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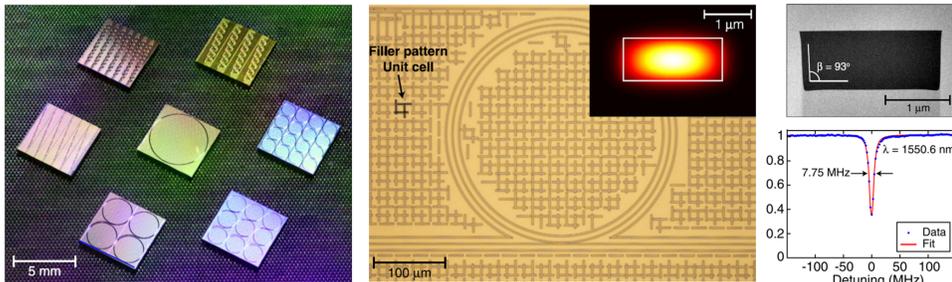
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Silicon nitride: integrated platform for nonlinear photonics

Integrated photonics leverages semiconductor chip fabrication technology to generate, manipulate, and detect **light at the microscale**.

Silicon nitride (Si₃N₄) is an emerging amorphous platform with a wide transparency window, low-loss, and CMOS-compatible fabrication.

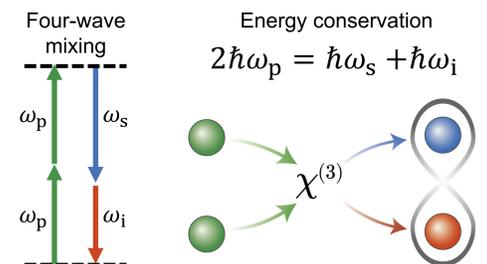


J. Liu et al, Nat. Commun. 12, 2236 (2021)

Spatial and temporal confinement in waveguides and microresonators enhance nonlinear interactions, i.e. multi-photon scattering processes:

$$\vec{P} = \epsilon_0 \chi^{(1)} \vec{E} + \epsilon_0 \chi^{(2)} \vec{E}^2 + \epsilon_0 \chi^{(3)} \vec{E}^3 + \dots$$

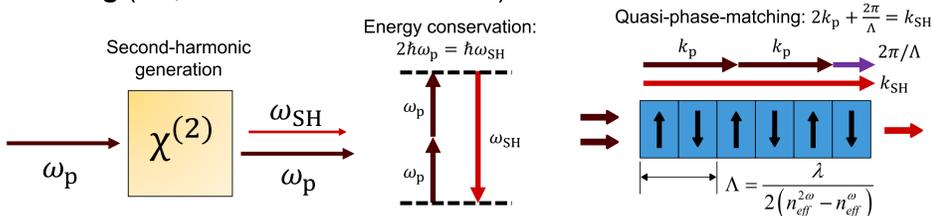
While Si₃N₄ lacks a **second-order nonlinearity** ($\chi^{(2)}$), it supports third-order ($\chi^{(3)}$) interactions, such as **four-wave mixing**, that can be used to generate photon pairs.



Photoinduced $\chi^{(2)}$: the coherent photogalvanic effect

Second-order (**three-wave mixing**) processes naturally occur in media lacking inversion symmetry, such as lithium niobate. They enable processes such as **second-harmonic generation** (SHG) and spontaneous parametric down-conversion (SPDC).

As they involve very different wavelengths, they generally require **phase-matching** (i.e., momentum conservation).



In Si₃N₄, the **coherent photogalvanic effect** (CPE) can break the inversion symmetry and inscribe a $\chi^{(2)}$ nonlinearity in the amorphous medium.

