Title: Dark Matter Search on Chips

Speakers: Christina Gao

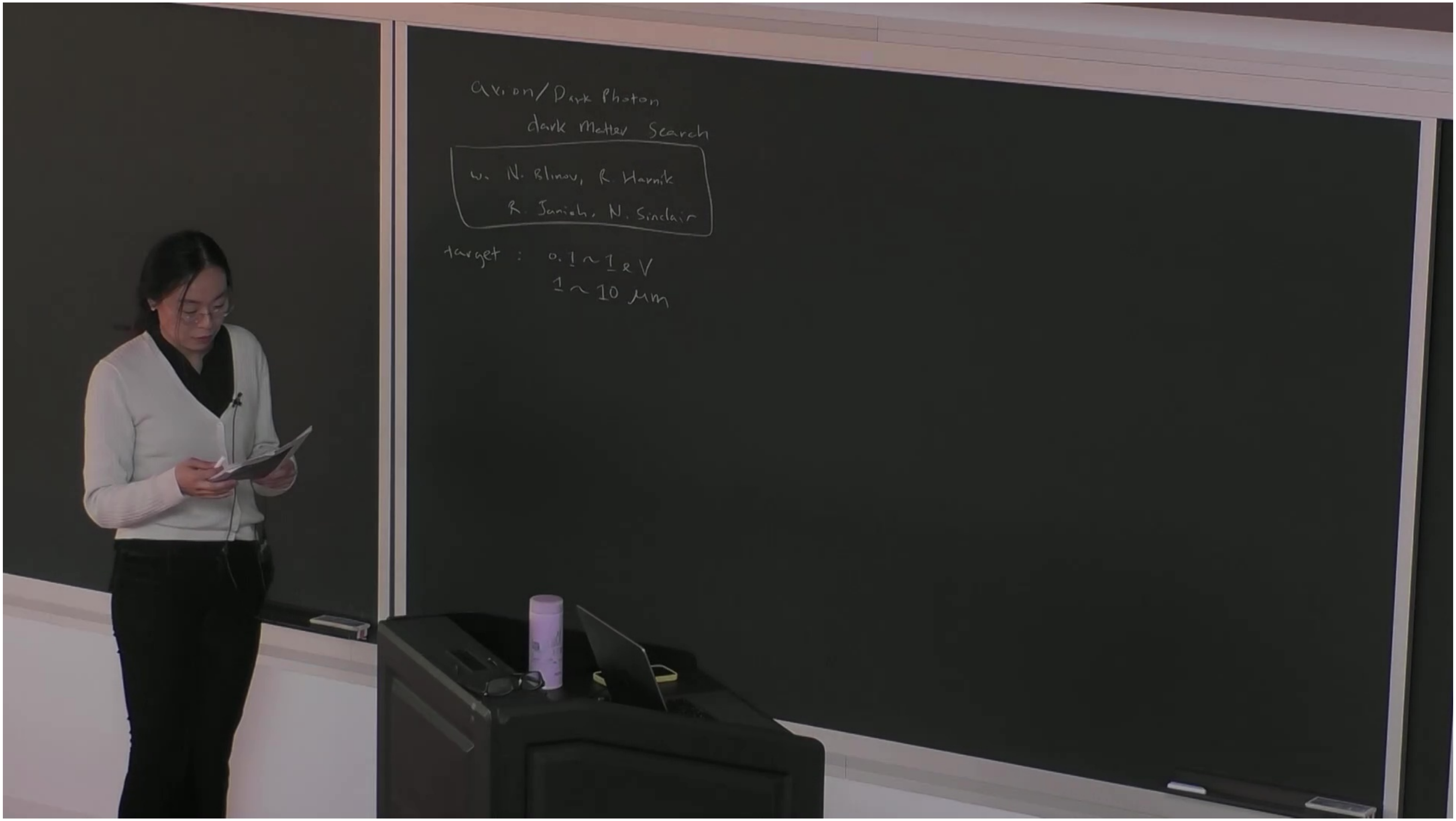
Series: Particle Physics

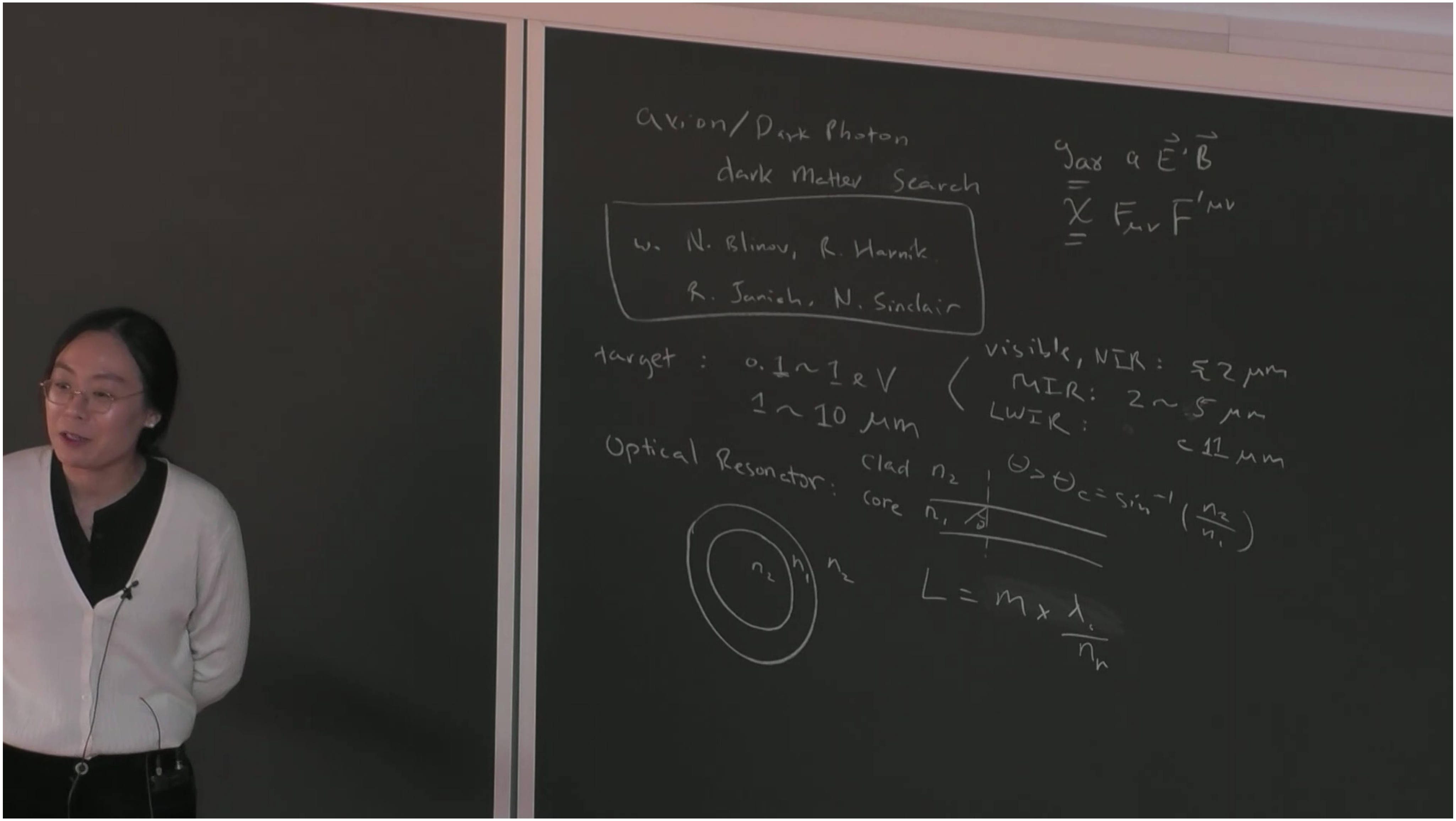
Date: November 03, 2023 - 1:00 PM

URL: https://pirsa.org/23110047

Abstract: Axions and axion-like particles are well motivated candidates for dark matter (DM) and have a signature two photon vertex. The most sensitive axion DM search is at the gigahertz (GHz) regime. It relies on microwave cavities with high quality factors resonantly converting axion DM to cavity photons in the background of a static magnetic field. However, axion DM mass could span a vast range above or below GHz. We describe a new proposal using integrated/on-chip photonic systems to search for axion DM at the optical frequency. This enables the use of waveguides to collect signal photons, which improves the detection efficiency, as well as the use of single photon, micron-sized detector, such as a skipper charge-coupled device, which has a dark count rate as low as 1e-9 per second per pixel. Furthermore, by coupling a series of resonators of different frequencies to a single receiver bus, the detection can be broadband in terms of the axion masses and has sensitivities to the axion-photon couplings expected for the QCD axion at the axion masses of around 0.2 eV.

Zoom link https://pitp.zoom.us/j/94515300239?pwd=VVBkaGM5K24yN2F4SFV0MGZ5Vk9LZz09


axion/Dark Photon
dark Matter Search
w. N. Blinov, R. Harnik
R. Janish, N. Sinclair
target : 0.1 ~ 1 eV
1 ~ 10 μm



axion/Dark Photon
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w. N. Blinov, R. Harnik
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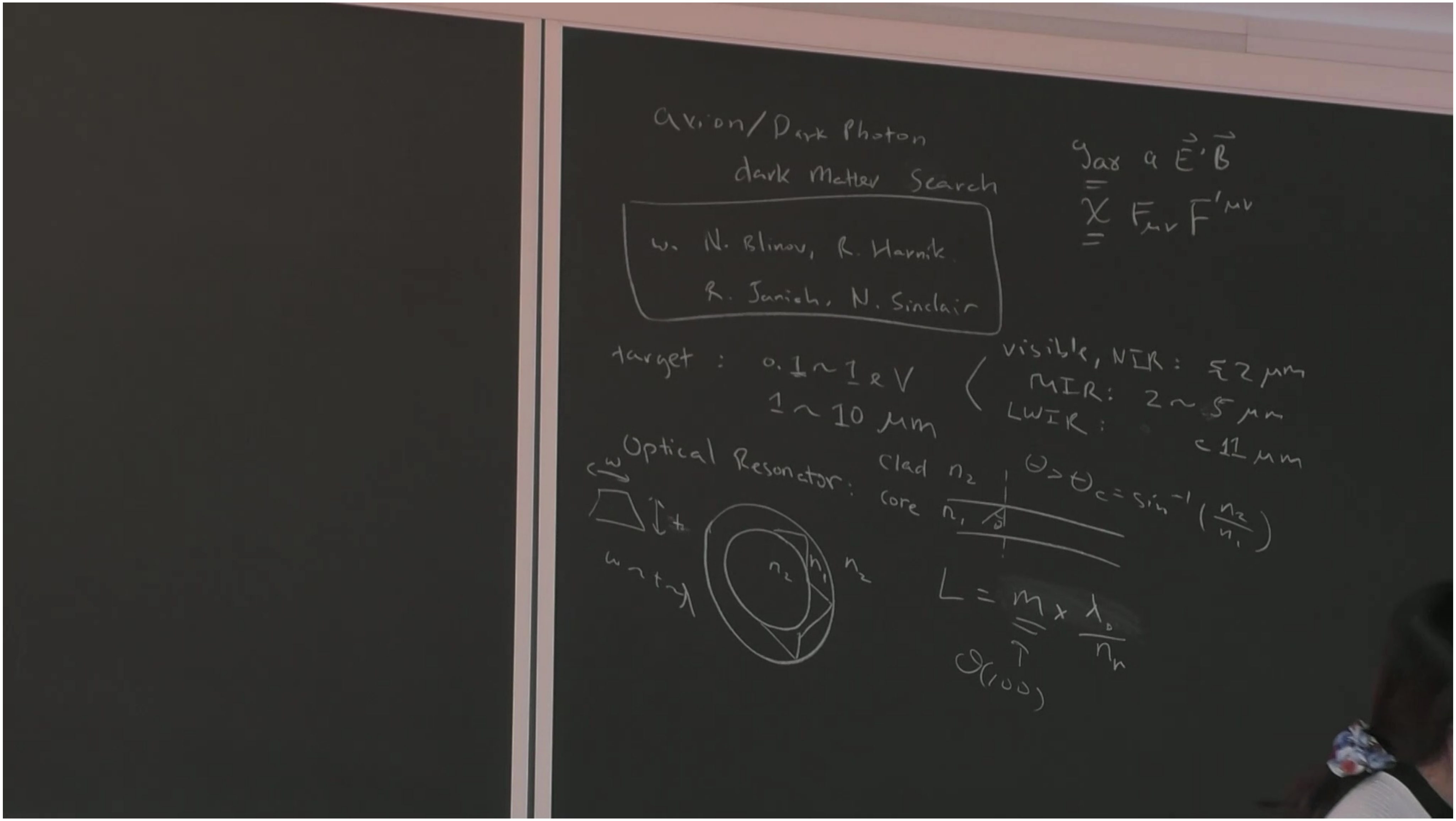
$g_{a\gamma\gamma}\, a\, \vec{E}\cdot\vec{B}$
$\chi\, F_{\mu\nu} F'^{\mu\nu}$
target : 0.1 ~ 1 eV
1 ~ 10 μm
visible, NIR: ≲ 2 μm
MIR: 2 ~ 5 μm
LWIR: < 11 μm
Optical Resonator:
Clad n_2
core n_1
$\theta > \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$
n_2 n_1 n_2
$L = m \times \frac{\lambda}{n_n}$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target : 0.1 ~ 1 eV
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visible, NIR : ≲ 2 μm
MIR : 2 ~ 5 μm
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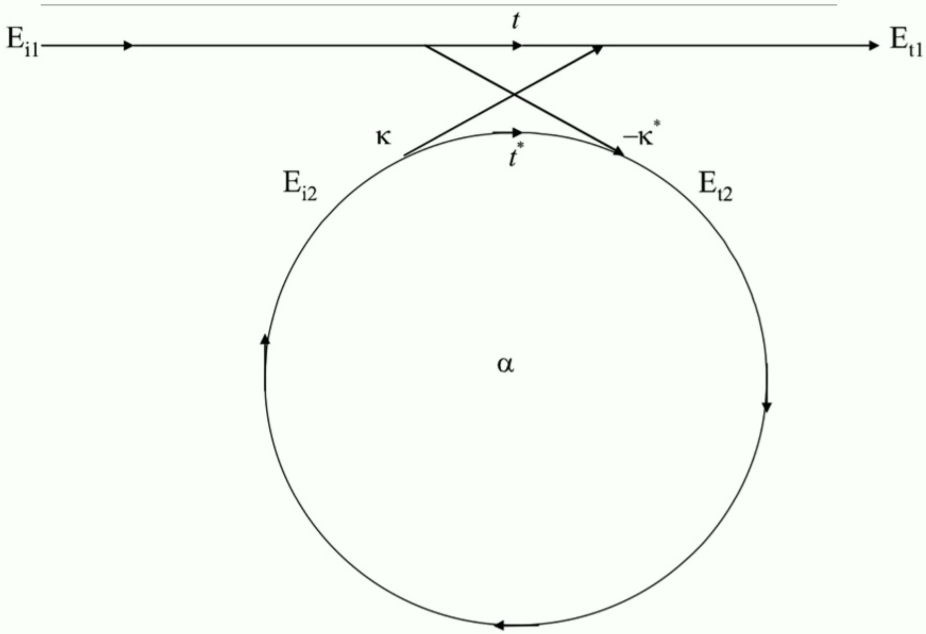
Optical Resonator:
clad n2
core n1
n2
n1
n2
L = m × λ0 / nn
O(100)

