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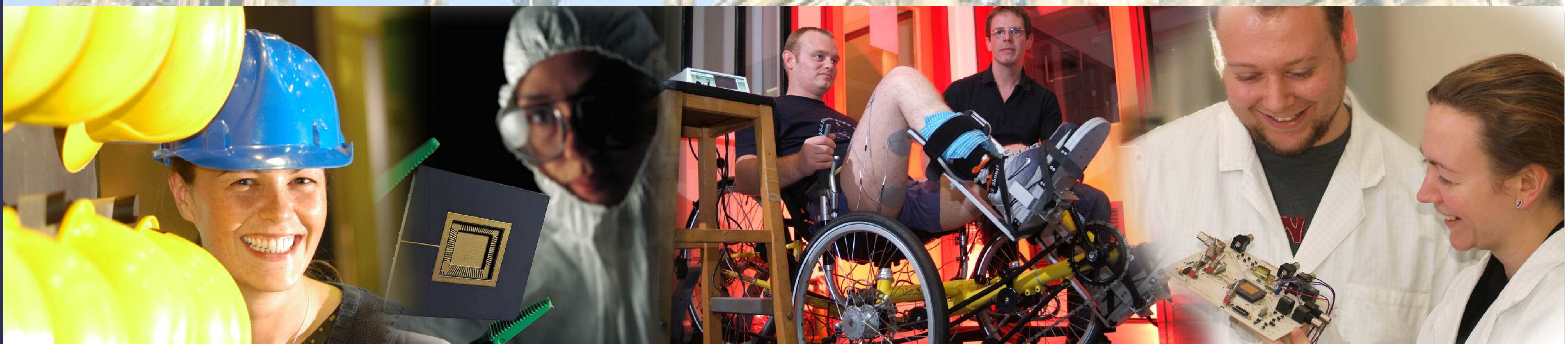
Developing Integrated Optical Frequency Convertors and Generators on a Semiconductor Chip



David C. Hutchings, Usman Younis

and Barry M. Holmes

Department of Electronics and Electrical Engineering, University of Glasgow

Sean J. Wagner, Amr S. Helmy

and J. Stewart Aitchison

Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto

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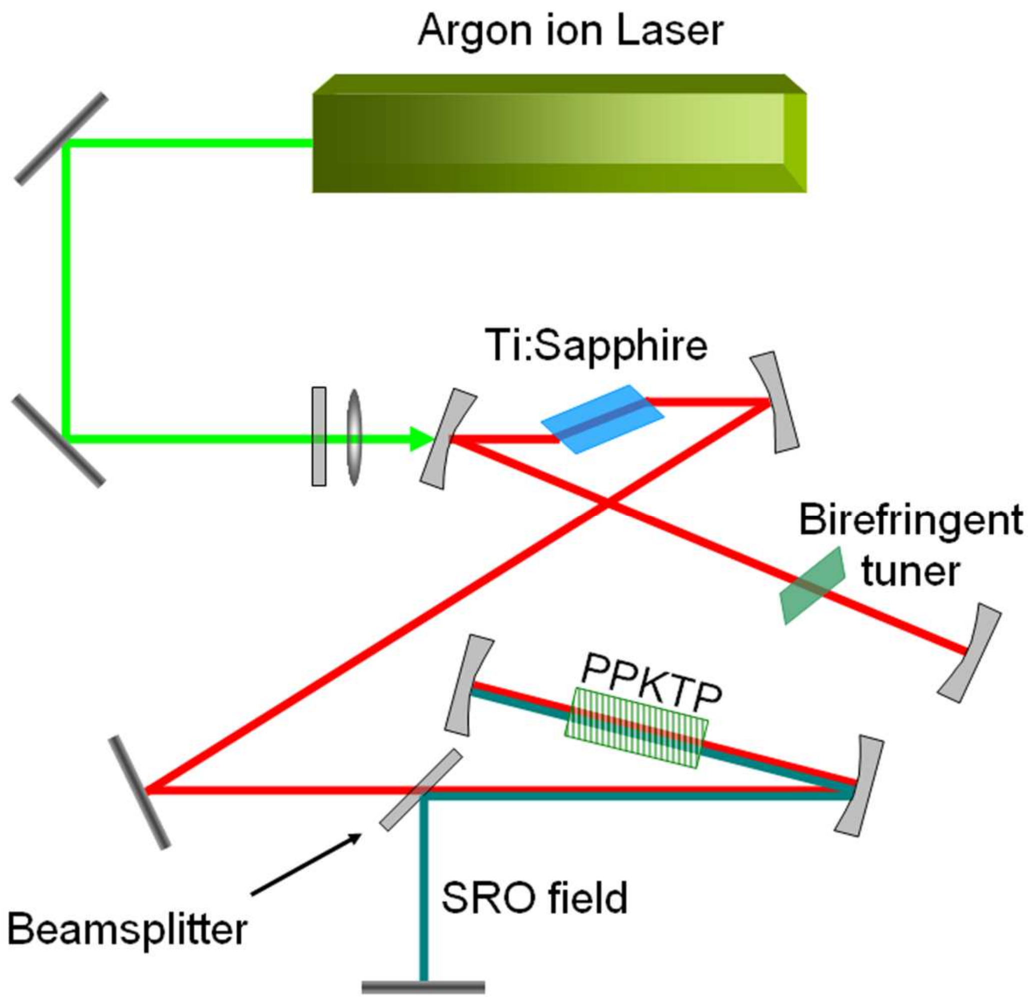
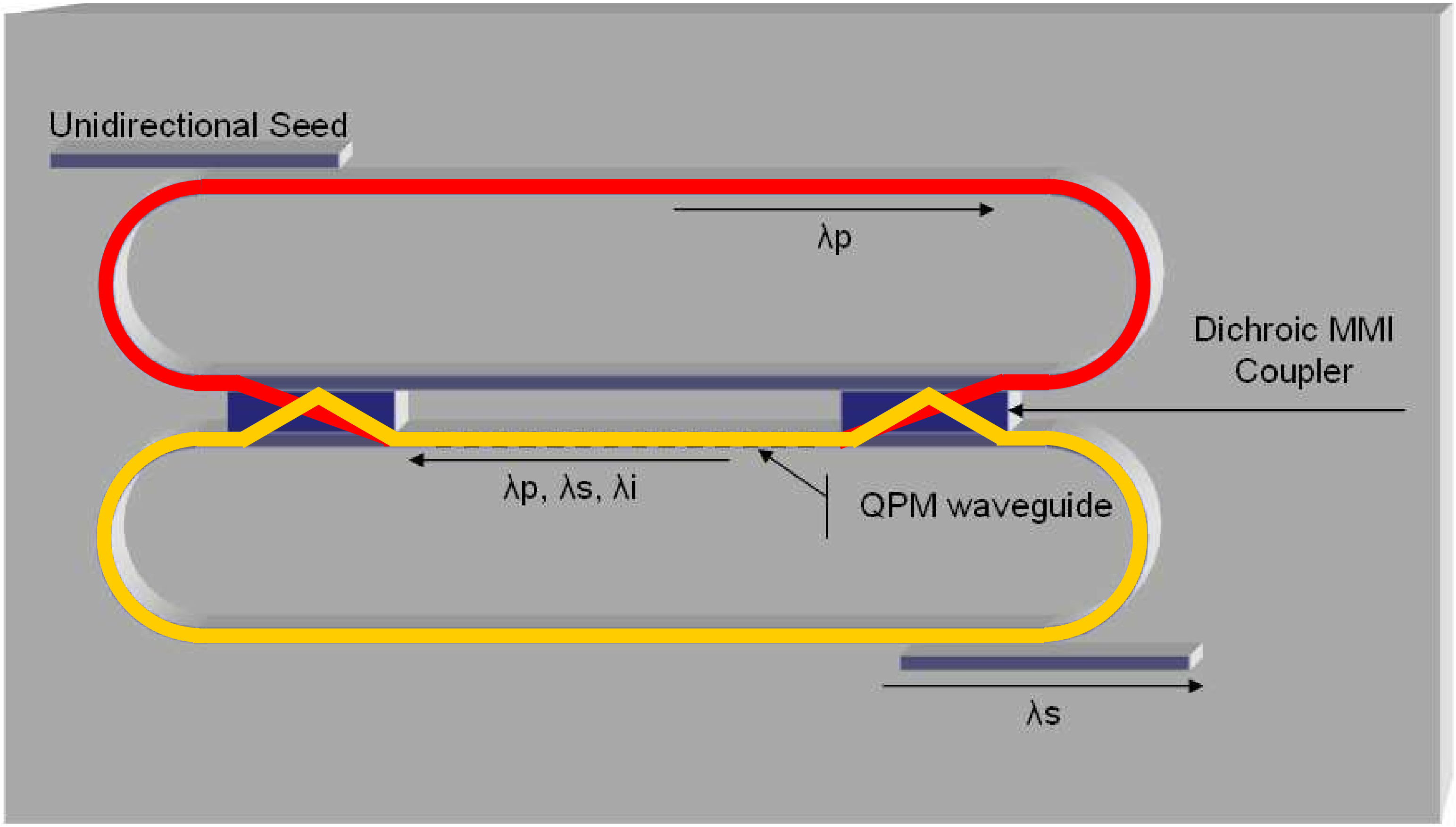
Bulk intra-cavity Optical Parametric Oscillator

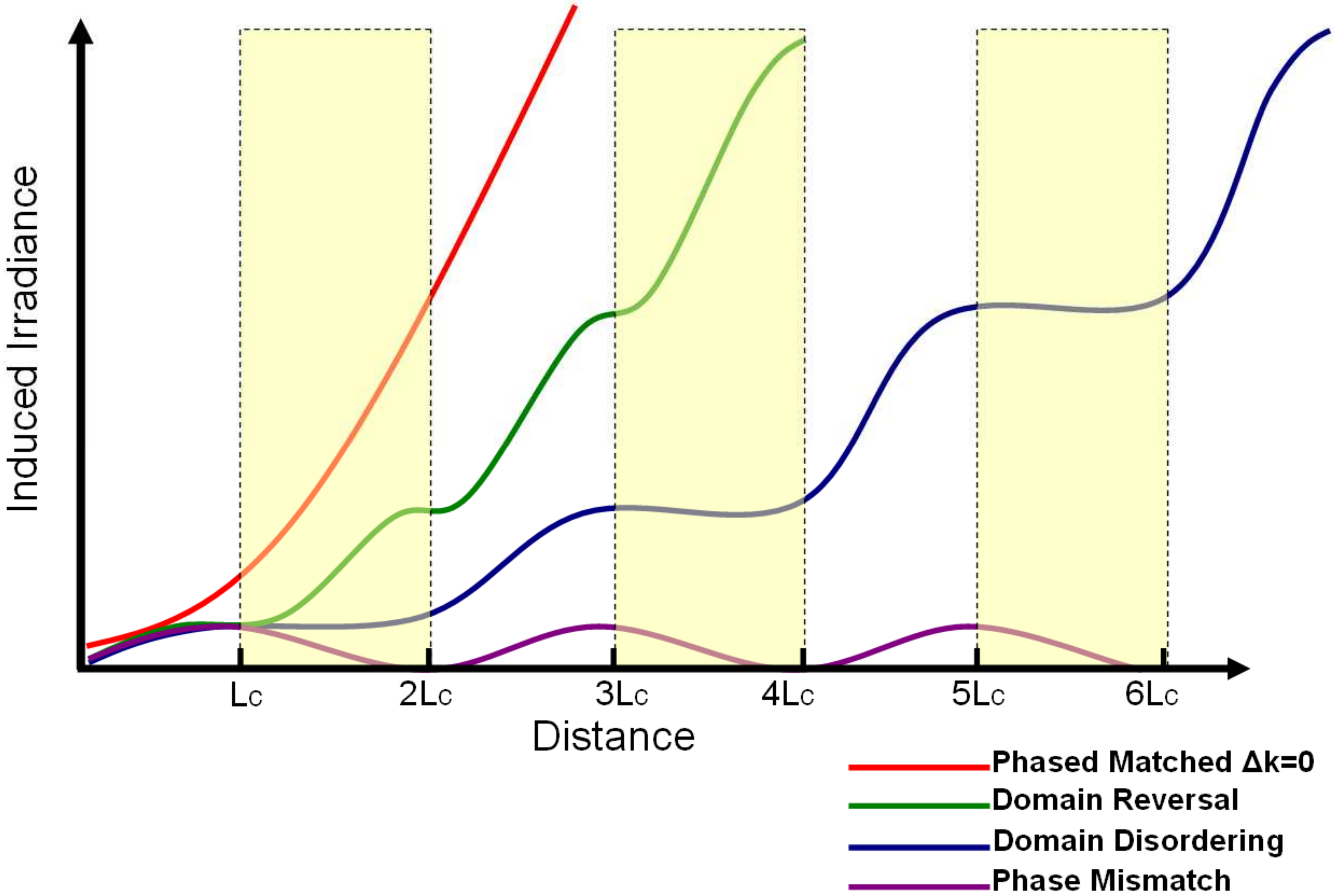


- e.g. pioneered by St. Andrews OPO Group and others
- now a commercial product, e.g. M Squared Lasers

