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Photonic integrated Circuits

--Lianping Hou

University of Glasgow

Outline

- From EIC to PIC
- PIC- why
- InP PIC evolution and photonic “Moore’s law”
- InP PIC integrated techniques
- Silicon photonics-what and why
- PIC future-with CMOS process

Attachments:

1. Introduction of JWNC
2. PIC mask and fabrication processes
3. Fabrication process of the 1.55 μm InGaAsP/InP DFB laser

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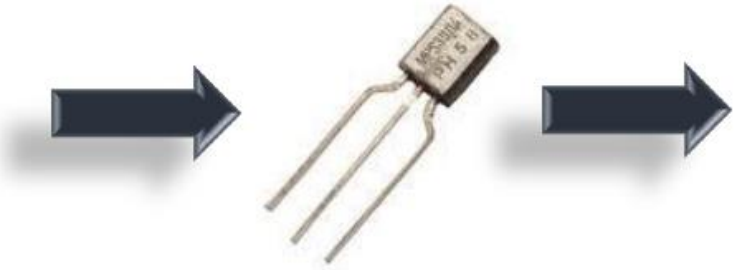
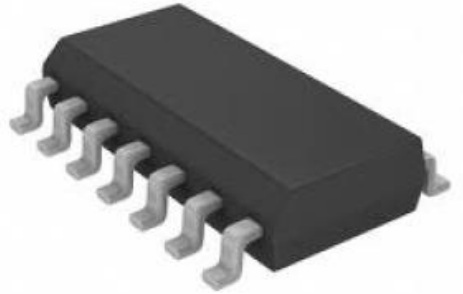
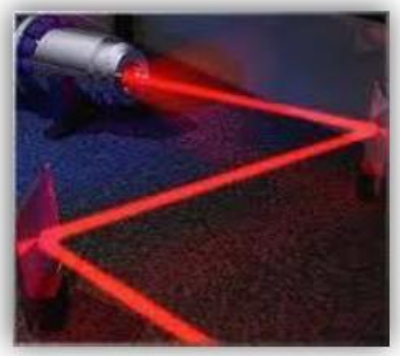
Photonic Integrated Circuits are the next logical step in the world of optics!

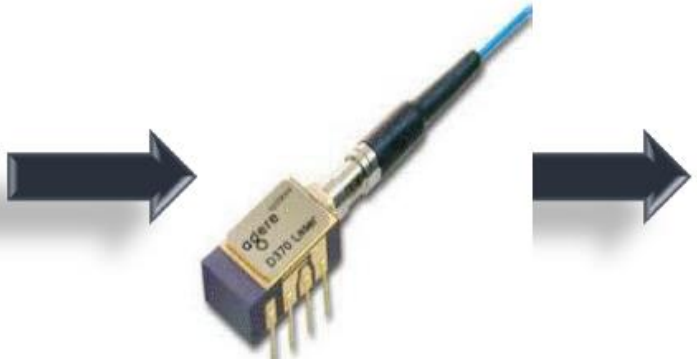
Electronics…

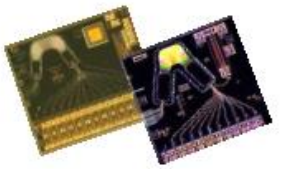




Optics…







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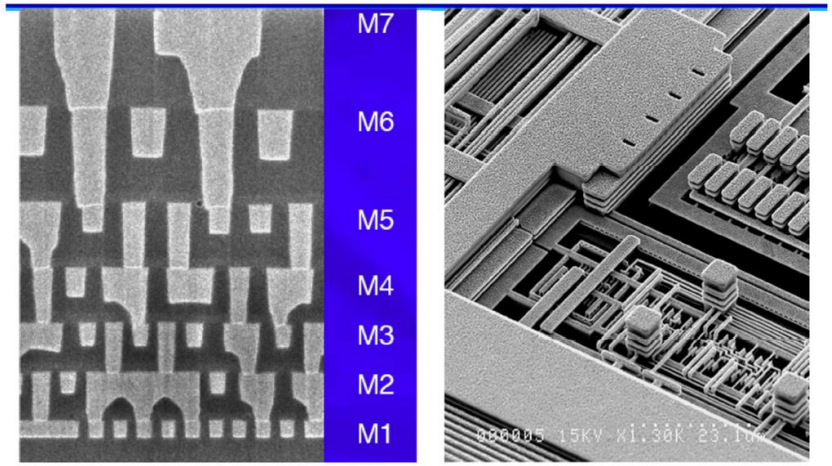
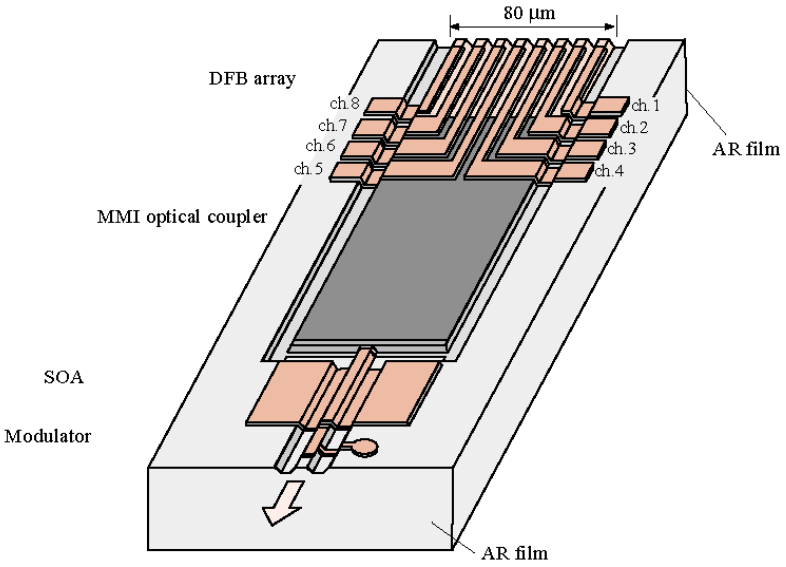
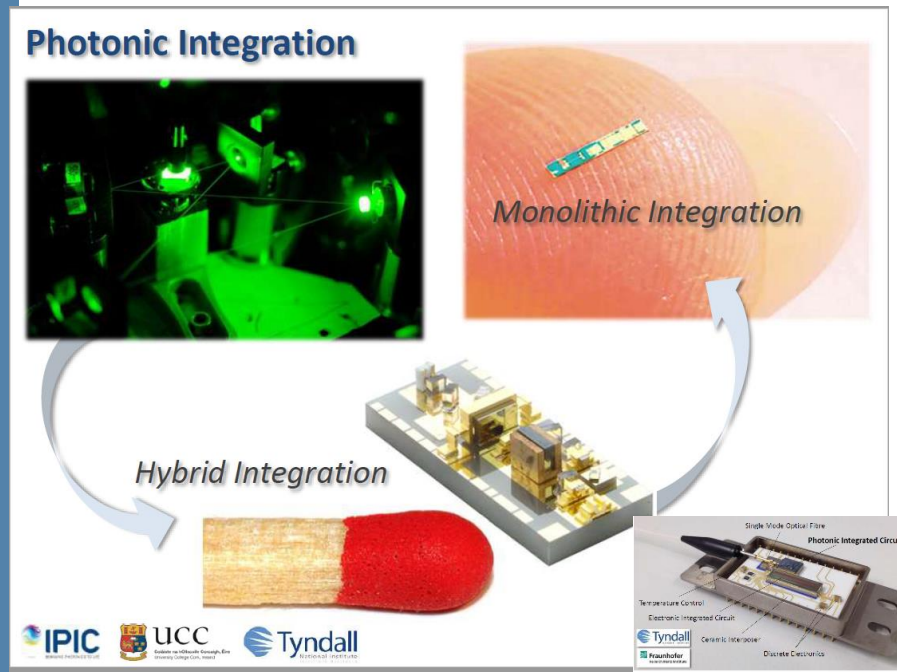
From electronic integrated circuits(EIC) to photonic integrated circuits(PIC)

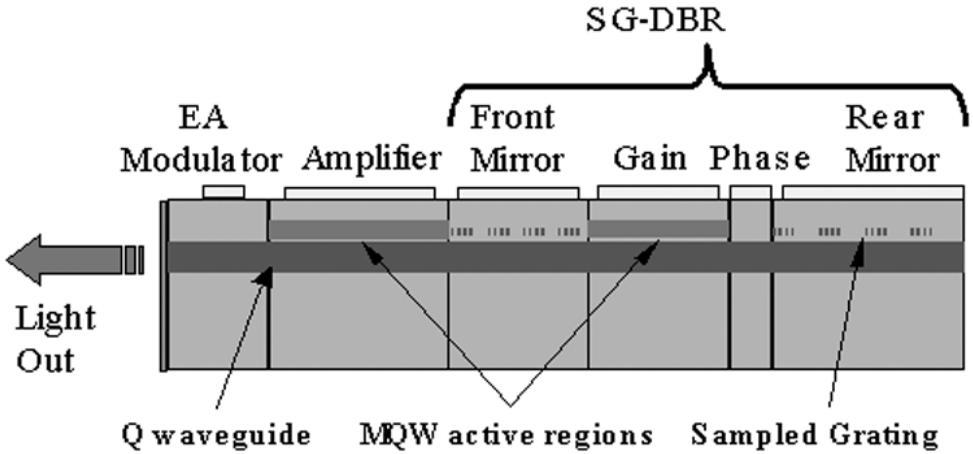
EIC



InP PIC







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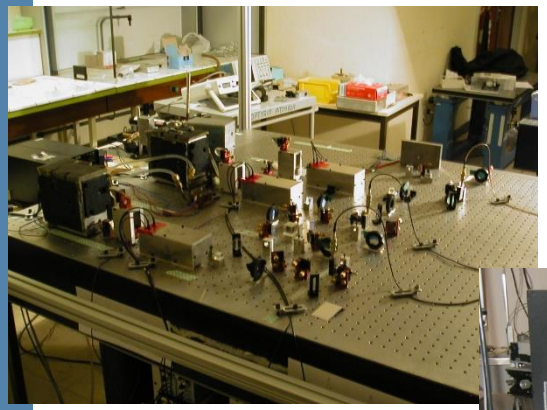
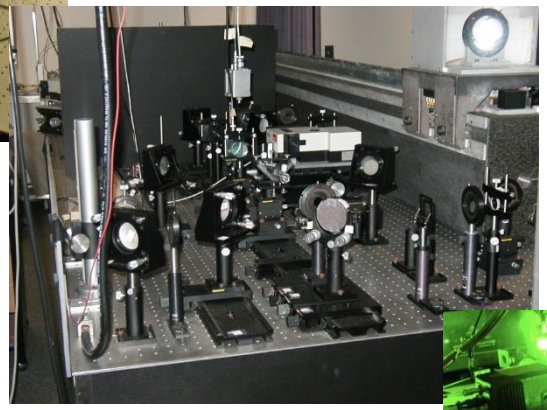
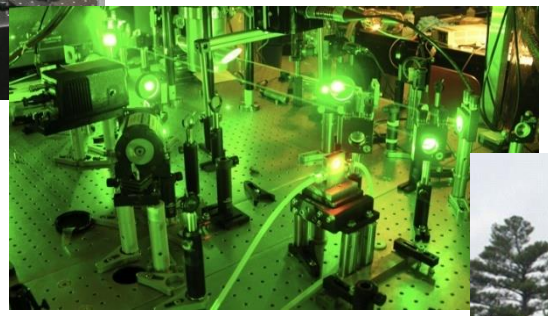
Photonic Integration: From this…..







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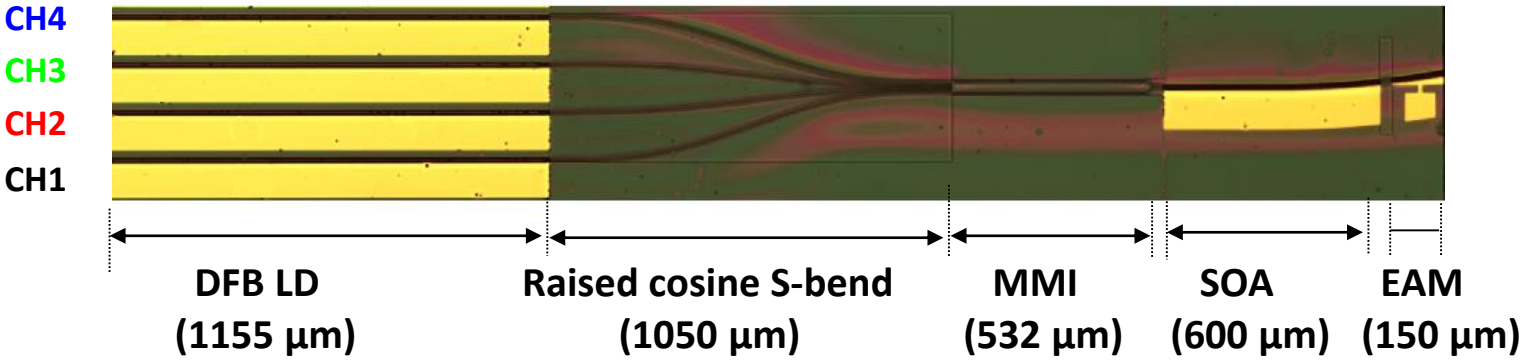
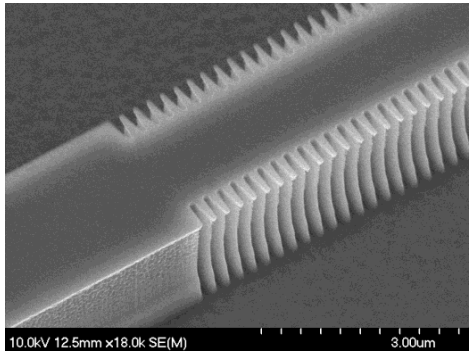
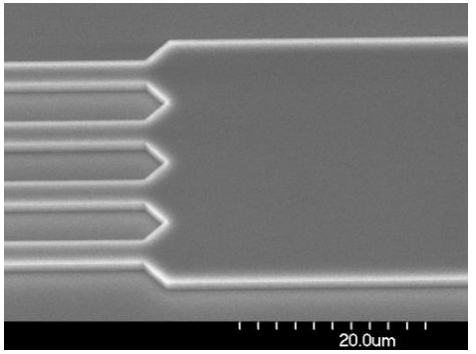
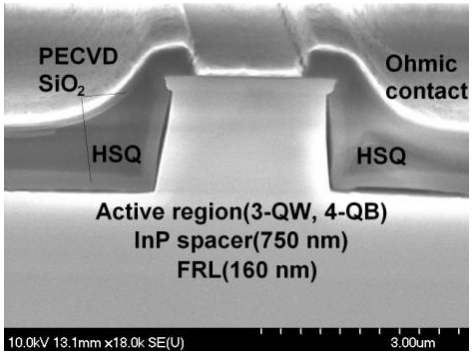
.....to this