Ring Resonator



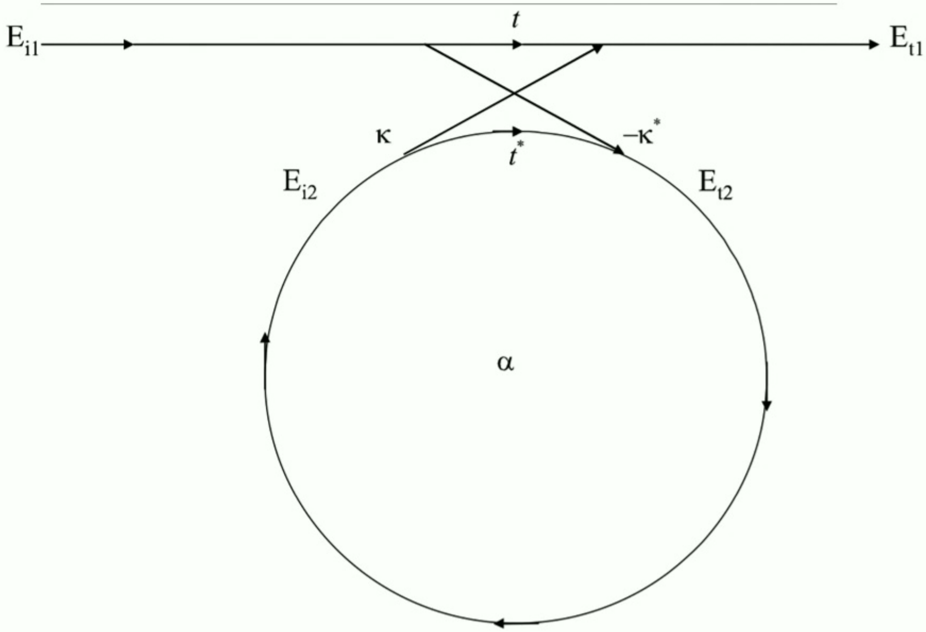
$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \qquad |\kappa^2| + |t^2| = 1$$

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

Loss

1

Ring Resonator



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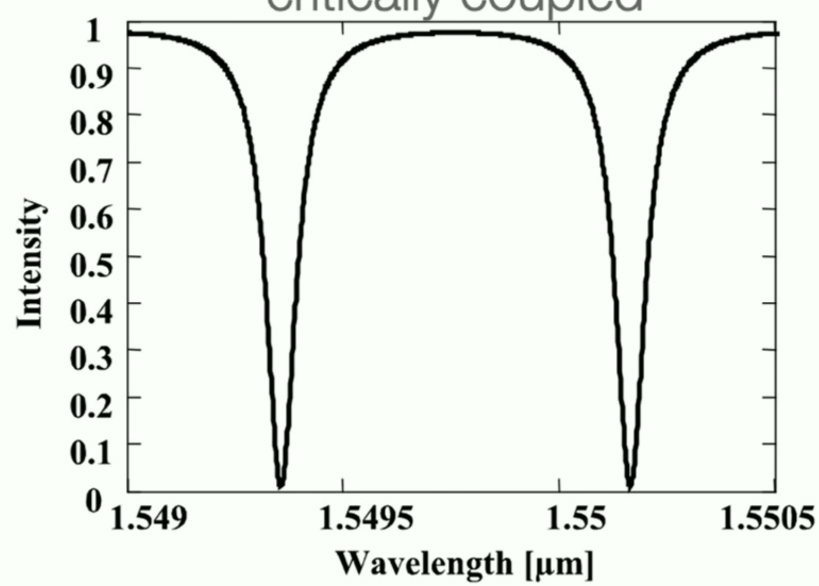
$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \qquad \theta \approx n_{\text{eff}}\omega L$$

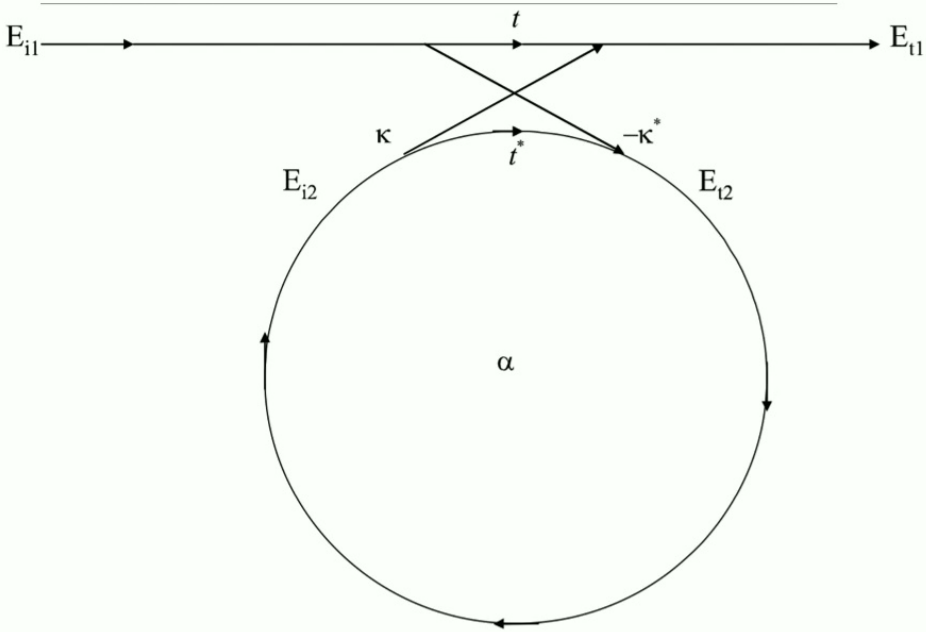
Loss

critically coupled



2

Ring Resonator



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

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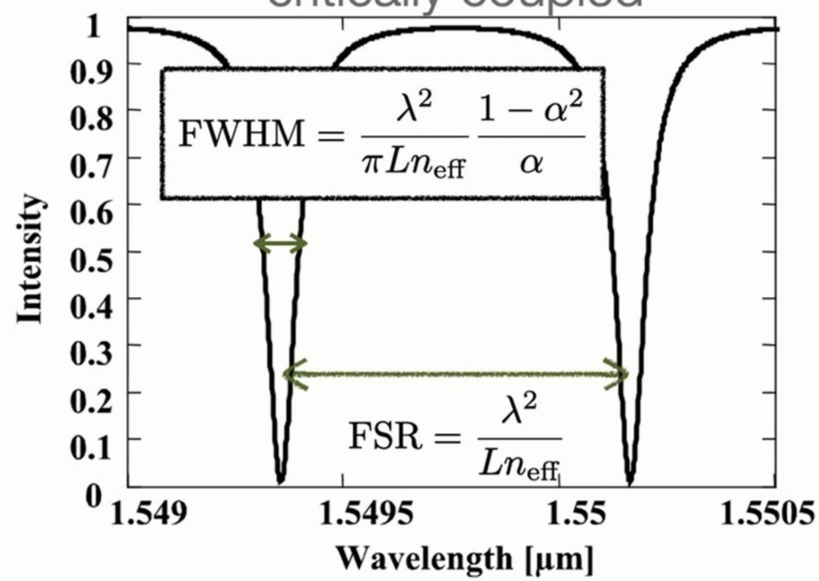
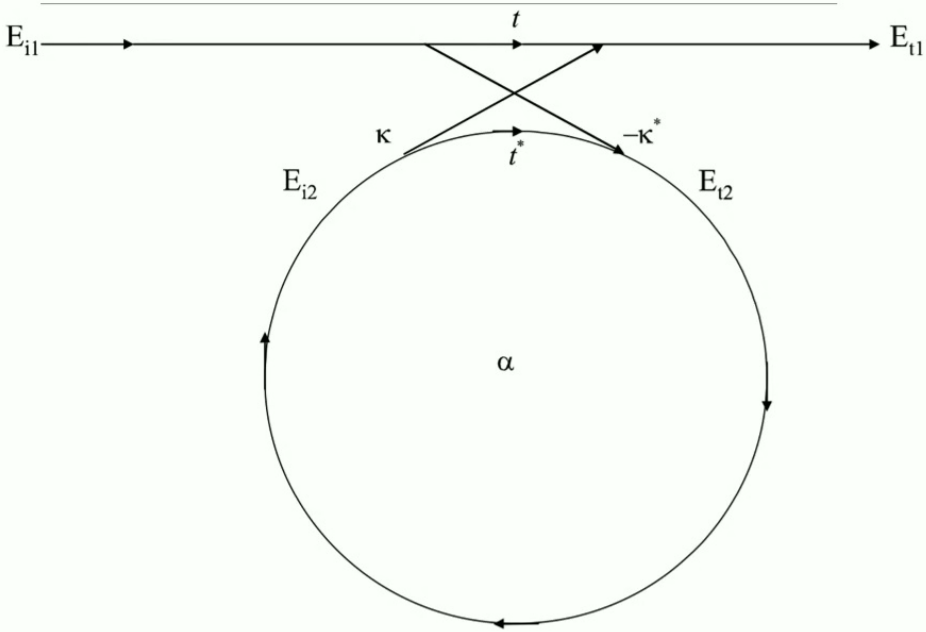
Loss