Integrated Optical Parametric Oscillator

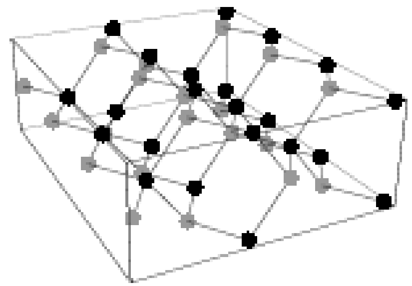


Quasi-Phase Matching



The generated wave must remain in phase with the nonlinear polarisation source to build up to a substantive level

$\chi^{(2)}$ in cubic semiconductors



- Common compound semiconductors in photonics have a zinc-blende (cubic) structure $\overline{4}3$m
- Introducing heterostructure, e.g. quantum well, breaks translational invariance in one direction
- For a $[001]$ grown heterostructure, z-direction is no longer equivalent to x, y breaking degeneracy: $\chi^{(2)}_{xyz}(\omega,\omega) \neq \chi^{(2)}_{zxy}(\omega,\omega)$

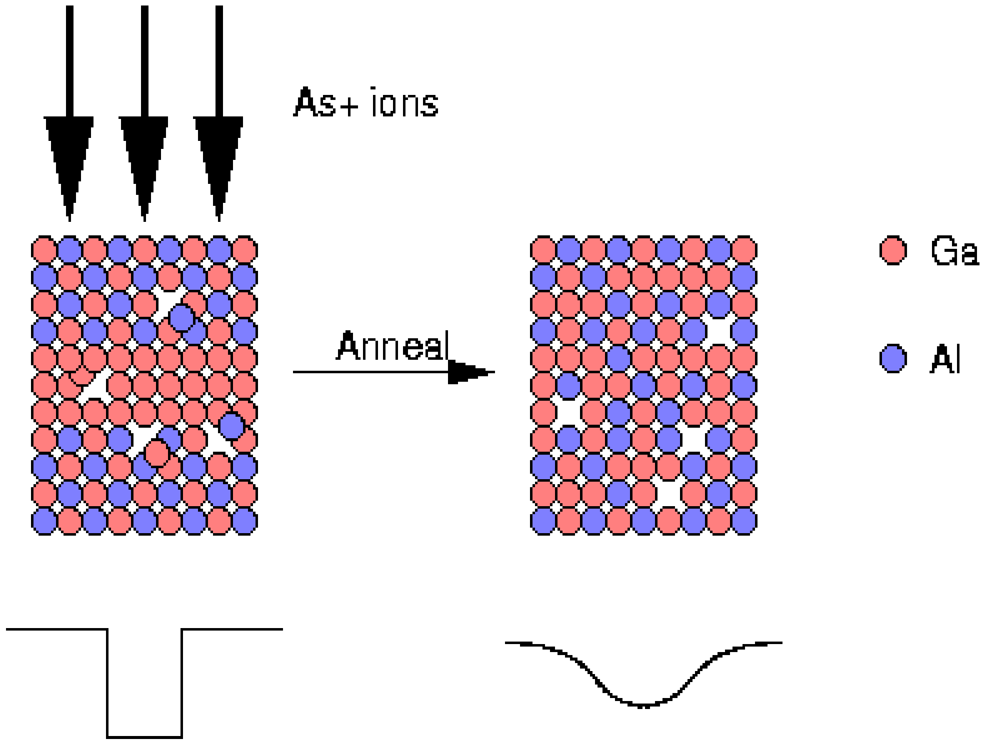
Quantum Well Intermixing

- Create point defects, e.g. by ion implantation

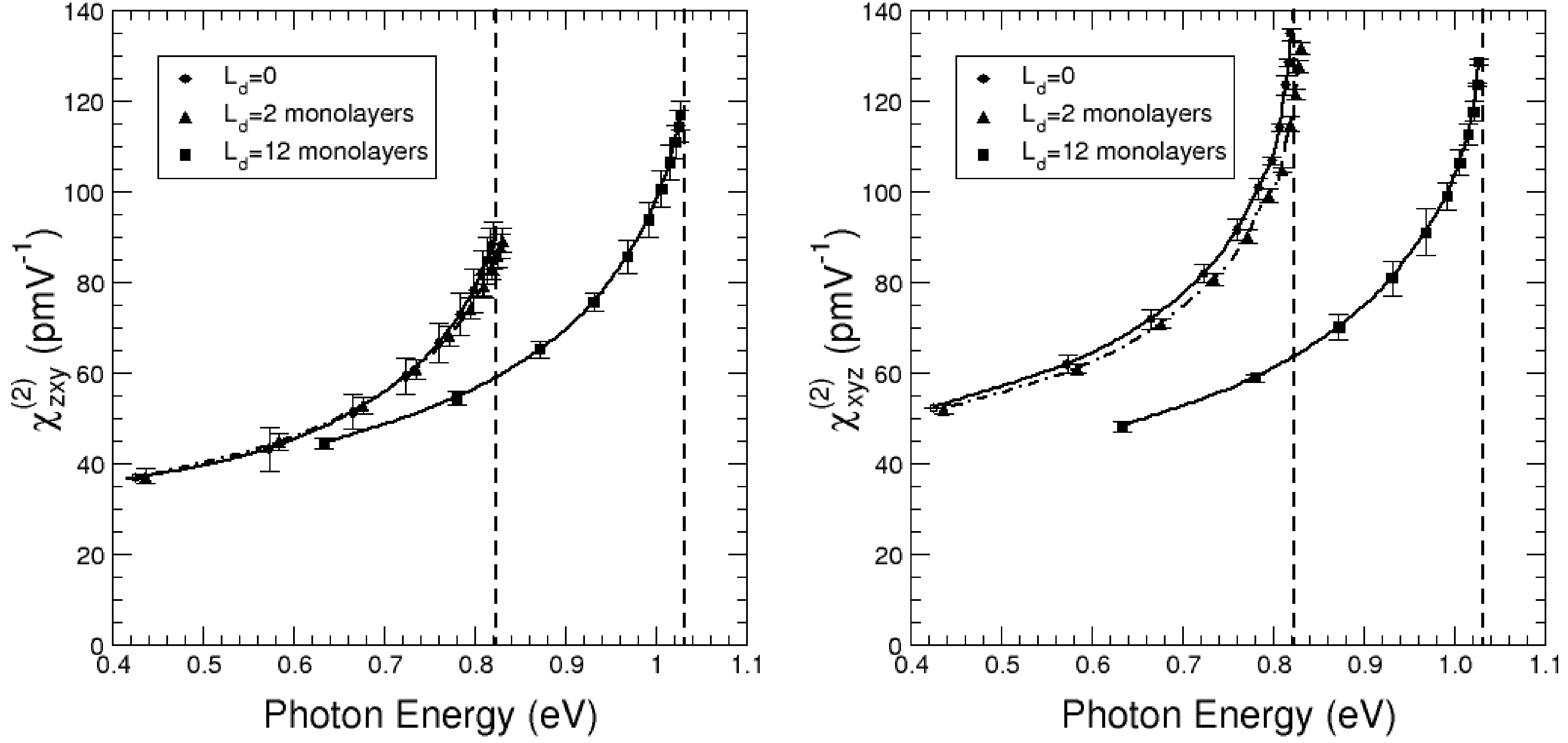
- Migration under Rapid Thermal Anneal causes diffusion of group III atoms

- Smallest bandgap is increased

- Resonance in optical properties blue-shifted
    - -linear for OE integration
    - -nonlinear for QPM

