Periodically-Poled Silicon

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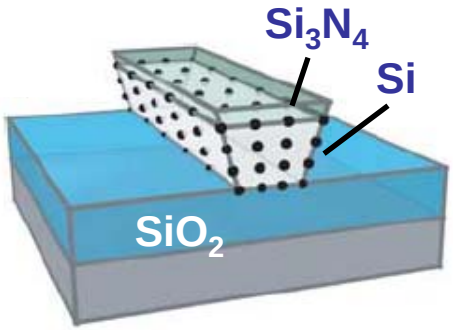
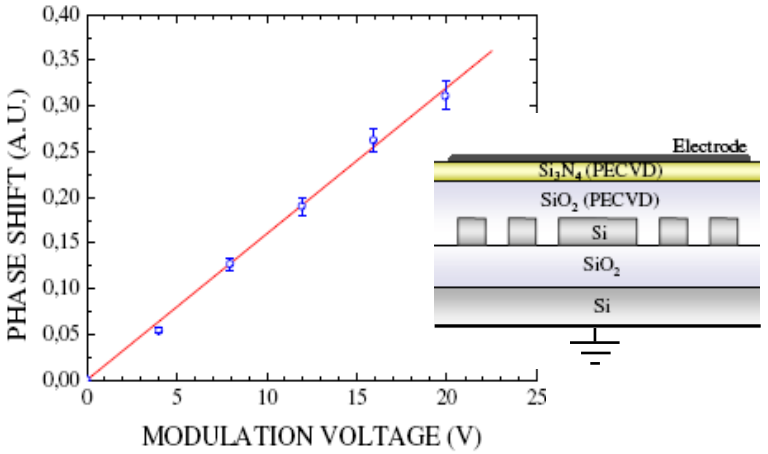
Breaking of silicon's centro-symmetry

- Silicon crystal is centro-symmetric
  → nearly no 2nd order optical nonlinearity $\chi^{(2)}$
  (equivalently, no linear electro-optical Pockel's effect)

- ***But, stress can break the centro-symmetry of silicon crystal to enable $\chi^{(2)}$ in silicon***



R. S. Jacobsen, et. al., Nature 441, 199-202 (2006)



Cladding stresses/strains (Si_3N_4) deform the waveguides
→ $\chi^{(2)} \sim 15\ pmV^{-1}$

Further enhanced by "slow light" in photonic crystal waveguides
→ $\chi_{enh}^{(2)} \sim 830pmV^{-1}$ within "slow-light" wavelength range.

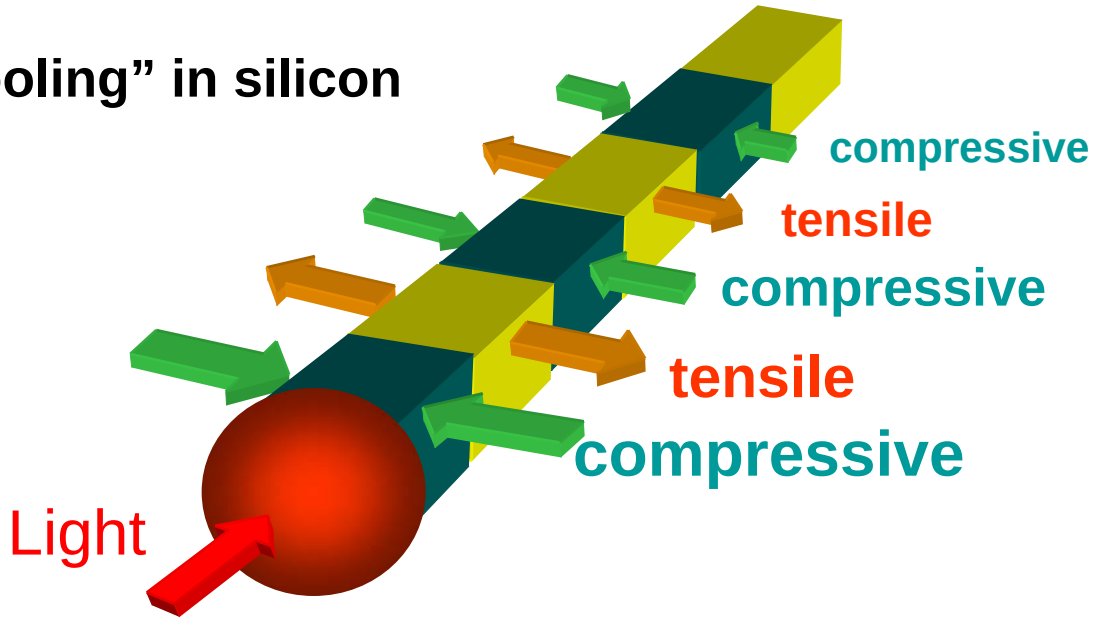
Our approach – "Periodic poling" in silicon