critically coupled



3

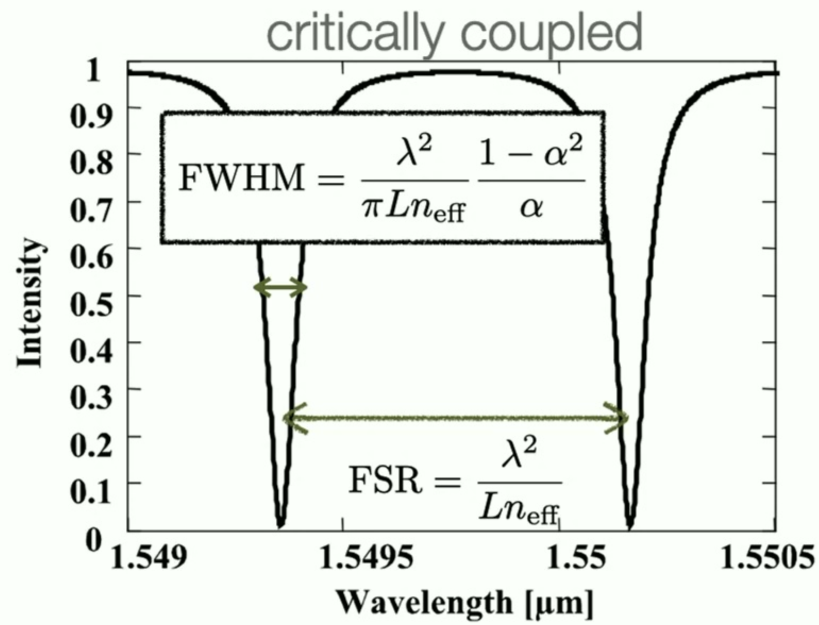
Ring Resonator



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

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

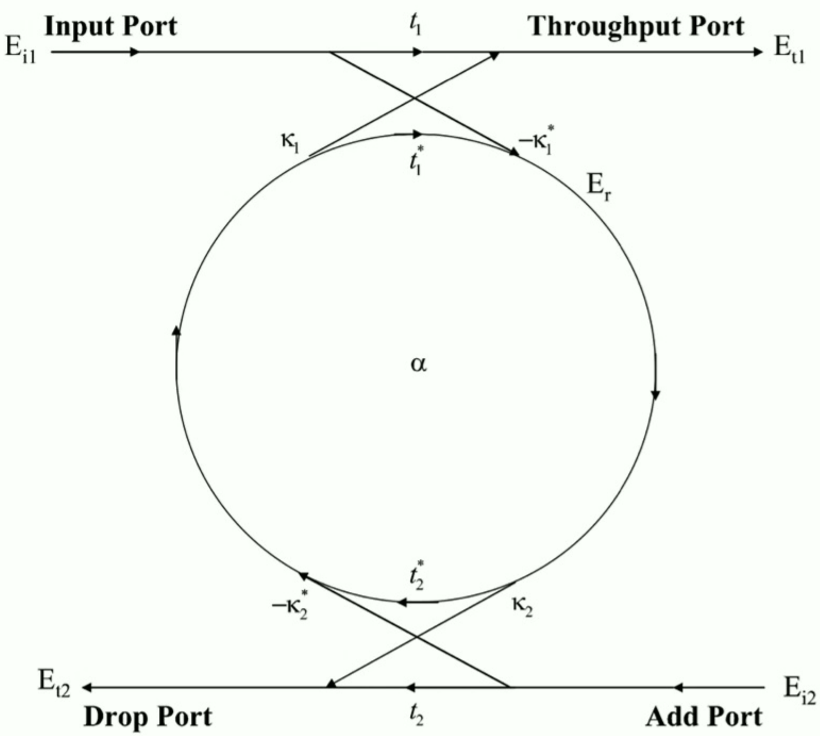
Loss



$$Finesse = \frac{\mathrm{FSR}}{\mathrm{FWHM}} = \frac{1-\alpha^2}{\alpha\pi}$$

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

Ring Resonator



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

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

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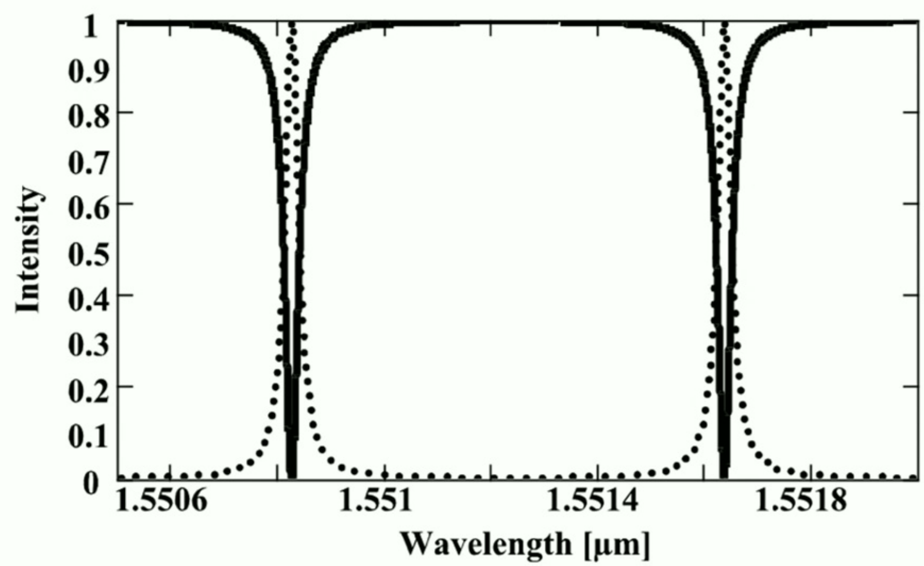
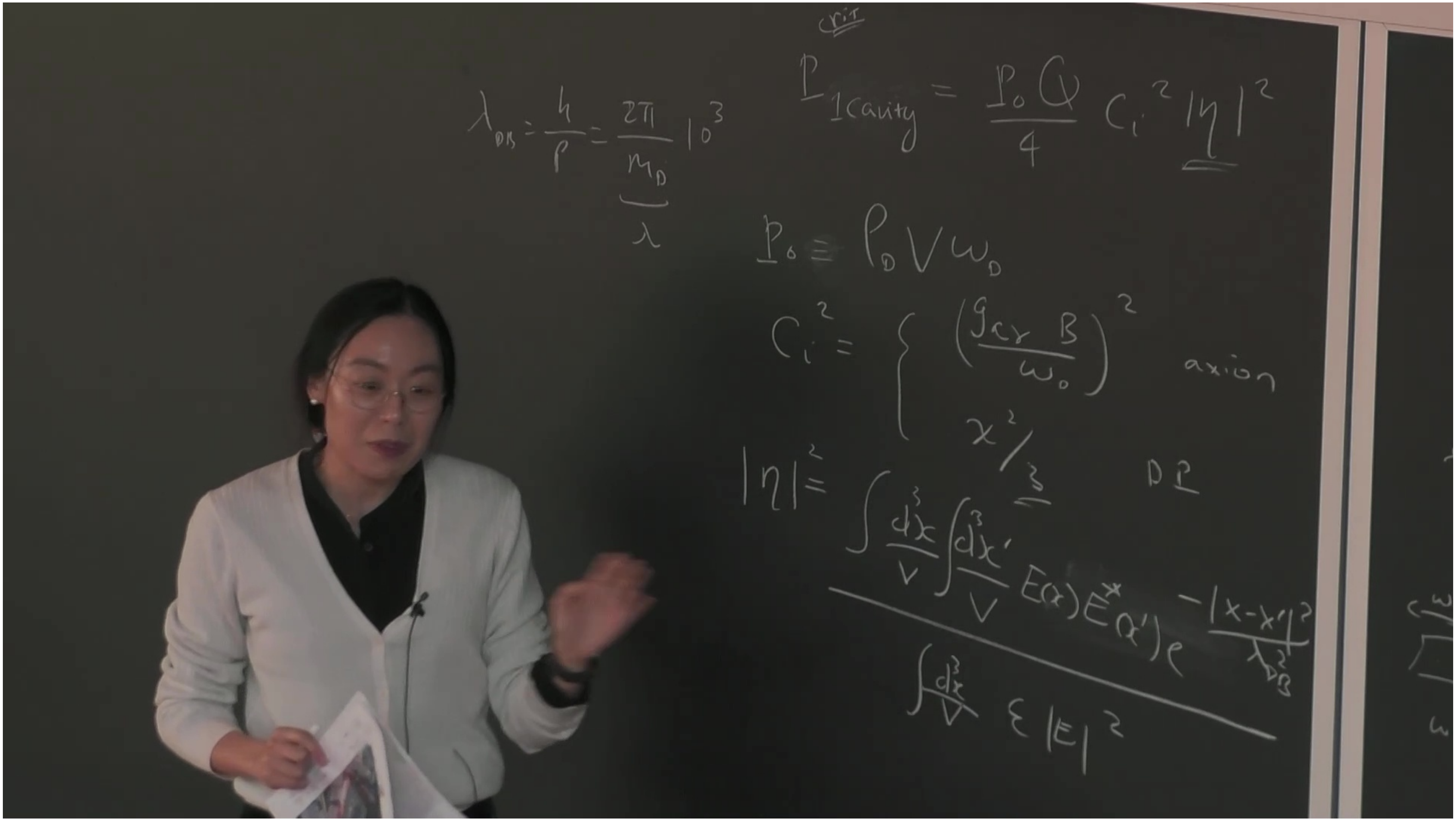
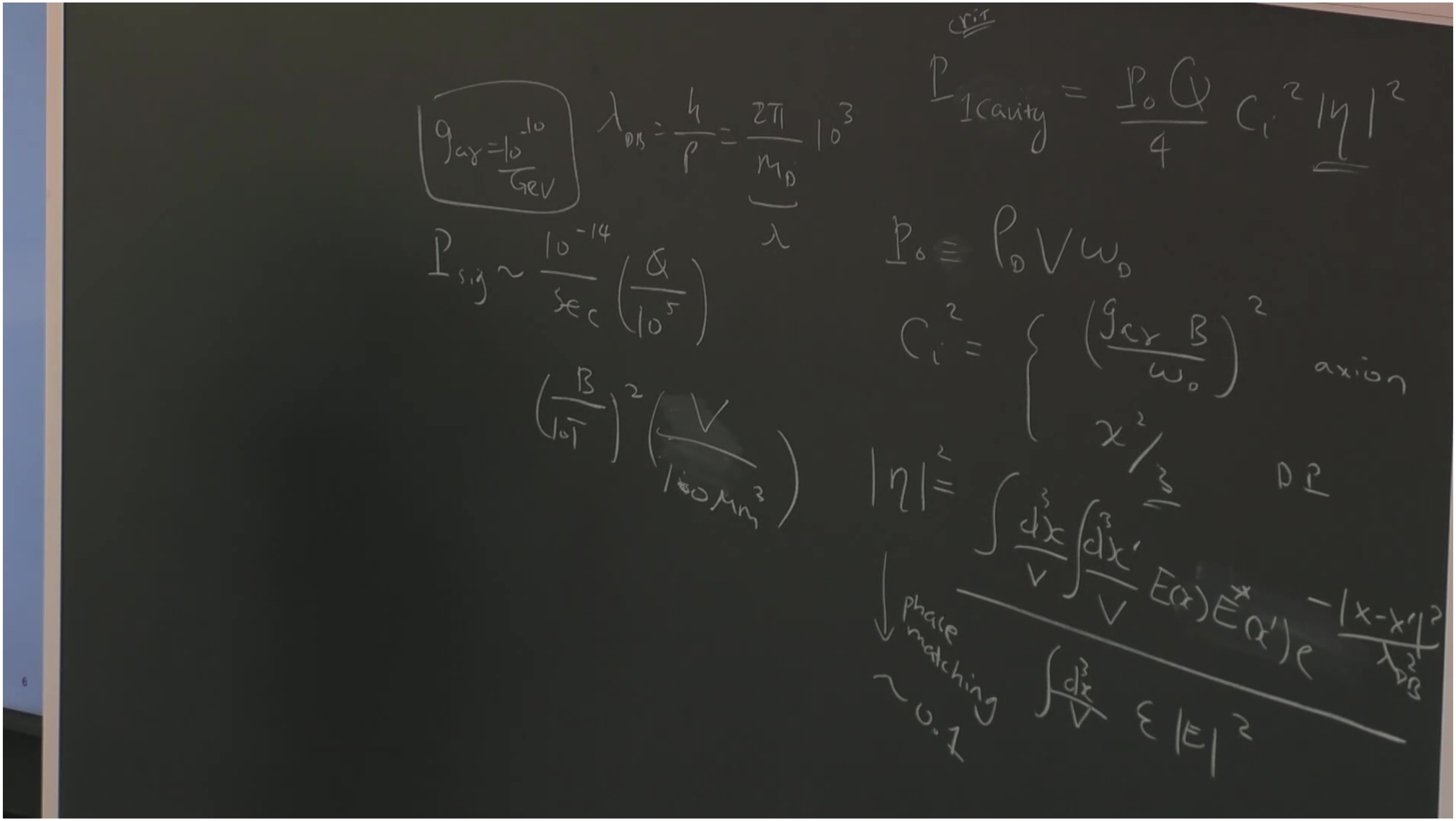
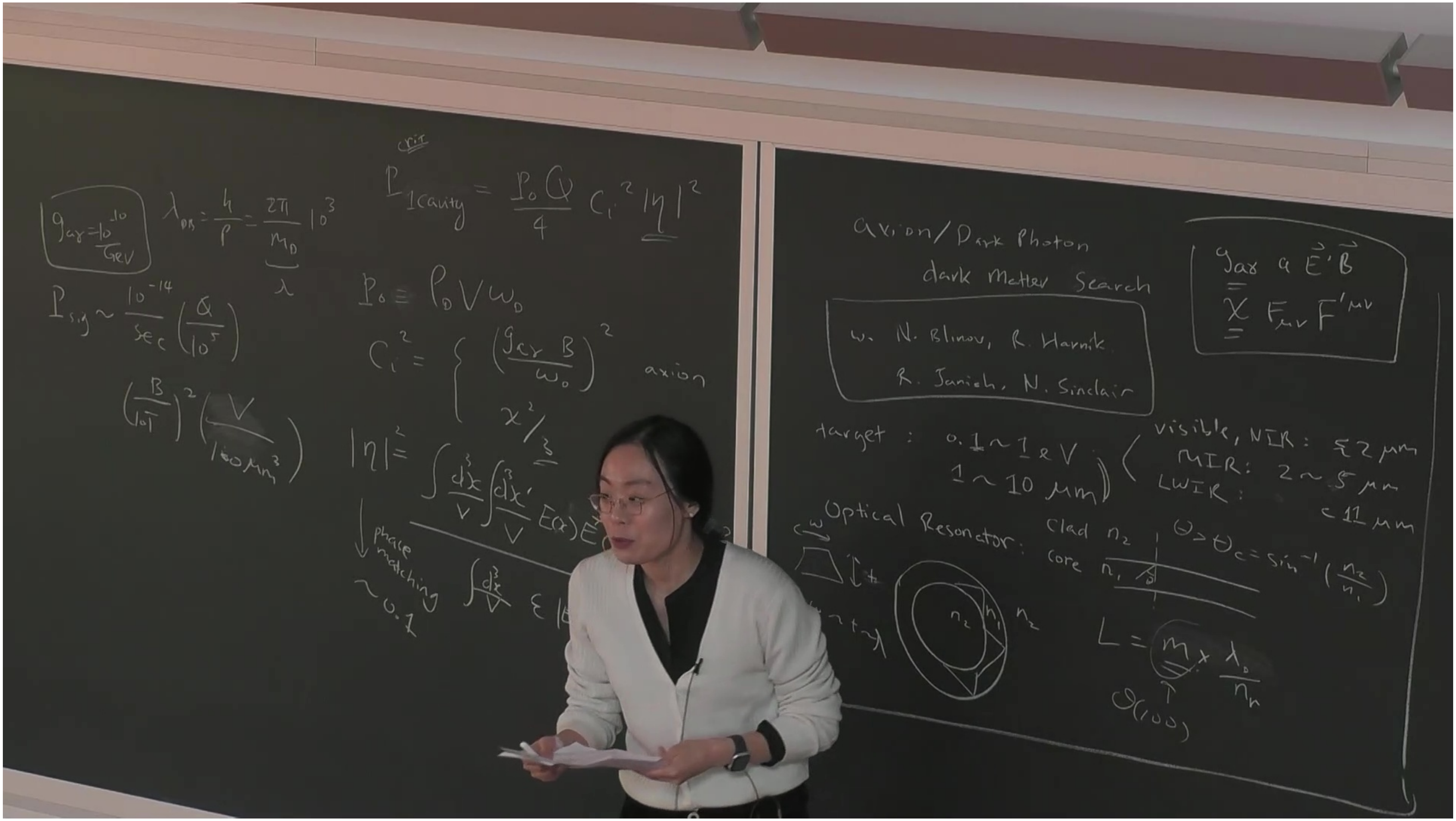
Loss



