Ferro-electric and III-V Semiconductors Frequency Conversion Devices

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Solid State Devices Group

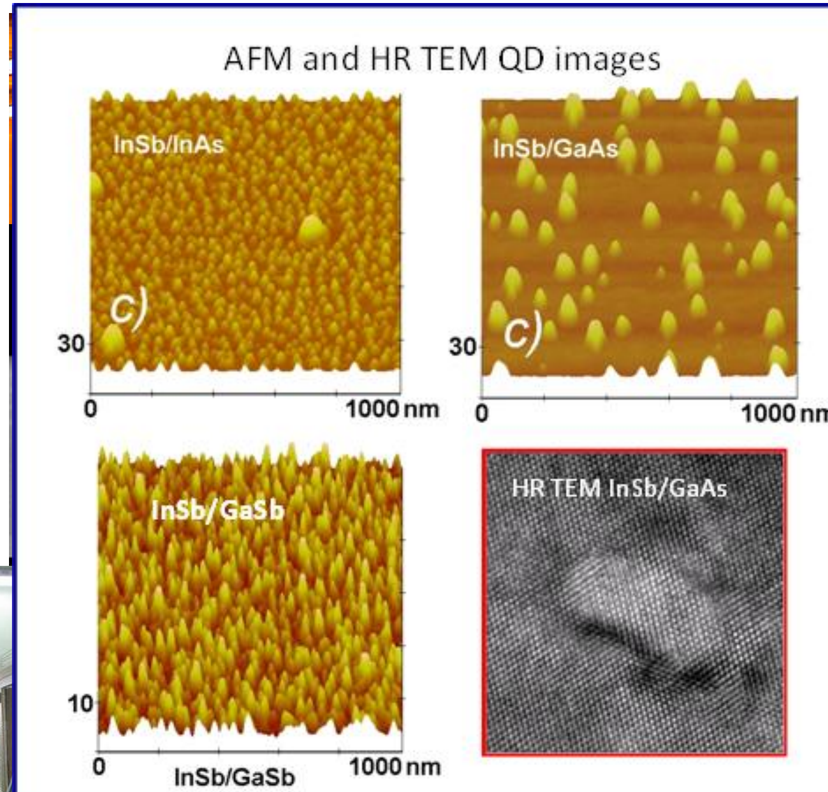
(7-Ph.D, 2-MA, 3-Stud., 1-Tec)

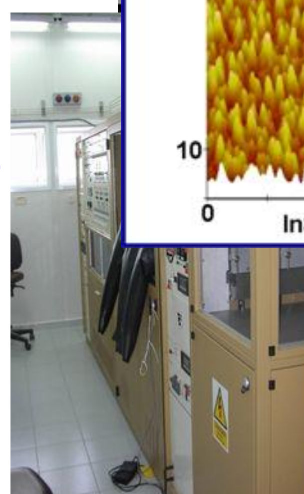
Research

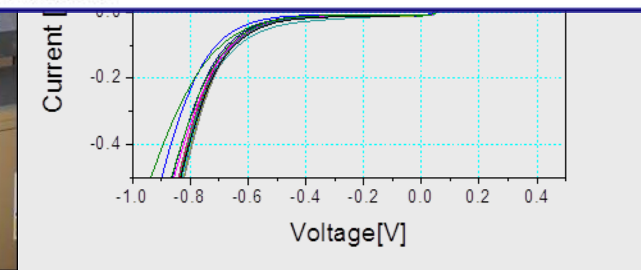
- Frequency conversion devices
- IR Semiconductors (Detectors, DL, QD)
- GaN (Detectors and Photonic devices)
- Silicon (High power switches)

Main Facilities

- Clean room (70-m^2, Class-100)
- MOCVD (As/Sb)
- Metal deposition, RIE, PECVD, RTP
- Characterization equipment:
  - X-ray
  - Photoluminescence (0.3-14μm, 10-350^{0}k)
  - Life-Time (10-350^{0}k)
  - FTIR
  - I-V
  - C-V
  - Ellipsometer







Frequency Conversion Devices, Research Group members (over the years)

- Moti Katz
- Ariel Bruner
- Moshe Oron
- David Eger
- Technical assistants: Pnina Shier, Galit Sthorm, Maya Veinger

Collaborations (Frequency Conversion)

- Gil Rosenman (TAU): Poling process of PPKTP
- Byer-Fejer Group (Stanford Uni): Stoichiometric $LiTaO_3$
- G. I. Stegeman group (CREOL) and L. Torner (ICFO. Barcelona): Quadratic spatial solitons.
- Ady Arie – TAU: Non-traditional frequency conversion devices in PPKTP and PPSLT
- G. Marcus A. Zigler (HUJI): Frequency conversion by high- power laser
- S. Xie (Harvard Uni.): Source for coherent anti-Stokes Raman scattering microscopy
- Raicol Crystals (Israel): PPKTP and PPSLT ("Magneton")

Goal of the group

Developing frequency conversion devices for efficient, compact and inexpensive Laser sources.

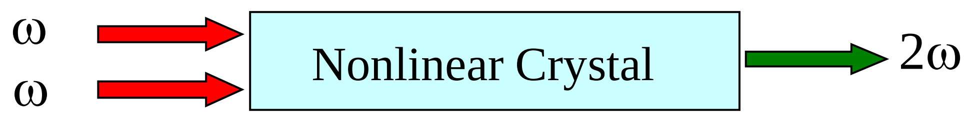
Outline

- Ferro-electric Frequency Conversion Devices
  - Ferro-electric crystals
  - Quasi Phase Matching (QPM)
  - Frequency Conversion examples
- III-V Semiconductors Frequency Conversion Devices
  - Orientation Patterned GaAs (OPGaAs) Waveguides process
  - Frequency Conversion in OPGaAs Waveguides

Nonlinear Interactions (Quadratic Term)

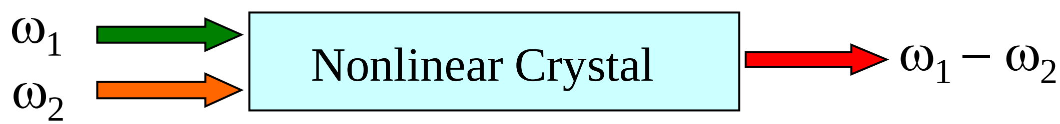
- Sum Frequency Generation (SFG):

- Second Harmonic Generation (SHG):

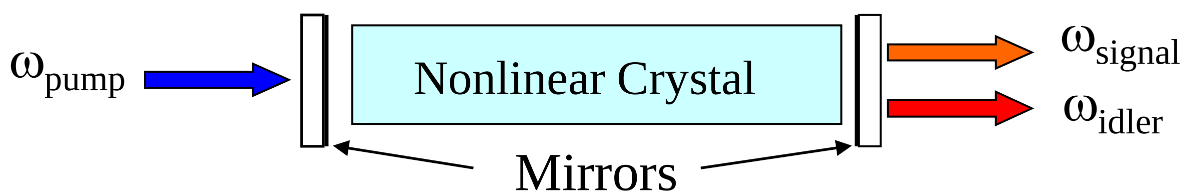


Up conversion

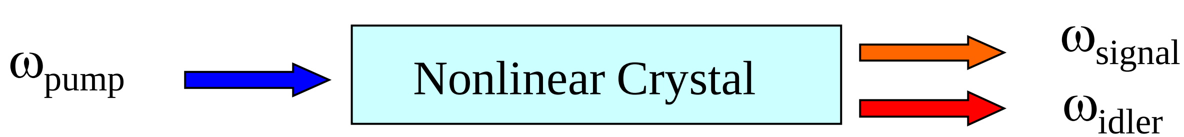
- Difference Frequency Generation (DFG):



- Optical Parametric Oscillator (OPO):



- Optical Parametric Generation (OPG):

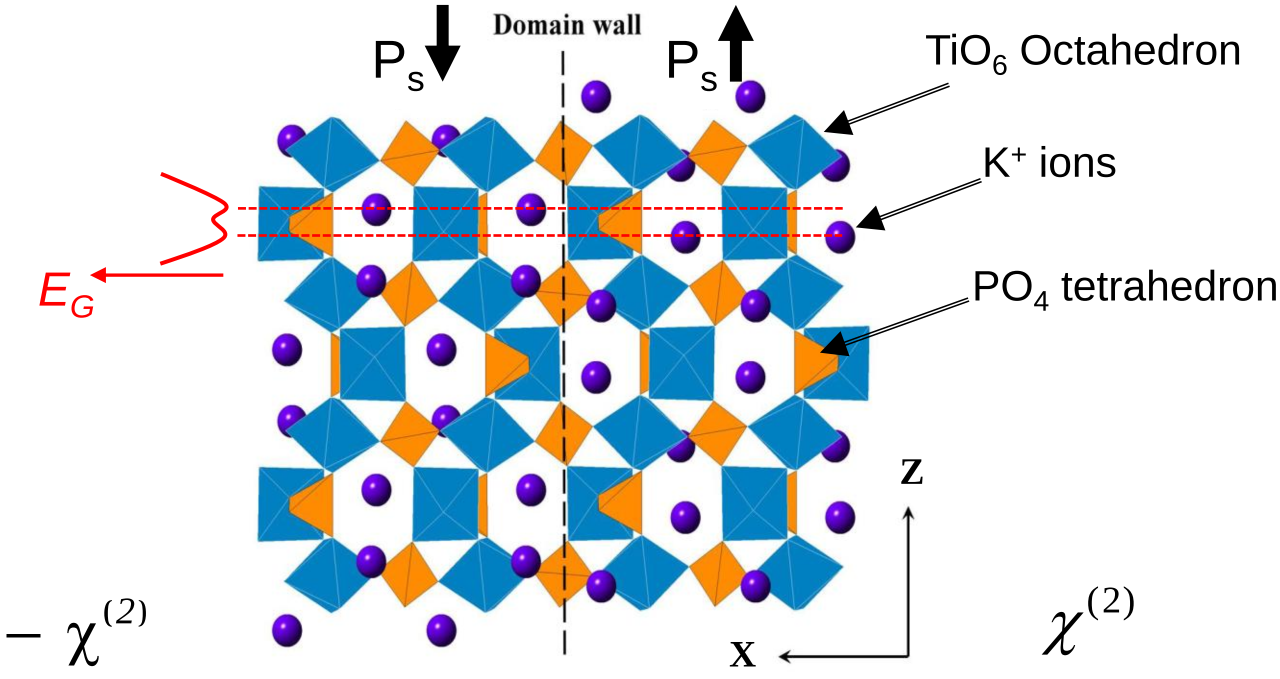


Down conversion

Ferro-electric crystals

Materials that have a spontaneous electric polarization that can be reversed by the application of an external electric field

$KTiOPO_4$ (KTP)

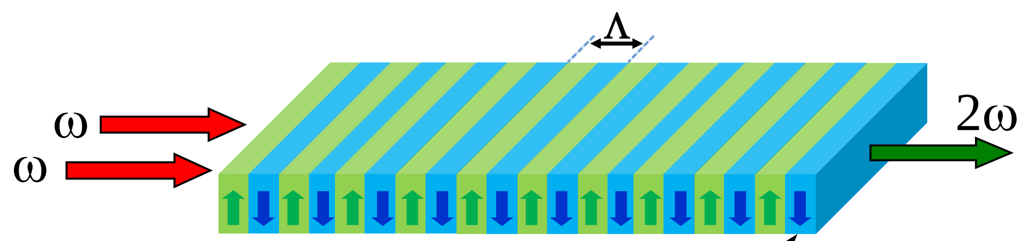


Quasi Phase matching by periodically poled structure in a non-linear crystal

For SHG:

Coherent length: $l_c = \lambda / 2(n_{2\omega} - n_{\omega})$

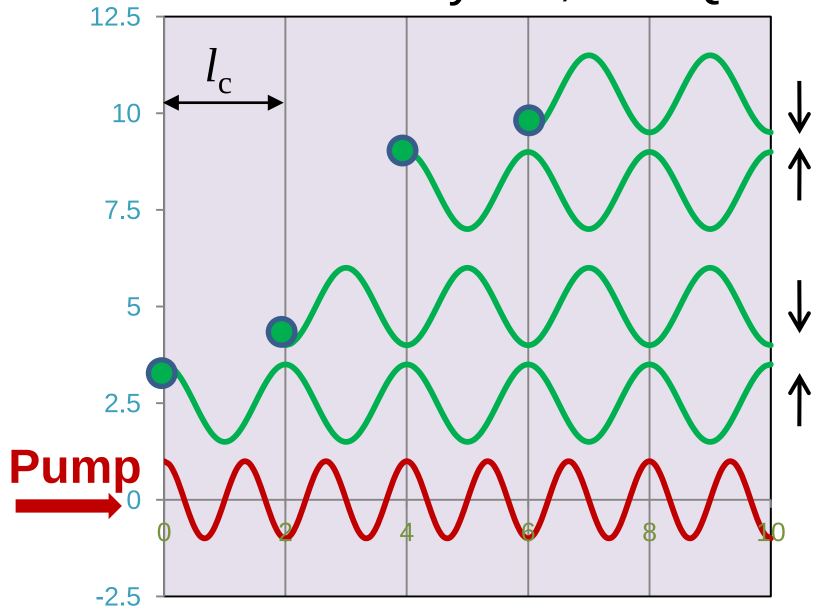
Period: $\Lambda = 2 l_c$



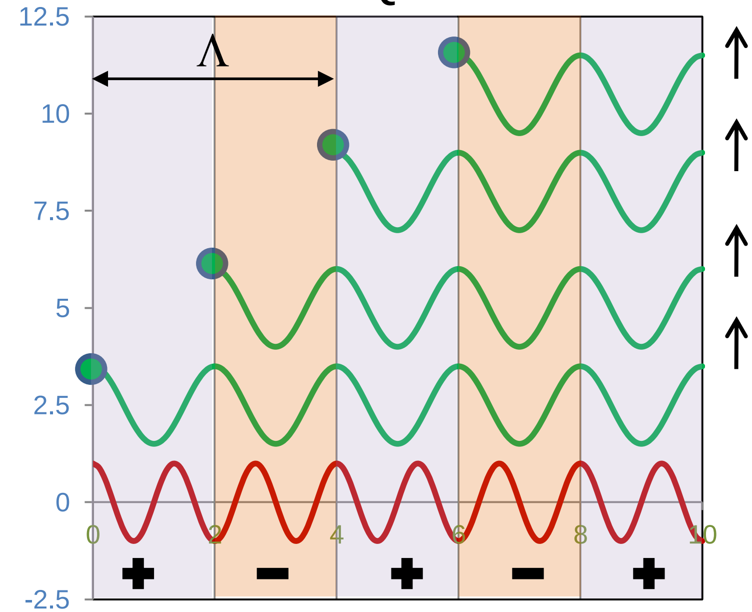
Periodic change of the sign of $\chi^{(2)}$

