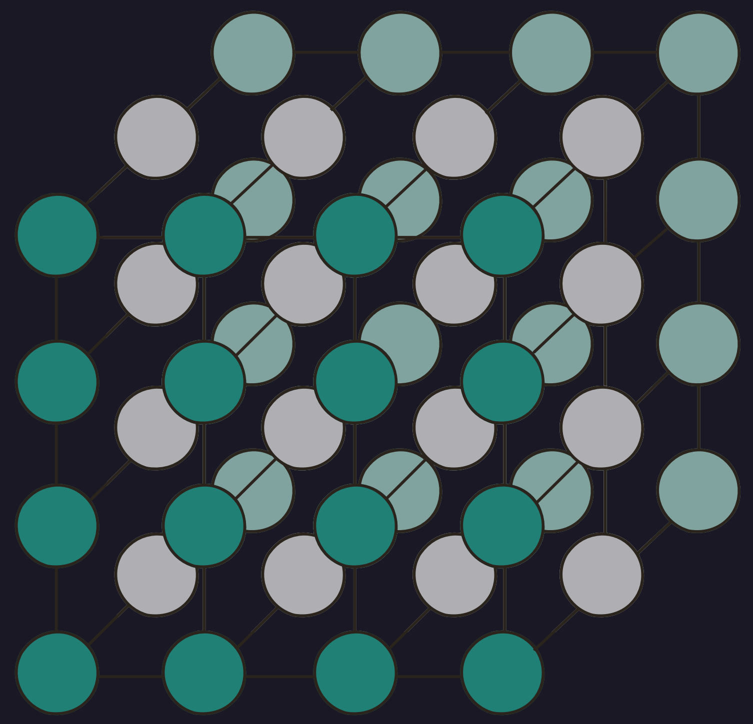
Reconfigurable Second Harmonic Generation (SHG) in Si_3N_4

