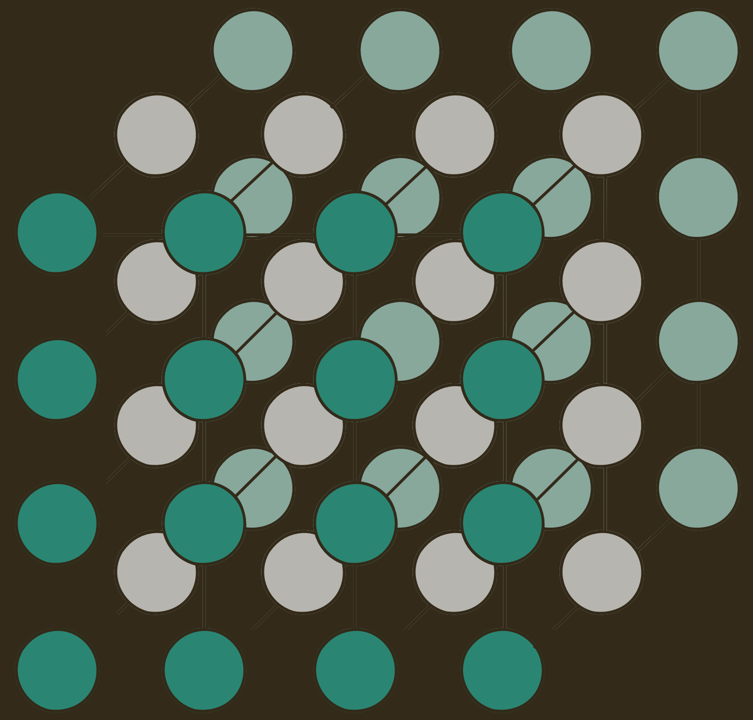
Reconfigurable Second Harmonic Generation (SHG) in Si_3N_4

Photonics Integrated Circuits

B. E. Castiblanco

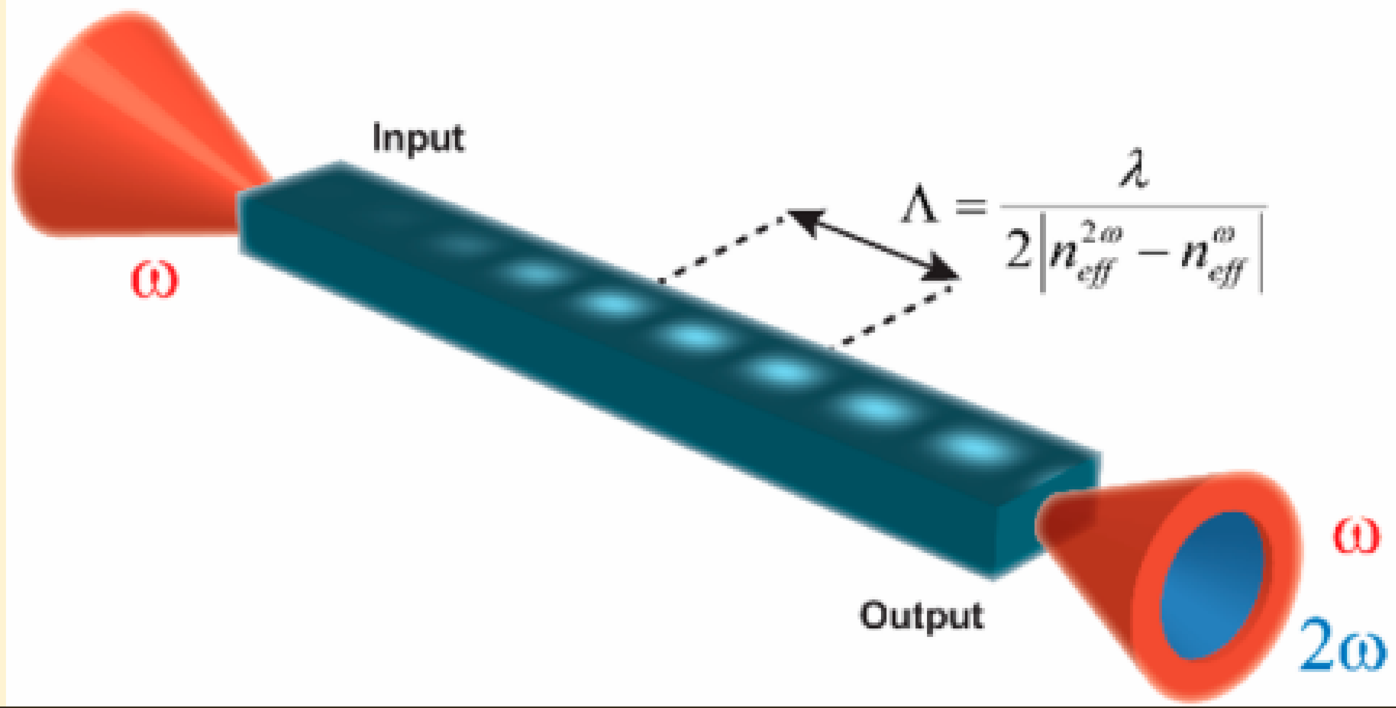
OUTLINE



1. Motivation: Why induce χ^2 in Si_3N_4
2. Design
3. Mode simulations
4. Temperature tuning and double-resonance hotspots
5. Effect of All-Optical-Poling (AOP): hotspot expansion and χ^2 growth
6. SHG performance
7. Outcomes, limitations, and conclusions

MOTIVATION: WHY INDUCE X² IN SI_3N_4

- Silicon nitride is CMOS-compatible
- But SiN is centrosymmetric → no χ(2)
- All-optical poling (AOP) can induce χ(2) inside SiN using only light [1,2]
- Why χ(2) instead of relying on χ(3)?



Taken from [2]

→ SHG is much more efficient

→ Generates 2ω (visible): applications to metrology and sensing applications

→ THG requires more optical power

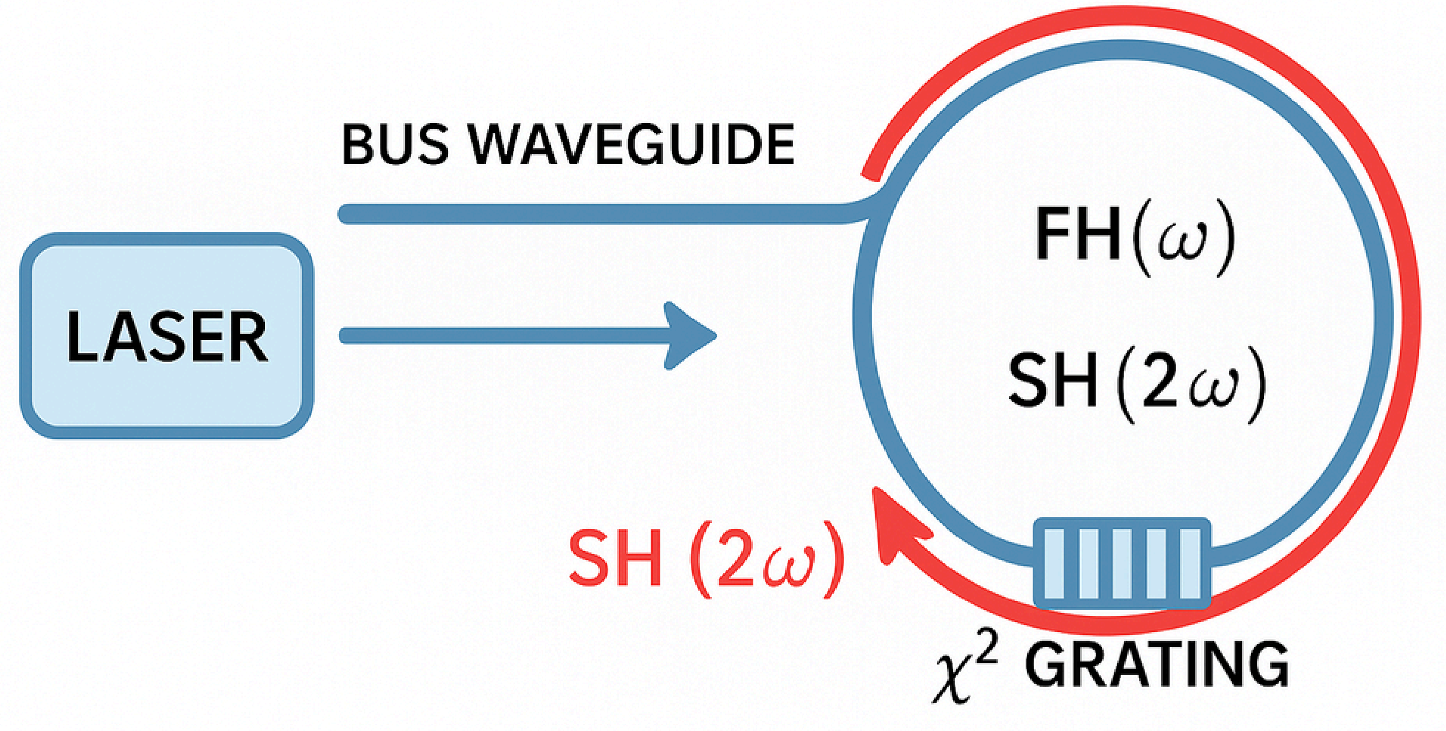
[1] Dianov & Starodubov 1995, Quantum Electron
[2] Nitiss et al. 2019, ACS Photonics