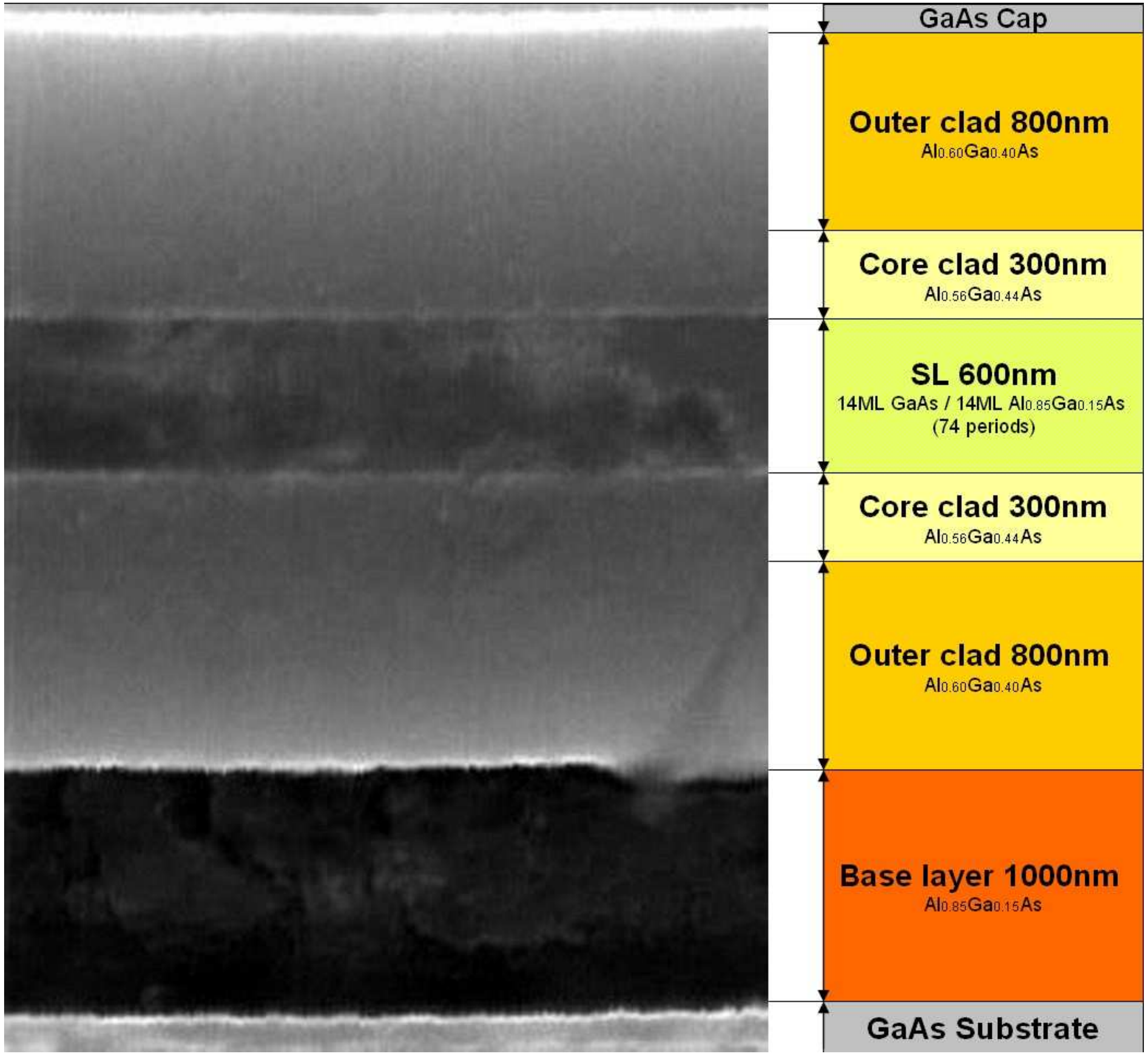


Calculated Modulation in Optical Nonlinearity



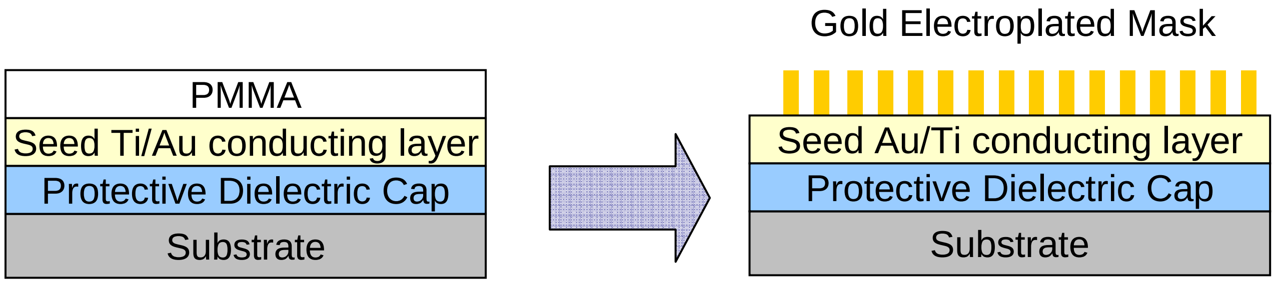
14:14 monolayer GaAs/AlAs as-grown and after intermixing

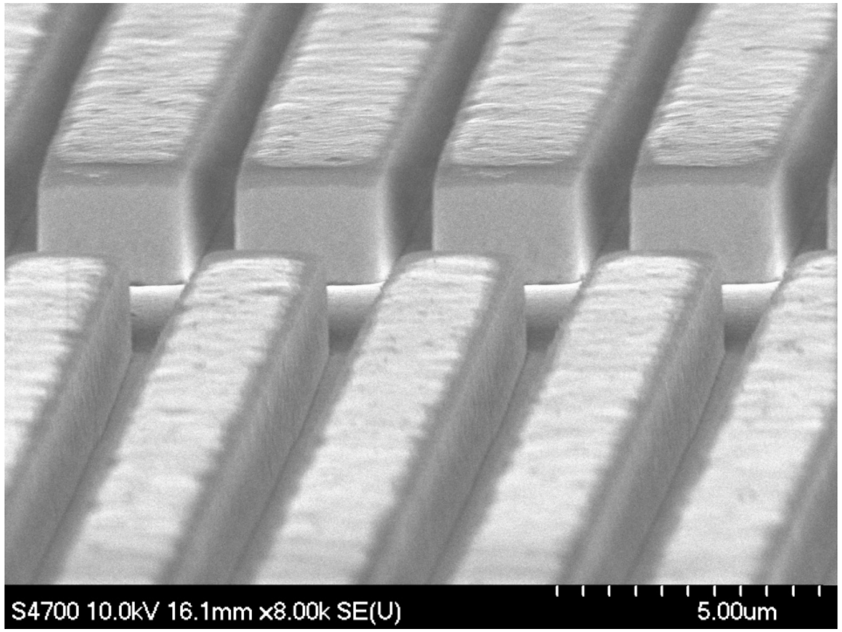
Intrinsic GaAs/AlGaAs wafer structure

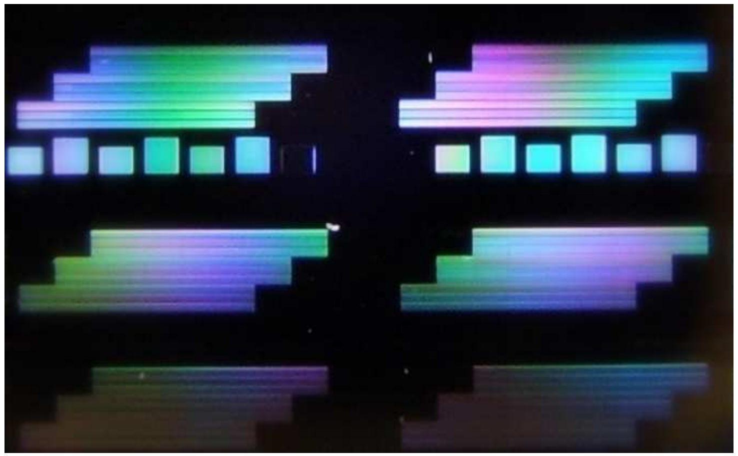


Periodic Gold Mask

- 3.5-4.5 µm period gratings written by e-beam in bi-layer PMMA
- Au grating grown to ~2 µm thickness by electroplating

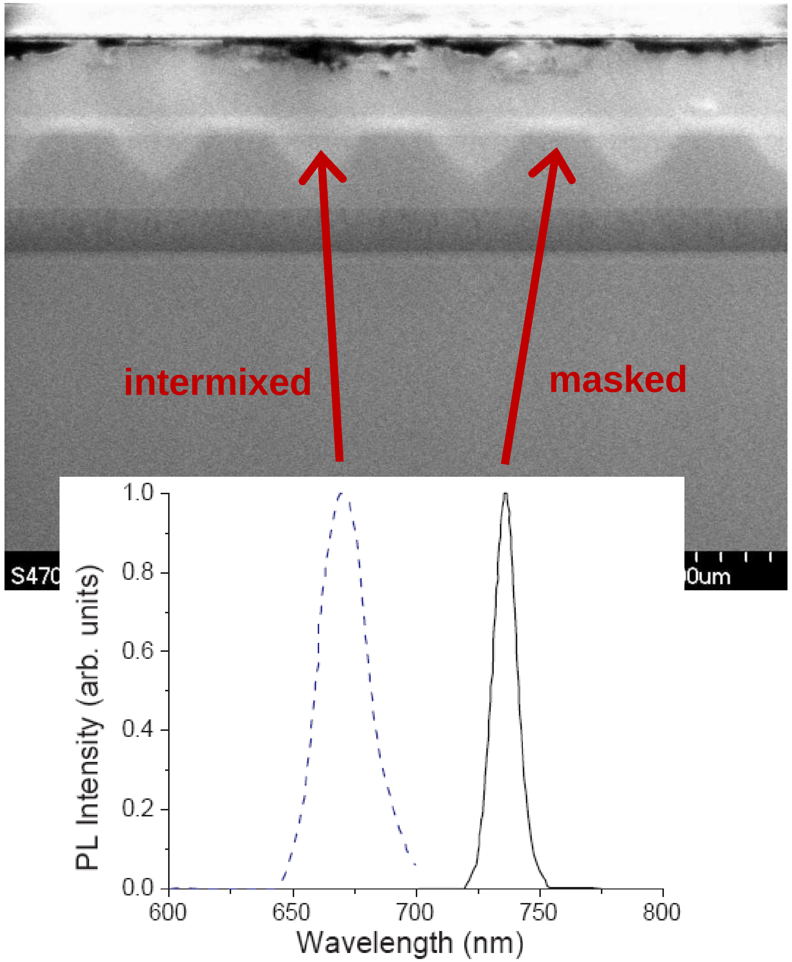


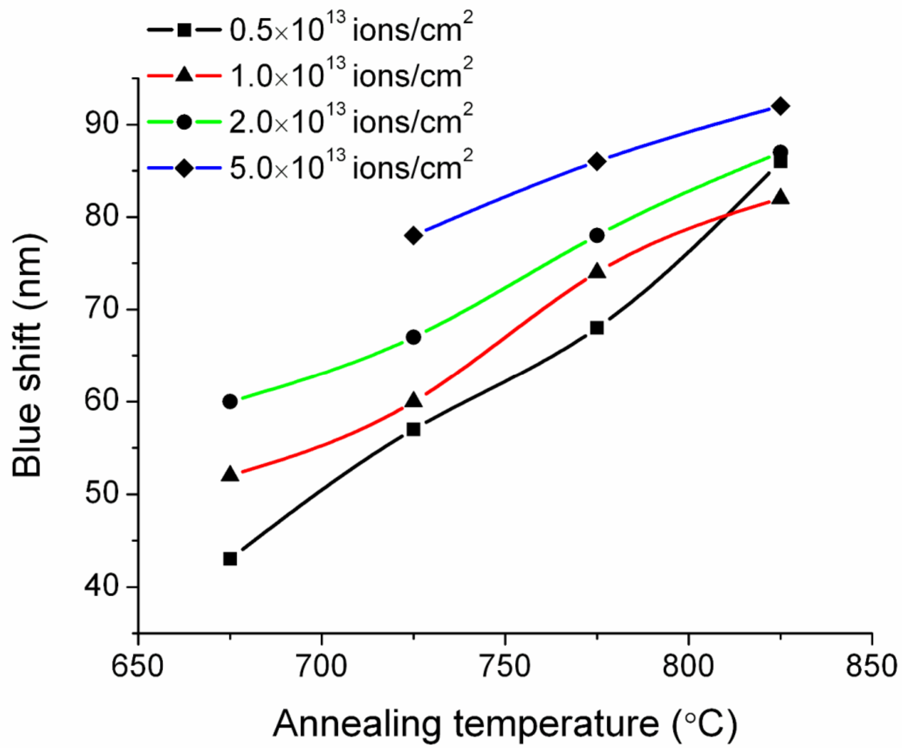




Ion Implantation Induced Intermixing

- 4 MeV As^{2+} ion implantation, typical dose 2×10^{13} ions/cm^2
- Rapid Thermal Anneal, typically at 775°C for 60s
- Ridge waveguides, typically 3 µm wide, fabricated by RIE