Inverted domain

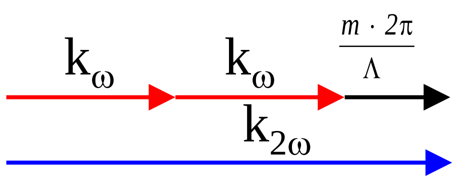
Mono domain crystal, No QPM



With QPM



Quasi-Phase Matching (QPM) frequency conversion by periodically poled crystals



Efficiency For plane wave SHG:

$$P_{2\omega}(L) = \eta_{nor} L^2 (P_\omega^2/\mathrm{A}) \mathrm{sinc}^2(\Delta k * L/2)$$

$$\eta_{nor} = \frac{2\pi^2 d_{eff}^2}{n_\omega^2 n_{2\omega} c \varepsilon_0 \lambda_{2\omega}^2} = Q \frac{d_{eff}^2}{n^3}$$

$$\Delta k = k_{2\omega} - 2k_\omega - \frac{m \cdot 2\pi}{\Lambda}$$

<u>QPM Condition:</u>

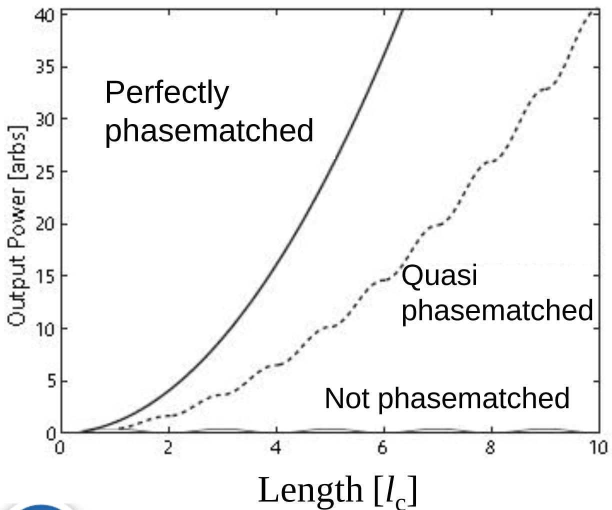
$$\frac{n_1}{\lambda_1} - \frac{n_2}{\lambda_2} - \frac{n_3}{\lambda_3} = \frac{m}{\Lambda}$$

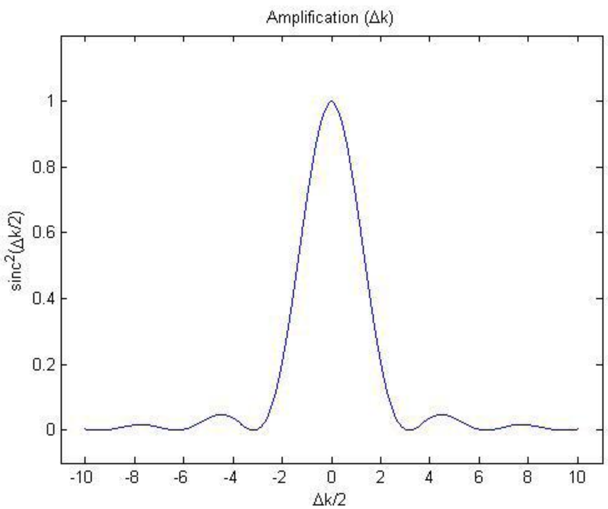
$$k_1 - k_2 - k_3 = \frac{2m\pi}{\Lambda}$$

$$\Lambda = 2l_c$$

m – QPM order

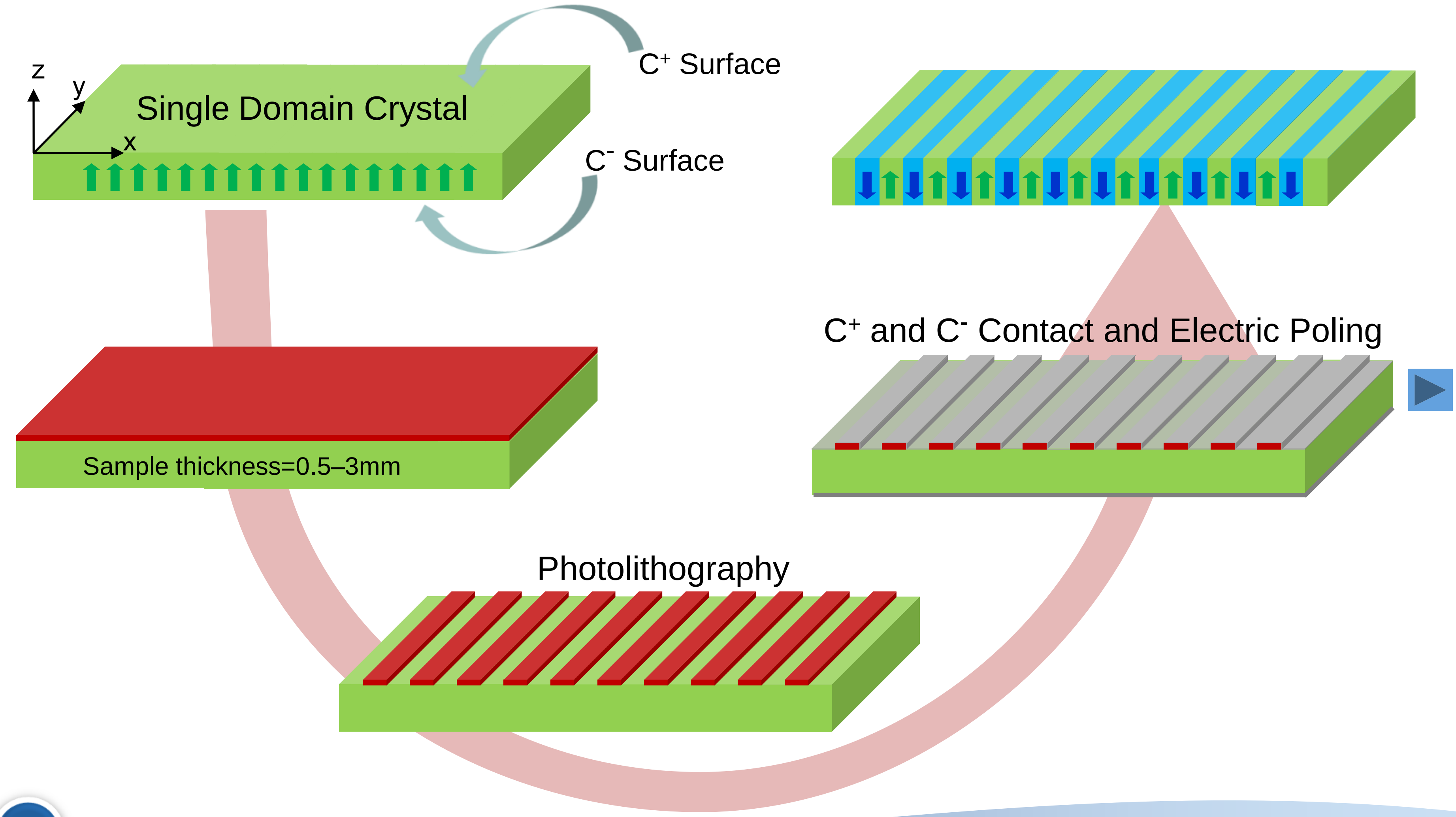
m/Λ can be +/ -





$$Max.\ d_{eff-QPM}^{m} = \frac{2}{\pi} = 0.637d$$

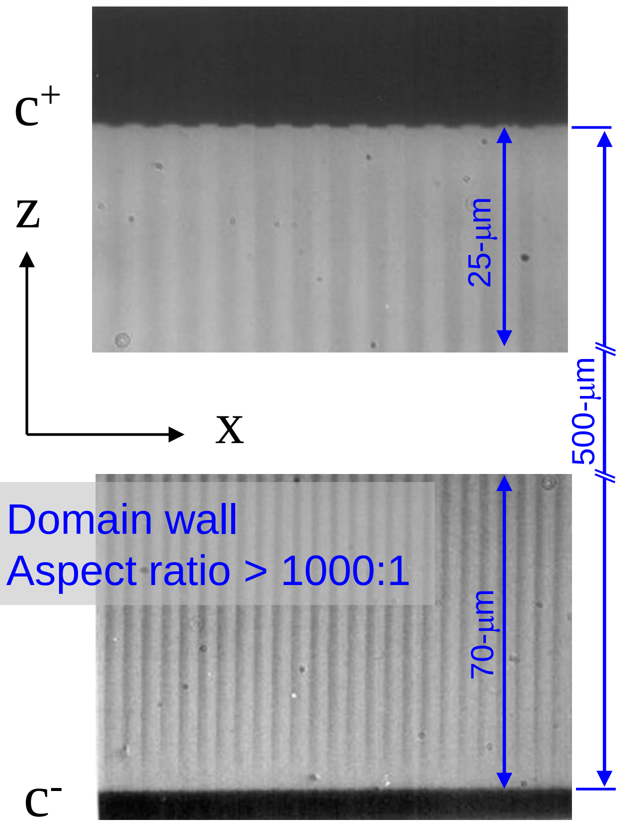
Poling process flow of Ferro-Electric crystals



Selective etching of periodically poled surfaces

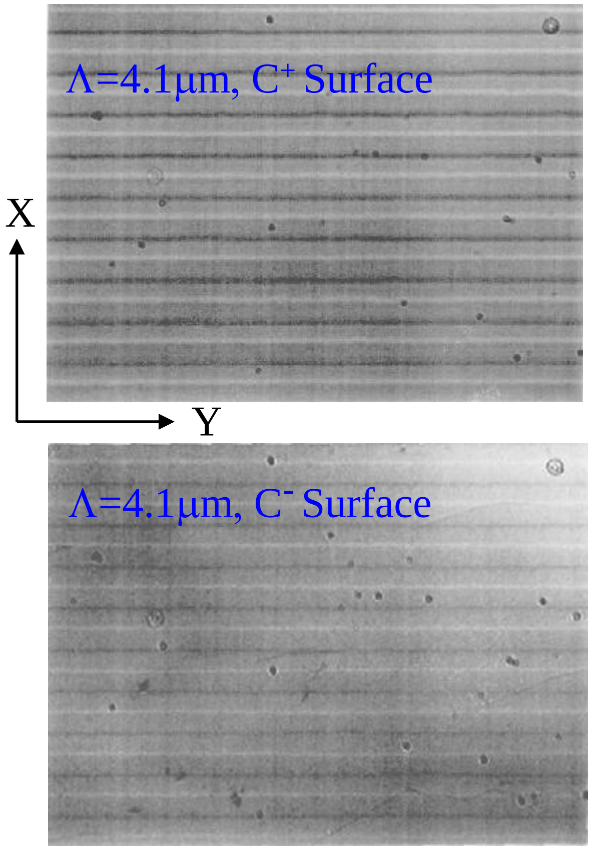
periodically poled KTP (PPKTP), Λ=4.1μm,