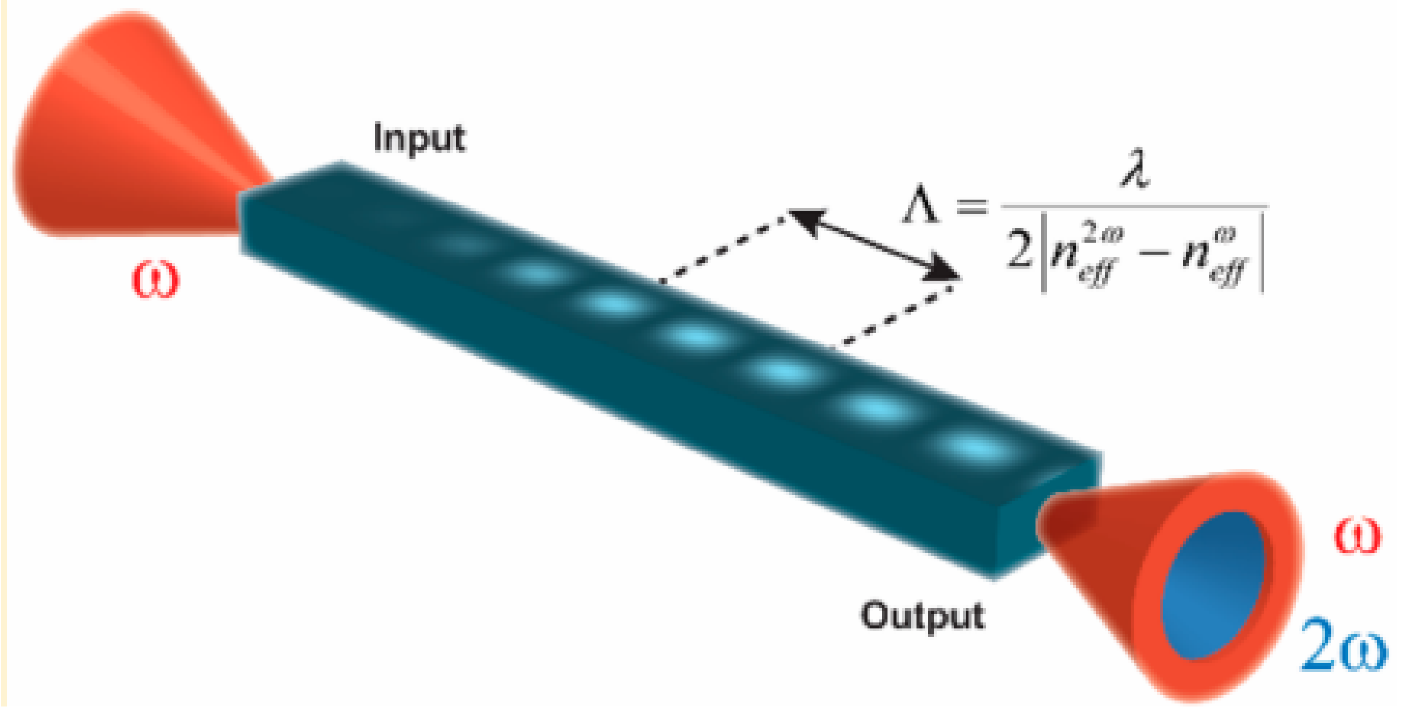
DESIGN

- Si_3N_4 microring (R = 900 μm) supports FH (ω) and SH (2ω) modes [3]
- Pump laser self-injection locks (SIL) to the FH resonance
- FH and SH circulating together → AOP writes χ(2) grating
- χ(2) grating provides Quasi-Phase Matching (QPM) → enhances SHG

[3] Clementi et al. (2023). Chip-scale SHG via self-injection-locked all-optical poling. Light: Sci. Appl..

Schematics





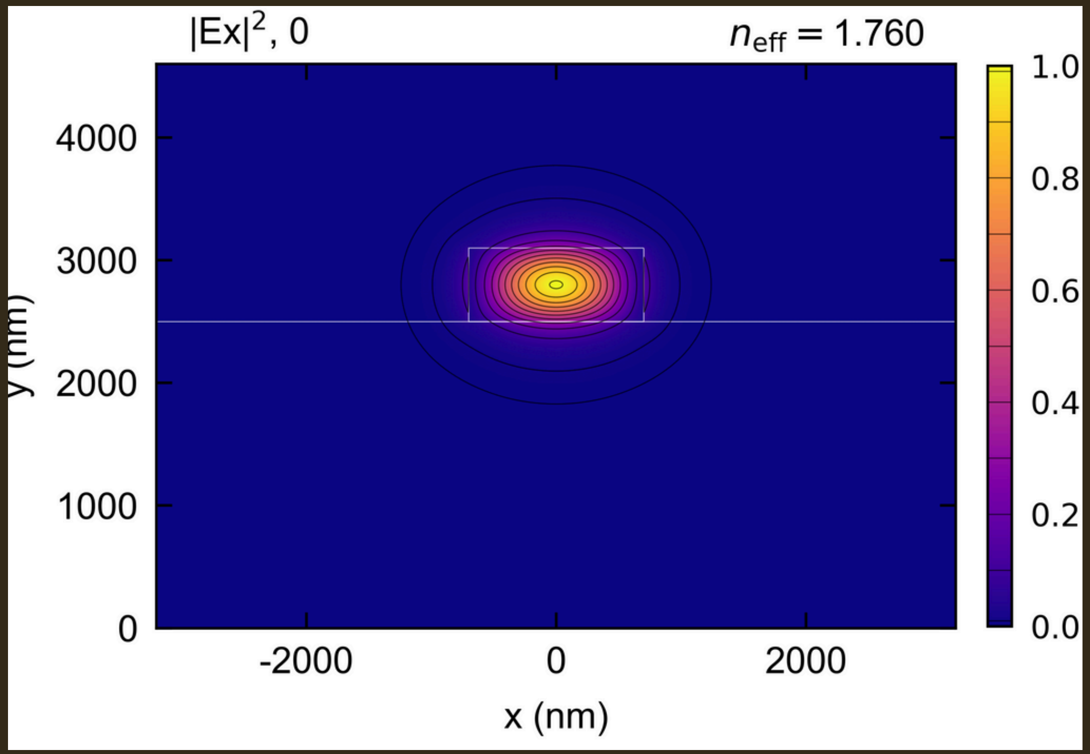
Taken from [2]

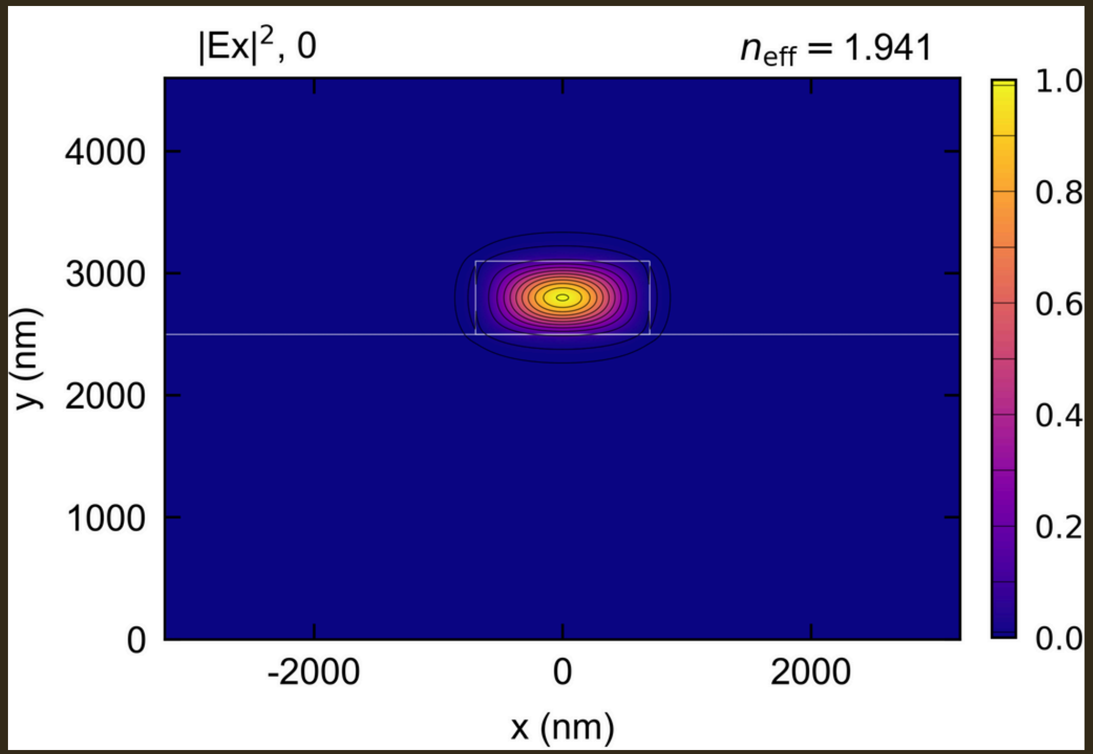
[2] Nitiss et al. 2019, ACS Photonics

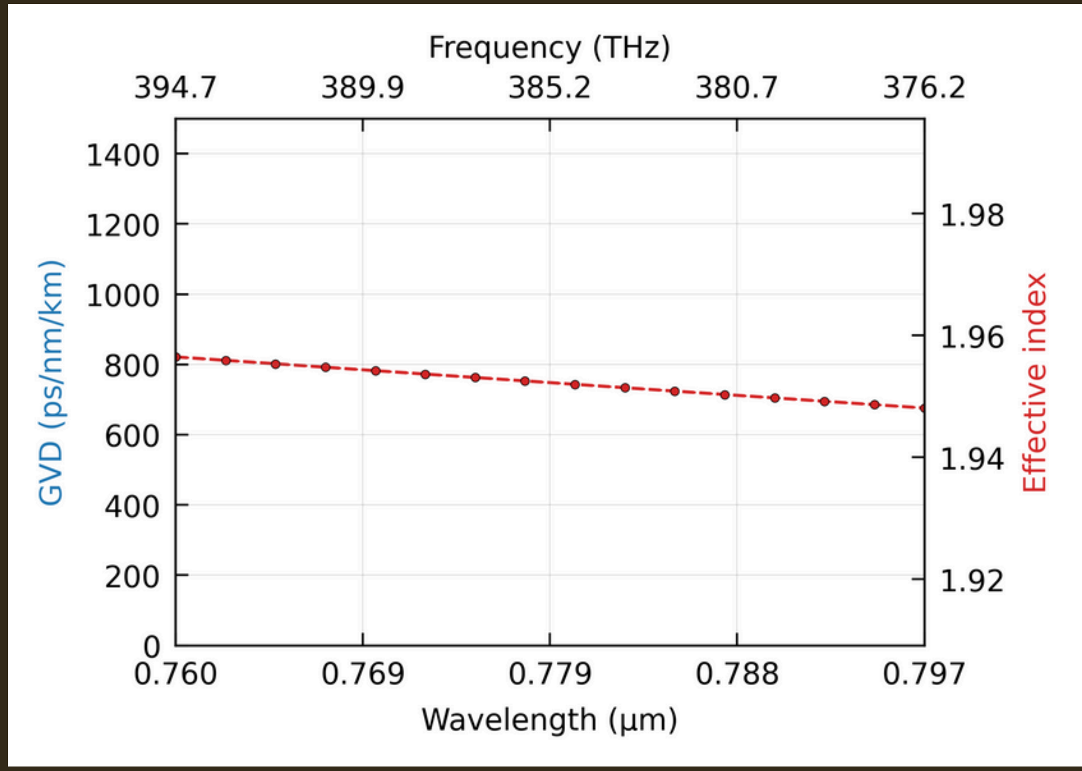
MODE SIMULATIONS

- Fully buried (silica) Si_3N_4
- Sweep in wavelenght (C-L bands):
  FH: 1520-1600 nm
  SH: 760-800 nm
  (approx linear disperssion/no $\chi(2)$)
- Extract n_eff(λ)
- Sweep in core width (0.8-1.6 μm)
- Straight waveguide approach:

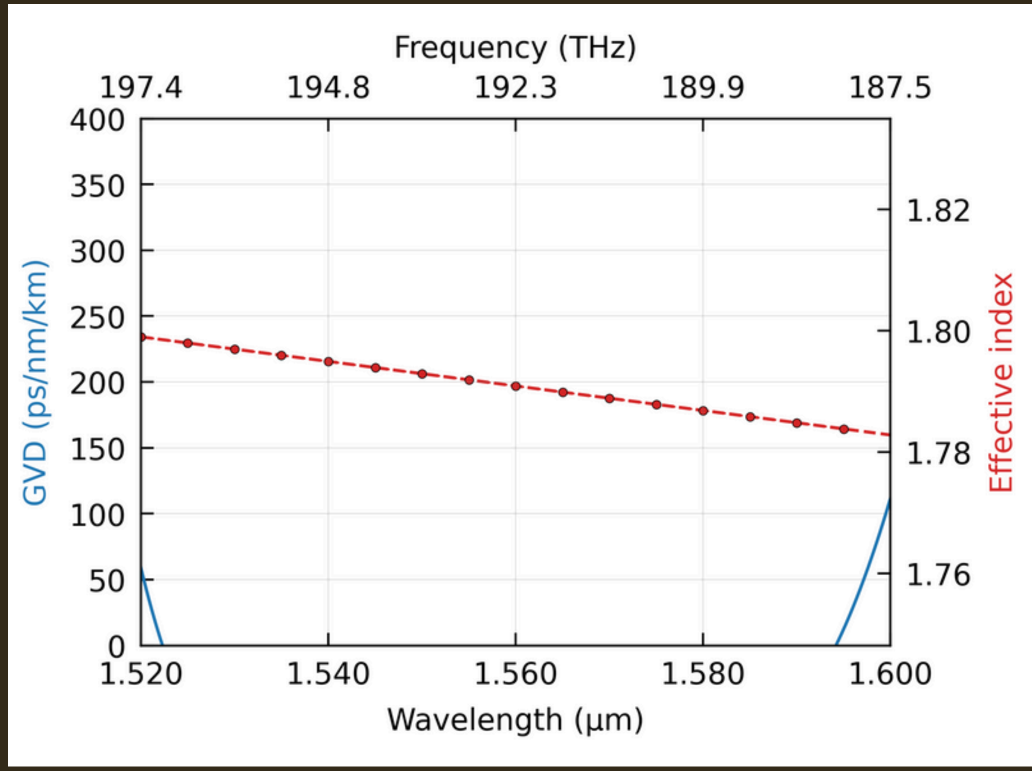
  R = 900 μm >> core width~ 1 μm







FH mode

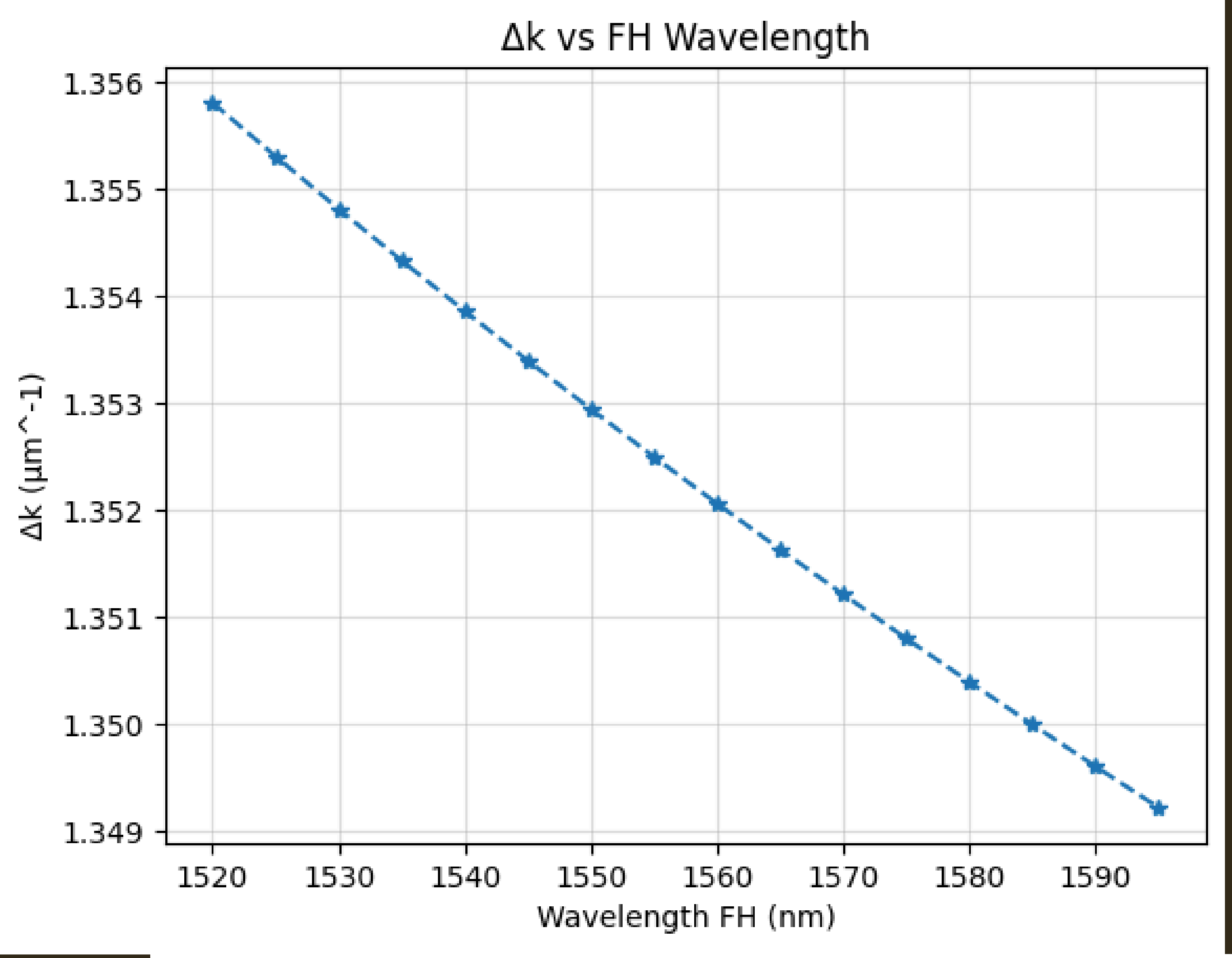


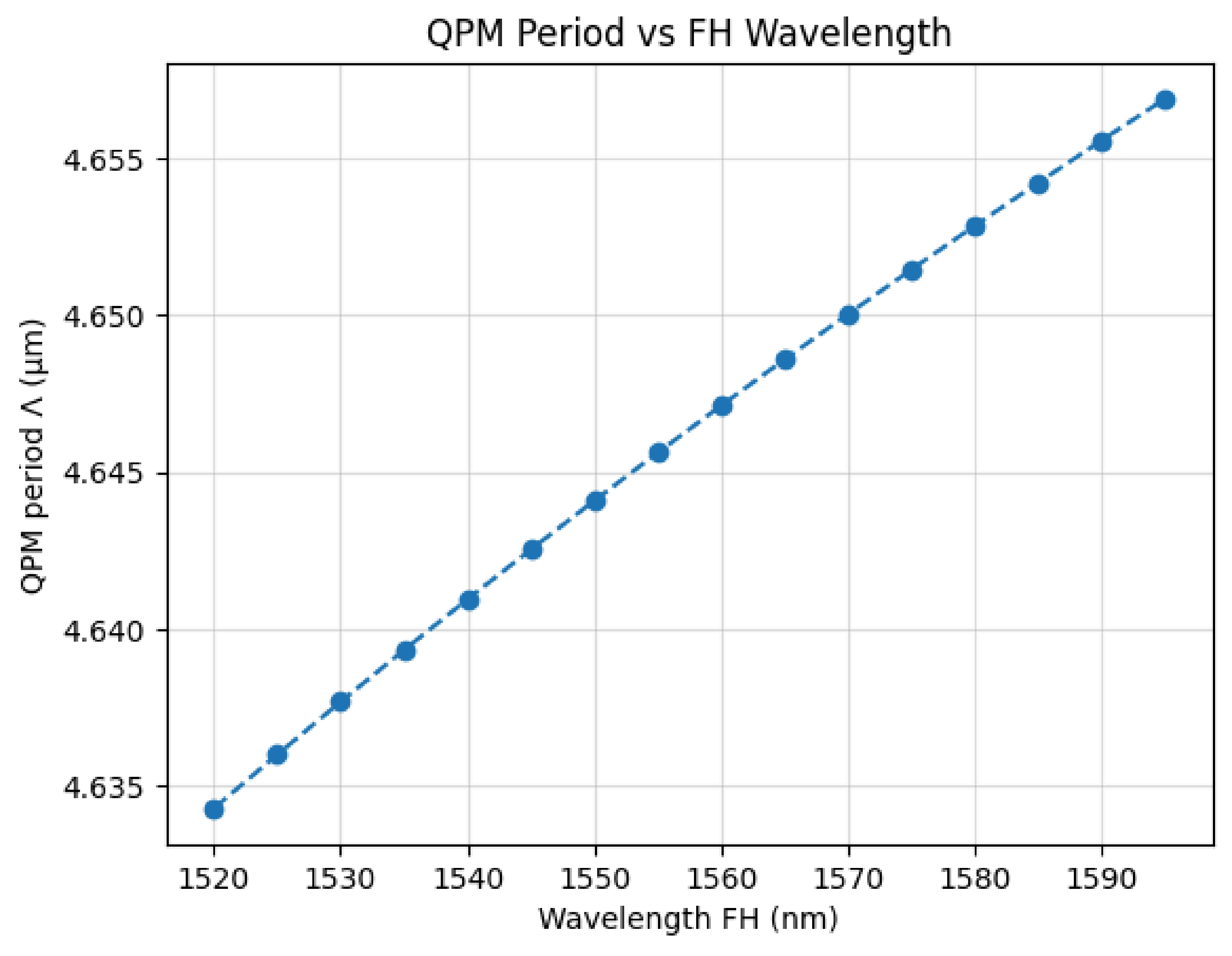
SH mode

MODE SIMULATIONS

- Δk varies smoothly with λ → QPM period Λ shifts linearly.
- Λ ≈ 4.64–4.66 μm for this Si_3N_4 geometry (consistent with [3]).
- Small Δk change → sensitive to dispersion and thermo-optic tuning.

Now, by combining Δk(λ) with thermal tuning, is possible to map the double-resonance hotspots.