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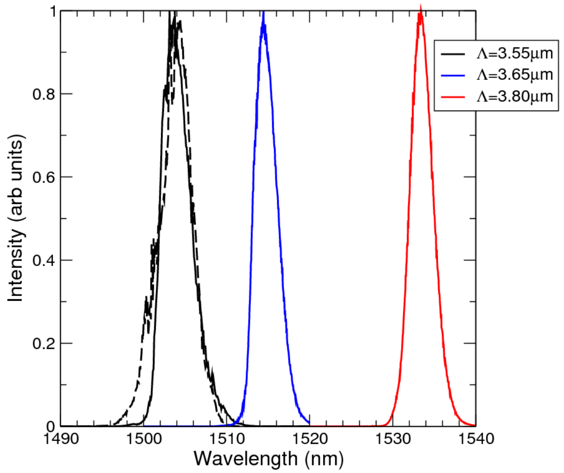
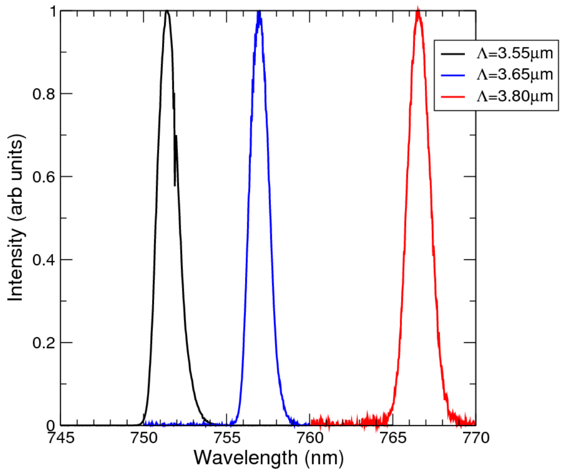
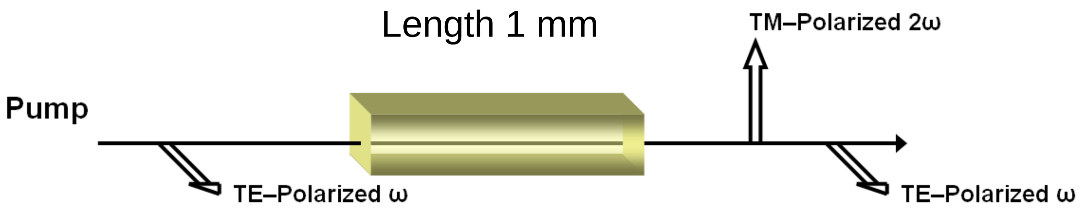
Pulsed (ps) type-I SHG

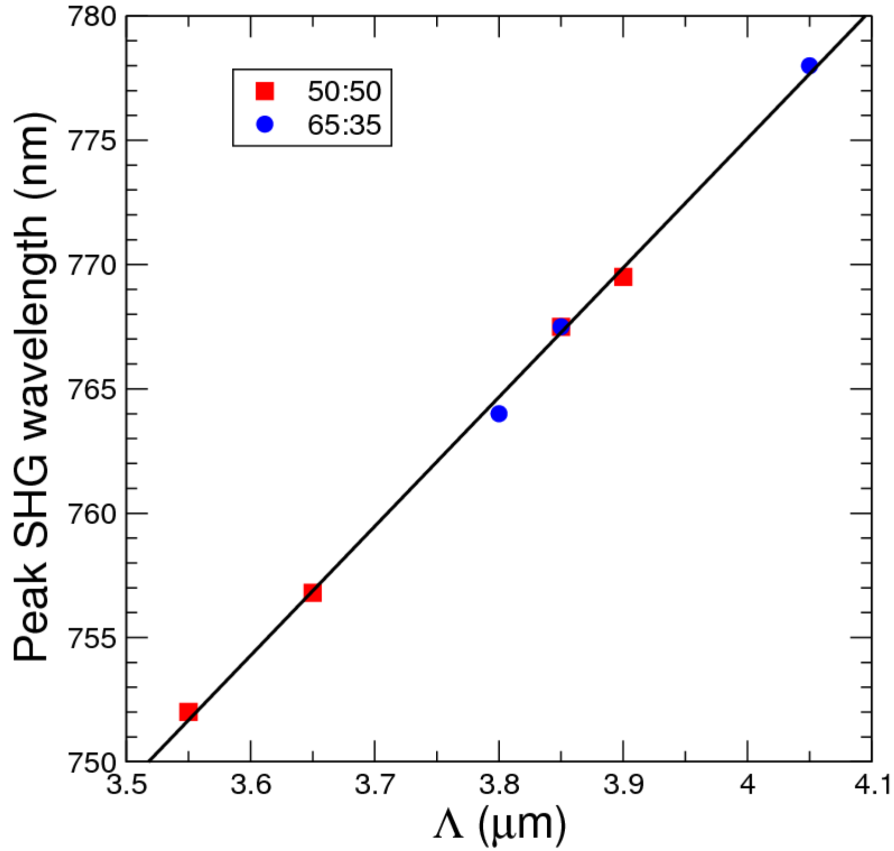
fundamental





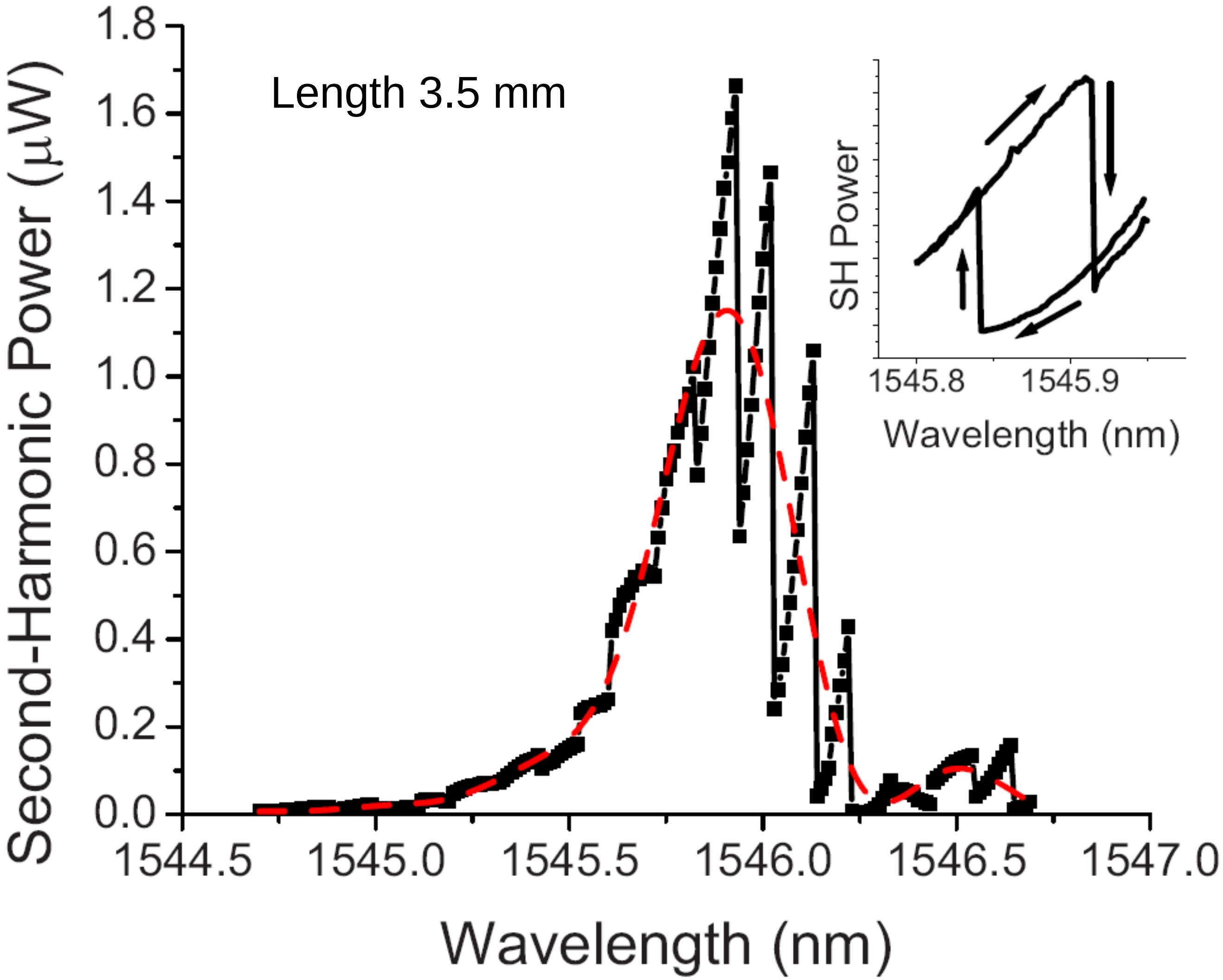
2nd harmonic





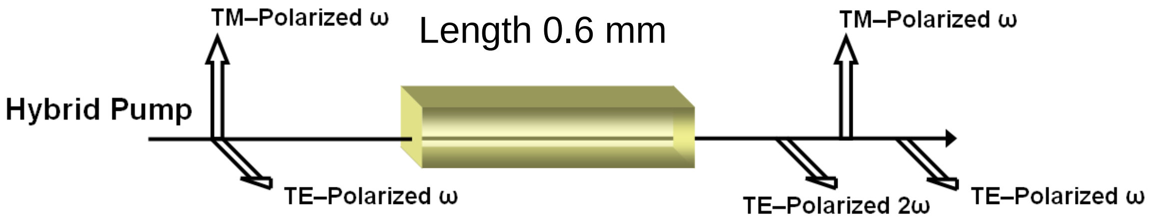
Wavelength vs grating period

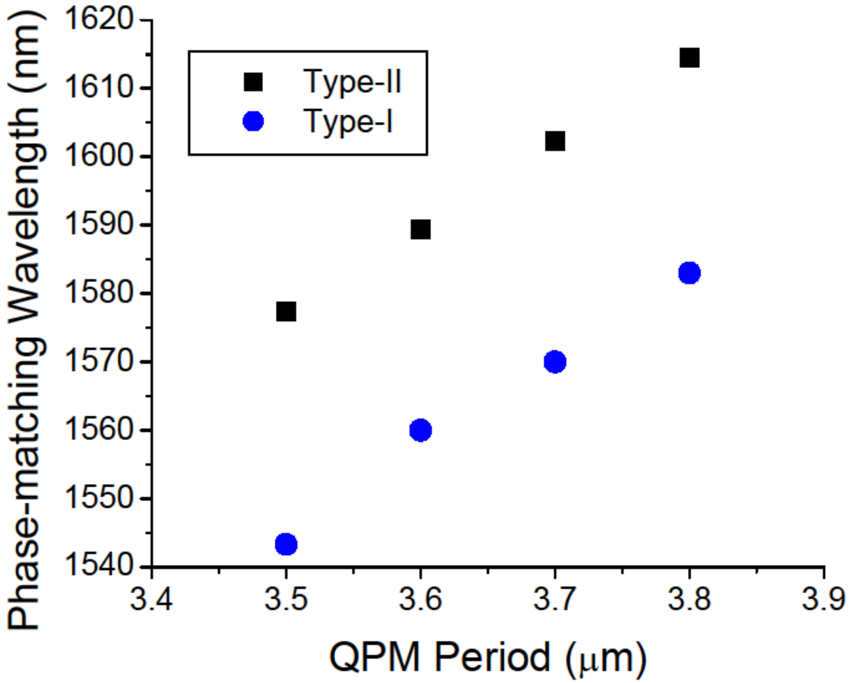
Continuous-wave type-I SHG

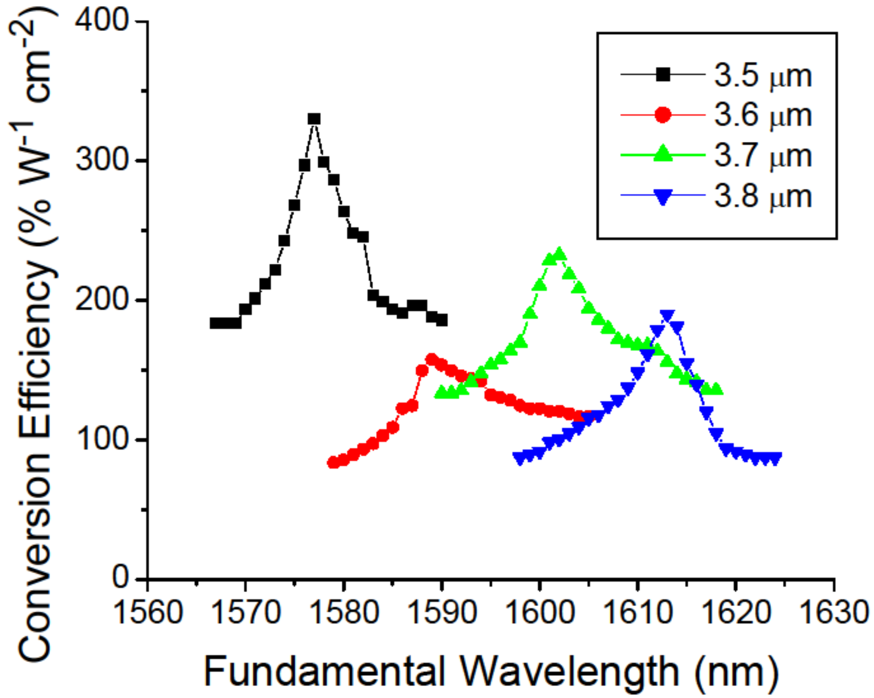


Applied Physics Letters **94**, 151107 (2009).

