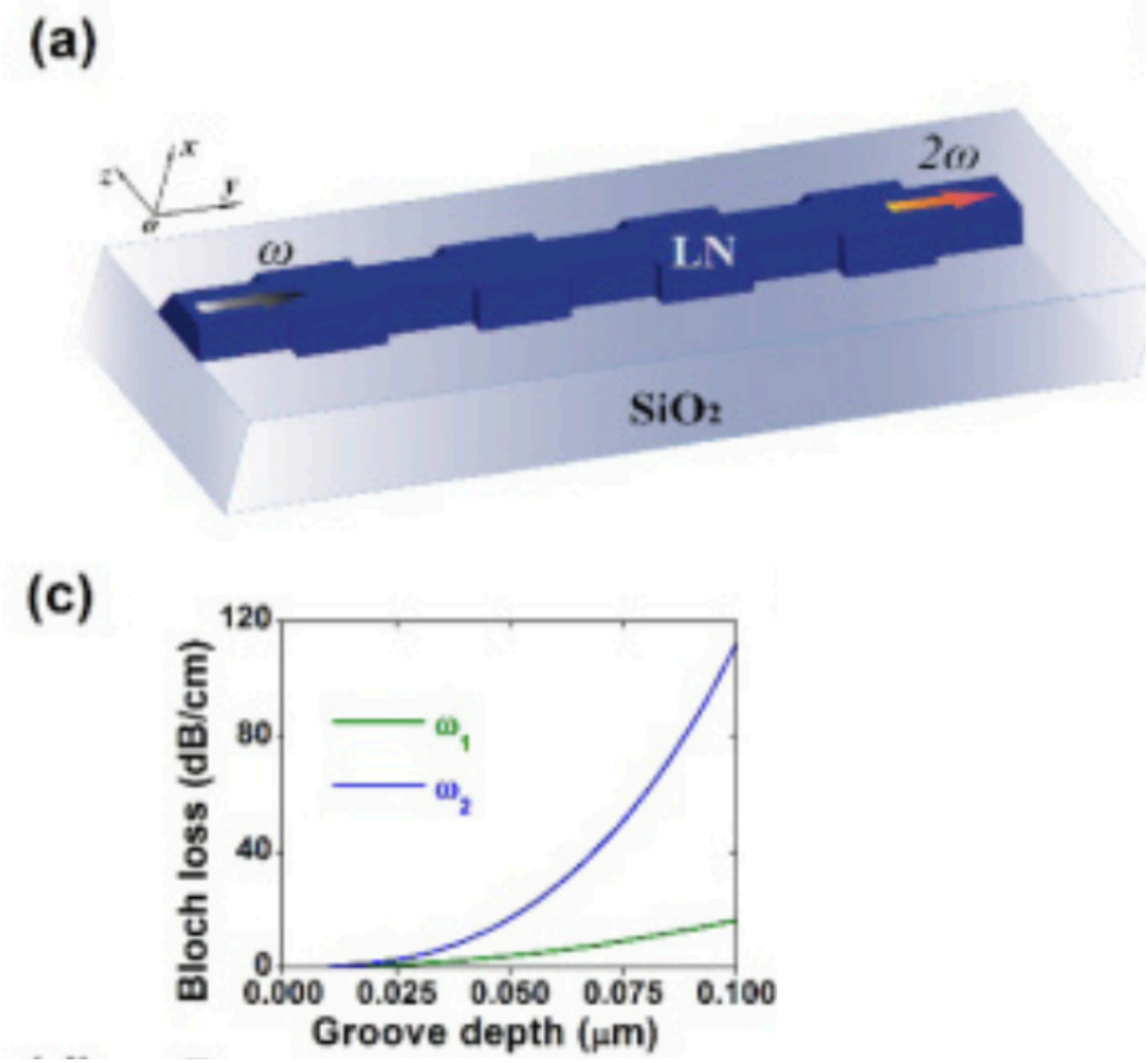
20 unit cells with finesse 5 (Q~100)

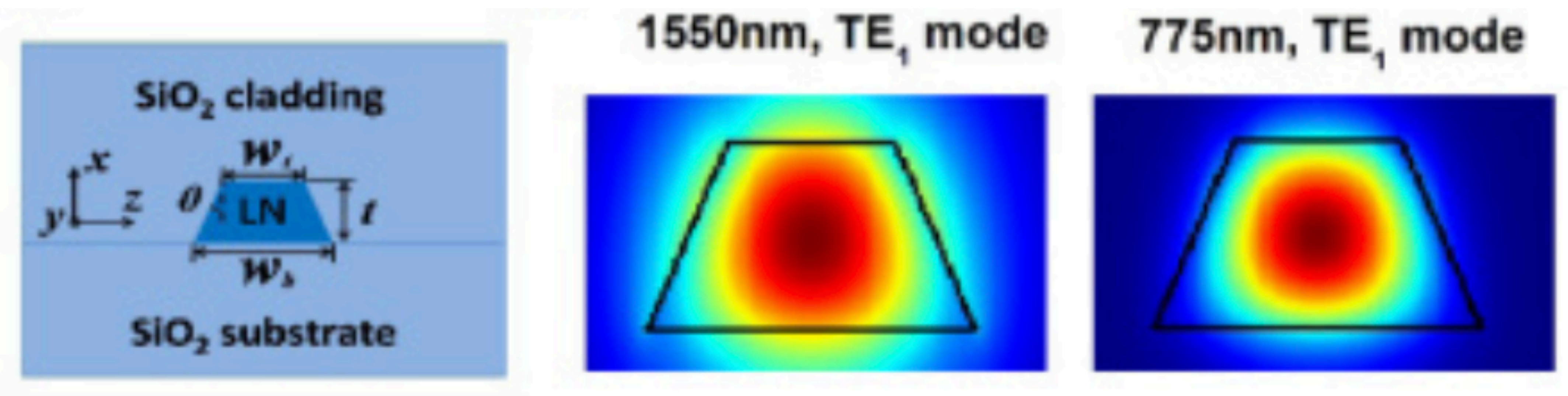


$$\eta_u \sim \frac{1}{n_2} - \frac{1}{n_1}$$

Example: Periodically Grooved LN-on-Insulator Waveguide

https://doi.org/10.1364/OE.25.006963





Q can be affected by:

- Surface/volume scattering loss
- Bending/radiation loss
- Absorption by the material

$$Q \approx \frac{\pi n_{\rm eff}}{\alpha \lambda_0} \sim 10^3 \left(\frac{180\,\frac{\rm dB}{\rm cm}}{\mathcal{L}}\right)\left(\frac{1.5\mu{\rm m}}{\lambda_0}\right)\left(\frac{n_{\rm eff}}{2}\right)$$

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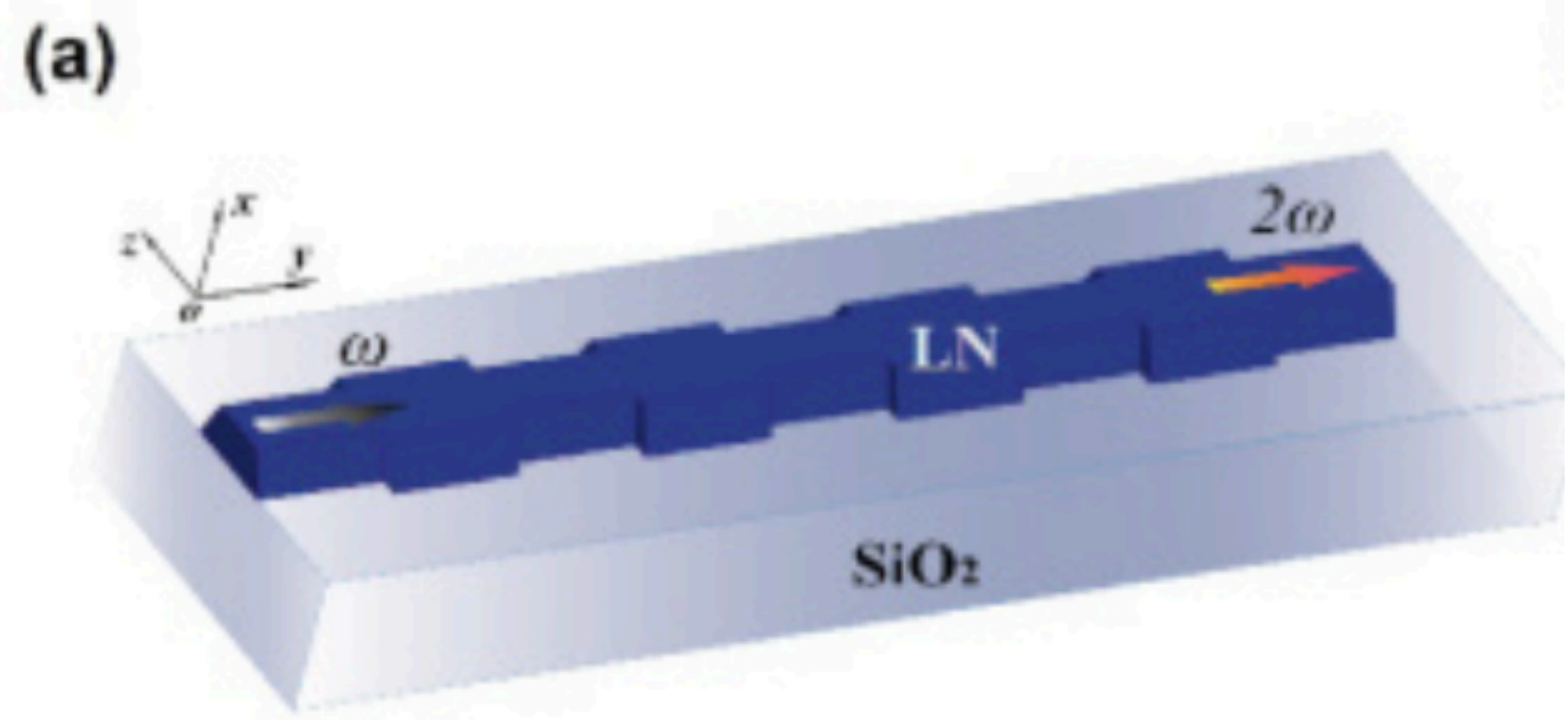

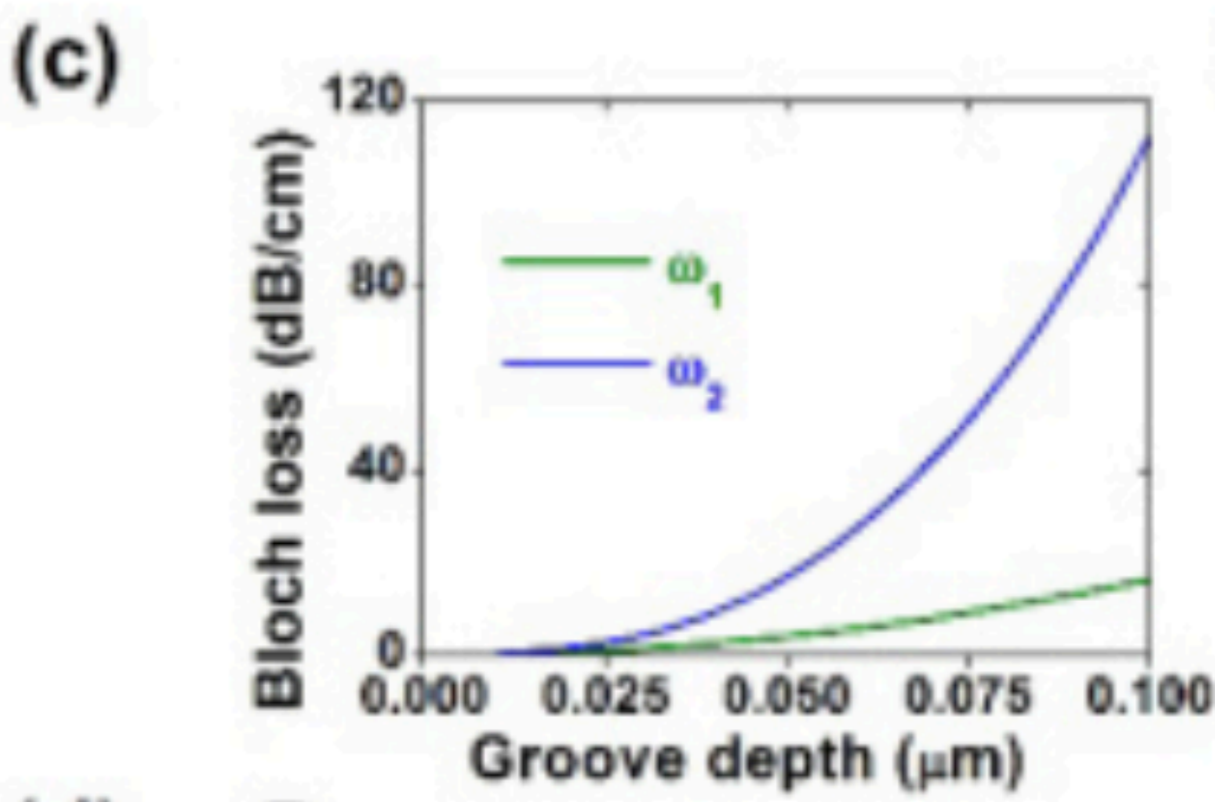

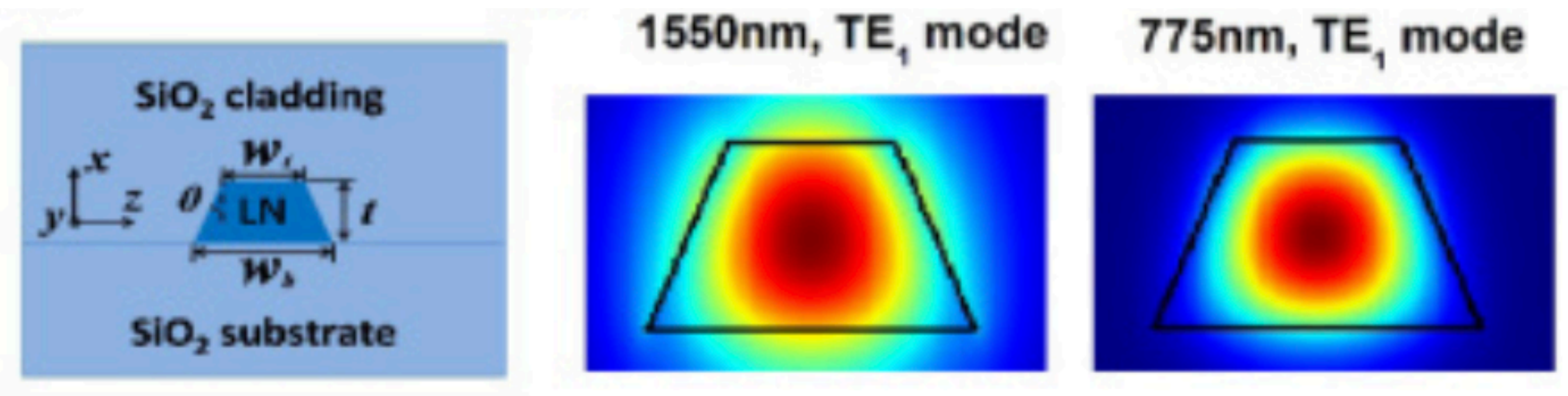

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Example: Si-on-Insulator Photonic Crystal Ring Resonator