Motivated by this, we propose

By applying periodic alternating stress (e.g. compressive and tensile), silicon is "periodically poled" !

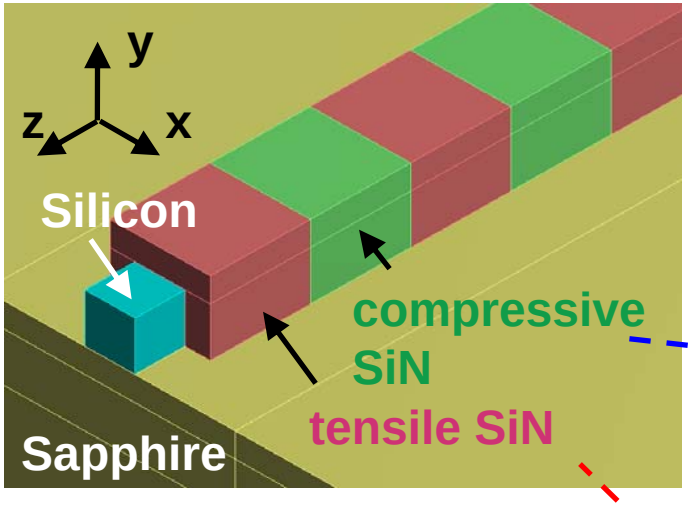
- **Enable $\chi(2)$ in silicon**
- **Enable quasi-phase matching for $\chi(2)$ processes (e.g. difference frequency generation) similar to LiNbO3, KDP etc.**