Pulsed (ps) type-II SHG



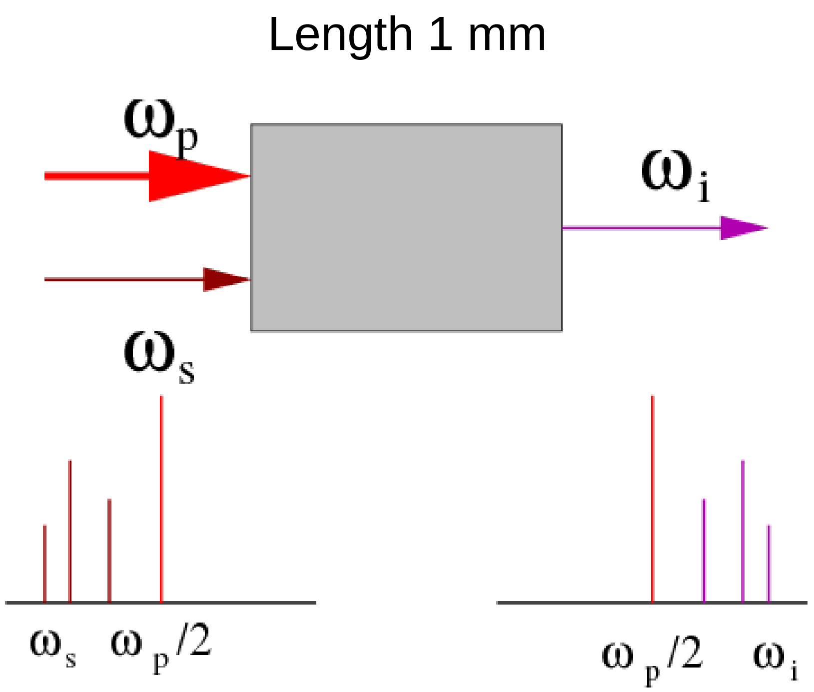


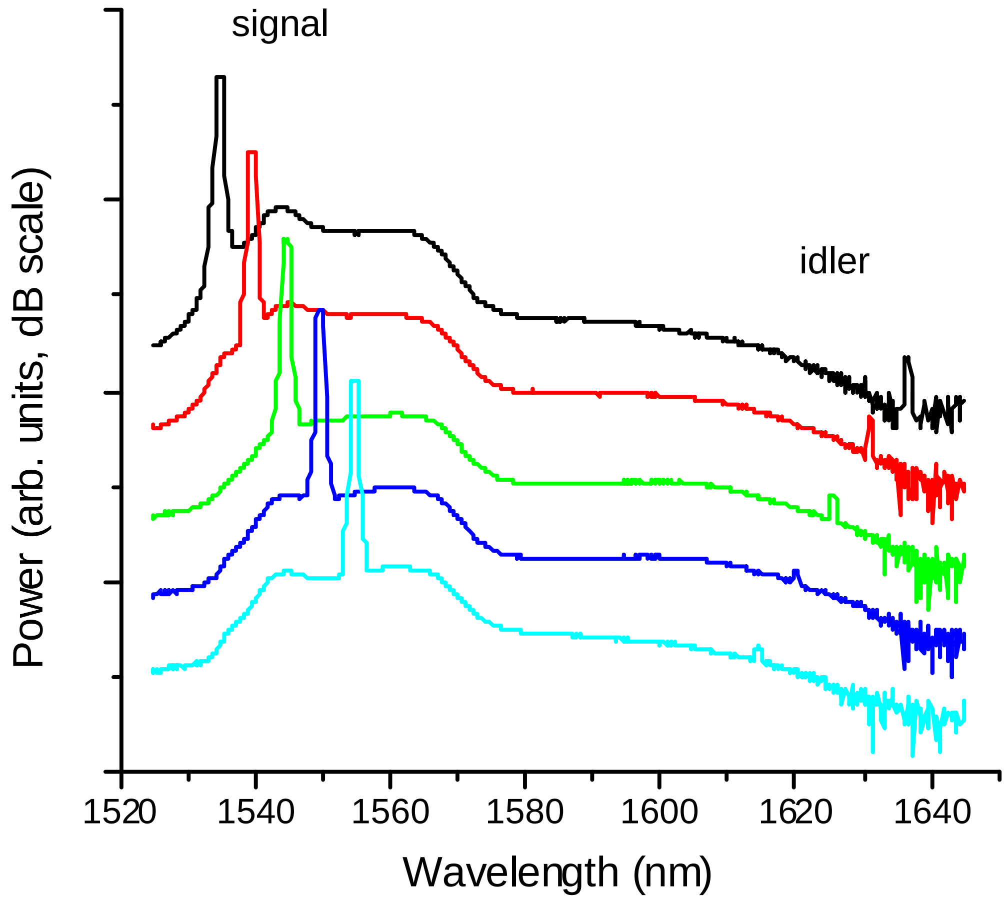


- Type-II orientation has short-λ in TE-polarised mode
- corresponds to conventional laser emission

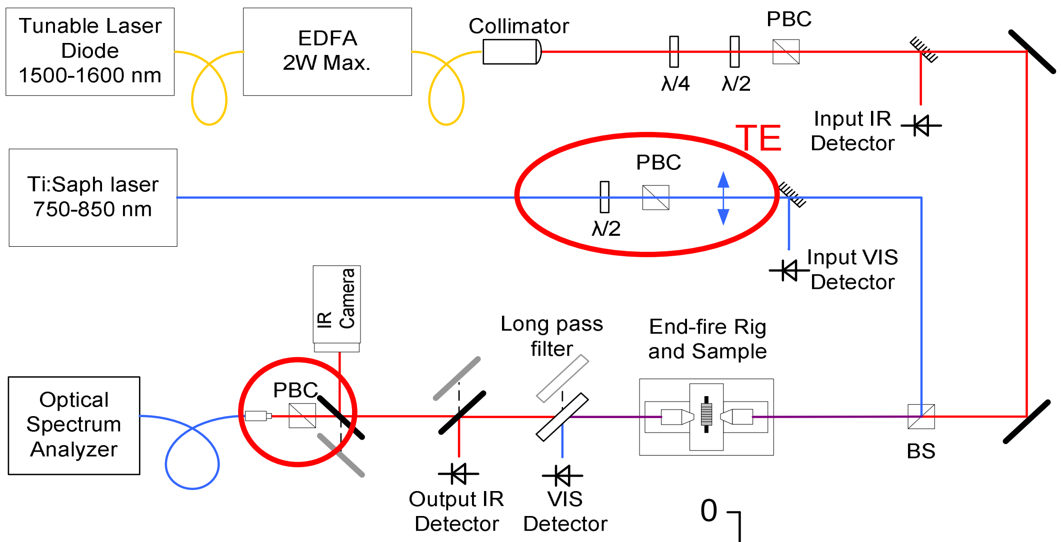
Difference Frequency Generation (type-I)

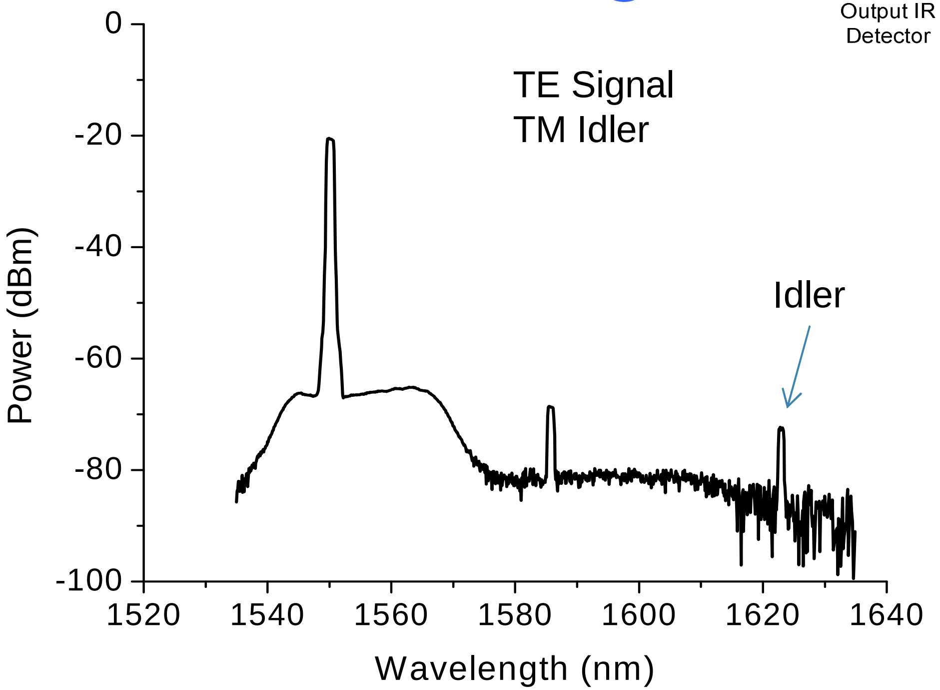
- Continuous-wave, Ti:sapphire λ=791.7 nm as TM pump
- cw, tunable C-band laser, amplified with EDFA as TE signal
- idler (up to 9 nW) generated in L- & U-bands