https://doi.org/10.1364/OL.39.001282

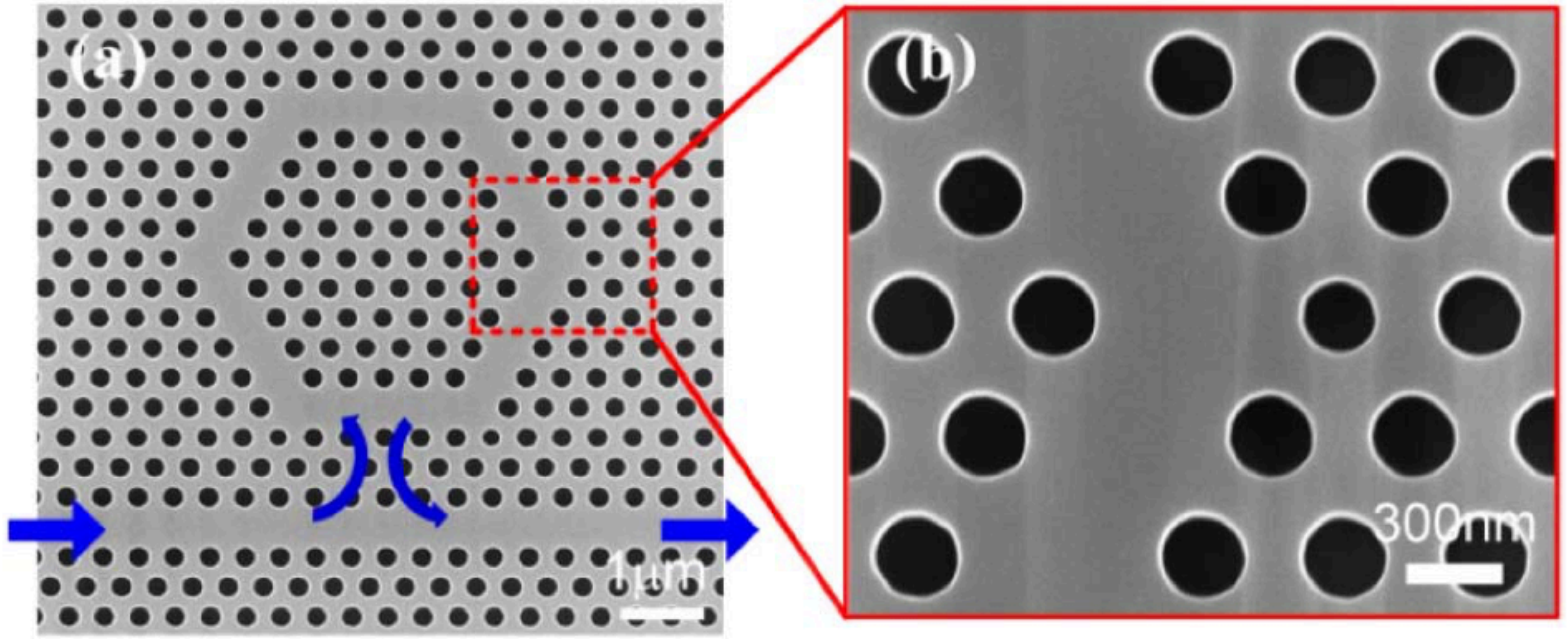
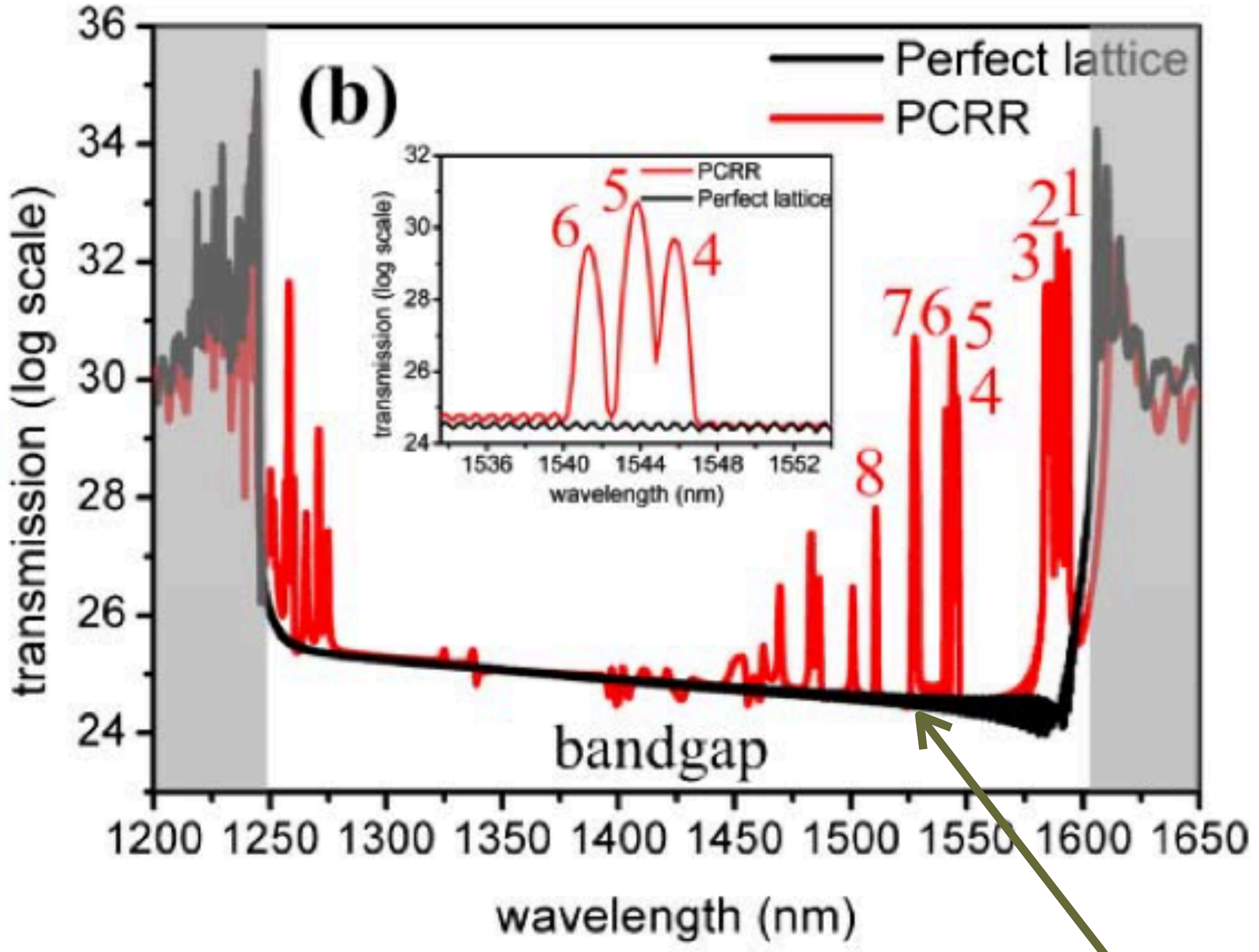
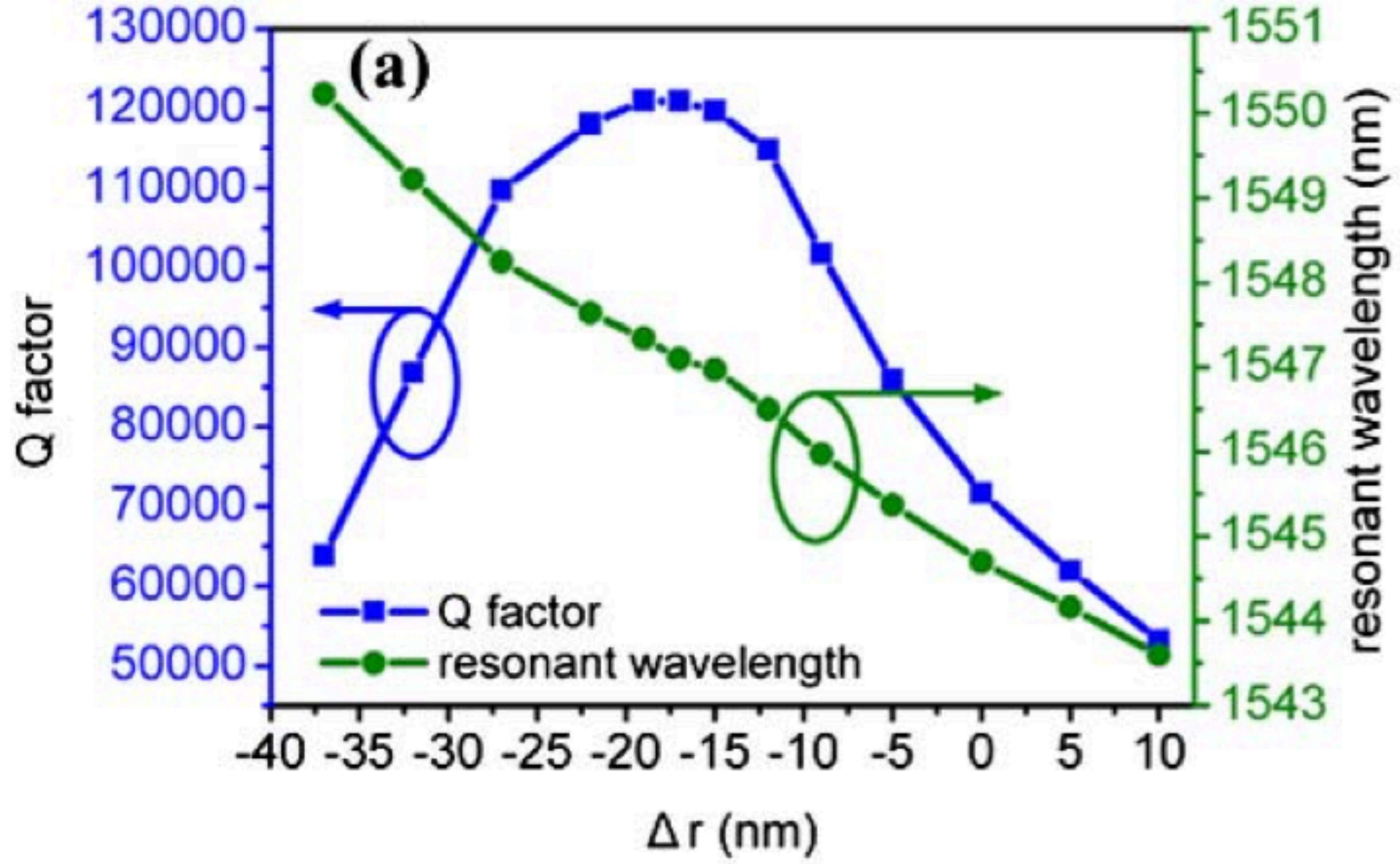


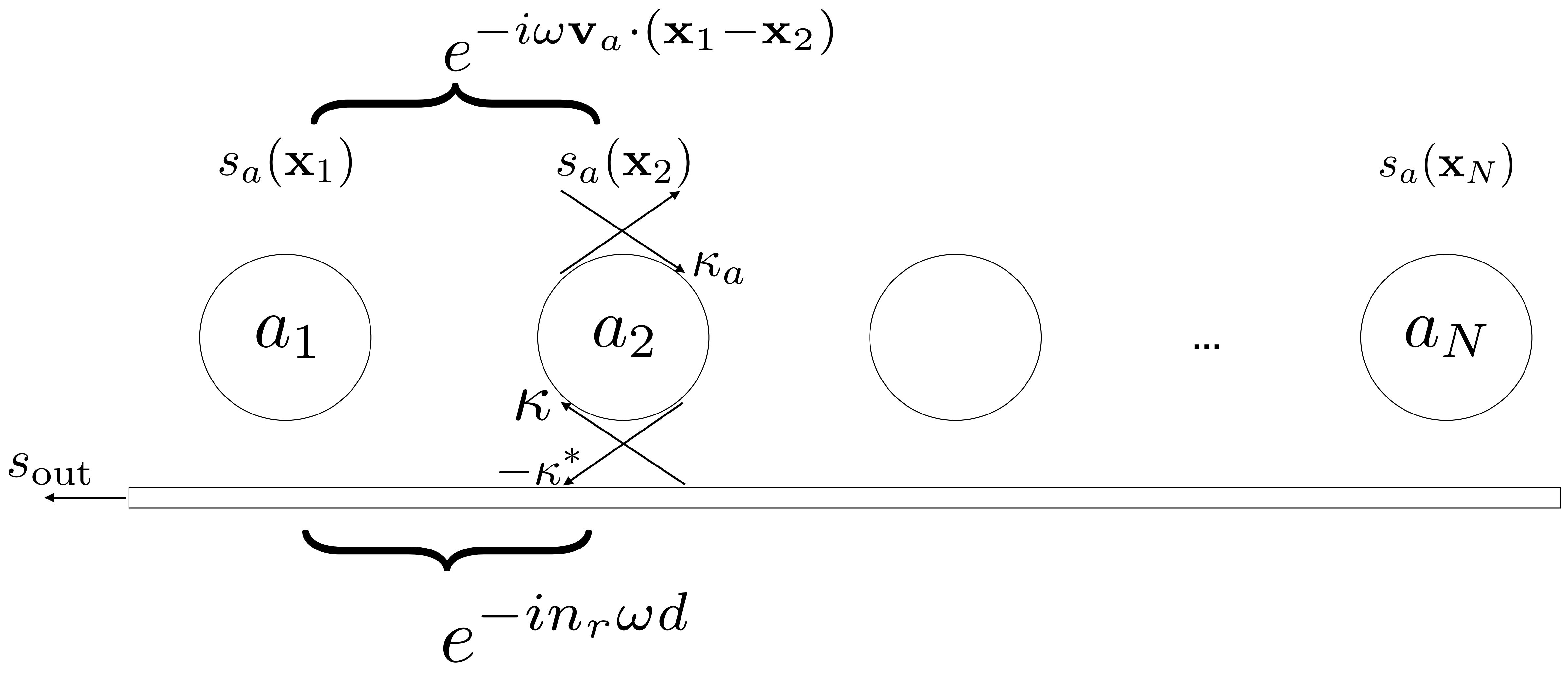
Fig. 4. (a) SEM image of the fabricated modified PCRR. (b) Magnified micrograph of the corner of the modified PCRR.