Y-cut

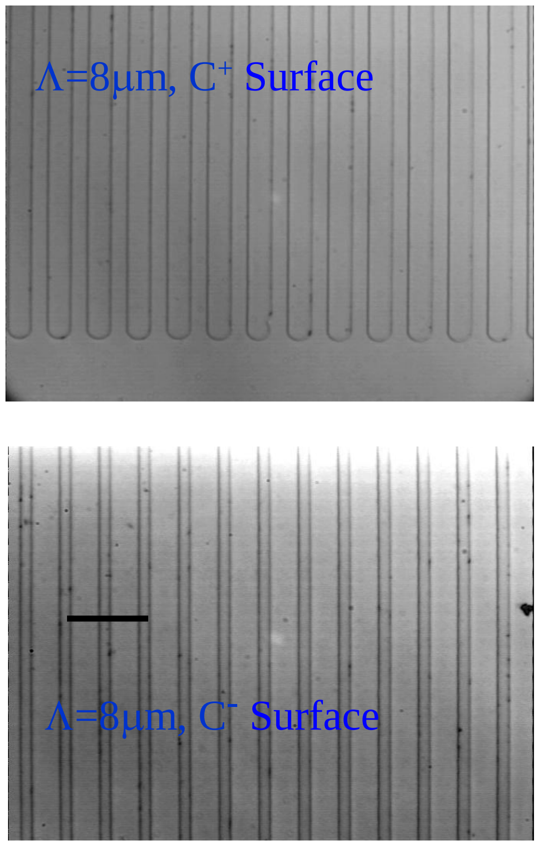


Domain wall
Aspect ratio > 1000:1

Top view of
C+ and C- Surfaces

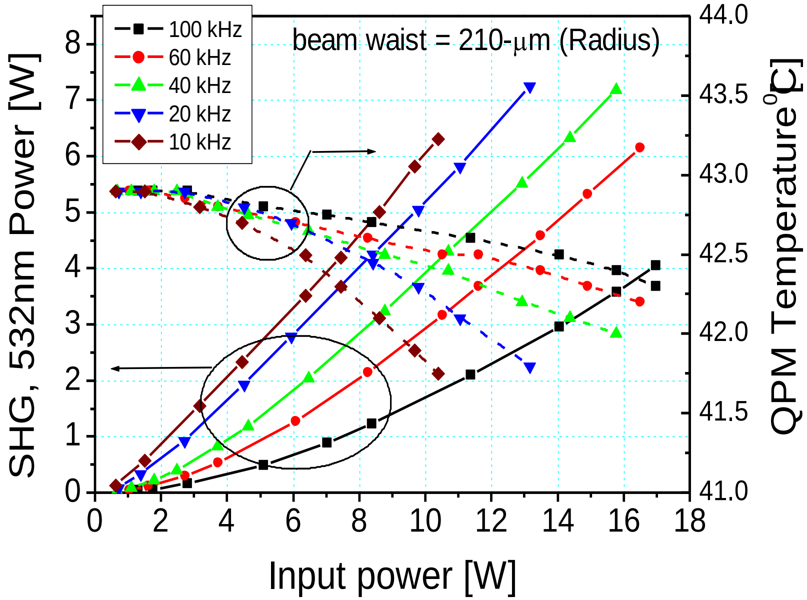


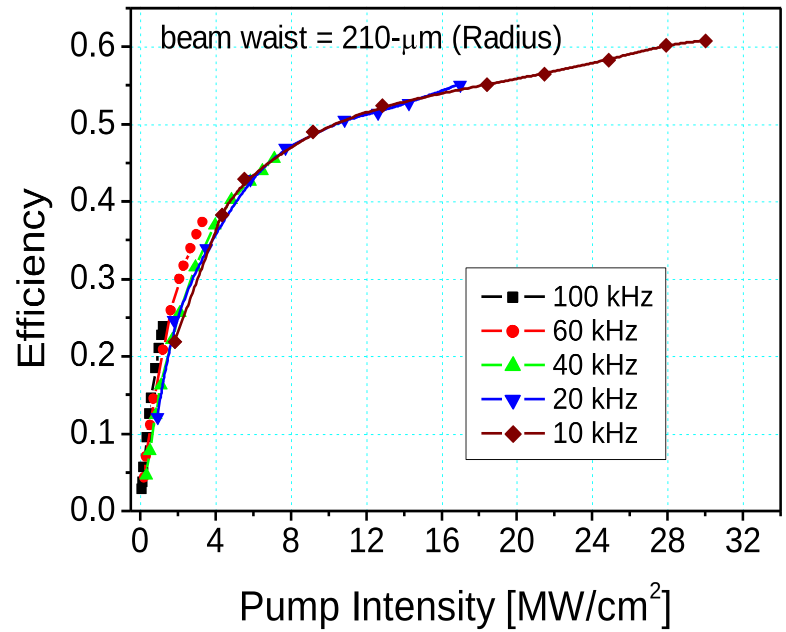
periodically poled Stoichiometric LT (PPSLT)



Multi-Watt green generation by SHG using PPSLT

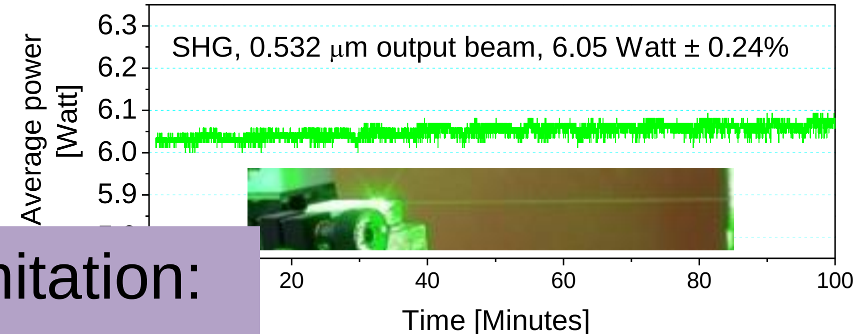
Pump laser: Nd:YVO_4, λ_p=1064nm, PPVSLT: L= 21mm, Λ=8.0-μm





Max. pump Intensity =30-MW/cm2
Max. ΔT_{QPM}=1.3^{0}C

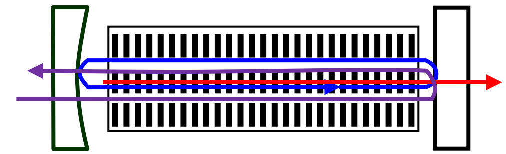
Max. efficiency = 61%



Main reason for efficiency limitation:
Thermal dephasing effect

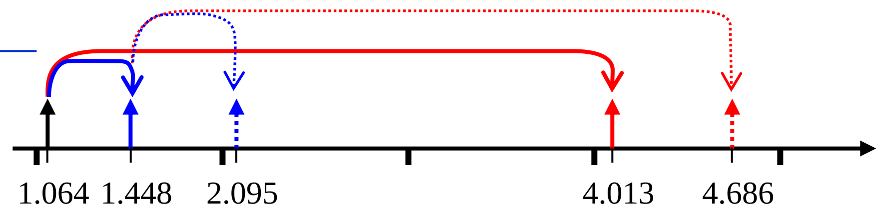
OPO to the Mid-IR (4μm) by PPSLT

Primary and Secondary OPO in single period



Secondary OPO:

Primary OPO:

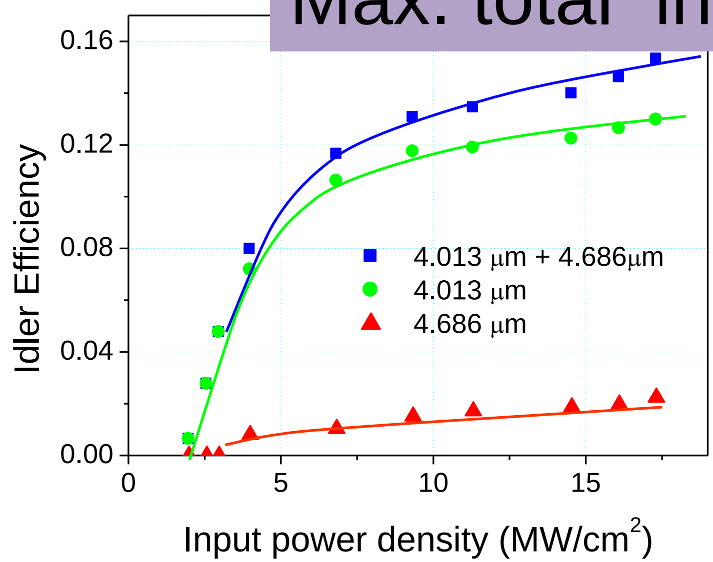


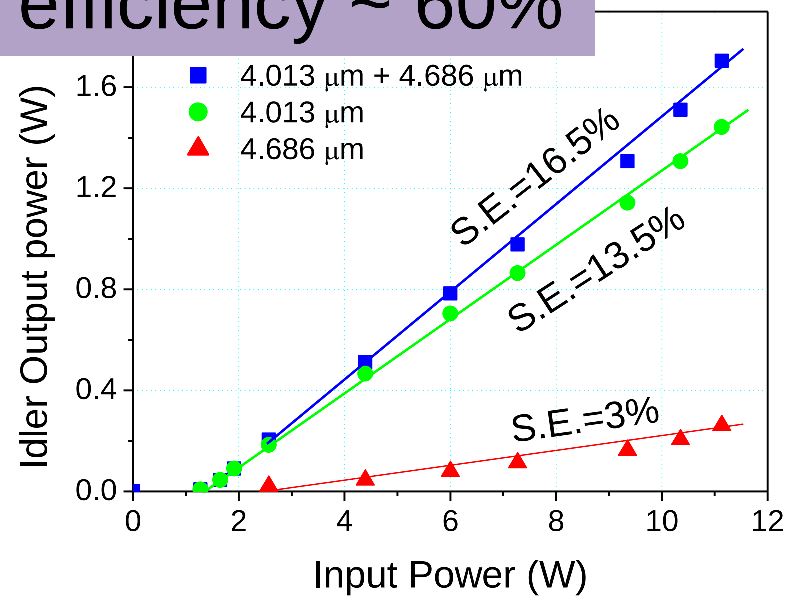
T ~ 54^{0}C, Λ=28,5μm,
w_0=280μm,
Uncoated Sample

Idler conversion

Max. total internal efficiency ~ 60%

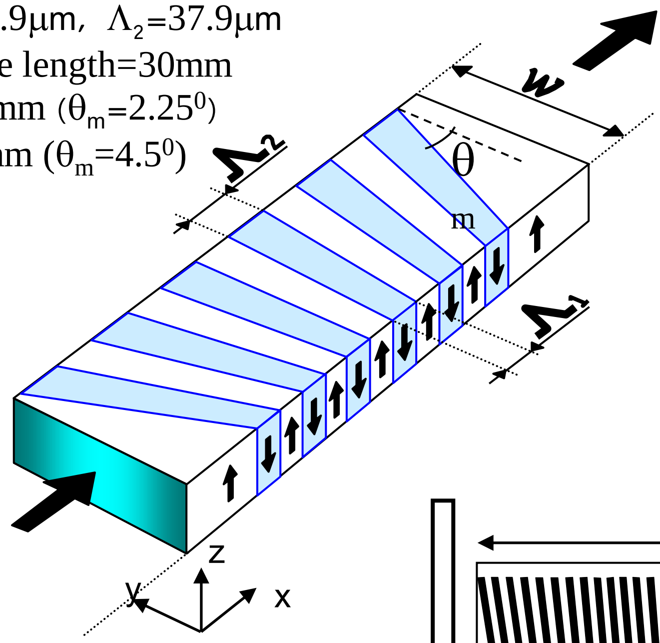
mp) power



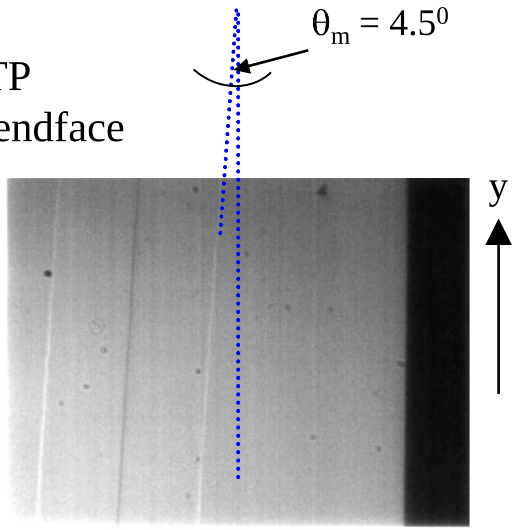


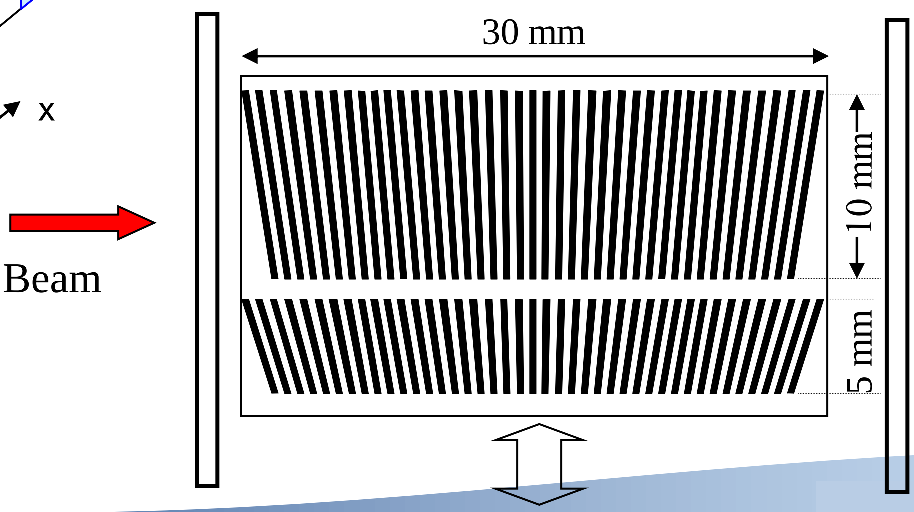
Fan-shaped Grating by PPKTP

$\Lambda(y)=\Lambda_1+(\Lambda_2-\Lambda_1)*y/w$
$\Lambda_1=36.9\mu m$, $\Lambda_2=37.9\mu m$
Sample length=30mm
w=10mm ($\theta_m=2.25^0$)
5mm ($\theta_m=4.5^0$)