EFFECT OF ALL-OPTICAL-POLING (AOP): HOTSPOT EXPANSION AND X² GROWTH

All-Optical-Poling (AOP):

- **Space-charge field grows via photogalvanic effect [1]:**
- **Feed χ^2 into SHG coupled-mode equations:**
- **With AOP χ(2) grating → effective mismatch [2]**

$$\chi^{(2)}_{\text{eff}}(z,t) = 3\chi^{(3)} E_{\text{sc}}(z,t)$$

$$g \propto \frac{\chi^{(2)}_{\text{eff}}}{\sqrt{A^2_{\text{eff},\omega} A_{\text{eff},2\omega}}}$$

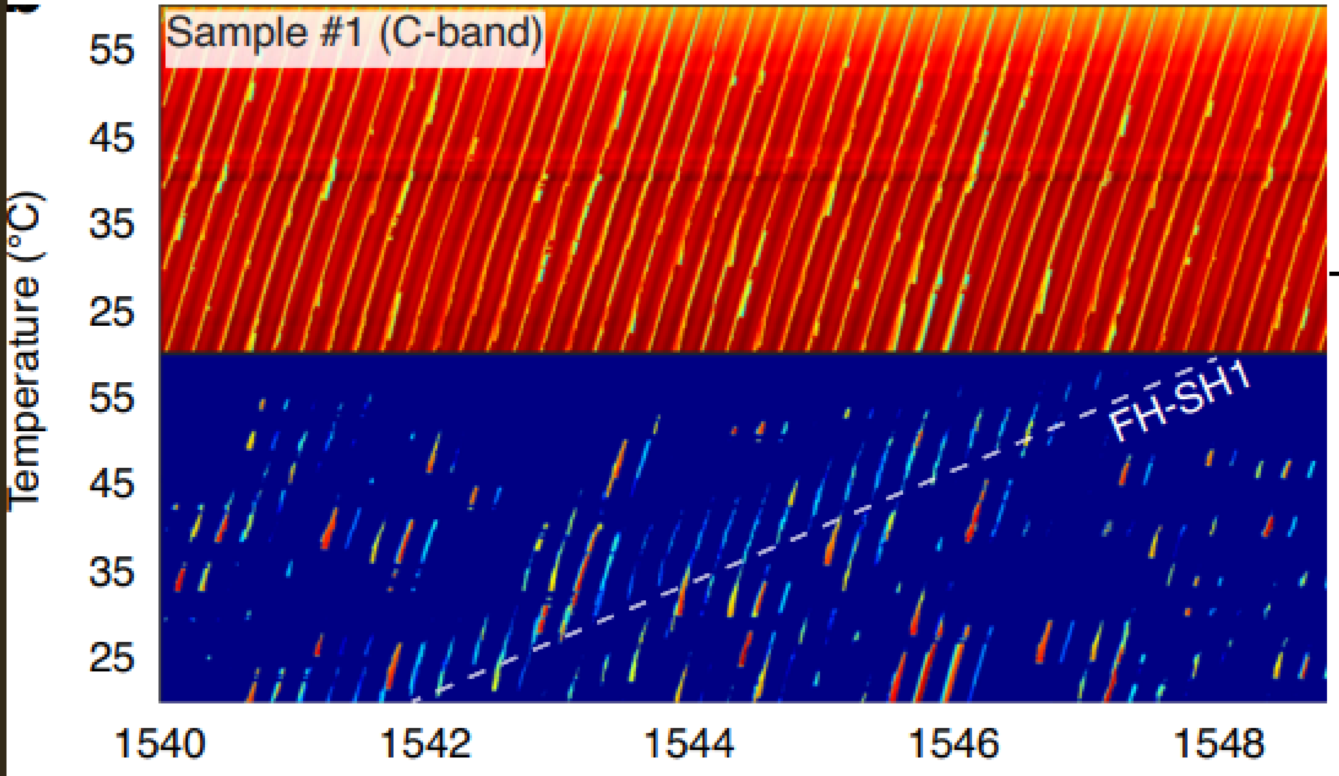
$$\Delta k_{\text{eff}} = \Delta k - K_G$$

[1] Dianov & Starodubov 1995, Quantum Electron
[2] Nitiss et al. 2019, ACS Photonics

TEMPERATURE TUNING

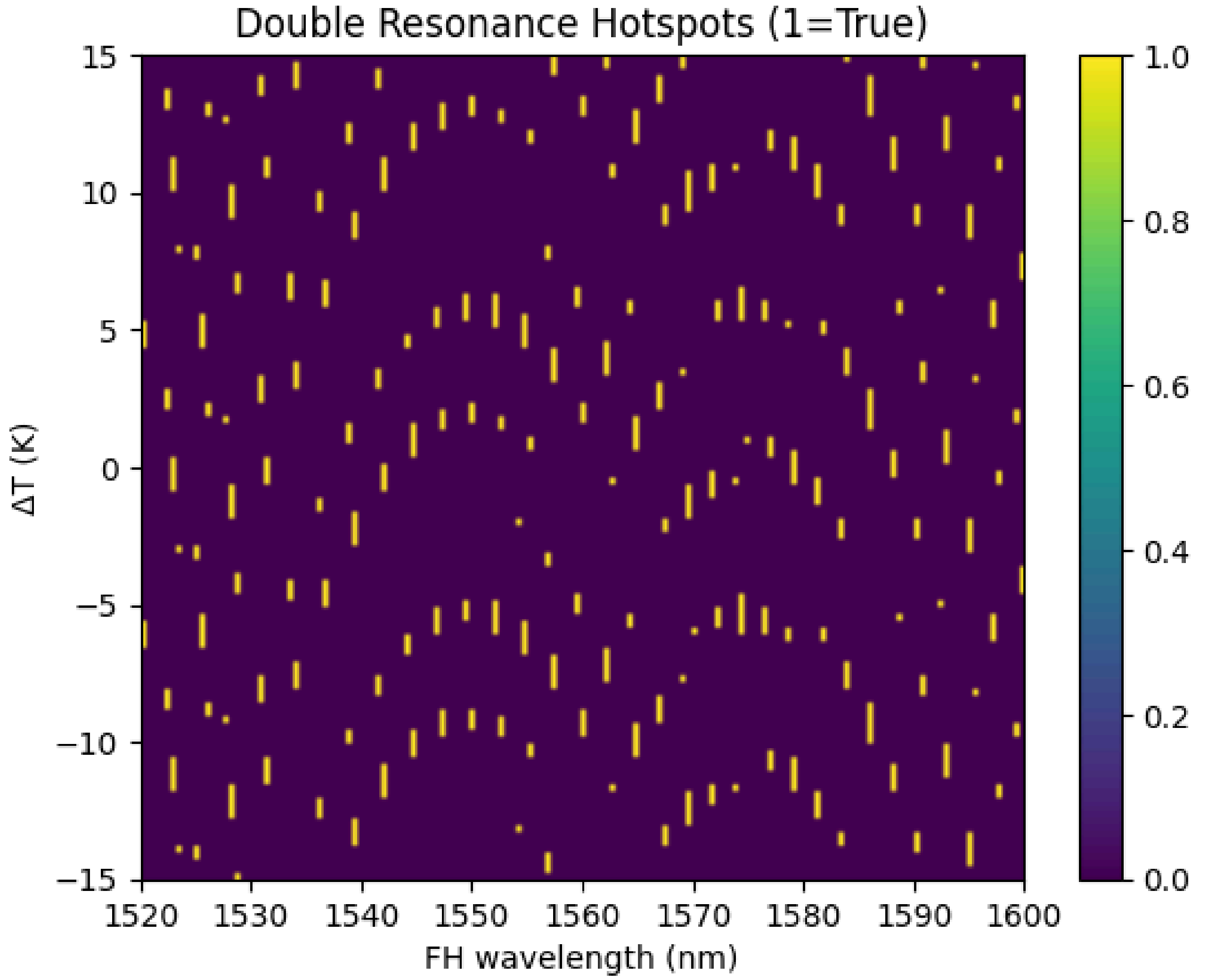
$$n_{\mathrm{eff}}(T) = n_{\mathrm{eff}}(T_0) + \frac{dn}{dT}(T - T_0)$$

- **Linear Thermo-Optic tunning:**
  - **FH and SH resonances move differently with temperature**
  - **Double resonance requires both to overlap → temperature scanning required: (λ, ΔT) hotspot map.**
  - **Each vertical streak corresponds to a resonant mode pair (w, 2w).**



Taken from [3]