Multiple wavelength lasers → Beam combiners → Amplifiers → Switches

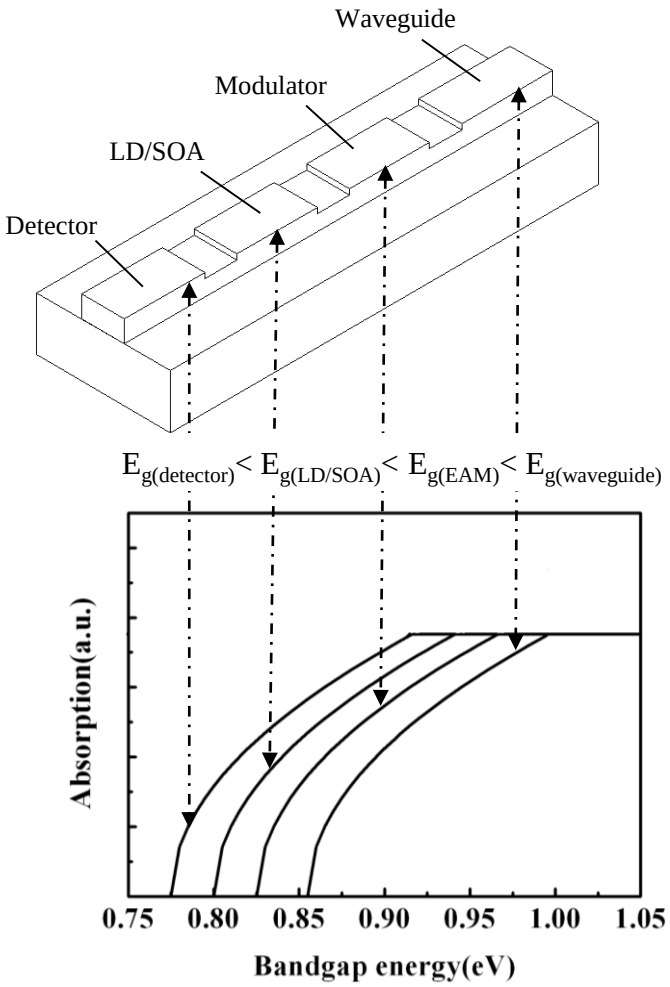




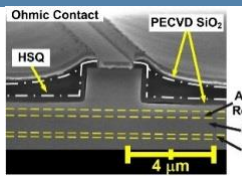




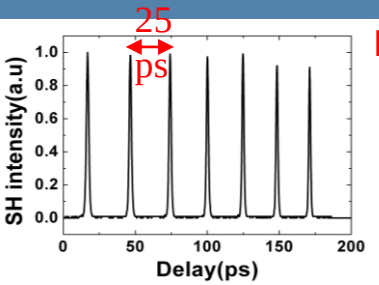
InP PIC



1) lasers

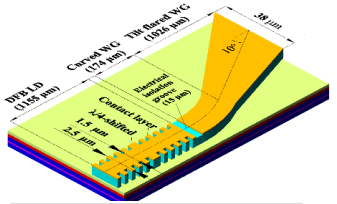


Gain sections

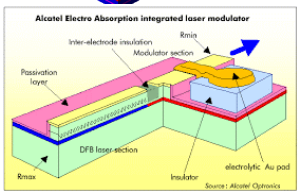


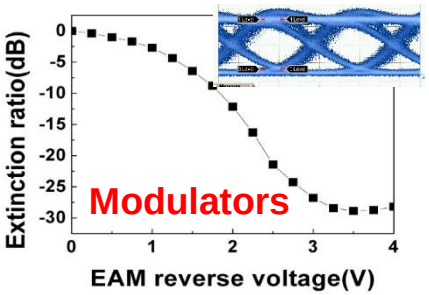
Pulse

2) Optical amplifiers

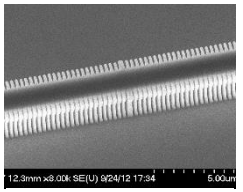


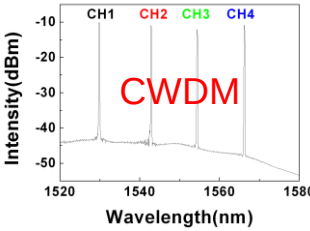
3) Optical modulators

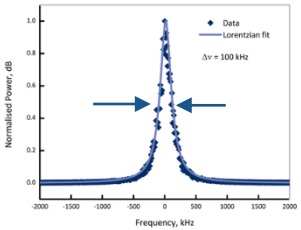




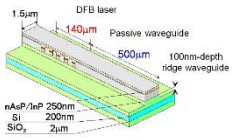
4)Reflectors and filters



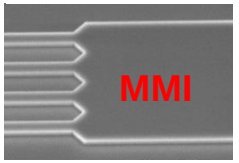


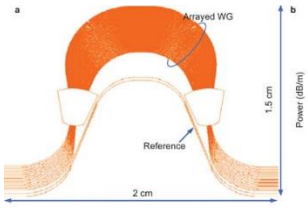


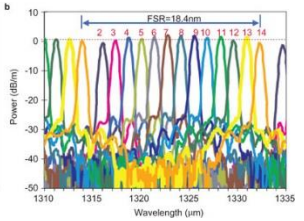
5) Low loss interconnect waveguide



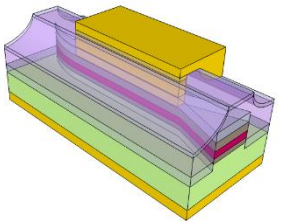
6)Power splitters

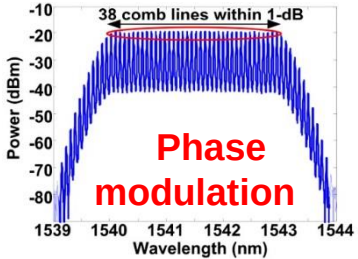






7) Detectors





Precise control of light: (power, wavelength, linewidth, phase, pulse)

InP PIC advantages

Advantages:

(1) Increased bandwidth

(2) Expanded frequency(Wavelength)division multiplexing

(3) Low-loss couplers

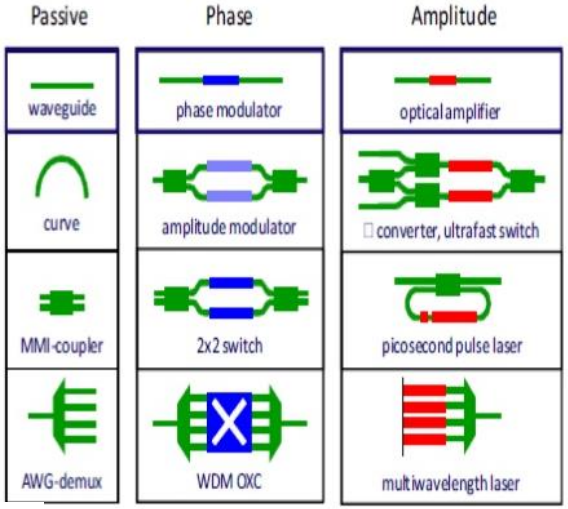
(4) Expanded multipole switching(number of poles, switching speed)

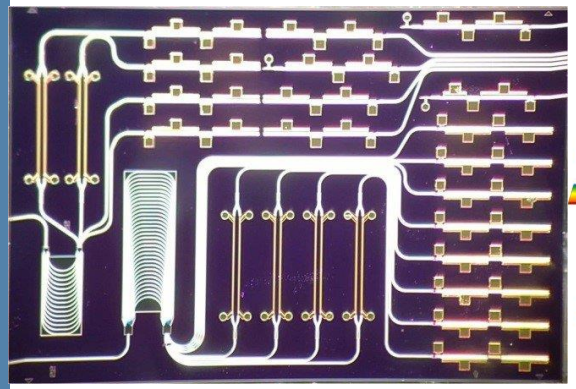
(5) Small size, weight, lower power consumption

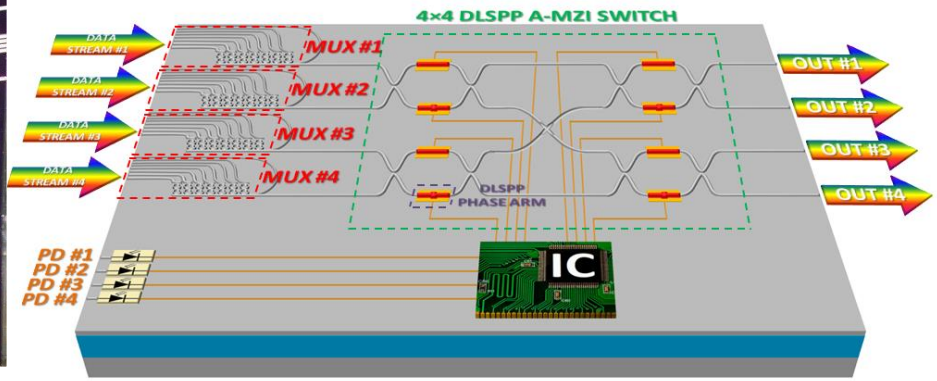
(6) Batch fabrication economy

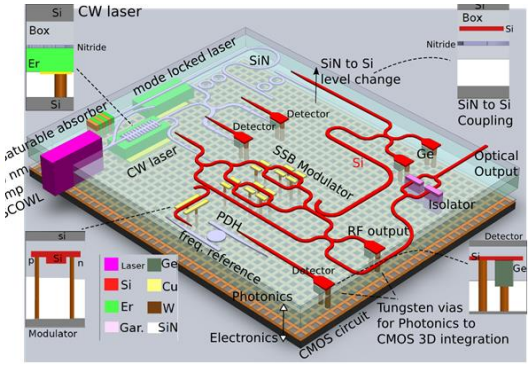
(7) Improved reliability

(8) Improved optical alignment, immunity to vibration

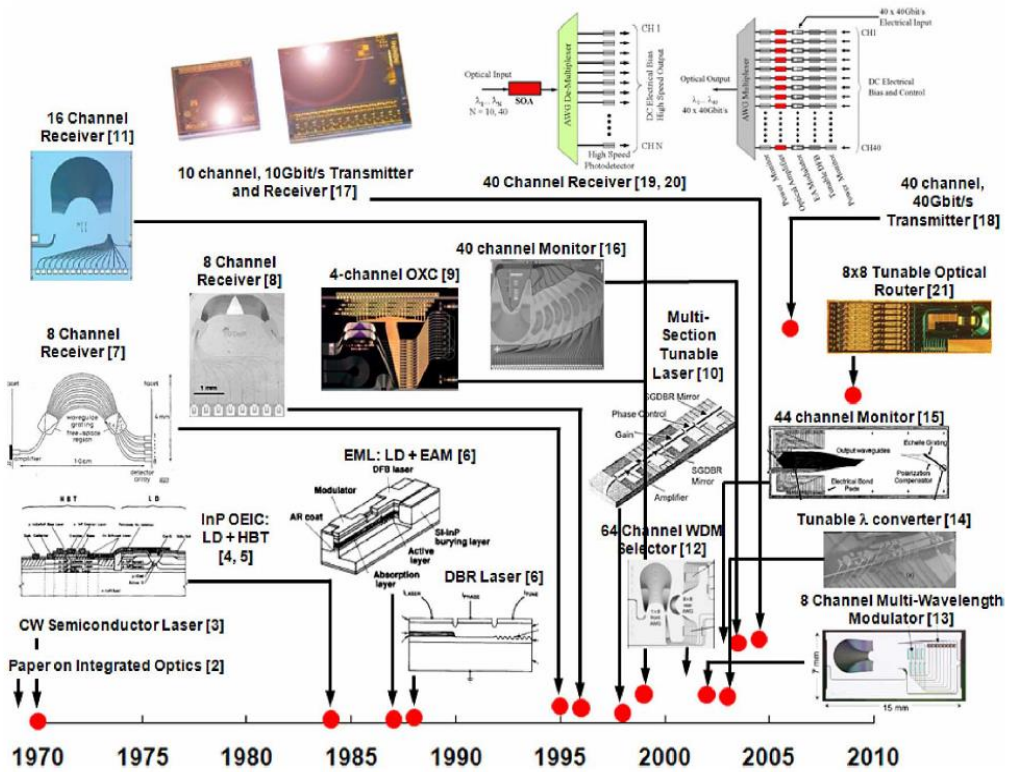


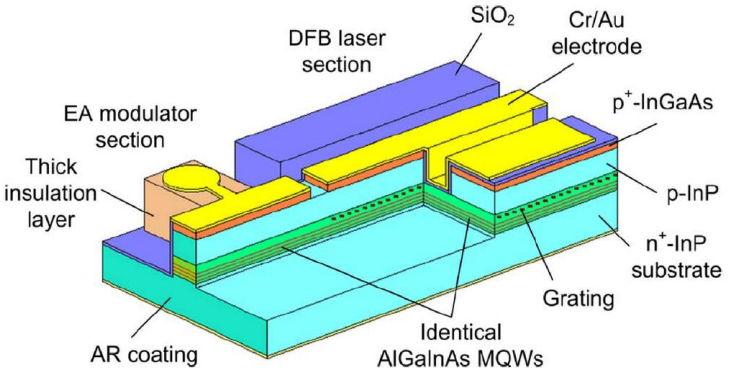


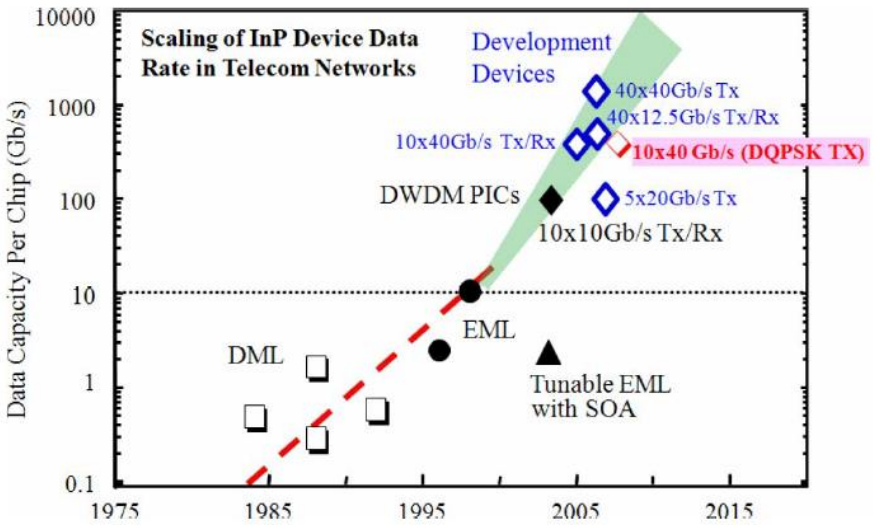




InP PIC evolution and photonic “Moore’s law”



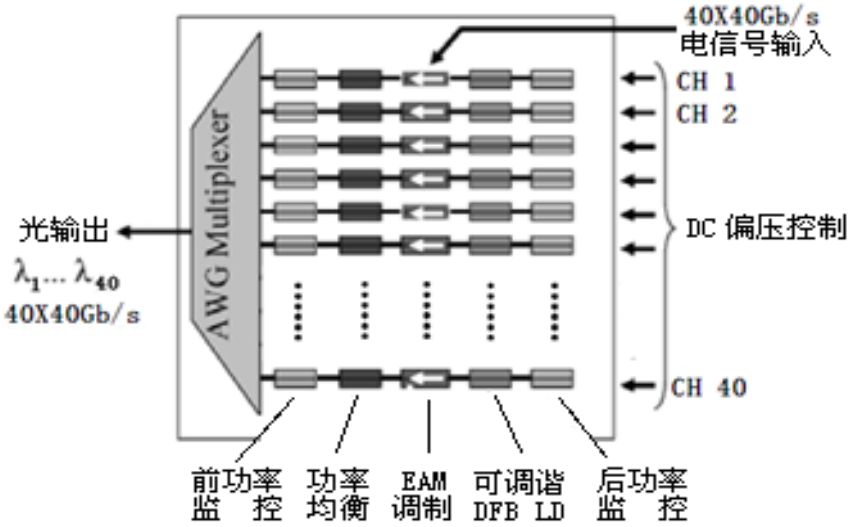


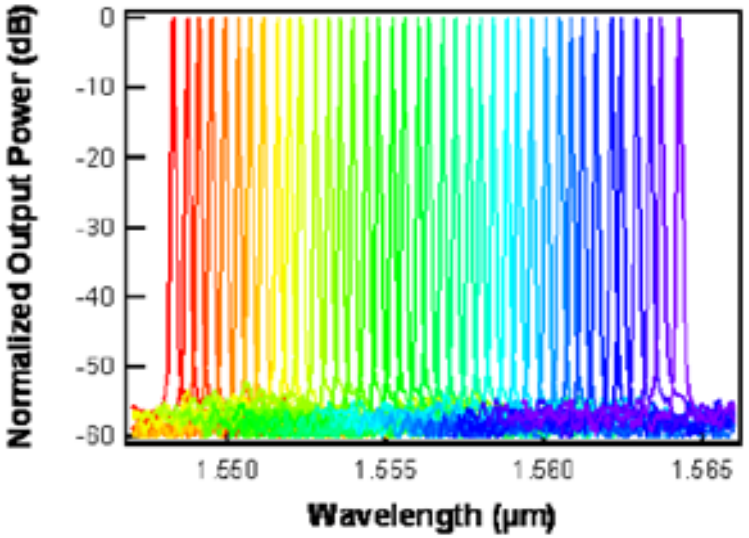


Scaling of data capacity per chip for InP-based transmitters utilized in commercial telecommunications networks (in filled, black symbols). Over the last 25 years, the data capacity per chip has doubled an average of every 2.2 years.

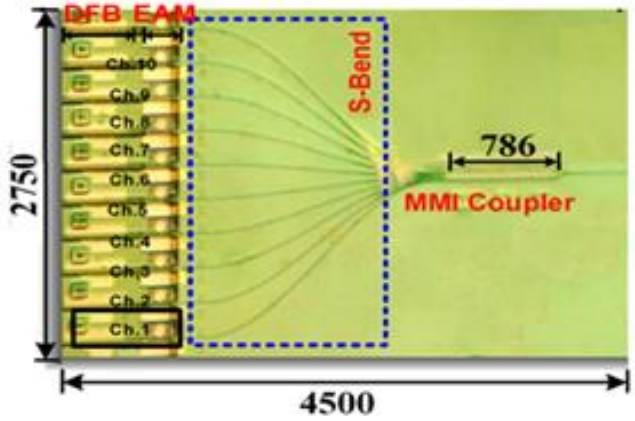
R. Nagarajan et al., IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 16, NO. 5, 2010

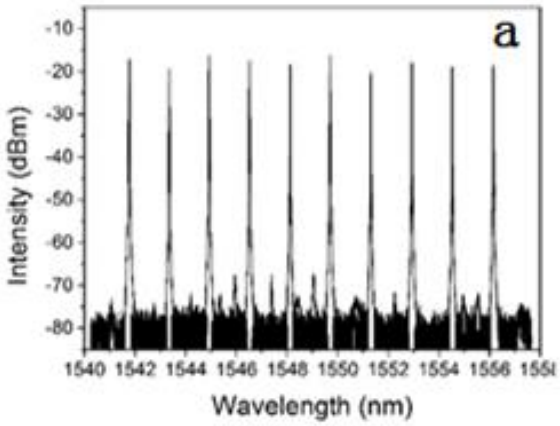
40 channel 1.6Tb/s WDM PIC transmitter

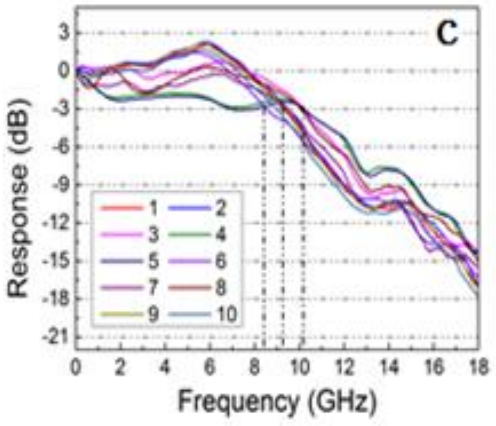




Infinera





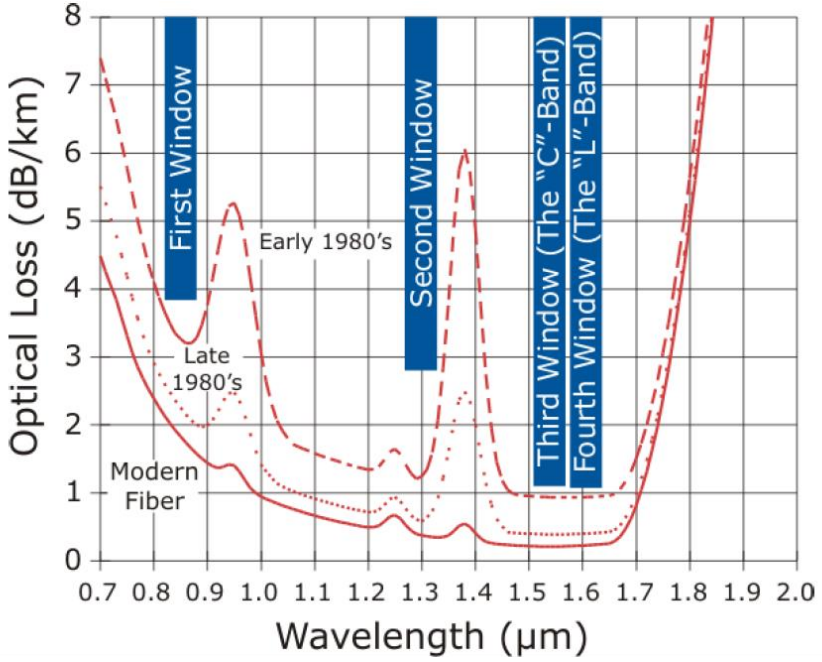


IOS, CAS

Fibre optic transmission Bands

1)backbone network
2) Access network
3) Fiber to home :