Etched $C^{(-)}$ PP-KTP
Surface near the endface

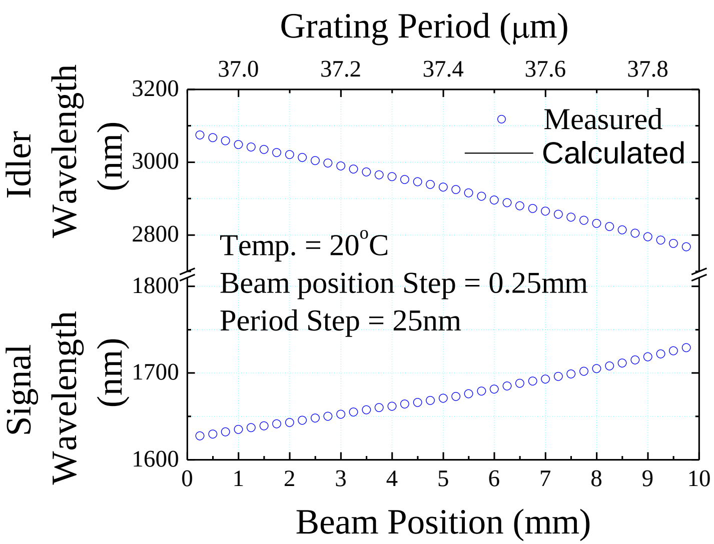




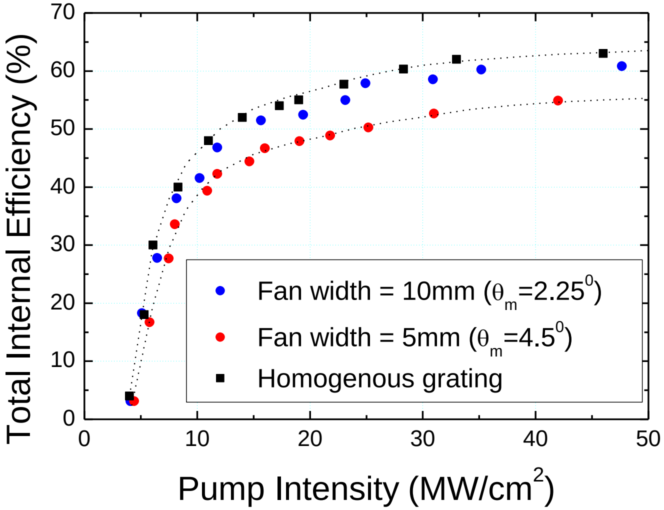
OPO Fan-shaped grating experimental results

Pump: intensity = 20MW/cm^2, 1kHz, 35nsec, λ_p=1064nm, w_0=80µm, L= 30mm, Λ=36.9µm-37.9µm, θ_{max}=2.5^0

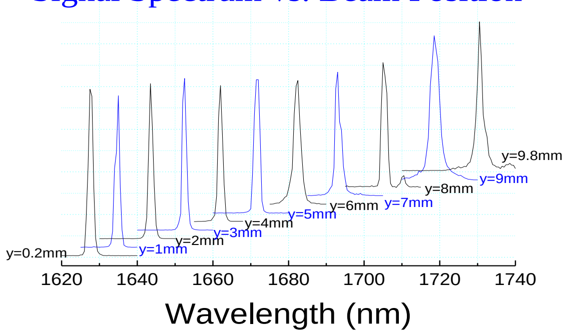
Wavelength Tuning Curve vs. Beam Position



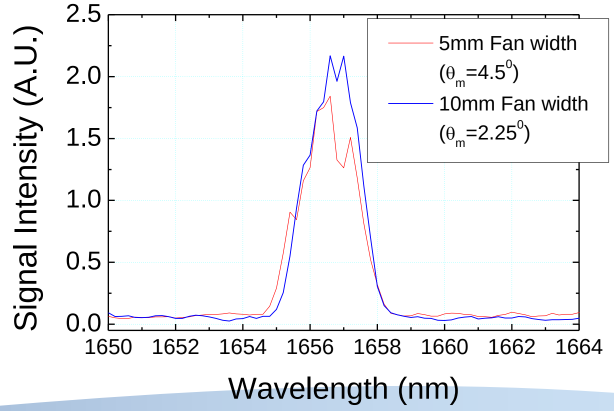
Efficiency vs. Pump Intensity



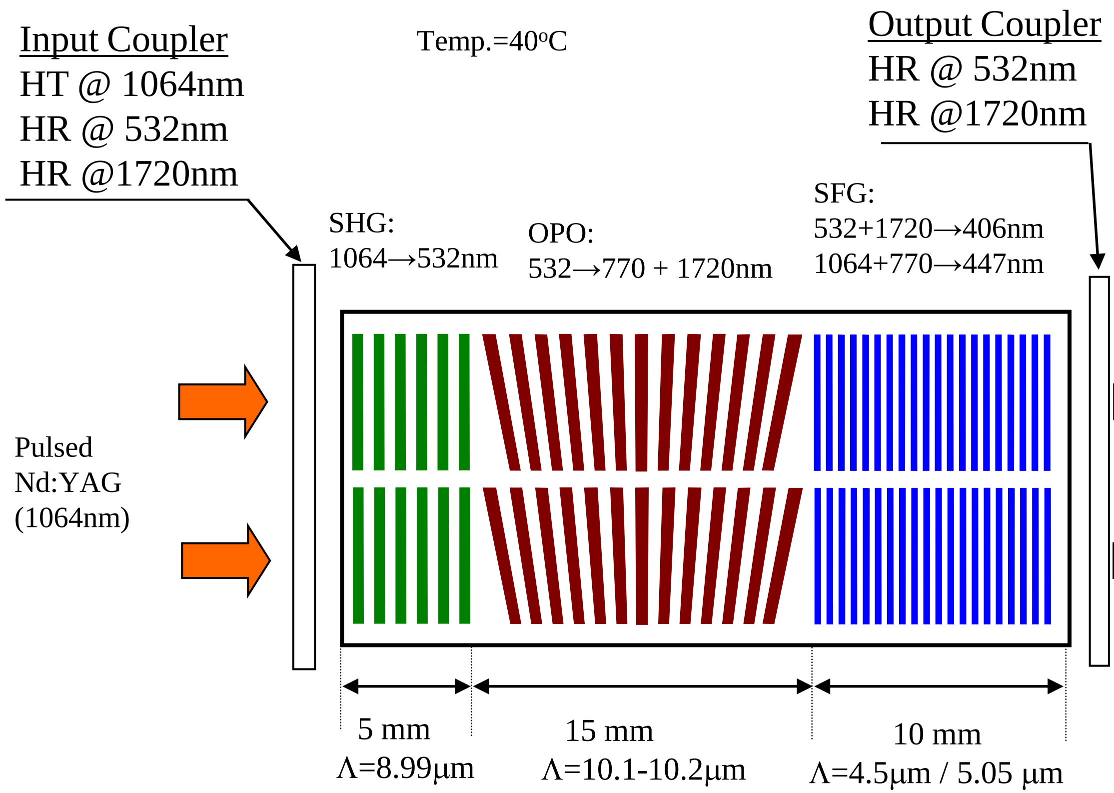
Signal Spectrum vs. Beam Position

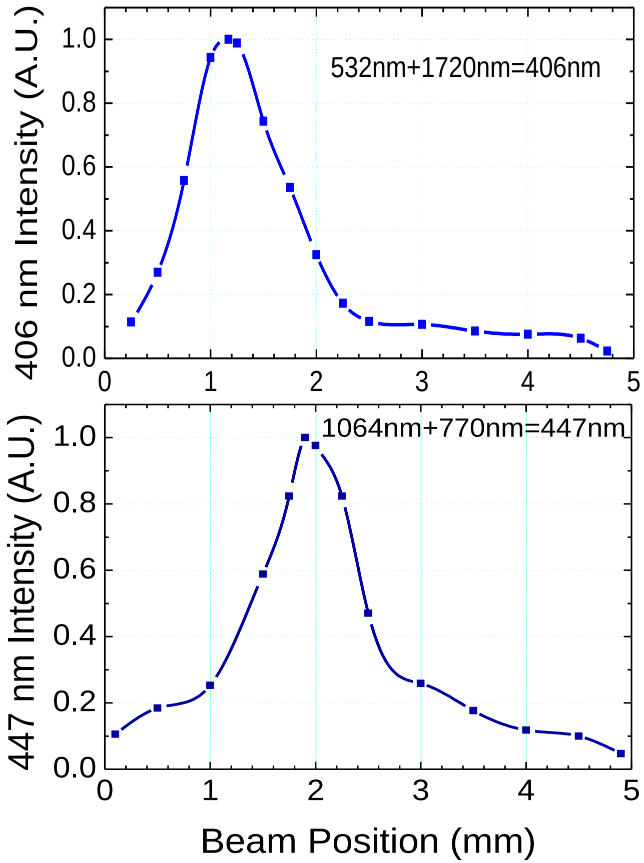


Spectral Bandwidth



Light Conversion Through a Triple Grating.



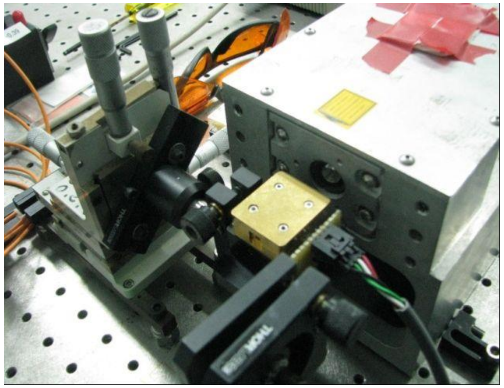


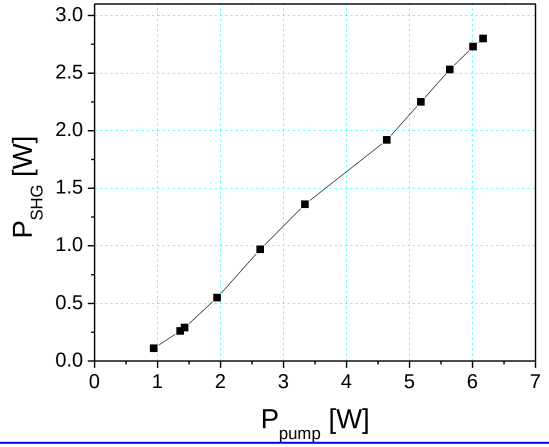
Two degrees of freedom are needed:
1. Temperature - SHG.
2. Sample position of the OPO grating for achieving the correct wavelength for the SFG at the same temperature.

SHG by Direct Coupling of PP samples to the pump lasers

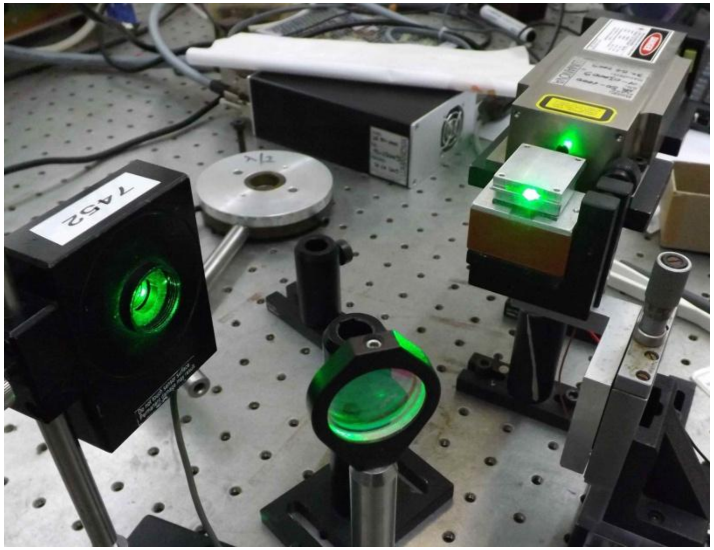
No lens used between the laser and the Periodically-poled sample

Simple and robust system



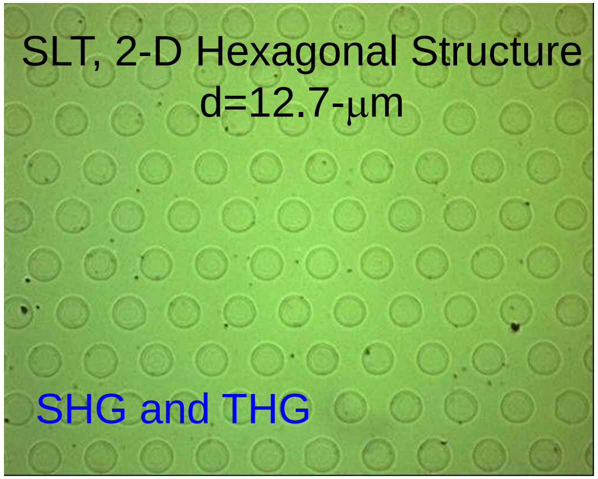


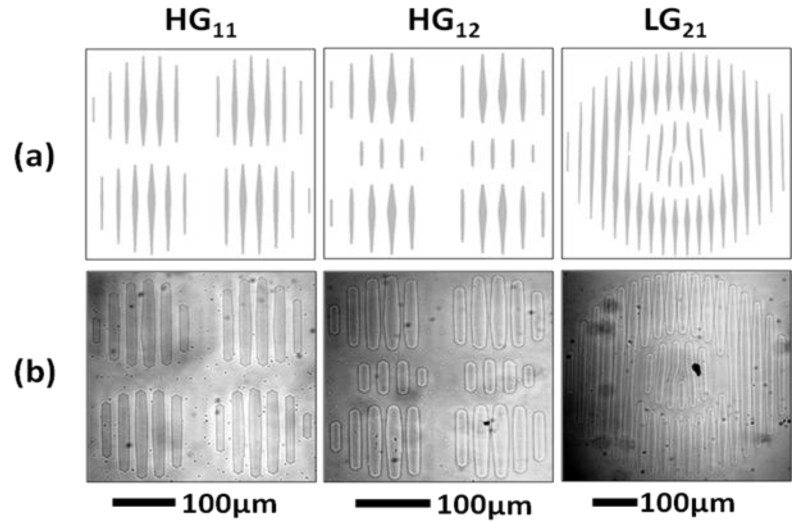
Pump: Nd:YVO_4,1.064-µm, 10-30kHz, 25-40-nS, w_o~300-µm, Max. Efficiency=48%
Sample: PPSLT 3x30x1-mm, Λ=8-µm



Pump: Nd, 1.064-µm, 50-Hz, 1-nS, 1mJ/pulse
w_o~350-µm. Sample: PPSLT 3x30x1-mm, Λ=8-µm,
Efficiency ~50%

Non-traditional frequency conversion devices





SLT,
Beam shaping
(Ady Arie group, TAU)

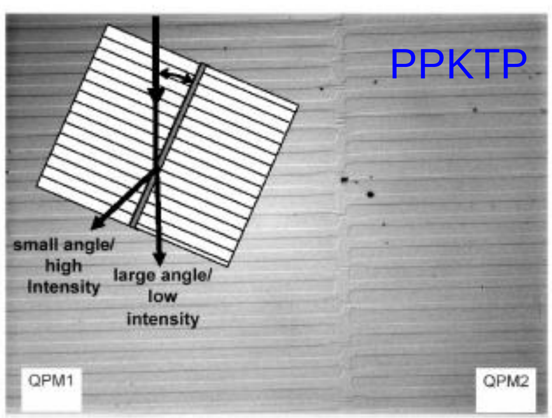
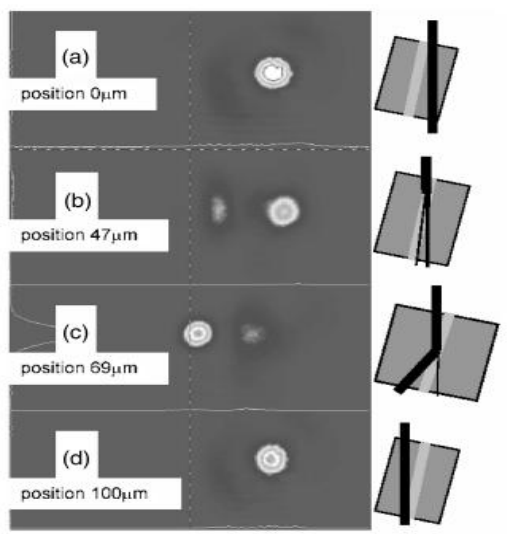


Fig. 2. Microscope picture of the sample QPM gratings and the boundary. Inset, geometry of the light beam–sample interaction.