Photonics Integrated Circuits

B. E. Castiblanco

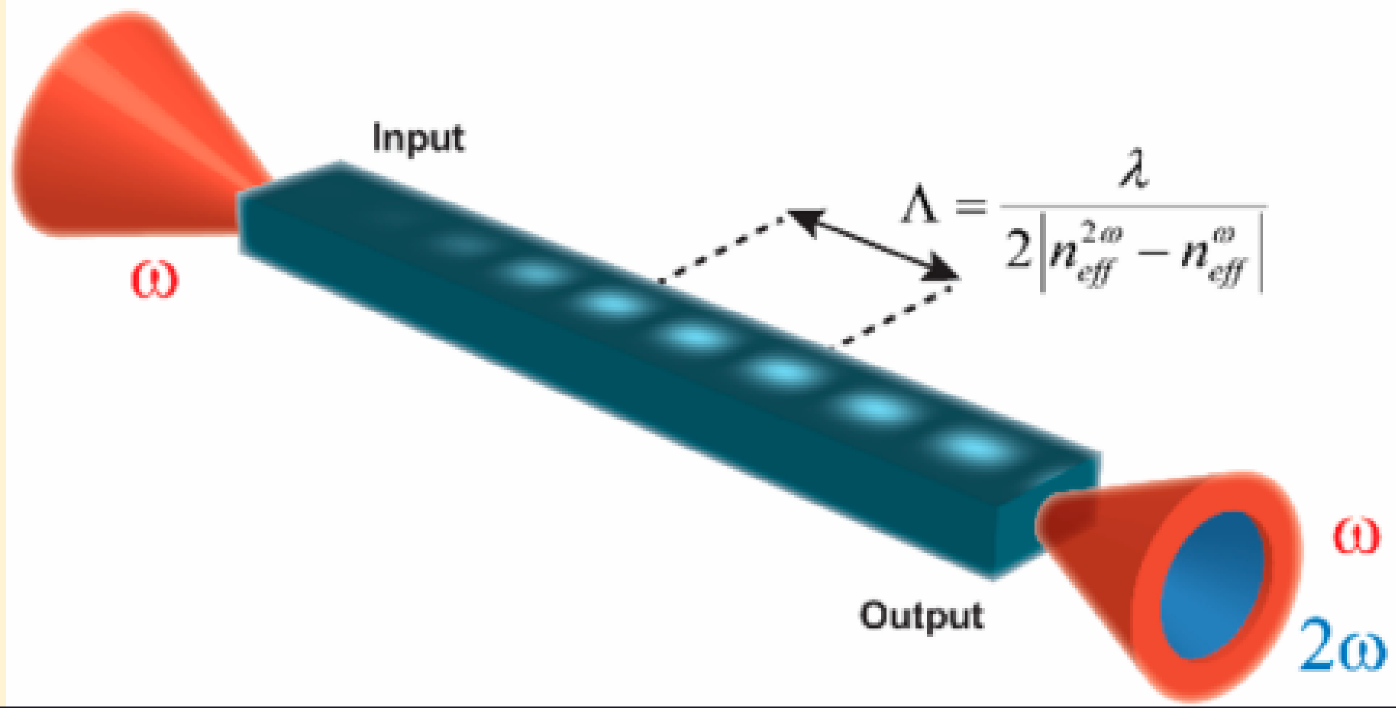
OUTLINE



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

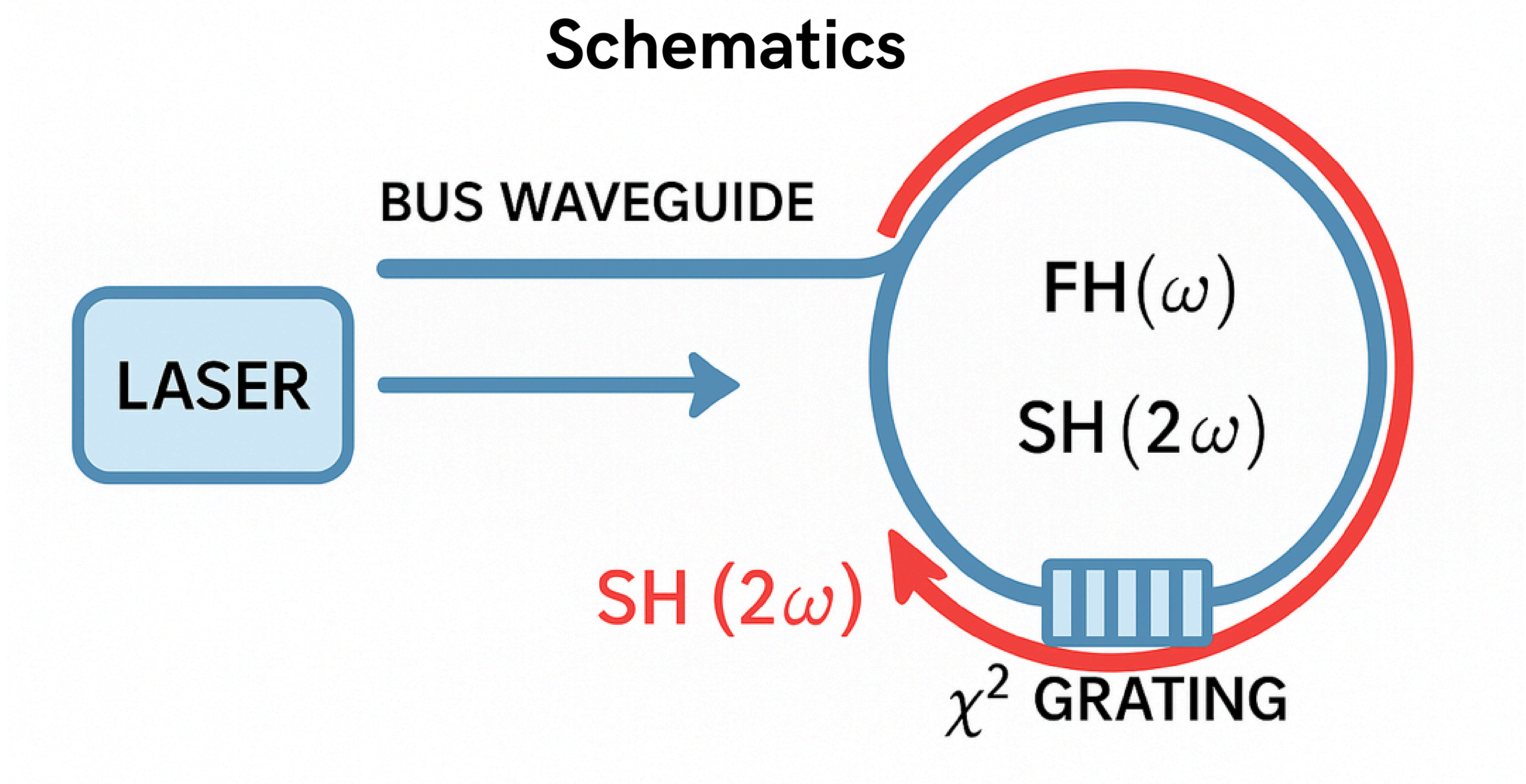
→ THG requires more optical power

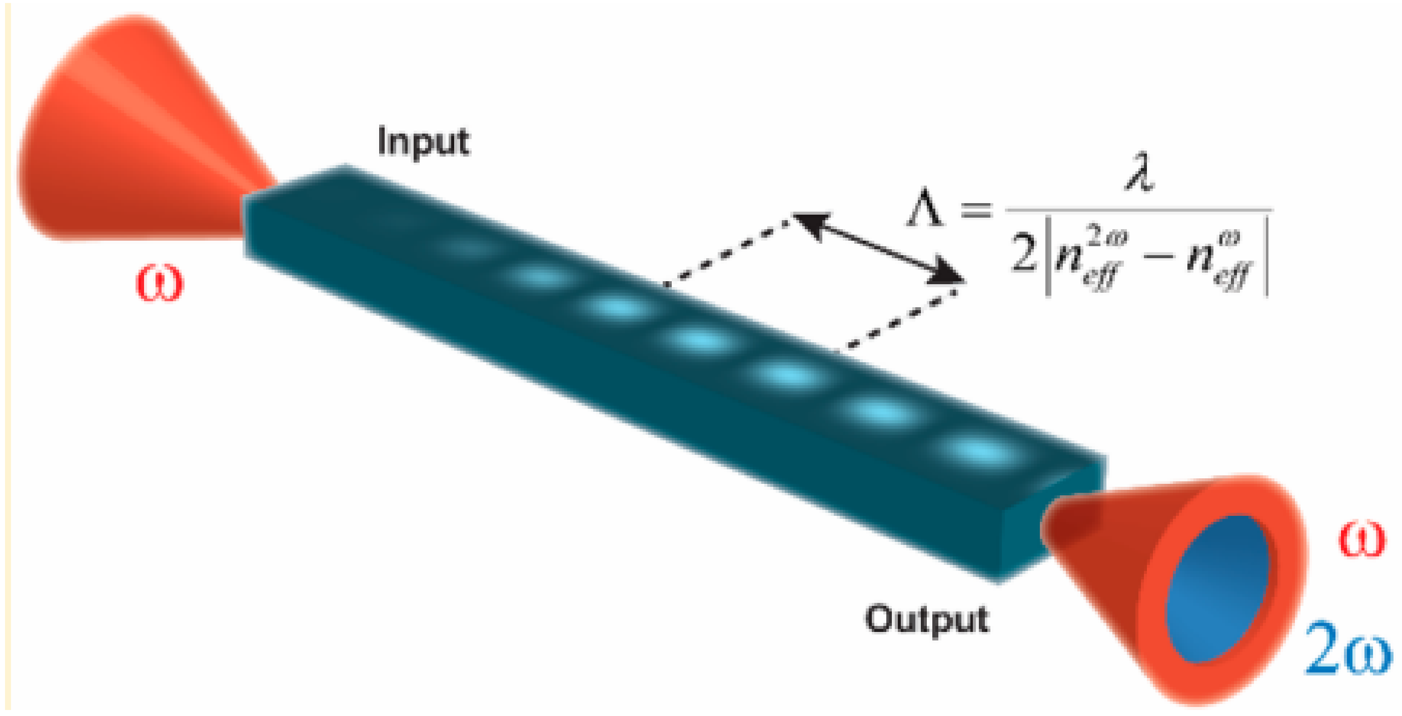
[1] Dianov & Starodubov 1995, Quantum Electron
[2] Nitiss et al. 2019, ACS Photonics

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..





Taken from [2]

[2] Nitiss et al. 2019, ACS Photonics

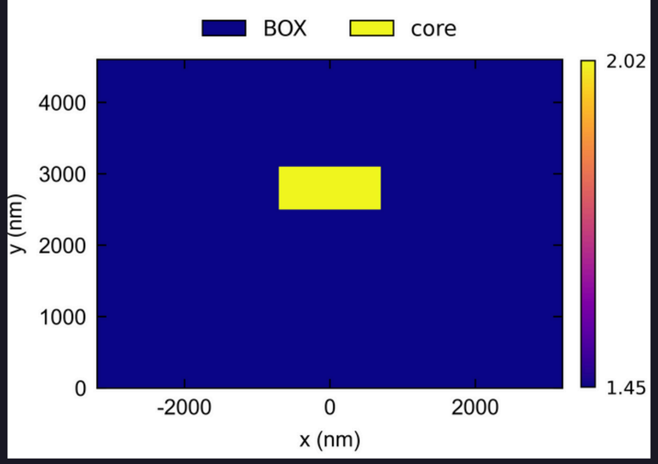
Purpose of this work:

Use simulated SiN waveguide modes (EMode) to assess whether double-resonant SHG assisted by AOP is feasible.

Methodology

EMode data → Phase mismatch Δk → QPM period $\Lambda(\lambda)$ → Thermo-optic resonance tuning → Double-resonance hotspot map → AOP-induced χ^2 → SHG coupled-mode model

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 $\chi(2)$)

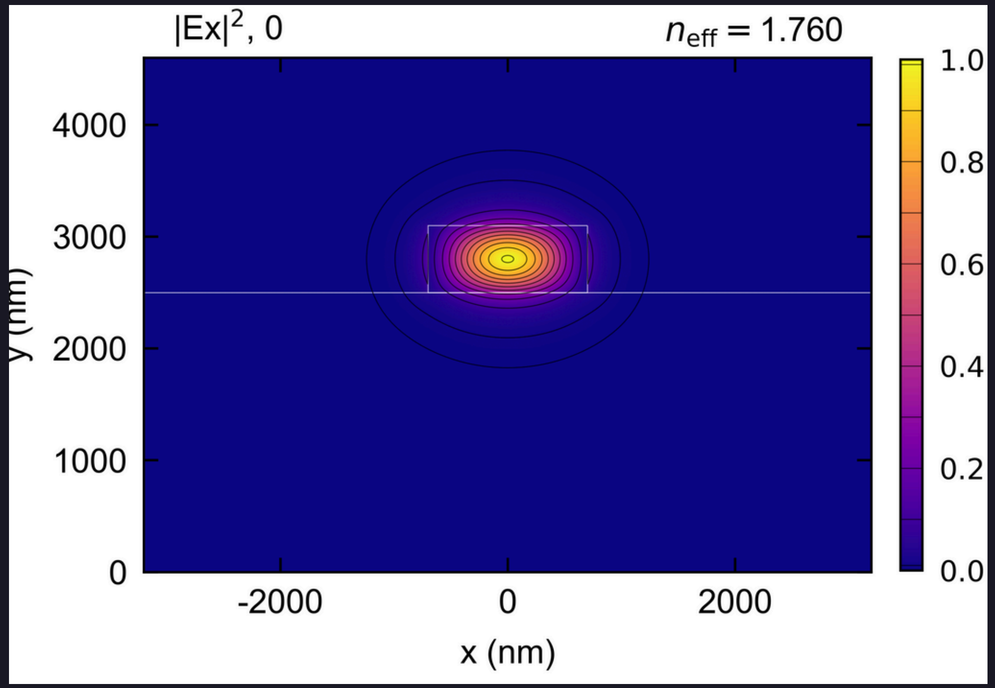
- Extract n_eff(λ)

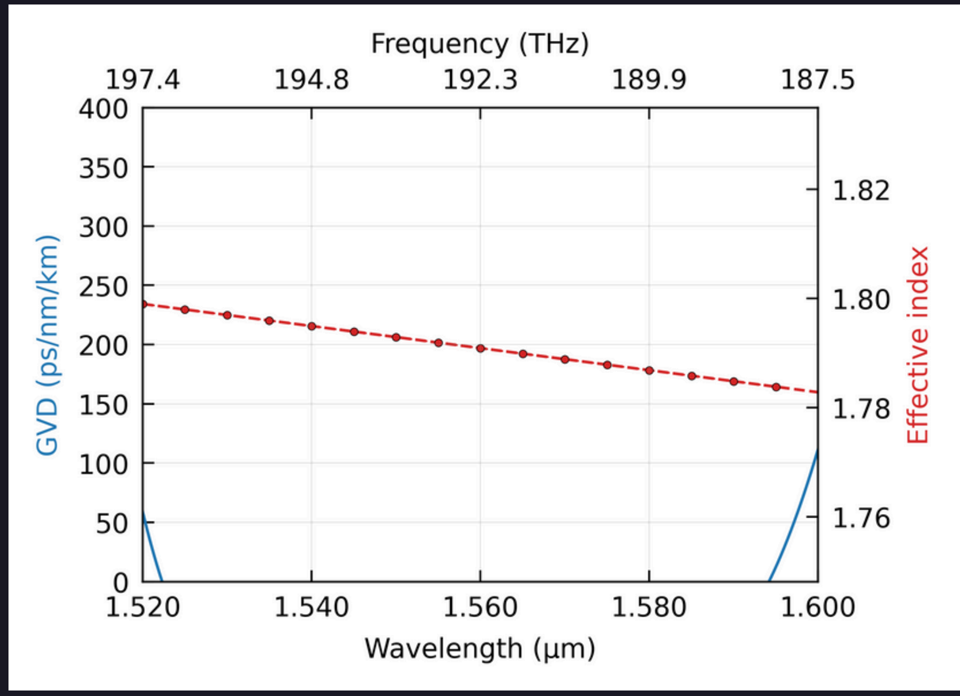
- Sweep in core width (0.8-1.6 μm)

