INTEGRATED NONLINEAR PHOTONICS

Concepts, methods and research

AARHUS
UNIVERSITY
DEPARTMENT OF ELECTRICAL AND COMPUTER
ENGINEERING

GUEST LECTURE
8 MAY 2025

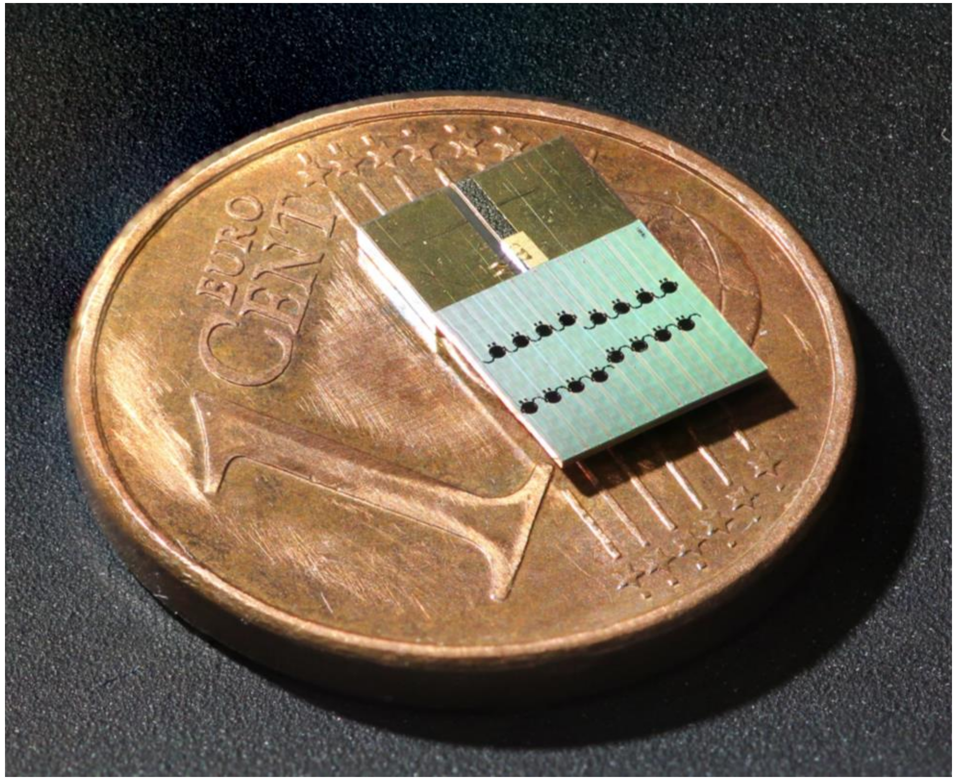
ASGER BRIMNES GARDNER
PHD STUDENT

AGENDA

- Integrated nonlinear photonics:
  - What?
    - Why?
      - How?
        - Who?

- Example: quantum frequency conversion

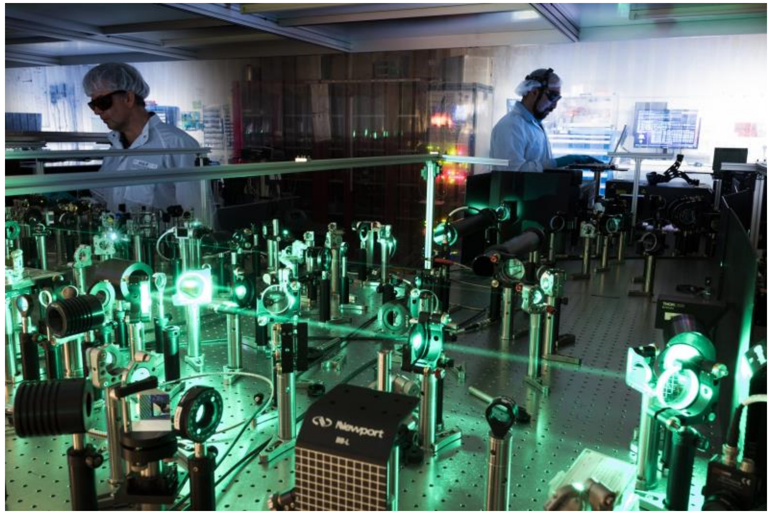
- Example: deep-UV generation



INTEGRATED NONLINEAR PHOTONICS

What?

- **Complex** optical systems on a chip
- Transferral of **laboratory** optical systems to **mass-producable** devices: Photonic Integrated Circuits (**PICs**)
- Comparison: Electronic Integrated Circuits (**EICs**)

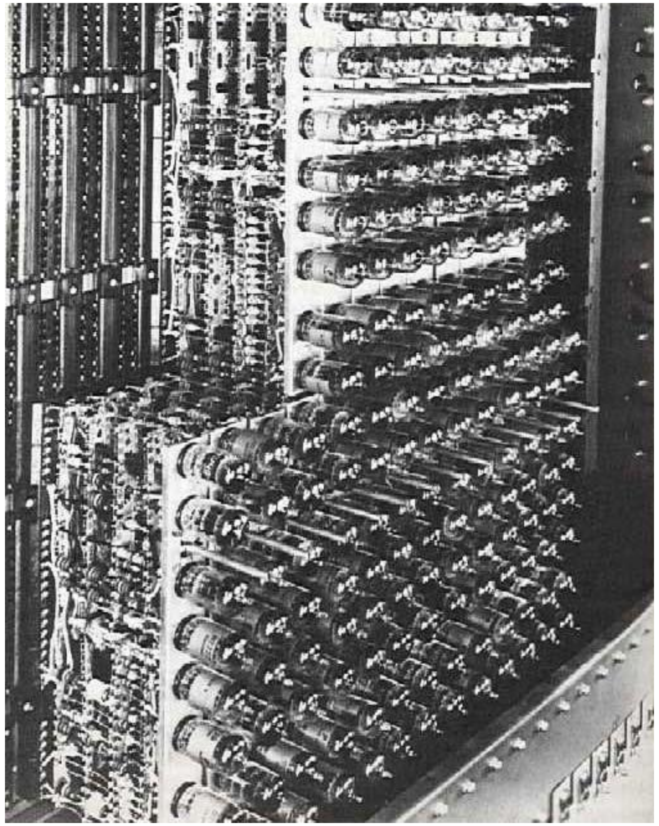


European XFEL

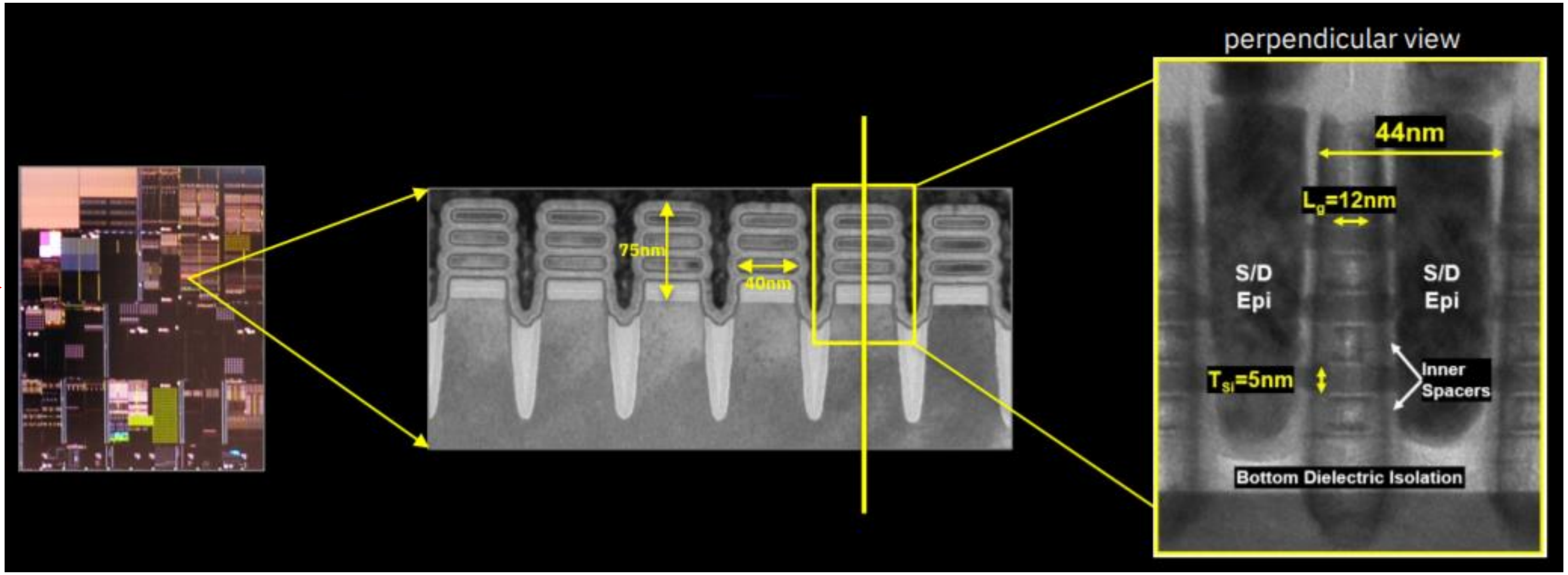
Di Zhu *et. Al.*, "Integrated photonics on thin-film lithium niobate," Adv. Opt. Photon. 13, 242-352 (2021)

INTEGRATED NONLINEAR PHOTONICS

IBM 701 (1953)



IBM 2 nm node transistors (2021)



INTEGRATED NONLINEAR PHOTONICS

Why?

- SWaP: **S**ize, **W**eight **a**nd **P**ower
- Use cases include:

  - the Internet

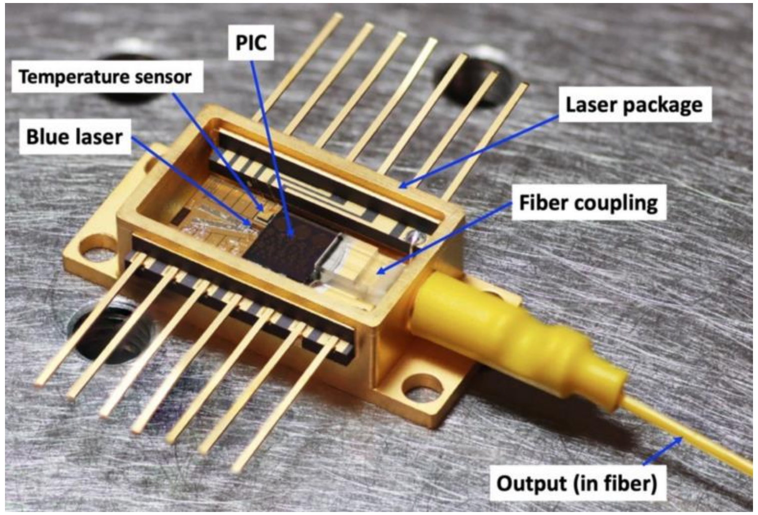
  - data centers

  - sensing

  - (quantum) computing

TOPTICA

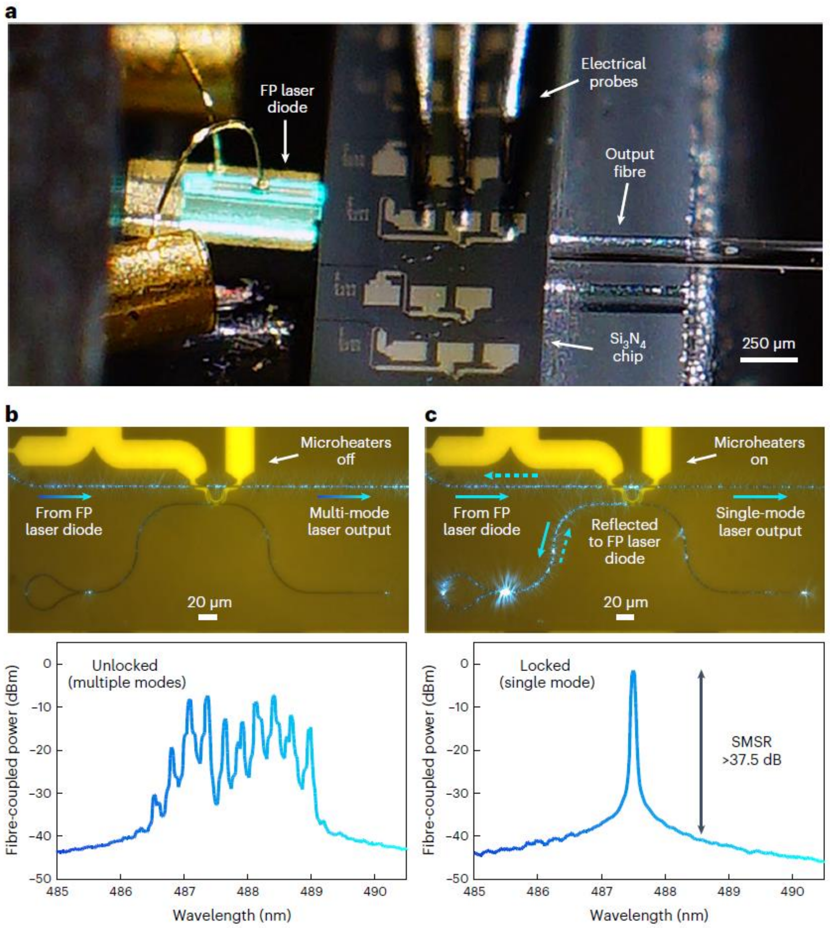
DEEPLIGHT™



INTEGRATED NONLINEAR PHOTONICS

How?

- Confining light to **micro/nanoscale** structures opposed to **free-space** beams

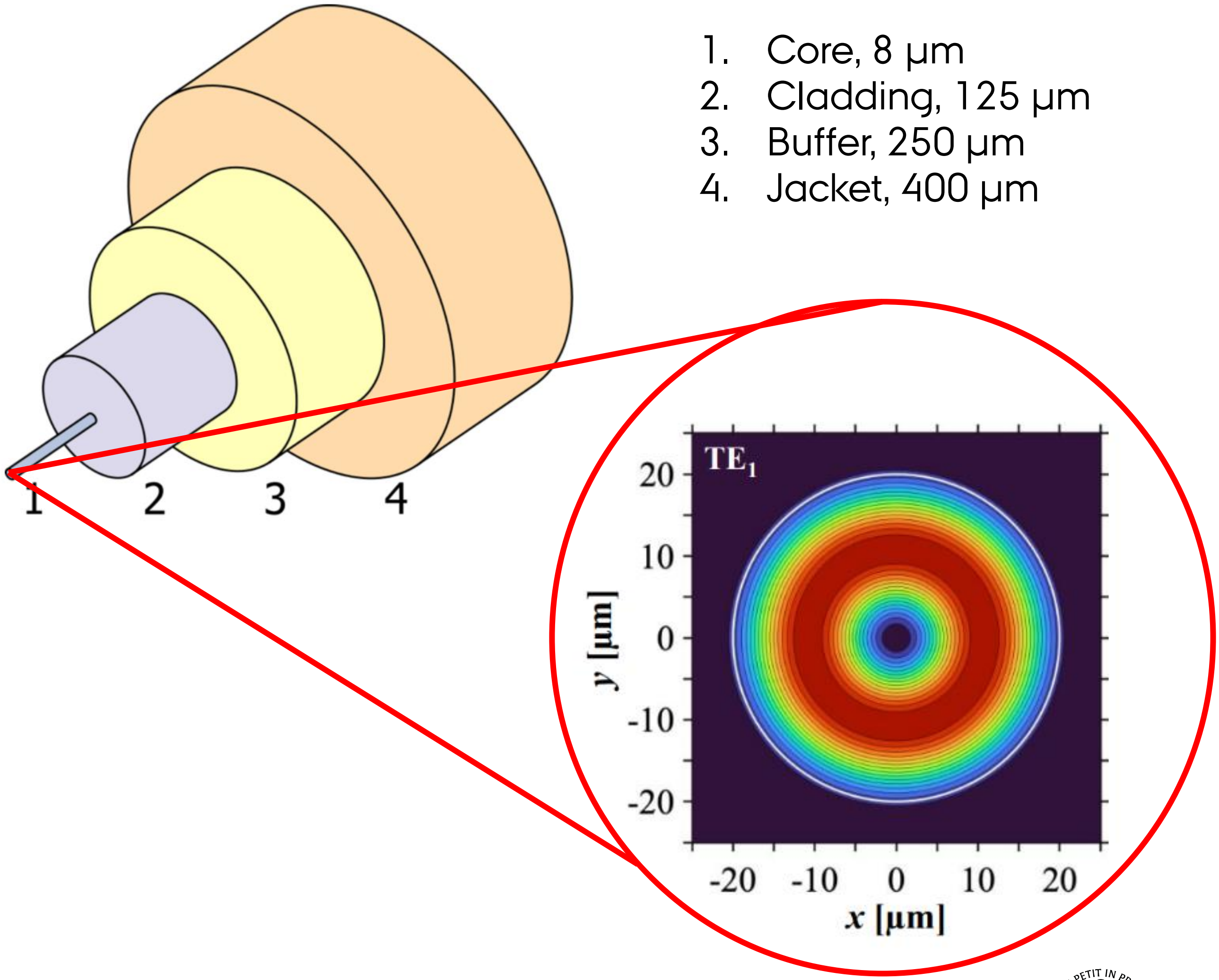


Corato-Zanarella *et al.* Widely tunable and narrow-linewidth chip-scale lasers from near-ultraviolet to near-infrared wavelengths. *Nat. Photon.* **17**, 157–164 (2023).