Quadratic spatial solitons
(G. Stegeman group and
L. Torner group)

Quadratic soliton self-reflection at a quadratically nonlinear interface

Orientation-Patterned GaAs (OP-GaAs)

Why GaAs (or other III-V compound)?

- Large nonlinearity
  - GaAs, d_{14} ~ 100-pm /V
  - GaP, d_{14} ~ 50-pm /V
- Extensive transparency
  - GaAs: 0.9 μm - 17 μm
  - GaP: 0.5 μm - 11 μm
- High thermal conductivity
  - GaAs: 50-W/m K
  - GaP: 110-W/m K

$LiNbO_3$, d_{33}=27-pm/V
$LiTaO_3$, d_{33}=16-pm/V
KTP, d_{33}=15-pm/V

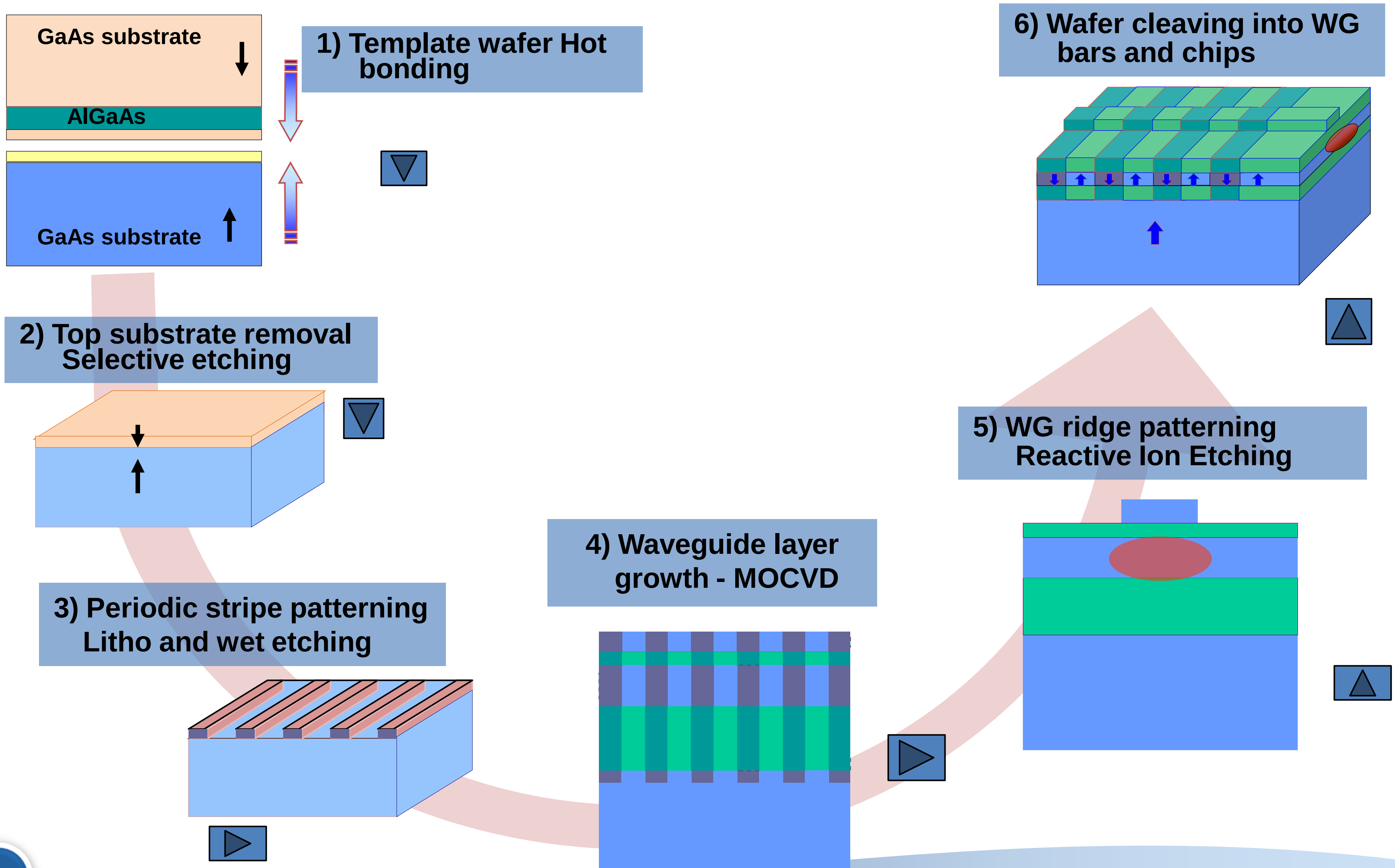
$LiNbO_3$: 0.4 μm – 4.5 μm
$LiTaO_3$: 0.35 μm – 4.5 μm
KTP: 0.4 μm – 3.4 μm

$LiNbO_3$: 5-W/m K
$LiTaO_3$: 8-W/m K

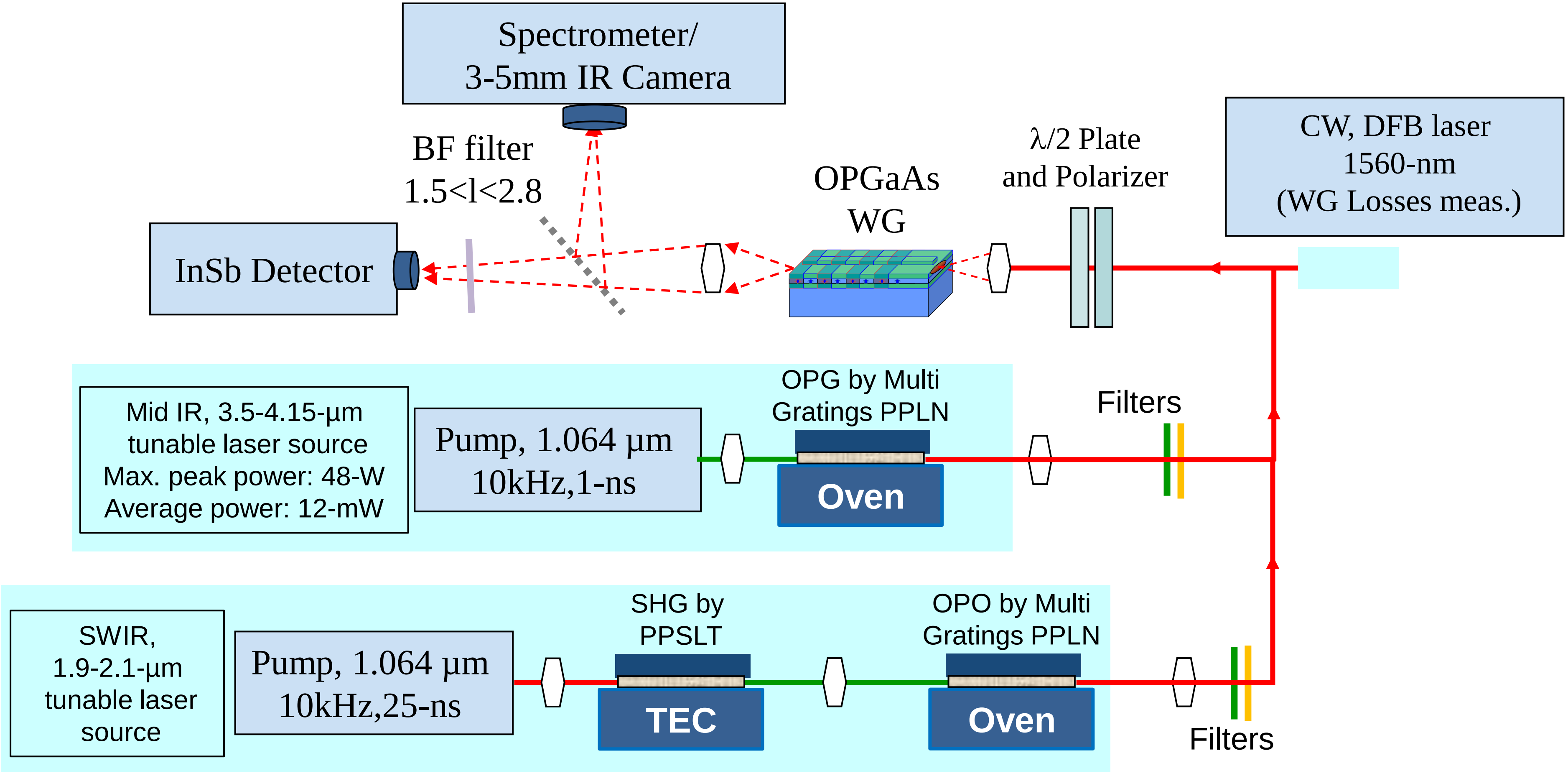
According to our calculation, a waveguide structure consisting of high nonlinear coefficient GaAs will enable efficient frequency conversion devices utilizing (relatively low peak power) CW diode laser pumping

GaAs is not a Ferro-electric crystal.
How to make a QPM waveguide structure ?

Wafer fabrication - process flow



Losses, SHG and OPO measurement system

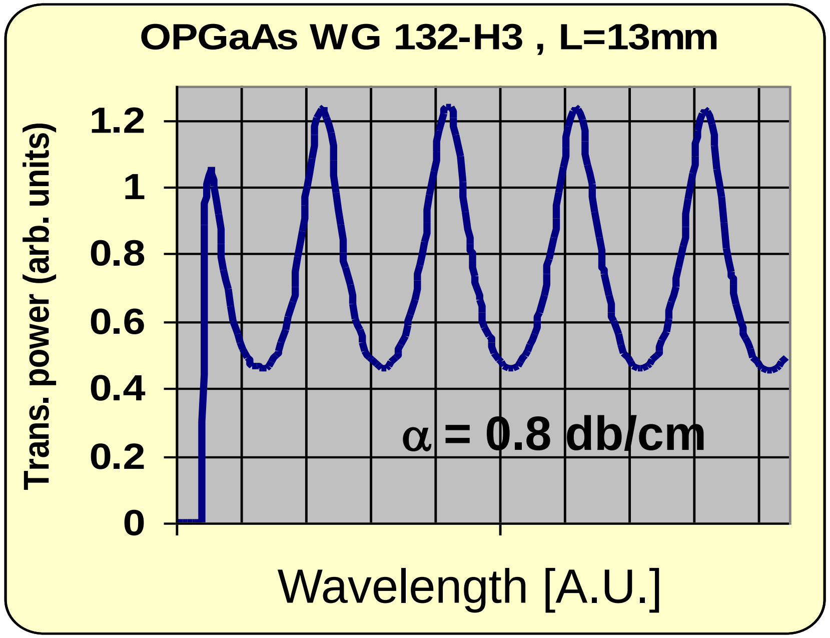


Measurement of WG losses

Loss measurement in OPGaAs WG @ 1.56um

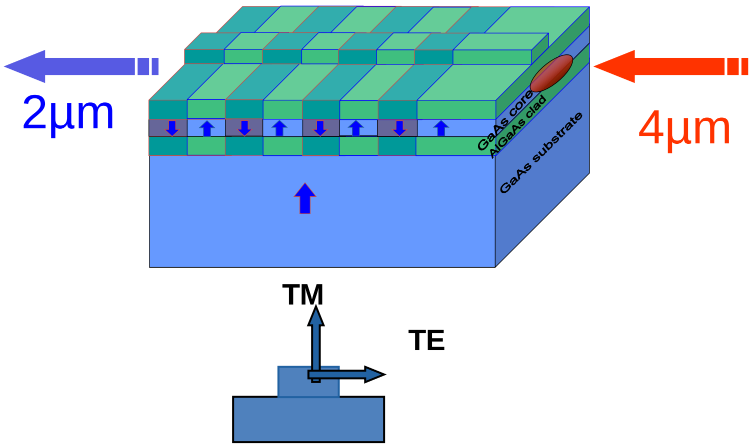
(Using Fabry-Perot interference method)