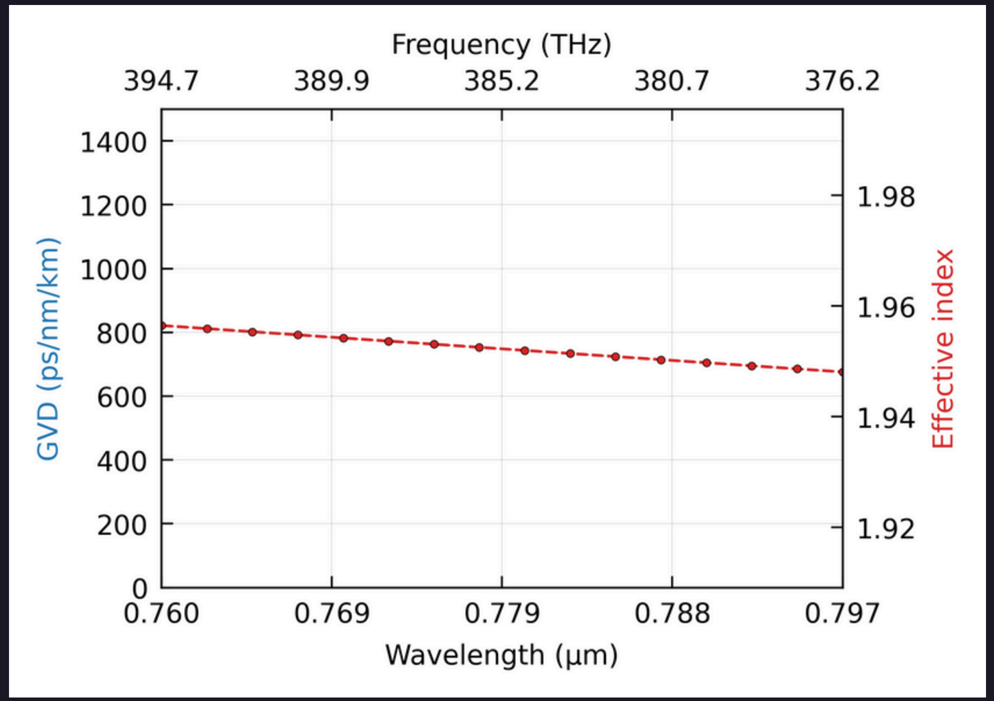
- Straight waveguide approach:

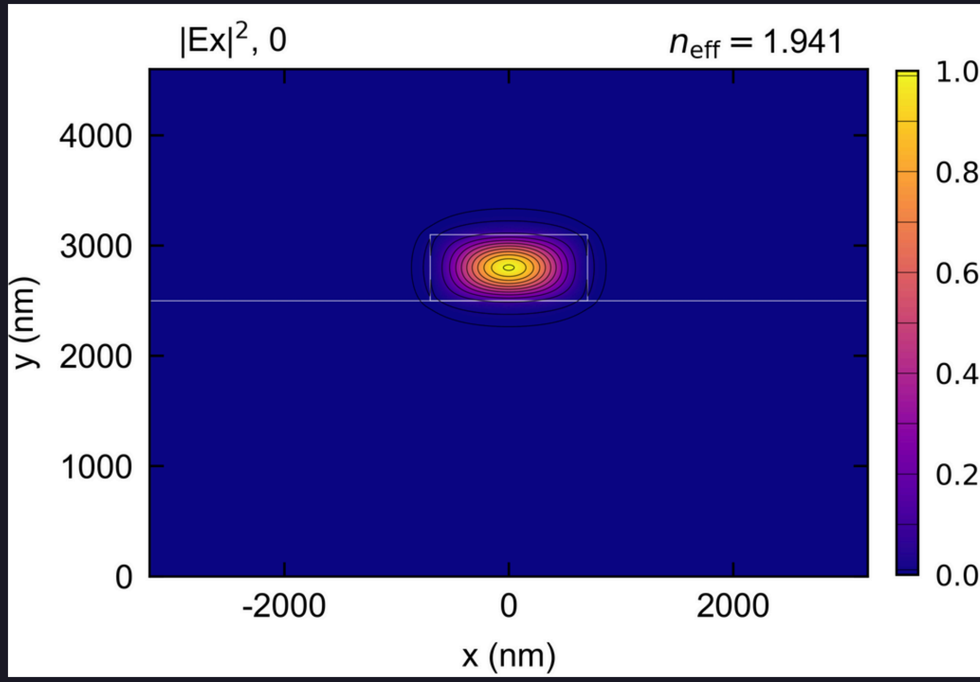
  R = 900 μm >> core width~ 1 μm

FH mode









SH mode

MODE SIMULATIONS

1. Extracted effective refractive indices using EMode:

- n,ω(λ)
- n,2ω(λ/2)