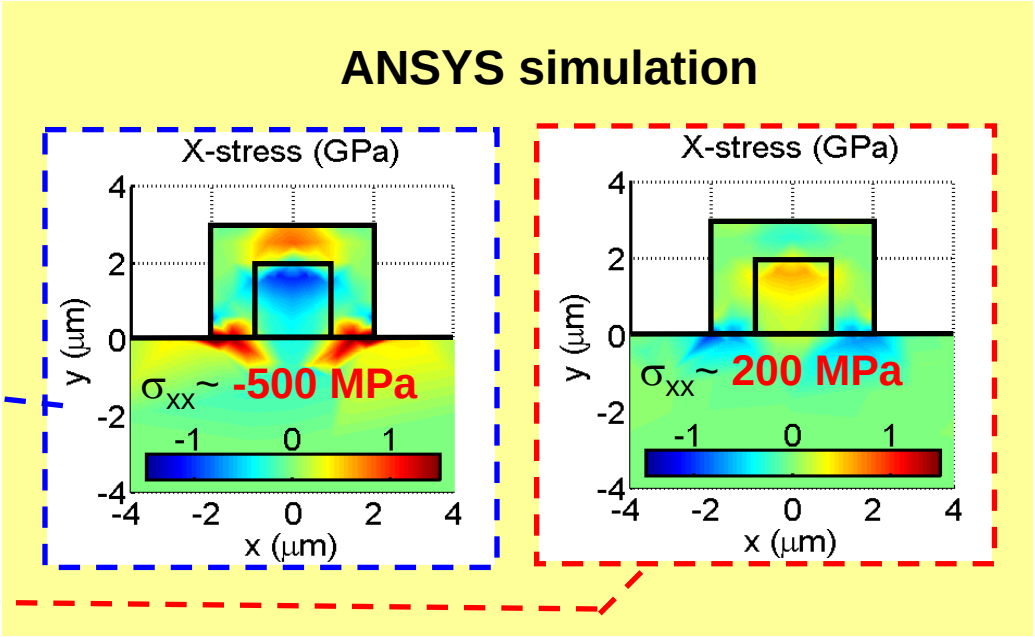
"Periodic poling" in silicon *(PePSi)*



PePSi waveguide structure

- Stress applied by cladding silicon nitride film (SiN)
  - Can be varied from compressive (+ve) to tensile (-ve) though deposition condition
- Periodic arrangement of different SiN film is used for silicon poling





- Assuming + 1 GPa and - 500 MPa in compressive and tensile SiN film respectively
  - ~ -500 MPa and + 200 MPa average stress is confined inside the waveguide core

$\chi^{(2)}$ induced along the waveguide

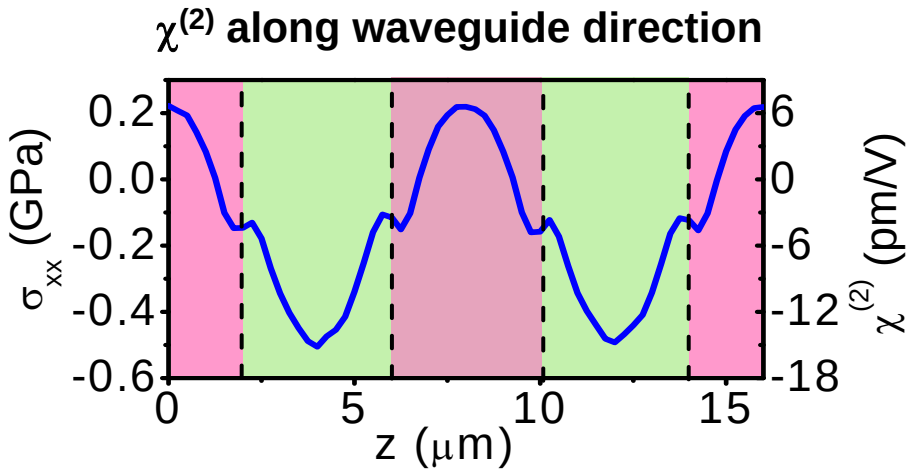
- Silicon's crystal centro-symmetric is broken by inhomogeneous stress or stress gradient

- Here, we use a a heuristic tool constructed from parameters of the classical anharmonic oscillator model

$$\Delta\chi^{(2)} = \frac{4q^3}{m^2\varepsilon\omega^4 a^4} S_i$$

where q is the electron charge, m is the electron mass, ε is the dielectric permittivity, a is the lattice constant, ω is the angular frequency of light, and S is the strain.