WG: 3μm x 9μm x 13mm, Λ=39μ

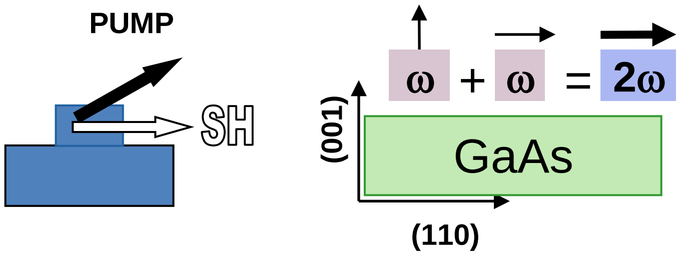


- ✓ Lowest losses in our OPGaAs WGs- **0.8 db/cm**
- ✓ Typical WG loss range : **1.0-1.5 db/cm**

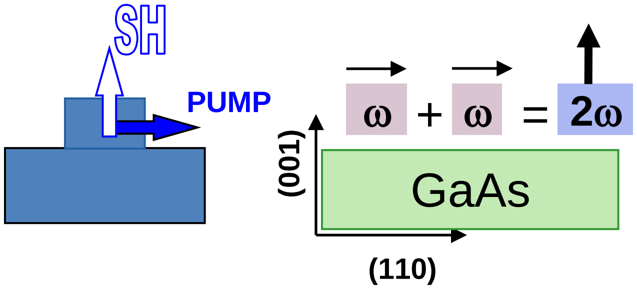
First reported SHG (4-µm to 2-µm) in OPGaAs WGs



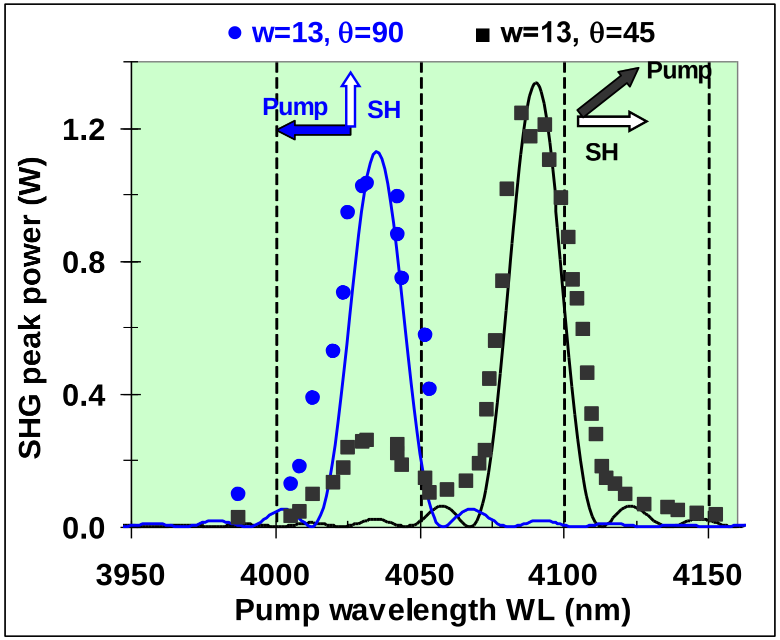
OPG Pump (pulse): λ= 3.5-4.15um,
WG: core=13um x3um , L=10mm , Λ=39um



Type II (TE+TM→TE)



Type I (TE+TE→TM)



Type I SHG: TE+TE →TM

Type II SHG: TE+TM →TE

* M.B. Oron et al, Optics Letters, **35,** 2678 (2010).

SHG of uncoated OPGaAs WGs

Conversion efficiency for ideal WG :

$$\eta_o = \frac{8\pi^2 d_{eff}^2}{n^3 c \varepsilon_0 \lambda_p^2 A_{eff}}$$

(For α=0, d_{14}= 94pm/V) η_o **= 28%W^{-1}cm^{-2}**

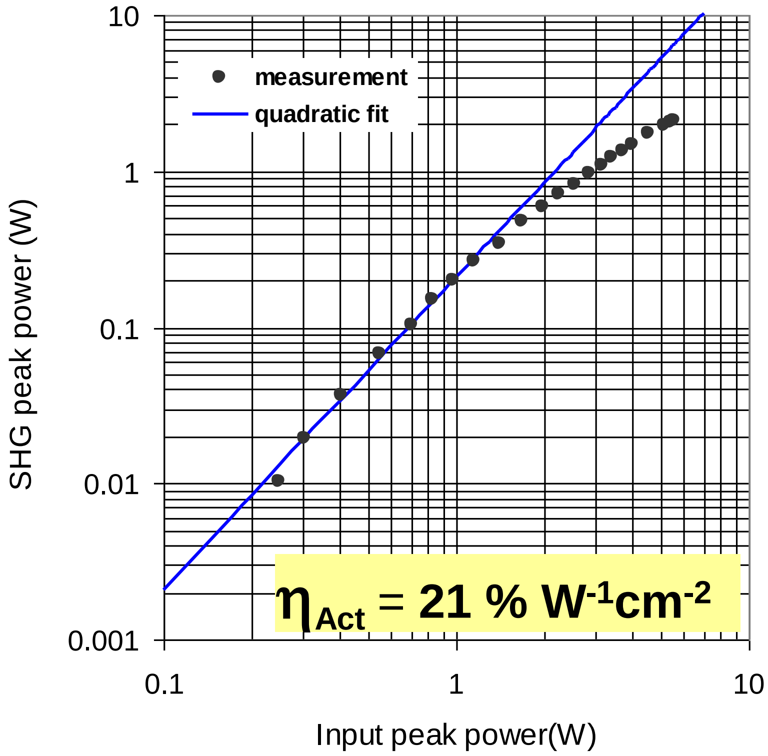
$$T = \left[\frac{\exp(-2\alpha_f L) - \exp(-\alpha_{2f} L)}{2\alpha_f L - \alpha_{2f} L}\right]^2$$

η_{act}/η_0 =T= 0.75

Highest reported for patterned WGs

WG: Λ=**39**um ,L = **1c**m, core= **3 x13**um

Pump: **10**KHz,**1**nsec, λ= **4.095**um, θ = **45^0**

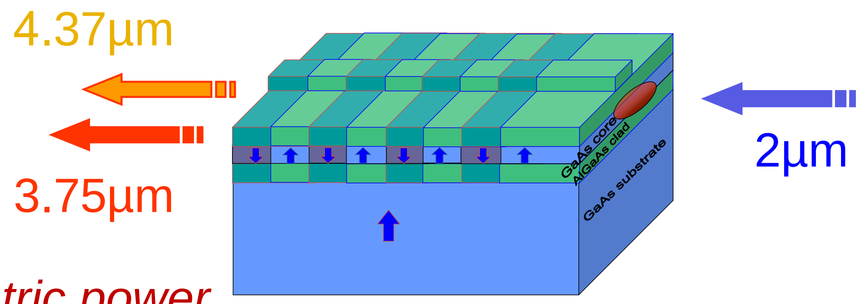


η_{Act} = 21 % W^{-1}cm^{-2}

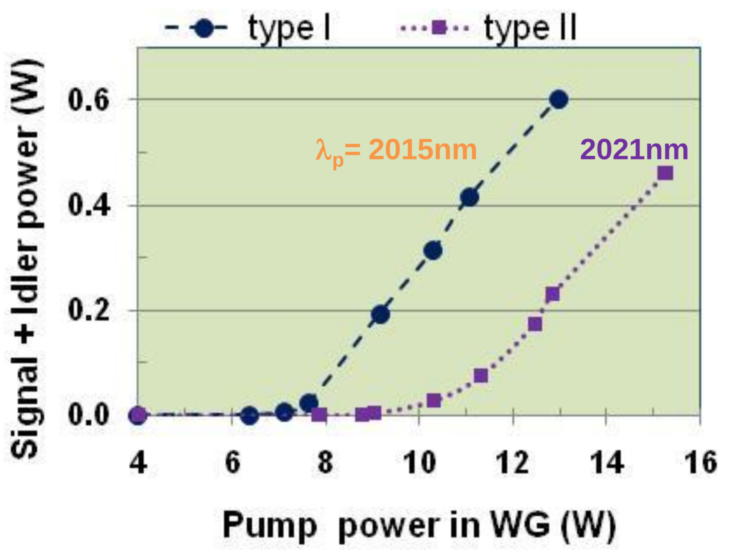
High NL coefficient and Low loss→ High SHG efficiency

* M.B. Oron et al, Optics Letters, **35,** 2678 (2010).

First reported OPGaAs WG – OPO by pulse laser

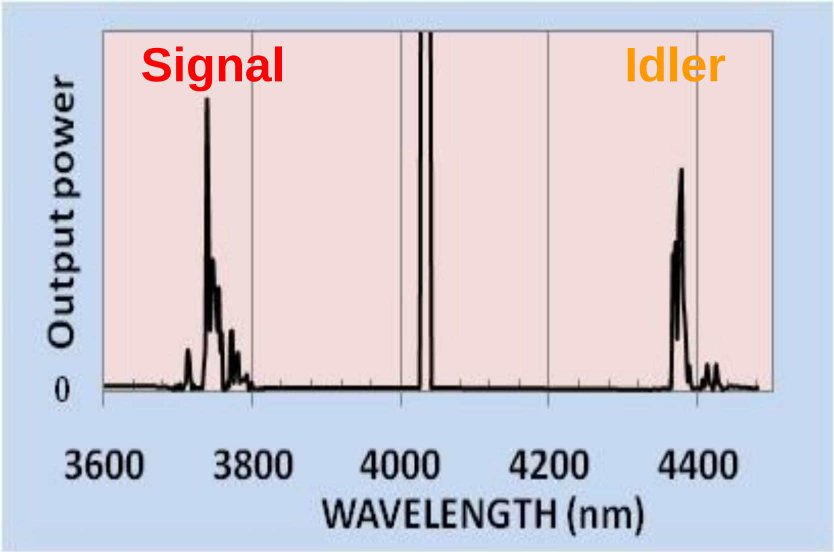


Parametric power



OPO threshold (peak) power

P_{th} (Type-I) = 7W P_{th} (Type-II) = 9W

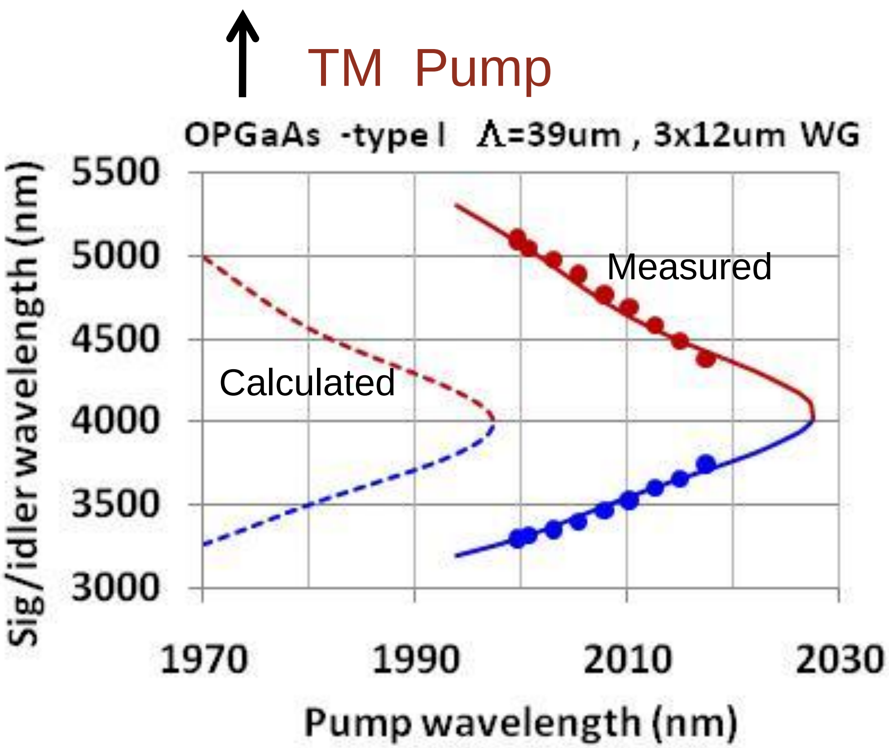


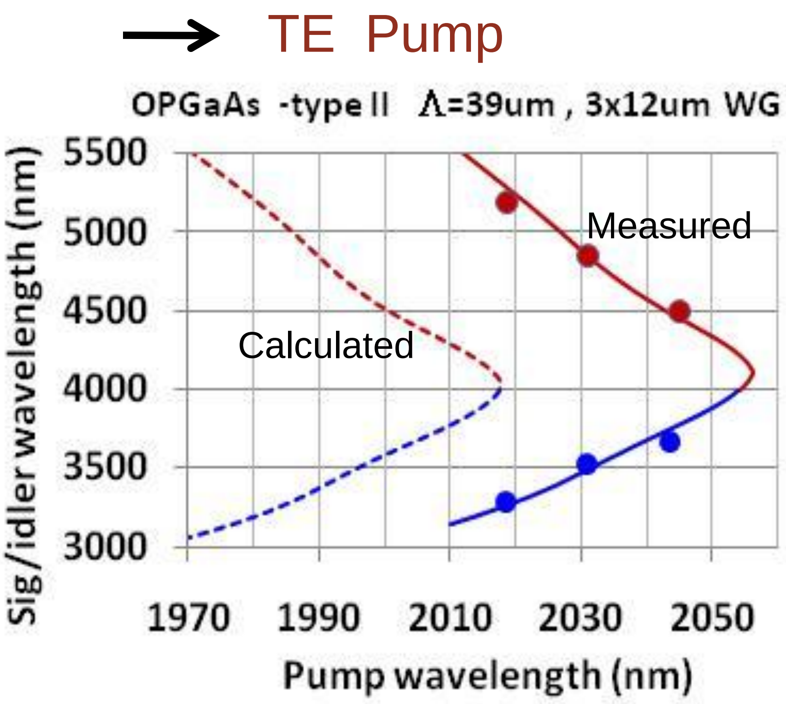
Parametric power spectral scan

Pump : 12W , 2017nm-TM

WG: 3mx12mx13mm

OPO Tuning Curves





*First reported calibrated tuning curves in GaAs WGs**

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* *M. B. Oron, P. Blau, S. Pearl, M. Katz*
, SPIE proceedings Vol. 8325 (2012)

Summary

Ferro-electric Frequency Conversion Devices

- High quality, ferro-electric, poled structures have been developed at Soreq.
- Efficient frequency conversion by SHG, OPO, OPG and SFG (in the range of Blue light to MIR) were demonstrated by these crystals.