2. Compute propagation constants

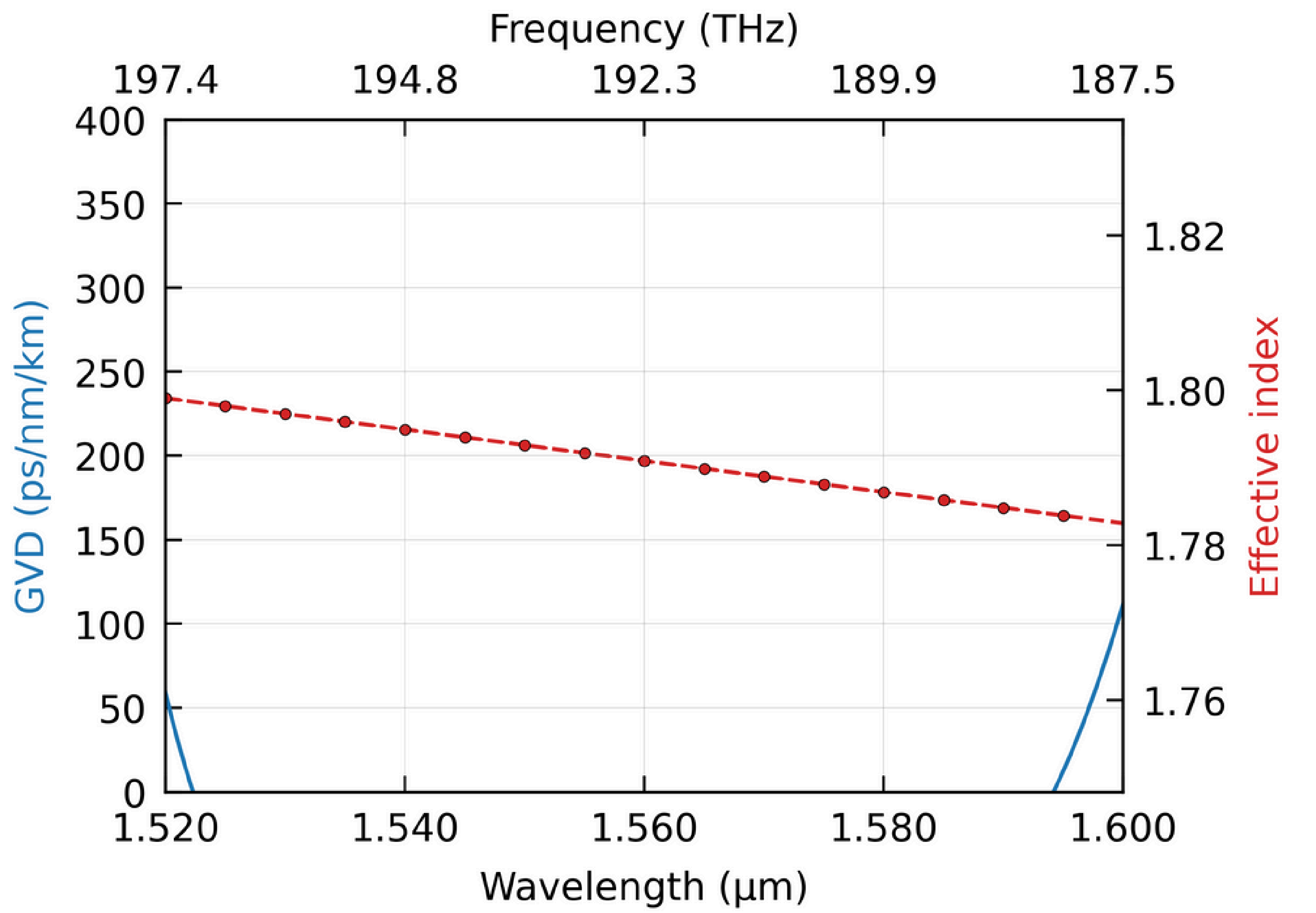
- β = 2π n / λ

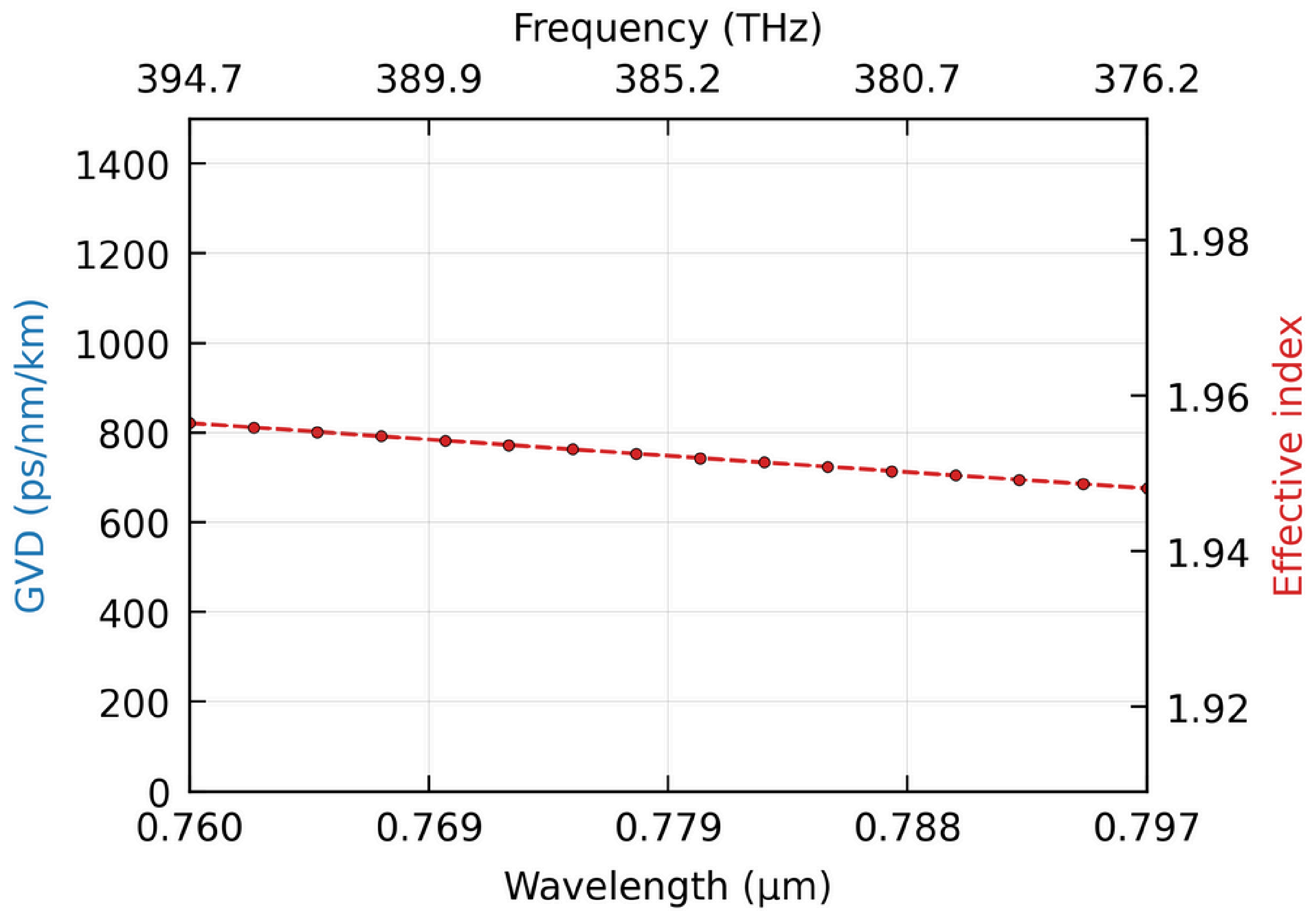
3. Compute phase mismatch

- Δk=β(2ω)−2β(ω)