INTEGRATED NONLINEAR PHOTONICS

How?

- Confining light to **micro/nanoscale** structures opposed to **free-space** beams
- Example: **optical fibers**



1. Core, 8 µm
2. Cladding, 125 µm
3. Buffer, 250 µm
4. Jacket, 400 µm

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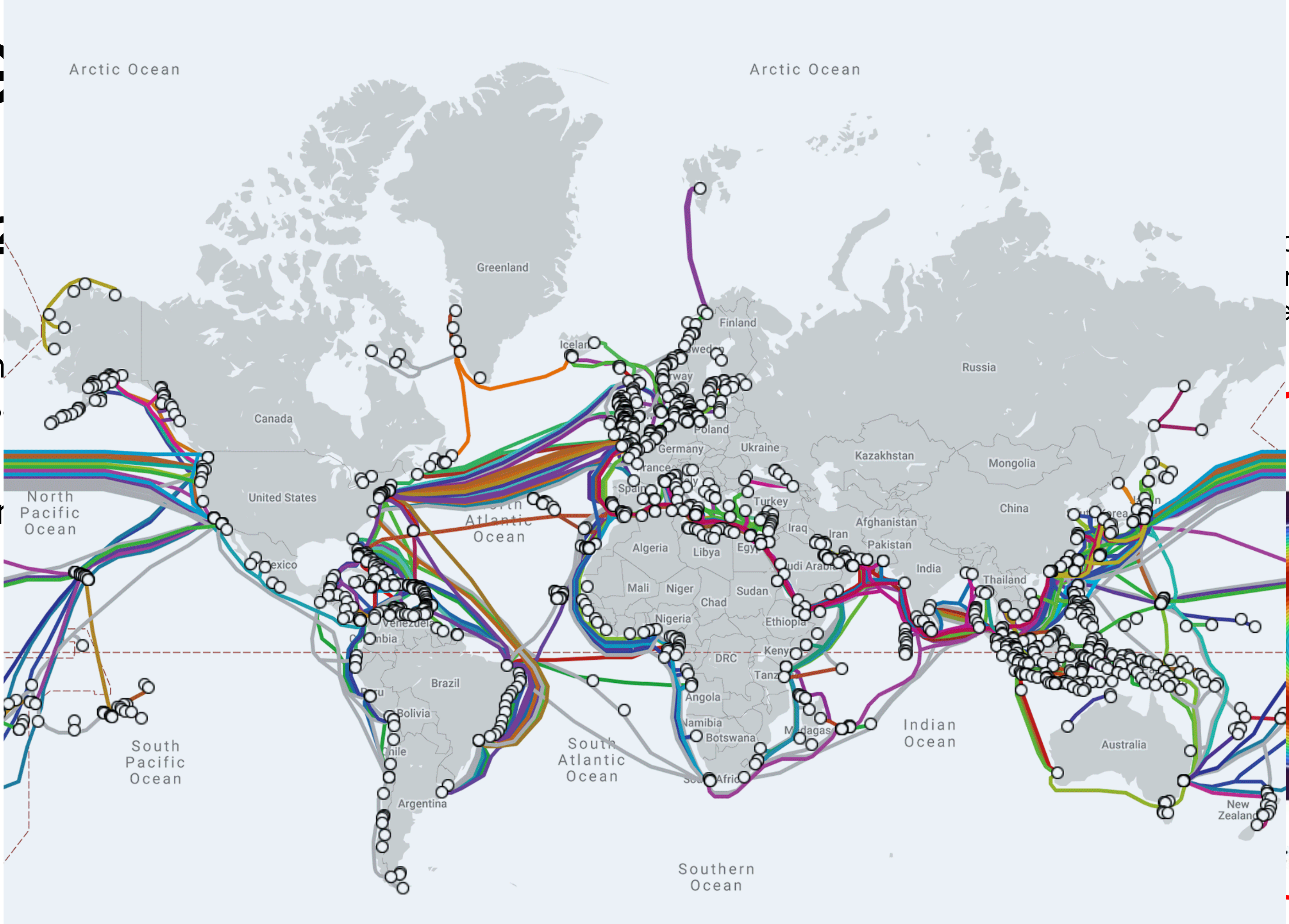
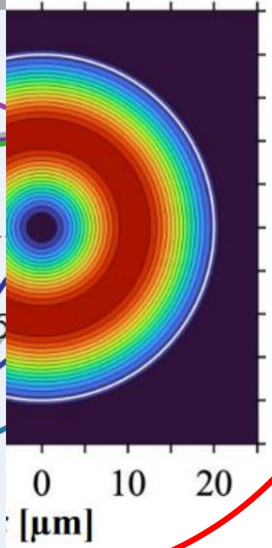
How?

- Con
opp
- Exa

8 µm
ding, 125 µm
r, 250 µm
et, 400 µm



Submarine Cable Map
TeleGeography, 2019



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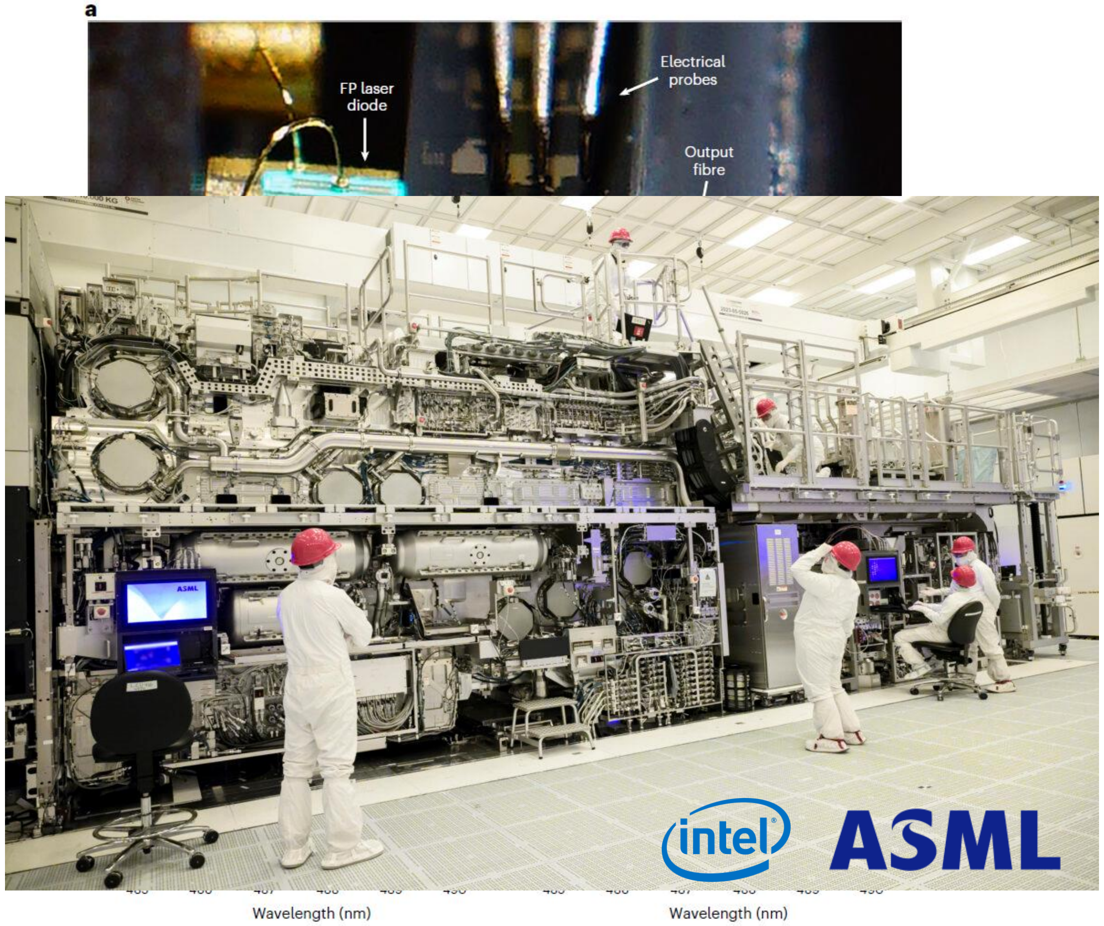
INTEGRATED NONLINEAR PHOTONICS

How?

- Confining light to **micro/nanoscale** structures opposed to **free-space** beams
- Designing analogues of mirrors, resonators, filters etc. at the **chip-scale**
- Leveraging the nanofabrication expertise of the Silicon-based **CMOS** industry



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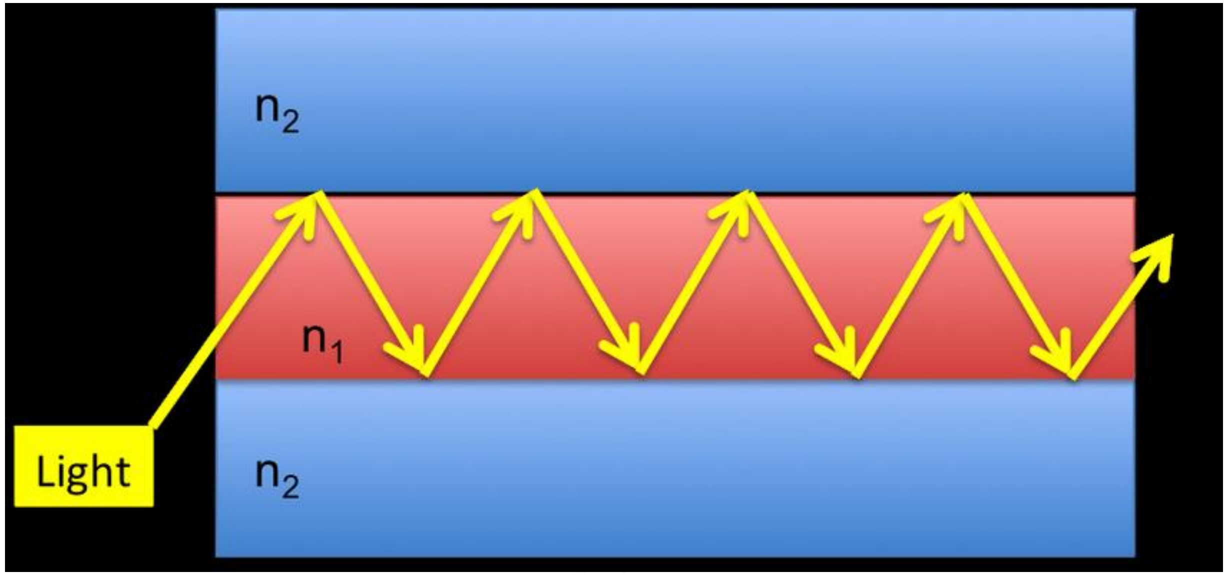
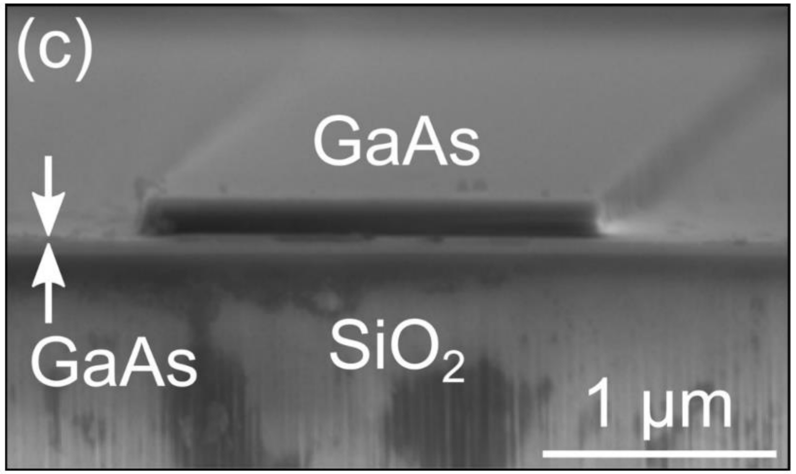
INTEGRATED NONLINEAR PHOTONICS

Key concept: optical modes

- Linear **solutions to Maxwell's equations** in a material cross-section
- **Spatial** distribution of electric and magnetic fields
- Calculated **numerically** to design and evaluate PICs **before** fabrication





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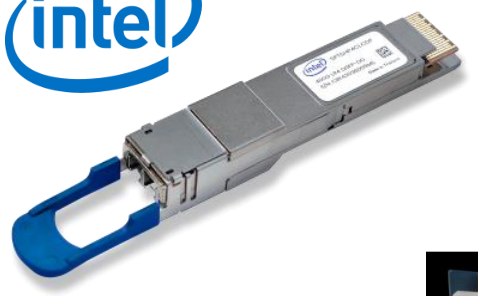
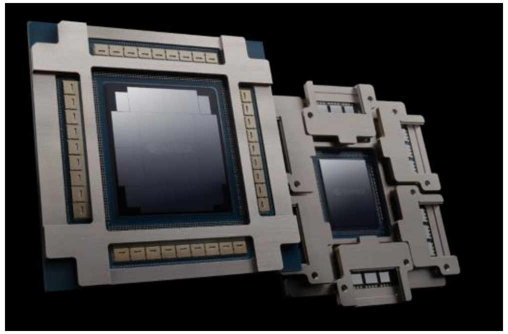
Who?