5


crit
$\lambda_{DB} = \frac{h}{p} = \frac{2\pi}{m_D} 10^3$
$P_{1\,cavity} = \frac{P_0 Q}{4} C_i^2 |\eta|^2$
$P_0 \equiv \rho_D V \omega_D$
$C_i^2 = \left(\frac{g_{a\gamma} B}{\omega_0}\right)^2$ axion
$\chi^2/3$ DP
$|\eta|^2 = \frac{\int \frac{d^3x}{V} \int \frac{d^3x'}{V} E(x) E^*(x') e^{-\frac{|x-x'|^2}{\lambda_{DB}^2}}}{\int \frac{d^3x}{V} \varepsilon |E|^2}$


$g_{a\gamma} = 10^{-10}/\text{GeV}$
$\lambda_{DB} = h/p = \frac{2\pi}{m_D} 10^3$
λ
$P_{sig} \sim \frac{10^{-14}}{sec} \left(\frac{Q}{10^5}\right) \left(\frac{B}{10T}\right)^2 \left(\frac{V}{100 \mu m^3}\right)$
crit
$P_{1 cavity} = \frac{P_0 Q}{4} C_i^2 |\eta|^2$
$P_0 \equiv \rho_D V \omega_D$
$C_i^2 = \left\{ \left(\frac{g_{a\gamma} B}{\omega_0}\right)^2 \right.$ axion
$\chi^2/3$ DP
$|\eta|^2 = \frac{\int \frac{d^3x}{V} \int \frac{d^3x'}{V} E(x) E^*(x') e^{-|x-x'|^2/\lambda_{DB}^2}}{\int \frac{d^3x}{V} \varepsilon |E|^2}$
phase matching
~ 0.1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axion
target : 0.1 ~ 1 eV
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visible, NIR: ≲ 2 μm
MIR: 2 ~ 5 μm
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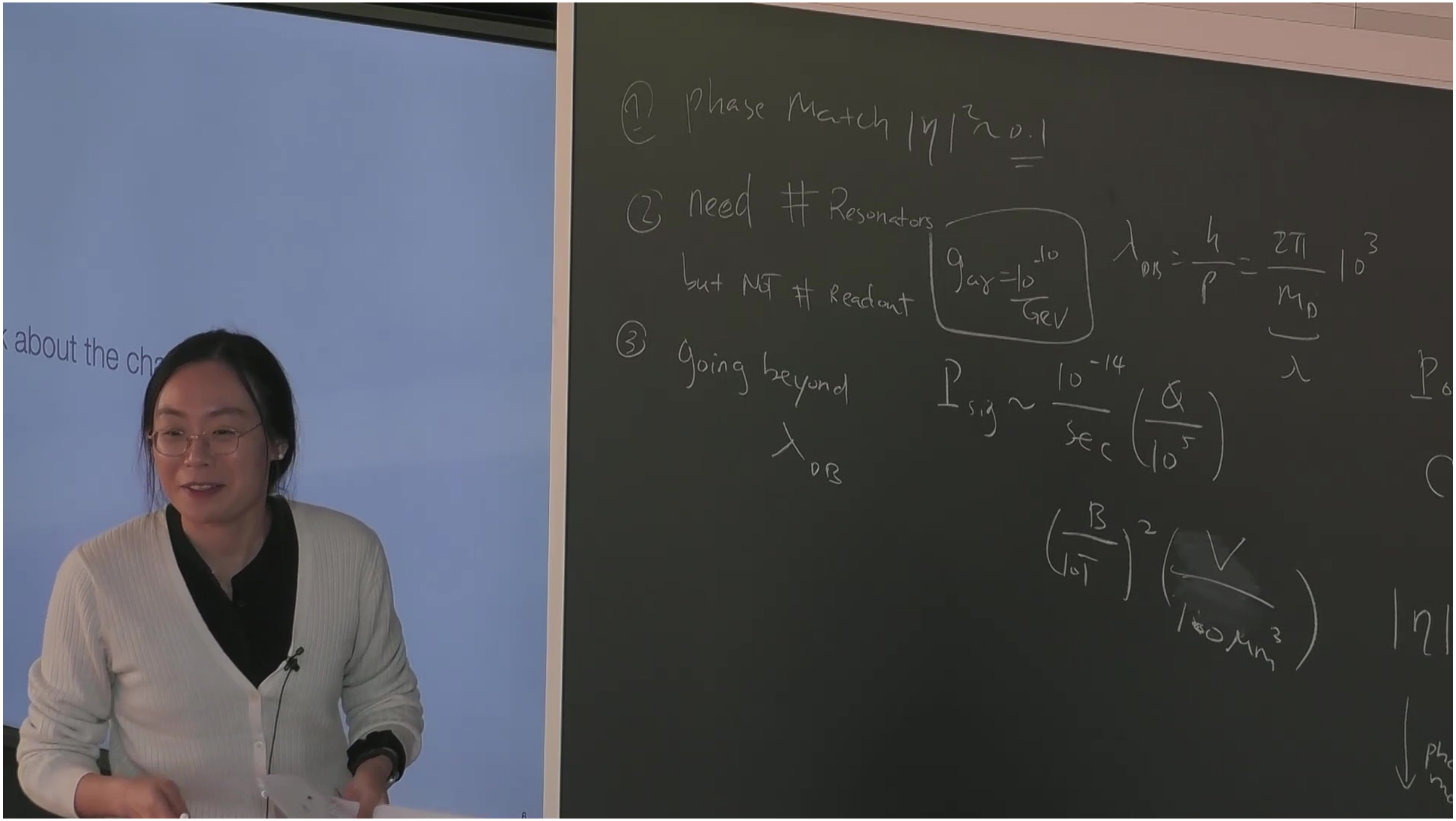
Optical Resonator:
Clad n2
Core n1
phase matching
~ 0.1


about the cha
① phase Match |η|² ~ 0.1
② need # Resonators
but NOT # Readout
g_aγ = 10^-10 / GeV
λ_DB = h/p = 2π/m_D 10³
λ
③ Going beyond
λ_DB
P_sig ~ 10^-14 / sec (Q/10⁵)
(B/10T)² (V/100 mm³)

Periodic Photonic Structure: Bloch Modes

$$\mathbf{E_K} = \mathbf{u_K}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}}\ , \quad \mathbf{u_K}(\mathbf{r}) = \mathbf{u_K}(\mathbf{r}+\mathbf{R}) \qquad \varepsilon(r) = \varepsilon(r+R)$$

Bloch wavevector — Lattice vector

8

Periodic Photonic Structure: Bloch Modes

$$\mathbf{E_K} = \mathbf{u_K}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}}\,, \quad \mathbf{u_K}(\mathbf{r}) = \mathbf{u_K}(\mathbf{r}+\mathbf{R}) \qquad \varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r}+\mathbf{R})$$