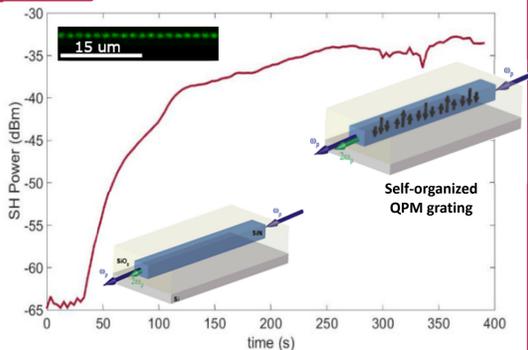
This **photoinduced $\chi^{(2)}$** automatically satisfies the quasi-phase-matching conditions (**all-optical poling**).

Coherent current:
 $J_{ph} = \beta (E_{\omega}^*)^2 E_{2\omega} e^{i\Delta k z} + c.c.$

Induced DC field:
 $E_{dc} = J_{ph} / \sigma$

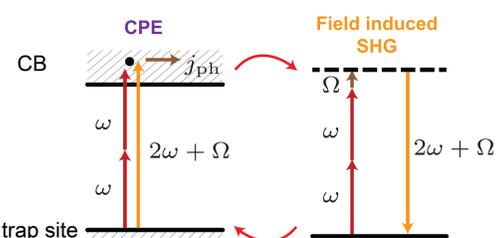
Effective nonlinearity:
 $\chi_{eff}^{(2)} = 3\chi^{(3)} E_{dc}$

A. Billat, D. Grassani, et al. Nat. Commun. 8 (1), 1016 (2017); O. Yakar, et al. Laser Photonics Rev. 16, 2200294 (2022)



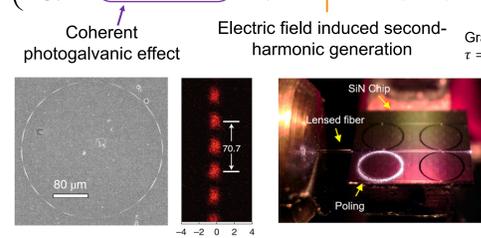
Resonant all-optical poling

In microresonators, the **circulating light is enhanced** by temporal confinement. This enhances both the CPE and SHG interaction, making **all-optical poling faster and more efficient** by orders of magnitude

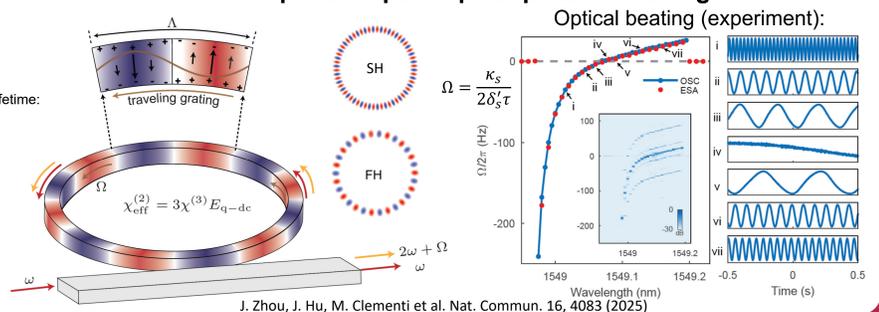


Theory (coupled mode equations)

$$\begin{cases} \frac{\partial A_p}{\partial t} = -\left(\frac{\kappa_p}{2} + i\delta'_p\right) A_p + \sqrt{\kappa_p \eta_p} P_{in} & \text{Pump field} \\ \frac{\partial A_s}{\partial t} = -\left(\frac{\kappa_s}{2} + i\delta'_s\right) A_s + i(\gamma_{spip} A_i) A_p^2 & \text{SH field} \\ \frac{\partial A_i}{\partial t} = \beta' (A_p^*)^2 A_s e^{-i\psi_{in}} - \frac{A_i}{\tau} & \text{Nonlinear grating} \end{cases}$$



The steady-state solution is a **traveling nonlinear grating**, that moves around the ring circumference as a transverse wave, oscillating at frequency $\Omega = \frac{\kappa_s}{2\delta'_s \tau}$. The mismatch in frequency is complementary to the one in momentum \rightarrow **spatiotemporal quasi-phase matching**