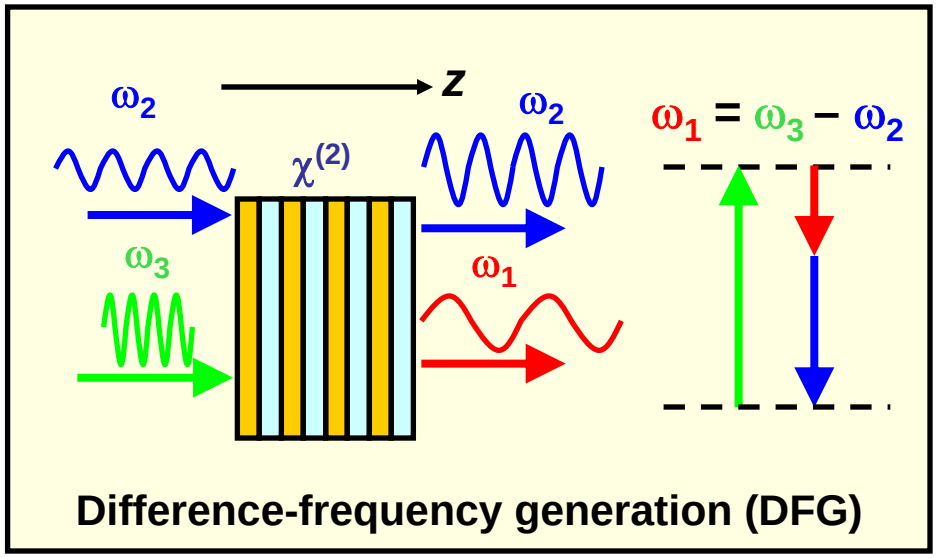
- Interestingly, this formula produces $\chi^{(2)}$ values qualitatively agrees with the measurements of Jacobsen et al.



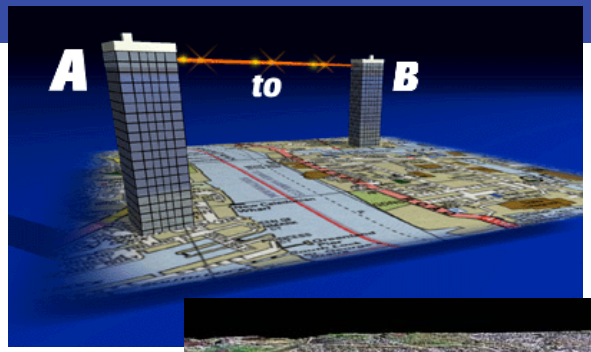
Quasi-phase matched $\chi^{(2)}$ process

- With periodic poling in silicon, efficient $\chi^{(2)}$ nonlinear optical process is enabled such as
  - second harmonic generation (SHG), sum frequency generation (SFG)
  - difference frequency generation (DFG), OPO and OPA

- Using common available near IR sources, rare mid-IR or even THz sources can be made available using difference frequency generation (DFG) with PePSi



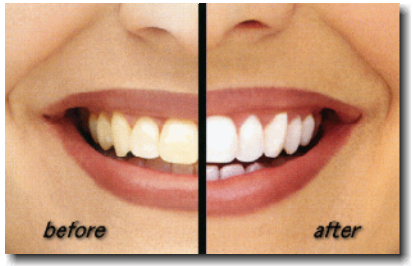
Mid-IR applications



- Free-Space Optical Communication Link
  - Fog penetration

- LADAR
  - Excellent propagation, minimal turbulence effects
- Medical applications
  - Skin resurfacing
  - Dentistry

Er:YAG laser

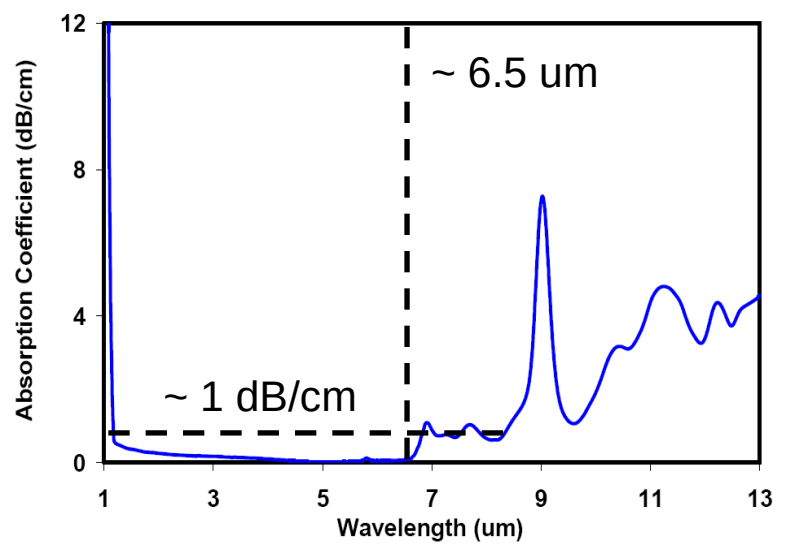


We propose:

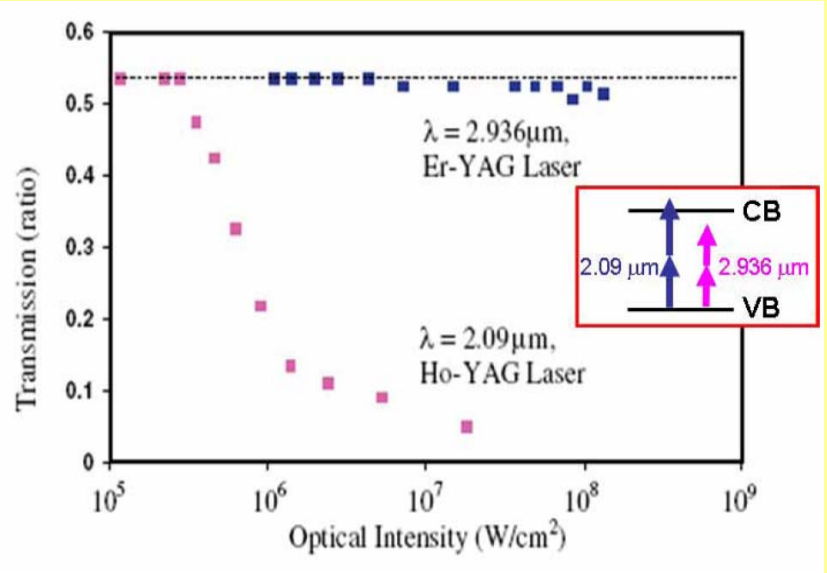
Efficient mid-IR generation by quasi-phase matched difference frequency generation (QPM-DFG) in PePSi.

Why silicon for mid-IR?