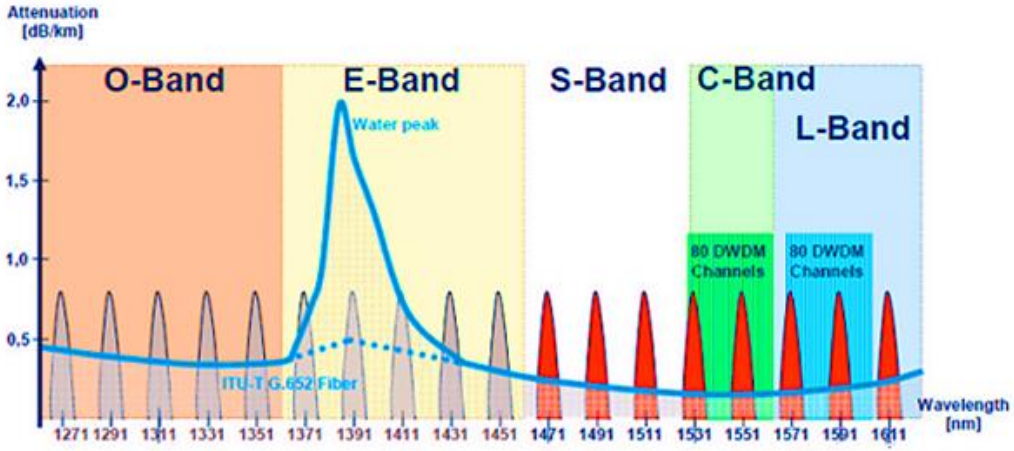
	Window Range	Operating Wavelength
First Window	800 nm – 900 nm	850 nm
Second Window	1,260 nm – 1,360 nm	1,310 nm
Third Window	1,500 nm – 1,600 nm	1,550 nm



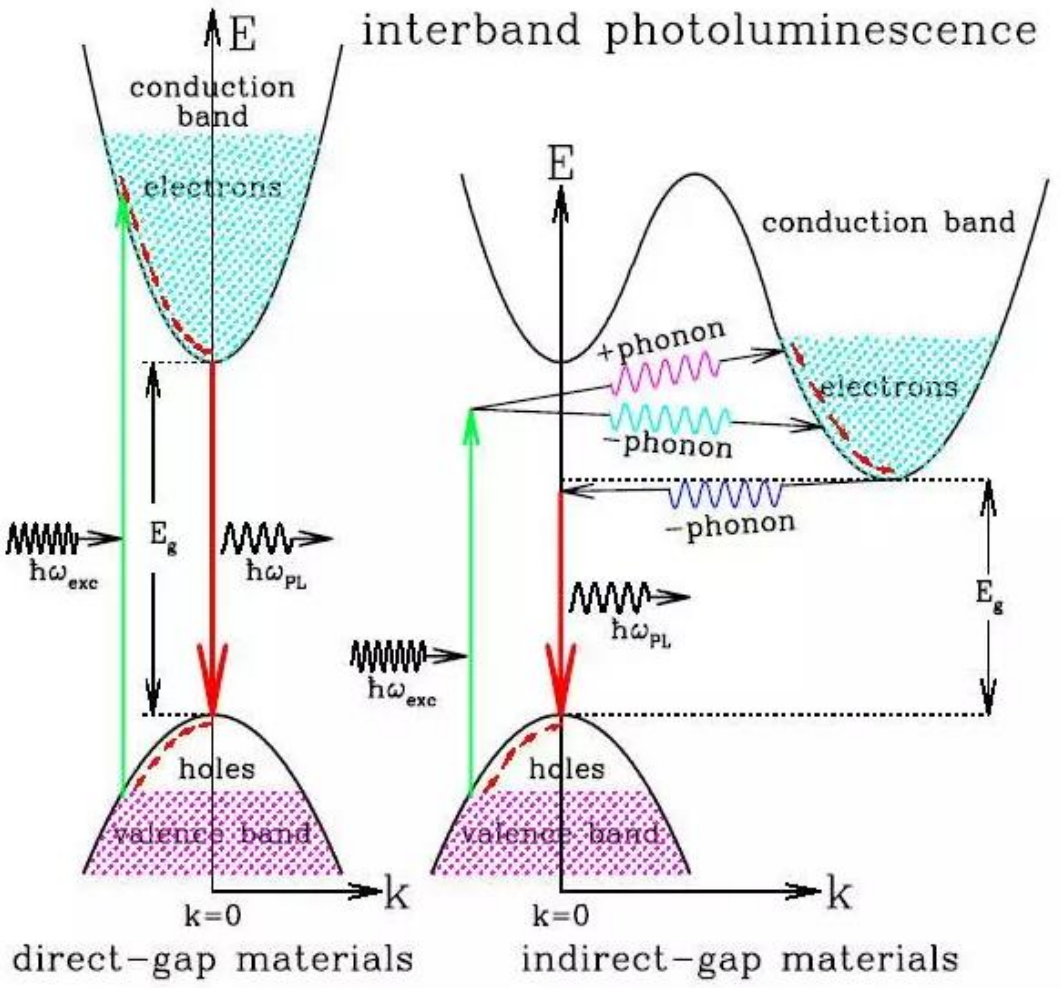
Optical loss:
1) 850nm: 2.0~3.0dB/km
2) 1310 : 0.33~0.35 dB/km
3) 1550: 0.19~0.21 dB/km

TRANSMISSION WINDOW

Band	Wavelength range	Description
O- band	1260 nm- 1360 nm	Original band
E- band	1360 nm- 1460 nm	Extended band
S- band	1460nm- 1530 nm	Short wavelength band
C- band	1530 nm- 1565 nm	Conventional band
L- band	1565 nm- 1625 nm	Long wavelength band
U- band	1625 nm- 1675 nm	Ultra long wavelength band



Direct-gap and indirect-gap materials



InP, GaAs
InGaAsP, AlGaInAs

Si, Ge

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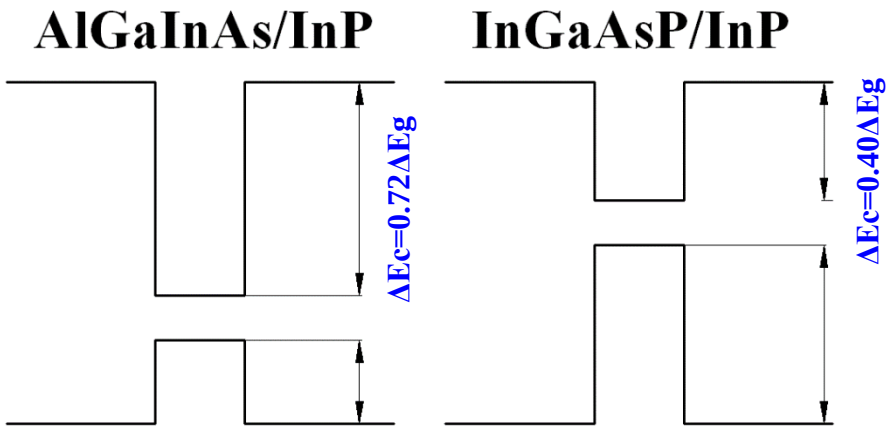
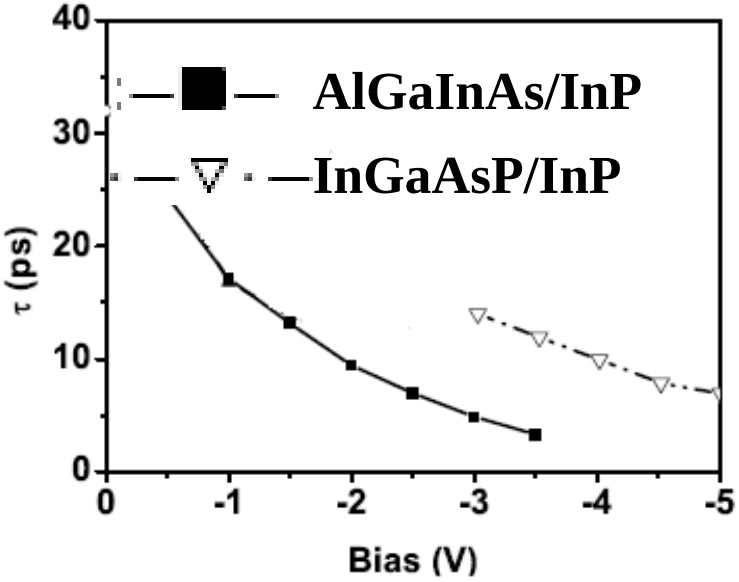
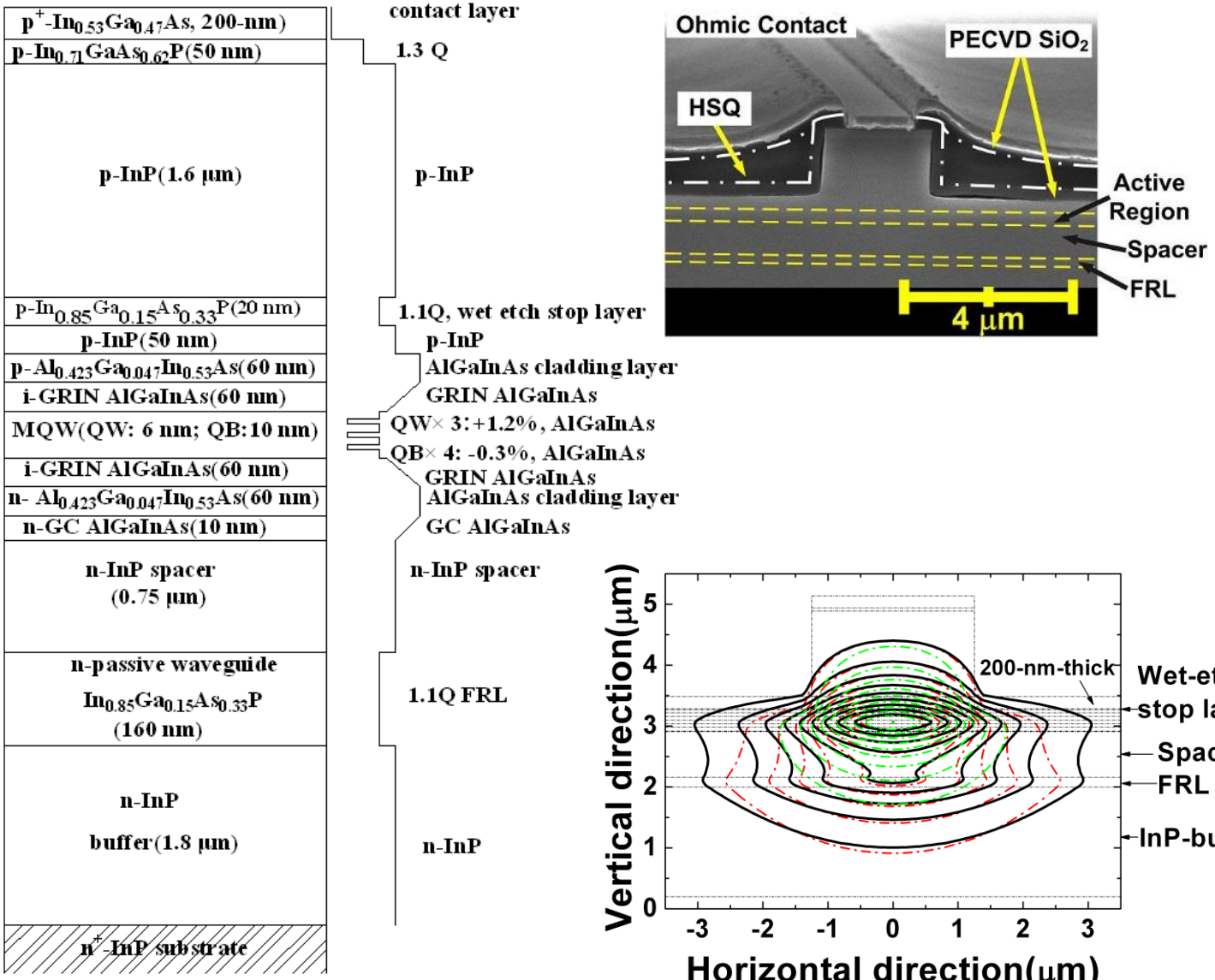
Two material systems for 1.55 μm PIC

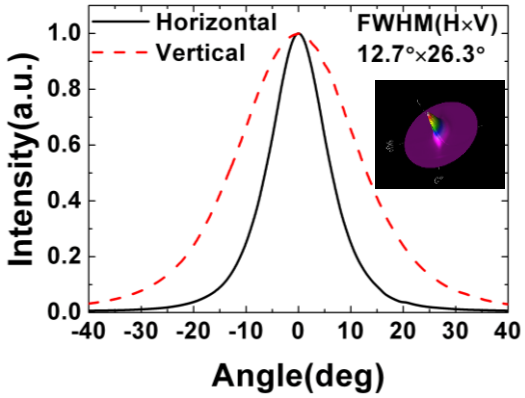
- **Using AlGaInAs/InP material:**
  - $\Delta E_c = 0.72 \Delta E_g$
  - Improved electron confinement
  - Helps to alleviate hole pile-up
  - Higher T_0

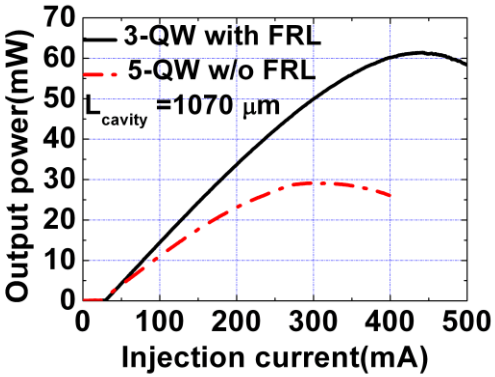




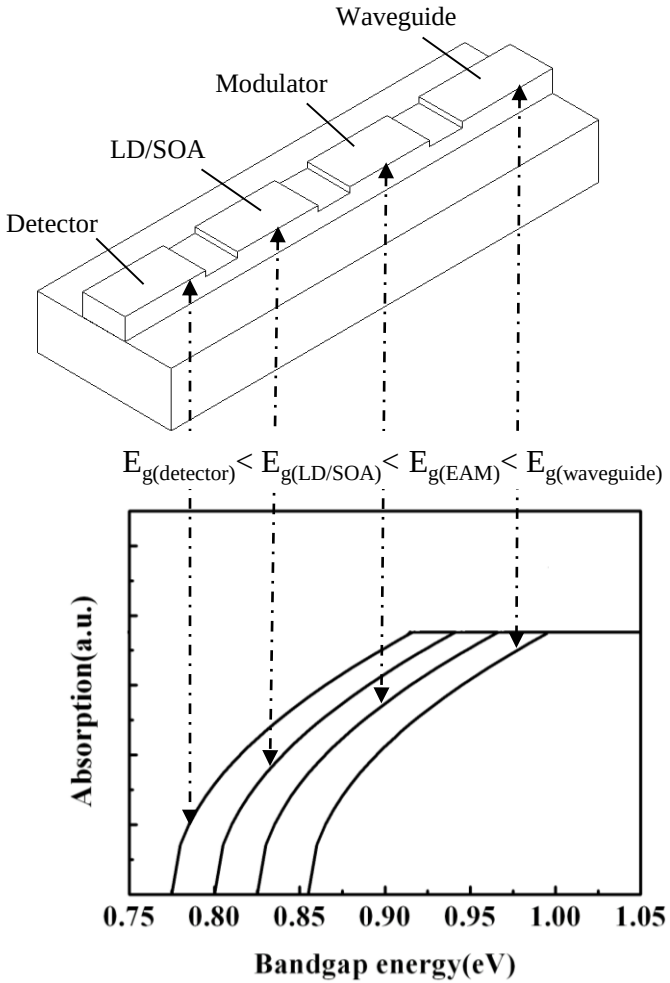
1.55 μm AlGaInAs/InP wafer structure







How InP PIC and challenge



Waveguide: should be transparent to the laser wavelength
→ E_g (laser) < E_g (waveguide)