Data centers:





Sensing:

Compute/quantum:

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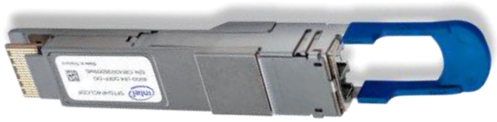
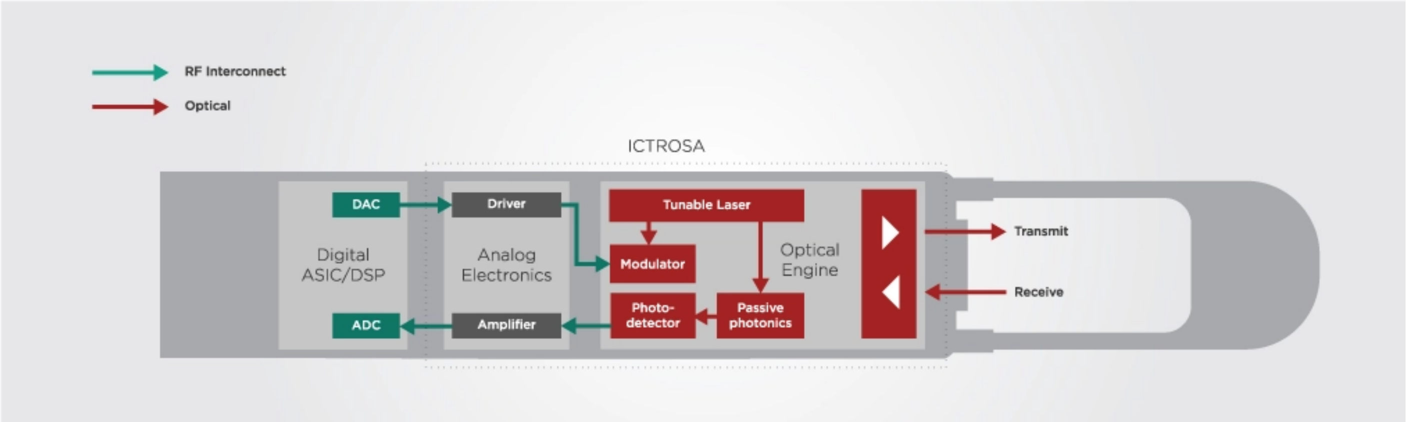
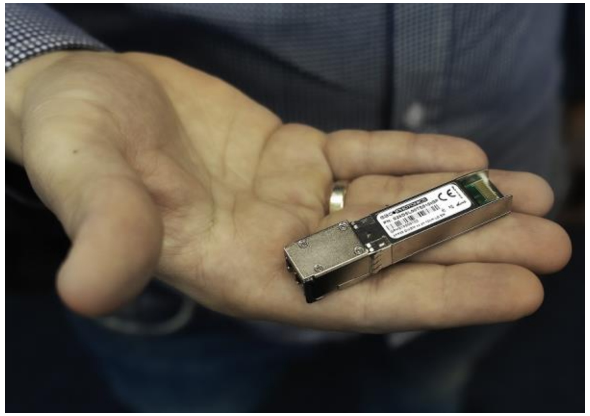
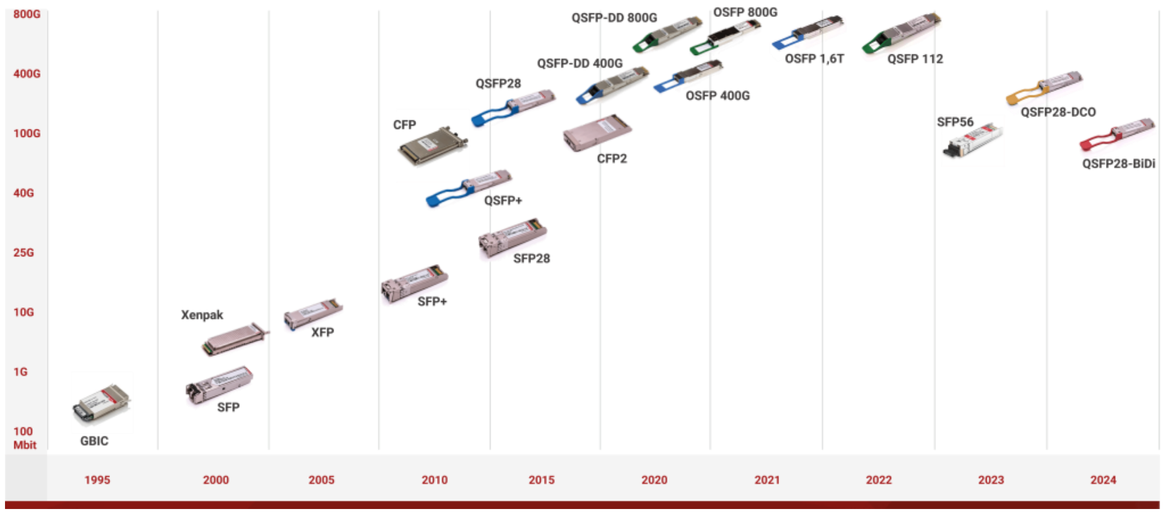
Who?









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Key takeaways:

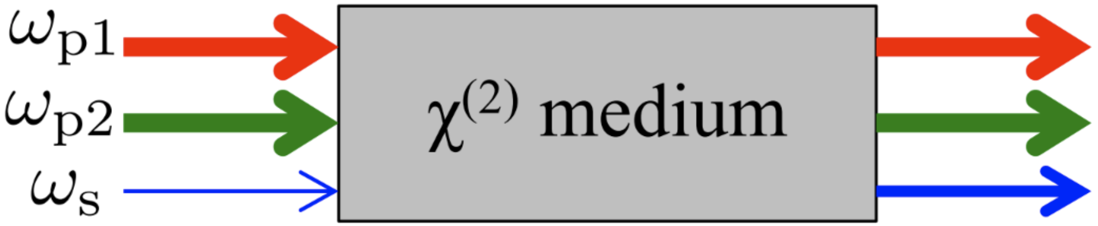
- Advanced optical systems at the **chip-scale:** PICs
- Based mainly on **Silicon**: CMOS-compatibility
- Enabling technology for the modern **Internet**, **sensors**, and (coming) **quantum computers**

INTEGRATED **NONLINEAR** PHOTONICS

What, why and how:

- Integrated photonics on a platform with a **nonlinear** optical response:
  SiN, LiNbO3, LiTaO3, **GaAs**, InGaP ...

- Access to useful optical effects:
  - frequency conversion
  - frequency comb generation
  - supercontinuum generation
  - optical switching
  - etc.



- Depends on the **type** of nonlinearity: $\chi^{(2)}$ or $\chi^{(3)}$

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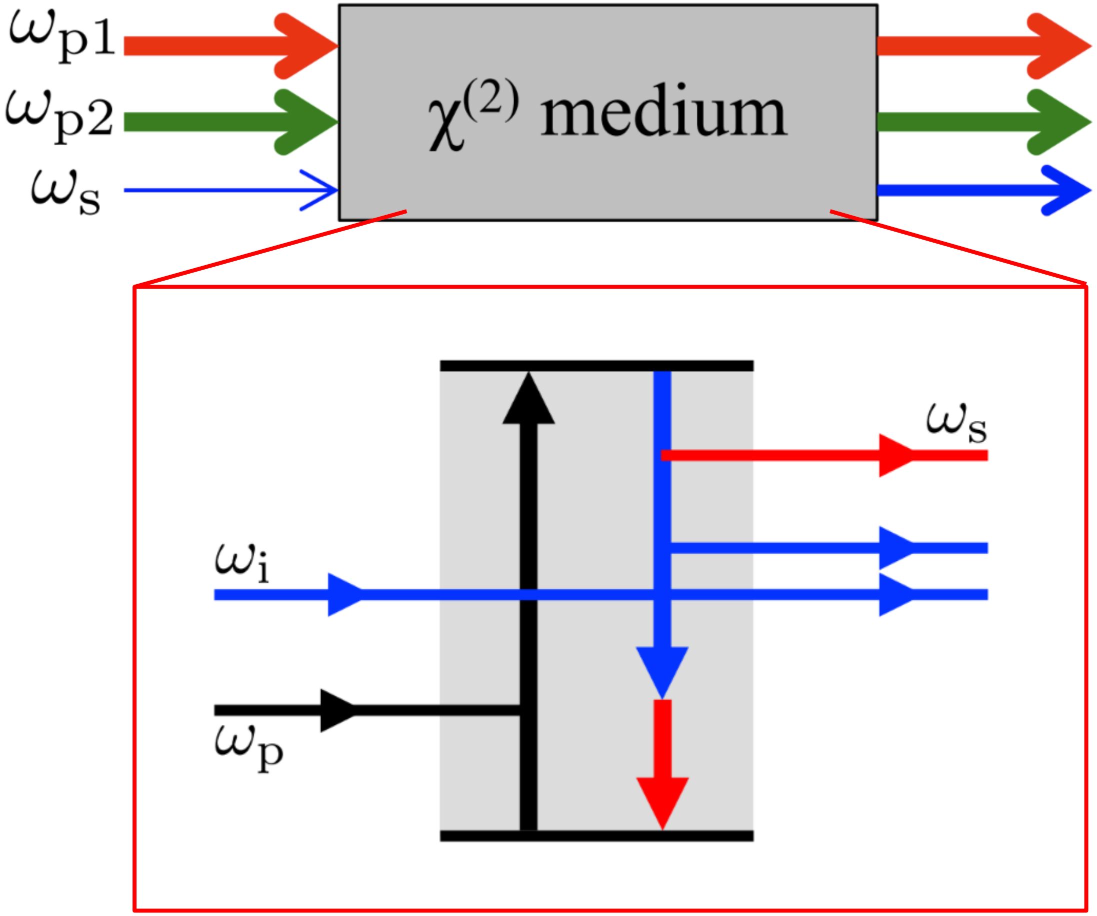
Example: $\chi^{(2)}$-nonlinearity

- **Three-wave** mixing
- **Second-harmonic**, **difference-**frequency and **sum**-frequency generation (SHG, DFG, SFG)



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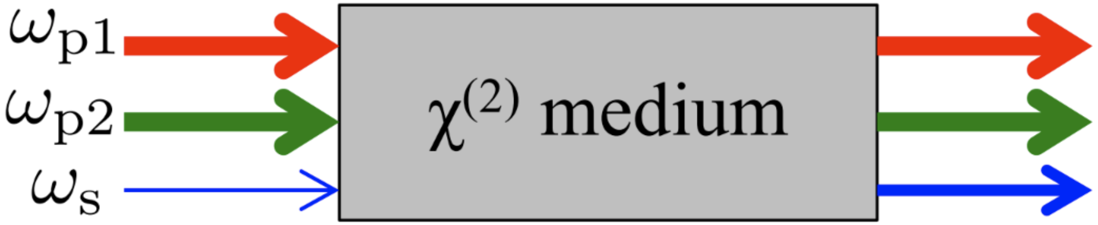
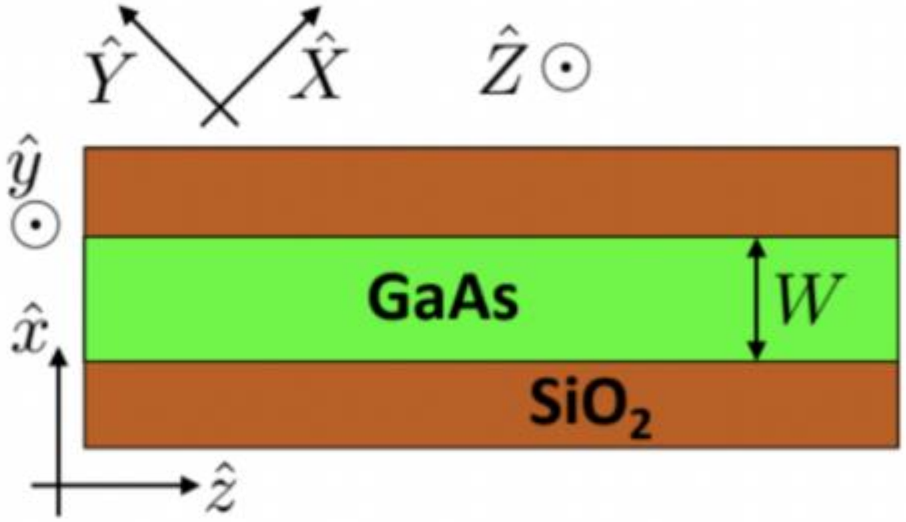
Example: $\chi^{(2)}$-nonlinearity

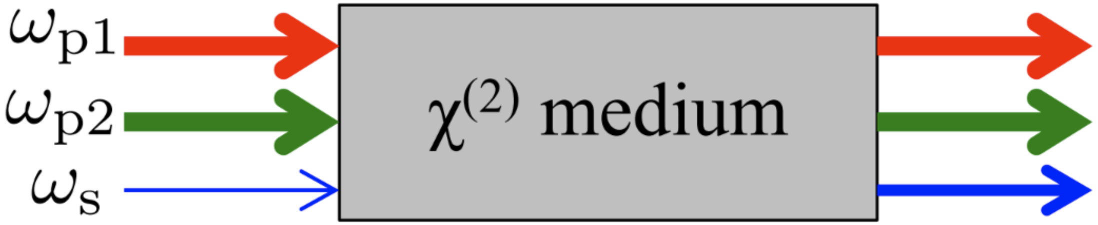
- Interaction is **mediated** by the **nonlinear polarization** of the medium
- Quantified by the nonlinear **tensor,** which depends on **crystal** geometry: $\hat{x}, \hat{y}, \hat{z} \neq \hat{X}, \hat{Y}, \hat{Z}$
- The tensor is a **material** property; **only** non-zero elements for **non-centrosymmetrical** crystals





INTEGRATED NONLINEAR PHOTONICS

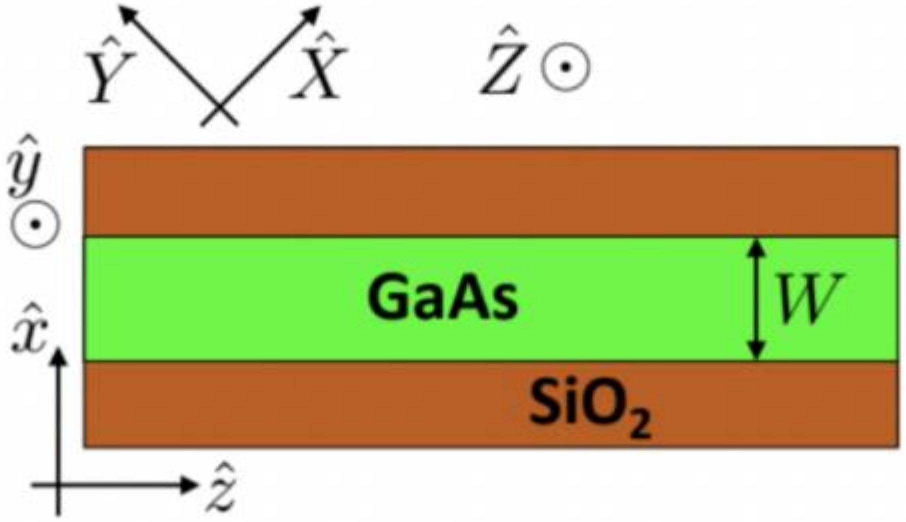
Example: $\chi^{(2)}$-nonlinearity



- Equation for the **generated** light:

$$\partial_z \mathcal{Z} = i\frac{\omega}{4Q} e^{-i\varphi} \iint_{\mathbb{R}^2} \vec{\mathcal{P}}^{\mathrm{NL}} \cdot \vec{\mathfrak{e}}^{*} \mathrm{d}x\, \mathrm{d}y$$

- The generated amplitude along z results from normalized signal mode interaction with the pump mode and nonlinear tensor in the waveguide cross-section reliant on phase matching



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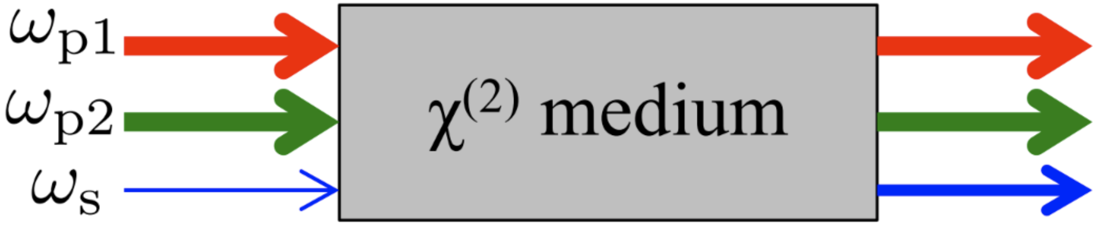
Example: $\chi^{(2)}$-nonlinearity