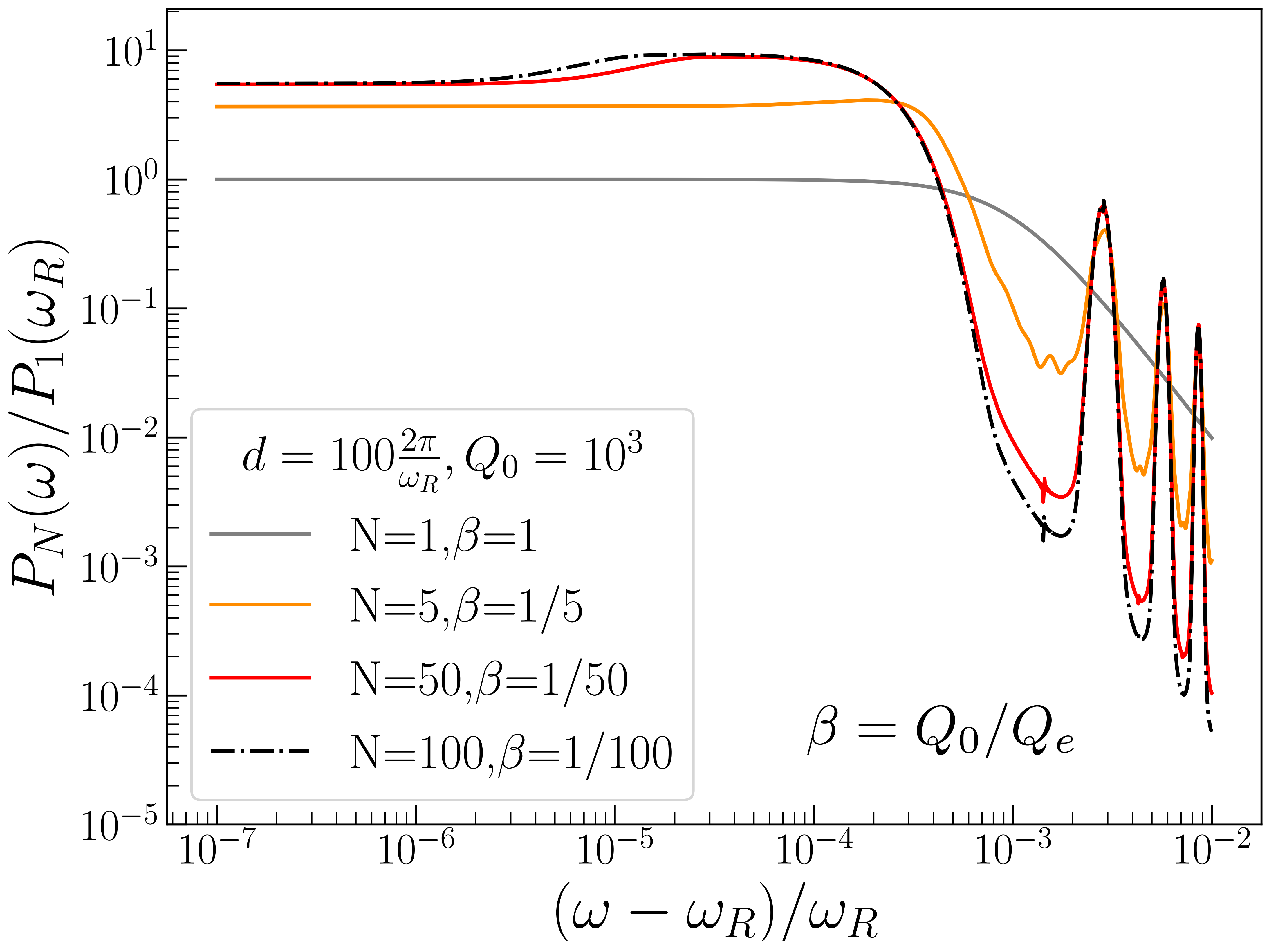
Coupling N Resonators in Parallel

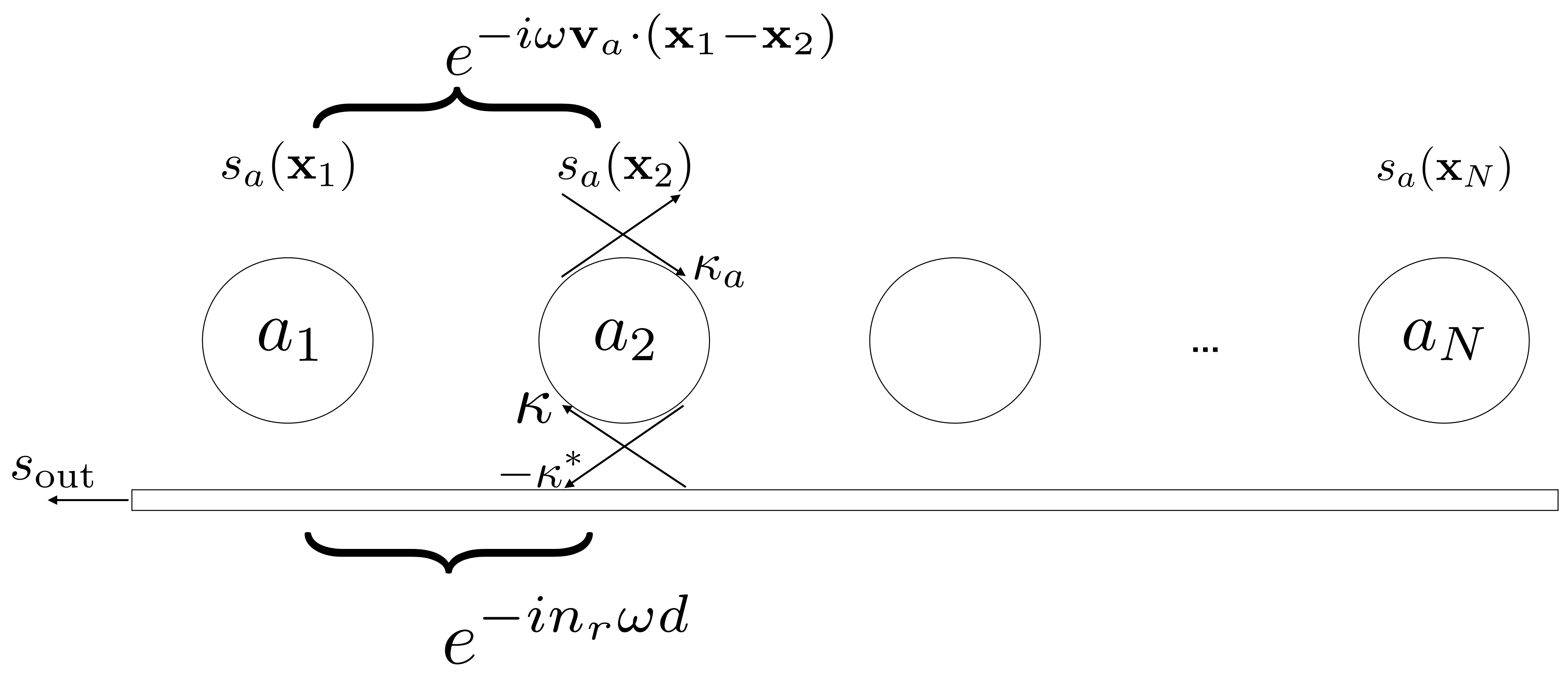
N Resonators in Parallel



- Solve the output using Heisenberg Langevin equations
- Gaussian distribution of $\mathbf{v}_a$ is assumed.
- DM sources a standing wave that can couple to either left or right-traveling wave in the bus.

Same Frequency

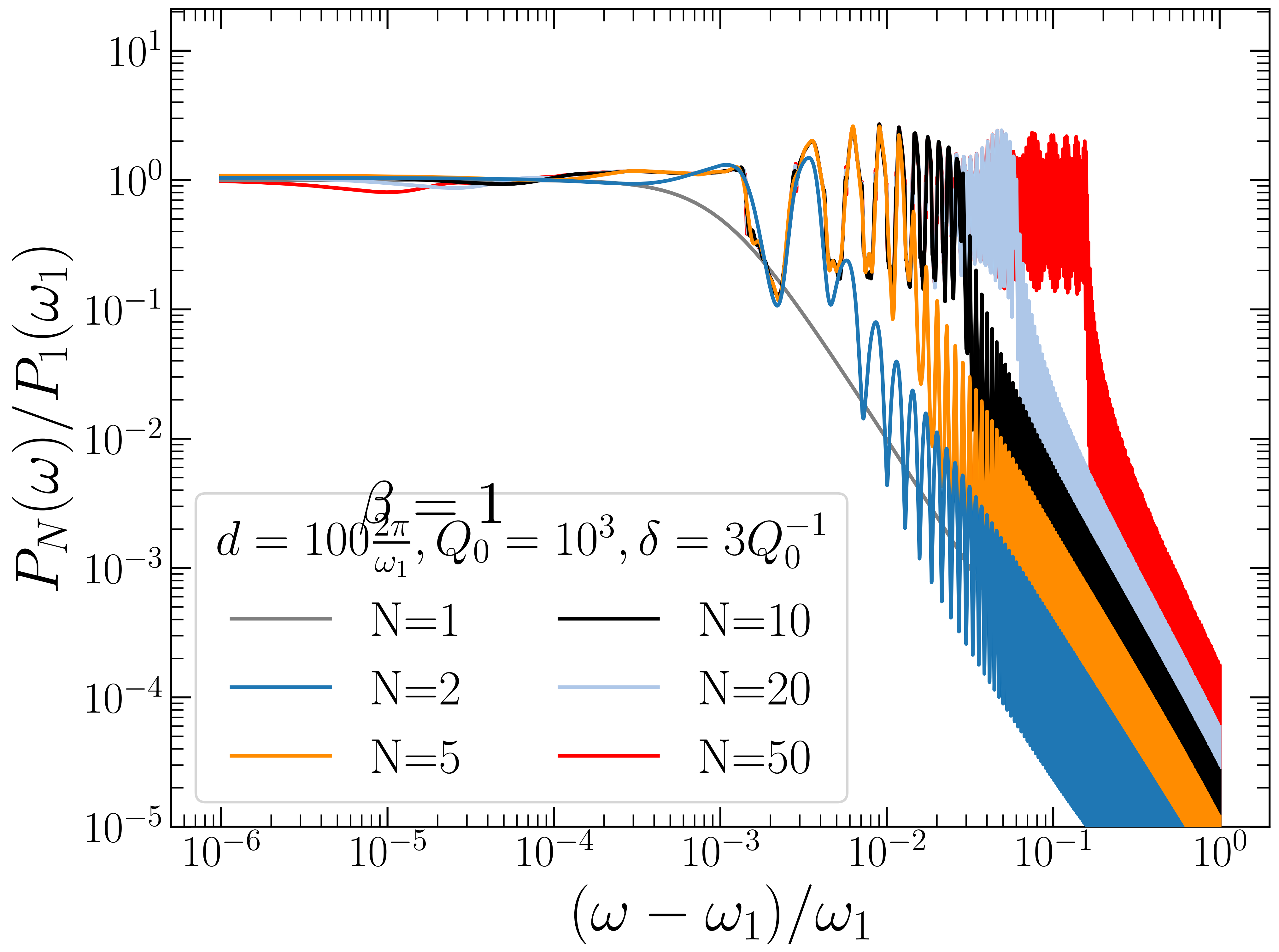


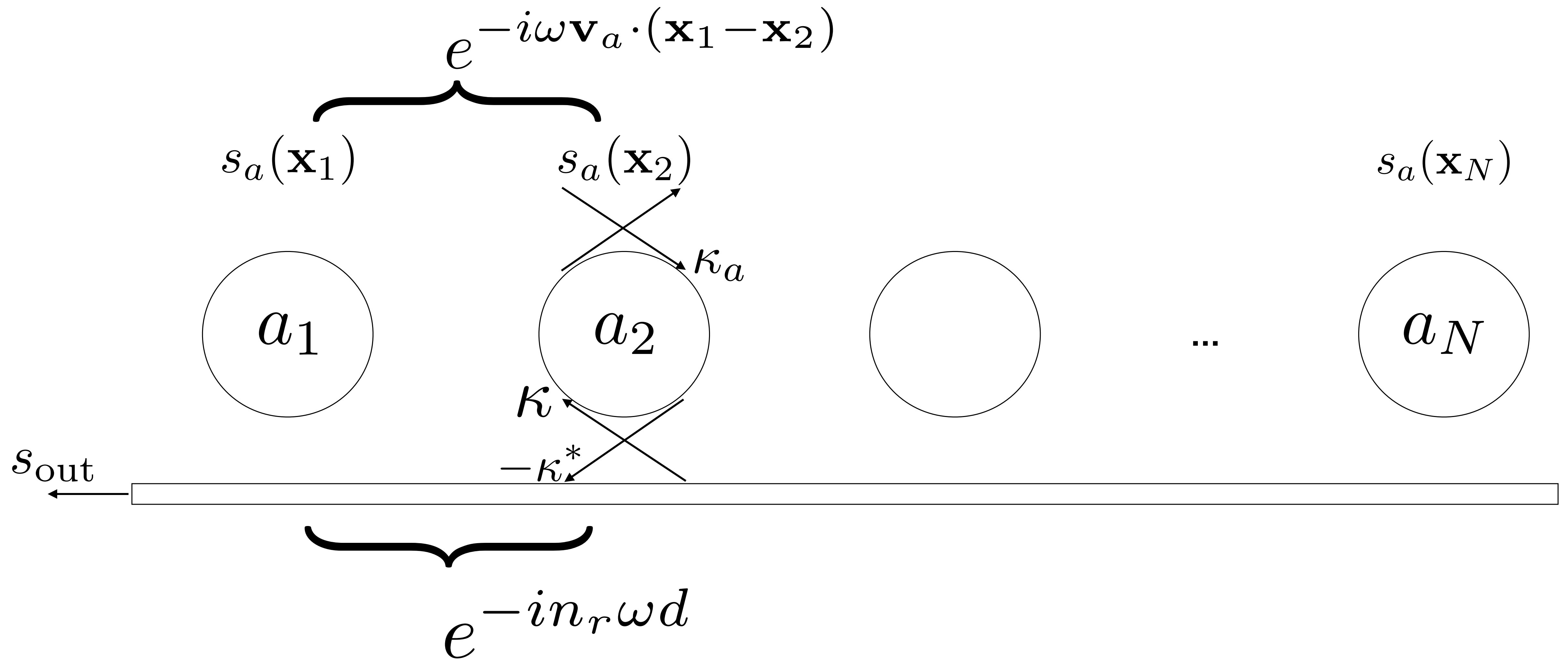


No gain after going beyond the DM coherence length.

Different Frequencies

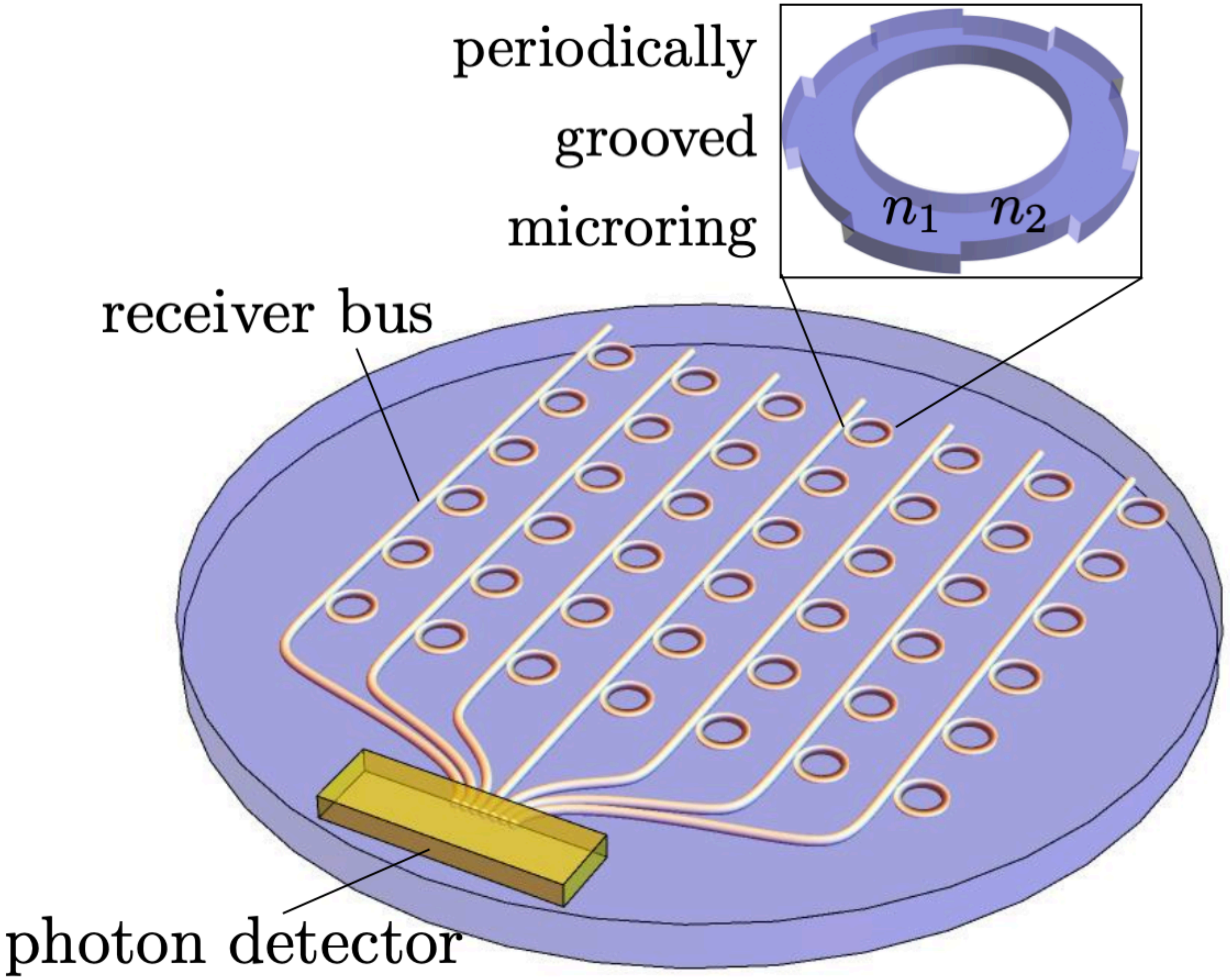
$\omega_R(1+\delta)^{i-1}, i = 1, 2, \cdots, N$