Modulator: red-shifted by electric field
→ E_g (laser) < E_g (modulator)

Detector: should absorb the laser wavelength
→ E_g (detector) < E_g (laser)

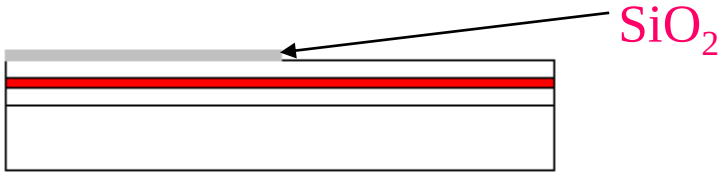
- **Accurate control the different bandgap wavelength of different components on a single substrate;**
- **Efficient optical coupling between the various components;**
- **The electricity and optical crosstalk between the various components;**
- **The optimization of each components independently;**
- **The coupling efficiency between the chip and the fiber;**
- **The simplicity of the optical integration technology;**
- **The yield of the PIC;**

Four common photonic integration technologies:

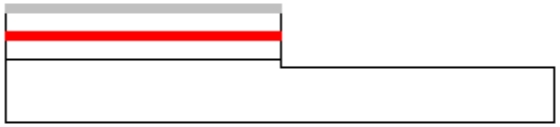
- **Butt-joint regrowth**
- **Selective area growth (SAG)**
- **Quantum well intermixing (QWI)**
- **Asymmetric Twin waveguide (ATG)**

Butt-joint

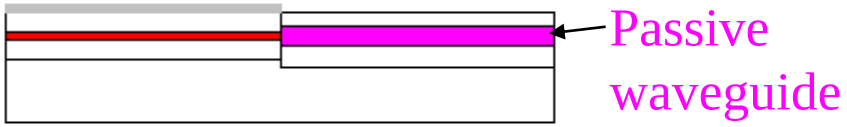
(a) active material growth



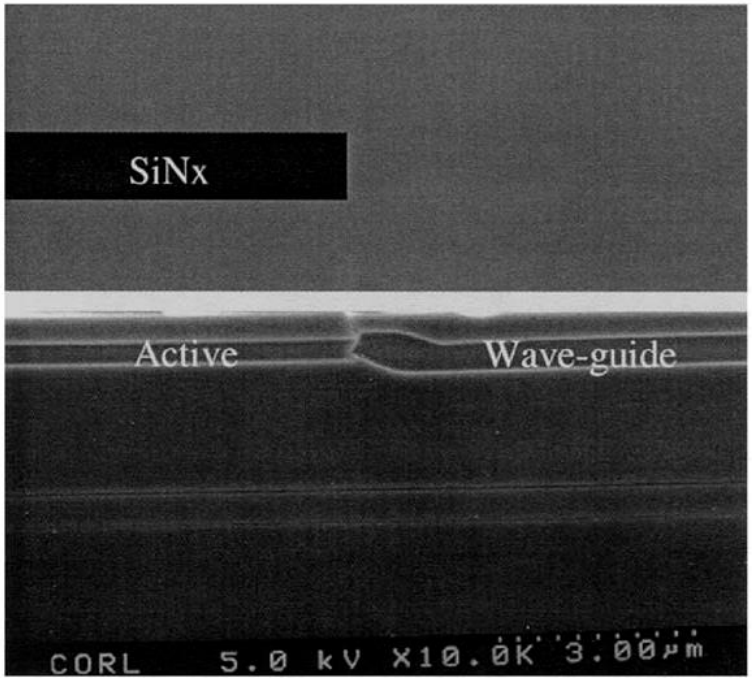
(b)SiO_2mask fabrication



(c) etch with SiO_2 mask

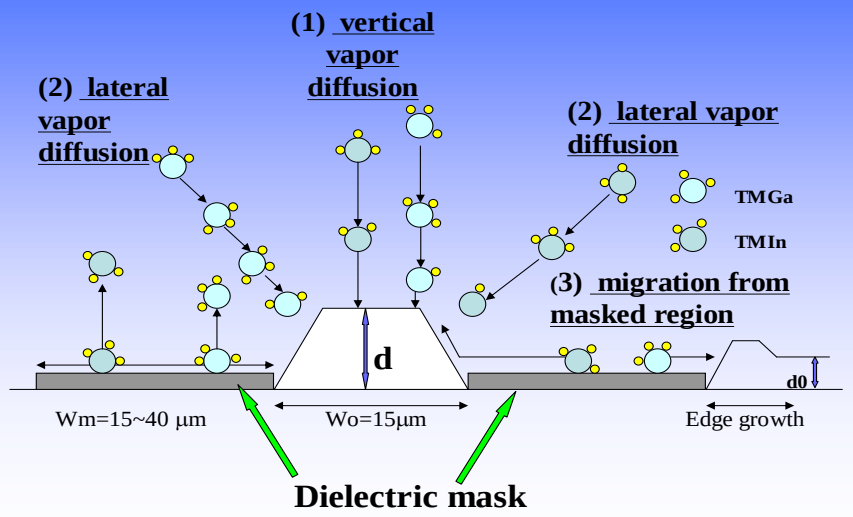


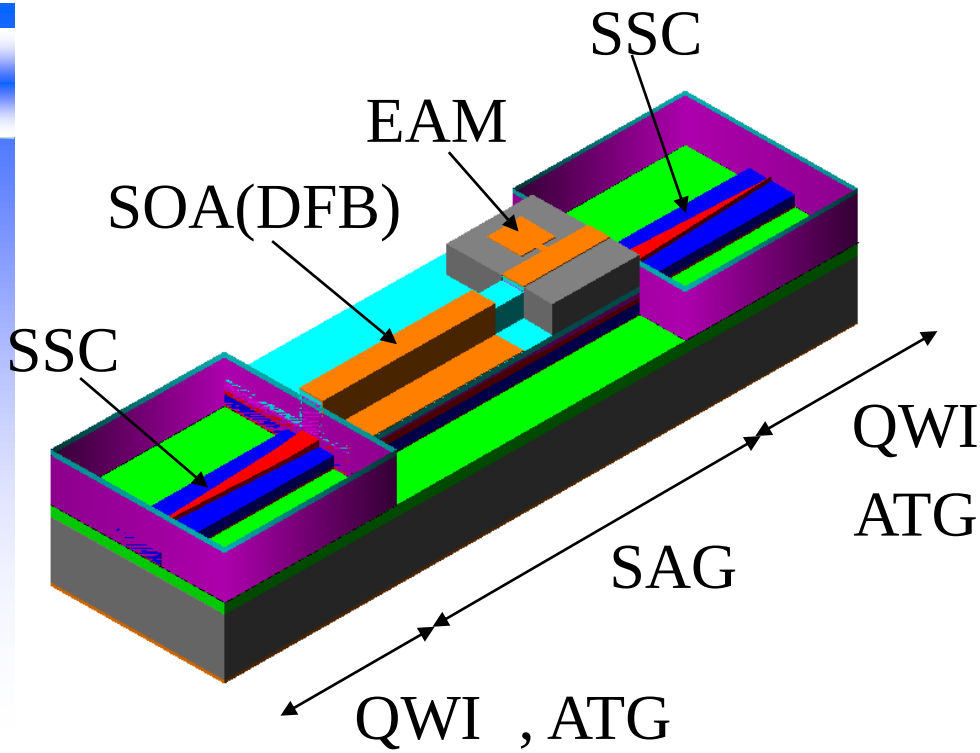
(d) Passive waveguide growth

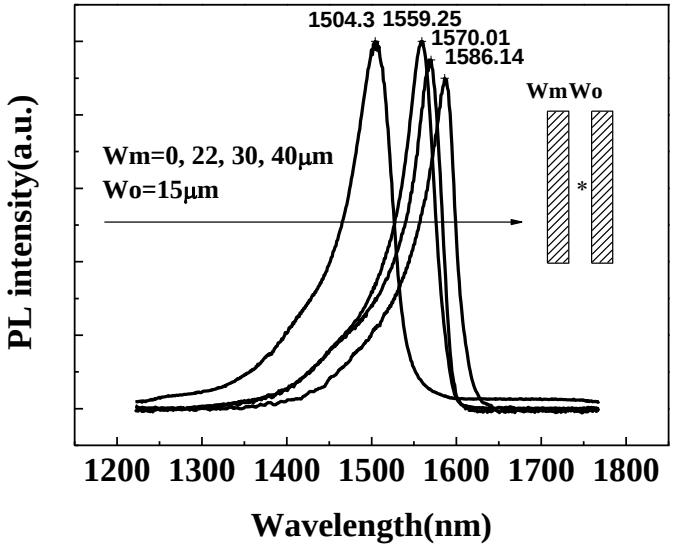


Its best metric is that each component can be optimized independently, and the challenge is how to etch material 1 accurately and get a nice butt-joint interface in order to reduce the scattering loss

Selective-Area-Growth(SAG）







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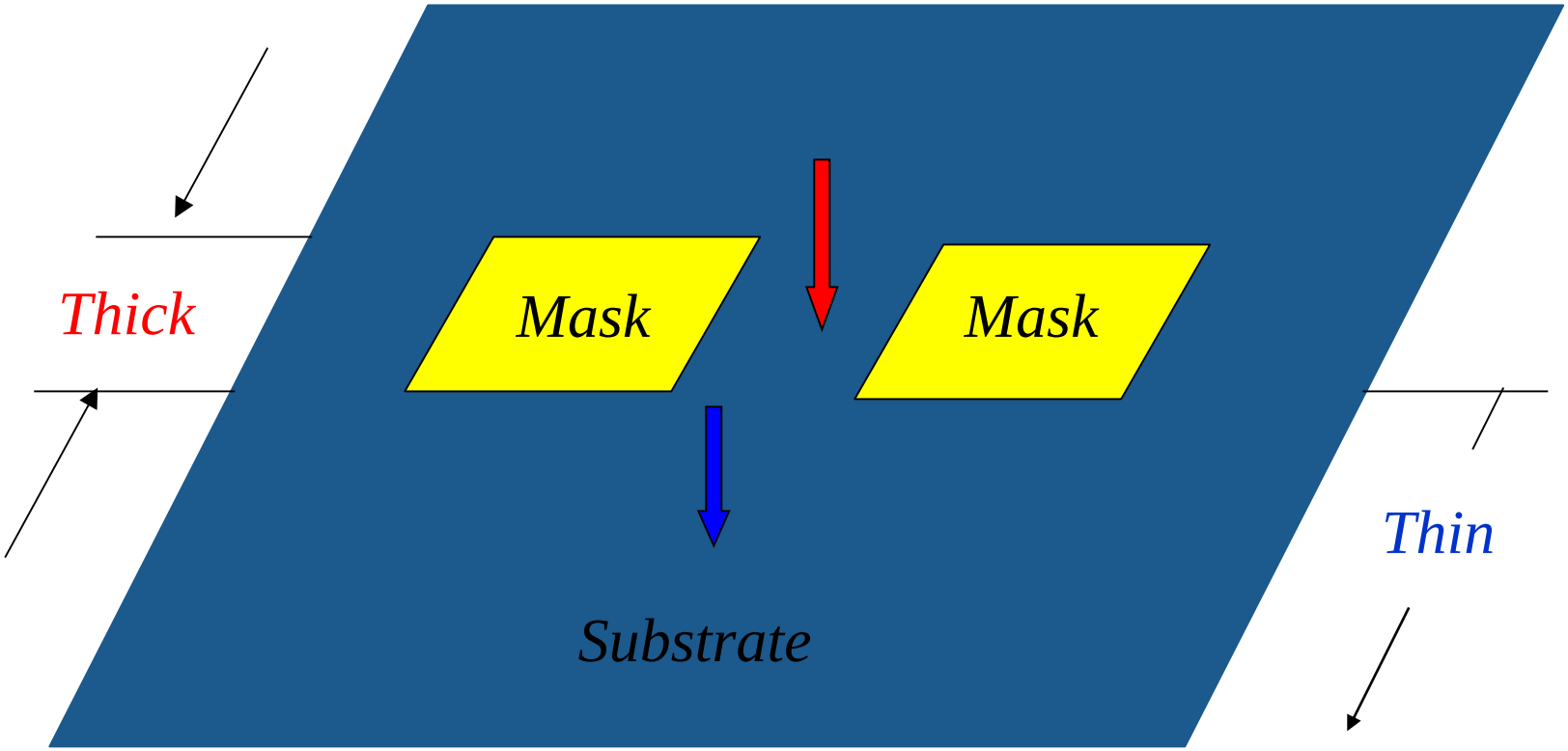
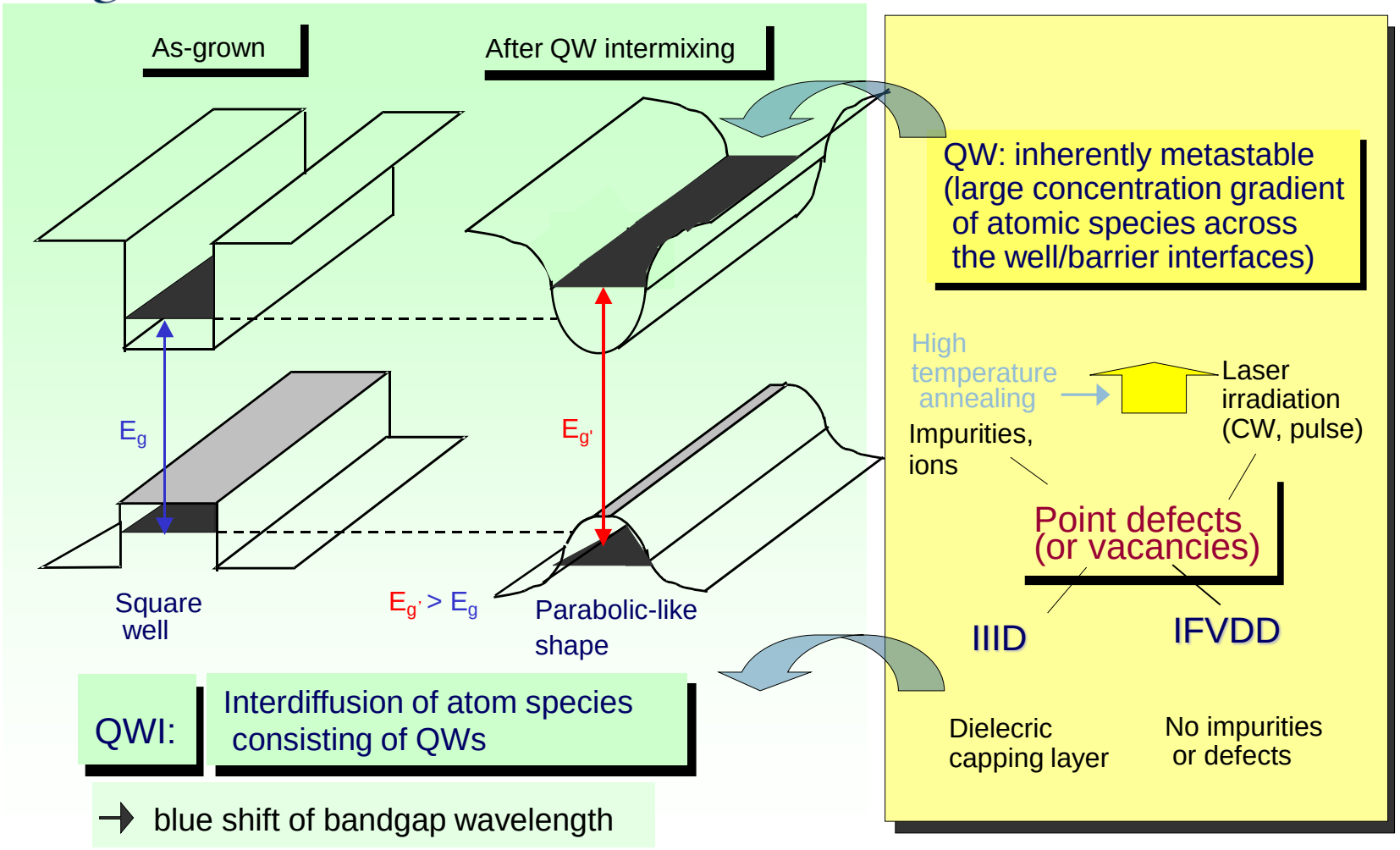
SAG process