Silicon low loss window



Nonlinear loss due to TPA

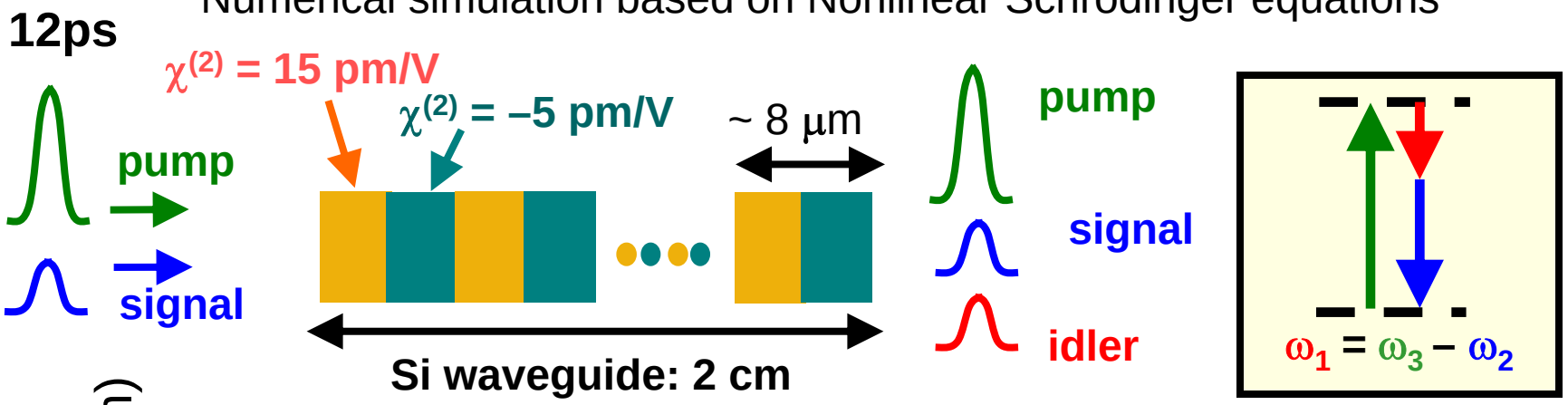


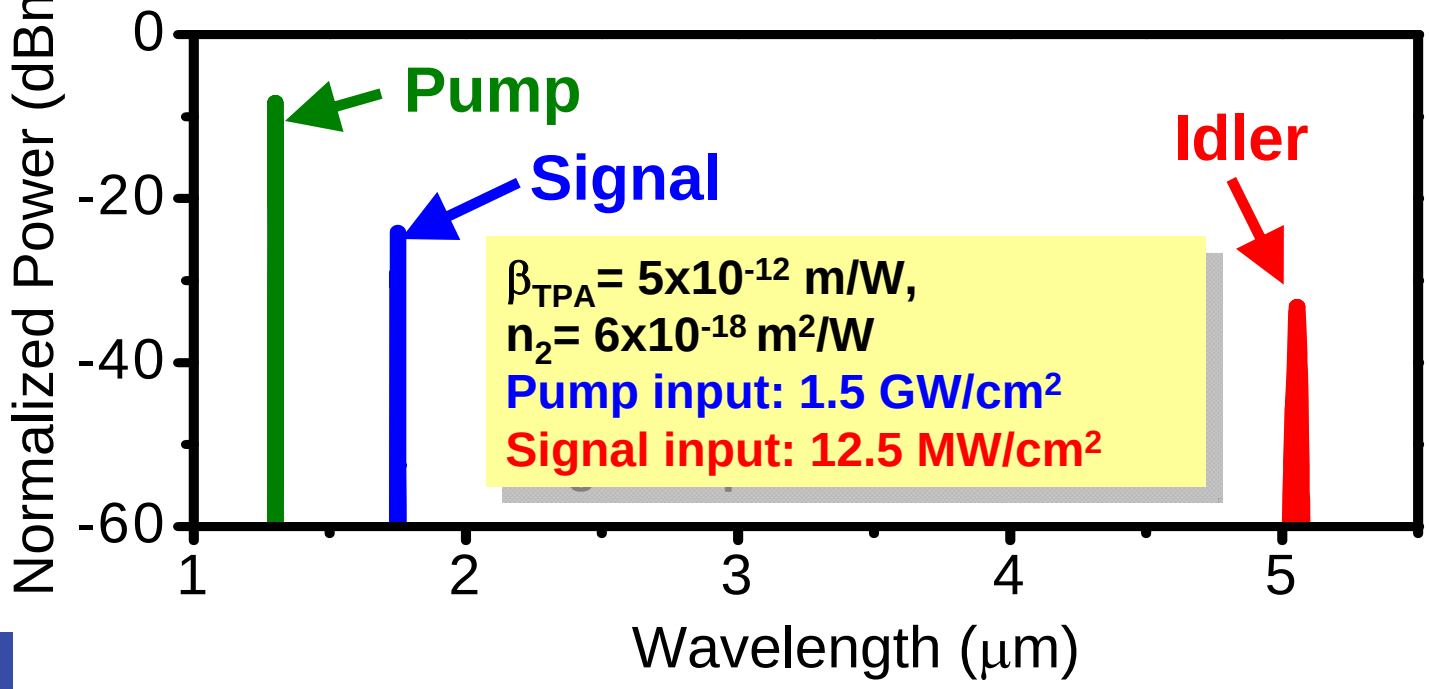
V. Raghunathan, "Demonstration of a Mid-infrared silicon Raman amplifier," Opt. Express 15, 14355-14362 (2007)

- Silicon have low sbsorption window up to ~ 6.5 μm
- Nonlinear absorption at mid-IR window is suppressed (no TPA in Mid-IR)