4. Compute QPM period

- Λ=2π/ | Δk |

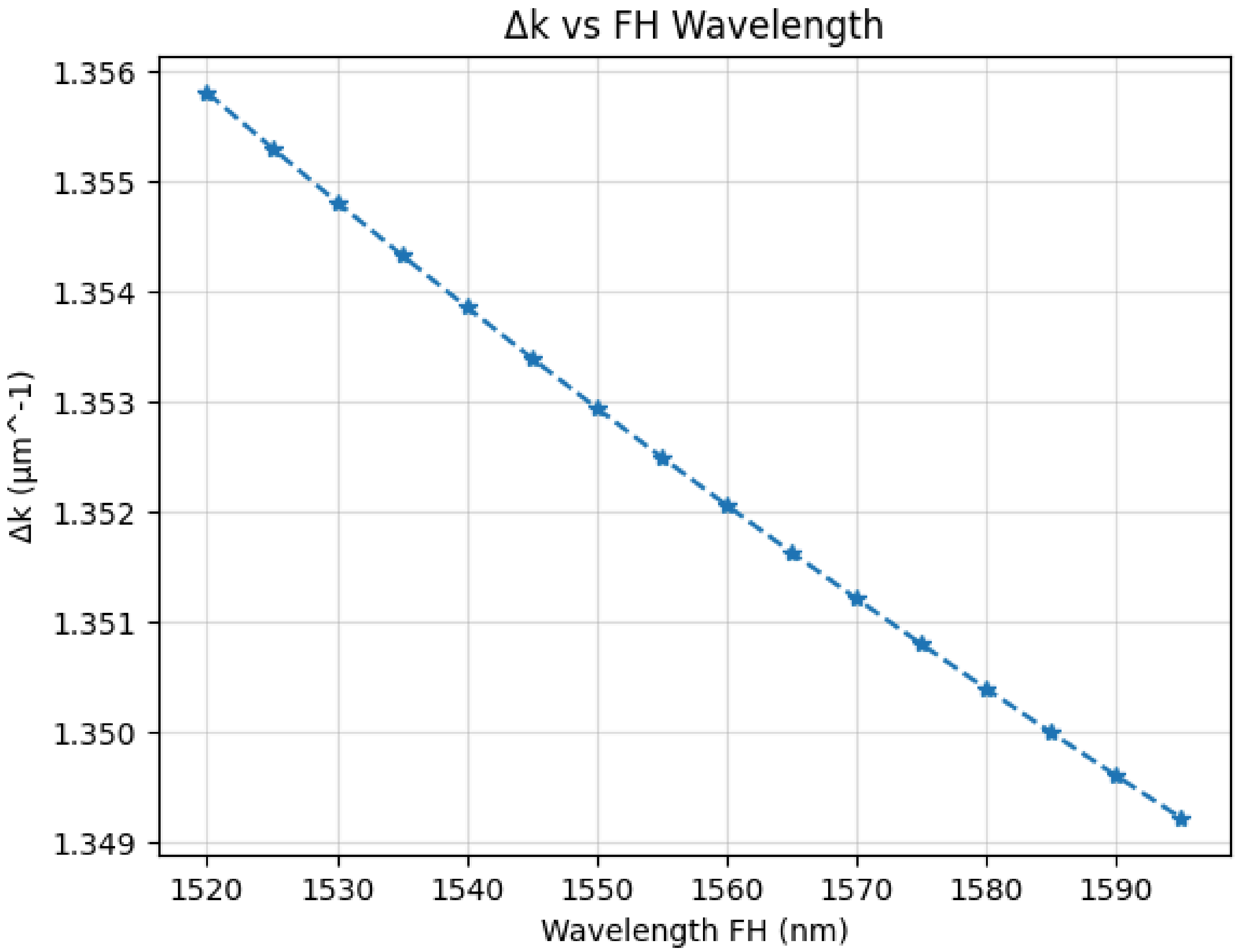


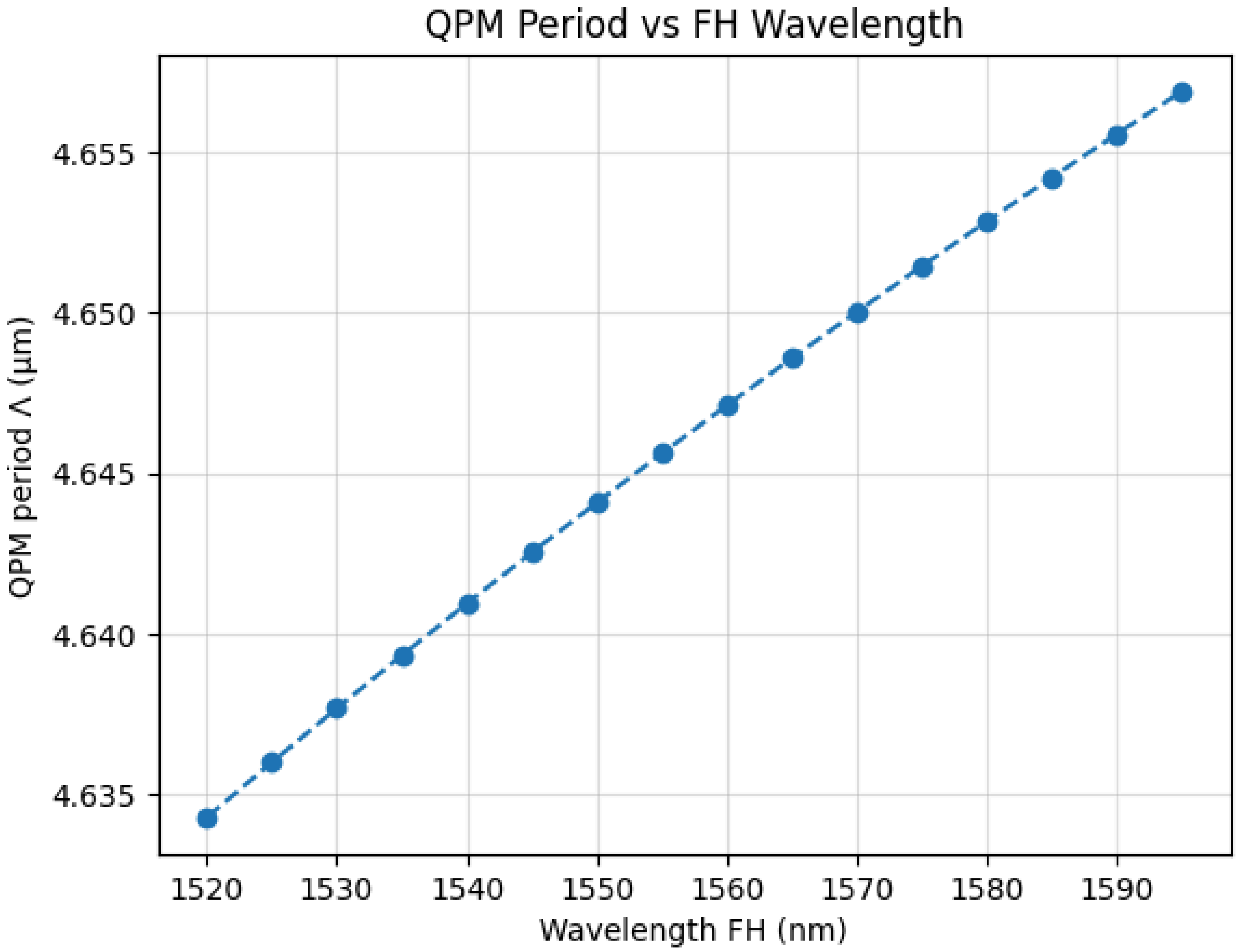


MODE SIMULATIONS

- 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.





TEMPERATURE TUNING

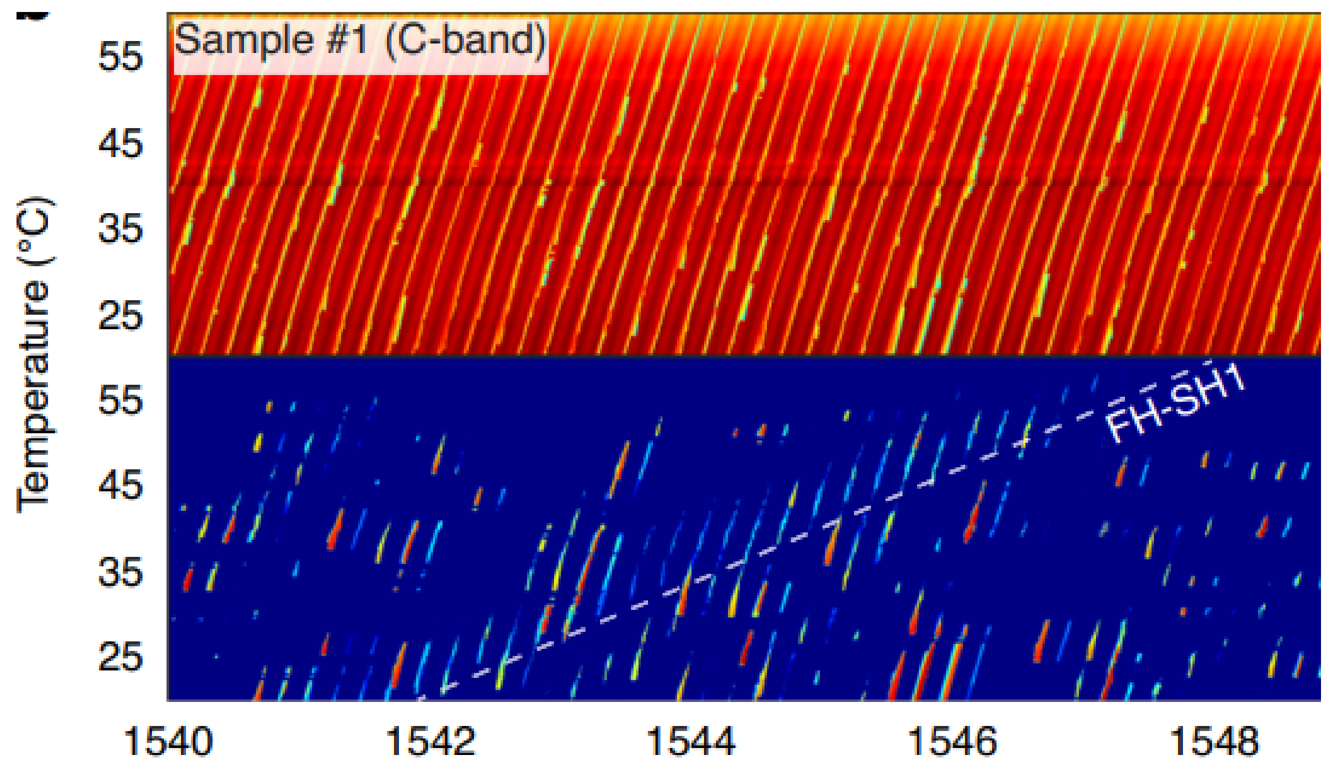
- Ring resonance condition:

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

- Linear Thermo-Optic tunning:

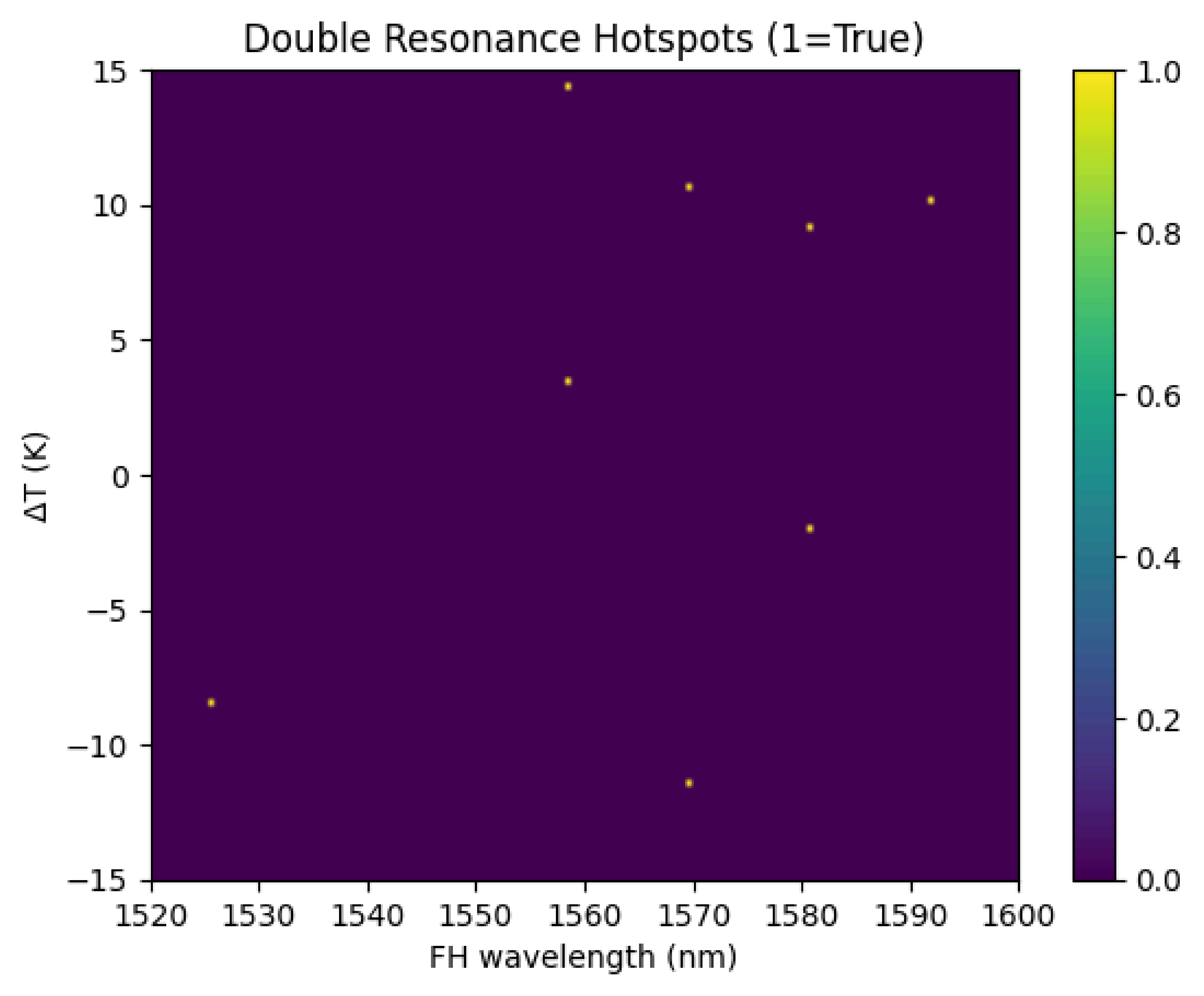
$$n_{\text{eff}}(T) = n_{\text{eff}}(T_0) + \frac{dn}{dT}(T - T_0)$$