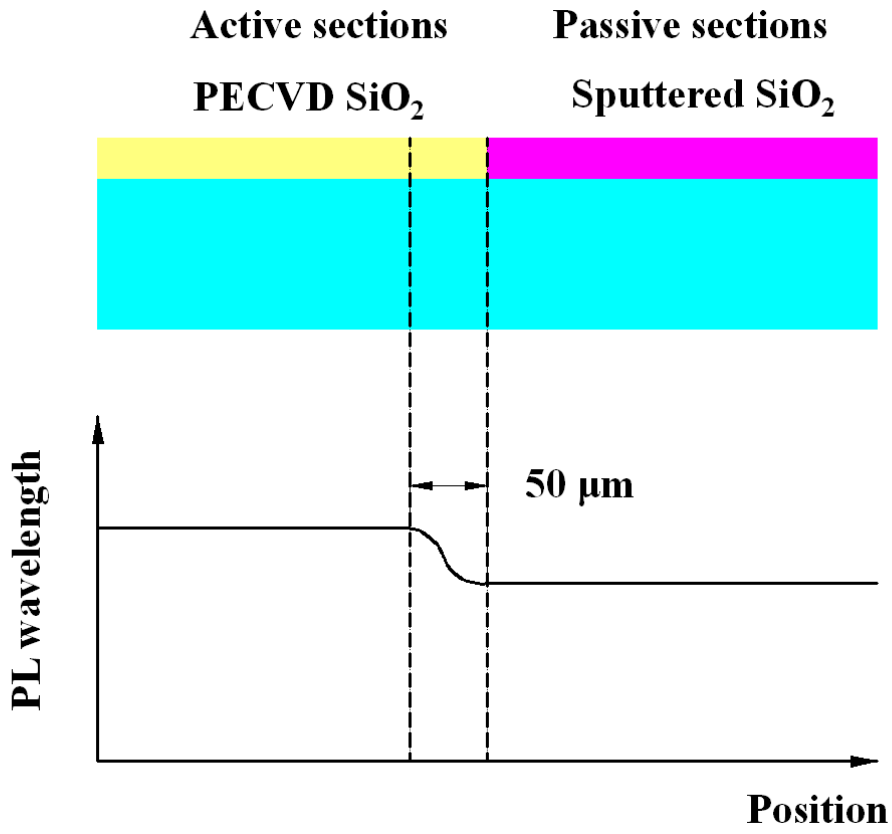


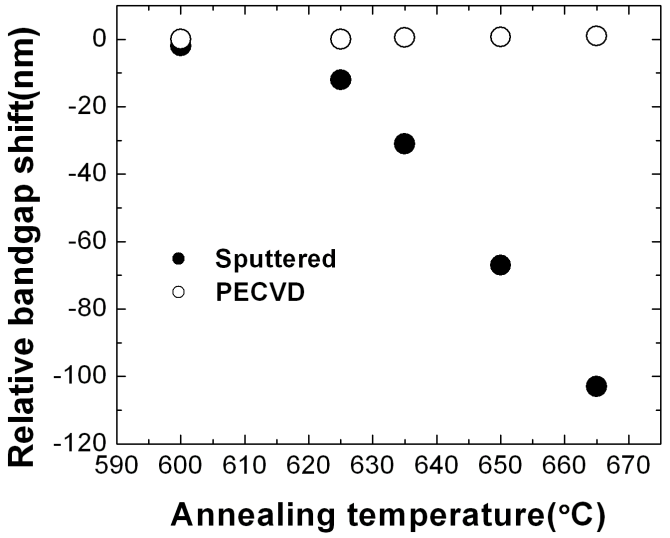
Quantum well intermixing

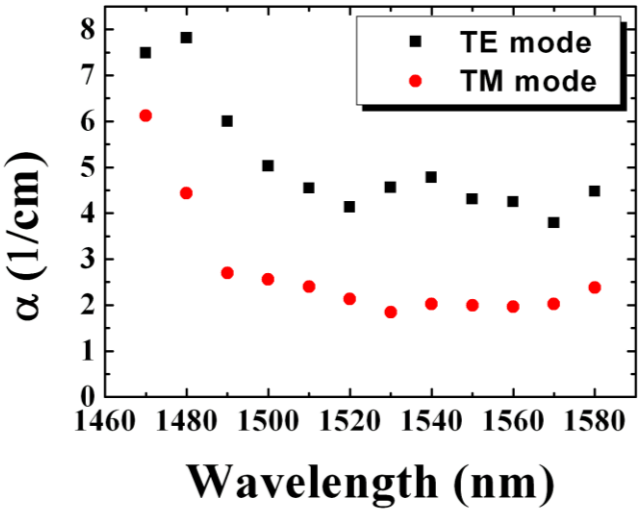


- **low-energy ion implantation QWI(LEII-QWI)**
- **Universal damage enhanced QWI**

Passive waveguides formed using QWI

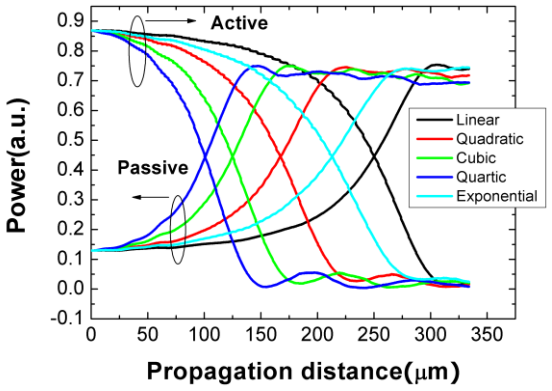






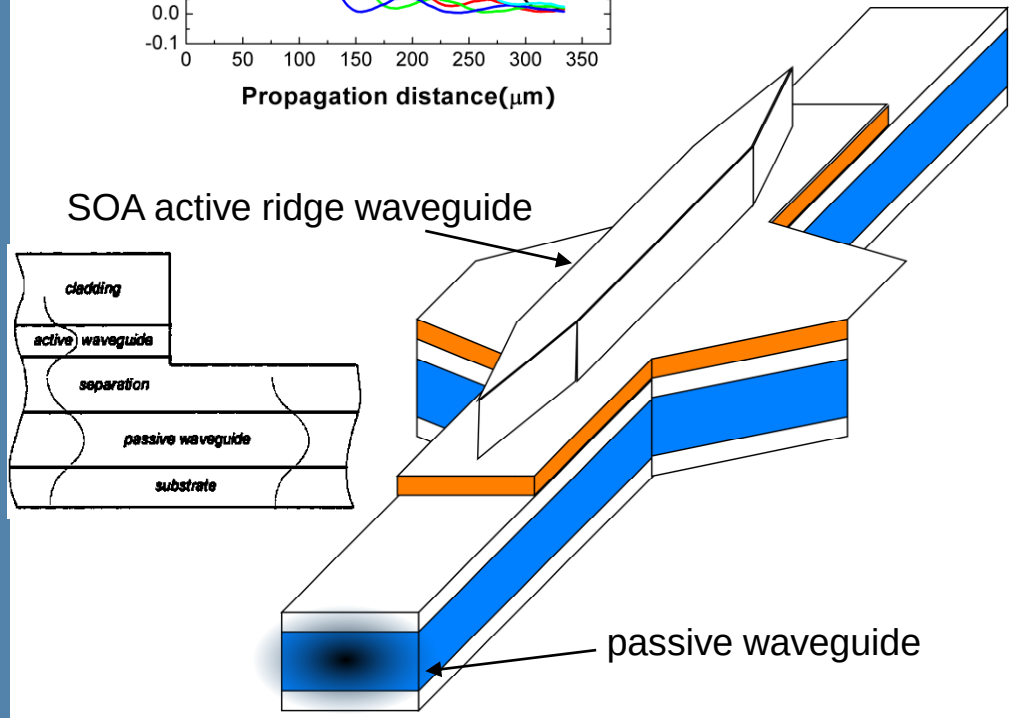
Compared with conventional selectively etched and re-grown techniques for photonic integration, technique of post-growth processing based on quantum-well intermixing (QWI), offers a simple, flexible and low-cost alternative

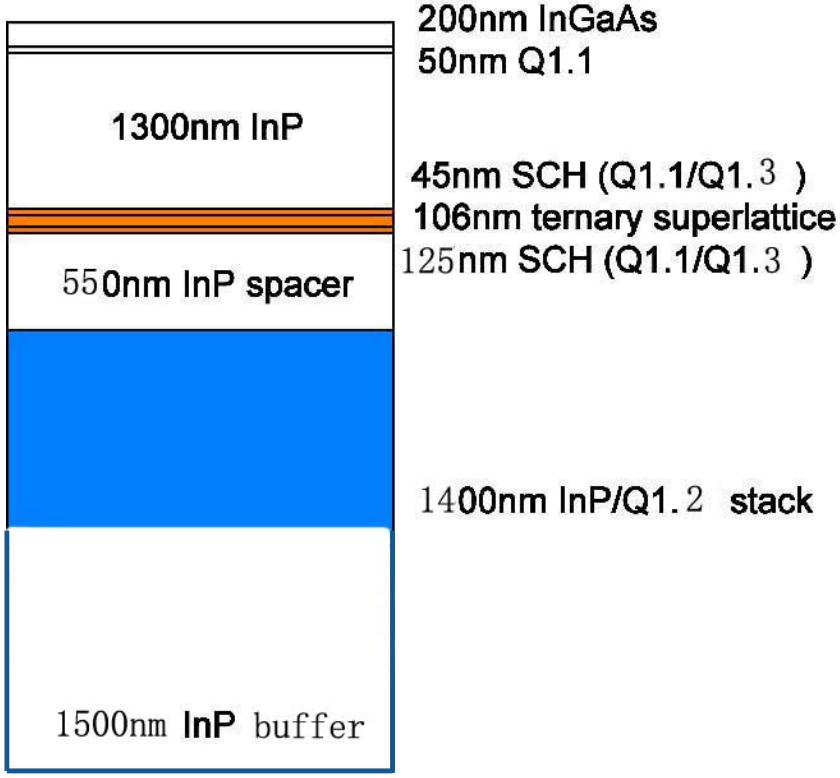
Asymmetric Twin waveguide (ATG)



Passive / active integration

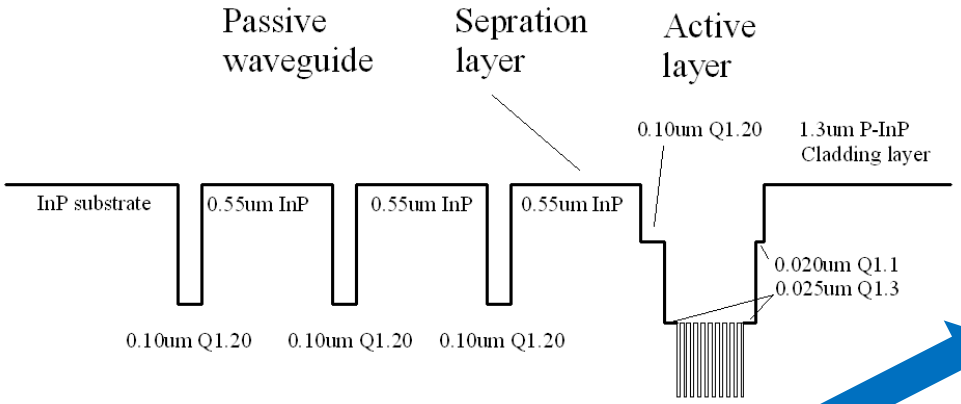
SOA active ridge waveguide

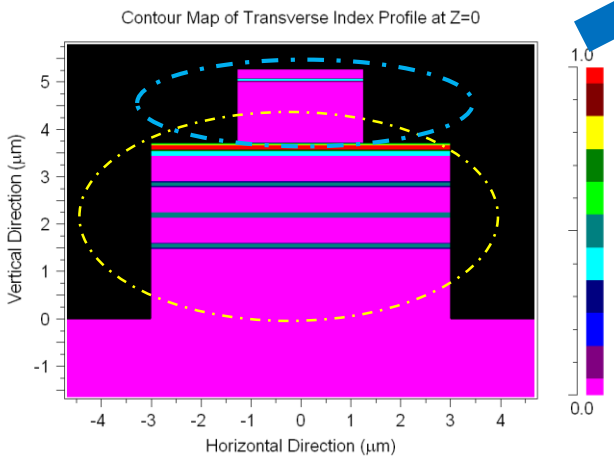




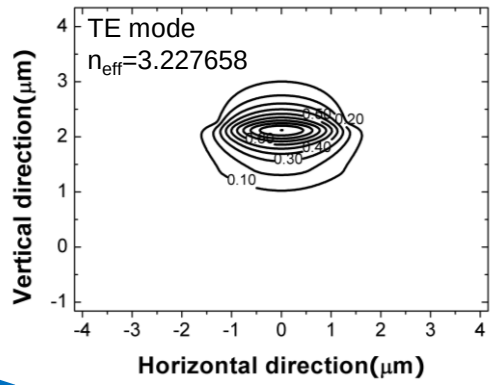
- Large mode in passive waveguide for high fibre coupling efficiency / passive fibre coupling
- Taper vertical coupler
- Polarisation independent gain

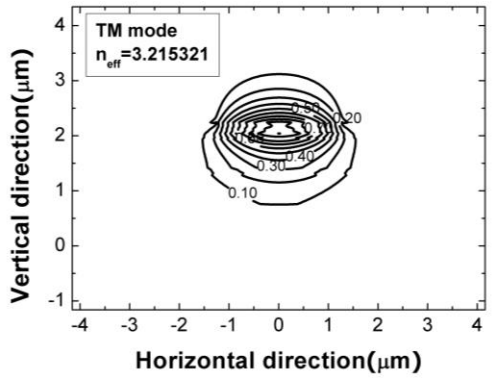
Active and passive waveguide near field pattern

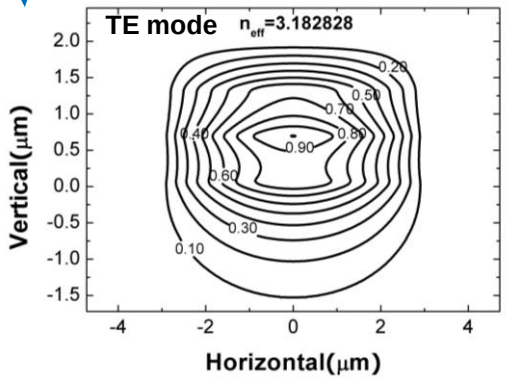


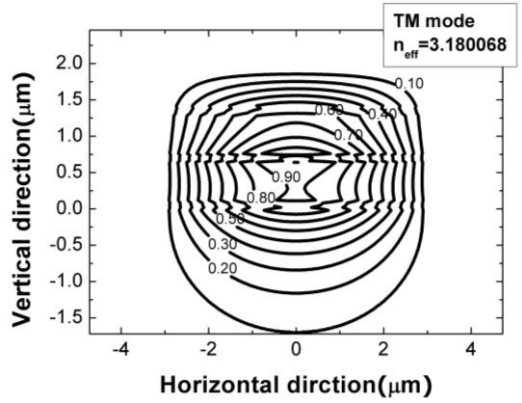


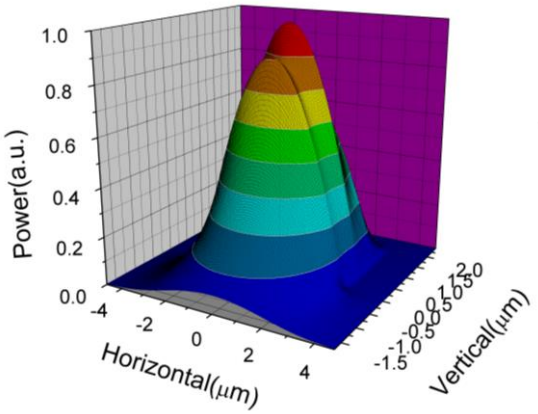
10 lattice-matched InGaAs wells (4.1nm) and 11 tensile-strained (0.62%) InGaAs barriers (6.3 nm)