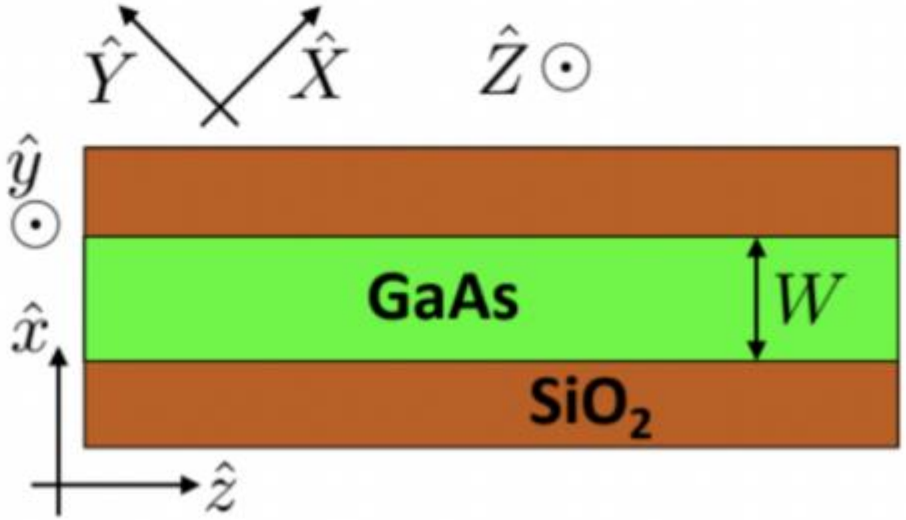
- Factorize equation with p1 = p2:

$$\partial_z Z_s = i\frac{\omega_s}{c}\kappa e^{-i\Delta k z} Z_p^2$$

- The **strength** of the **nonlinear coupling** is quantified by:

$$\kappa_\nu \equiv \frac{c\varepsilon_0}{2Q}\iint_{\mathbb{R}^2}(D\vec{v}_\nu)\cdot\vec{\mathfrak{e}}_\nu^*\,\mathrm{d}x\,\mathrm{d}y$$





INTEGRATED NONLINEAR PHOTONICS

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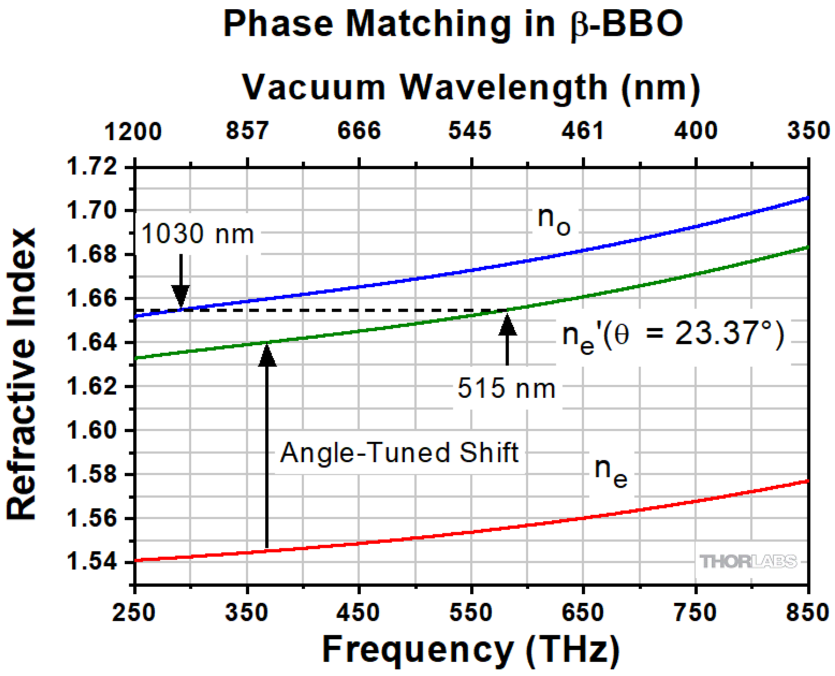
- The signal generated along z depends on the coupling coefficient, the phase matching and the pump amplitude squared

- The coupling coefficient is **static** and depends on the normalized cross-sectional interaction between the pump mode and signal mode through the nonlinear tensor

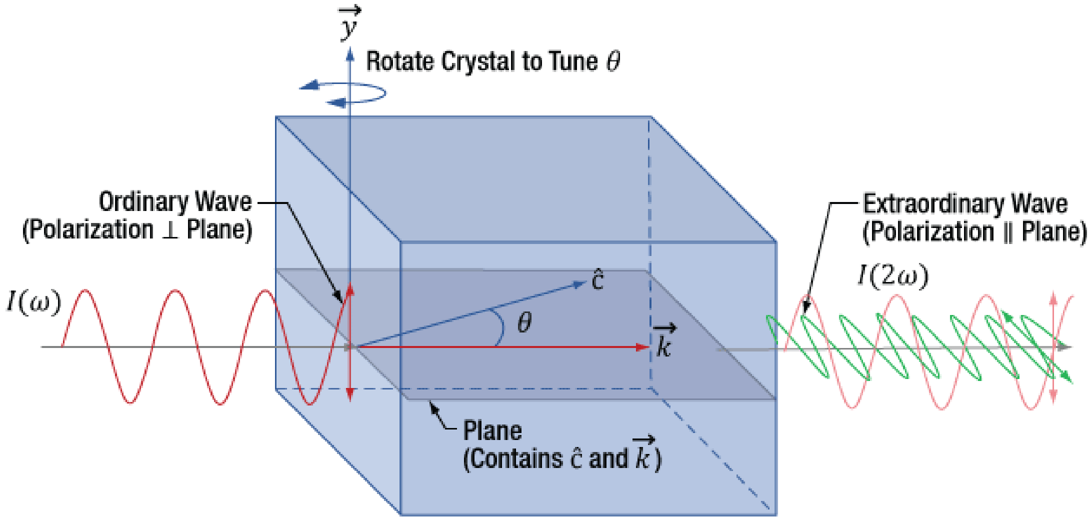
From **Prof. Galland's notes:**

$$\frac{\partial A_\alpha}{\partial z} = \frac{i\omega_\alpha c}{2n_\alpha}\chi^{(n)}_{eff} A_1^{(*)}(z)\ldots A_n^{(*)}(z)\, e^{i\Delta k z}$$

Key concept: phase matching



Thorlabs: BBO Crystals for Second Harmonic Generation:
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=15444



Type-I Phase Matching Using a β-BBO Crystal

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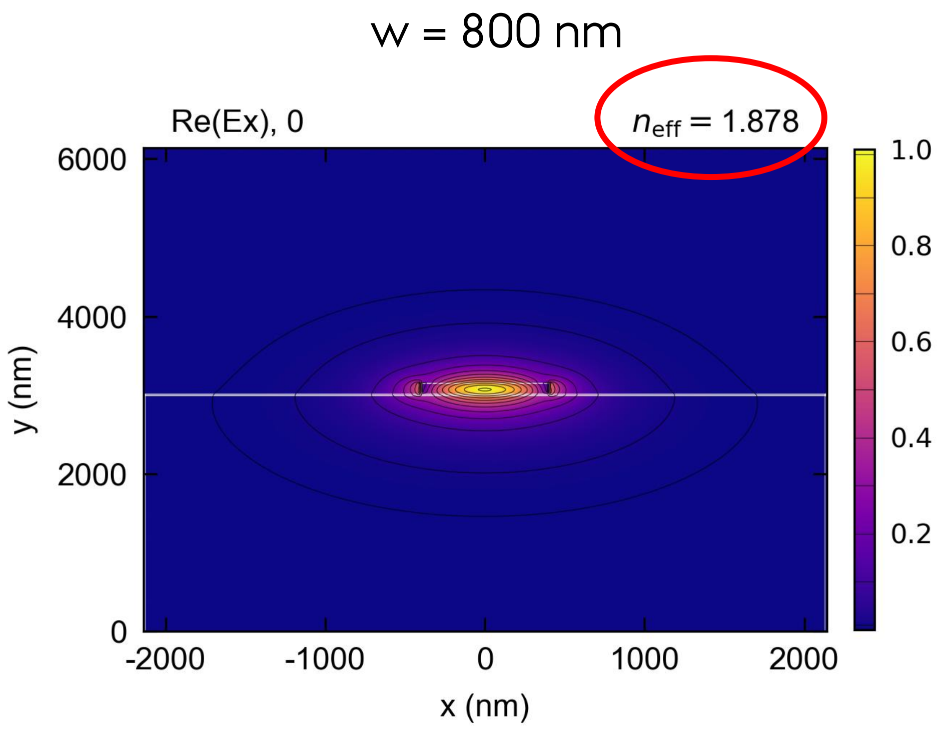
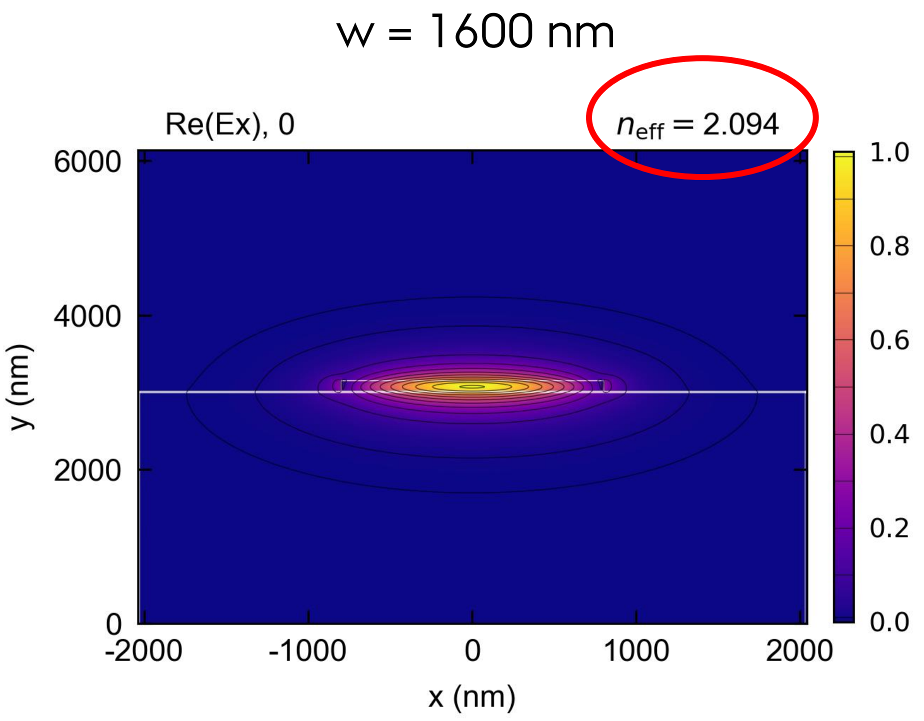
- **Dispersion engineering** to adjust **effective** refractive index

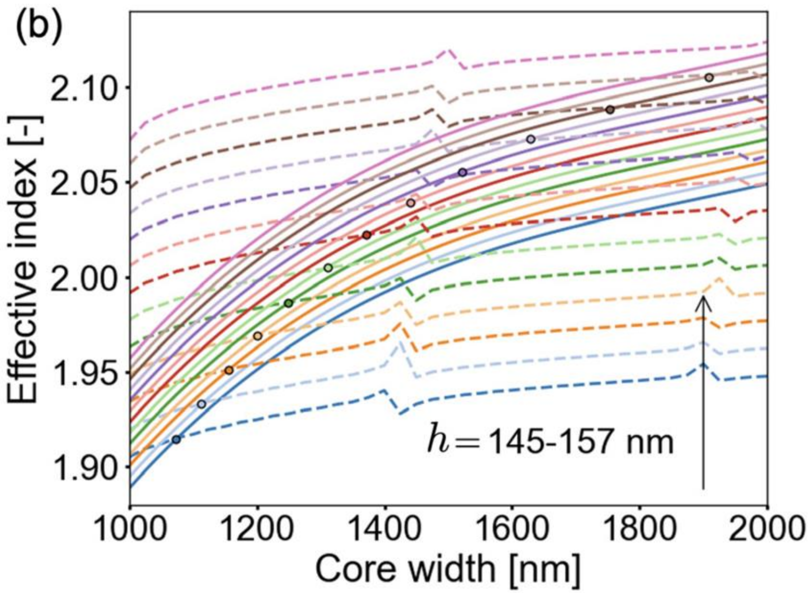


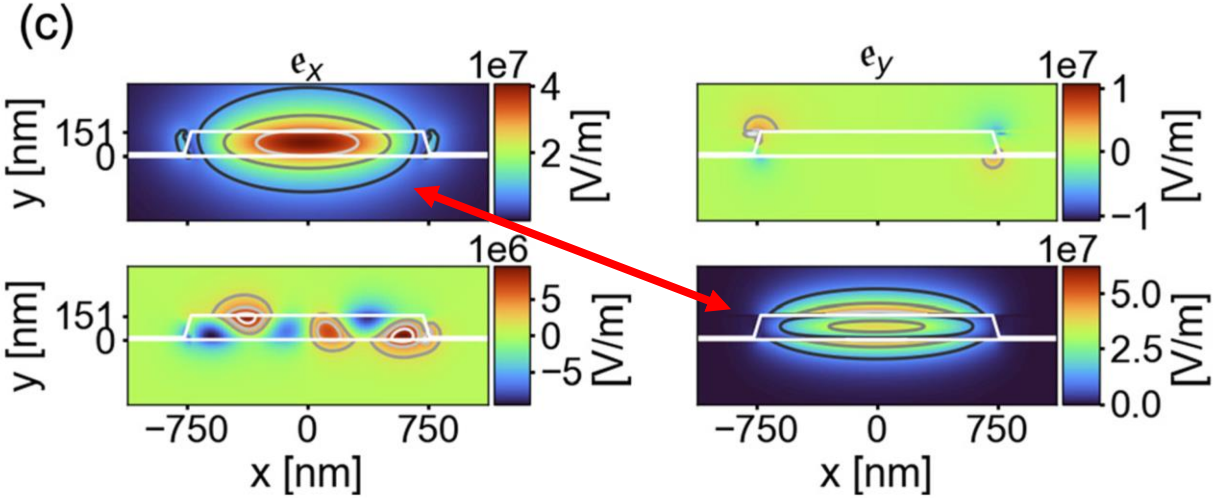


INTEGRATED NONLINEAR PHOTONICS

Key concept: phase matching

λ_p = 1960 nm





Emil Z. Ulsig *et. al*, "Efficient and widely tunable mid-infrared sources using GaAs and AlGaAs integrated platforms for second-order frequency conversion," Opt. Express 32, 36986-37000 (2024)

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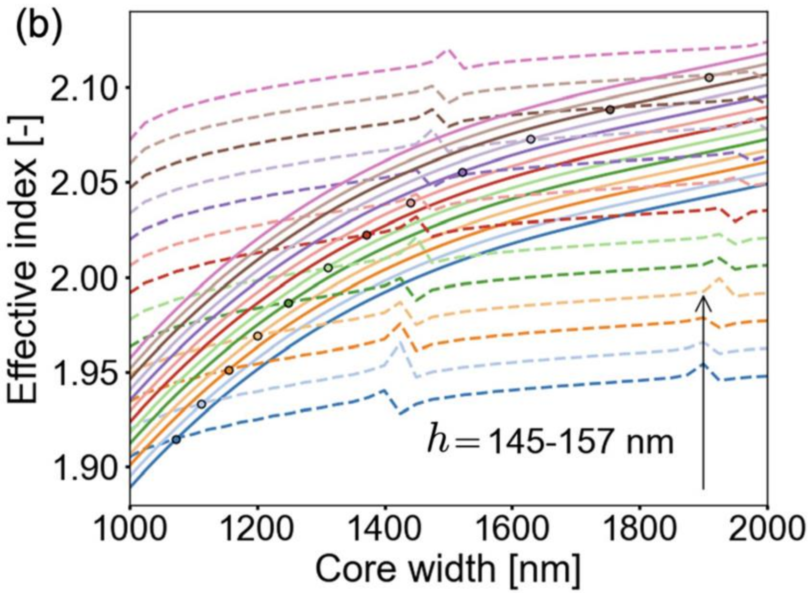