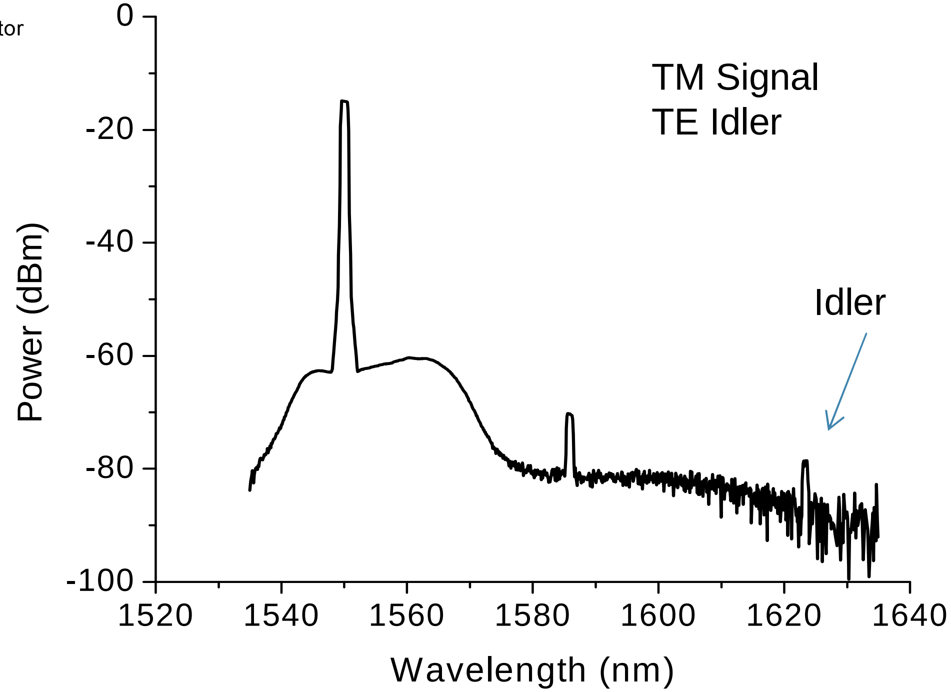




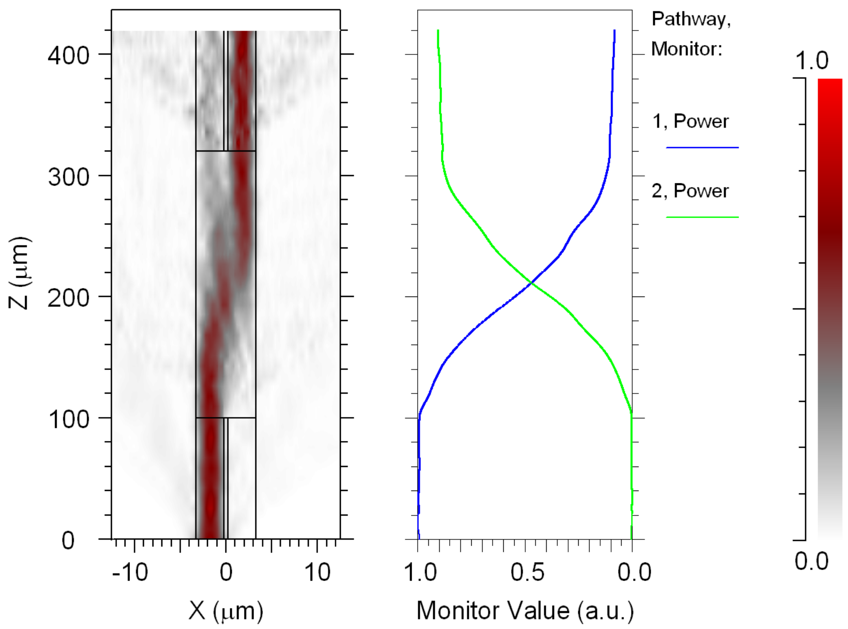
Difference Frequency Generation (type-II)

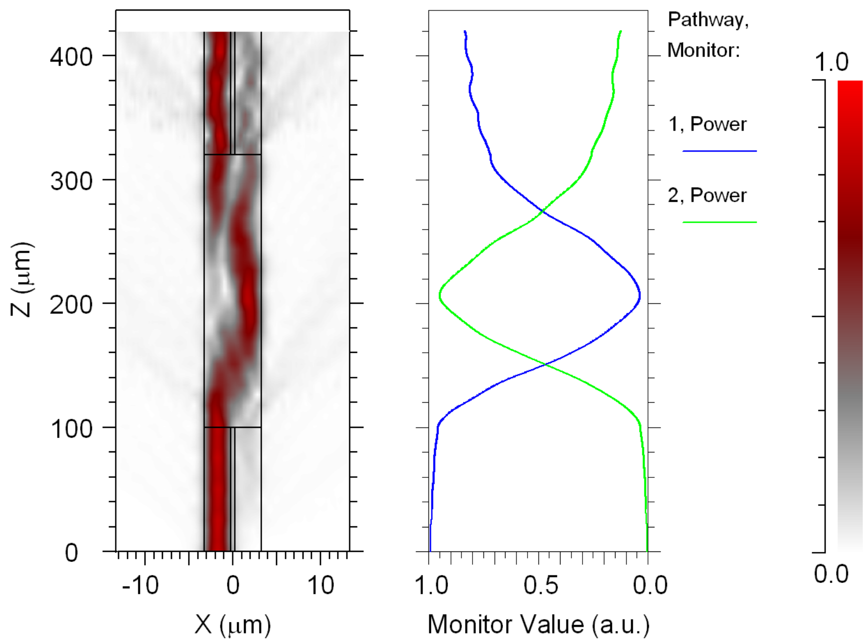






MMI Dichroic Coupler Design





Cross operation of the coupler near band gap

780 nm

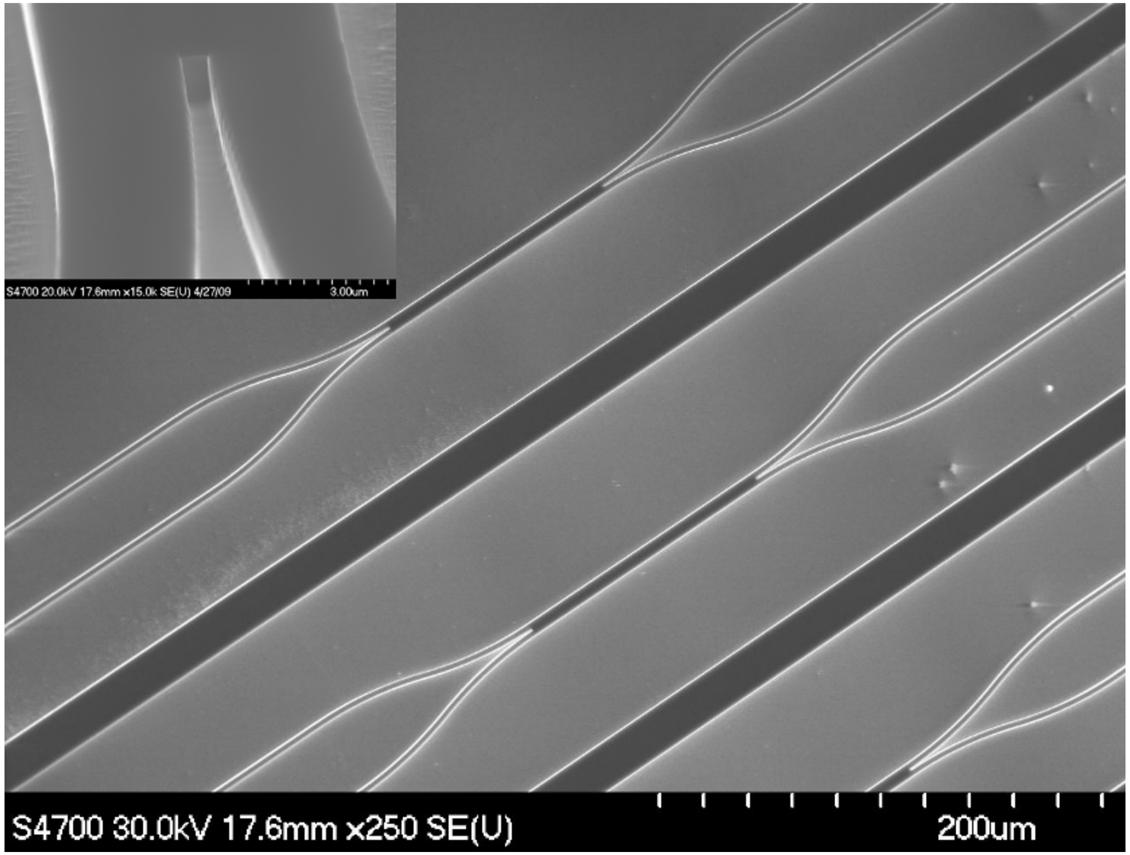
Bar operation near half band gap

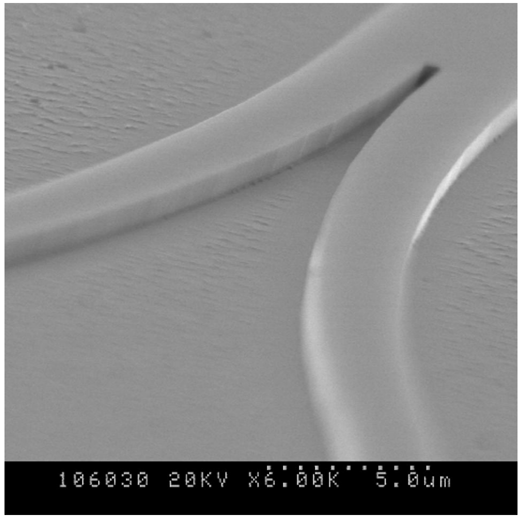
1550 nm

MMI Dichroic Coupler Fabrication

HSQ Patterning

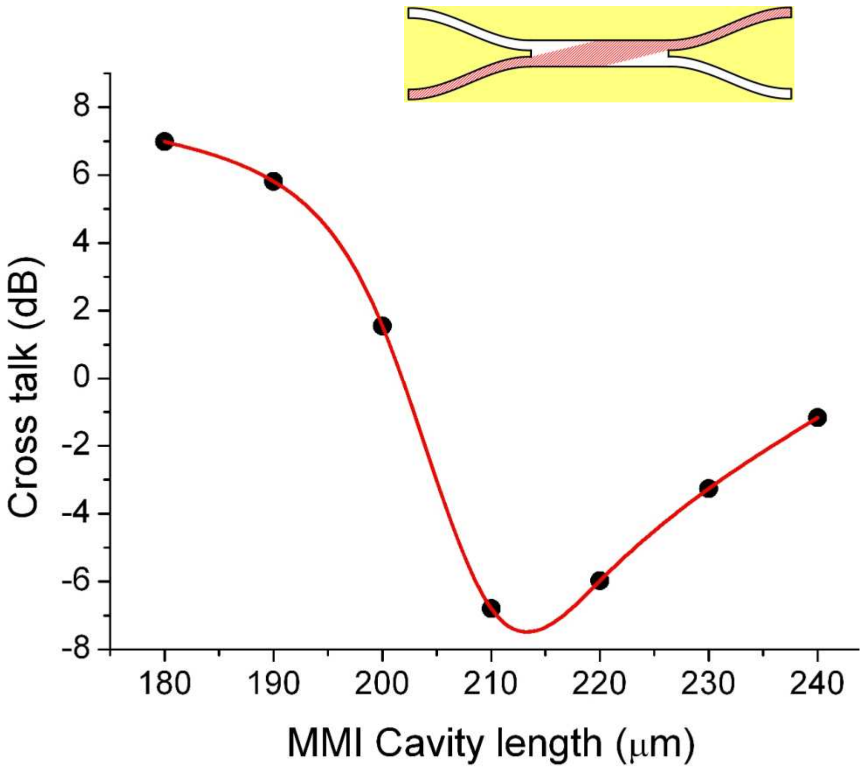
Real Time *in-situ*
$SiCl_4$ RIE with
laser interferometry.
Etch Depth tolerance
in ±20 nm