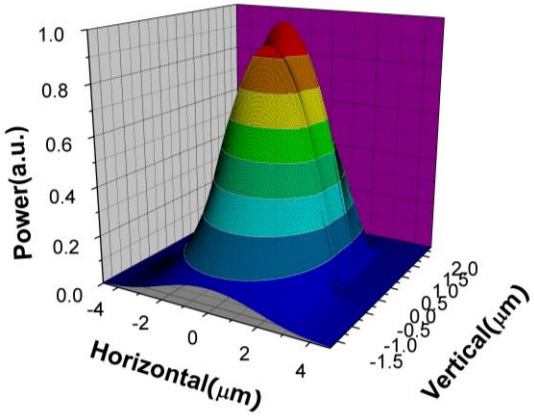




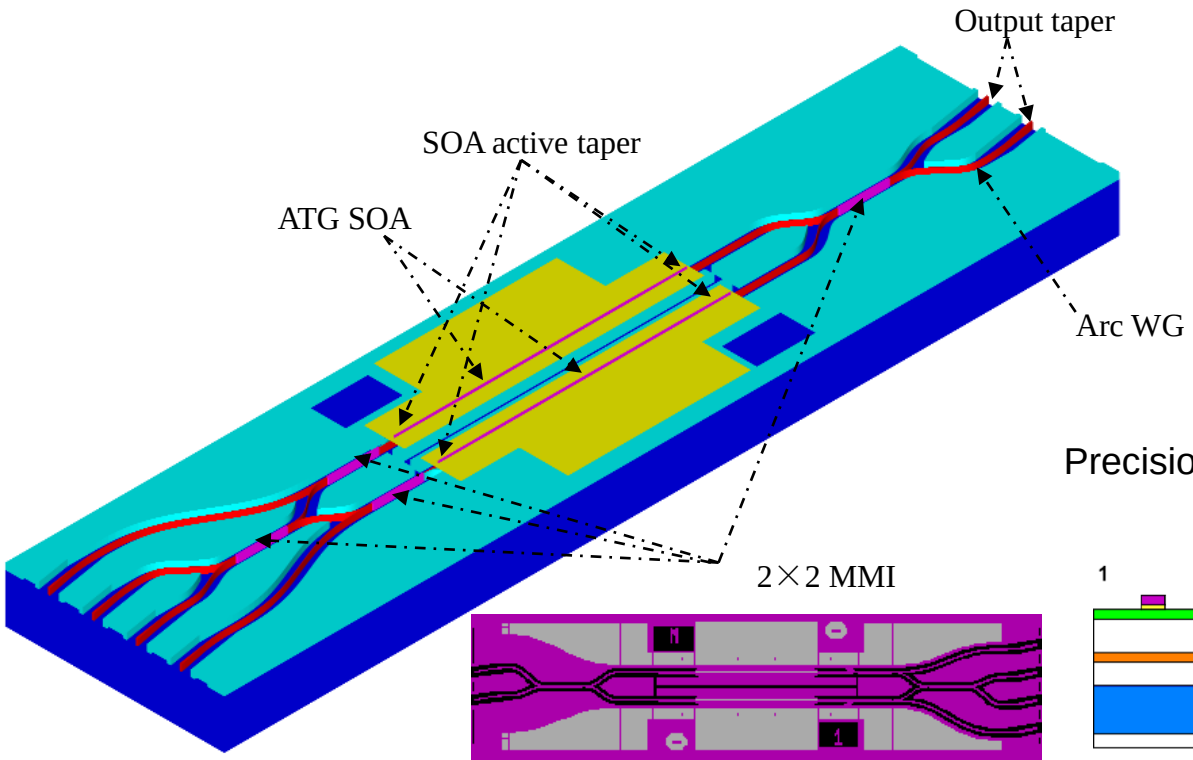


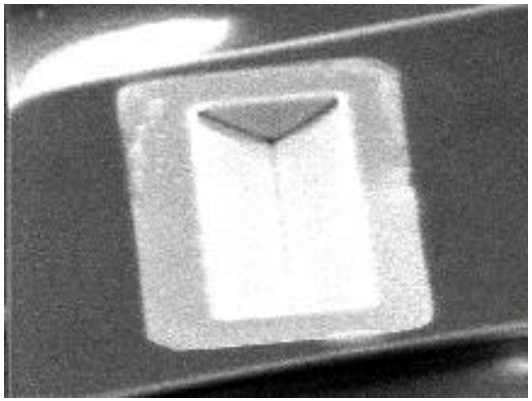




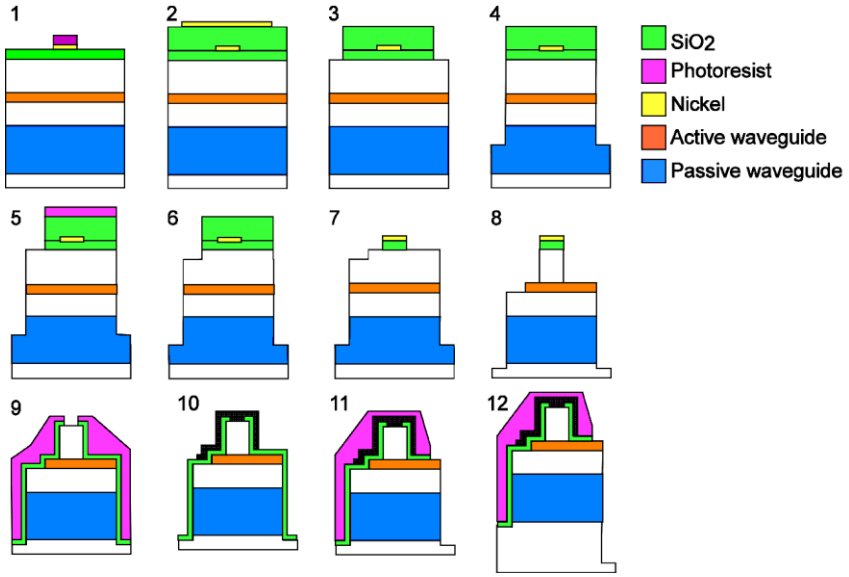


PIC based on ATG (Multi-functional integrated arrays of interferometer switches (MUFINS))





Precision cleaving grooves for passive chip positioning



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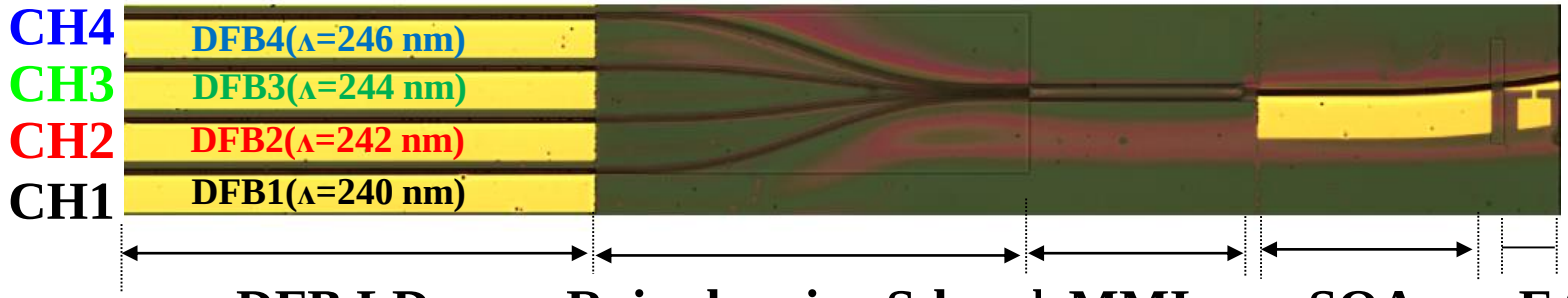
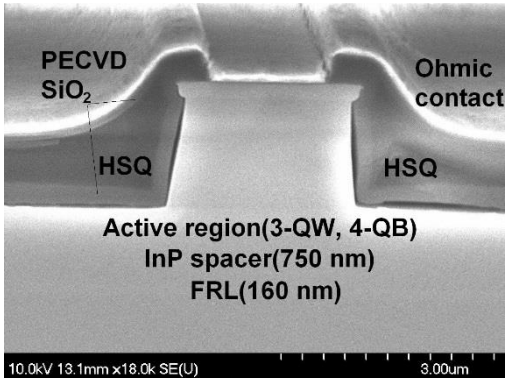
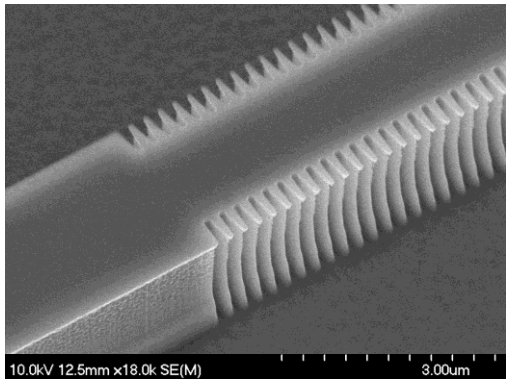
Comparison of different photonic integration techniques

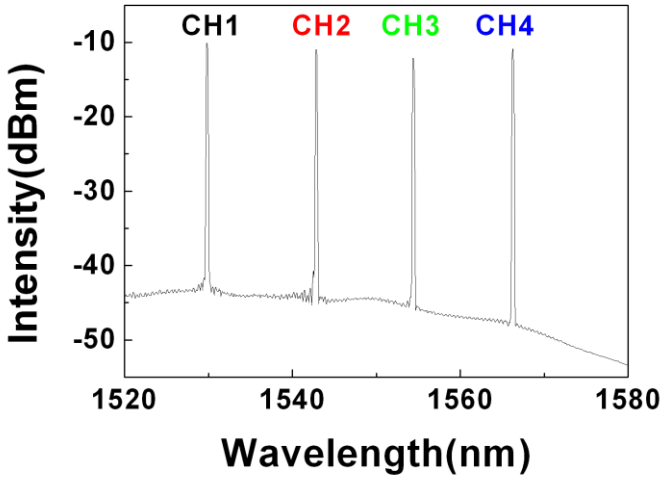
PIC techniques / Process characteristics	SAG	Butt-joint	QWI	ATG
Regrowth?	N	Y	N	N
Number of integrated band gap materials	Multiple (Depends on the mask design)	Each regrowth adds a material	Multiple (By Controlling the concentration of point defects in different regions)	An etching usually adds a kind of material
Precise control of lithography and etching techniques?	N	Y	N	Y
Interface between different materials	Gradual transition 50~100 μm	Steep	2-3 μm	Gradual transition 100~200 μm
Optimization of different material?	N	Y	N	Y
Integration of bulk material?	N	Y	N	Y
Precise control of the band gap wavelength?	Y	Y	N	Y
Other	Can achieve the gradual change in thickness			

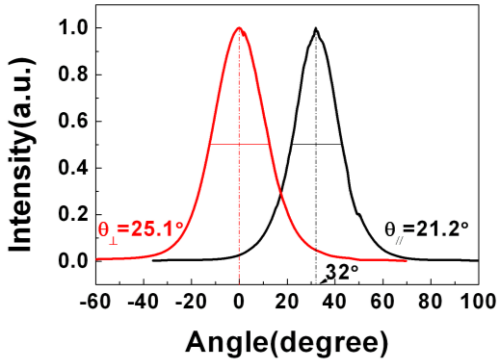
CWDM source based on AlGaInAs/InP monolithically integrated DFB laser array

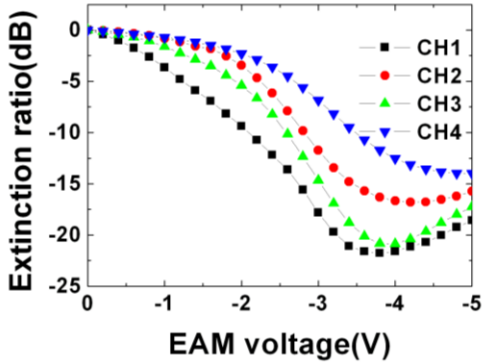






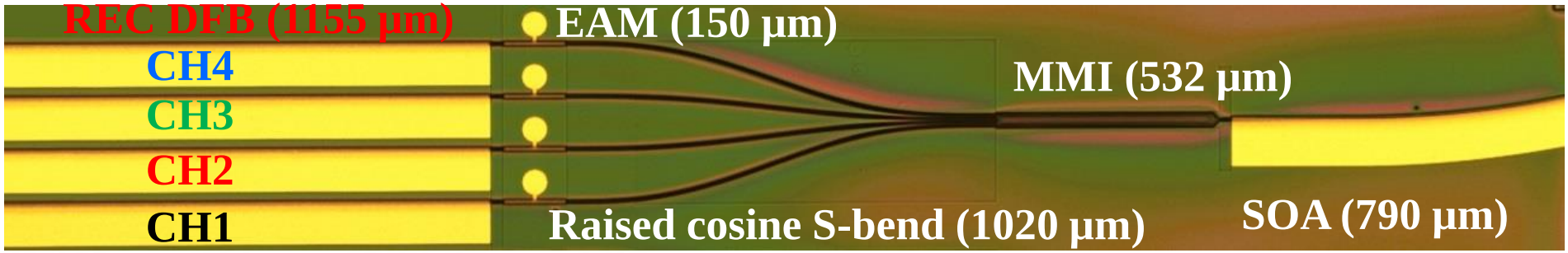


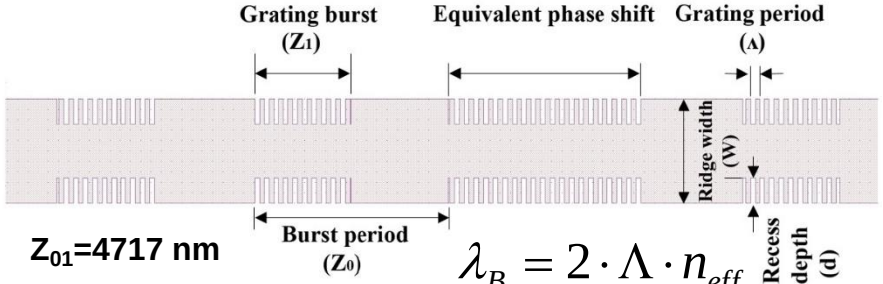




L. Hou et al., *Opt. Lett.*, Vol. 36, No.21, pp.4188-4190, 2011.

DWDM source using sample grating





Z_{01}=4717 nm

Z_{02}= 4764 nm

Z_{03}= 4811 nm

Z_{04}= 4858 nm

ΔZ_0= 47 nm

Λ=232 nm

d=0.6 µm

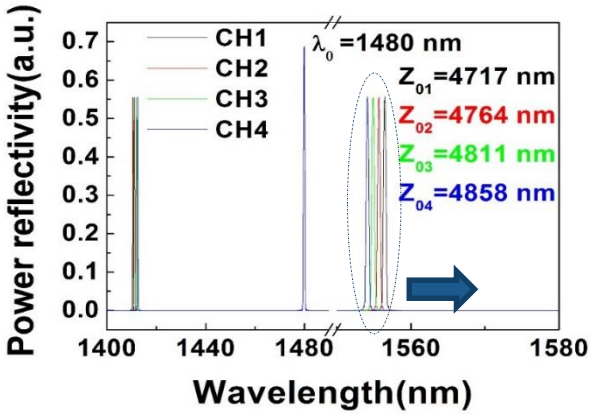
$Z_1=Z_0/2$

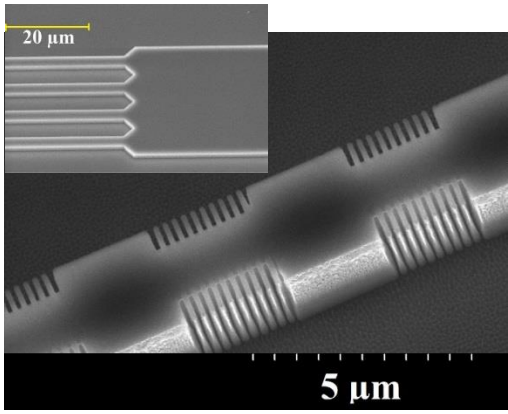
$$\lambda_B = 2 \cdot \Lambda \cdot n_{eff}$$

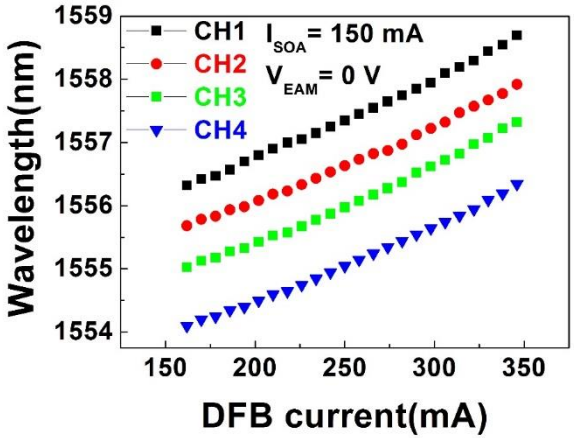
$$\Delta\lambda_{B\min} = 2 \cdot \Delta\Lambda \cdot n_{eff}$$

$$= 2 \times 0.5 \times 3.2$$

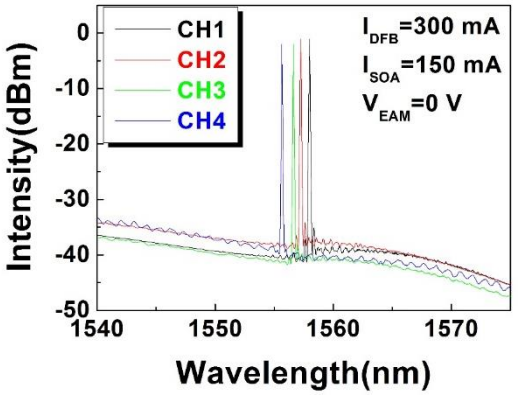
$$= 3.2\,\text{nm}$$

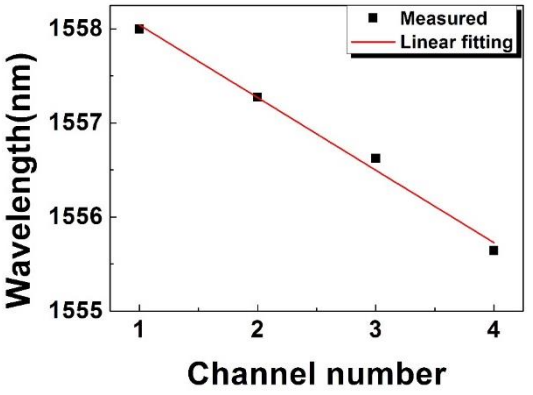






~0.8 nm





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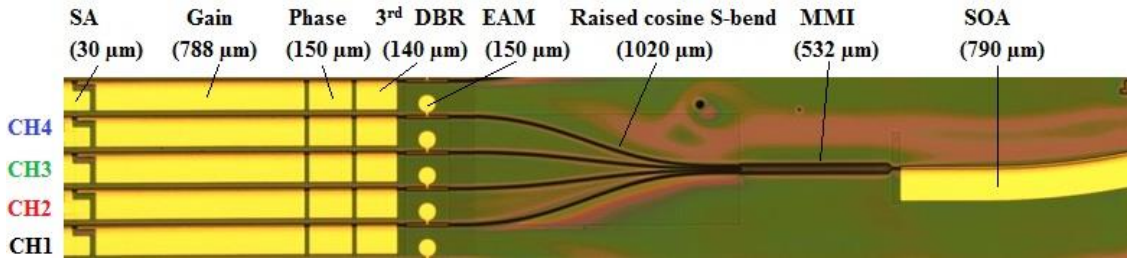
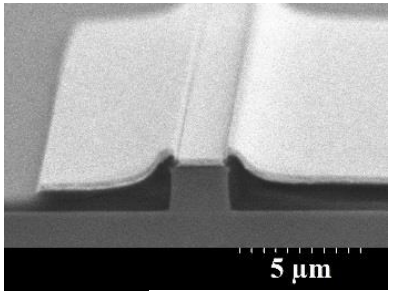
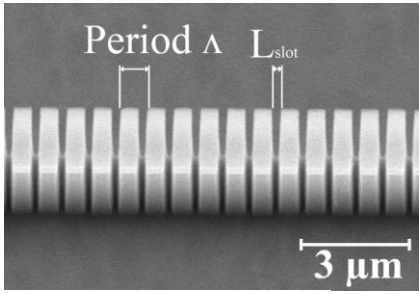
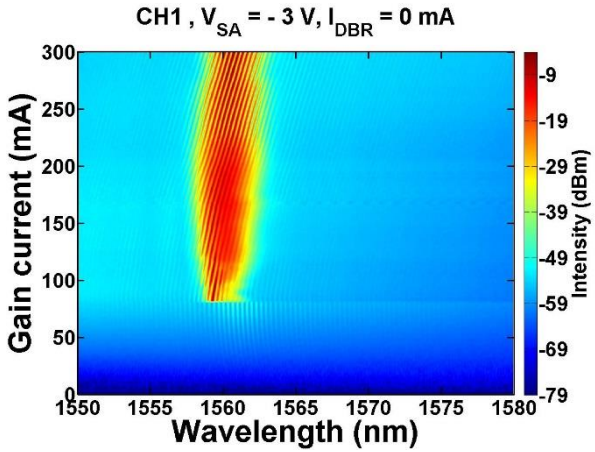
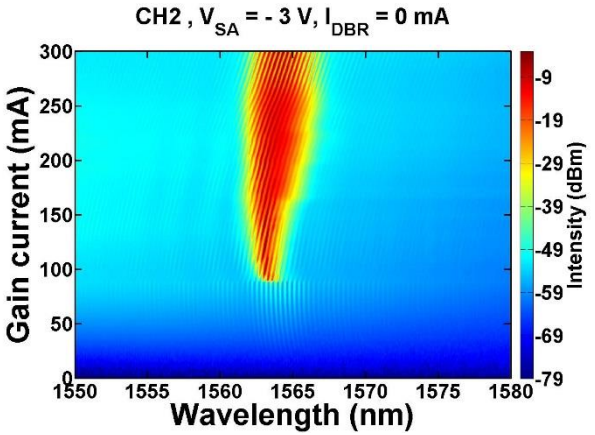
Monolithically multi-Colour 40 GHz Mode-locked laser array