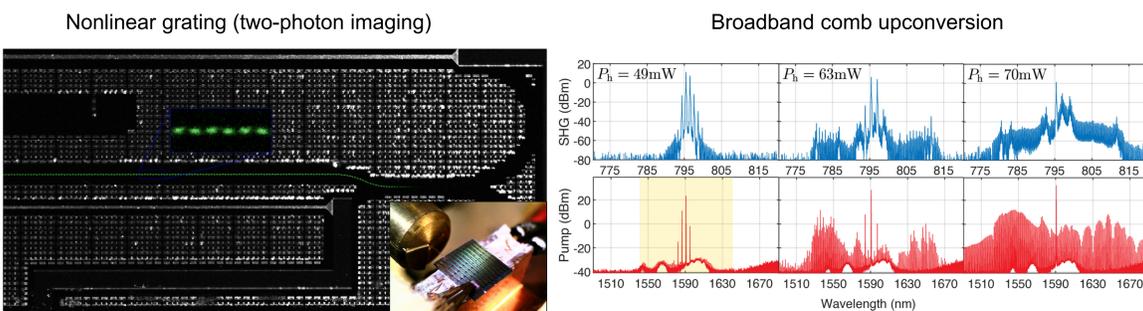
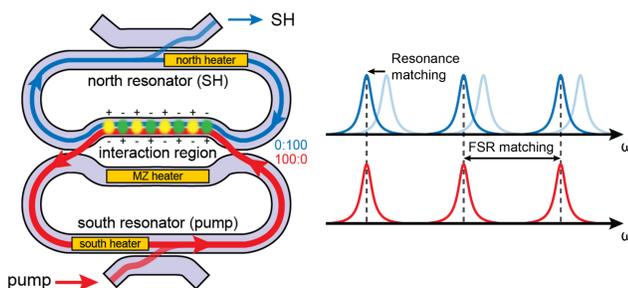
J. Zhou, J. Hu, M. Clementi et al. Nat. Commun. 16, 4083 (2025)

Reconfigurable second-harmonic generation

In a single resonator, getting a **doubly resonant condition** (pump-SH) is difficult due to dispersion.

Systems of **multiple resonators** coupled together increase the number of design degrees of freedom.

All-optical poling grants **reconfigurable quasi-phase-matching** across wide spectral regions.

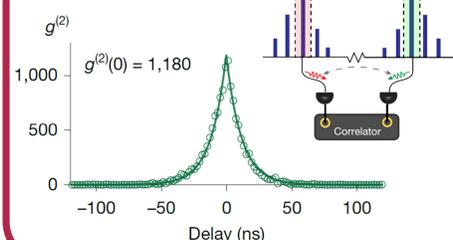
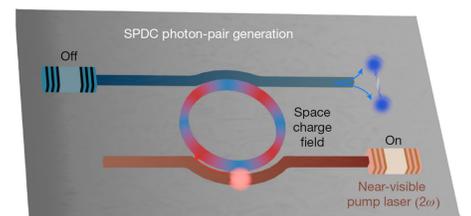
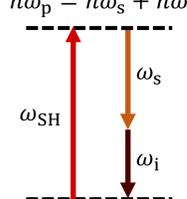


M. Clementi, L. Zatti, J. Zhou, M. Liscidini, & C.S. Brès. Ultrabroadband milliwatt-level resonant frequency doubling on a chip. Nat. Commun. 16, 6164 (2025)

Perspective: photoinduced quantum photonics

The photoinduced $\chi^{(2)}$ can be used to **generate photon pairs** through spontaneous parametric down-conversion, endowing silicon nitride photonics with new capabilities.

Spontaneous parametric down-conversion (SPDC):
 $\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$



B. Li et al. Nature 639, 922-927 (2025)