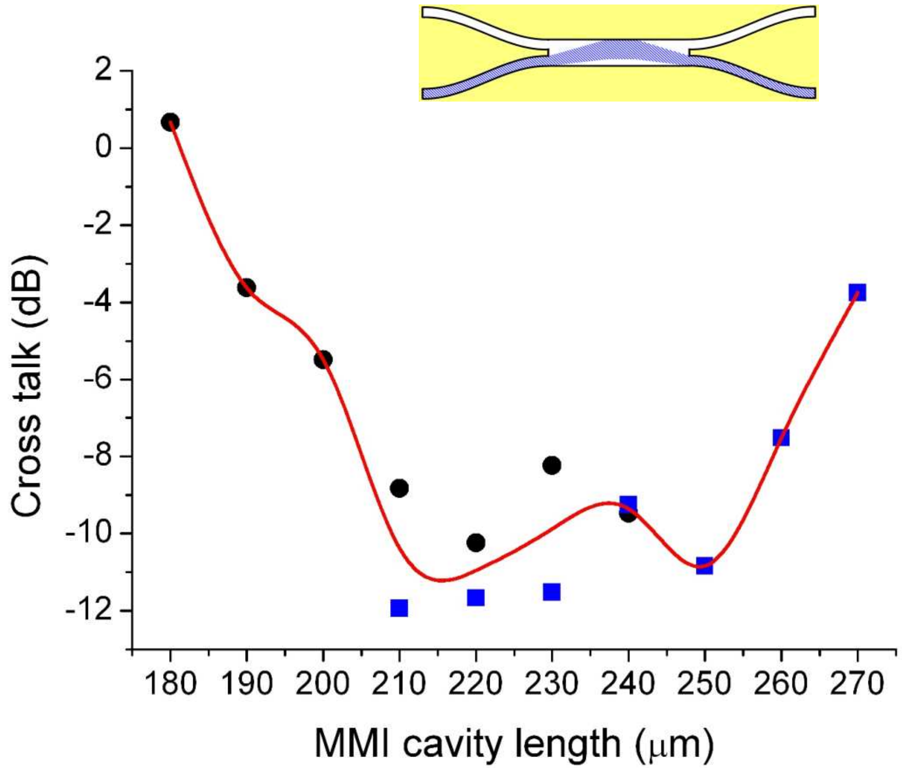


MMI Dichroic Coupler Characterisation

"Bar" cross-talk near band-edge
780 nm



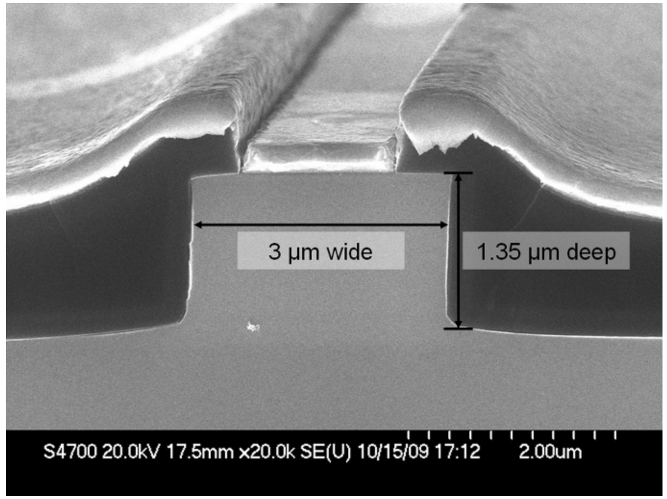
"Cross" cross-talk near half-band-edge
1550 nm



Optimum coupler length ~220 μm

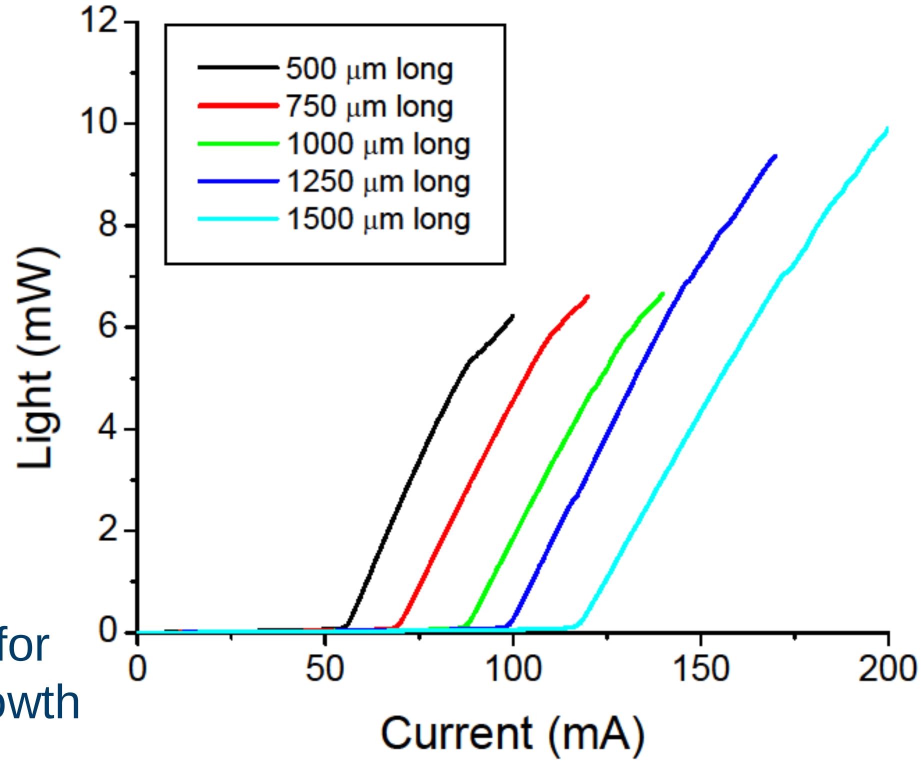
Lasing in GaAs/AlGaAs superlattice

- 100 nm of GaAs/AlGaAs superlattice grown in centre of waveguide by MOVPE
  - within *p-i-n* structure
  - as-grown wafer displays electro-luminescence at 772 nm
  - annealed under same conditions for QWI



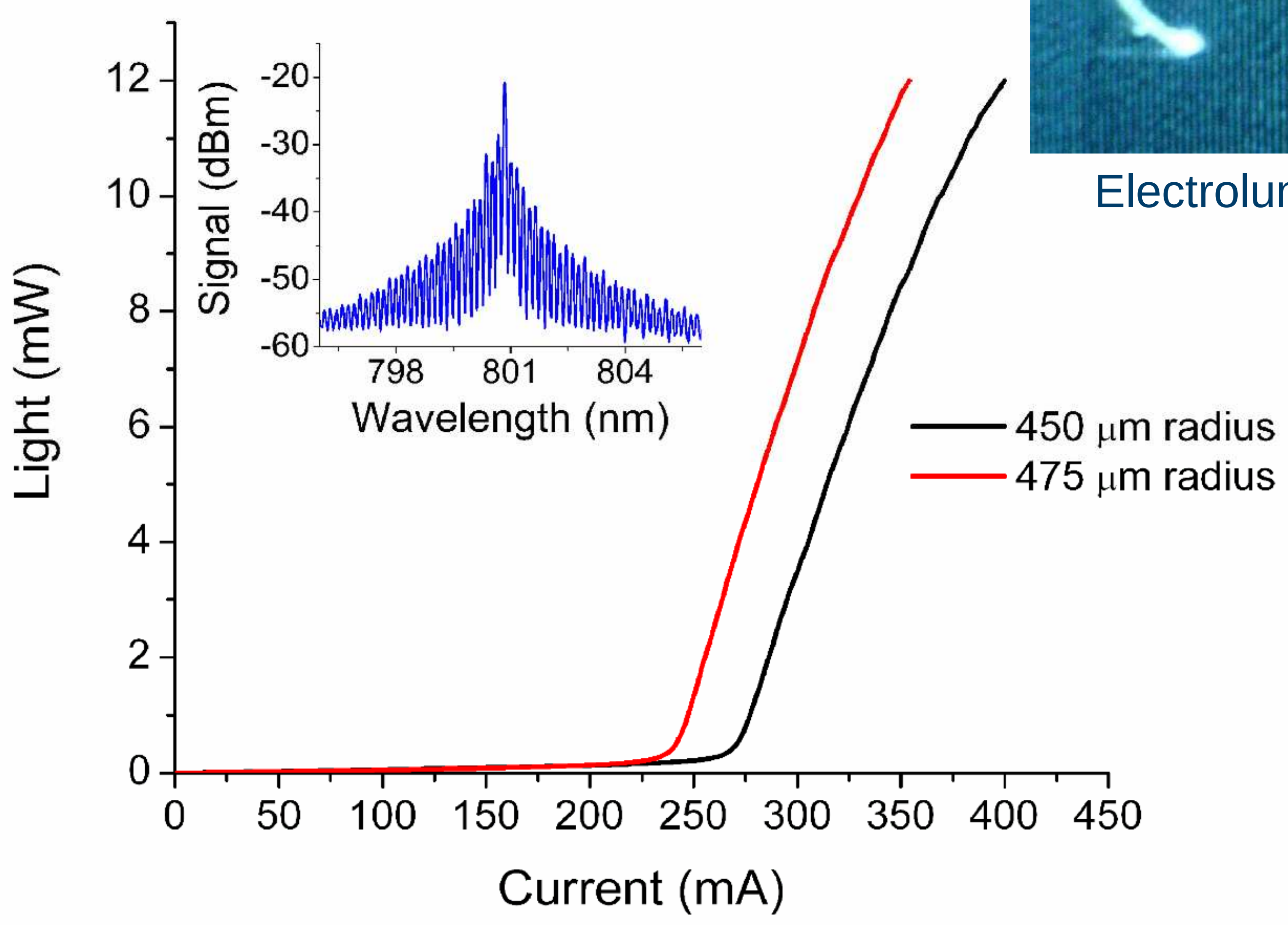
- Fabry-Perot ridge waveguide lasers fabricated by RIE

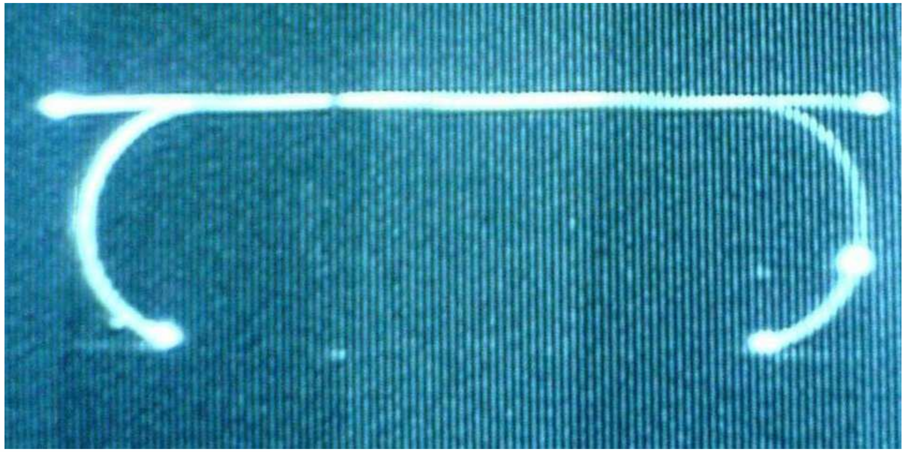
- Lasing around 801 nm



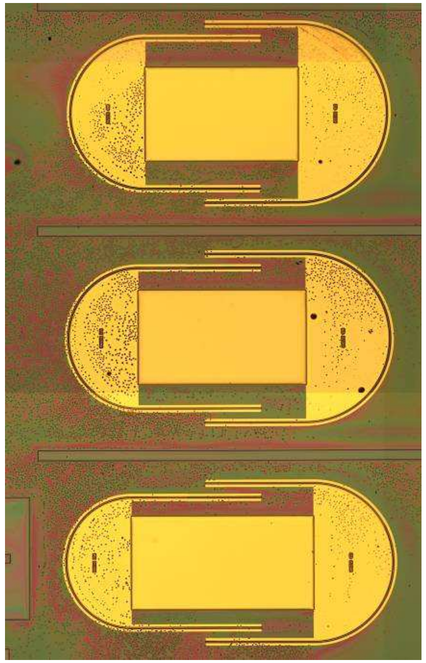
A special thanks to John Roberts @Sheffield for perseverance in the development of wafer growth