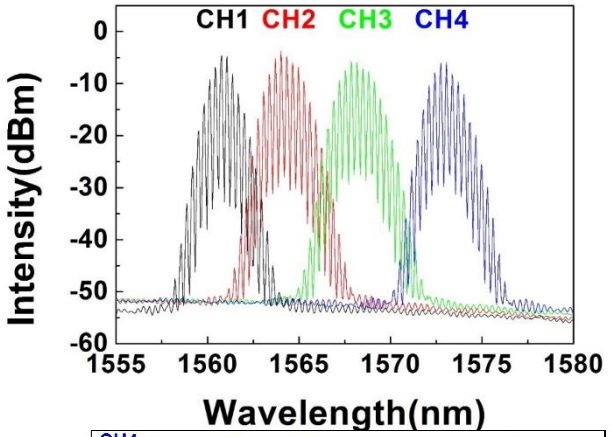


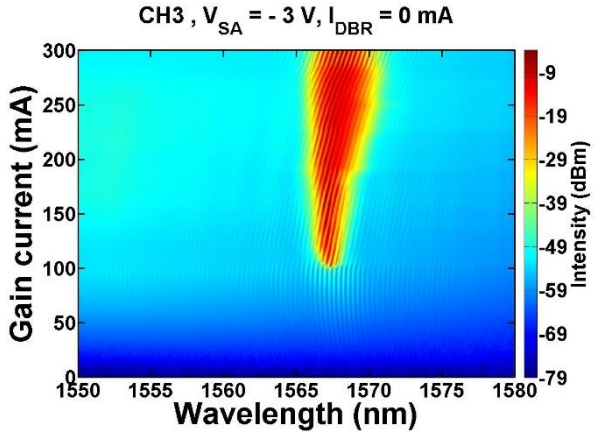


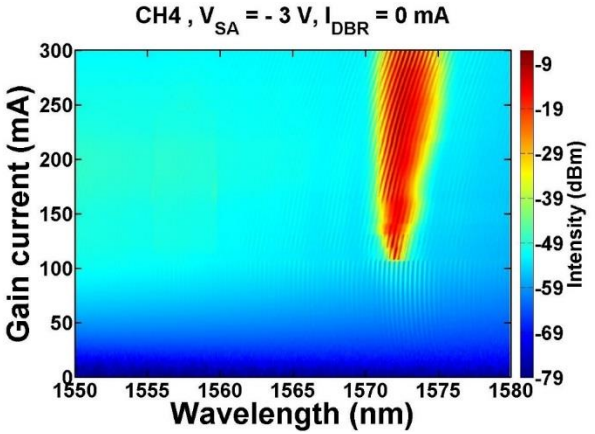


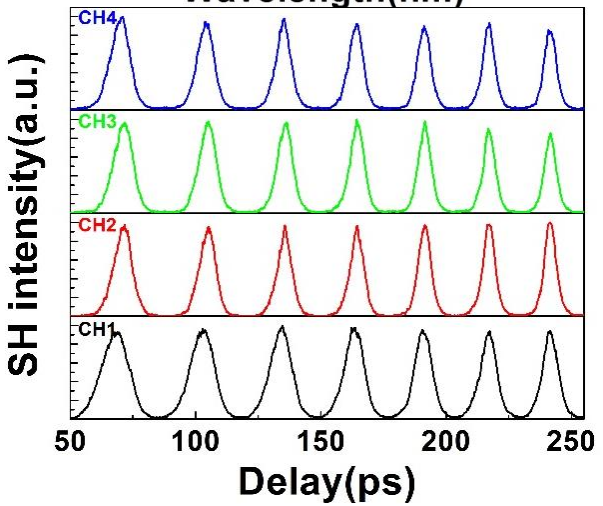






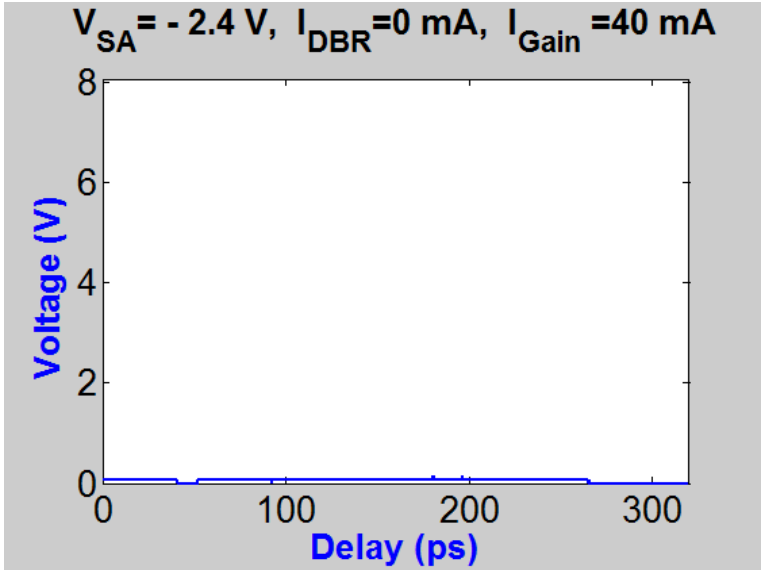




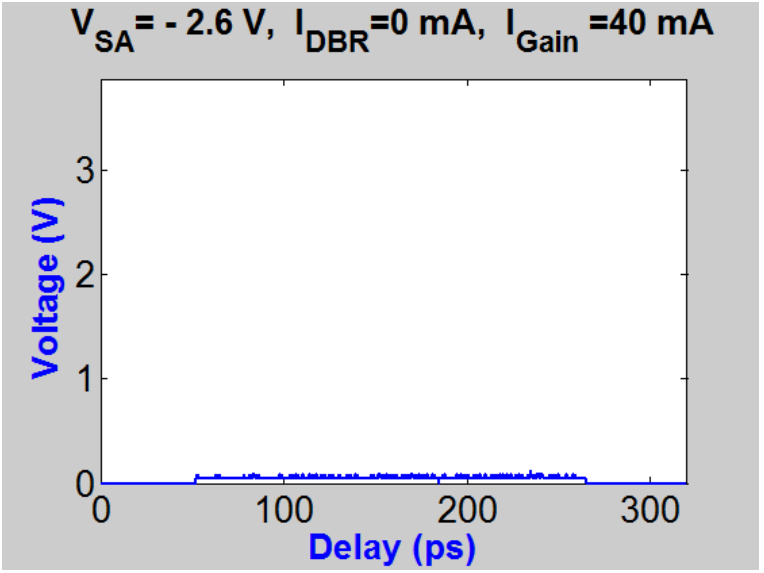


Four channels autocorrelation traces display

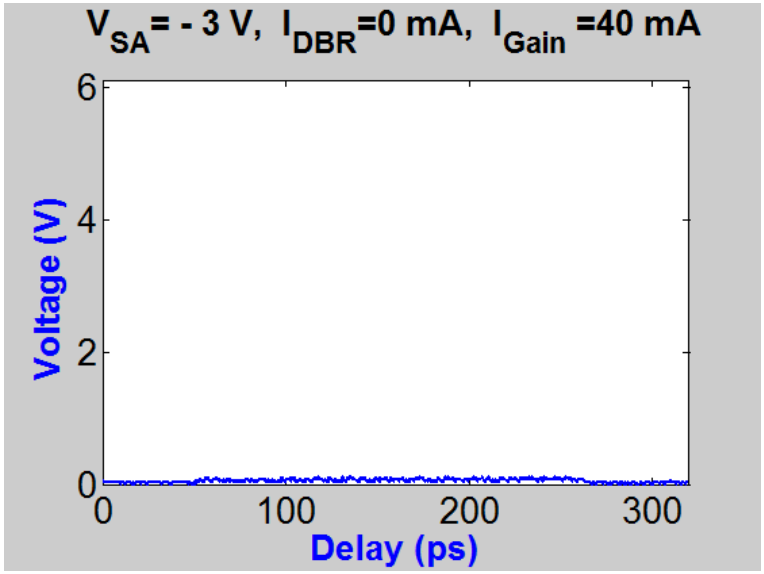
CH1



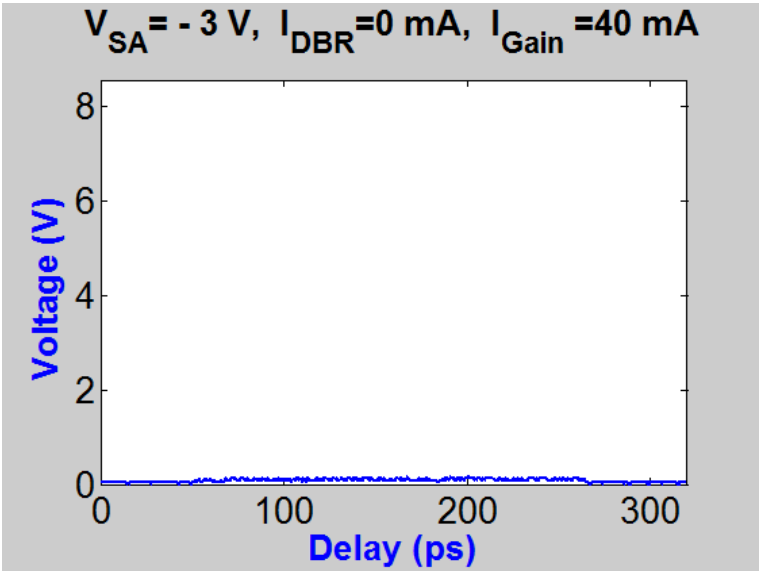
CH2



CH3

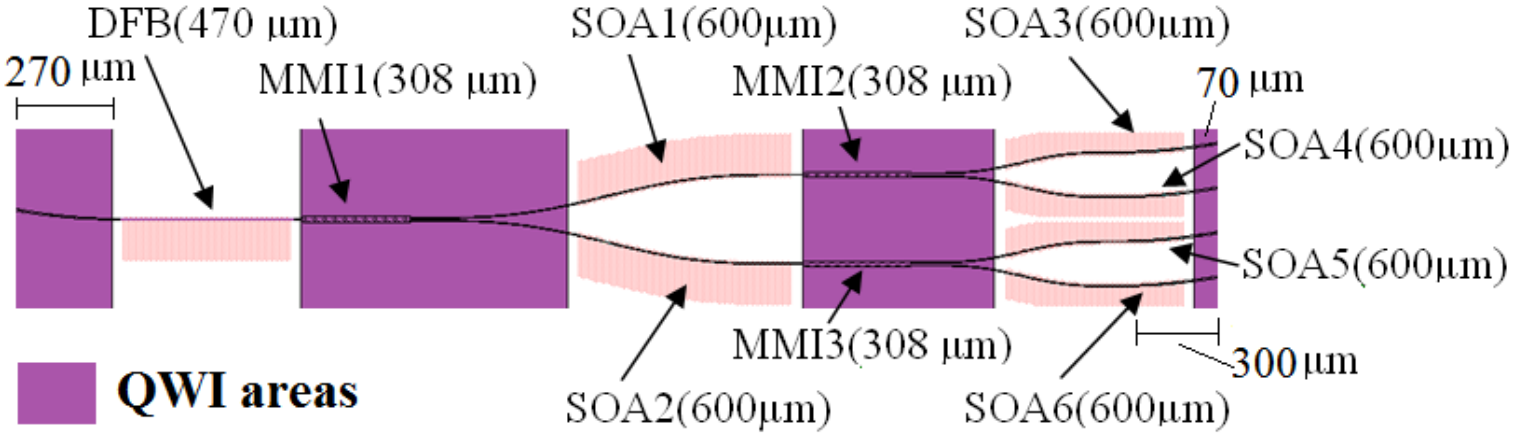


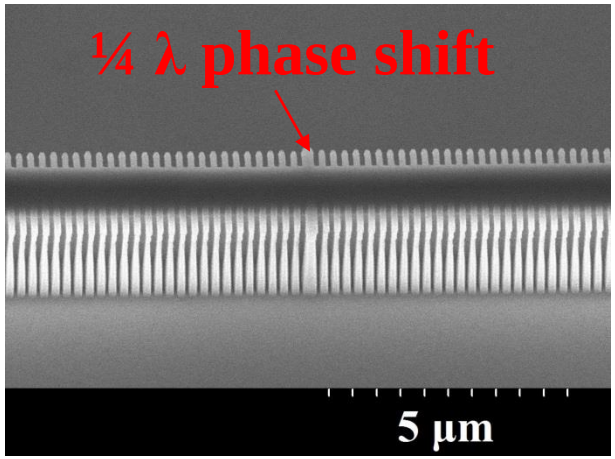
CH4

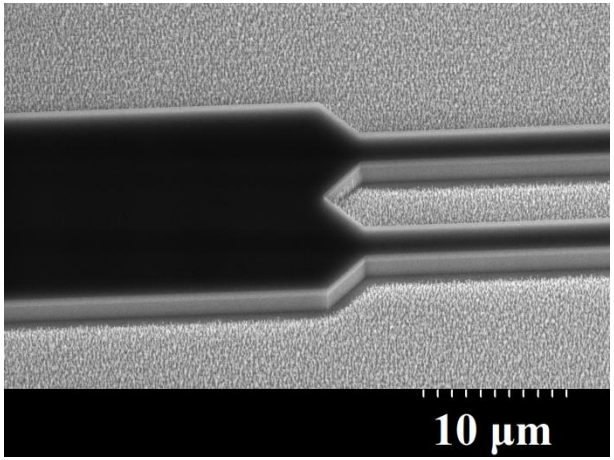


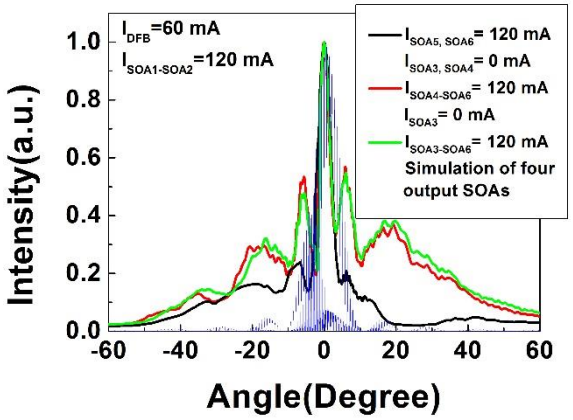
1.55 μm DFB Laser Monolithically Integrated with Power Amplifier Array

The 70- μm-long QWI area to the SOA3-SOA6 output region can dramatically improve the COD threshold current density, giving high reliability