Challenge: High power frequency conversion close to 100% efficiency.

OPGaAs-WG

- A technological platform for design & OPGaAs-WG OPO devices has been established at Soreq
  - Transparent OPGaAs WGs of ~ 1db/cm were fabricated
  - SHG & OPO has been demonstrated for the first time in OPGAAs WGs
  - Calibrated tuning curves for OPO operation have been established

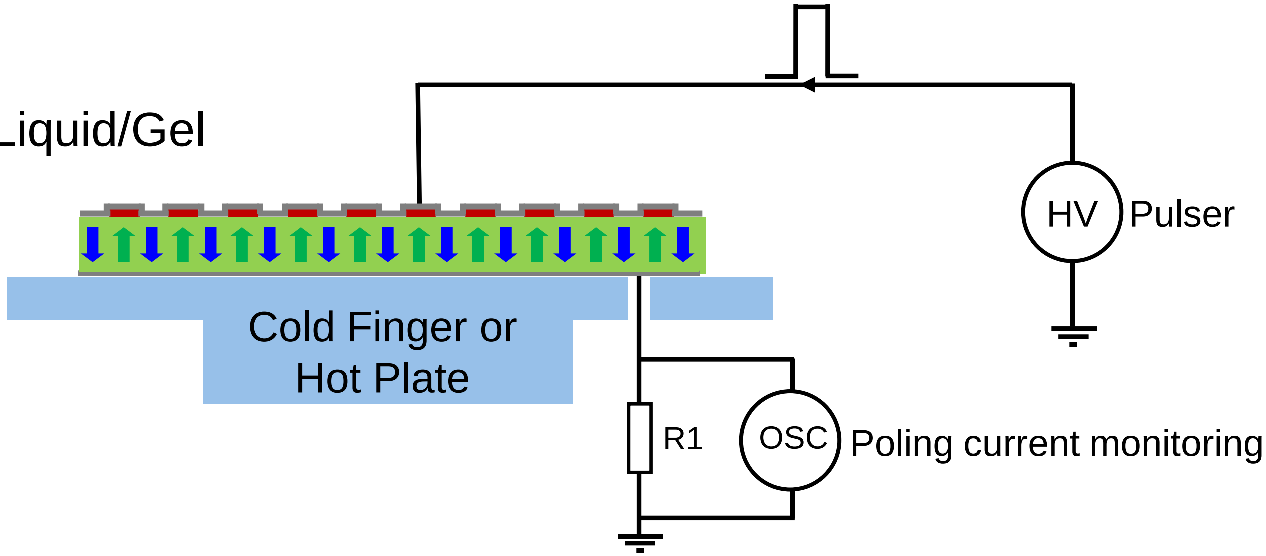
Challenge: High efficient and robust cw laser source at the MIR (OPO, 2 to 4 micron or SHG, 9 to 4.5 micron)

Thank You

Electric Poling

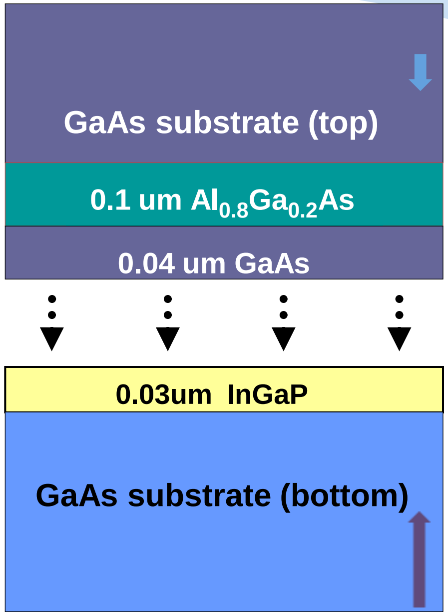
Many possible parameters

- Electric pulse
  - Pulse height
  - Pulse width
  - Single pulse/Multi pulse
  - Pulse shape
- Contact types
  - Metal/paste/Liquid/Gel
- Temperature

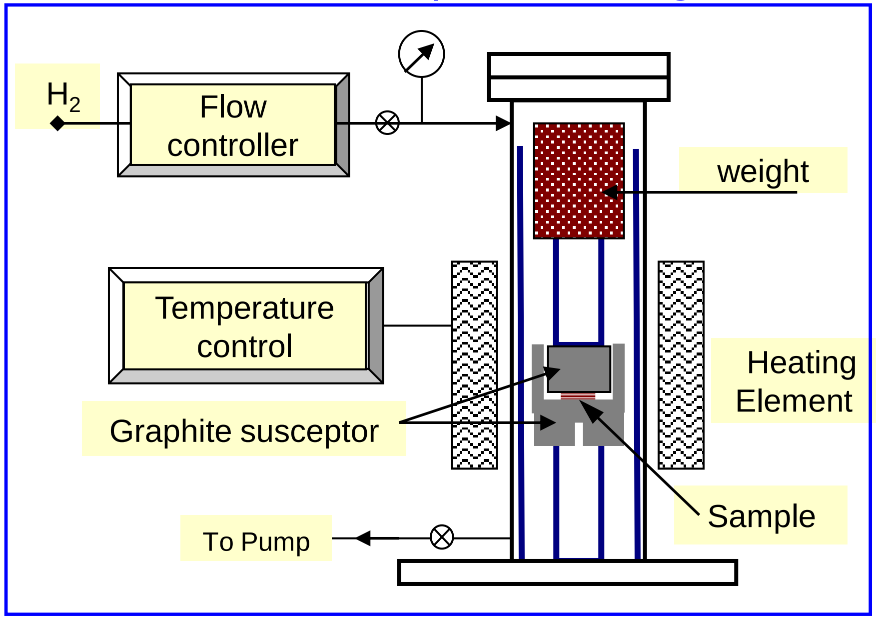


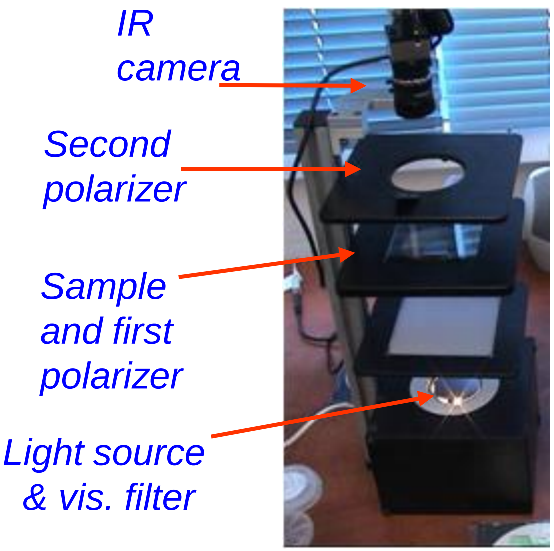
Template wafer fabrication

- MOCVD growth of the top and bottom 2” wafers
- Wafer pair alignment and cold bonding
- Hot bonding in an H_2 reactor (*T= 520-600C)*
- Bond quality characterization by IR transmission

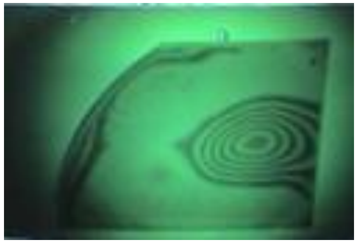


In-house developed bonding oven



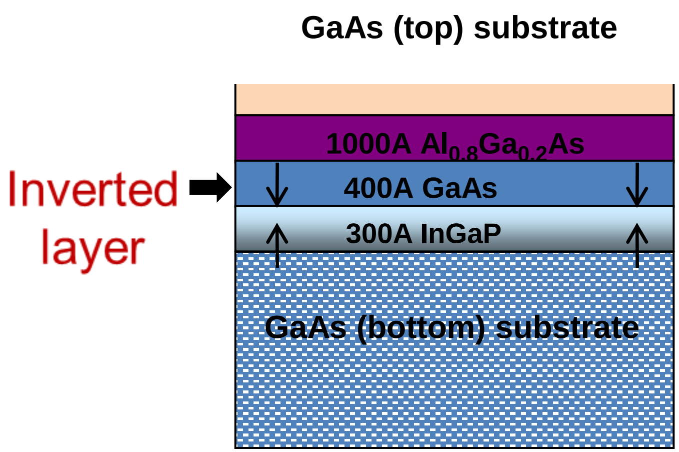


IR image
by Cross polarizeres

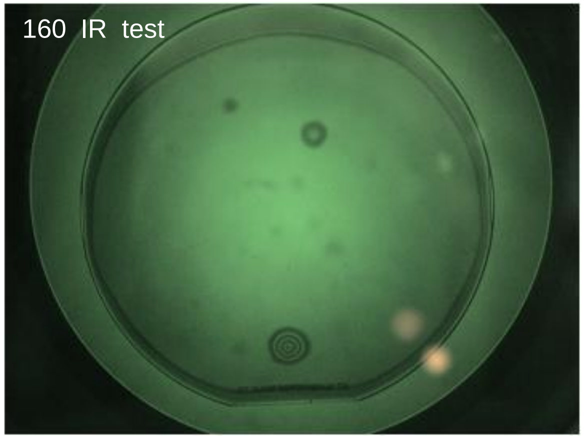


Substrate removal – Lapping and selective etch

- Lapping/Polishing of 90% of top substrate
- Selective wet etch of GaAs residual layer
- Selective wet etch of AlGaAs etch-stop layer

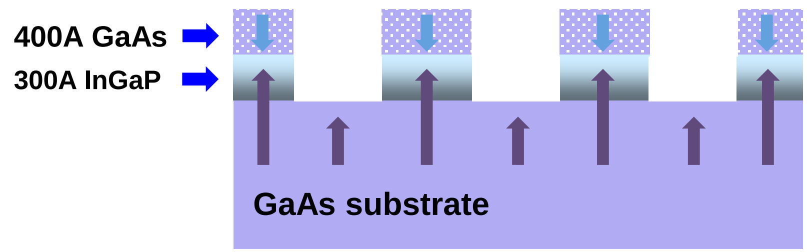


Good correlation found between IR bonding test and final template defects

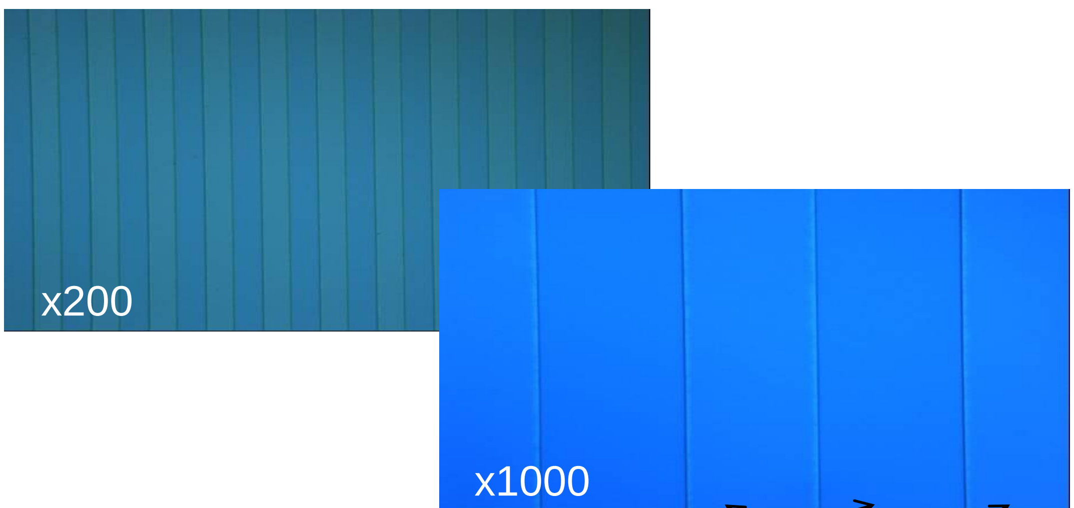


Template fabrication - channel etching

- *SiO_2 mask definition by lithography*
- *Selective removal of GaAs layer*
- *Selective removal of InGaP layer*
- *Removal of SiO_2 mask*