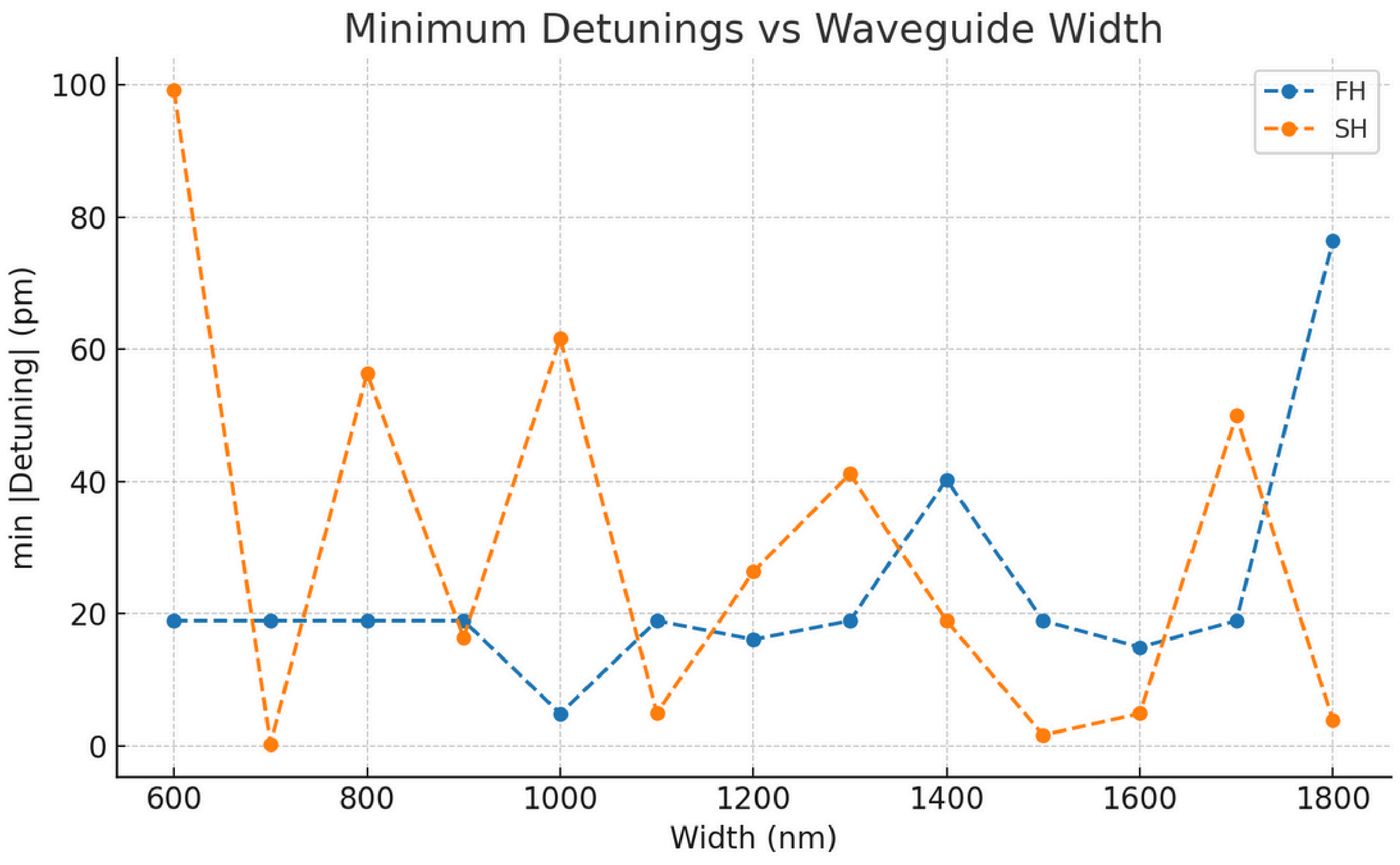
Double resonance exploration

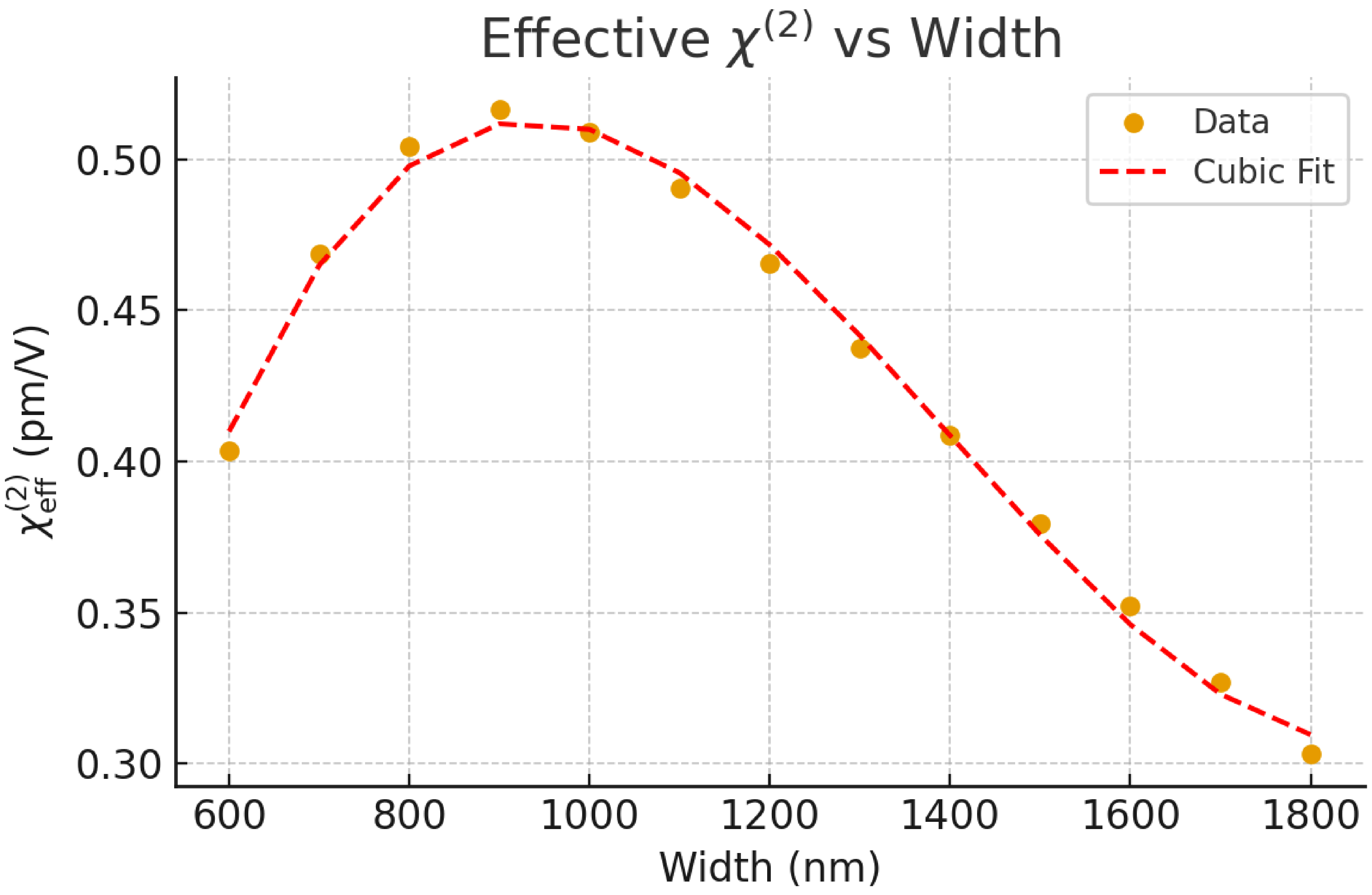


[3] Clementi et al. (2023). Chip-scale SHG via self-injection-locked all-optical poling. Light: Sci. Appl..

SHG PERFORMANCE

Minimum detuning enhances double resonance





Maximum spot at 900nm width:

$$\chi^2 = 0.516 \text{ pm/V}$$

R^2 =0.995

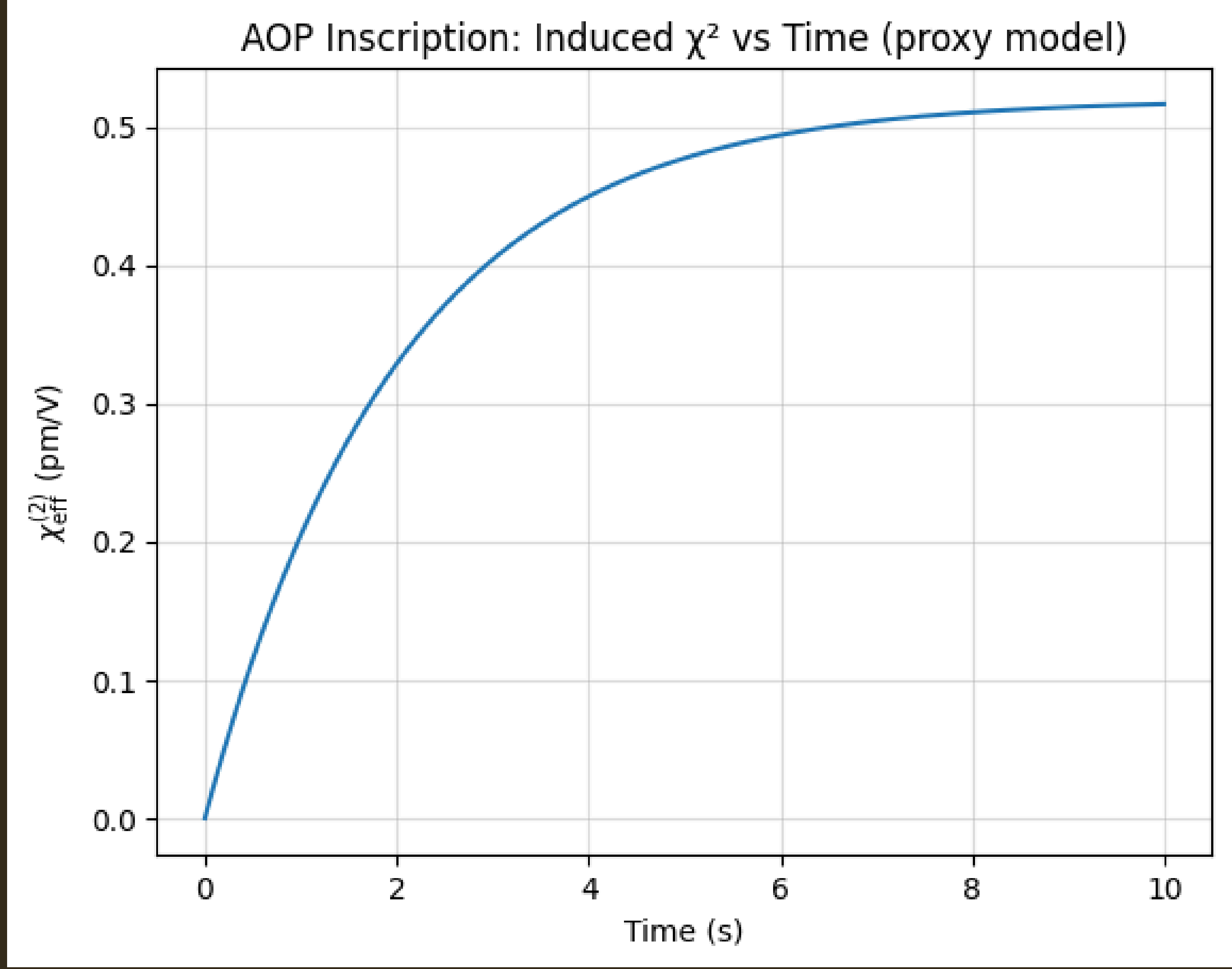
SHG PERFORMANCE

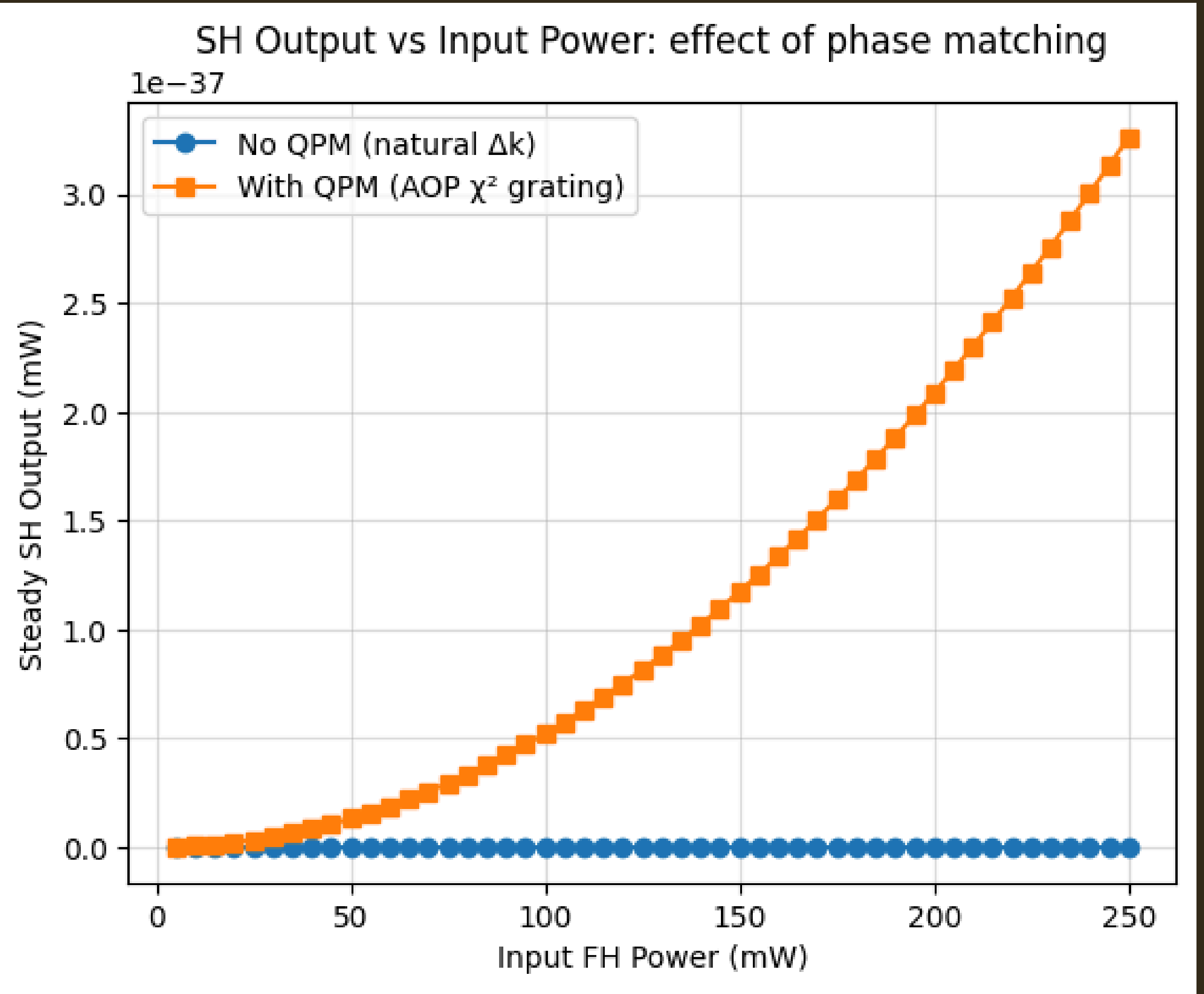
- χ^2 grows gradually as the photogalvanic field builds up. →
- Saturates after a few seconds: steady χ^2 available for SHG.