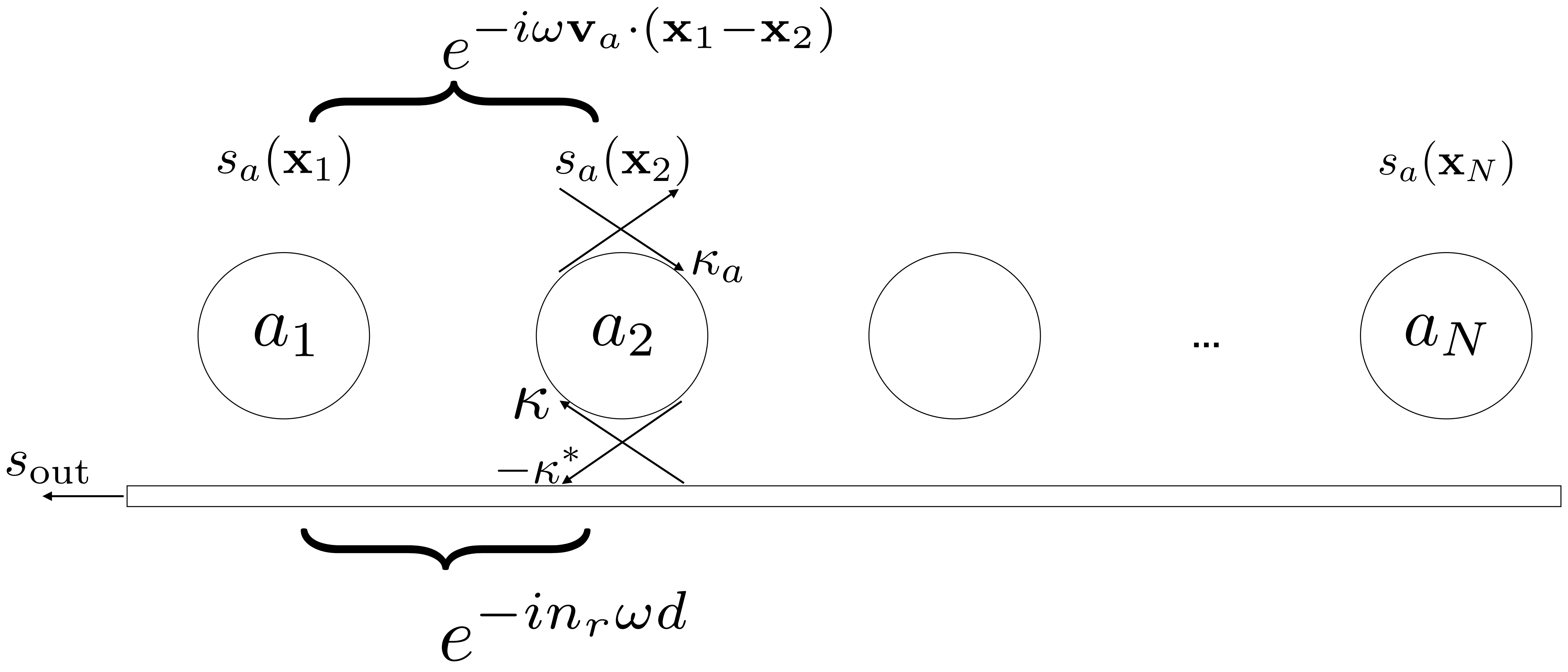




Signal width grows like $\delta \times Q_0$.

Sketch of the Setup





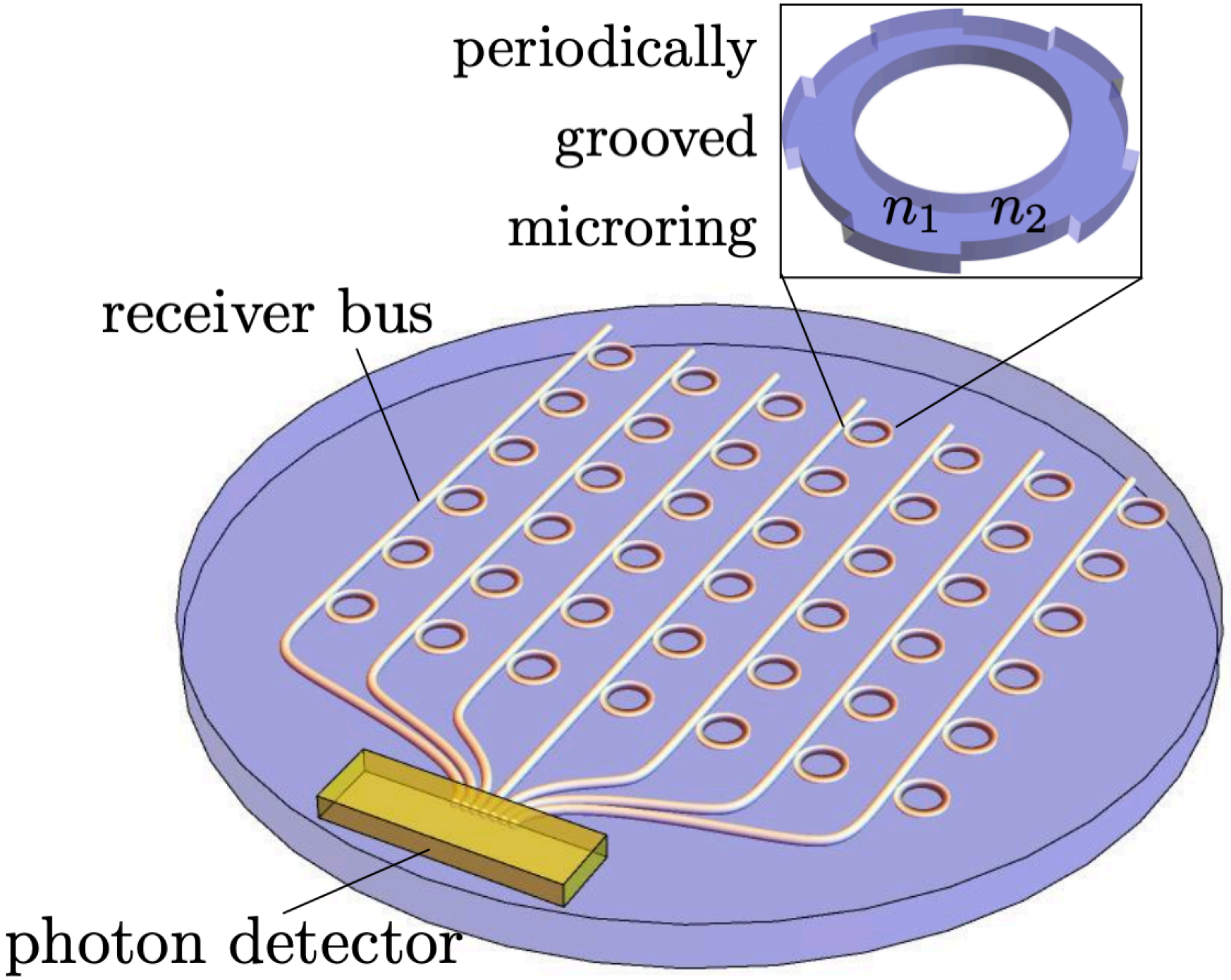
"Active" Fraction of a Chip

$$\xi_{\rm act} \equiv \frac{V_{\rm int}}{\frac{1}{4}\pi D^2 t_s} \sim 0.1\% \left(\frac{100}{N_u}\right)\left(\frac{t_w/t_s}{0.01}\right)$$

N_u = # of unit cells in each resonator

t_w = thickness of the resonator

t_s = thickness of the substrate



Projected Sensitivity

Axion DM Search Needs a Background Magnetic Field

$$\xi_{\rm act} \equiv \frac{V_{\rm int}}{\frac{1}{4}\pi D^2 t_s} \sim 0.1\% \left(\frac{100}{N_u}\right)\left(\frac{t_w/t_s}{0.01}\right)$$

B(T)	Bore (mm)	$V_{\rm act}$(cm^3)	$B^2V_{\rm act}$(PeV)	References
40	34	9×10^{-3}	6.9×10^{4}	[29]
21	123	0.118	2.5×10^{5}	[30]
9.4	800	100	4.2×10^{7}	[31]
11.7	900	127	8.3×10^{7}	[32]
20[a]	680	72.6	1.38×10^{8}	[33]

Above ~1.1 eV, Skipper CCD

Below ~1.1 eV, Superconducting Nanowire Single Photon Detector

Assume the dark count dominates the background. Need to cool down to <~100K for MIR and even more for LWIR.

Axion DM Search Needs a Background Magnetic Field

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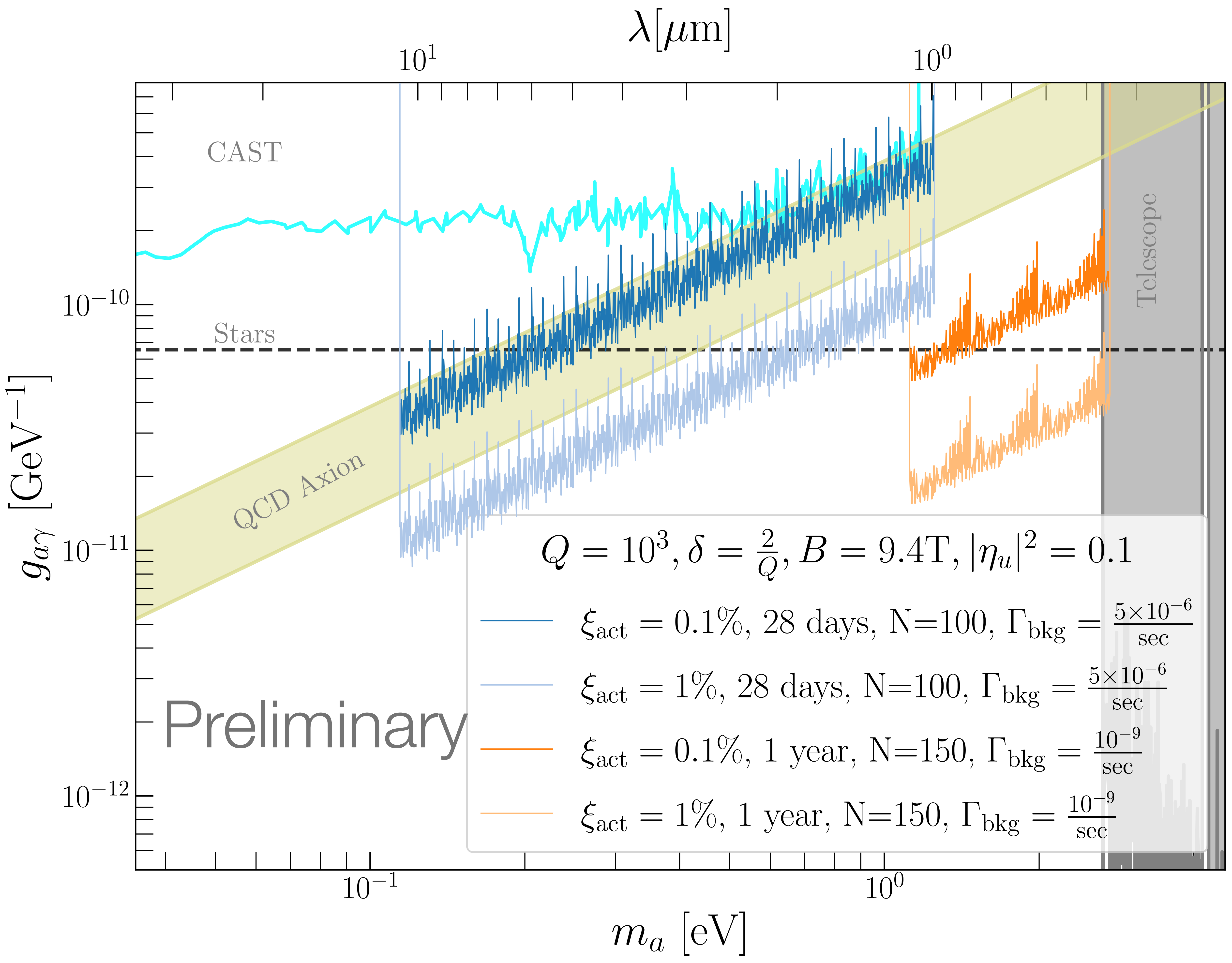
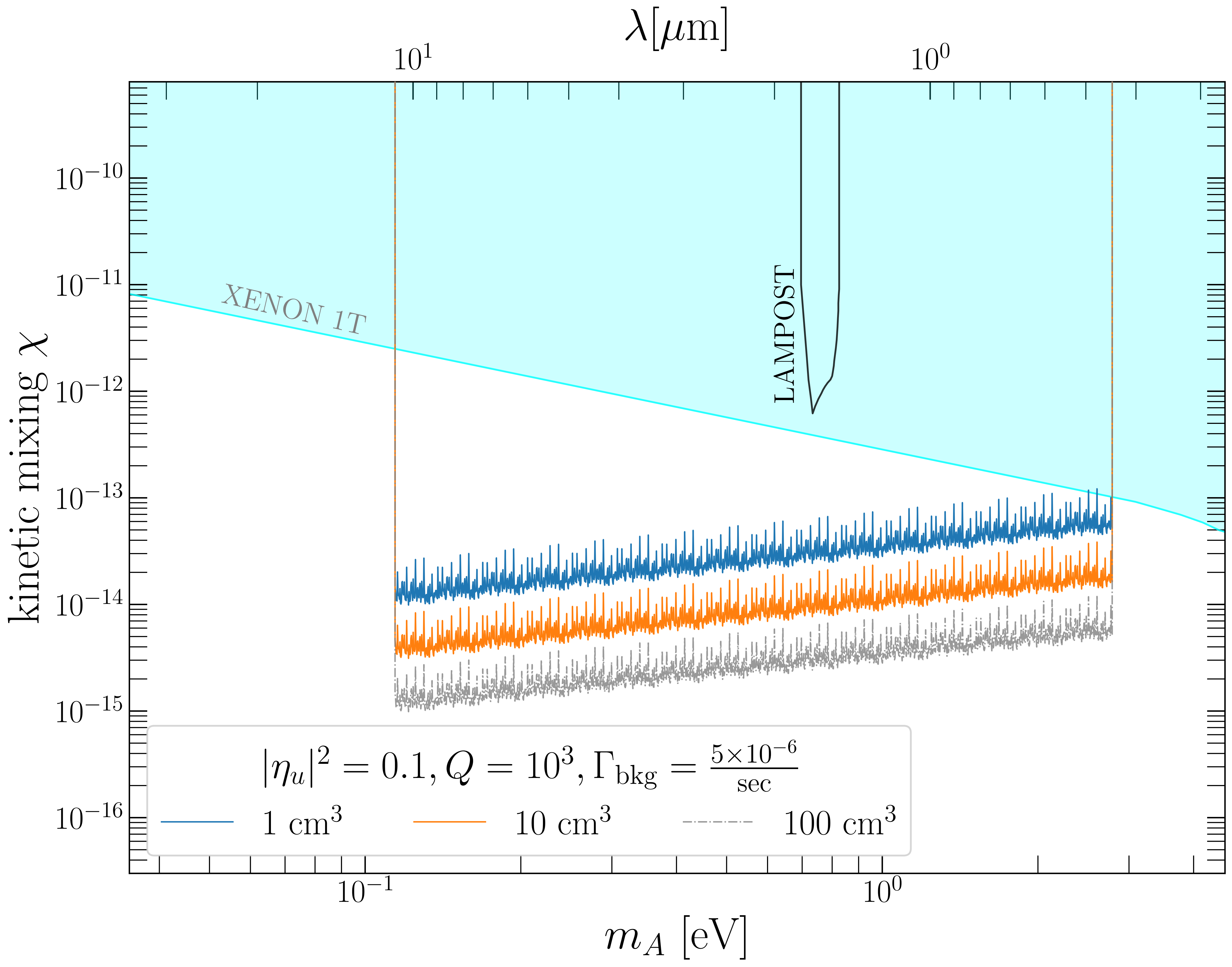


Conclusion & Future

- Integrated Photonics can be applied in the DM direct detection at optical frequencies.
- Photonic Crystal Cavities constitute the best option to phase match. 2D and 3D photonic crystals, though harder to mass produce, could provide better phase matching and volume filling.
- Optical resonators' properties may undergo significant changes under cryogenic temperatures.