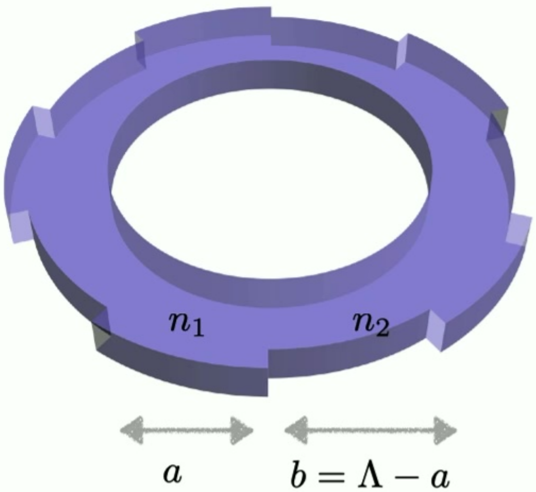
Bloch wavevector — Lattice vector

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

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

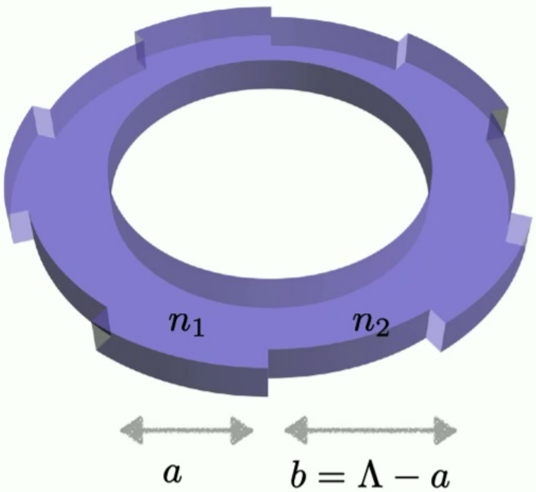
Resonator size << λ_{dB}

1D Toy Model



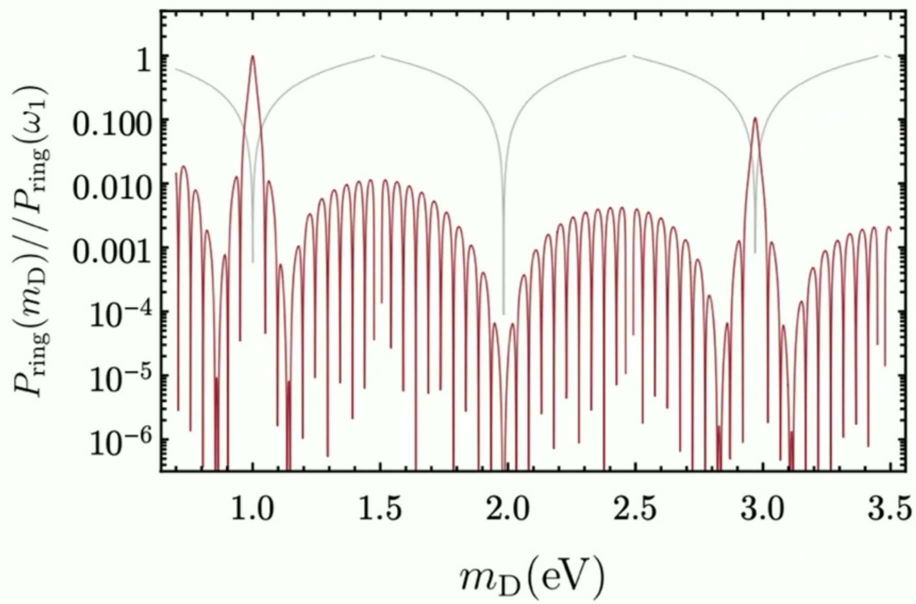
$$\beta_{1,2} = n_{1,2}\omega$$

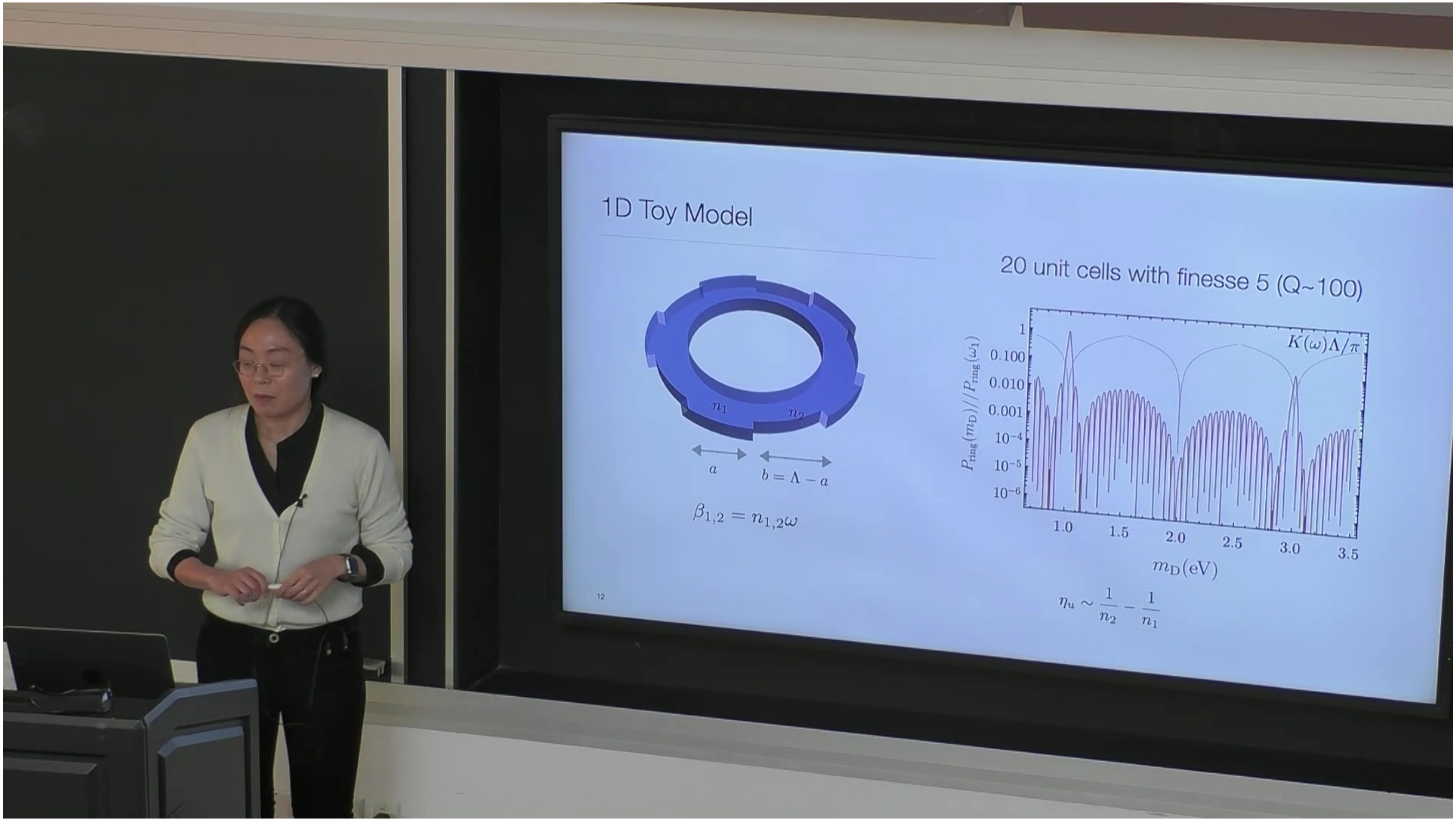
1D Toy Model



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

20 unit cells with finesse 5 (Q~100)





1D Toy Model
20 unit cells with finesse 5 (Q~100)
n_1
n_2
a
$b = \Lambda - a$
$\beta_{1,2} = n_{1,2}\omega$
$K(\omega)\Lambda/\pi$
$P_{\rm ring}(m_{\rm D})/P_{\rm ring}(\omega_1)$
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
1.0
1.5
2.0
2.5
3.0
3.5
$m_{\rm D}$(eV)
$\eta_u \sim \frac{1}{n_2} - \frac{1}{n_1}$
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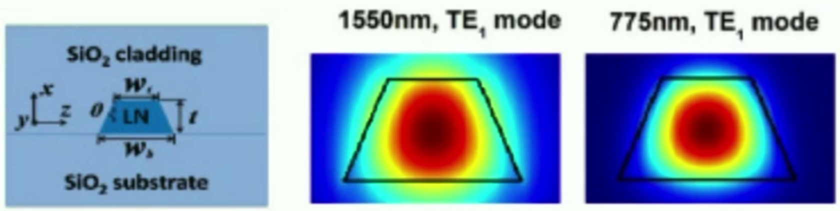
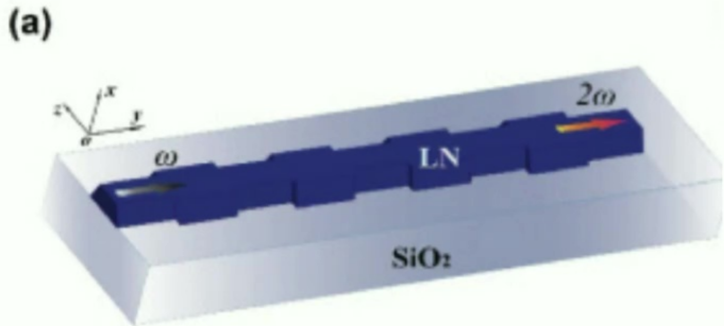
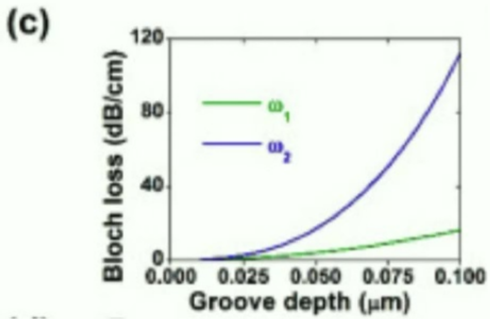
Example: Periodically Grooved LN-on-Insulator Waveguide







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

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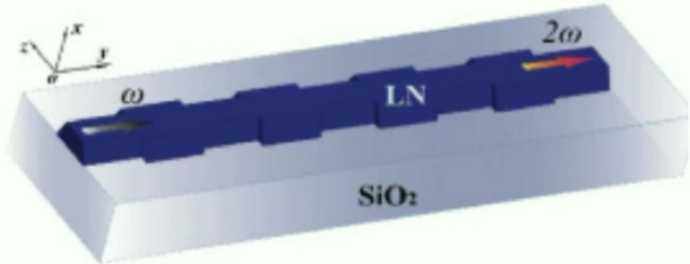
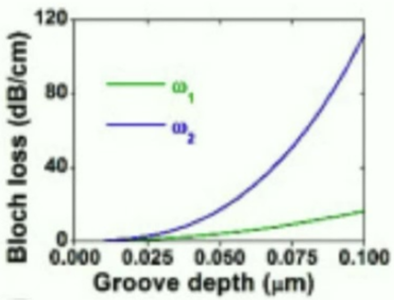
Effective Index Theory

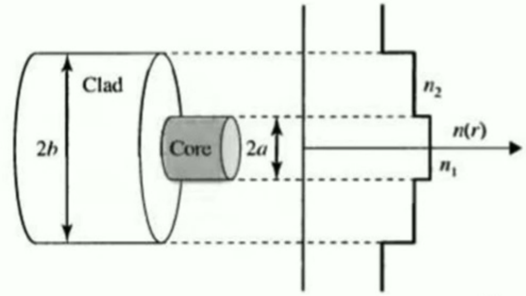
How big can n_{eff} be changed by grooving?

(a)

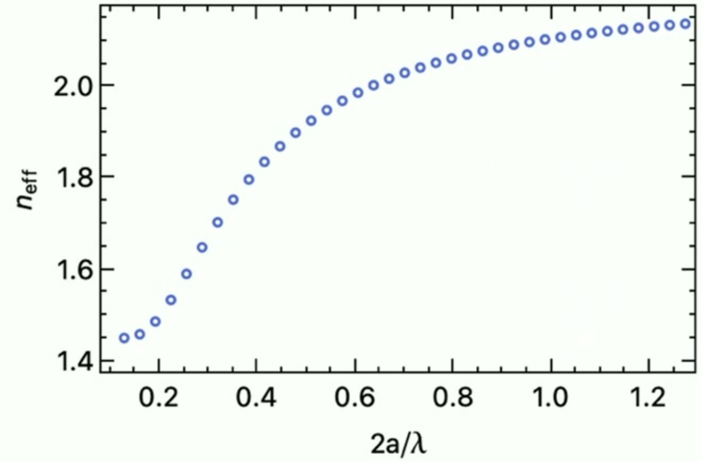


(c)