$$\chi^2 = 0.516 \text{ pm/V}$$

- With AOP grating (orange): phase mismatch is compensated. →
- SH power grows rapidly and reaches a finite steady level.

$$P = 3.6\times10^{\wedge}(-37) \text{ mW}$$





OUTCOMES AND LIMITATIONS

OUTCOMES:

- Extracted $\Delta k(\lambda)$ and $\Lambda(\lambda)$ from Si_3N_4 cross-section
- Exploration of the double resonance hotspots and min detunning
- Demonstrated SHG performance with χ^2 from simulated AOP, finding a maximum value:

$$\chi^2 = 0.516 \text{ pm/V}$$

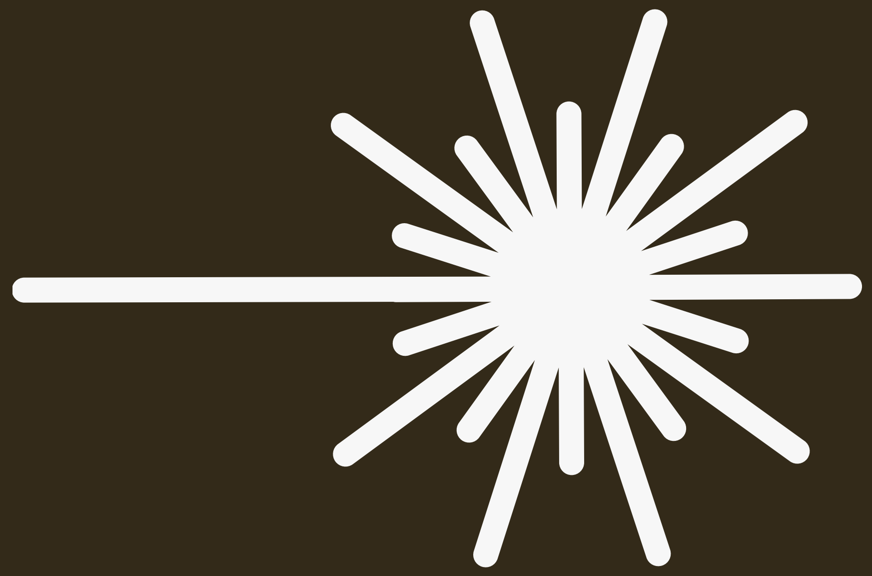
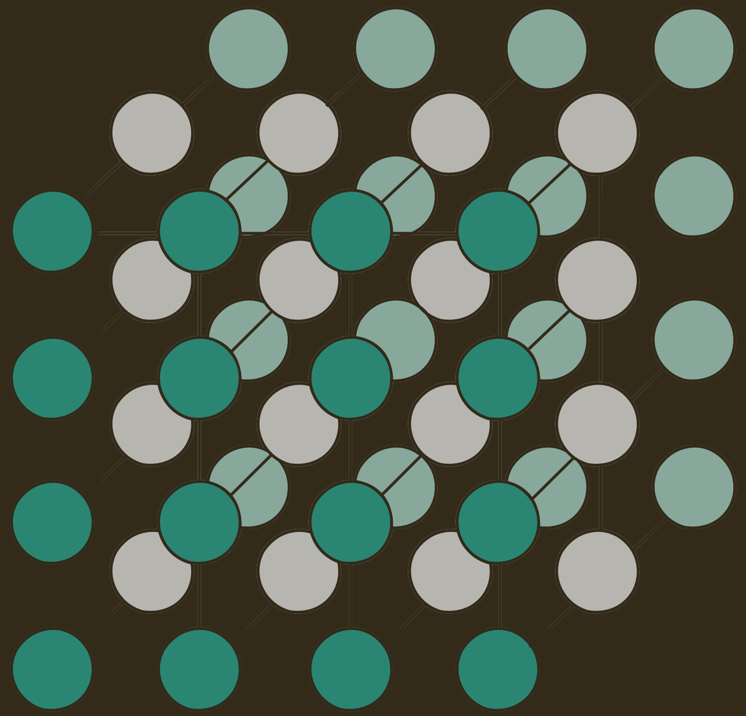
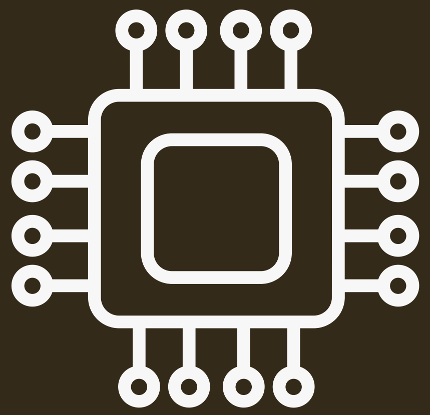
LIMITATIONS:

- No full 3D ring modes (using straight-waveguide approx)
- Only one geometry fully explored
- Low performance compared with other platforms as Lithium Niobate:

$$\chi^2\_LN = 54 \text{ pm/V}$$

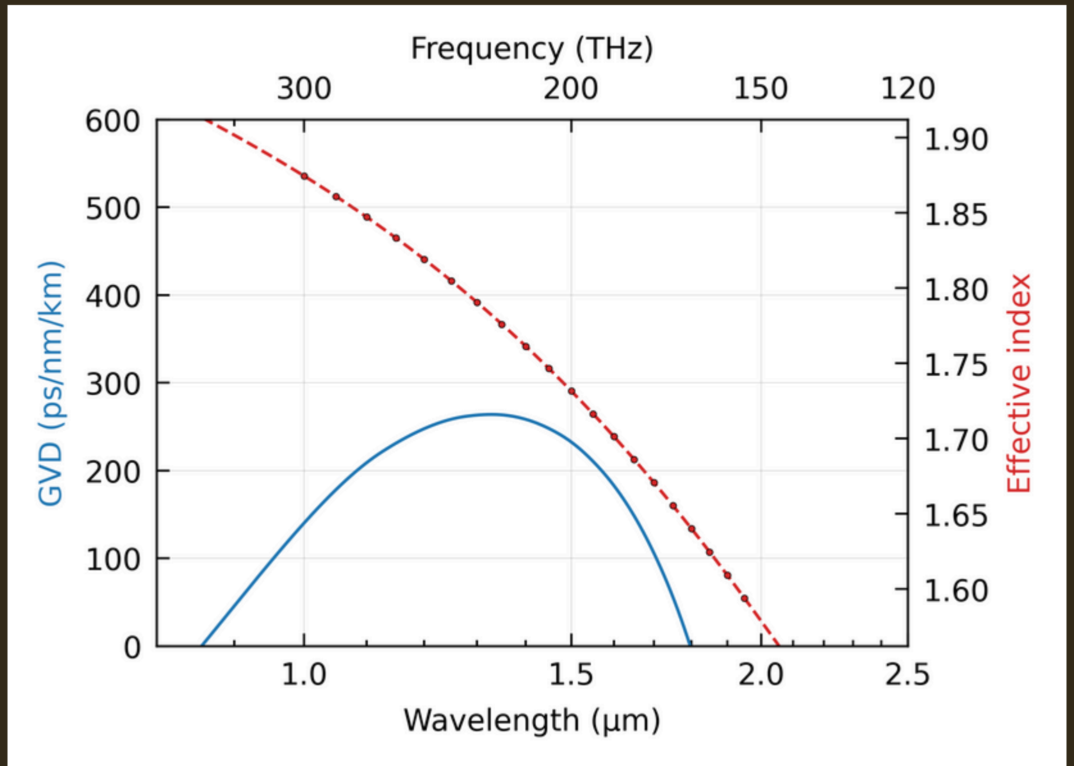
CONCLUSIONS

- AOP enables $\chi(2)$ and improves double-resonance in Si_3N_4.
- EMode simulated data (Δk, Λ) gives a clear design guidance.
- Hotspot maps show how poling enhances the usable bandwidth.
- Framework ready to explore more geometry sweeps and experimental comparison.