  - FH and SH resonances move differently with temperature
  - Double resonance requires both to overlap → temperature scanning required
  - This defines the (λ, ΔT) hotspot map



Taken from [3]

Almost no double-resonant hot-spots



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

All-Optical-Poling (AOP):

- Space-charge field grows via photogalvanic effect [1]:

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

- Feed χ^2 into SHG coupled-mode equations:

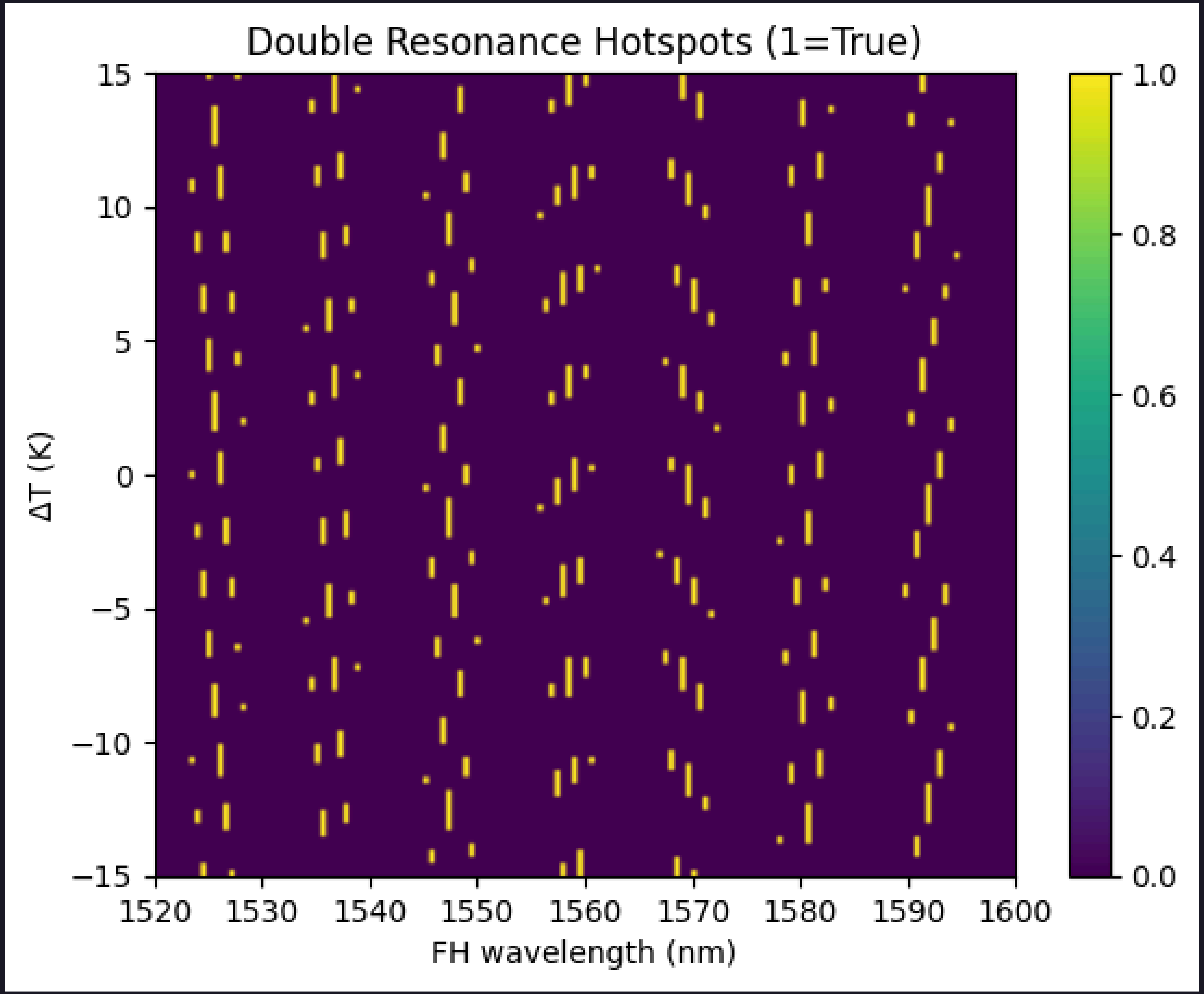
$$g \propto \frac{\chi^{(2)}_{\text{eff}}}{\sqrt{A^2_{\text{eff},\omega}A_{\text{eff},2\omega}}}$$

- With AOP χ(2) grating → effective mismatch [2]

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

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

- **Hotspots mark where FH and SH resonances occure simultaneously.**
- **Each vertical streak corresponds to a resonant mode pair (w, 2w).**
- **This pattern shows that double resonance is extremely discrete and sensitive to ΔT and wavelength.**



SHG PERFORMANCE

- χ^2 grows gradually as the photogalvanic field builds up.

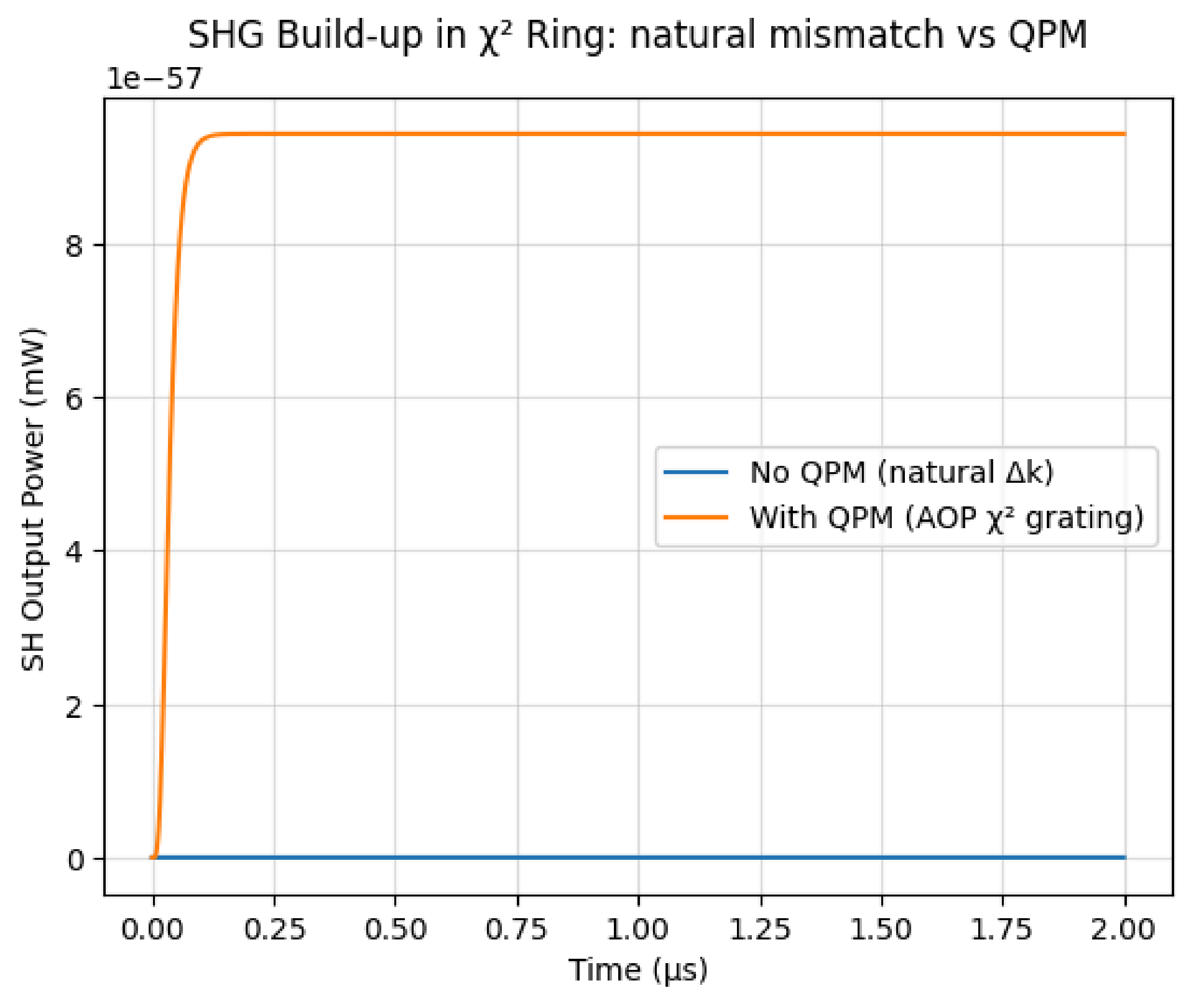
- Saturates after a few seconds: steady χ^2 available for SHG.