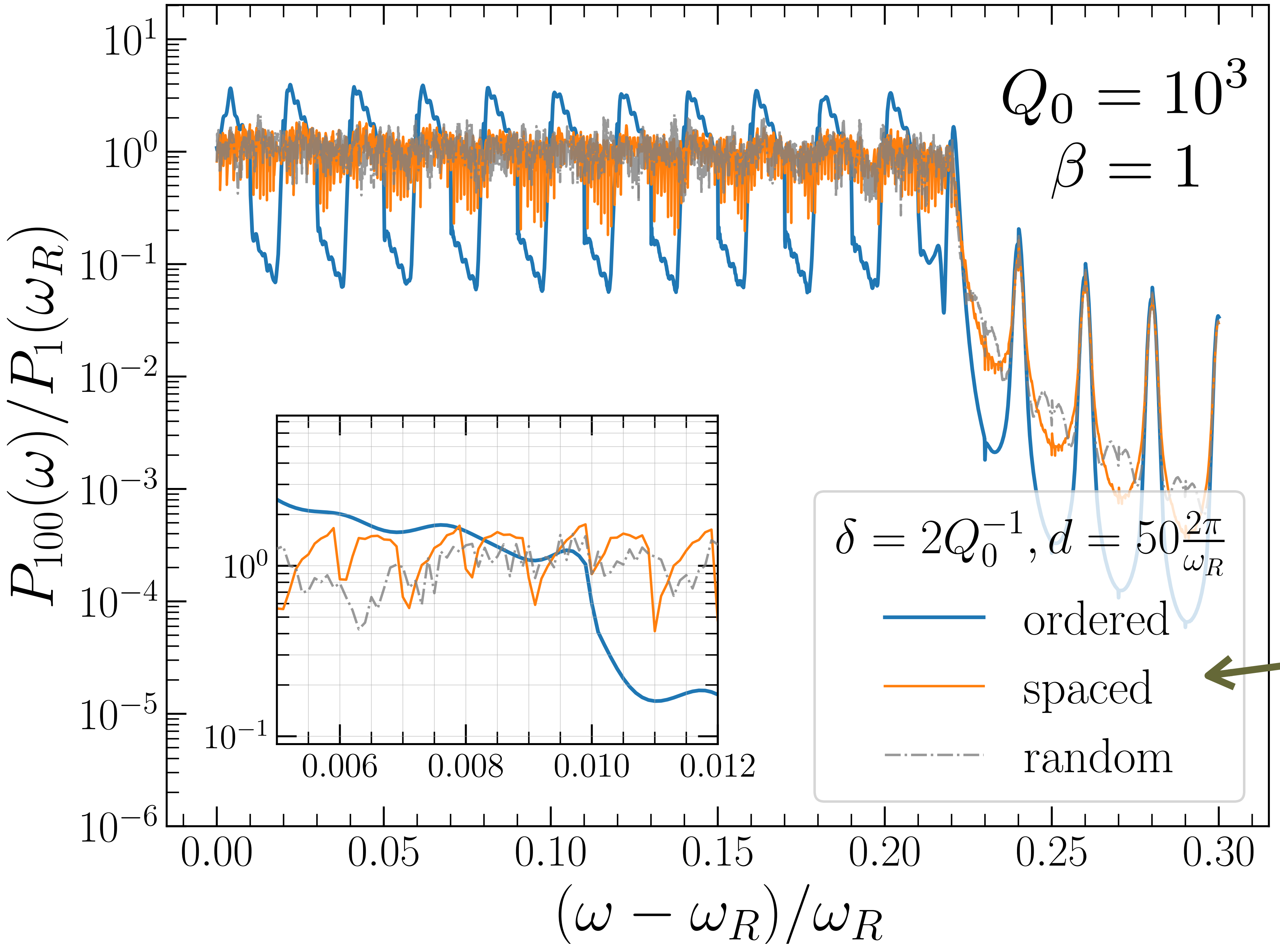
Dark photon-photon kinetic mixing

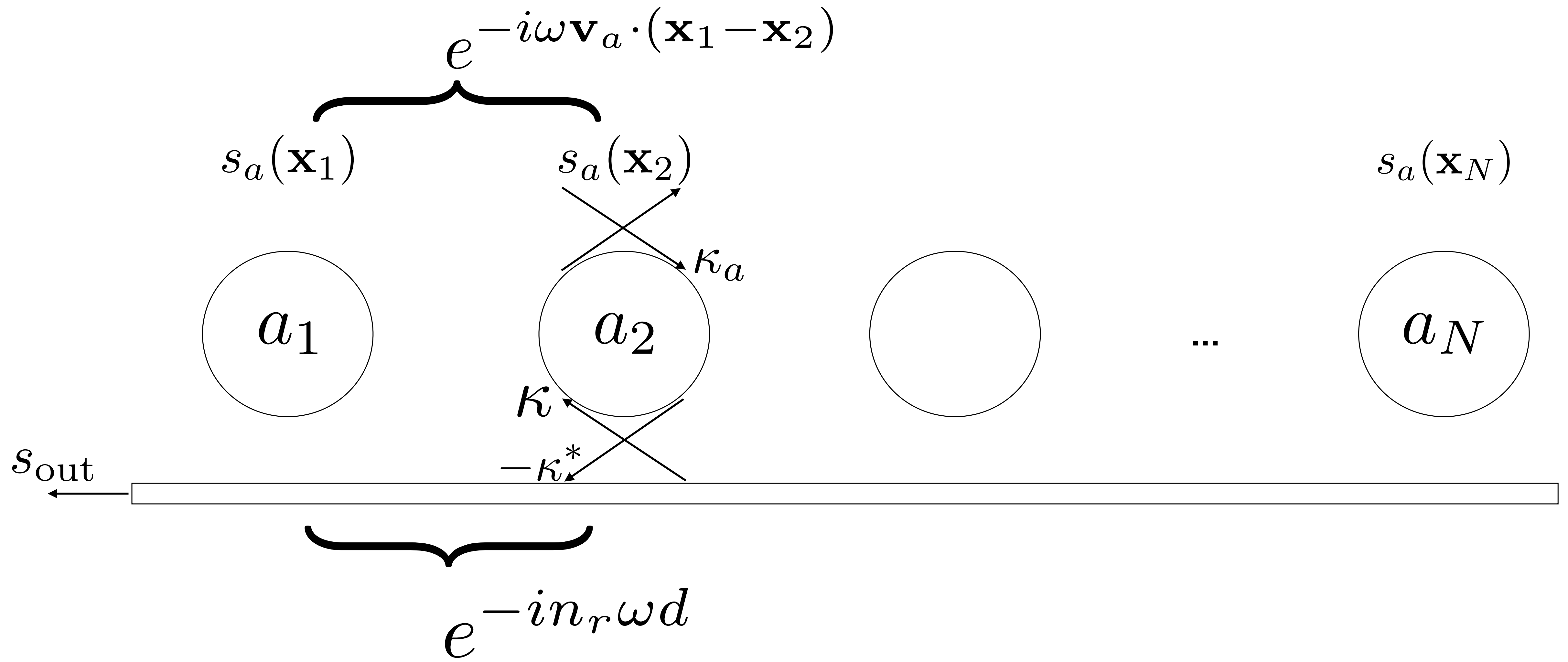


Backups

Different Frequencies

$\omega_R(1+\delta)^{i-1}, i = 1, 2, \cdots, N$



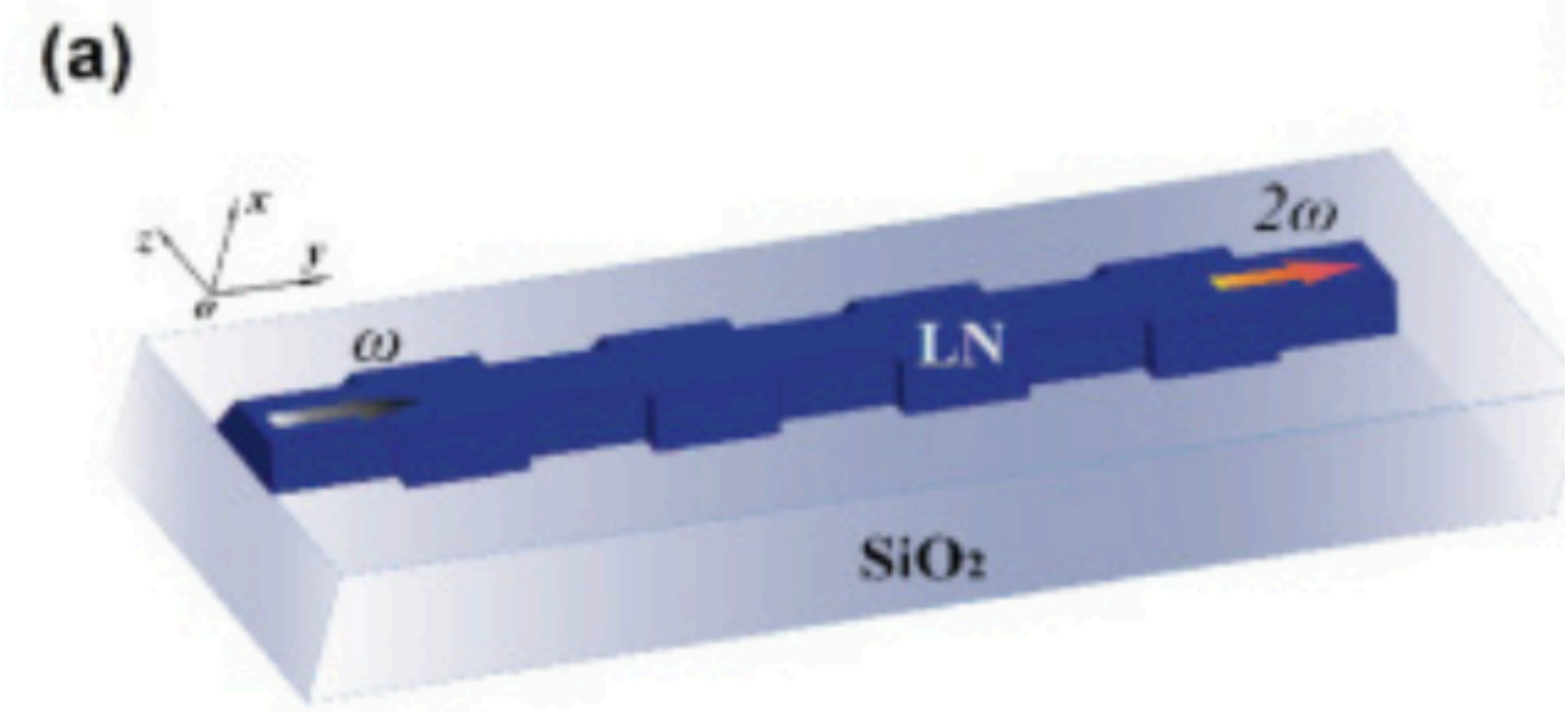


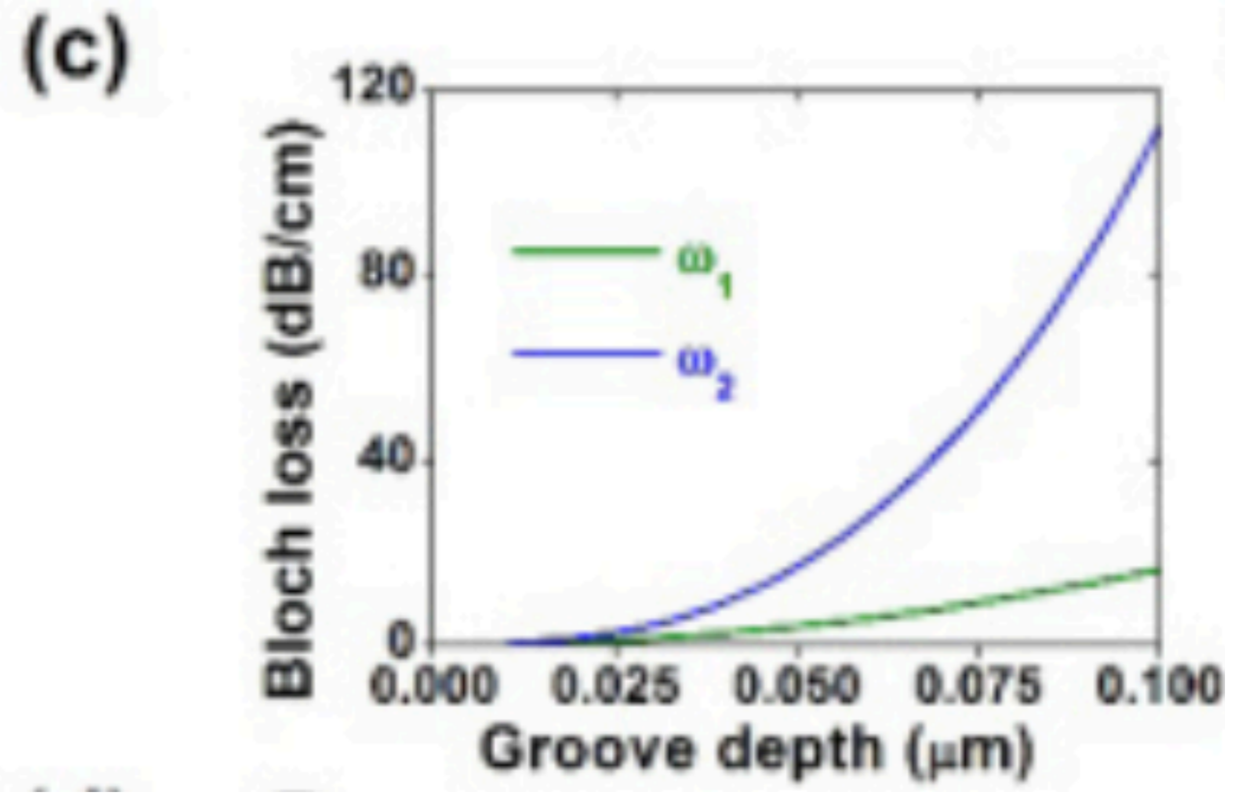
For lth resonator $\omega_R(1+\delta)^{g(l)}$

$$g(l) = \begin{cases} \lfloor \frac{l}{10} \rfloor + \frac{N}{10}((l \bmod 10) - 1) + 1 & l \bmod 10 \neq 0 \\ (l + 9N)/10 & l \bmod 10 = 0 \end{cases}$$