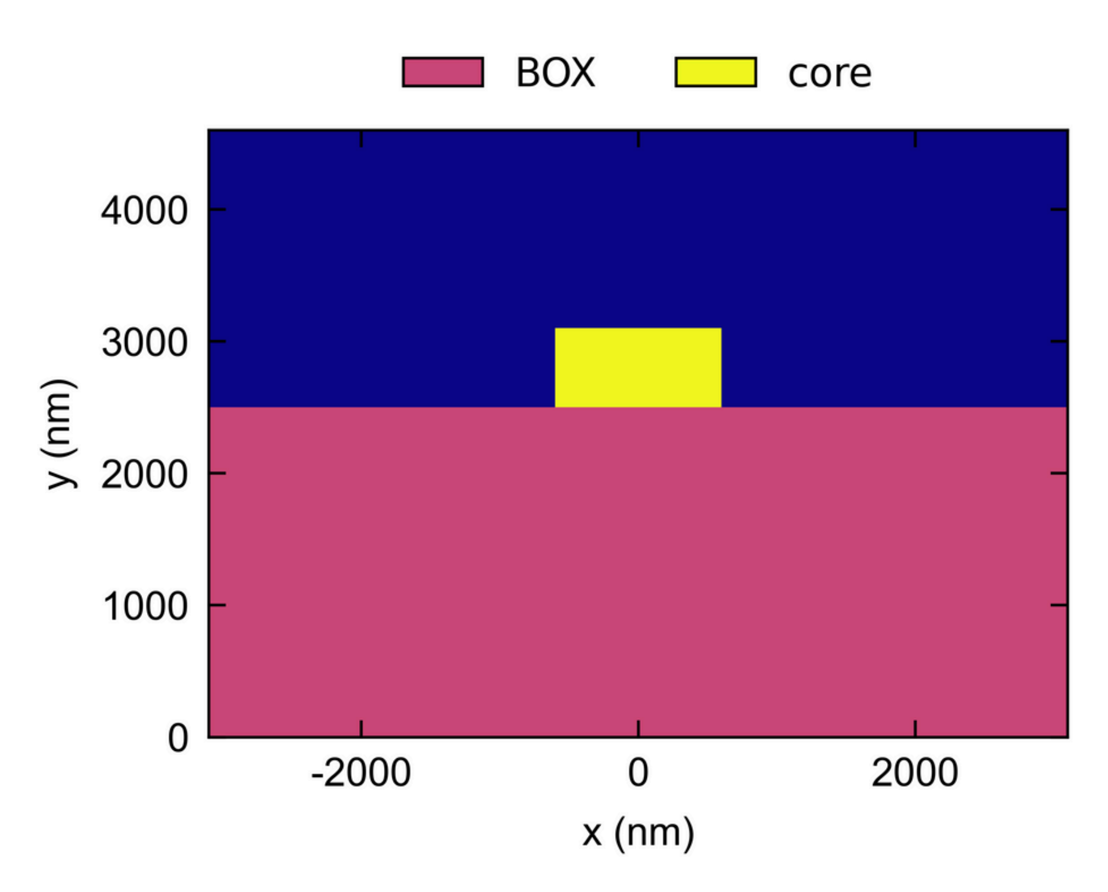
  

THANKS

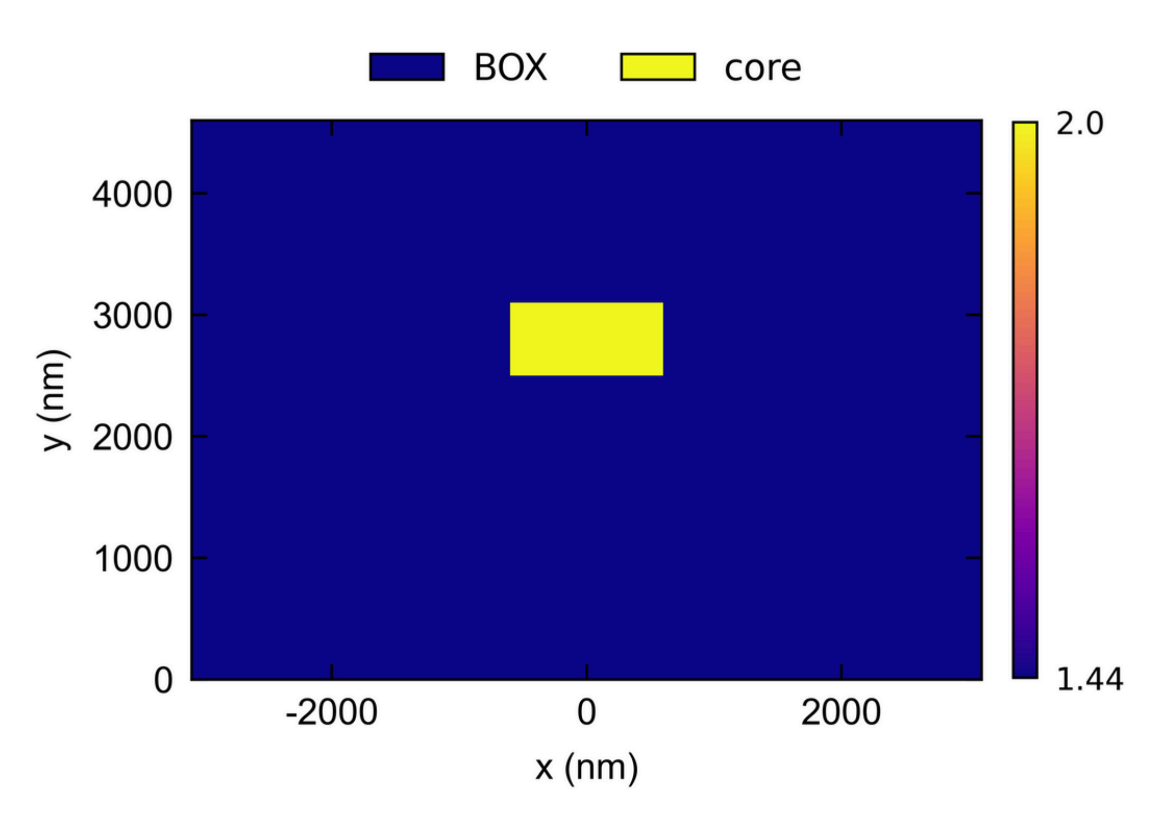
APPENDIX



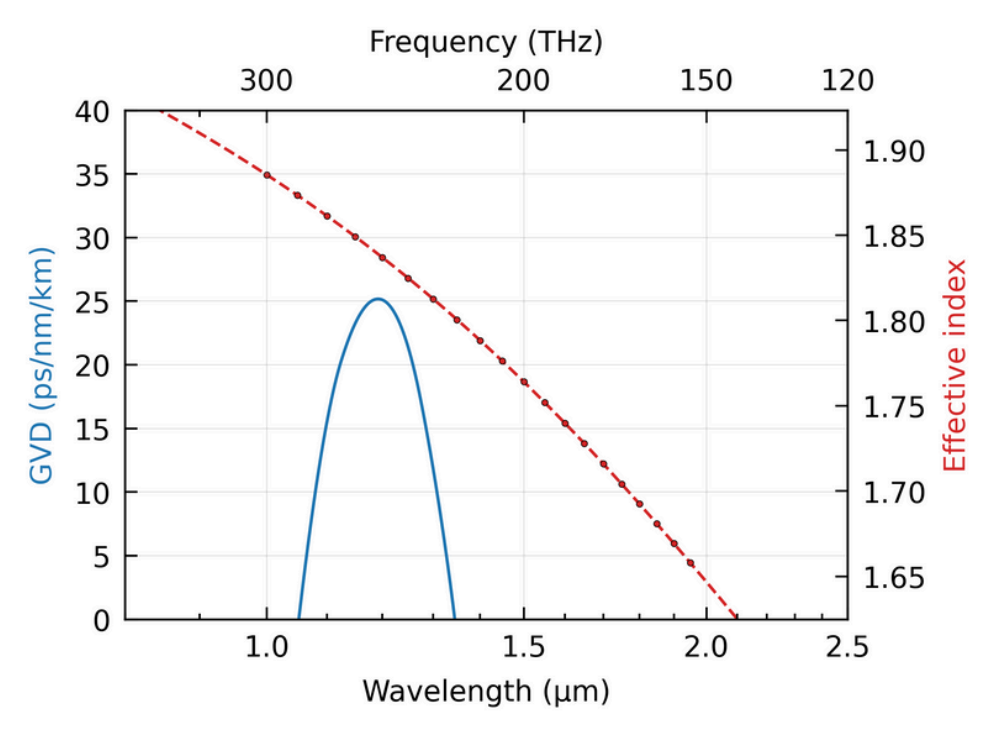
Frequency (THz)
300
200
150
120
600
500
400
300
200
100
0
GVD (ps/nm/km)
1.90
1.85
1.80
1.75
1.70
1.65
1.60
Effective index
1.0
1.5
2.0
2.5
Wavelength (μm)



BOX
core
4000
3000
2000
1000
0
y (nm)
-2000
0
2000
x (nm)



BOX
core
2.0
1.44
4000
3000
2000
1000
0
y (nm)
-2000
0
2000
x (nm)



Frequency (THz)
300
200
150
120
40
35
30
25
20
15
10
5
0
GVD (ps/nm/km)
1.90
1.85
1.80
1.75
1.70
1.65
Effective index
1.0
1.5
2.0
2.5
Wavelength (μm)

APPENDIX

$$n(\lambda) = \sqrt{1 + \frac{3.0249}{1 - (0.135341/\lambda)^2} + \frac{40314}{1 - (1239.84/\lambda)^2}}$$

Wavelength range: 310 nm to 5504 nm

K. Luke, Y. Okawachi, M. R. E. Lamont, A. L. Gaeta, and M. Lipson, "Broadband mid-infrared frequency comb generation in a Si3N4 microresonator," Opt. Lett. 40, 4823 (2015).

APPENDIX: MODE SIMULATIONS

1. Extracted effective refractive indices using EMode:

- n,ω(λ)
- n,2ω(λ/2)