→

- With AOP grating (orange): phase mismatch is compensated.

- SH power grows rapidly and reaches a finite steady level.

→



OUTCOMES AND LIMITATIONS

OUTCOMES:

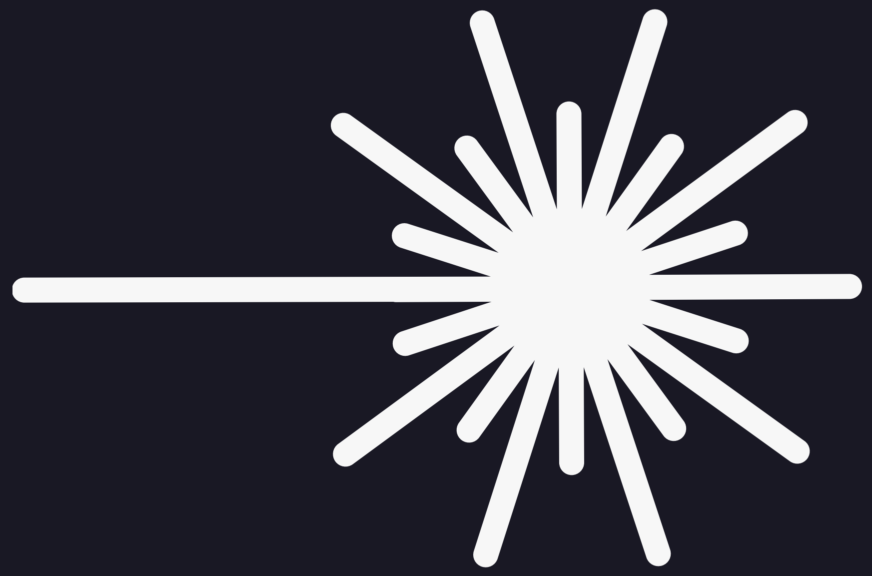
- Extracted realistic $\Delta k(\lambda)$ and $\Lambda(\lambda)$ from Si_3N_4 cross-section
- Computed double resonance hotspots
- Showed hotspot expansion after AOP: more usable operating points
- Demonstrated SHG performance with χ^2 from simulated AOP

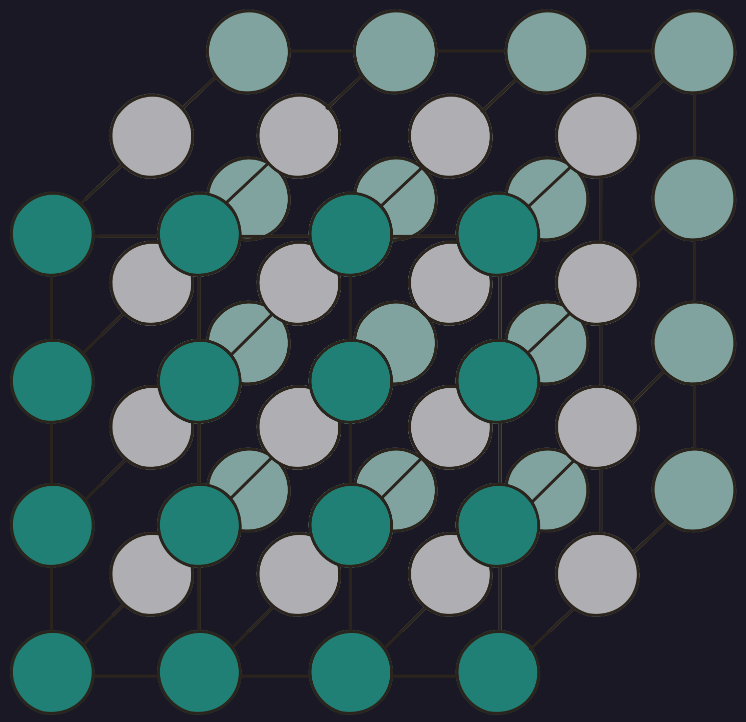
LIMITATIONS:

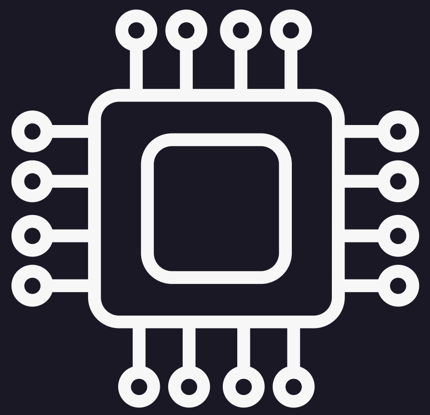
- No full 3D ring modes (using straight-waveguide approx)
- AOP is lumped (not spatially resolved)
- Nonlinear overlap approximated
- Only one geometry fully explored

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.