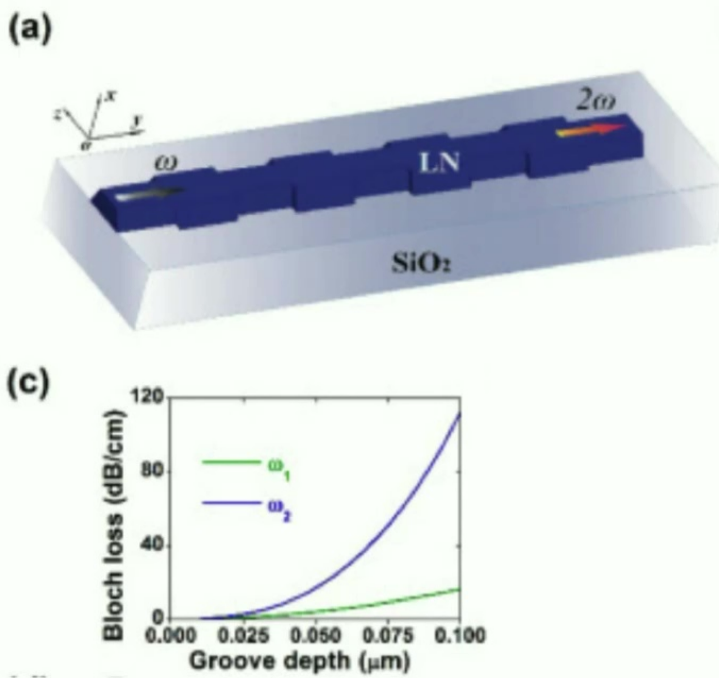


$$n_1 = 2.2, n_2 = 1.45, \mathrm{LP}_{01}$$



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

Surface Scattering Loss



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

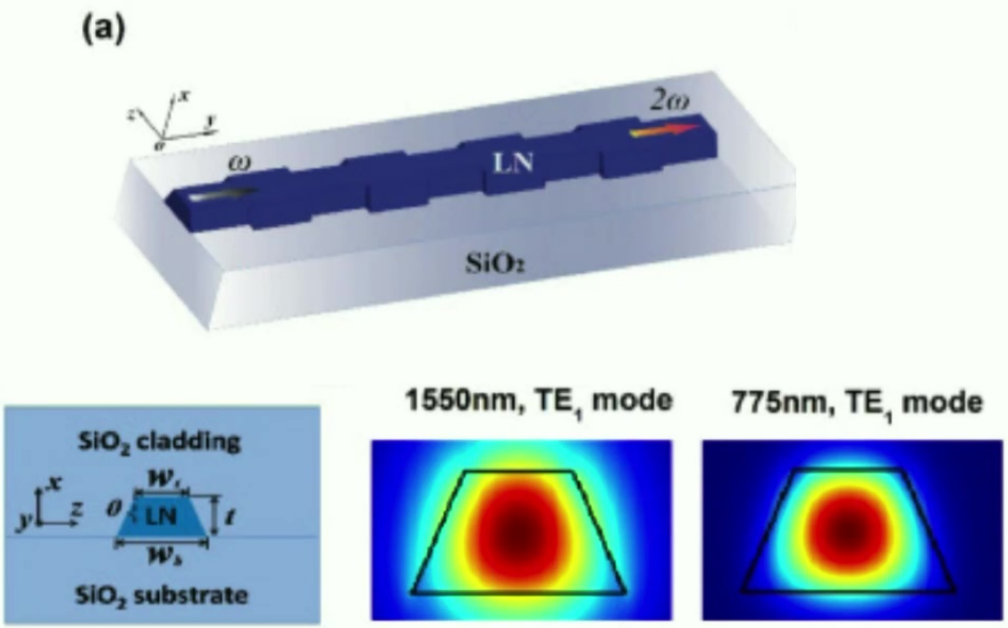
Surface Scattering Loss

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

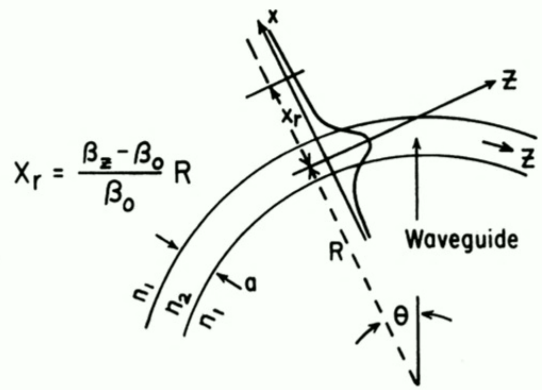
for L << 1 cm

Radiation Loss

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

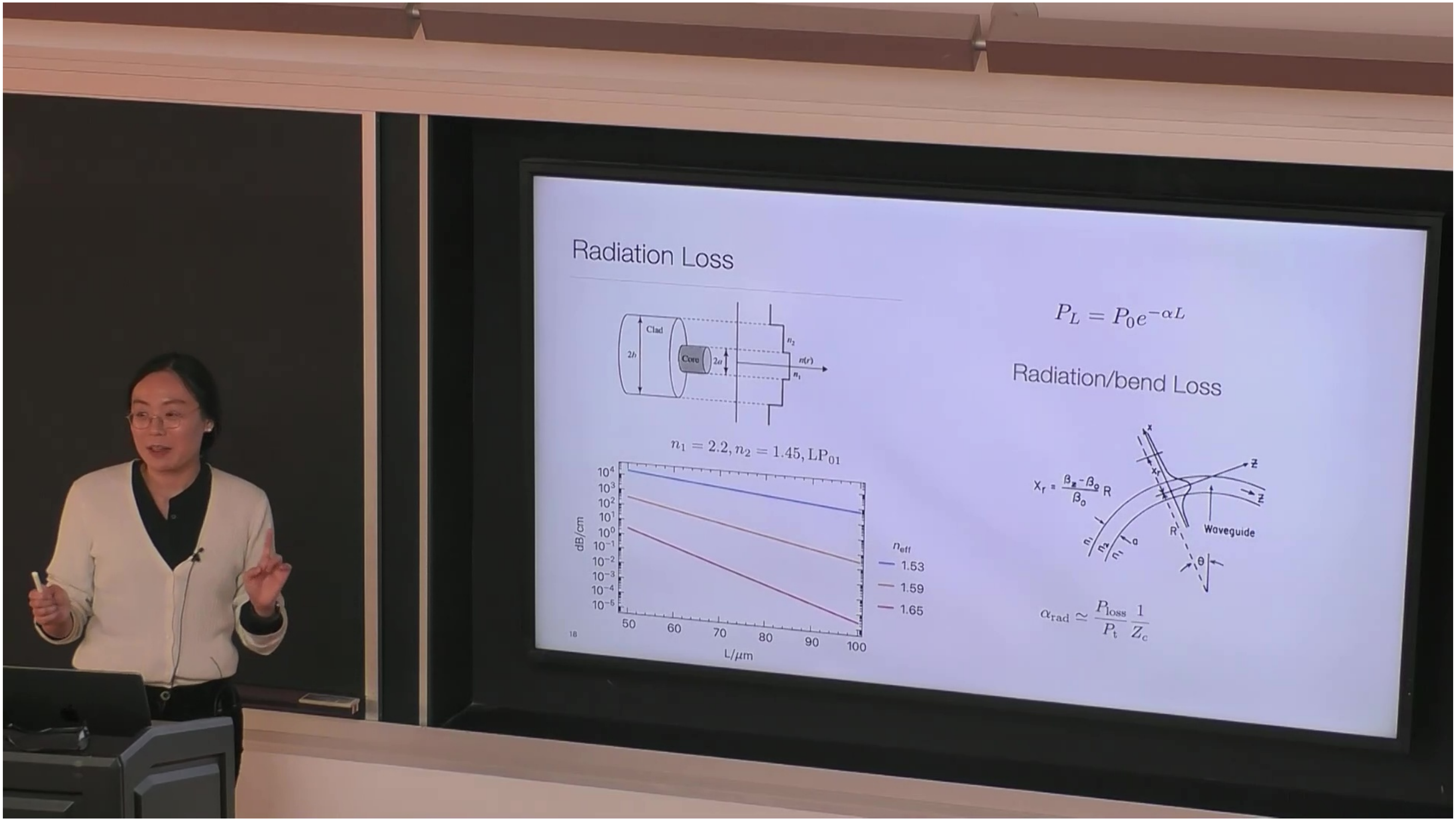


Radiation/bend Loss



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

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


Radiation Loss
Clad
Core
2b
2a
n(r)
$n_1 = 2.2, n_2 = 1.45, \mathrm{LP}_{01}$
dB/cm
L/μm
n_{eff}
1.53
1.59
1.65
$P_L = P_0 e^{-\alpha L}$
Radiation/bend Loss
$X_r = \frac{\beta_z - \beta_0}{\beta_0} R$
Waveguide
$\alpha_{\mathrm{rad}} \simeq \frac{P_{\mathrm{loss}}}{P_{\mathrm{t}}} \frac{1}{Z_c}$

Example: Si-on-Insulator Photonic Crystal Ring Resonator

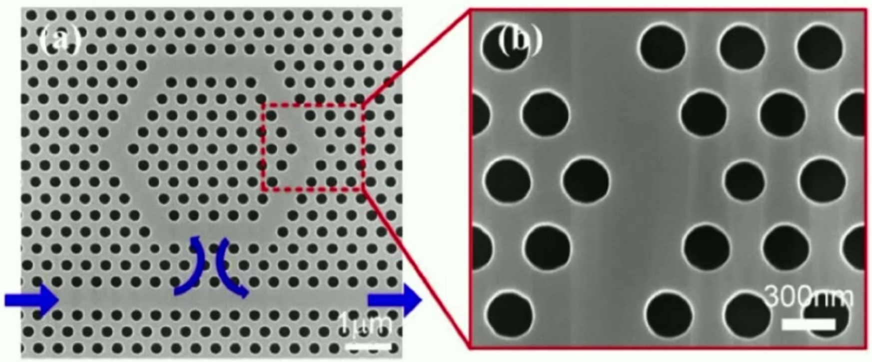
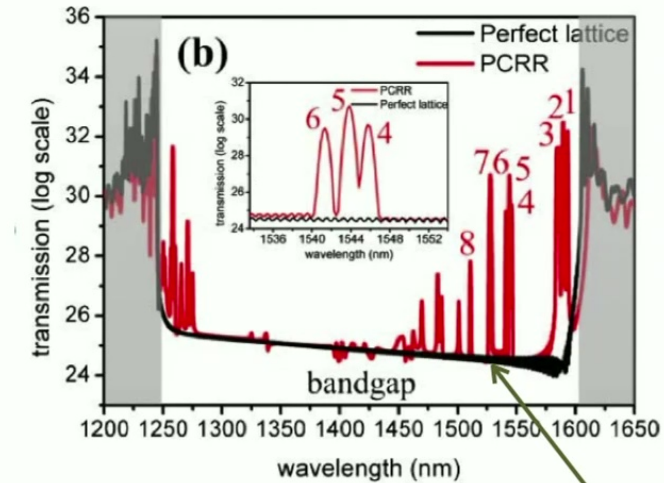
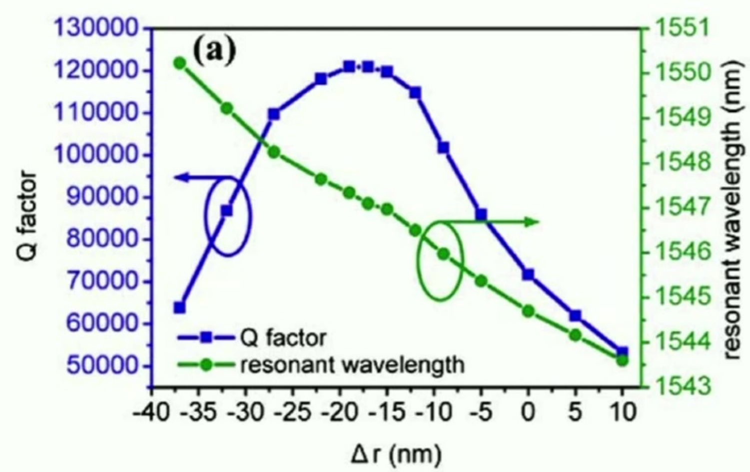


Fig. 4. (a) SEM image of the fabricated modified PCRR. (b) Magnified micrograph of the corner of the modified PCRR.