2. Compute propagation constants

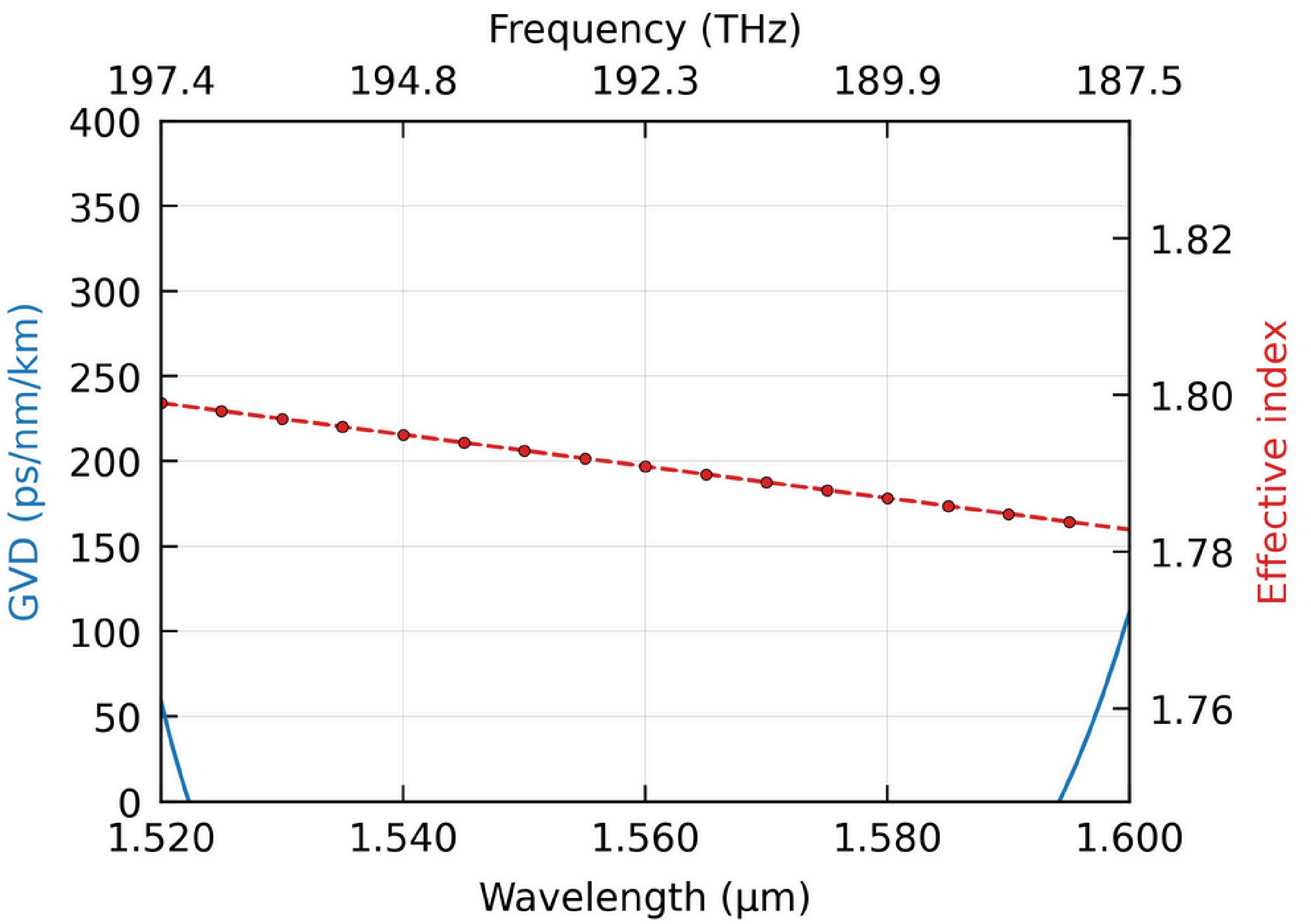
- $\beta = 2\pi n / \lambda$

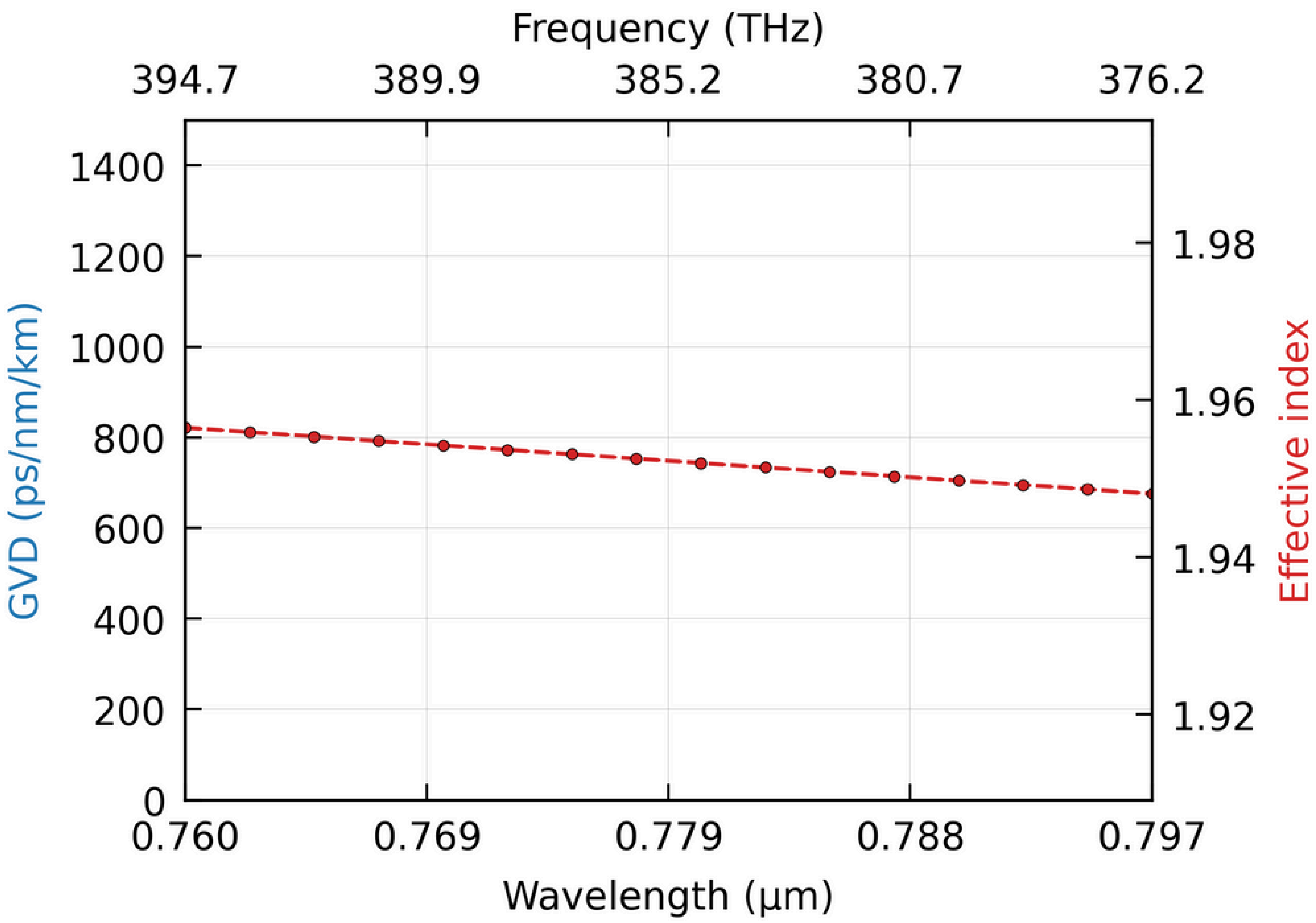
3. Compute phase mismatch

- $\Delta k = \beta(2\omega) - 2\beta(\omega)$

4. Compute QPM period

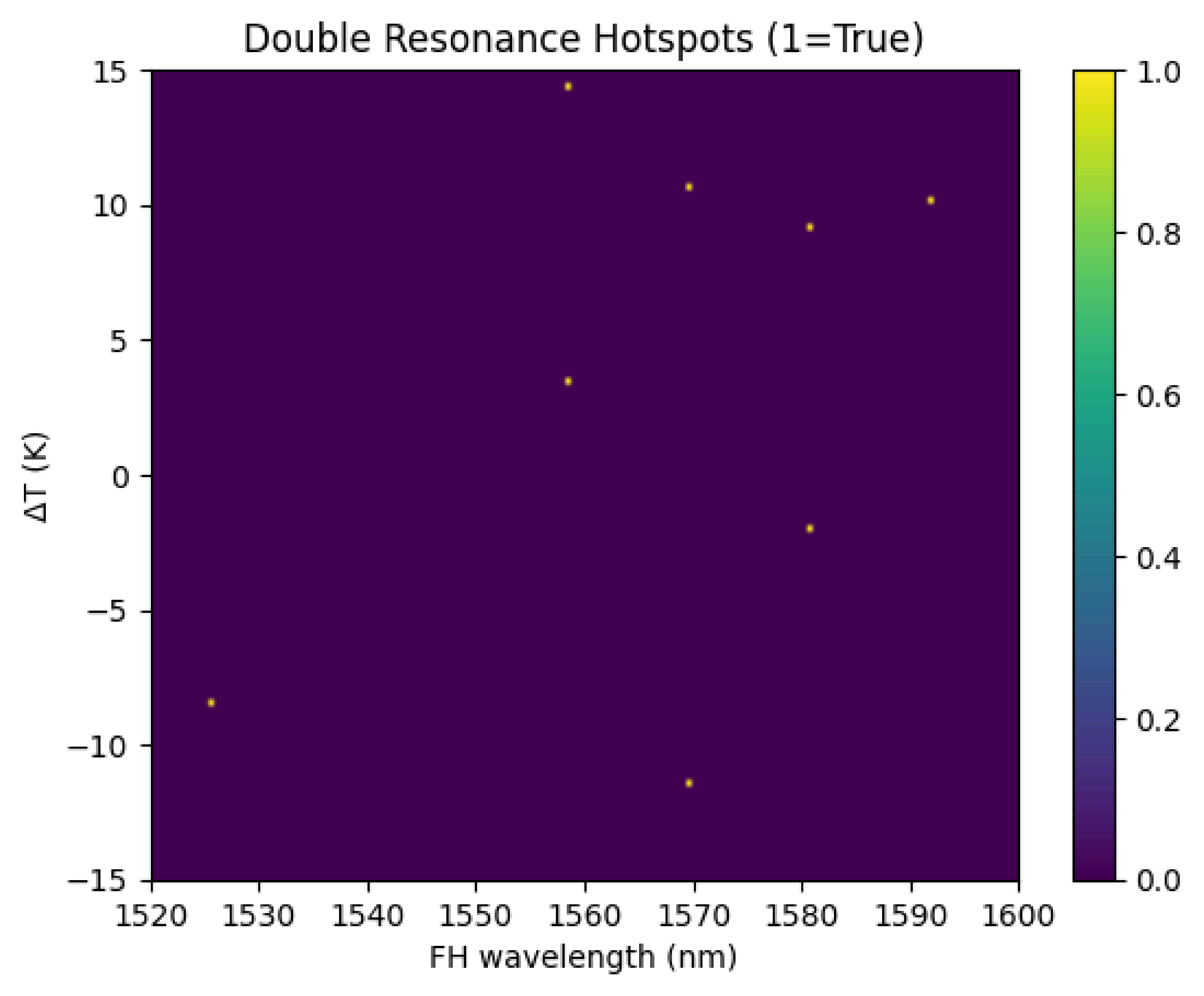
- $\Lambda = 2\pi / |\Delta k|$





APPENDIX

Almost no double-resonant hot-spots with a 1pm detunning



APPENDIX Cubic fit for the effective χ^2

$$\chi^{(2)}_{\mathrm{eff}}(x) = \left(5.30 \times 10^{-10}\ \frac{\mathrm{pm}}{\mathrm{V}\cdot\mathrm{nm}^3}\right) x^3 - \left(2.22 \times 10^{-6}\ \frac{\mathrm{pm}}{\mathrm{V}\cdot\mathrm{nm}^2}\right) x^2 + \left(2.76 \times 10^{-3}\ \frac{\mathrm{pm}}{\mathrm{V}\cdot\mathrm{nm}}\right) x - 0.562\ \frac{\mathrm{pm}}{\mathrm{V}}$$

With x the waveguide width in nm, and a Pearson coefficient $R^2 = 0.995$.

APPENDIX: Theoretical Model

For a microring of circumference $L = 2\pi R$, the resonance condition for a given mode is

$$m\lambda = n_{\text{eff}}(\lambda)L$$

Each resonance is characterized by a quality factor Q that can be decomposed into intrinsic (Q_{int}) and coupling (Q_{cpl}) contributions,

$$\frac{1}{Q_{\text{loaded}}} = \frac{1}{Q_{\text{int}}} + \frac{1}{Q_{\text{cpl}}}. \tag{12}$$

The (power) decay rate at angular frequency ω is

$$\kappa = \frac{\omega}{Q_{\text{loaded}}}, \tag{13}$$

with intrinsic and coupling components κ_{int} and κ_{ex} defined analogously. These rates are used in the time-domain coupled-mode equations for the intracavity fields.

We adopt a phenomenological rate equation for the average space-charge field $E(t)$:

$$\frac{dE}{dt} = A_{\text{CPG}} I_{\omega} I_{2\omega} - \frac{E}{\tau_{\text{erase}}},$$

We model the intracavity FH and SH fields by slowly varying complex amplitudes $a(t)$ and $b(t)$, normalized such that $|a|^2$ and $|b|^2$ are proportional to the intracavity powers. The coupled-mode equations for a doubly resonant $\chi^{(2)}$ cavity are

$$\dot{a} = \left(i\Delta_{\omega} - \frac{\kappa_{\omega}}{2}\right) a + ig\, ba^* + \sqrt{\kappa_{\omega,\text{ex}}}\, s_{\text{in}}, \tag{19a}$$

$$\dot{b} = \left(i\Delta_{2\omega} - \frac{\kappa_{2\omega}}{2}\right) b + ig\, a^2, \tag{19b}$$