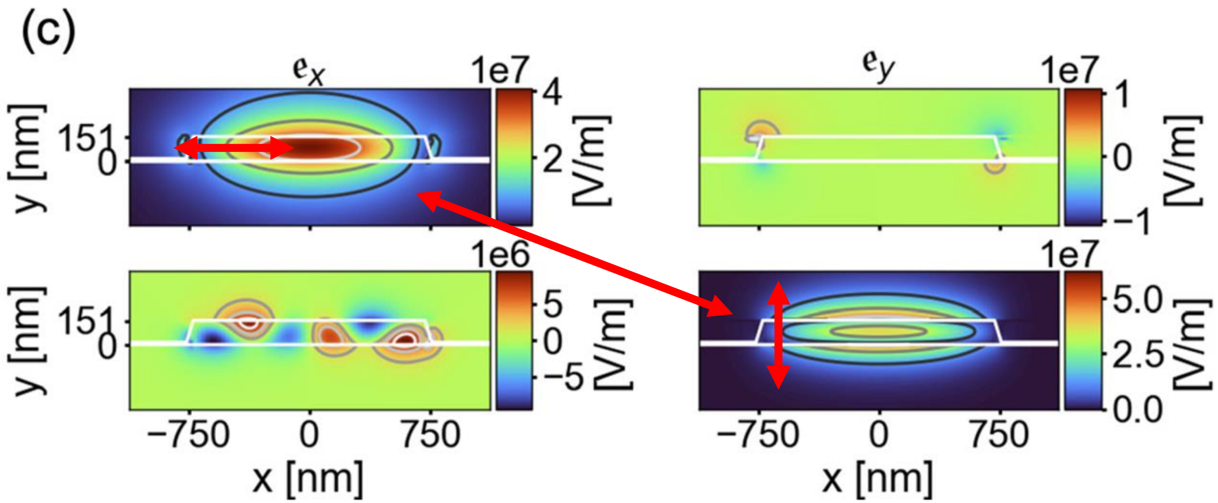

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$$\kappa_\nu \equiv \frac{c\varepsilon_0}{2Q} \iint_{\mathbb{R}^2} (D\vec{v}_\nu) \cdot \vec{\mathfrak{e}}_\nu^* \, dx \, dy$$

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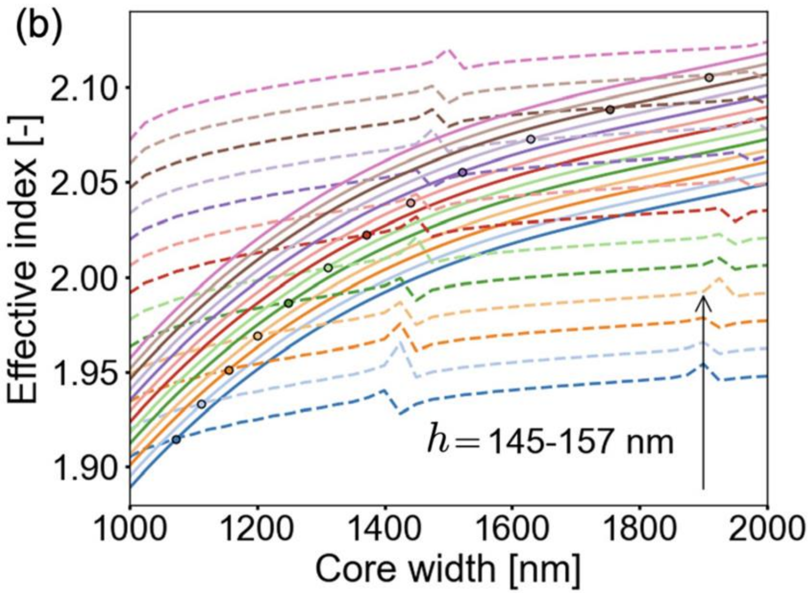

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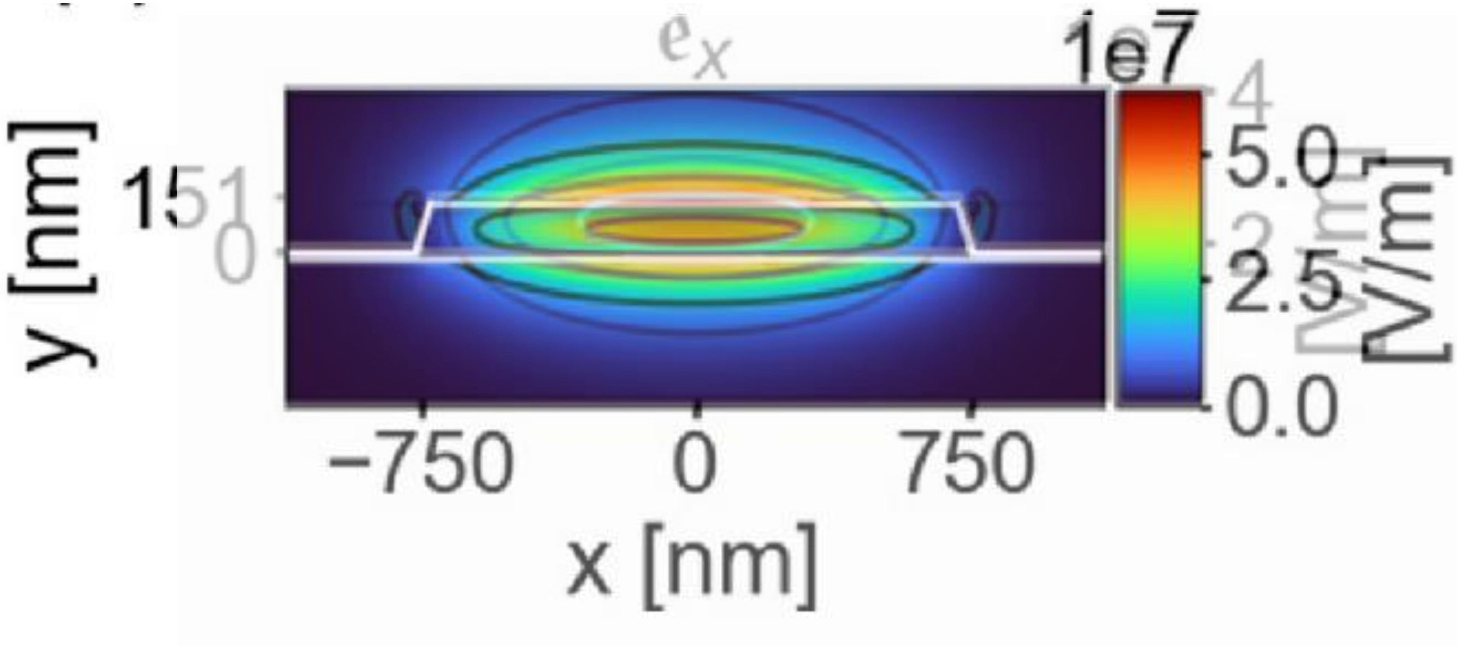

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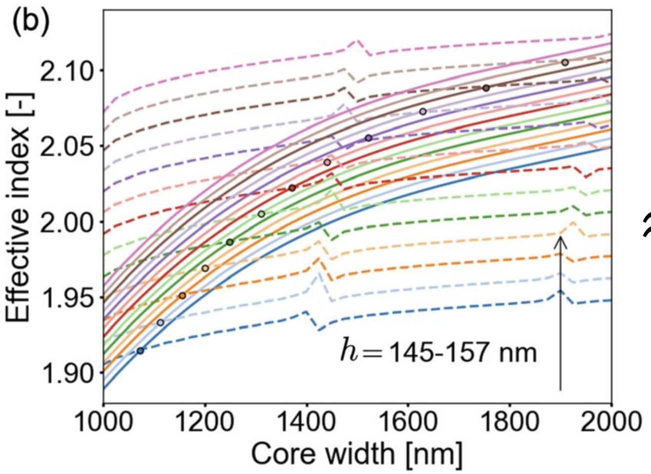
INTEGRATED NONLINEAR PHOTONICS

Key concept: phase matching

- In integrated photonics: **independent** of birefringence
- Conversion **strength** depends on **mode overlap**
- Enables **more** materials for frequency conversion, e.g. **GaAs**



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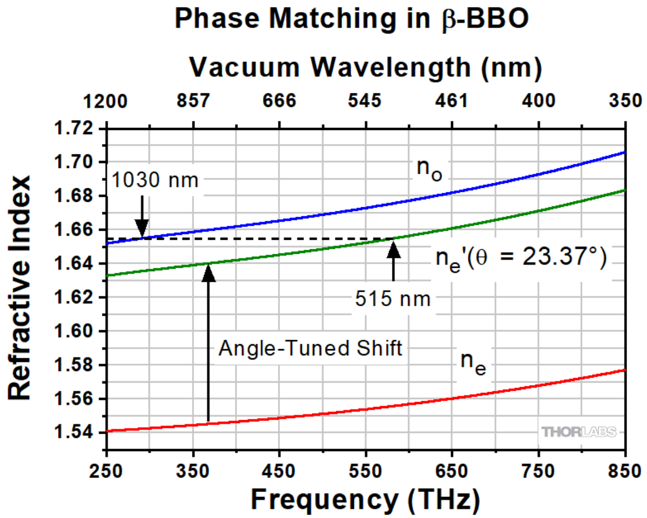

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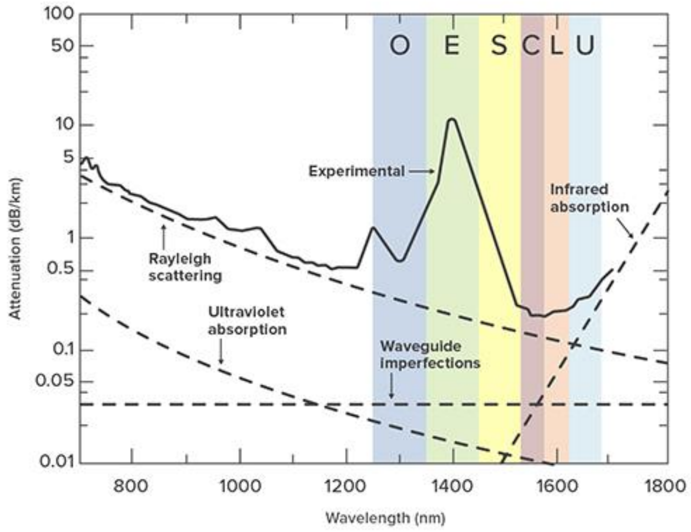
EXAMPLE: C-BAND SINGLE PHOTONS

- Danish propaganda:
  commercially available single-photon source
- Based on a **photonic integrated circuit (PIC)**
- Emission wavelength: **920-980 nm**



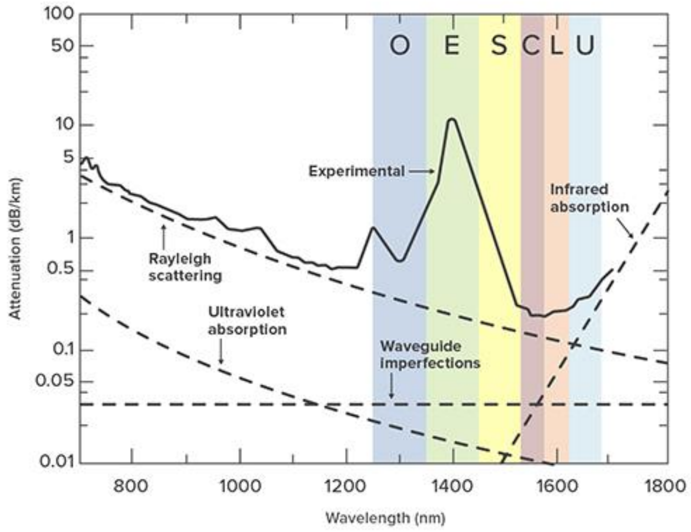
SPARROW
QUANTUM

Efficiency	Indistinguishability	Purity
>50%	>97%	>99%
How many photons are emitted into a Gaussian output mode.	How identical two photons are, even when emitted at very different times.	How well the source avoids emitting multiple photons at the same time.

https://sparrowquantum.com/

EXAMPLE: C-BAND SINGLE PHOTONS

- Retain **efficient & pure** single-photon generation
- Enable integration with **telecom** networks
- **Single-platform** integration (GaAs)



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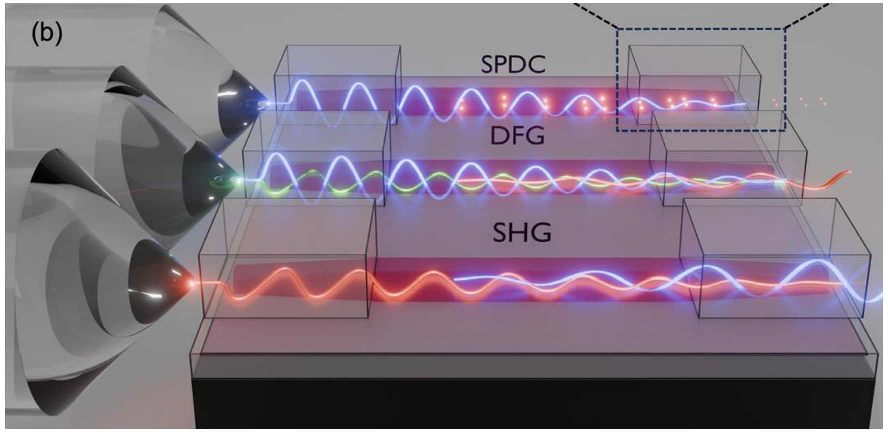
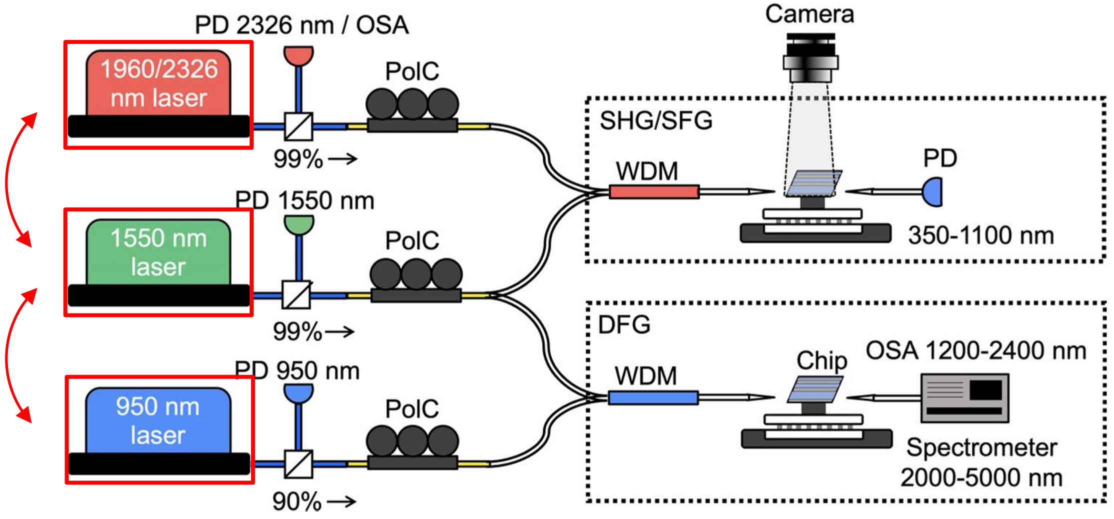
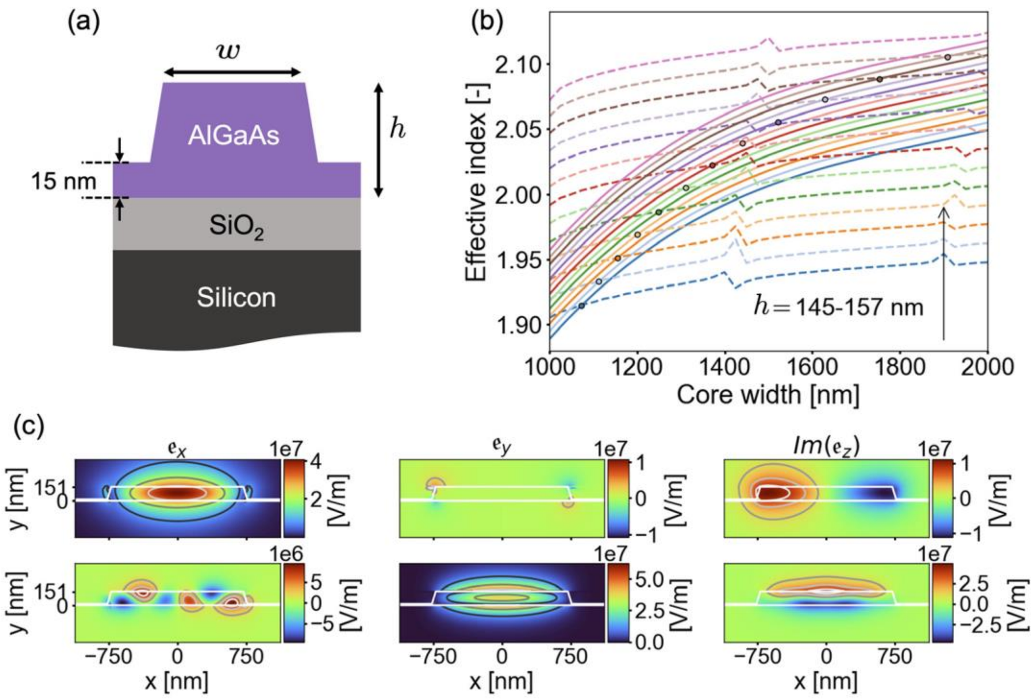