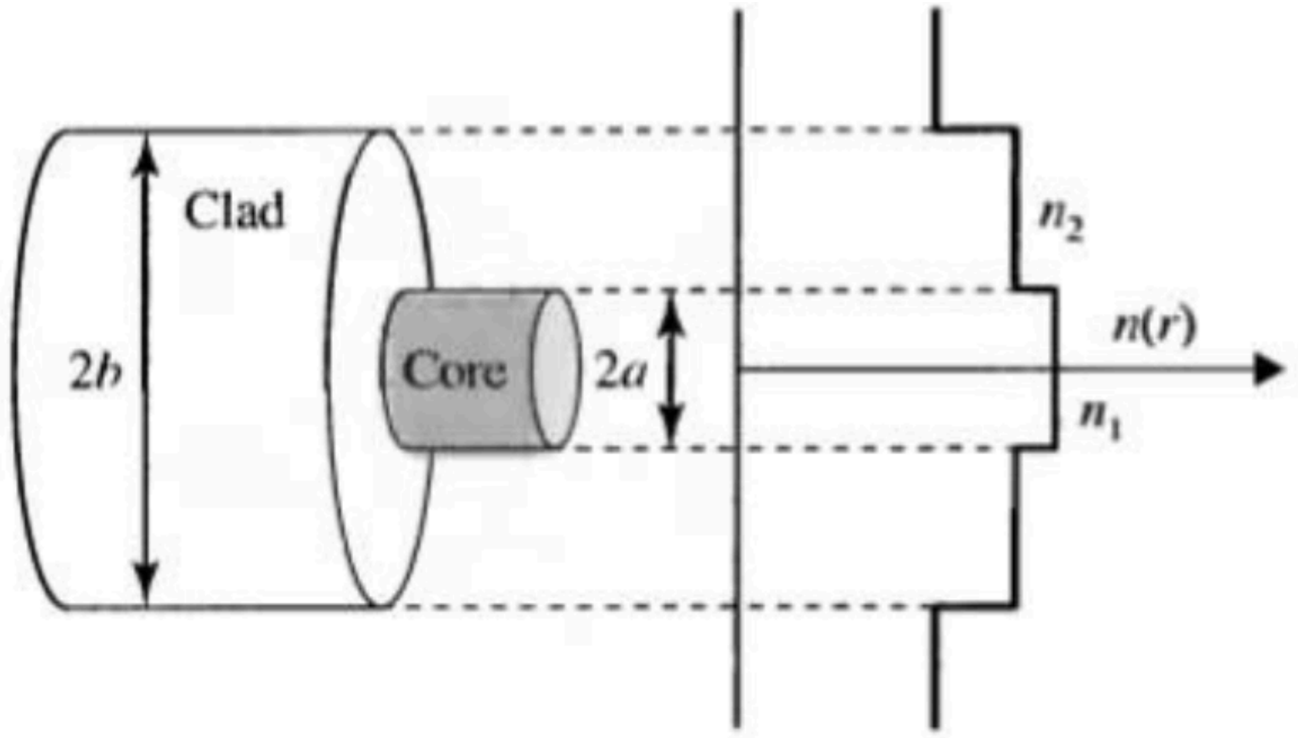
Effective Index Theory

https://doi.org/10.1364/OE.25.006963

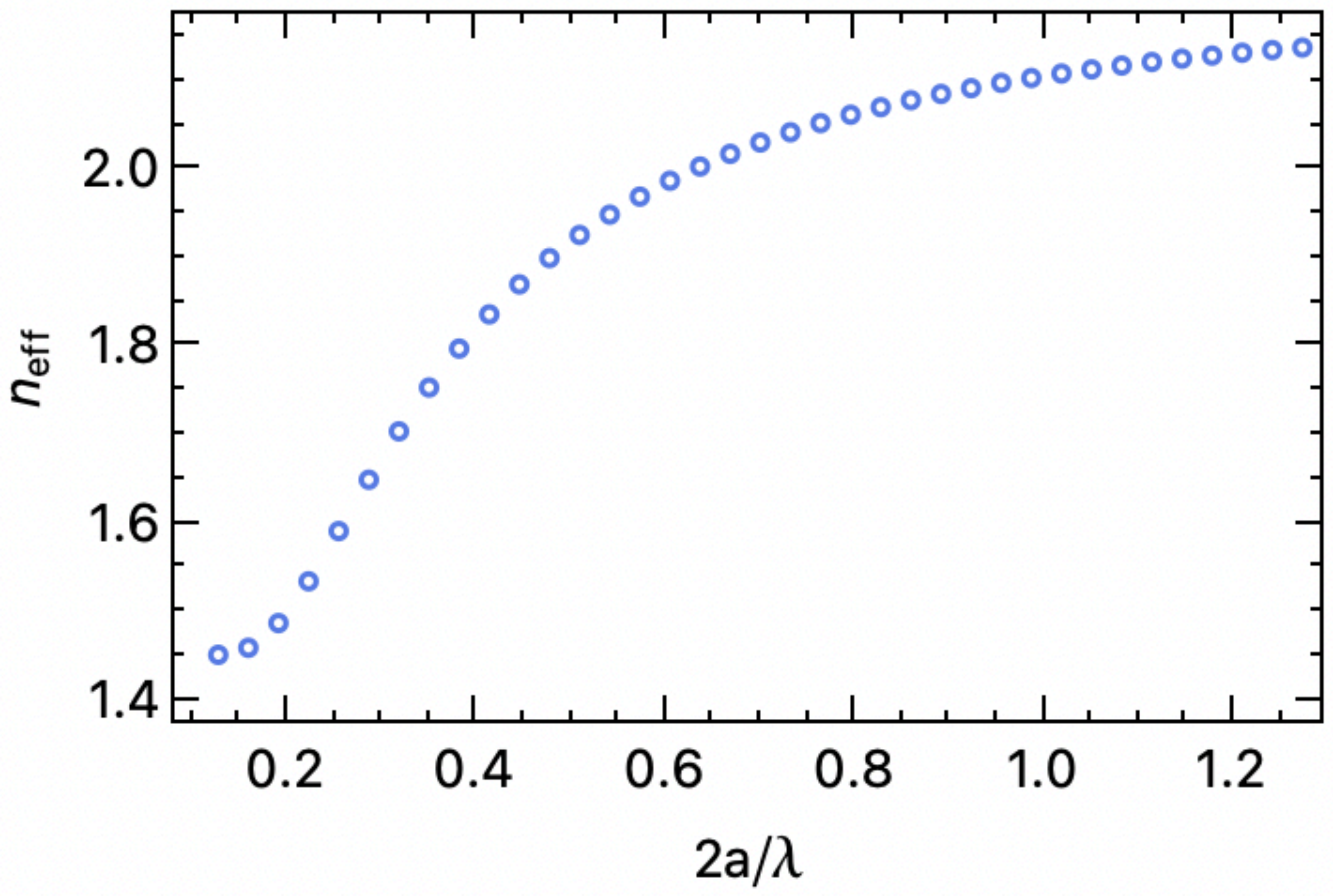




How big can n_{eff} be changed by grooving?



$$n_1 = 2.2, n_2 = 1.45, \mathrm{LP}_{01}$$



Surface Scattering Loss

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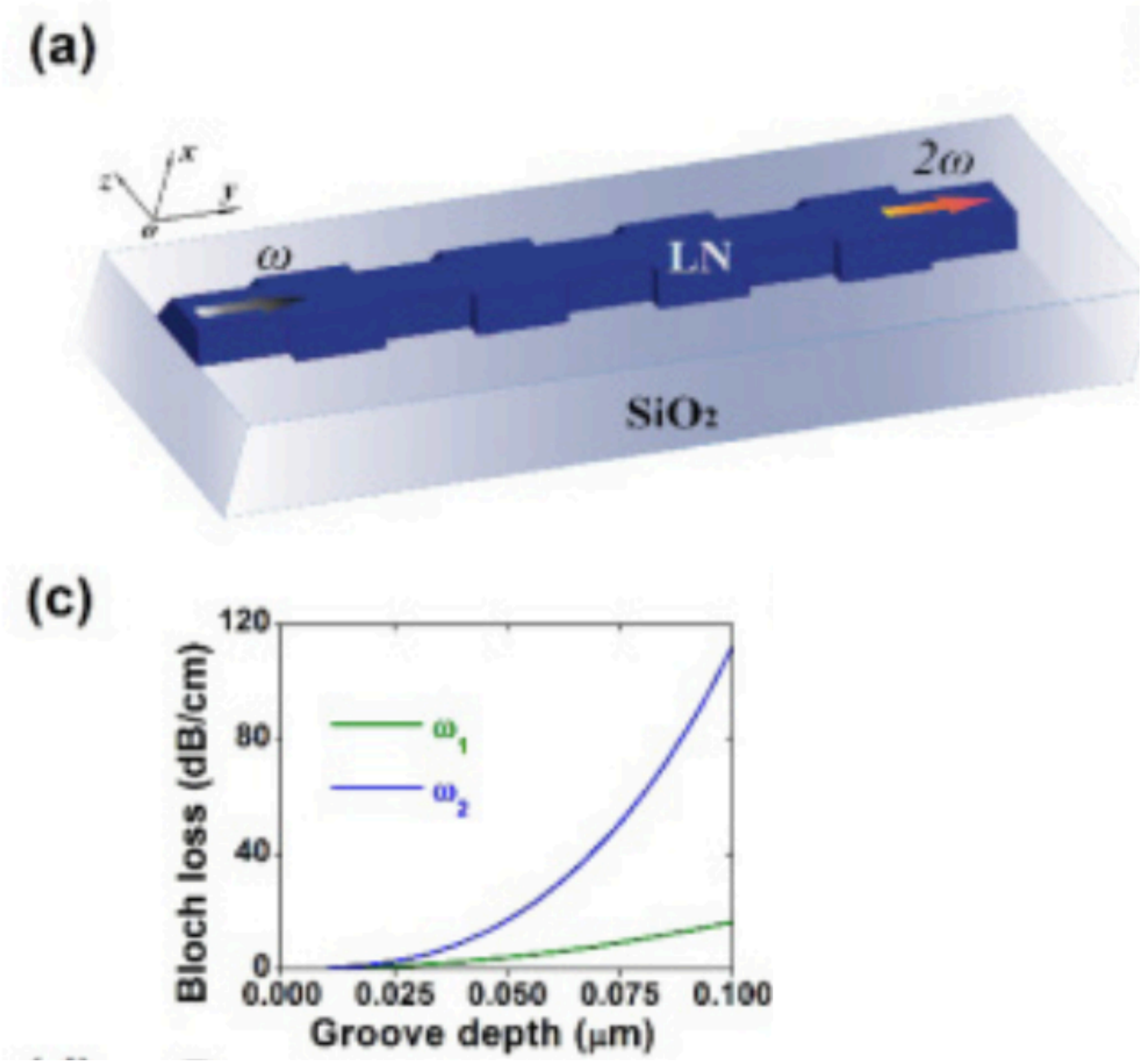

$$P_L = P_0 e^{-\alpha L}$$

Surface Scattering Loss

$$Q \approx \frac{\pi n_{\rm eff}}{\alpha \lambda_0} \sim 10^3 \left(\frac{180\,\frac{\rm dB}{\rm cm}}{\mathcal{L}}\right)\left(\frac{1.5\mu{\rm m}}{\lambda_0}\right)\left(\frac{n_{\rm eff}}{2}\right)$$

for L << 1 cm

Radiation Loss

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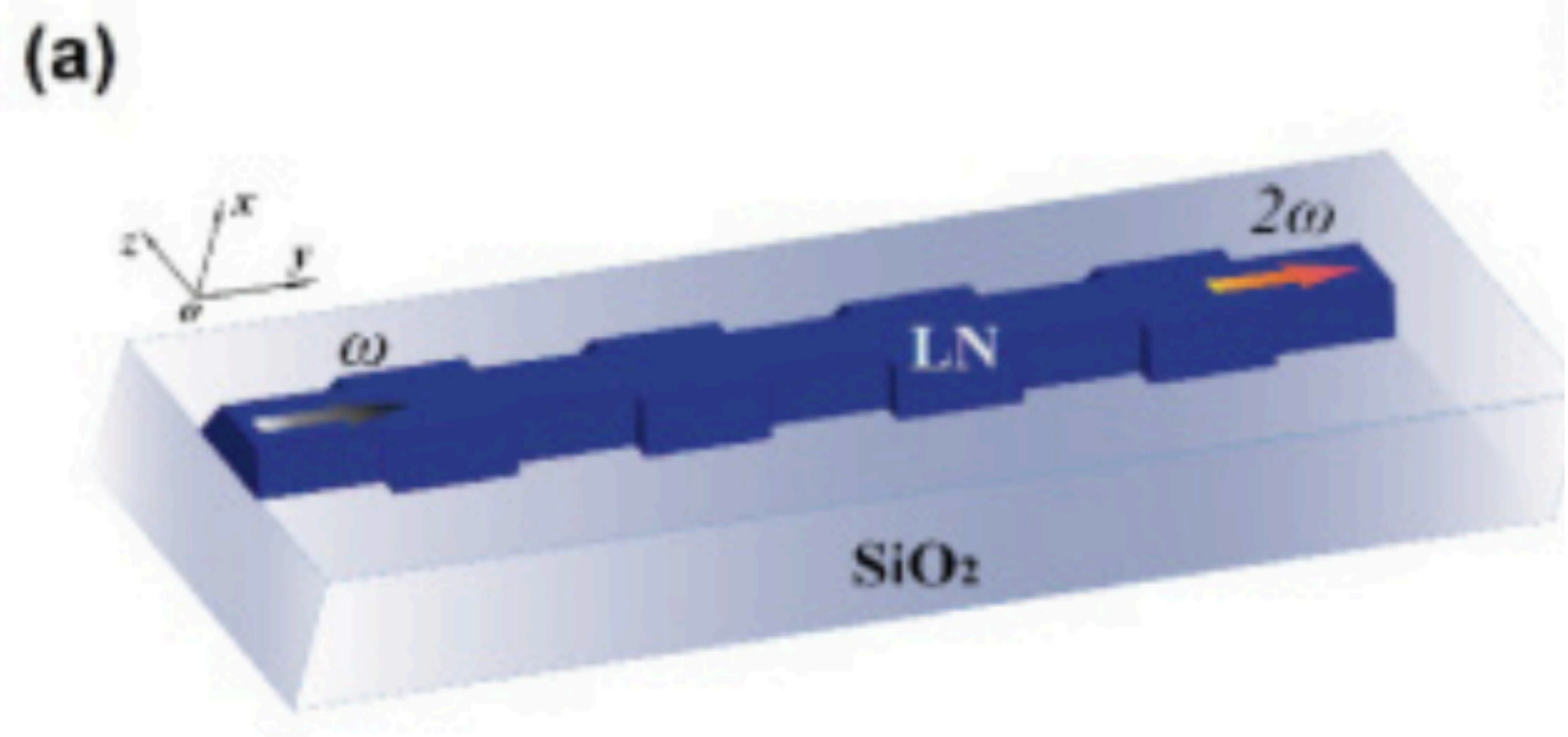