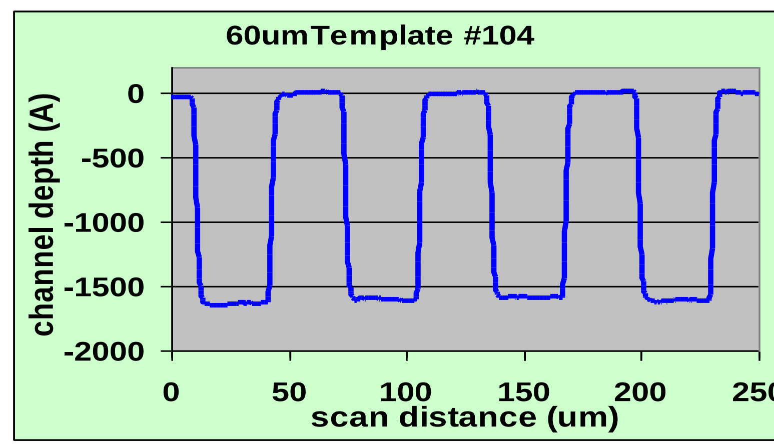
OPGaAs template – Surface views



Substrate

Inverted layer

Surface profile scan

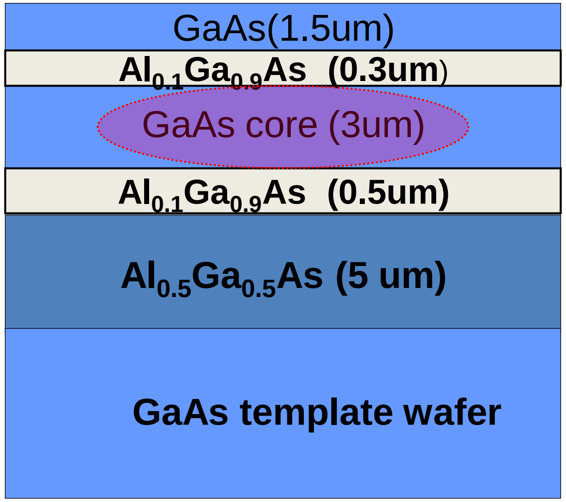


Layer growth on OPGaAs template

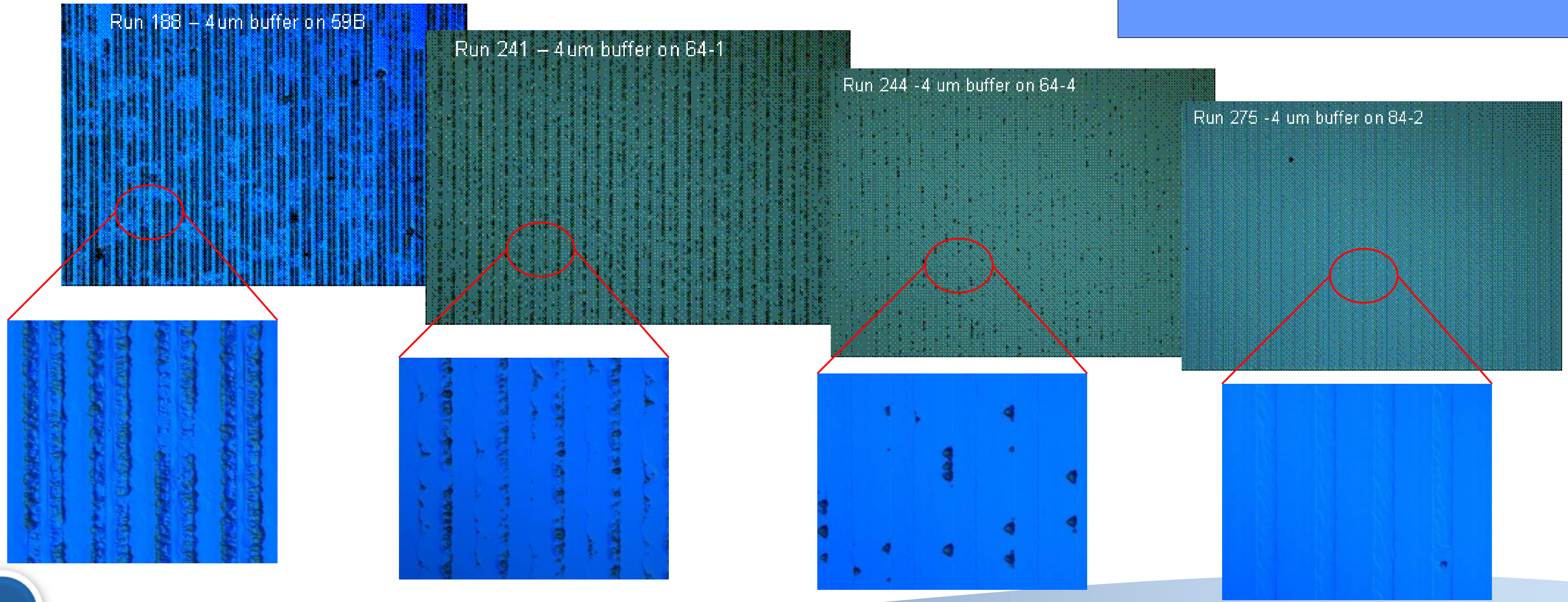
MOCVD growth challenges

*Low defect **thick** layer growth is required on:*

- *Heavily treated substrate*
- *Non planar, corrugated, multipolar surface*

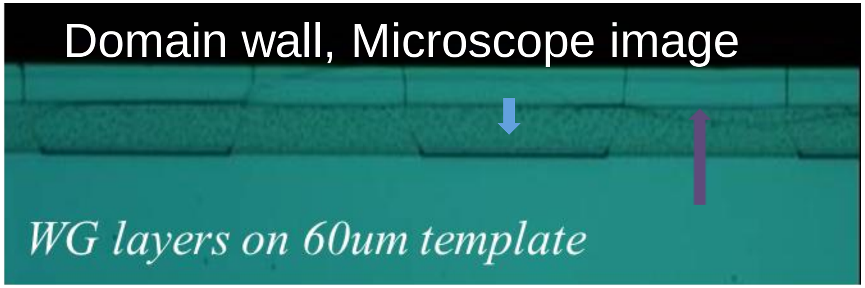


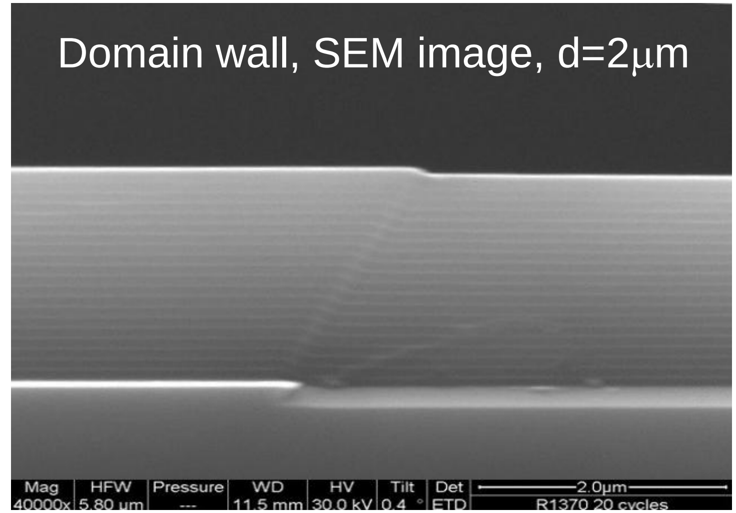
Optical-buffer MOCVD growth development

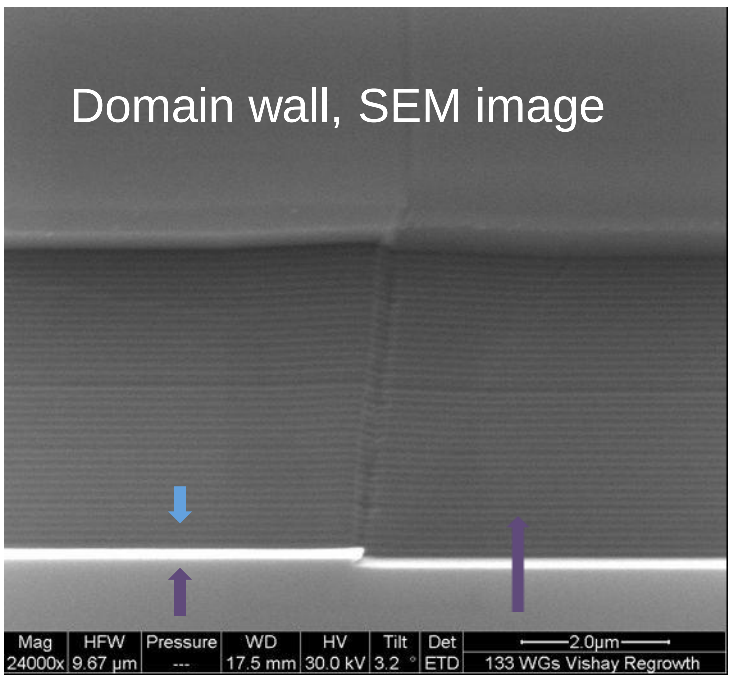


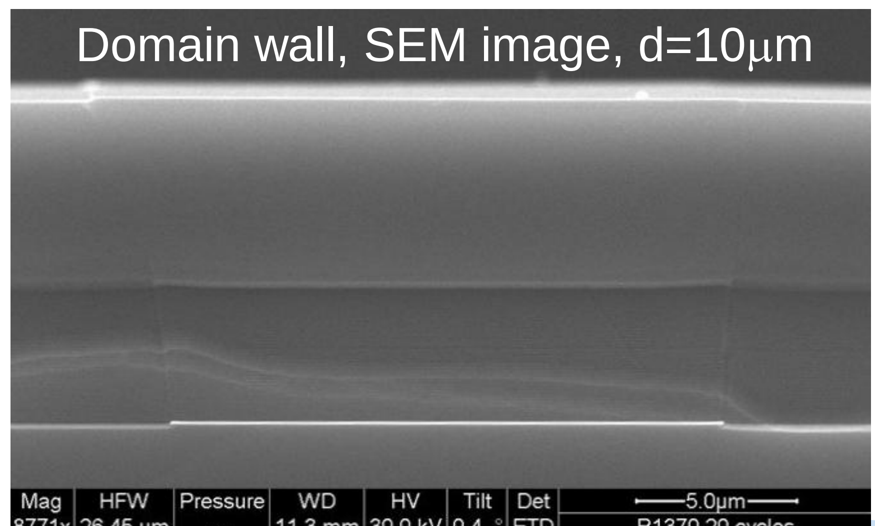
Cross section of layer growth on OPGaAs template

After domain reveal by etching



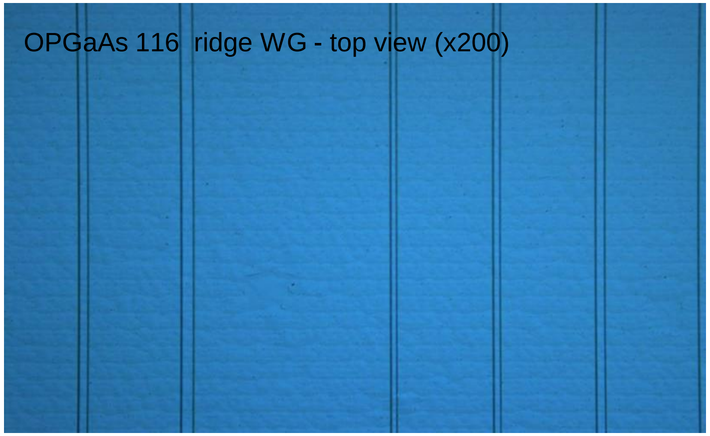






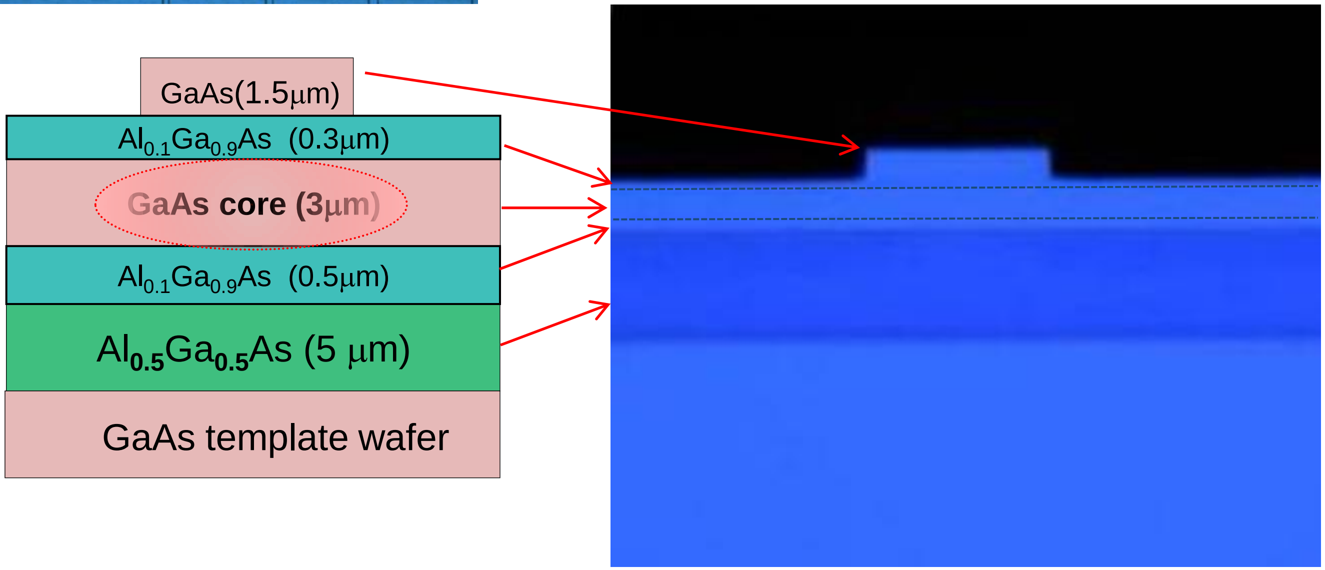
OPGaAs template fabrication – WG Ridge patterning

WG ridges top view (x200)



- ✓*Smooth morphology*
- ✓*No defects*
- ✓*Domains copied from template into WG*

WG ridge cross section



13mm uncoated OPGaAs chip on test carrier

OPGaAs Chip of ~30 WGs