EXAMPLE: C-BAND SINGLE PHOTONS

- **Sum and difference-frequency** generation (S/D FG): *Three-wave* mixing: P(ump), S(ignal), I(dler)
- **Modal** phase matching: $n_s = n_p$





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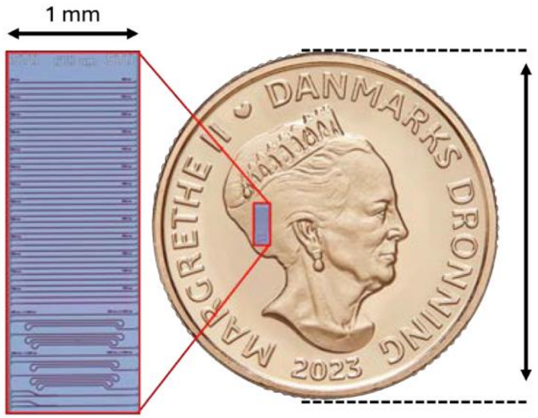
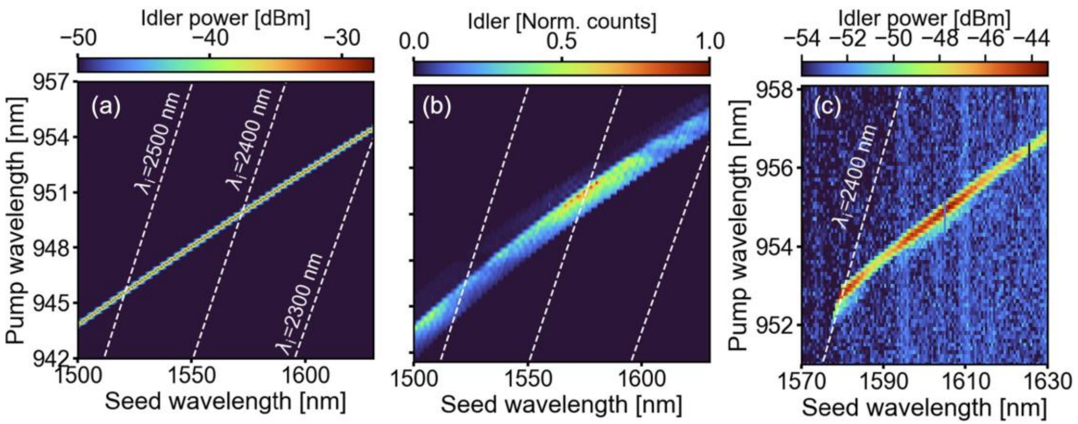
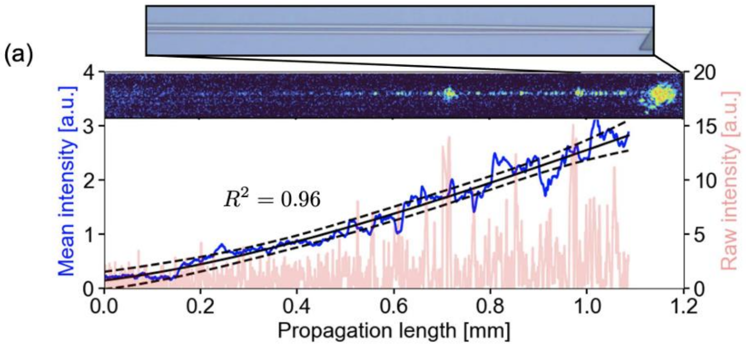
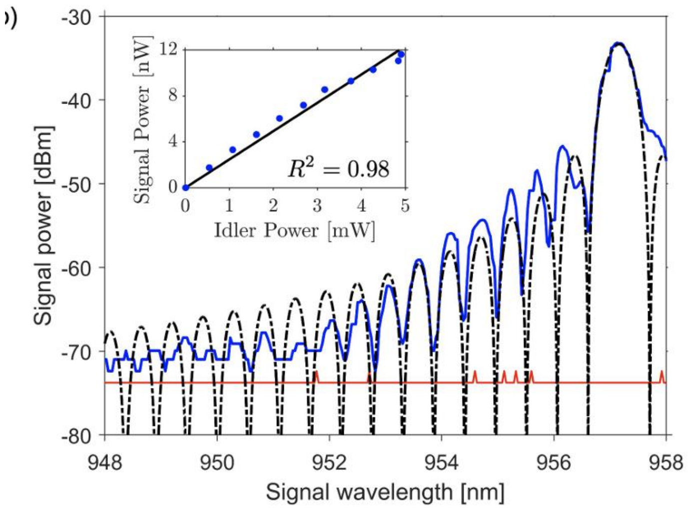
EXAMPLE: C-BAND SINGLE PHOTONS

- **DFG** and **SFG** between ~950 nm and 1550 nm
- Exercise: **SHG** in GaAs waveguides









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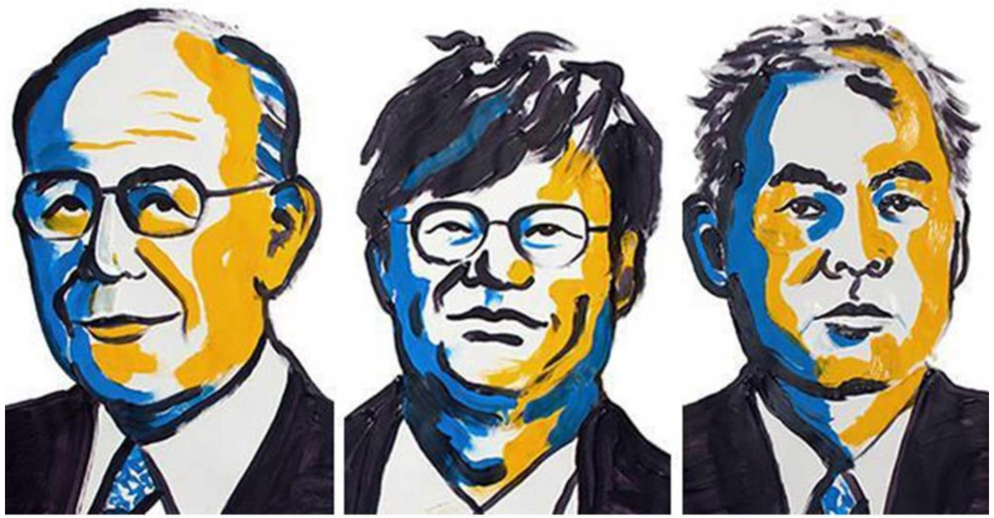
EXAMPLE: DEEP-UV GENERATION

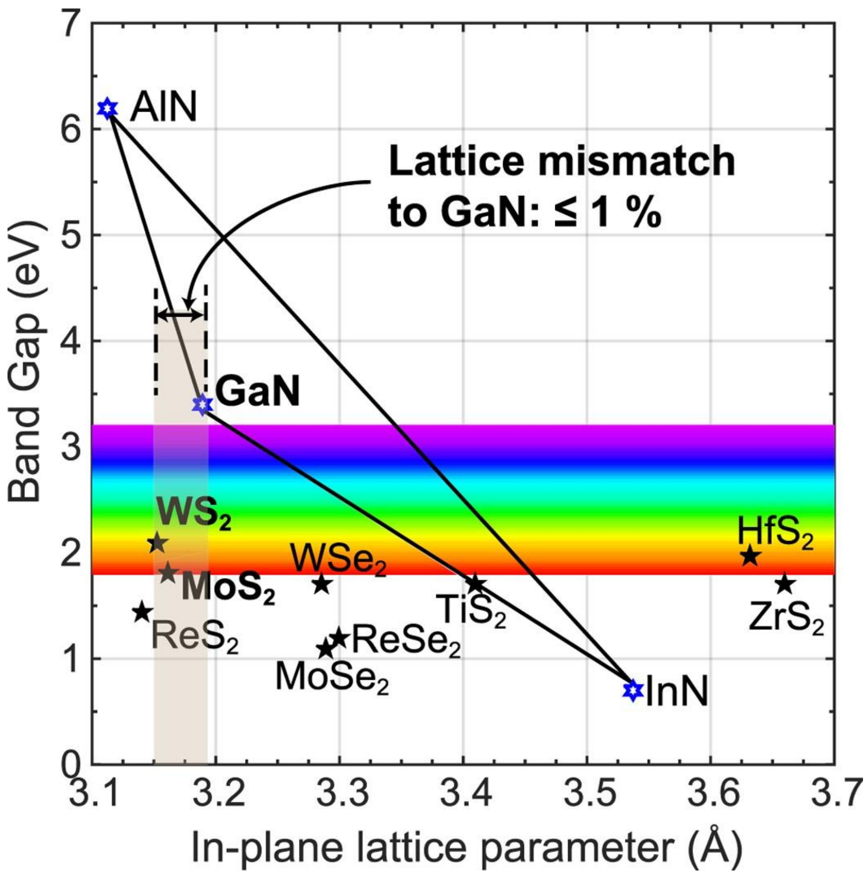
- 2014 Nobel Prize: Nakamura, Amano & Akasaki
  "for the invention of efficienct blue light-emitting diodes which has enabled bright and energy-saving white light sources



Veritasium: "Why it was almost impossible to make the blue LED":
https://www.youtube.com/watch?v=AF8d72mA41M

EXAMPLE: DEEP-UV GENERATION

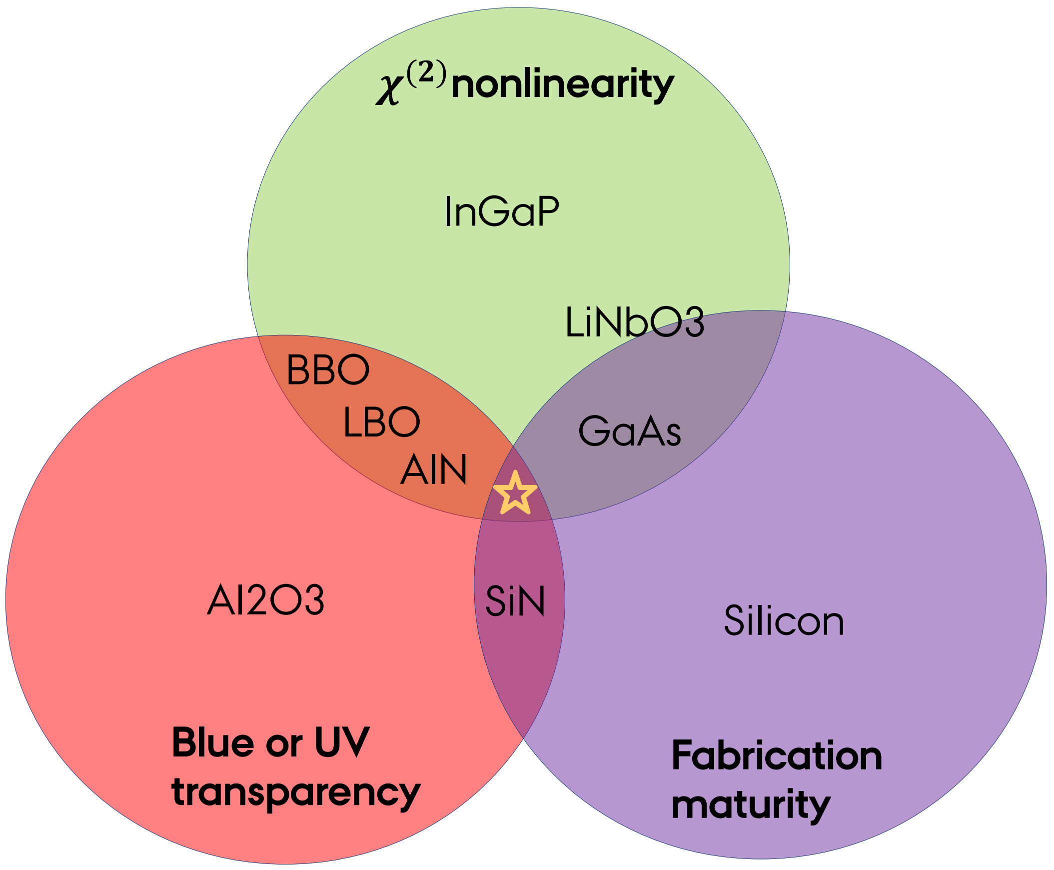
- AlInGaN-based compounds:
  Cover the **entire visible range** down to the deep-UV
- Demonstrated WPE (wall-plug efficiency) of >80%
- World record for laser emission: **271.8 nm**
  By laureate Amano's group
- Immense difficulties at very short wavelengths
  - growth defects
  - p-type doping
  - light extraction
  - etc.



Gupta, P., Rahman, A., Subramanian, S. *et al.* Layered transition metal dichalcogenides: promising near-lattice-matched substrates for GaN growth. *Sci Rep* **6**, 23708 (2016).