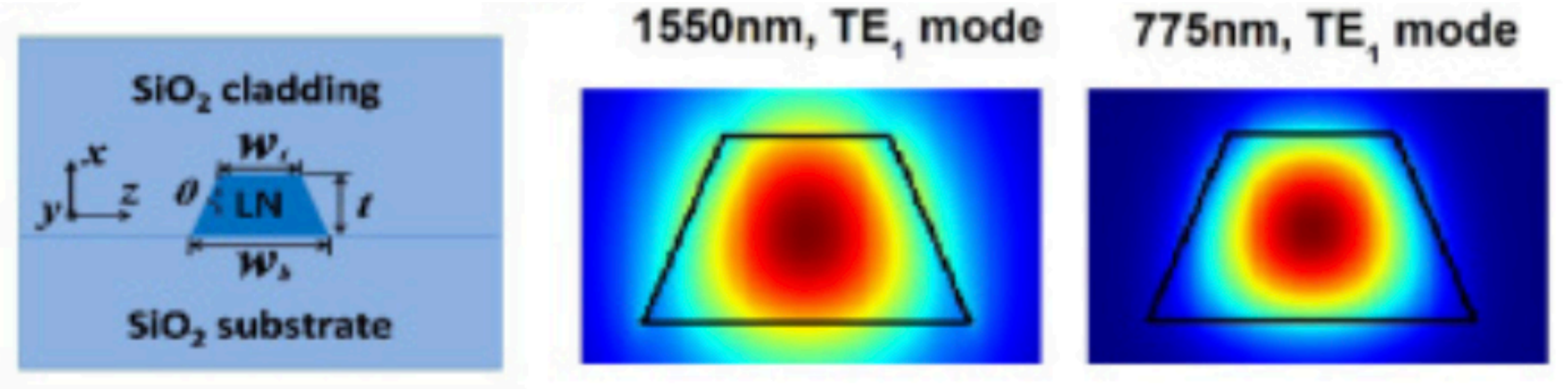

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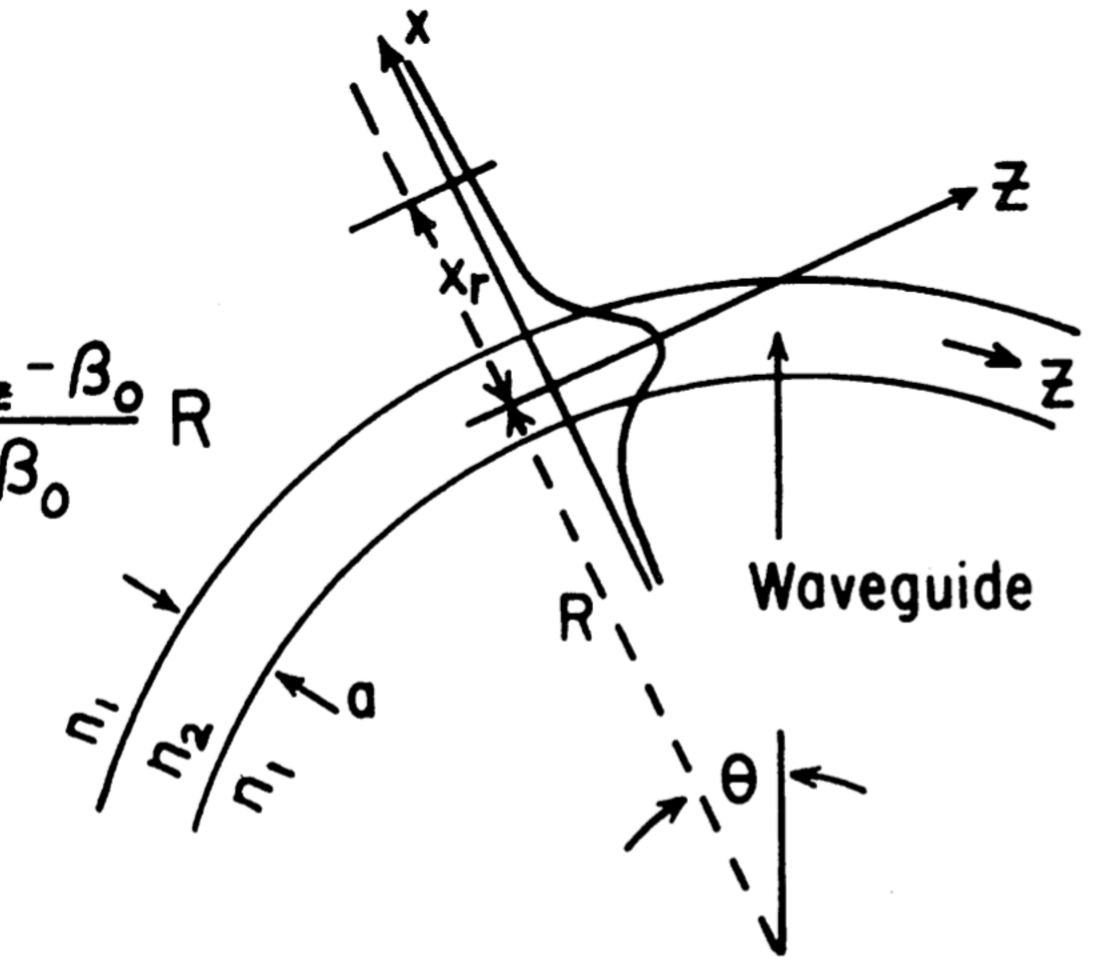
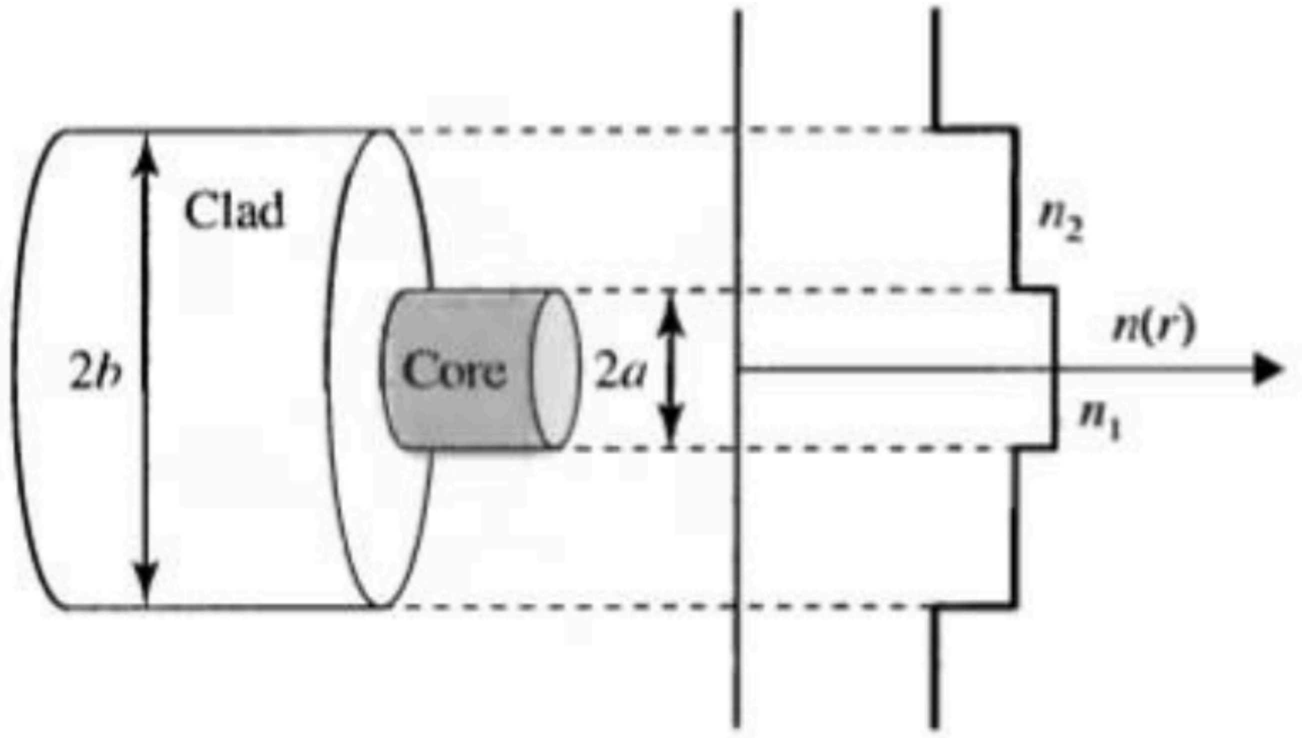
Radiation/bend Loss



$$X_r = \frac{\beta_z - \beta_0}{\beta_0} R$$

$$\alpha_{\rm rad} \simeq \frac{P_{\rm loss}}{P_{\rm t}} \frac{1}{Z_c}$$

Radiation Loss



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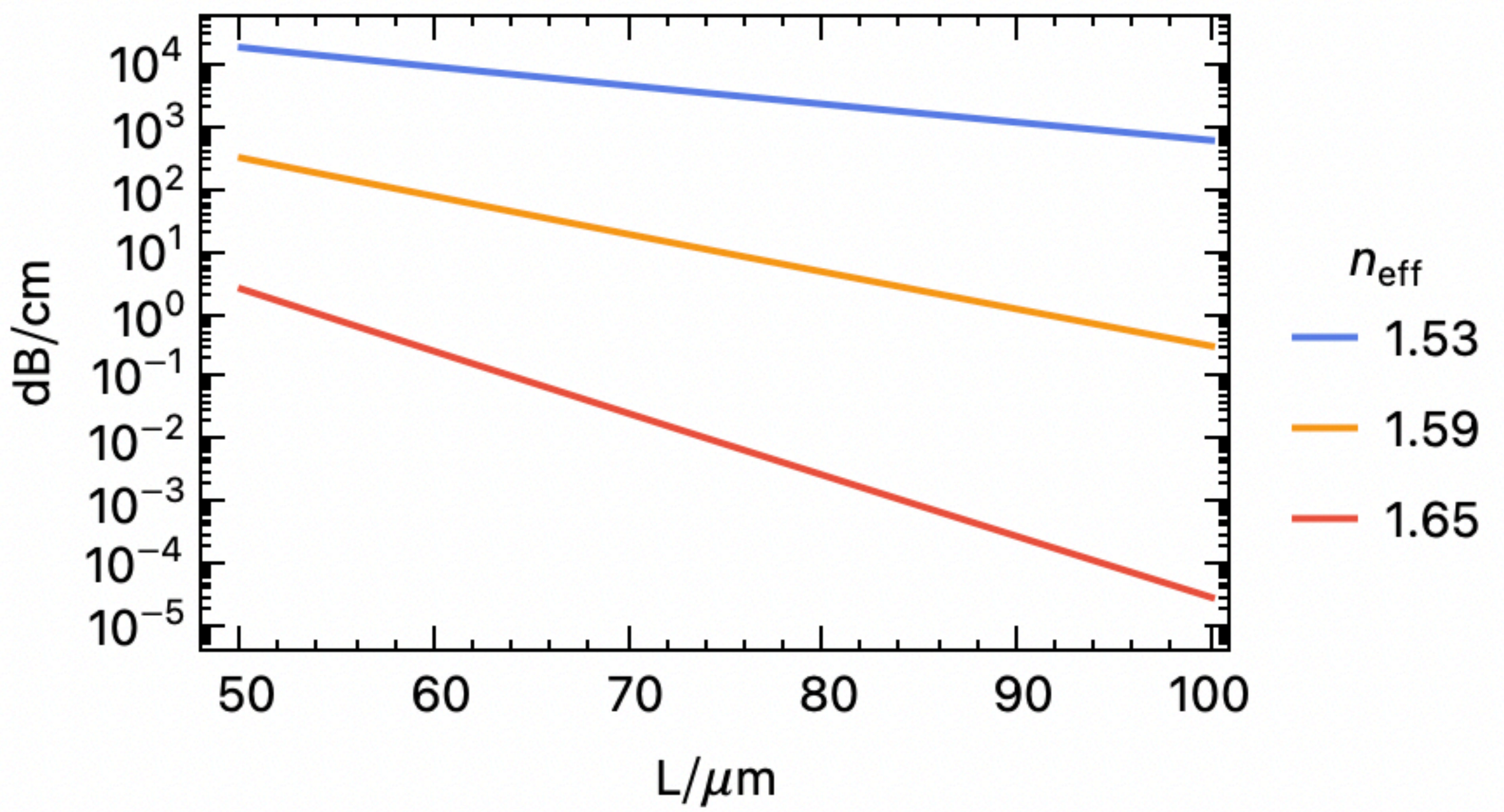

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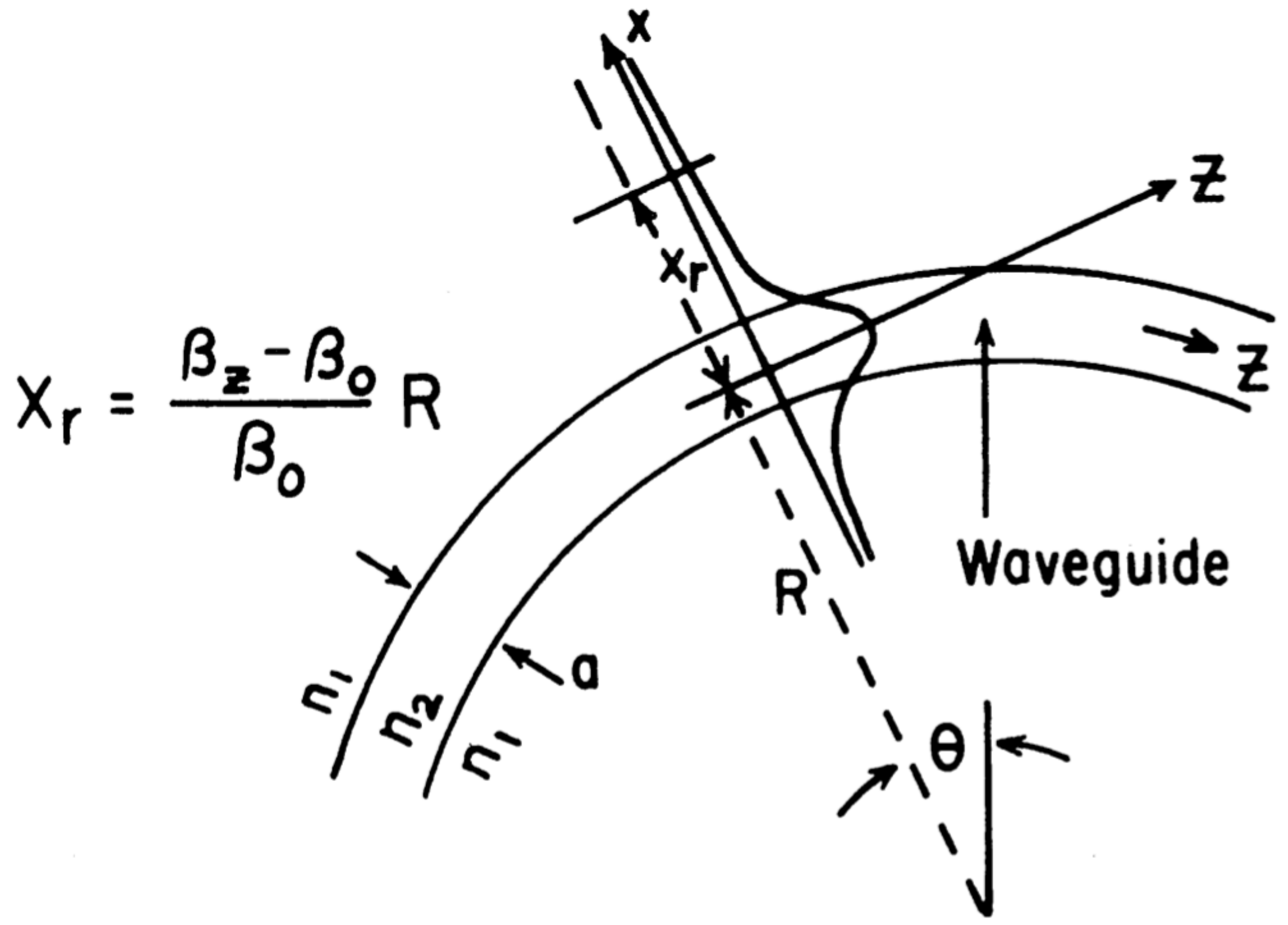

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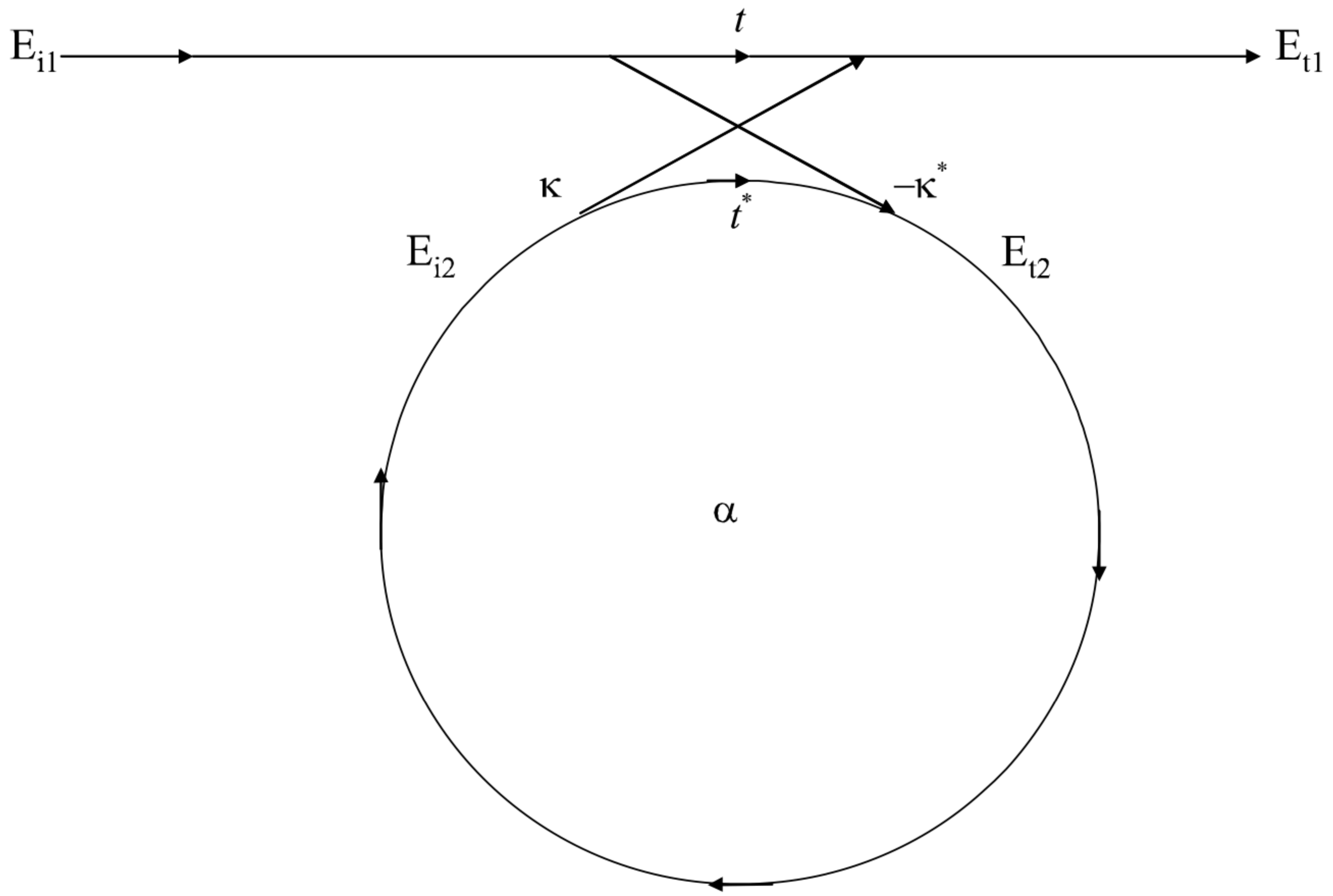
Ring Resonator