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

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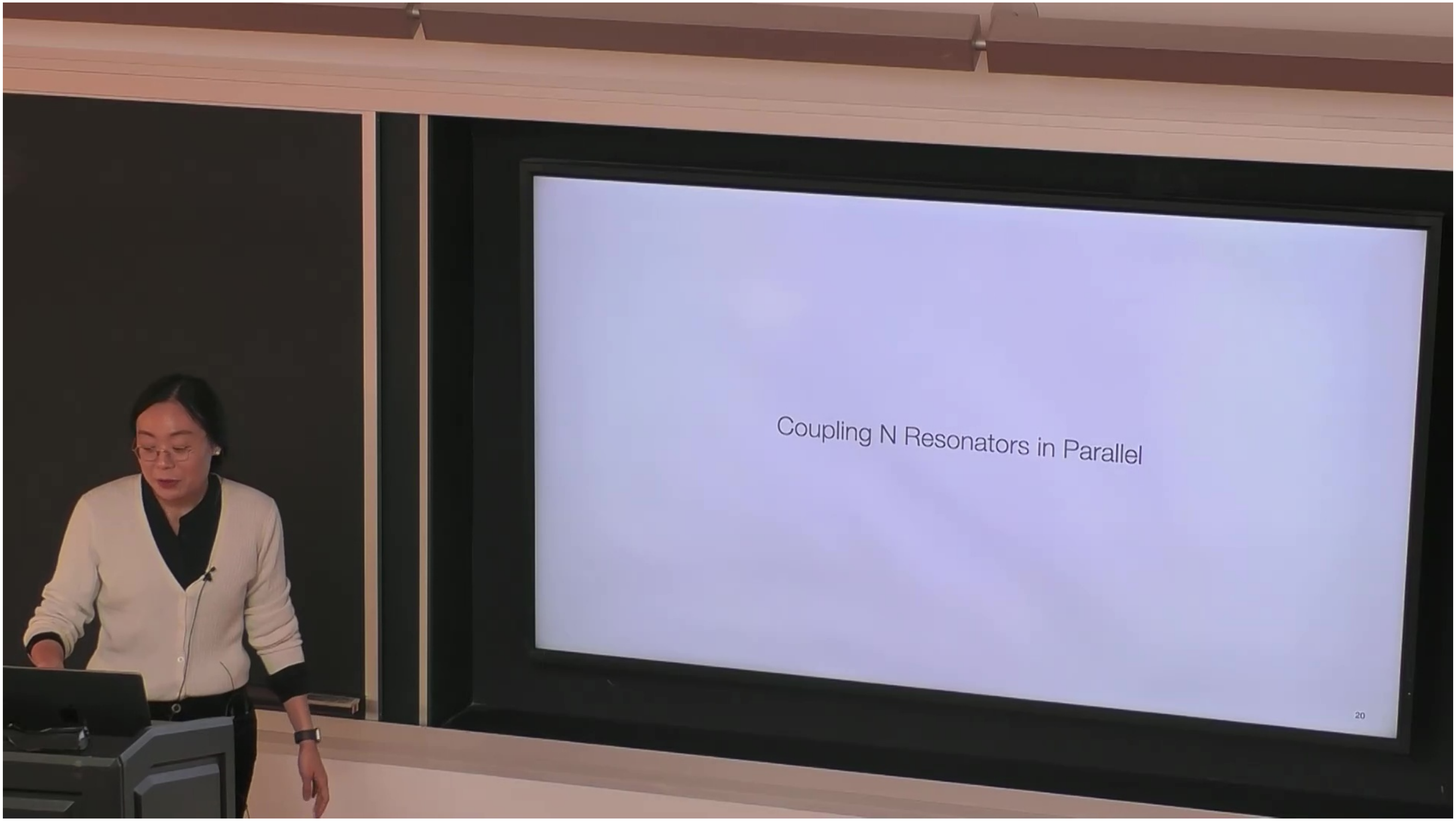
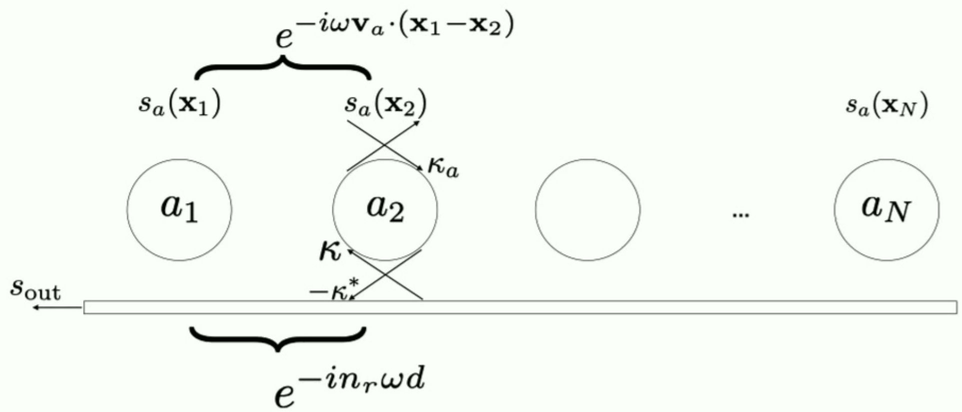
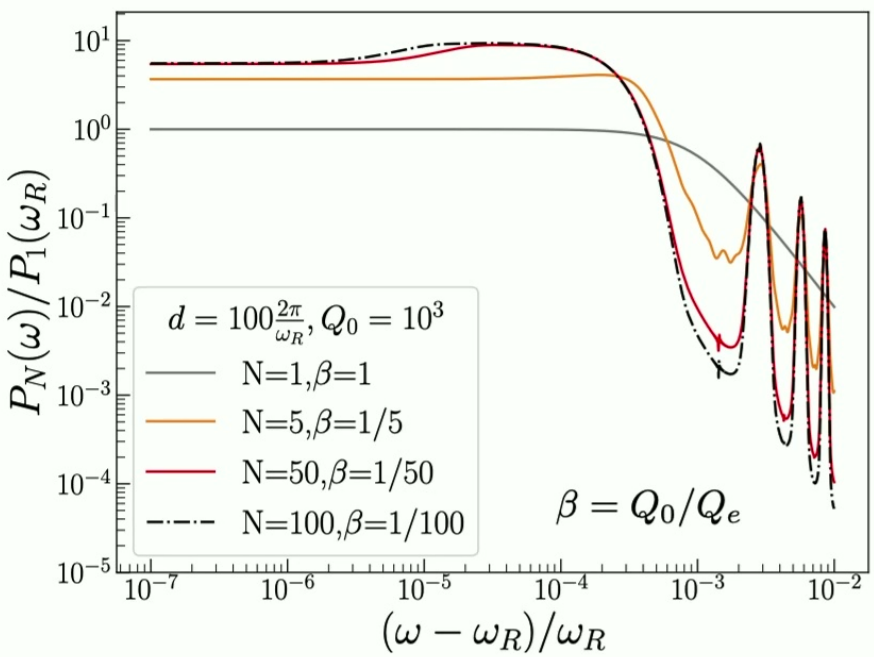

Coupling N Resonators in Parallel
20

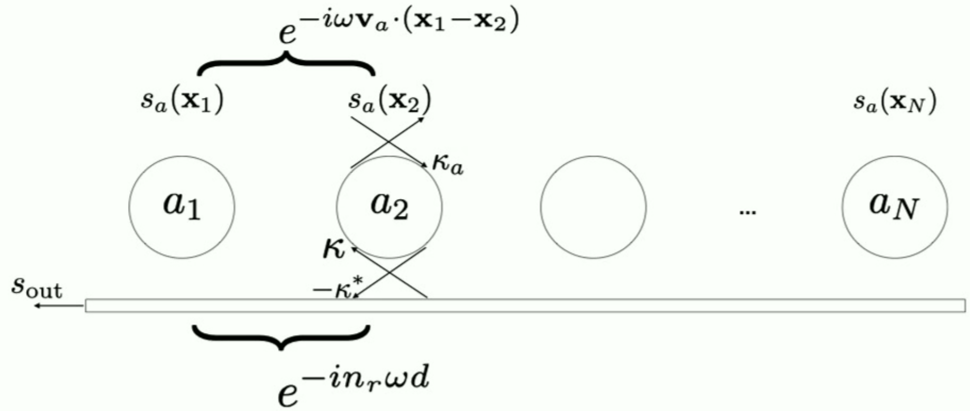
N Resonators in Parallel



- 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

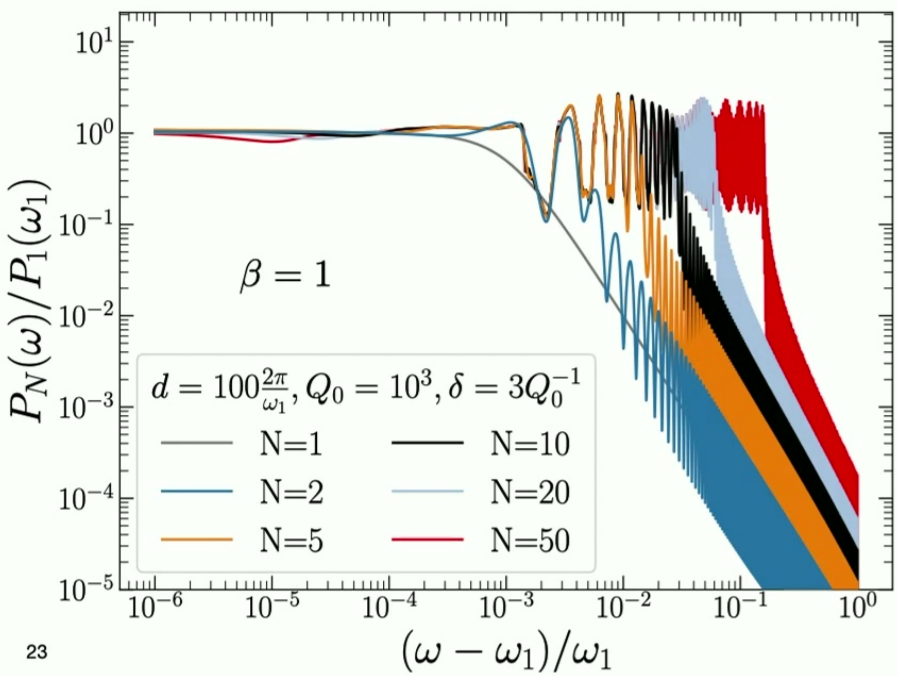


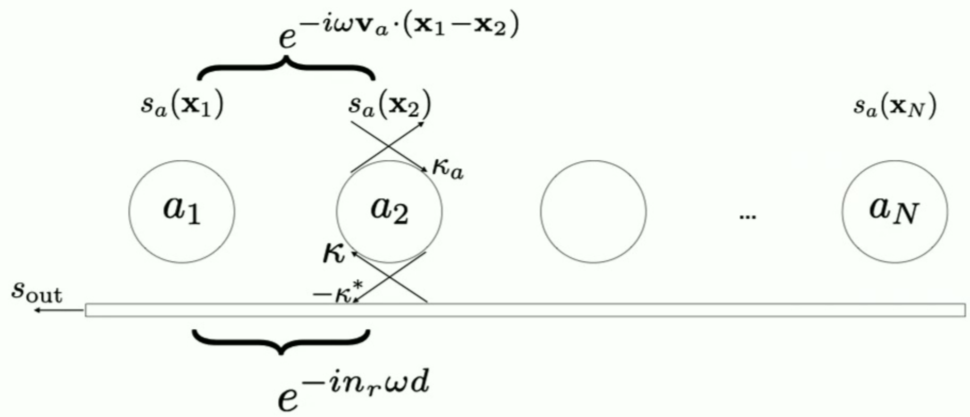


No gain after going beyond the DM coherence length.

Different Frequencies

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

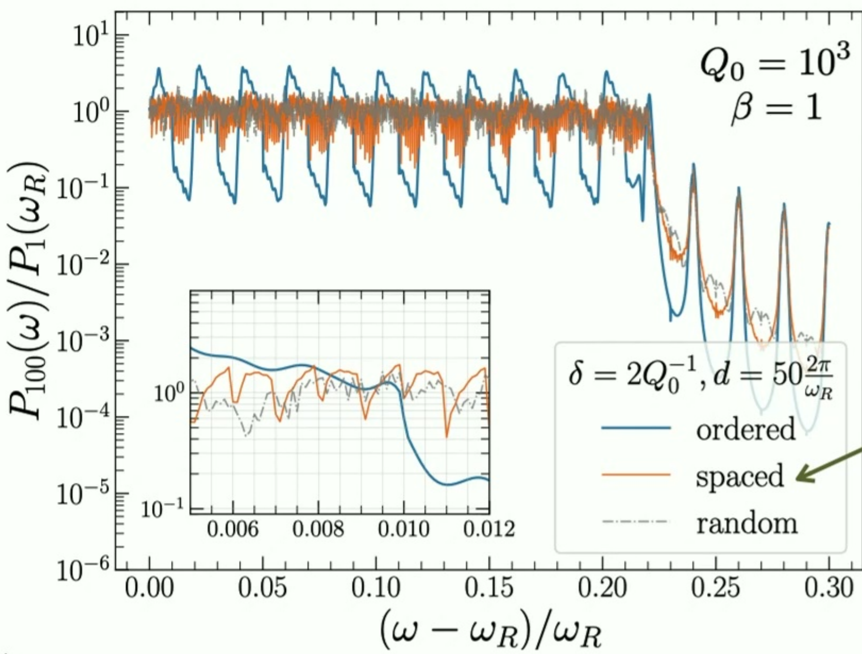


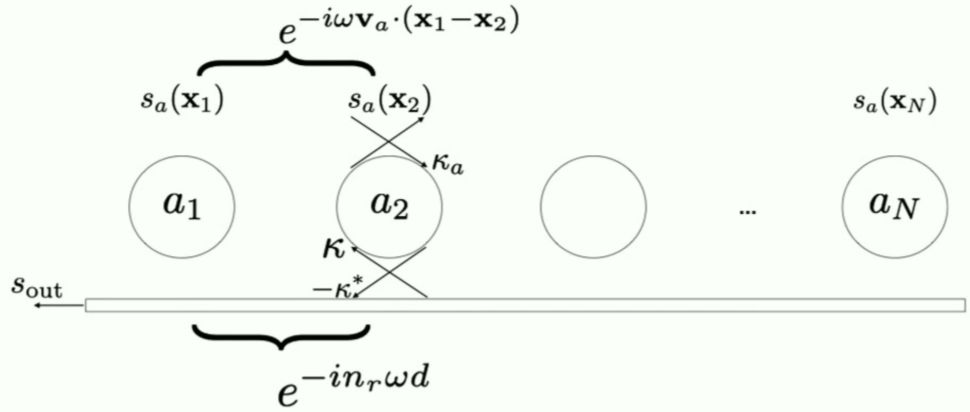


Signal width grows like $\delta \times Q_0$.