EXAMPLE: DEEP-UV GENERATION

- Potential solution: **nonlinear photonics**
- Allows for **compact** form-factor while "cheating" the bandgap
- **Photonic integration** of (active) pump laser and (passive) conversion chip
- Challenge: suitable **platform**

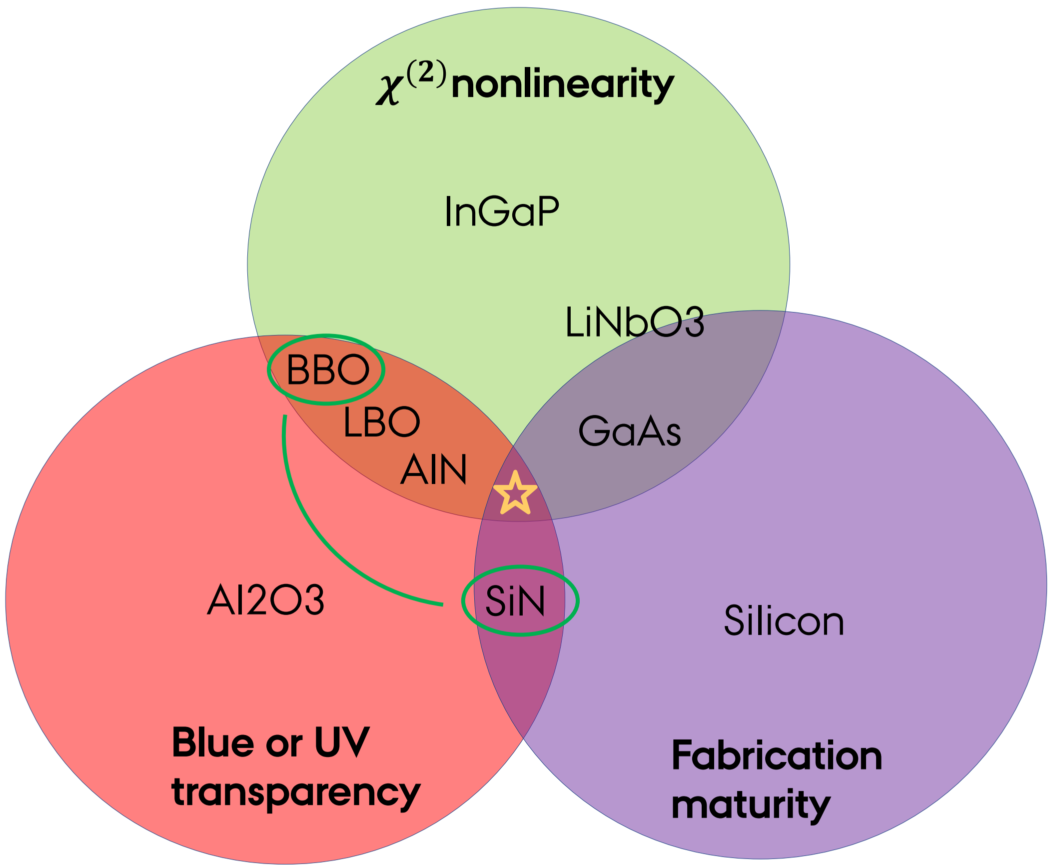


EXAMPLE: DEEP-UV GENERATION

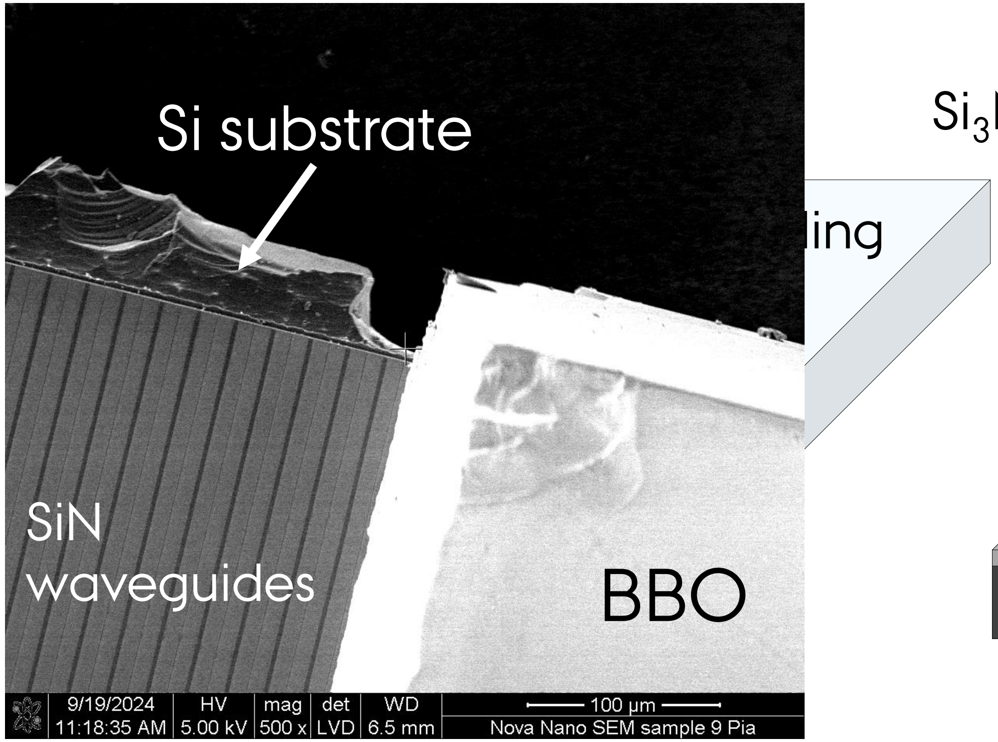
- Solution: **heterogeneous** integration: Combine **BBO** with **SiN**
- Leverage complimentary properties:

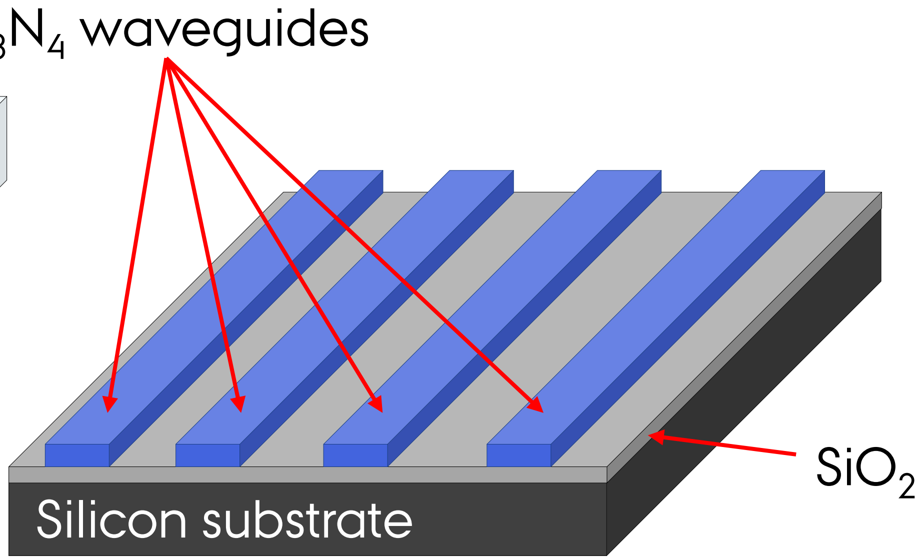
  BBO: $\chi^{(2)}$ **nonlinearity**, **UV** transparency

  SiN: Mature fabrication, **blue** transparency



EXAMPLE: DEEP-UV GENERATION



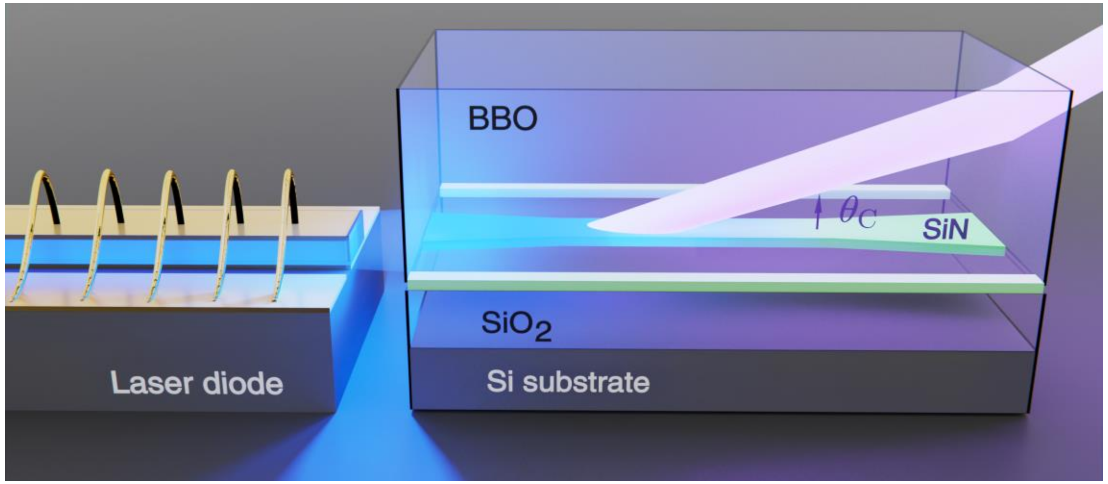


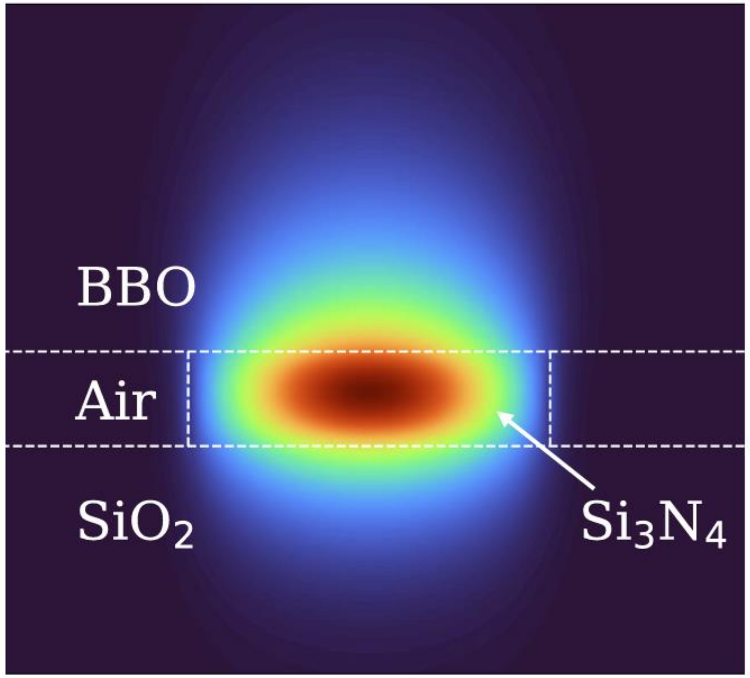
EXAMPLE: DEEP-UV GENERATION

- Challenge: **no** $\chi^{(2)}$ in waveguides

- Solution: **Cerenkov-type** SHG:

$$\cos(\theta_C) = \frac{n_p}{n_s}, \quad n_p < n_s$$



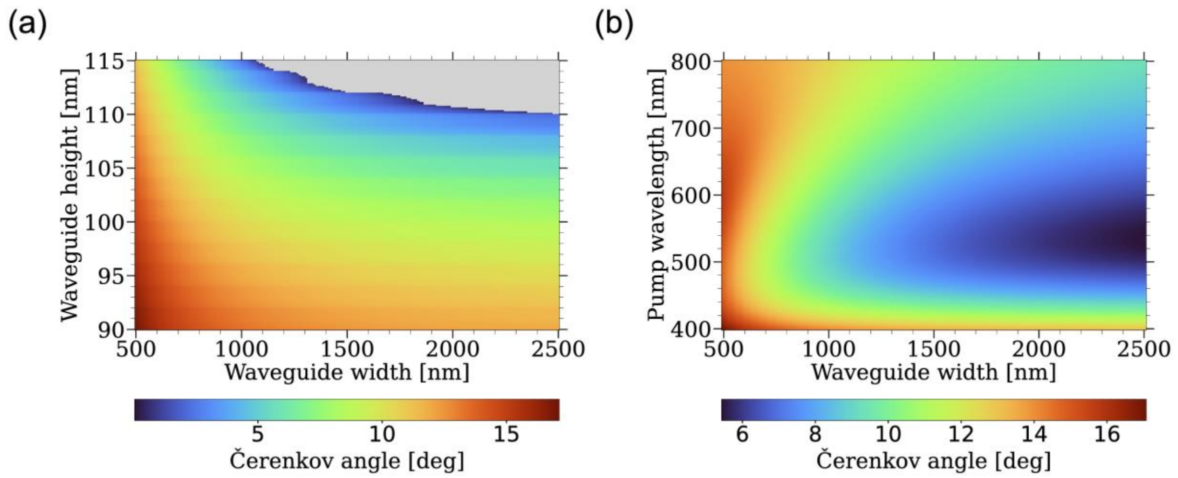


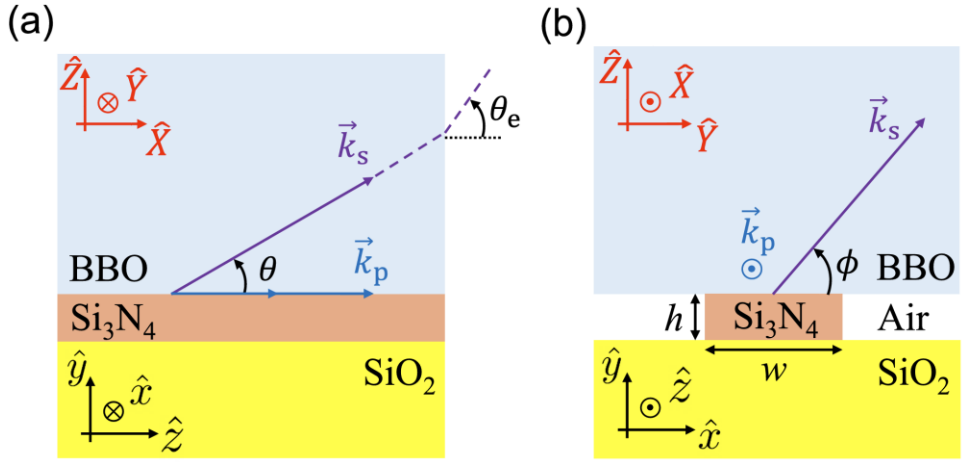
Asger B. Gardner *et. Al.*, "Robust and broadband UV laser utilizing Čerenkov phase matching on a hybrid photonic chip," Opt. Express 33, 19330-19341 (2025)

EXAMPLE: DEEP-UV GENERATION

- Maintains phase matching over a **broad** parameter space:

$$\cos(\theta_C) = \frac{n_p}{n_s}, \qquad n_p < n_s$$





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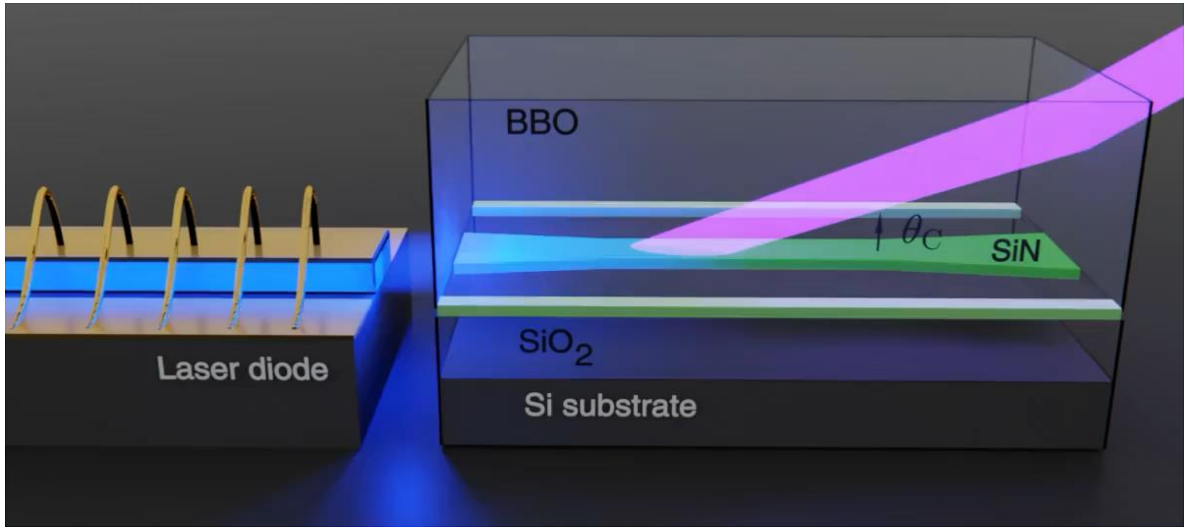

