Quasi-Phase-Matched Gallium Arsenide for Mid Infrared Frequency Conversion

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Mid-IR sources requirements and OPOs

- Tunability, multi-spectral
- High energy /peak power
- CW to short pulses
- Narrow or broad linewidth

Optical Parametric Oscillator (OPO)

Suitable MIR nonlinear crystal?

- Tunability, multi-spectral
- High energy /peak power
- CW to short pulses
- Narrow or broad linewidth
MWIR quasi-phase-matched crystal

Desirable properties for the NL crystal:

- High nonlinear coefficient
- Low absorption loss
- High laser damage threshold
- Low thermal lensing
- Non-critical phase matching

QPM vs BPM:

- High nonlinearities
- Non-critical interactions
- Engineering flexibility

<table>
<thead>
<tr>
<th></th>
<th>PPLN</th>
<th>ZGP</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmission</strong> (µm)</td>
<td>0.35-5</td>
<td>1-12</td>
<td>1-16</td>
</tr>
<tr>
<td><strong>Nonlinear Coefficient</strong> (pm/V)</td>
<td>27</td>
<td>75</td>
<td>96</td>
</tr>
<tr>
<td><strong>Thermal Conductivity</strong> (W/m.K)</td>
<td>5</td>
<td>35</td>
<td>52</td>
</tr>
<tr>
<td><strong>α (cm⁻¹)</strong> (&gt; 2 µm)</td>
<td>--</td>
<td>0,025</td>
<td>0,02</td>
</tr>
</tbody>
</table>

PPLN-like crystal for the mid-IR
Quasi-Phasematching (QPM) in GaAs

- Periods under 100 µm for near-infrared pump lasers

\[ \Lambda = \frac{2\pi}{\Delta k} \]

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Quasi-Phasematching (QPM) in GaAs

- Following Armstrong et al. (1962)…

Boyd et al. (1966)  Thompson et al. (1976)

Gordon et al. (1993)
Fabrication of Thick Orientation-Patterned GaAs

1) Fabrication of 2'' GaAs wafer with [001] orientation.

2) Fabrication of 2'' GaAs wafer with etch-stop layer and 0.1 µm GaAs layer regrowth.

3) Crystallographic inversion by wafer bonding process.

4) HVPE regrowth for >500 µm thickness.

5) Gratings defined by photolithographic process.

Mechanical & chemical etching.

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Growth techniques on QPM GaAs samples

CSVT growth on 212 µm DB-GaAs sample

HVPE growth on 212 µm DB-GaAs sample

OP-GaAs template

HVPE growth on 60 µm 2” OP-GaAs template (Thales)

HVPE growth on 60 µm OP-GaAs sample (Stanford/Thales)
Hydride Vapour Phase Epitaxy (HVPE)

Physics of GaAs growth: \( \text{GaCl}_g + \frac{1}{4} \text{As}_4g + \frac{1}{2} \text{H}_2g \rightarrow \text{GaAs} + \text{HCl}_g \)

Growth Characteristics:

- Perfect growth selectivity (preserve initial orientations)
- GaAs growth with low impurity concentration (residual \( \approx 10^{14} \text{ cm}^3 \))
- High frequency desorption of As/GaCl precursors on surface
  \[ \Rightarrow \text{Growth rate up to 35 \mu m/h} \]
Influences of HVPE growth parameters

Examples of HVPE growth anisotropy of GaAs crystal:

- **III/V = 9, T= 760 °C**
- **T= 780 °C, III/V = 3**

GaAs band // [-110], III/V = 3, T= 760 °C

Due to $\chi^{(2)} / -\chi^{(2)}$ orientations on OP-GaAs template:

⇒ Apparition of a morphology conflict during HVPE regrowth
**HVPE regrowth on OP-GaAs template (1)**

**Gratings period ~30 µm**

**Gratings period ~ 60 µm**

**Gratings period ~ 212 µm**
HVPE regrowth on an OP-GaAs template with intentional Si doping:

Gratings period: 60 µm

Growth parameters verify the condition: $v(113) \times \sin 55^\circ = v(-112) \times \sin 65^\circ$
Full wafer growth

2” multigrating 500 µm thick OP-GaAs

Cross section of a 3 cm-long OP-GaAs sample (63 µm grating period)

Growth characteristics:
- Growth rates:
  \( v(113) = 33 \, \mu m/h \)
  \( v(-112) = 30 \, \mu m/h \)
- 4 growth interruptions
Towards thicker samples

**Old growth conditions with shorts cycles:**

- 0.5 mm thickness (prior art)
- 0.8 mm thickness (summer 2009)
- 1.3 mm thickness (summer 2010)

**New growth conditions with long cycles:**

- 1.5 mm thickness (winter 2011)

- Thickness is limited by parasitic nucleation
- Thicker samples will require a new reactor
Optical transmission

Lowest loss measured 0.016 cm\(^{-1}\) at 2 µm (in resonant cavity)
First demonstration of GaAs OPO (2004): Stanford University & Thales

(K.L. Vodopyanov et al., Optics Letters, Vol 29, 16 (2004))

- OP-GaAs sample length: 13 mm
- HVPE layer thickness: 500 µm
- PPLN OPO pump

500 µm HVPE film

GaAs, QPM period = 61.2 µm

Signal & idler (µm)

Pump wavelength (µm)
Difference Frequency Generation

DFG at around 7.8 µm from Er and Tm CW fiber lasers: UoDusseldorf

**Fig. 2.** Measured (*) and calculated (solid curve) DFG output versus signal wavelength.

**Fig. 3.** DFG output power (*) and optimal pump (°) wavelength versus pump power.
High power GaAs OPO (2008): Institut St. Louis (ISL)
(C. Kieleck et al., Optics Letters, Vol 34, 3 (2009))

- 2.09 µm high rep.rate Ho:YAG pump, 3-5 µm emission.
- Up to 60% slope efficiency and 2.85 W output
- Efficiency comparable to ZnGeP₂
- 20 W Tm fiber laser
- 10 W Q-switched Ho:YAG
- 3.0 W MWIR at 40 kHz
- $M^2 = 1.4$
- Portable demo

A. Grisard et al., Proc SPIE 7836-06 (2010)
Parametric amplification of a DFB QCL

- 3 mW 4.5 µm CW DFB QCL
- 2.09 µm Ho:YAG 30 ns pulsed pump at 20 kHz
- 53 dB gain with 41 mm long GaAs crystal
- 600 W peak power
- \( M^2 = 1.3, \Delta \lambda < 0.5 \) nm (instr. limited)

Recent results using OP-GaAs

- 7.7 W average power ns OPO (ISL)
- Fiber laser pumped ns OPO (ISL)
- Intracavity ps DFG for THz generation (Stanford)
- Fs MIR frequency comb (Stanford)
- CW OPO (BAE US)
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  - IMPROV (http://www.fp7project-improv.eu)