Different Frequencies

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





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

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

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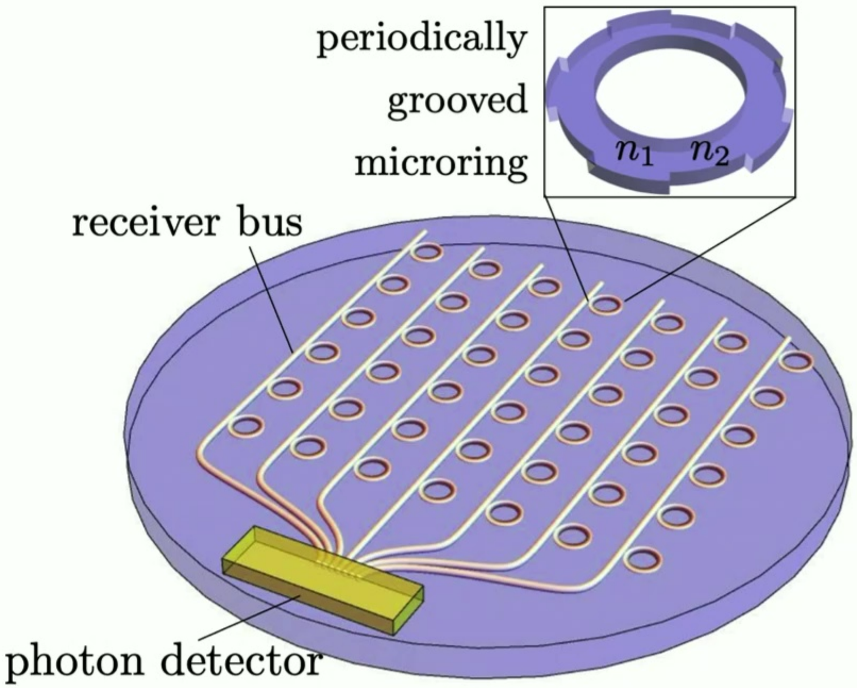
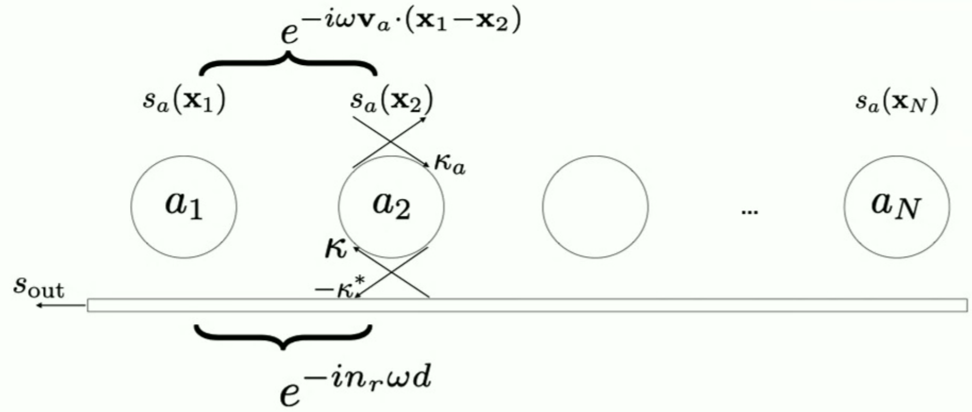
Sketch of the Setup





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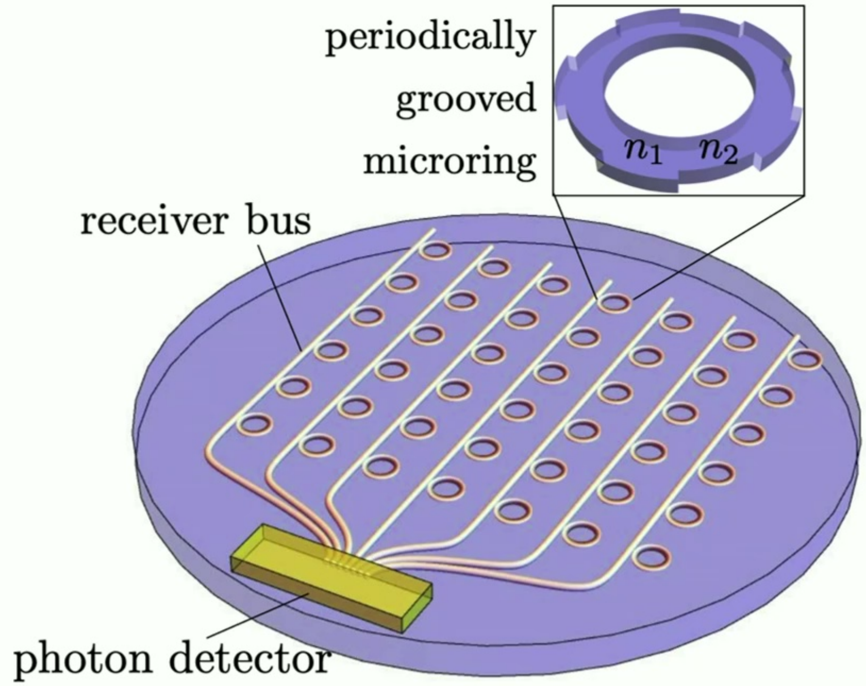
"Active" Fraction of a Chip

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

N_u = # of unit cells in each resonator

t_w = thickness of the resonator

t_s = thickness of the substrate



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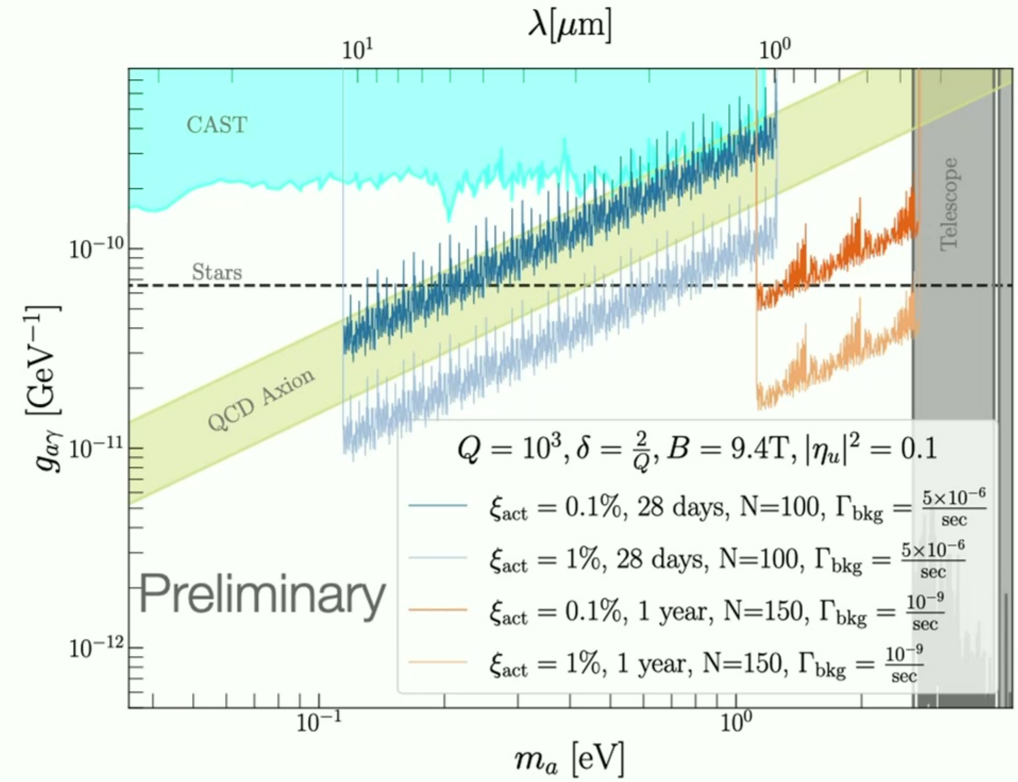
Axion DM Search Needs a Background Magnetic Field

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

B(T)	Bore (mm)	$V_{\rm act}$(cm^3)	$B^2 V_{\rm act}$(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]



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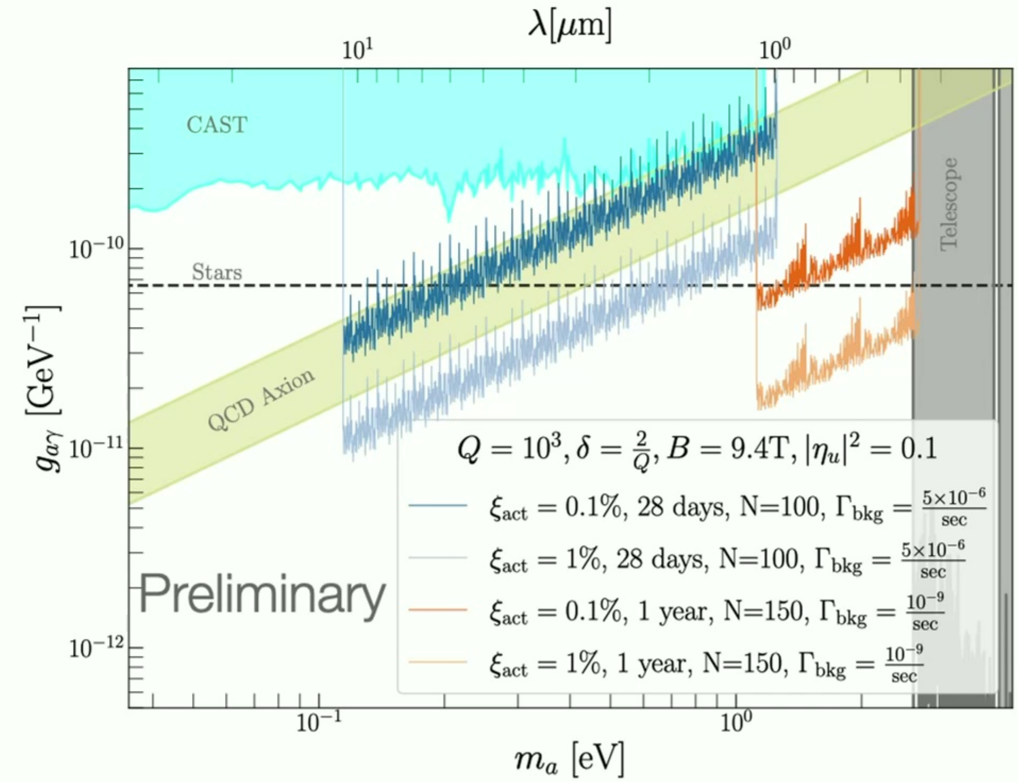

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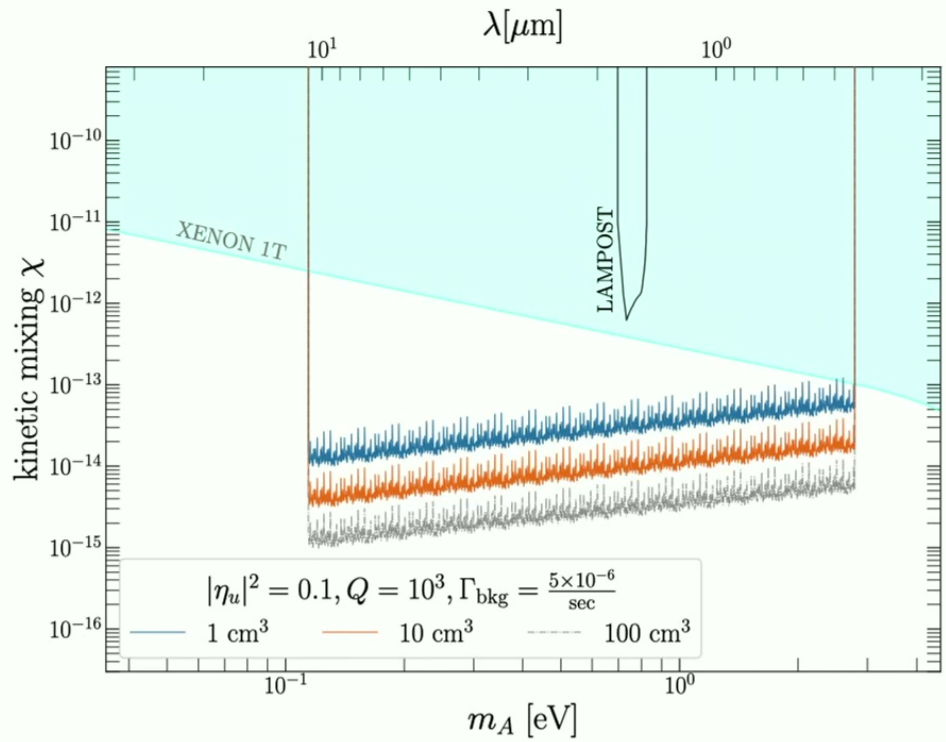
Conclusion & Future

- 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



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