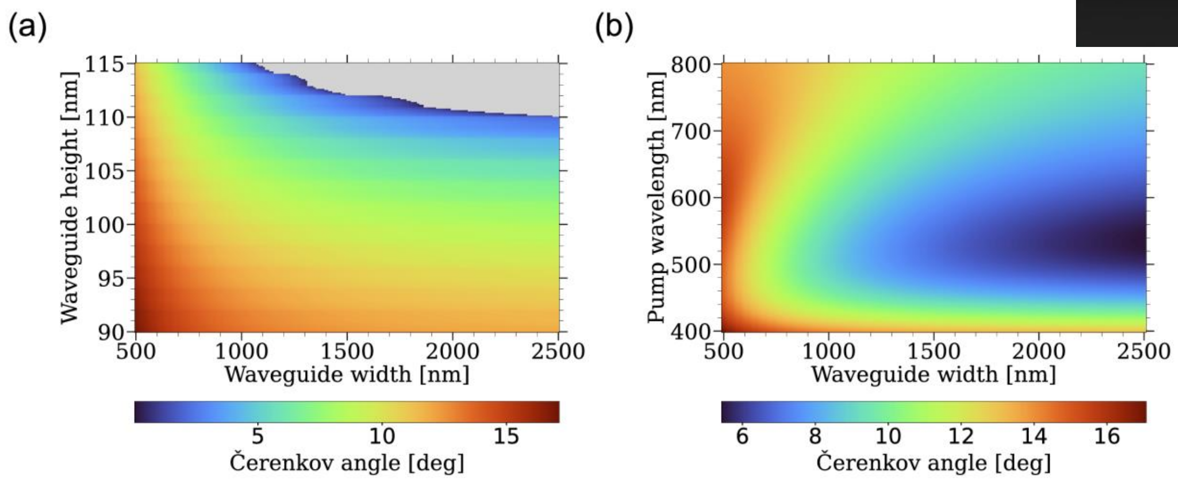

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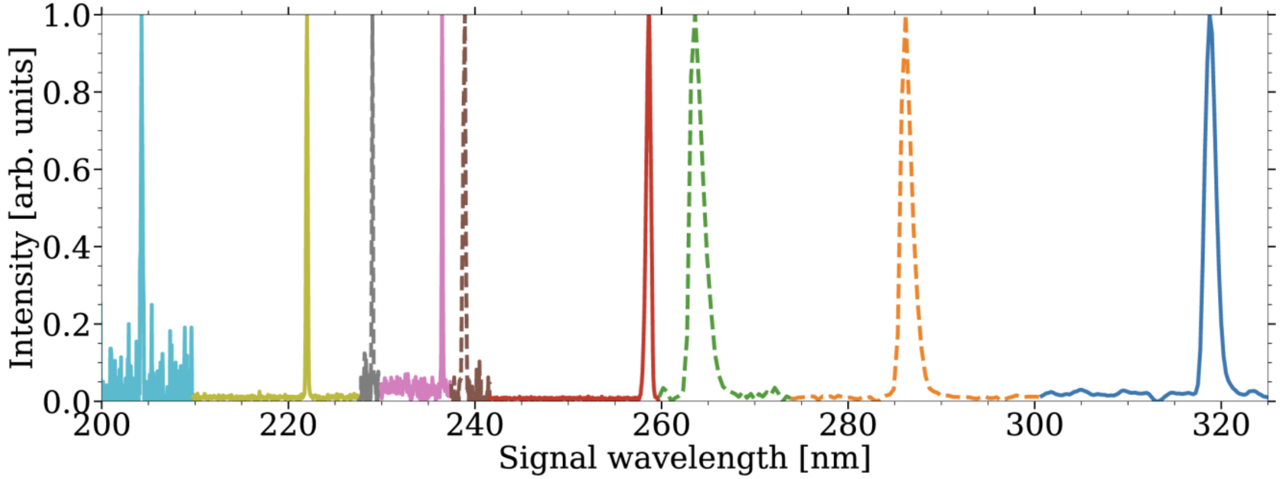

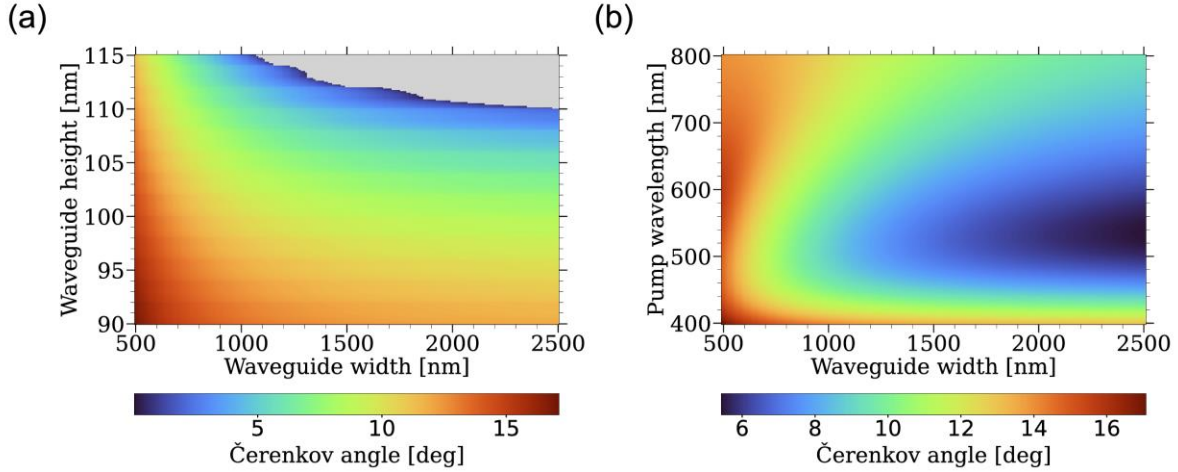

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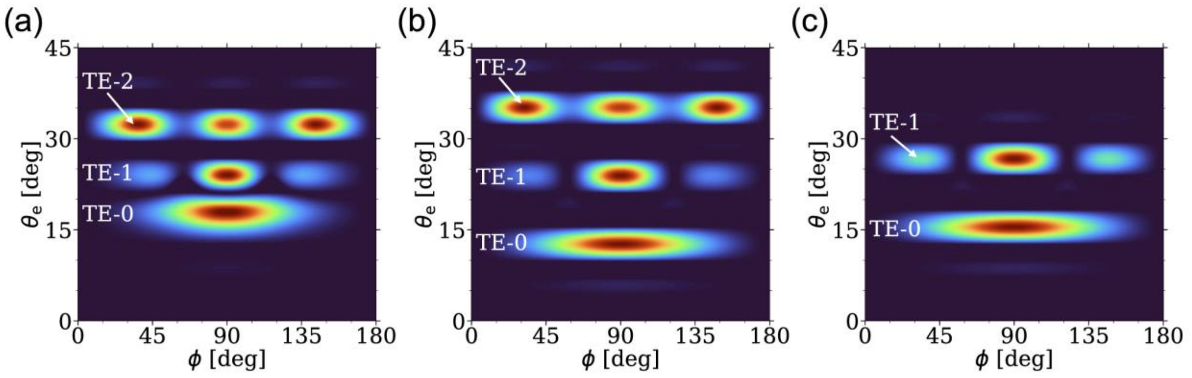
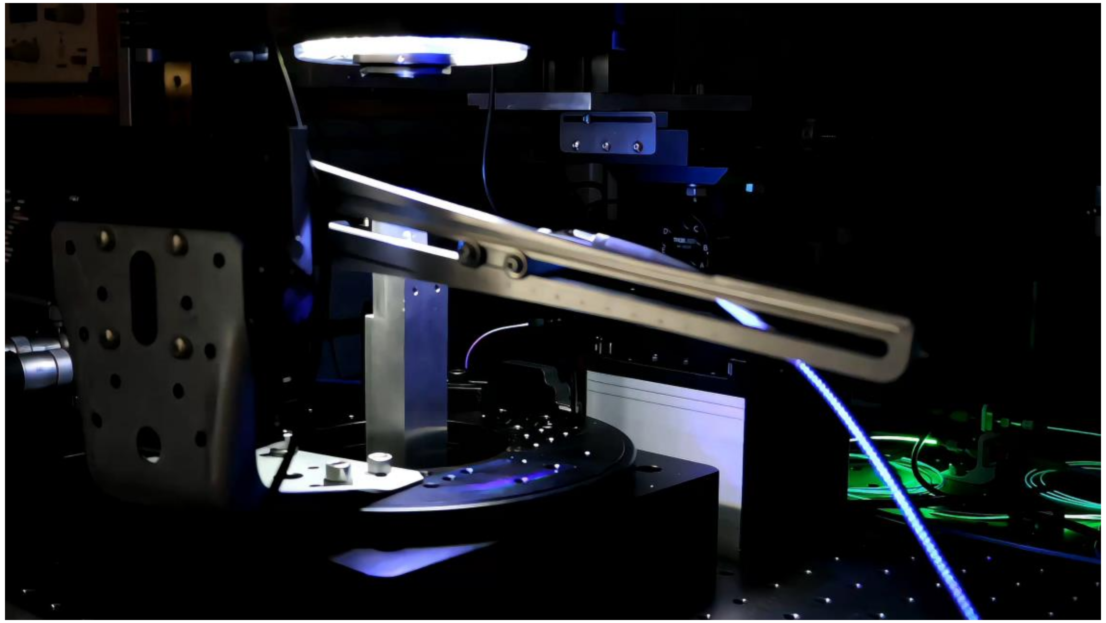
EXAMPLE: DEEP-UV GENERATION

- Generated light is **free-space**

- Results in complex output distribution





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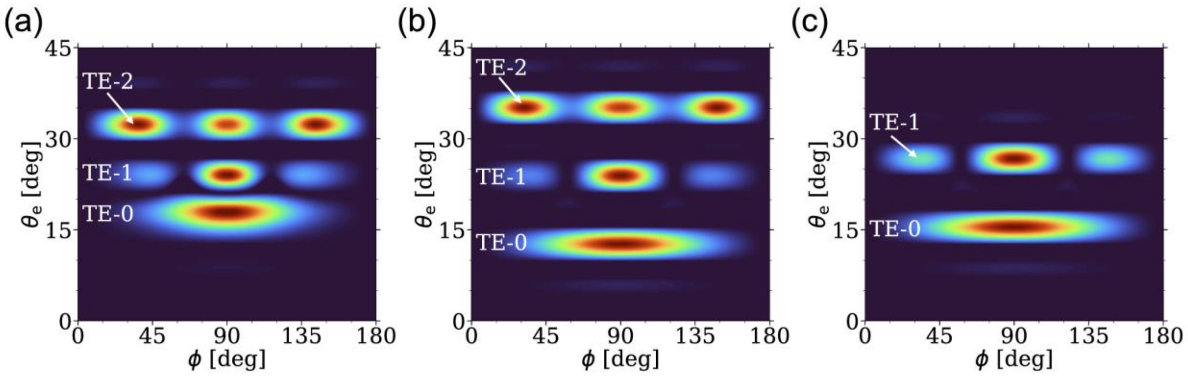

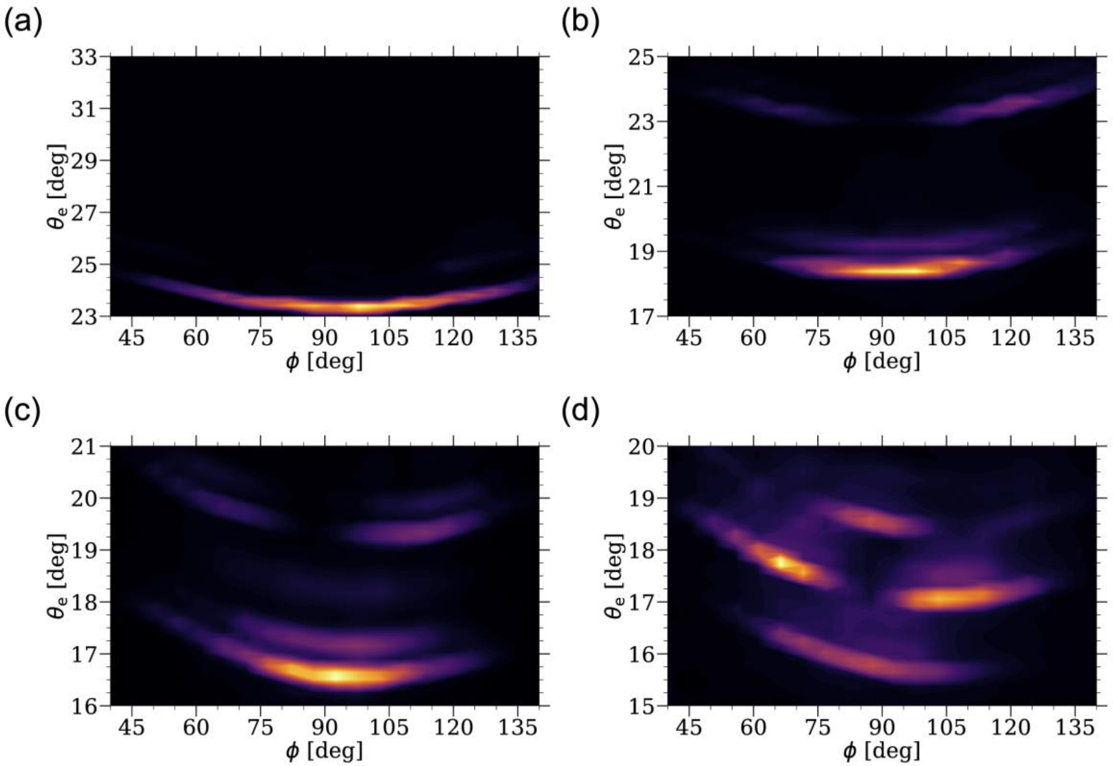

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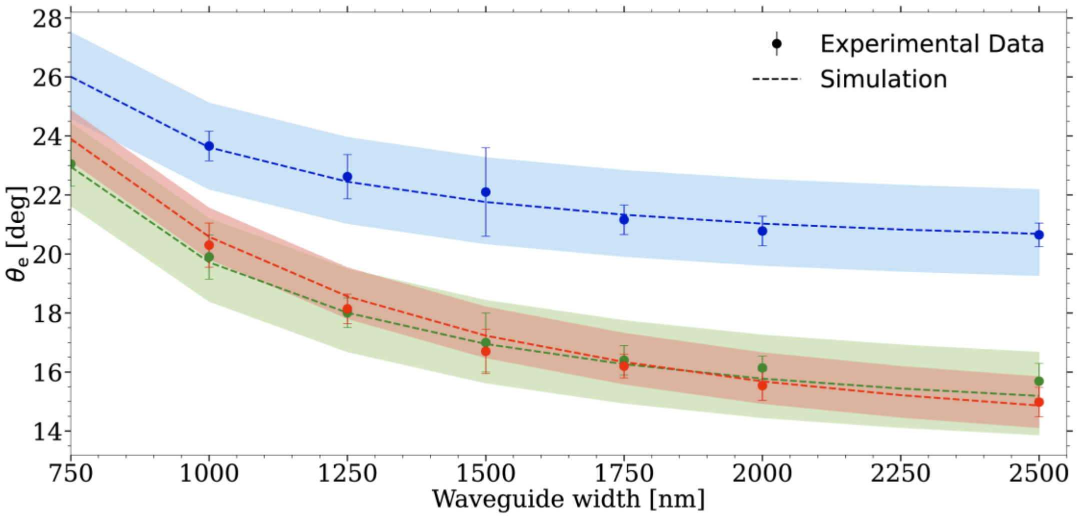
EXAMPLE: DEEP-UV GENERATION

- Extremely **robust** phase matching process
- Broadband coverage from single waveguides



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WRAP-UP

- Introduction to **integrated photonics**
- Introduction to **nonlinear** effects in photonic integrated circuits
- Two examples:
  - Frequency conversion for quantum applications
  - Deep-UV generation
- **Exercise** on SHG in a GaAs waveguide

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