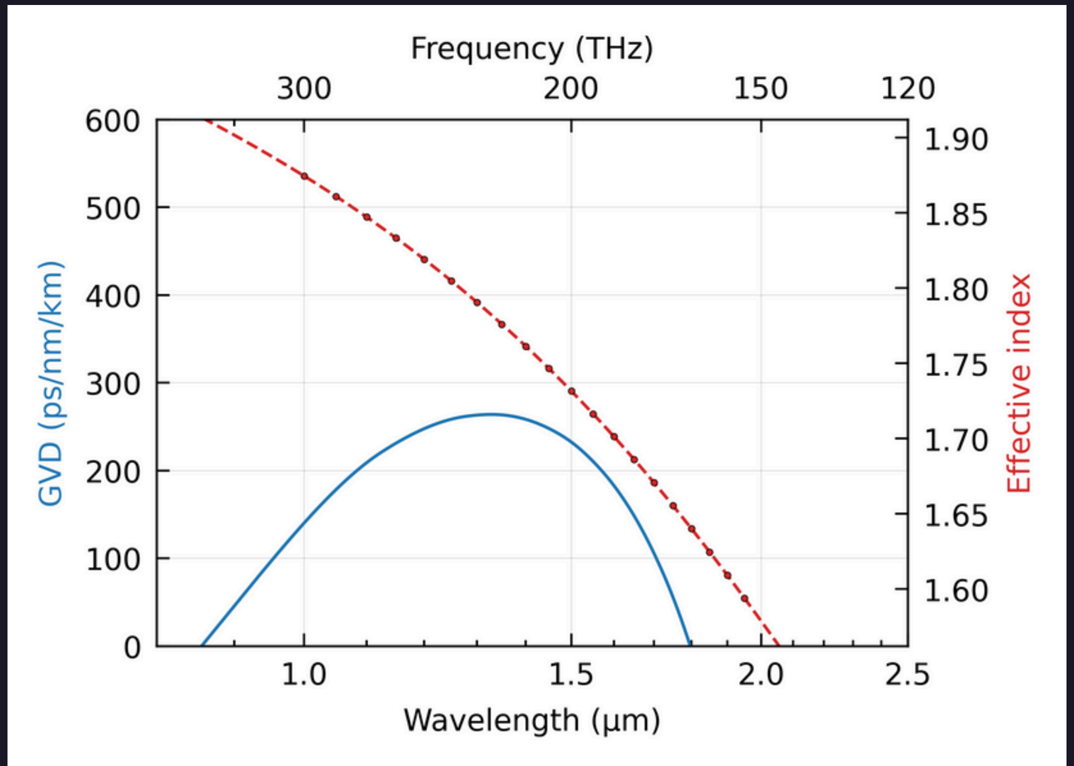


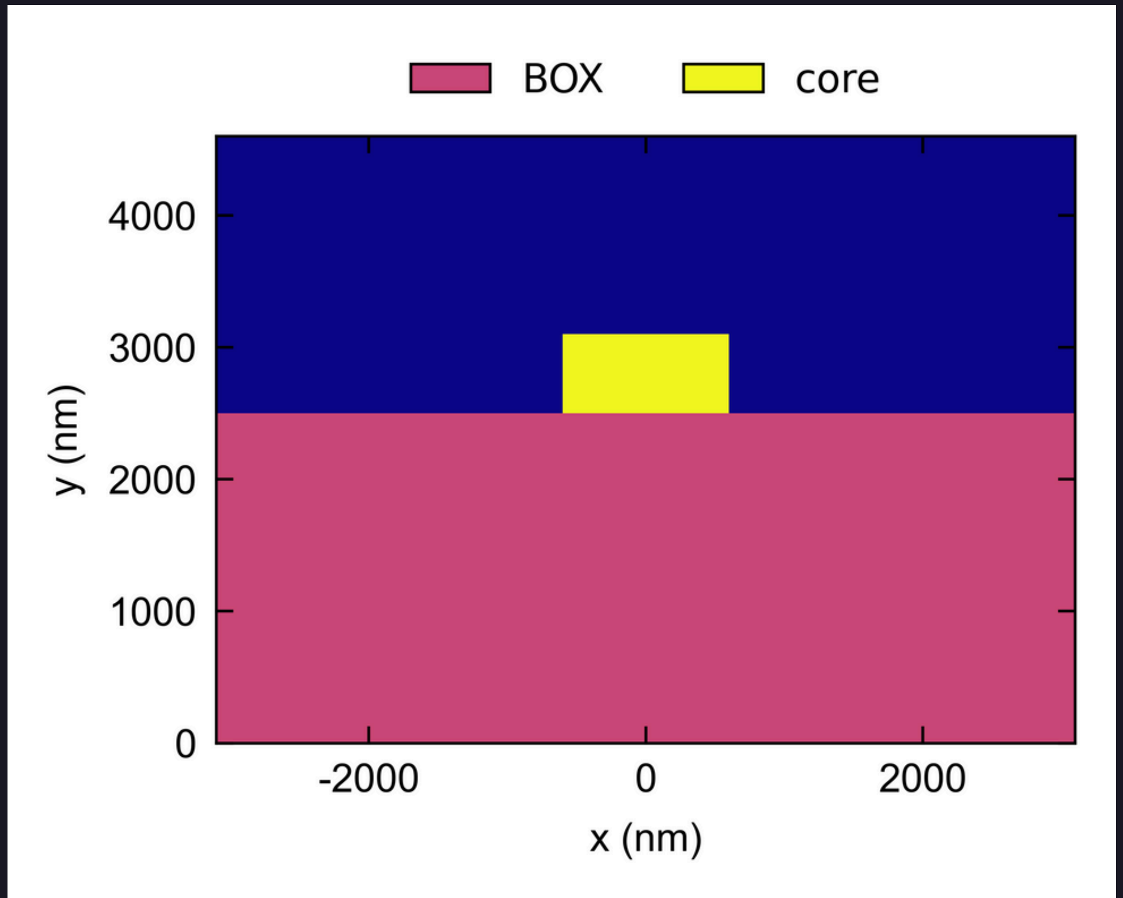


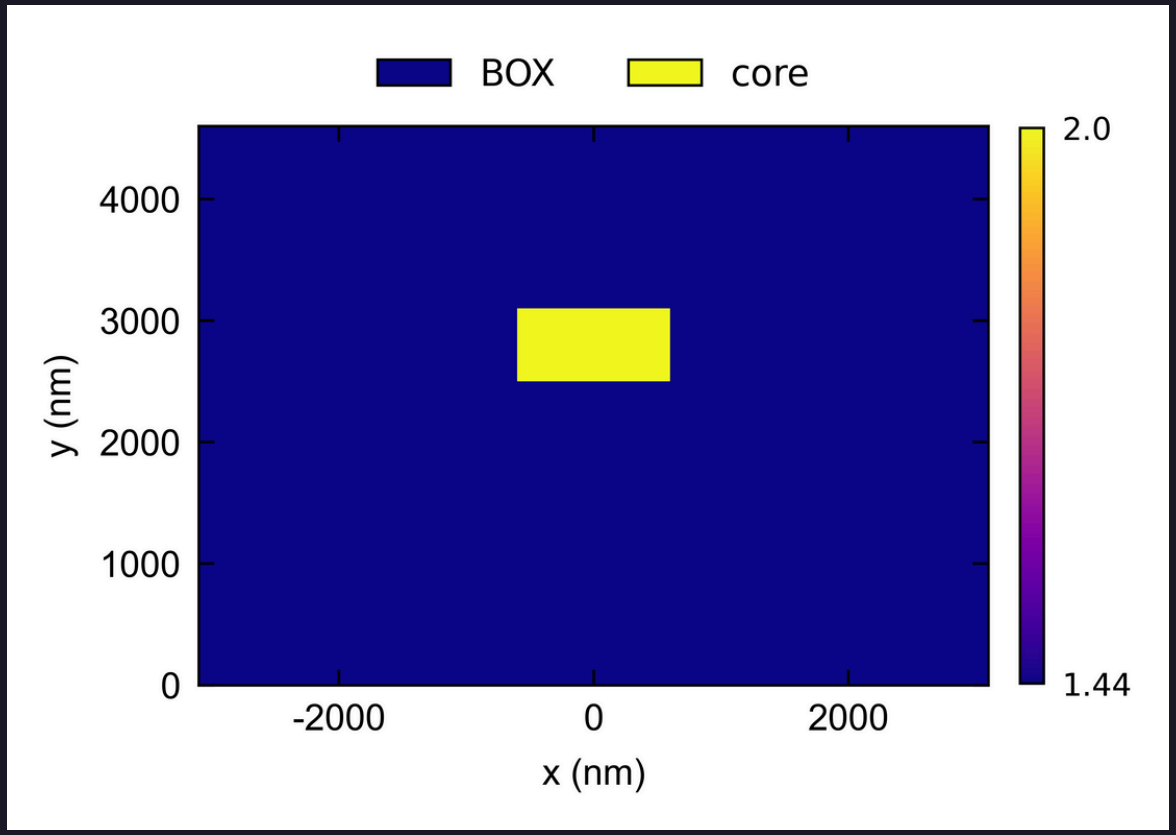


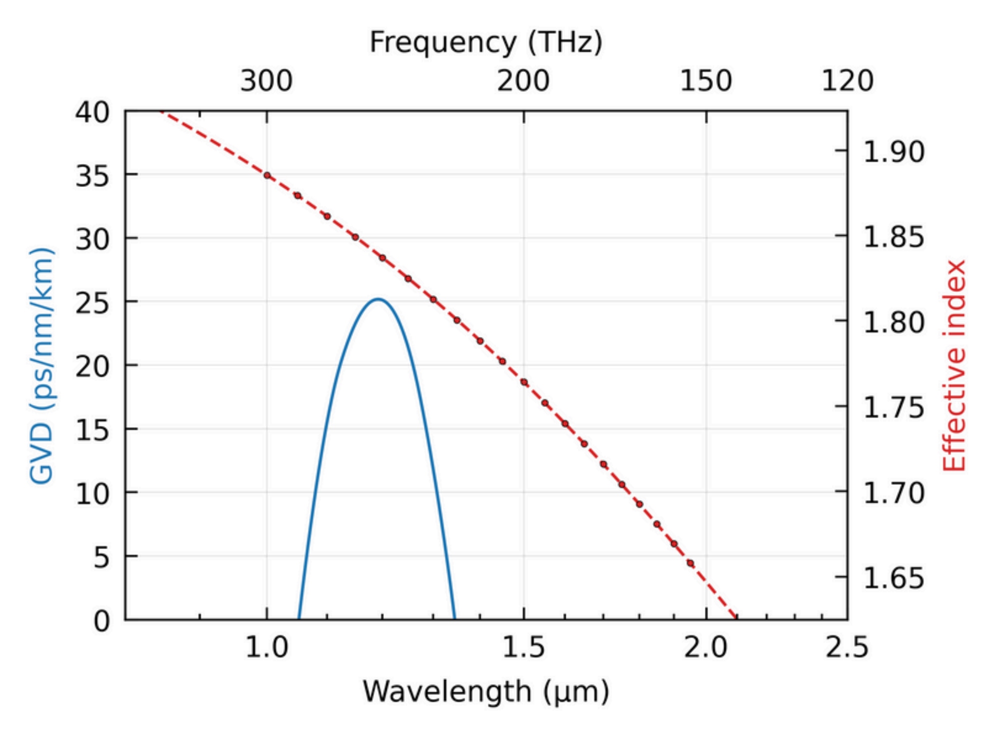
THANKS

APPENDIX


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


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


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


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