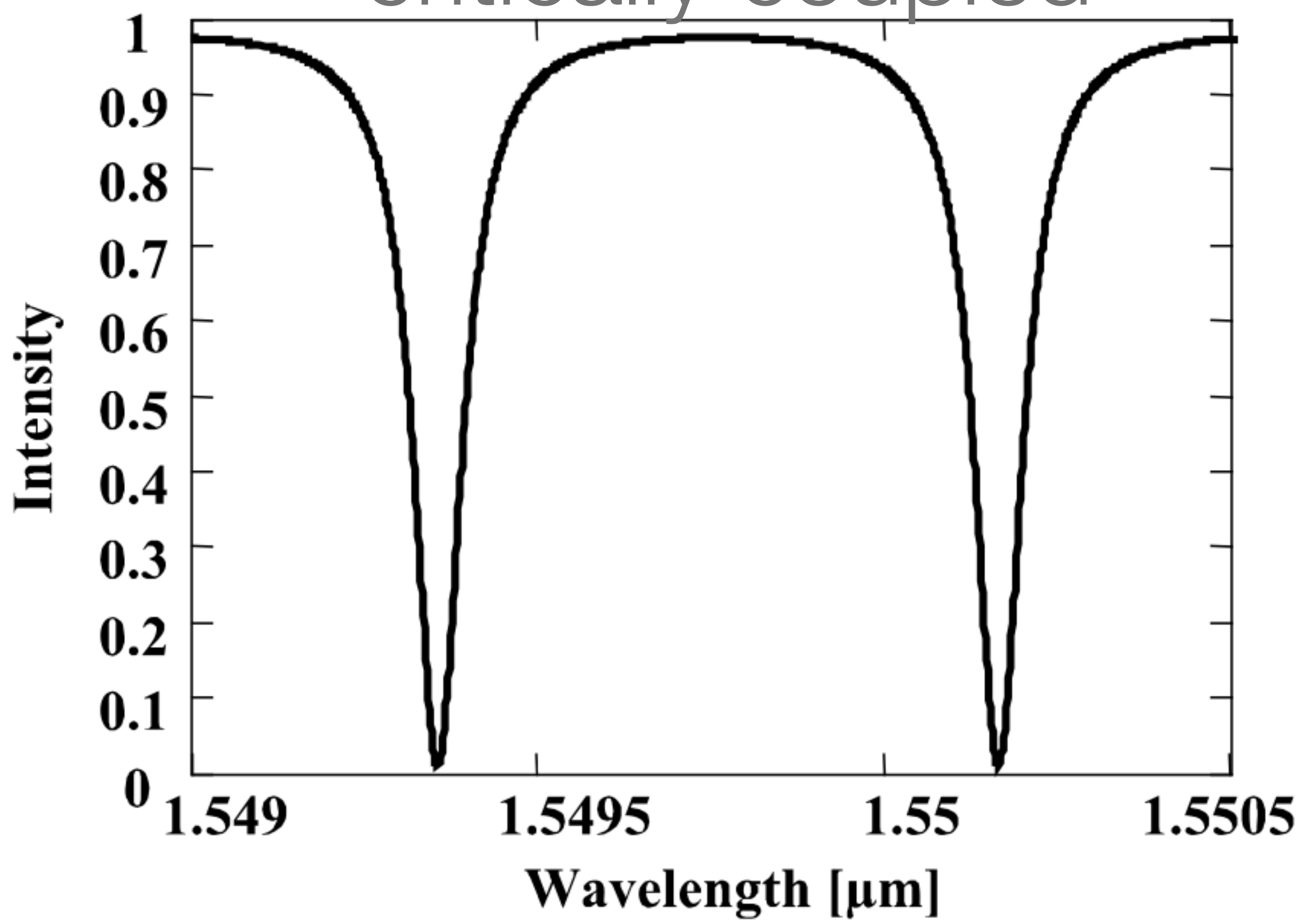


$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \qquad |\kappa^2| + |t^2| = 1$$

$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \qquad \theta \approx n_{\text{eff}} \omega L$$

Loss

critically coupled



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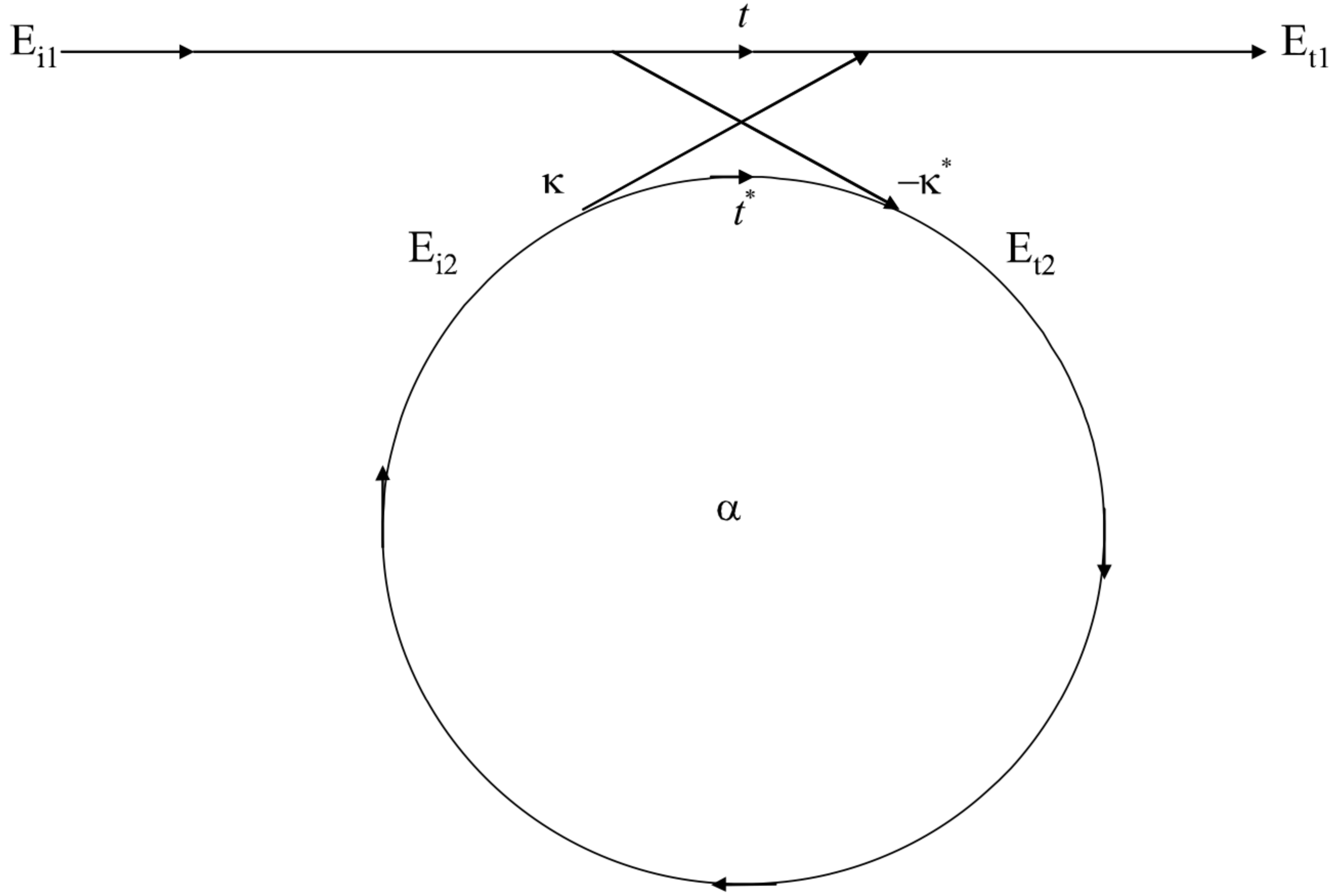

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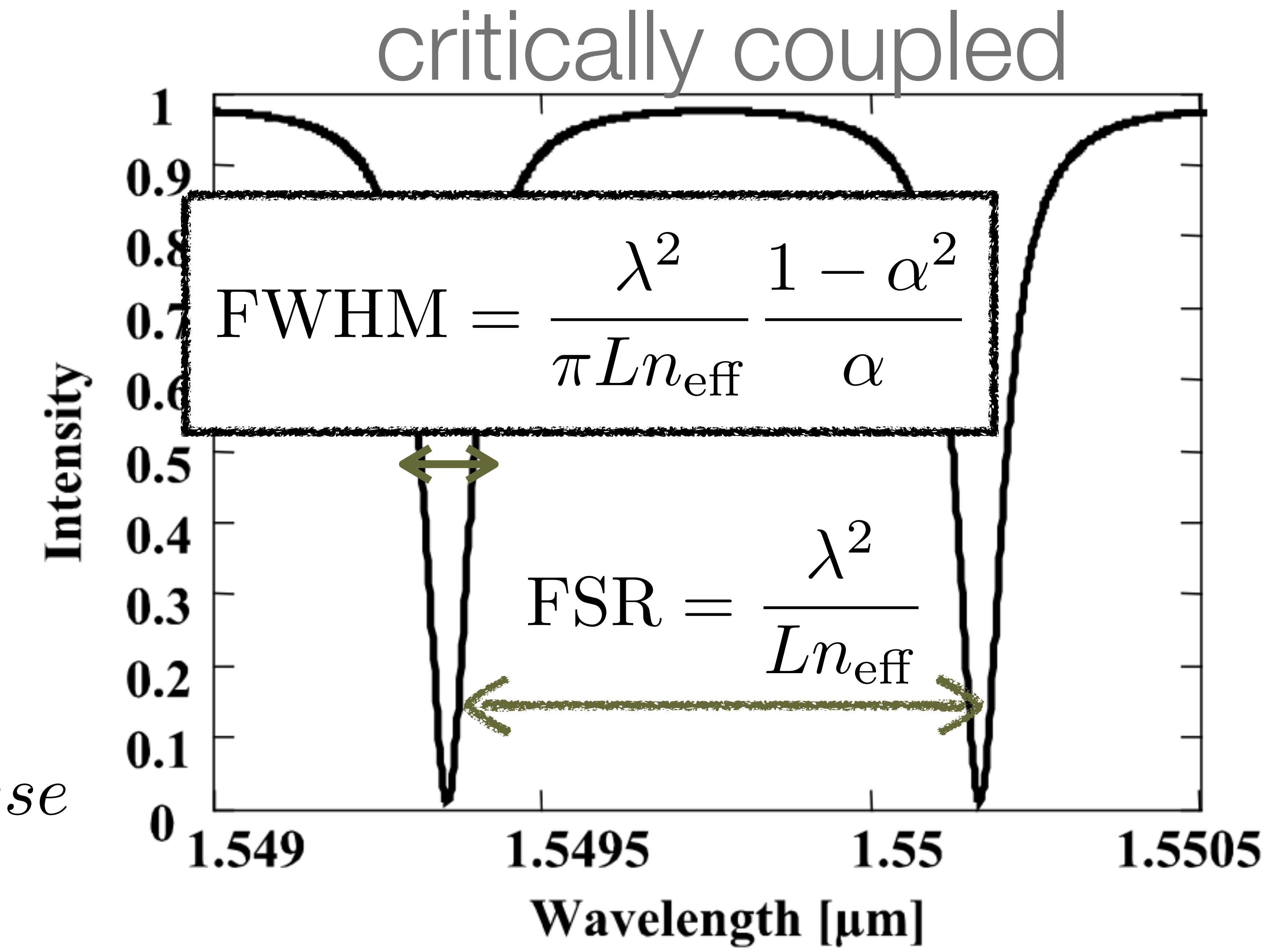
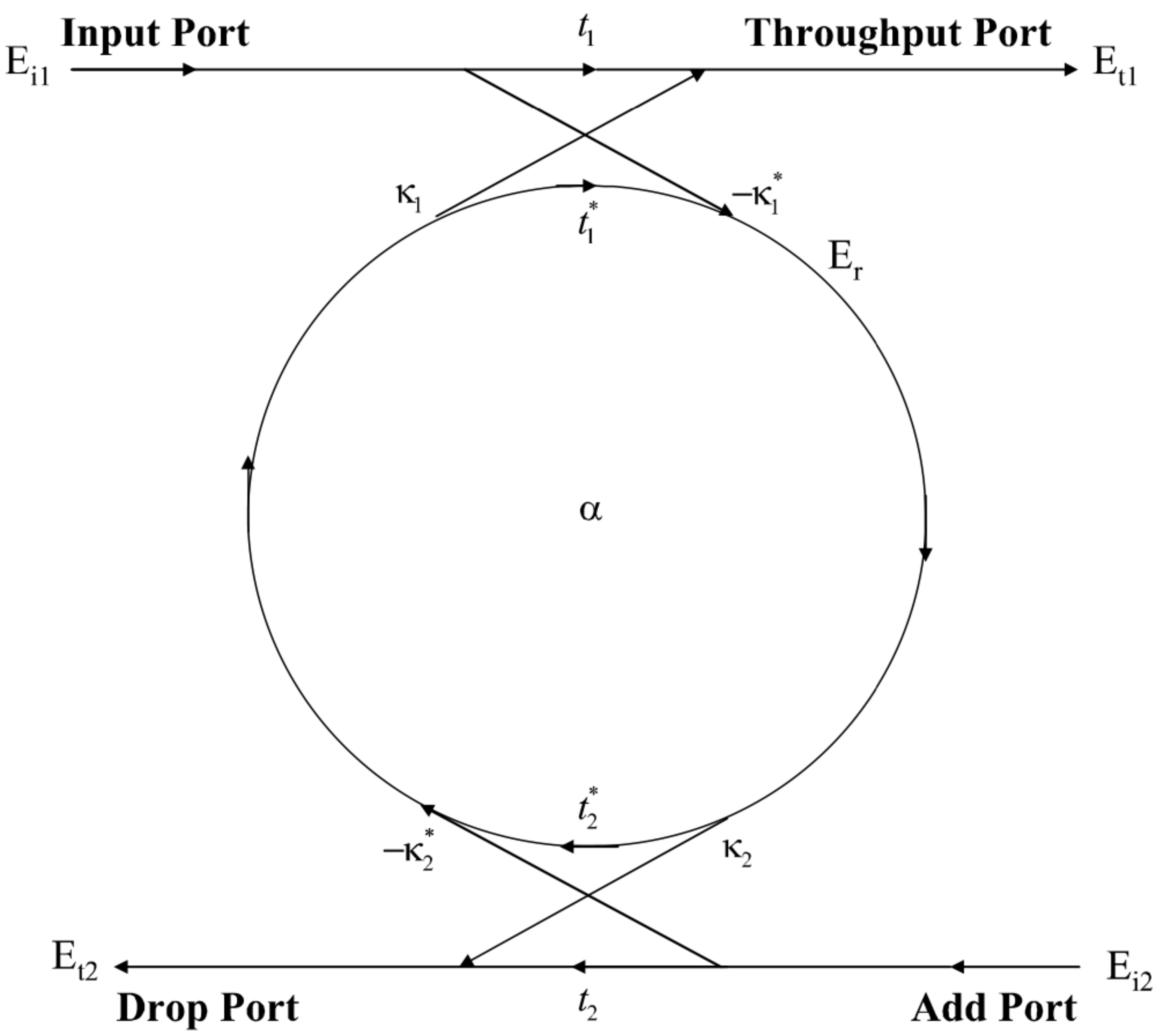


$$Finesse = \frac{\text{FSR}}{\text{FWHM}} = \frac{1-\alpha^2}{\alpha\pi} \qquad Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}} L}{\lambda} finesse$$

Ring Resonator



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