Half-Ring Lasers





Electroluminesence in ring & coupler



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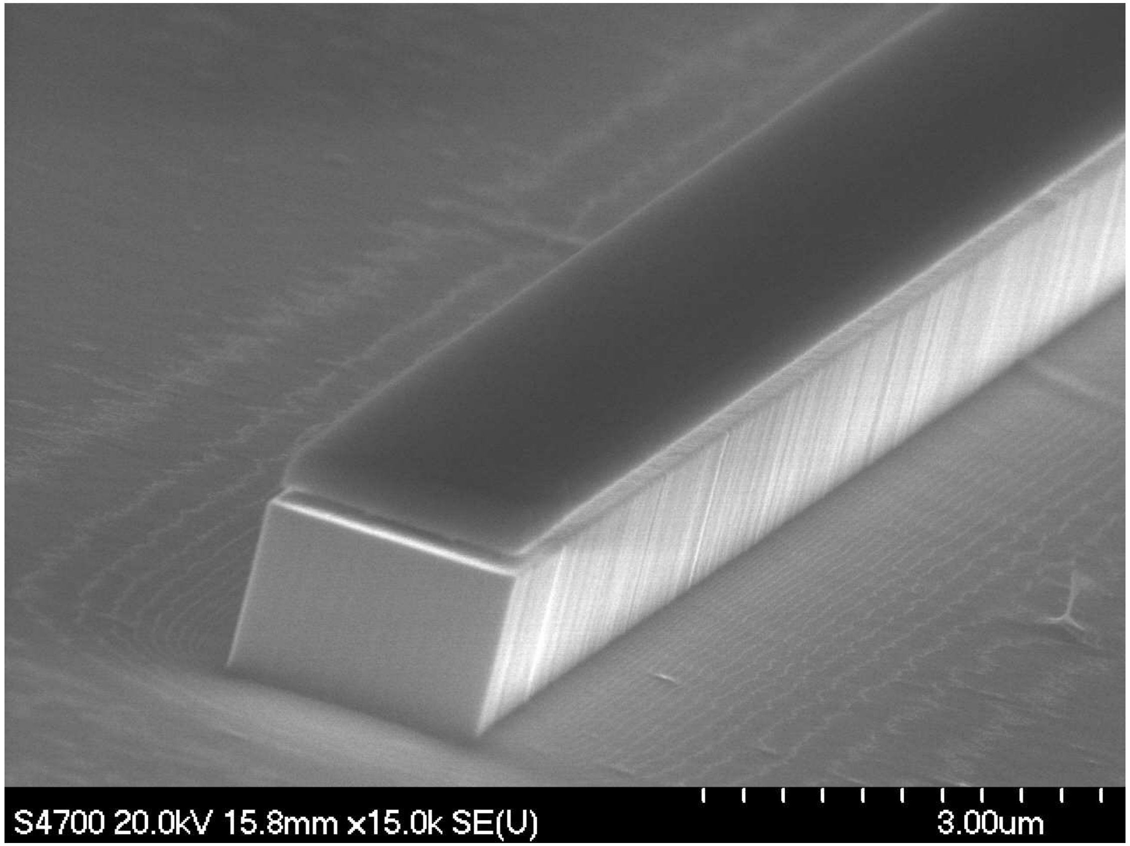
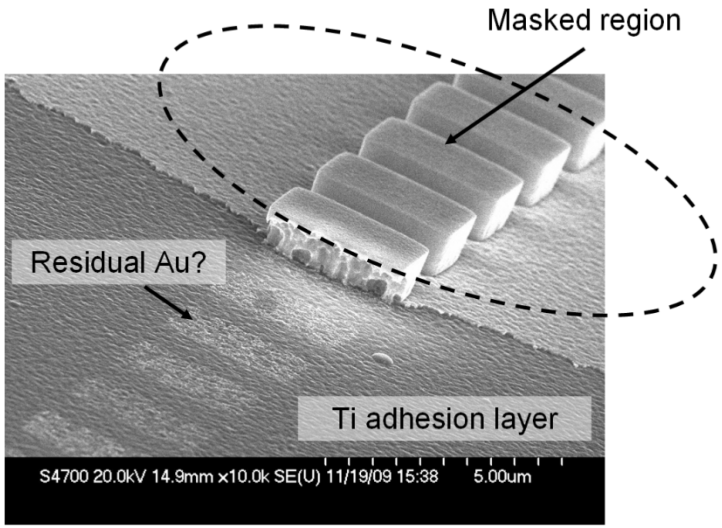
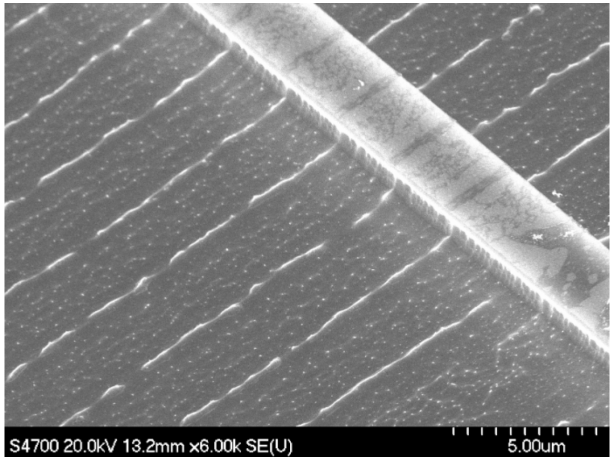
Improving waveguide fabrication



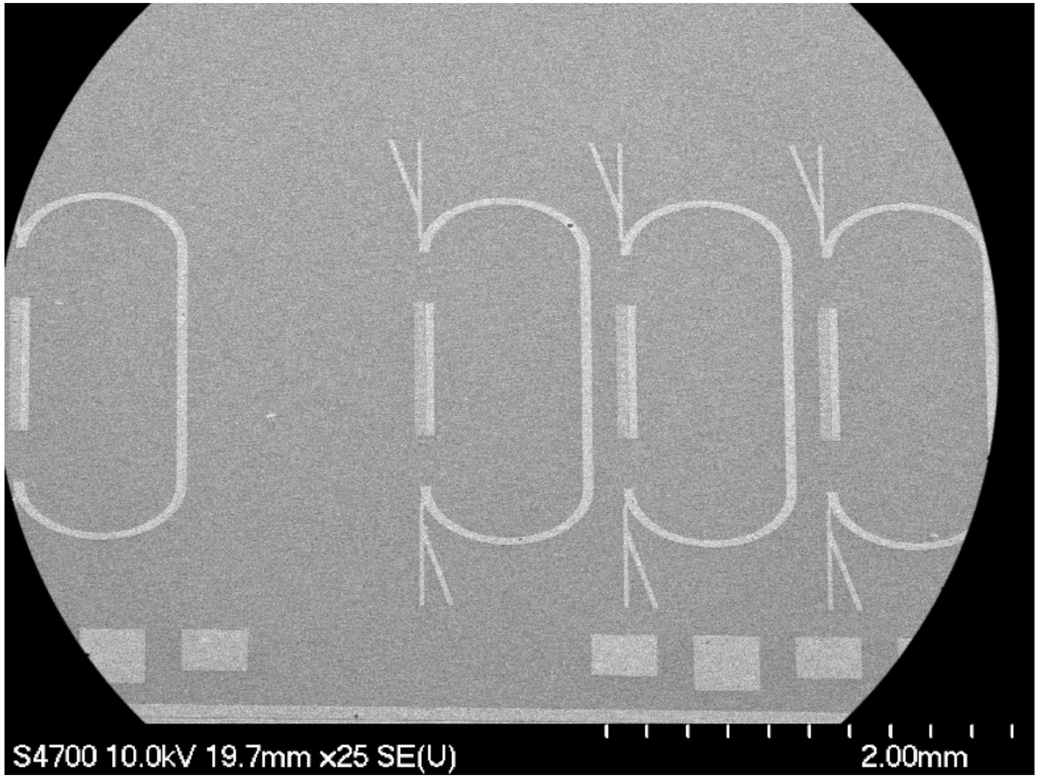


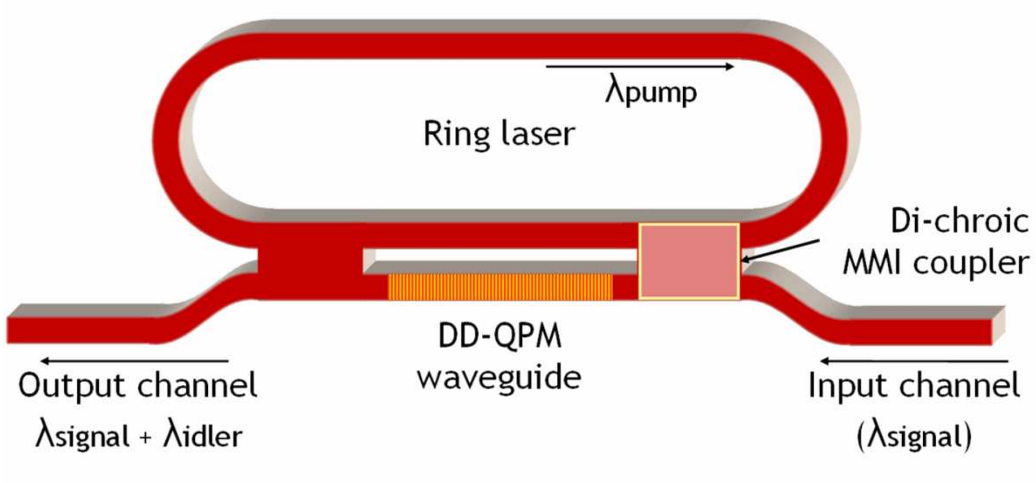


- SEM image of etched waveguide
- key step is removal of Au/Ti layers prior to waveguide fabrication

  (previous incomplete removal shown on the right)
- top superlattice layers visible as concentric rings

Ion Implantation Au Mask for Integrated DFG





Conclusions

- **Developed fabrication techniques for QPM waveguides**
- **Demonstrated frequency conversion in superlattice semiconductor waveguides**
  - **- Pulsed and cw type-I SHG**
  - **- Pulsed type-II SHG**
  - **- Difference Frequency Generation (WDM channel shift)**
- **Demonstrated MMI dichroic couplers**
- **Demonstrated lasing at pump wavelengths**
- **Individual elements in place for self-pumped optical frequency conversion and generation**
  - **- Self-pumped DFG**
  - **- Self-pumped Parametric Amplication & OPO**