Mid-IR generation using PePSi

Numerical simulation based on Nonlinear Schrödinger equations





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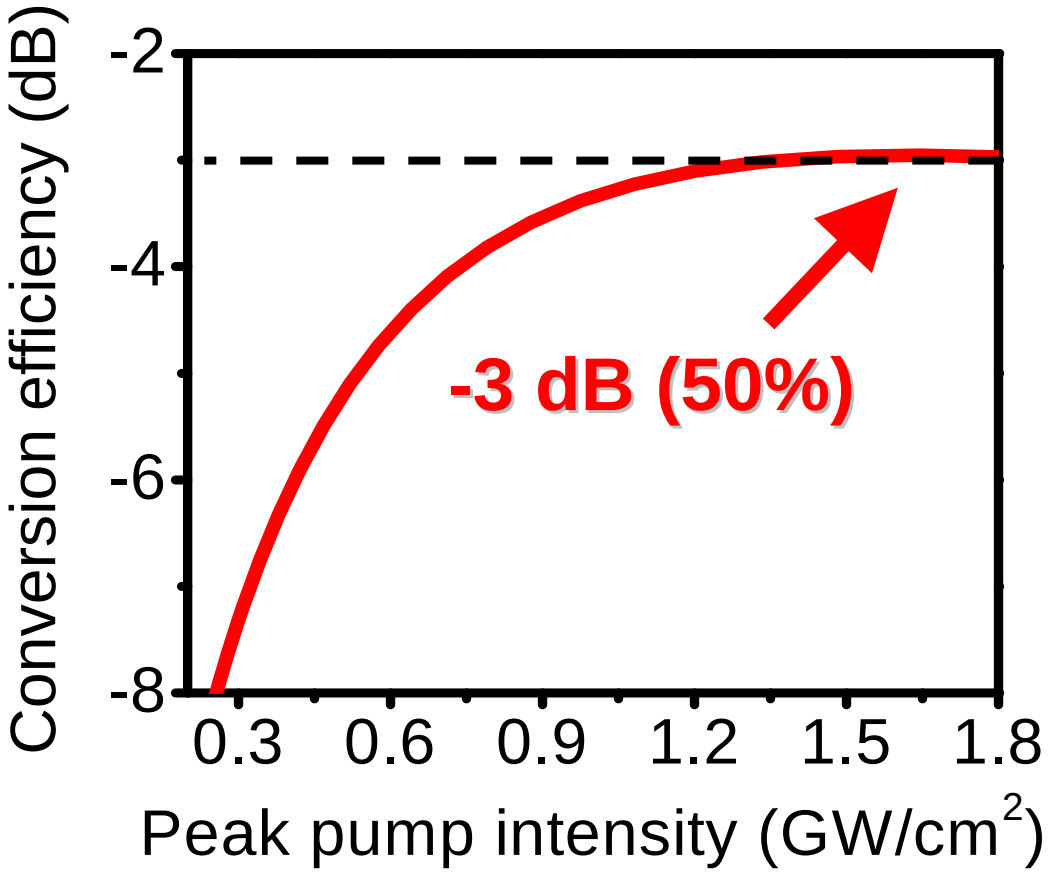
Mid-IR conversion efficiency



Efficient conversion efficiency of mid-IR generation (at ~5 μm) as high as – 3dB (~50%).

Conclusions

- Based on the phenomena of stress-induced $\chi^{(2)}$ demonstrated, we proposed a new periodic poling technique for silicon named as ***PePSi.***
- We simulate and investigate the poling of a silicon waveguide, $\chi^{(2)}$ can be poled from **15 pm/V** to **-5 pm/V** in each period.
- We also propose a application using PePSi for mid-IR generation, **conversion efficiency as high as 50%** is simulated.
- Besides mid-IR generation, silicon is also transparent in THz regime. PePSi can be a potential technique to make silicon as a **THz source.**

Q&As

Thank you