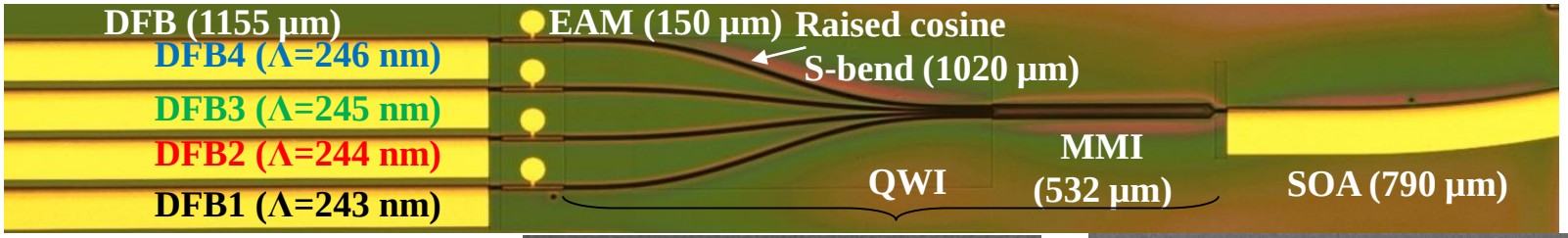


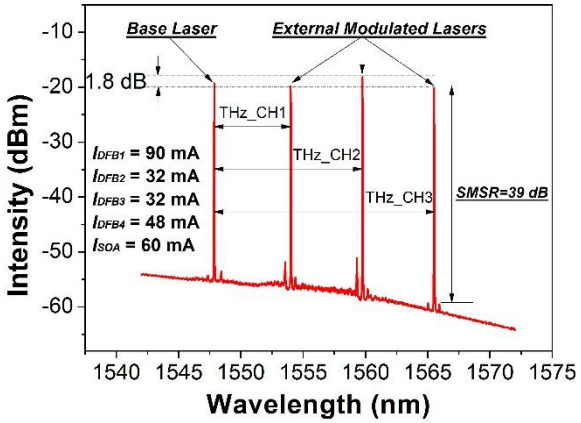


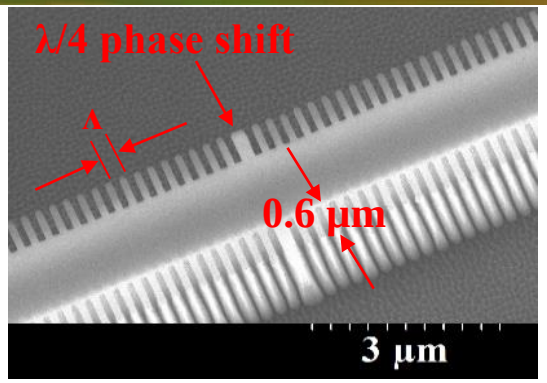


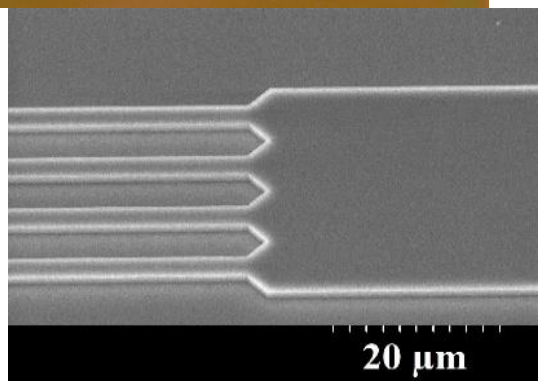
L. Hou, J. H. Marsh, "1.55 μm DFB laser monolithically integrated with power amplifier array," *Opt. Lett.*, Vol. 40, No.2, pp.213-216, 2015

Fully integrated optoelectronic synthesizer for THz communications

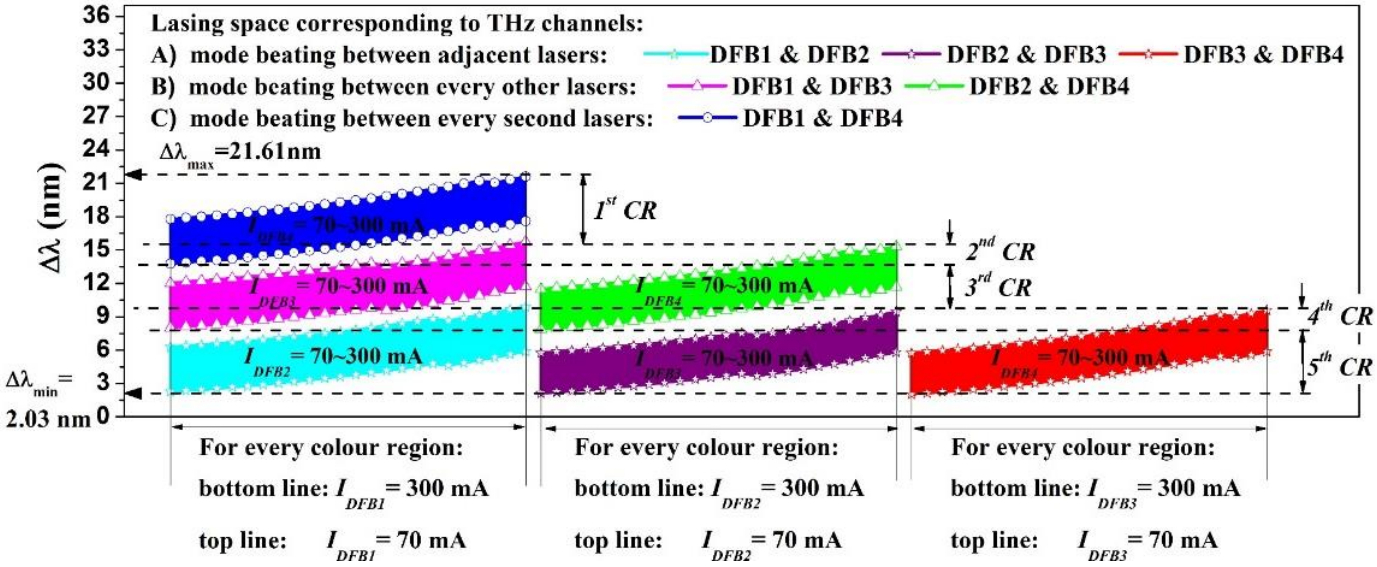








- **Optical beat signal can be tuned continuously from 0.254 THz to 2.723 THz.**
- **EAMs enable signal leveling and data encoding at data rates >5 Gb/s.**
- **PIC fabricated using regrowth-free, low-cost techniques.**
- **PIC has a degree of redundancy, making it suitable for high reliability applications.**



L Hou et al., *Scientific Scientific Reports Reports*, DOI: 10.1038/srep29084, 2016.

THz by photo-mixing

Photonics-based Tx & Direct Detection

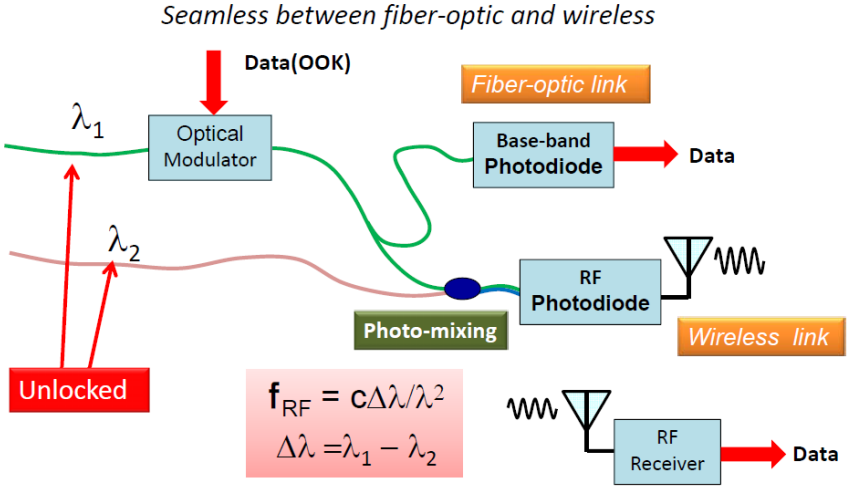
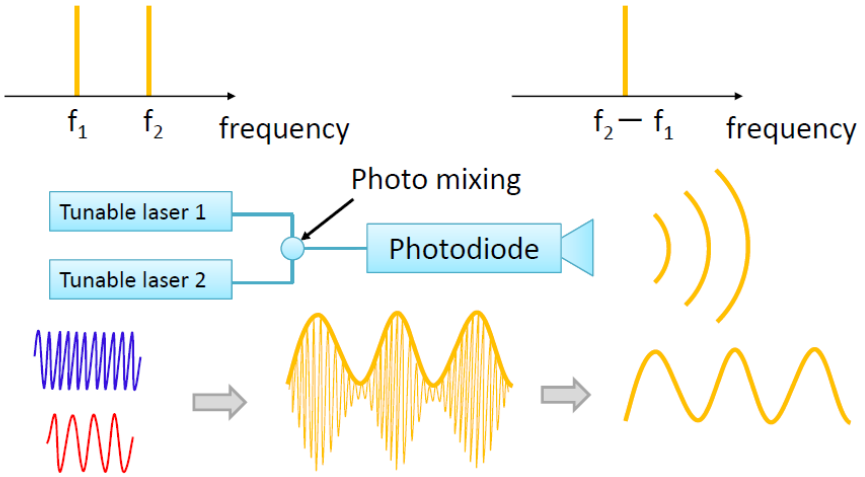
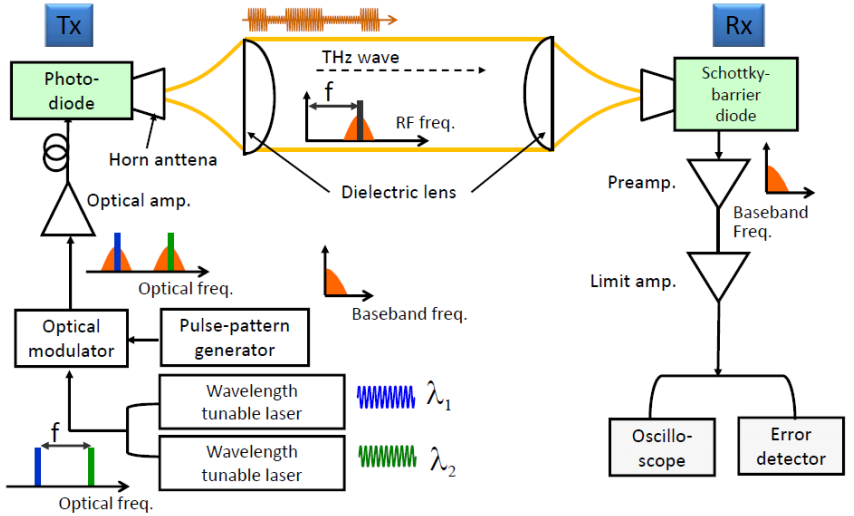
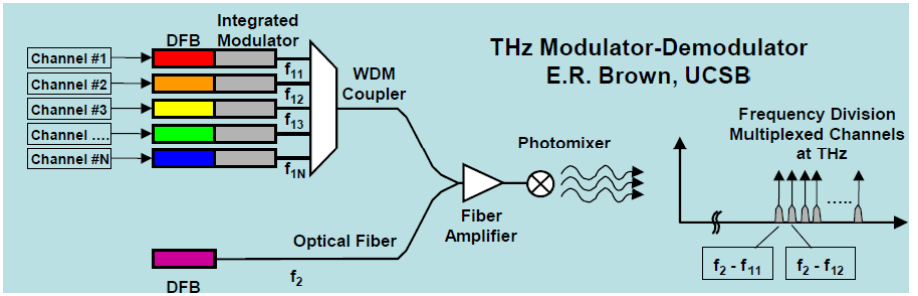


Photo-mixing



300-GHz Band Experiment





Could be entire THz range (0.3-3 THz)

ITU-designated band of frequencies from 0.3 to 3 THz

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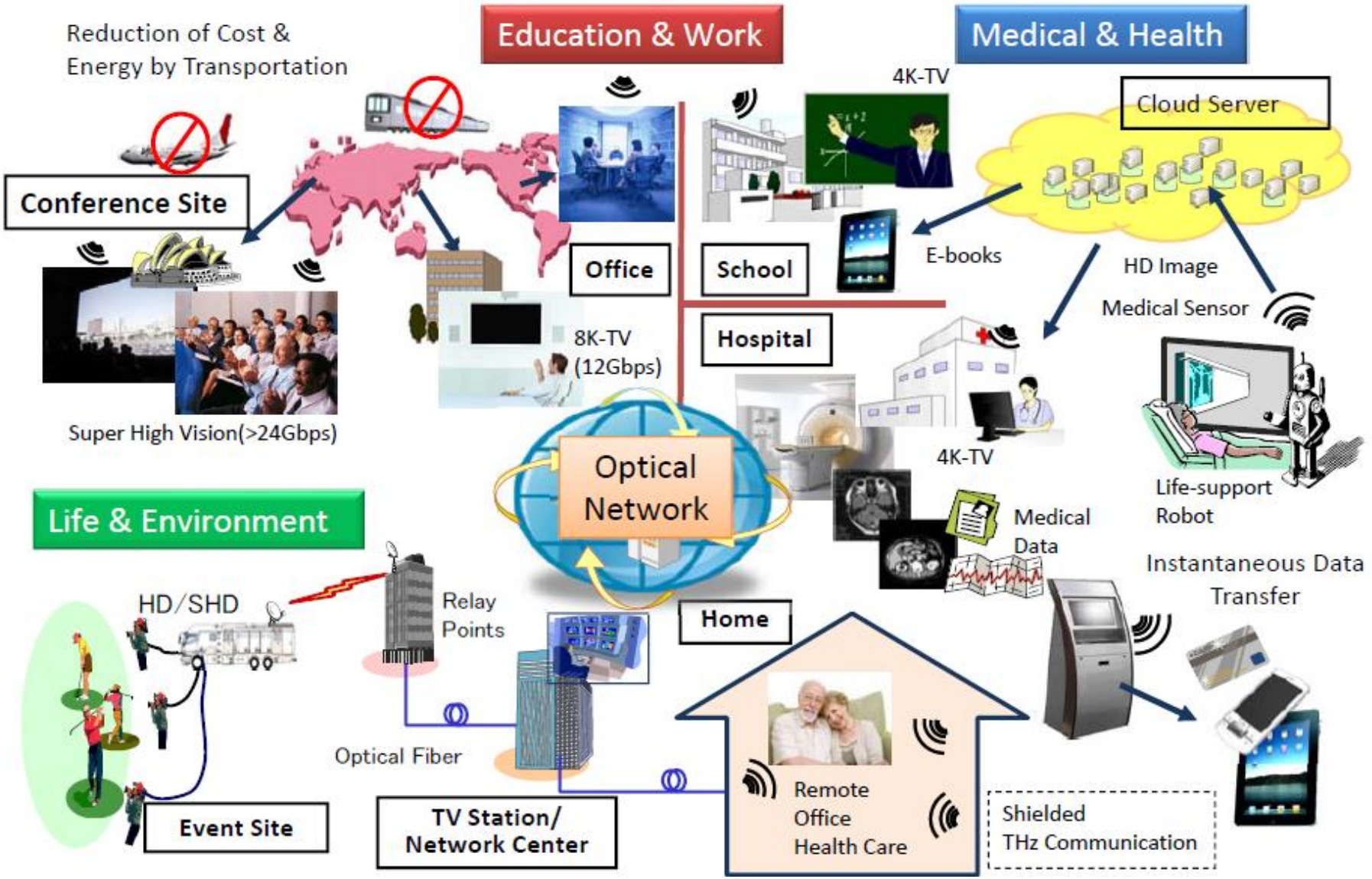
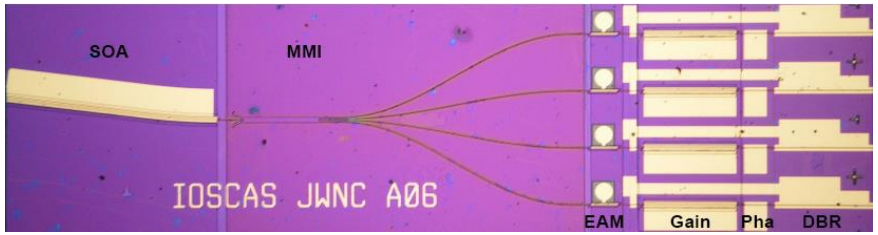
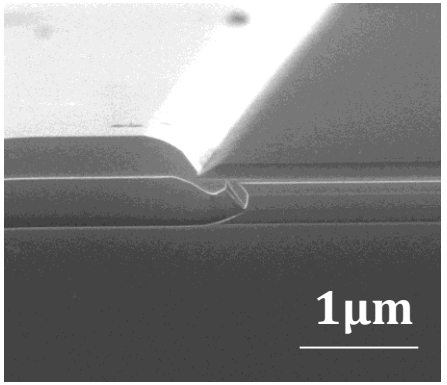
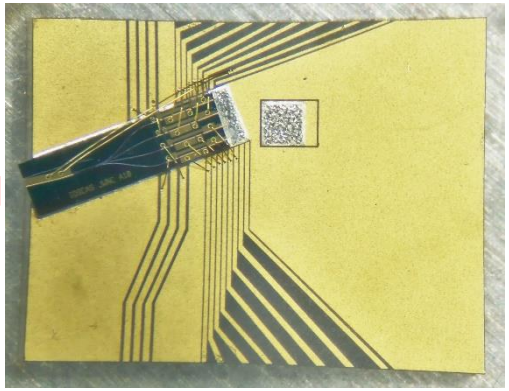
THz communication application



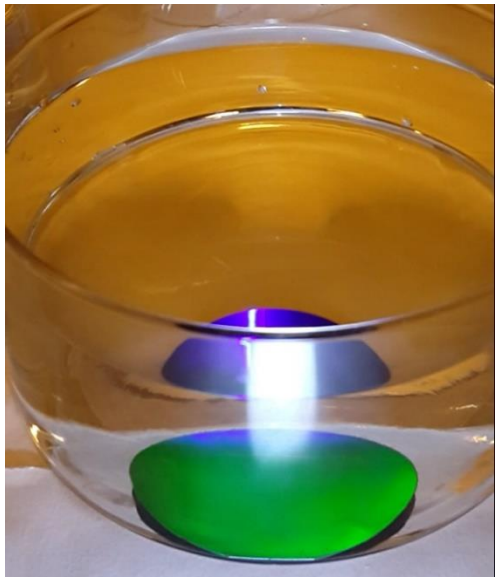
EAM modulated DBR laser array for TWDM-PON application

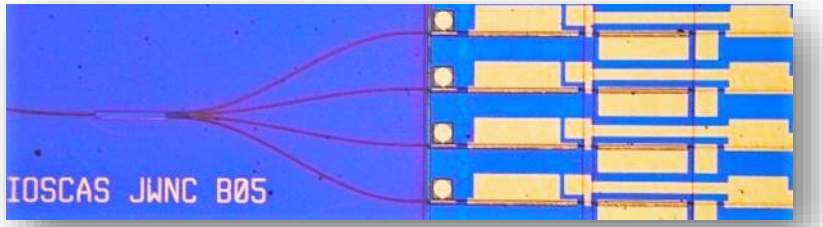


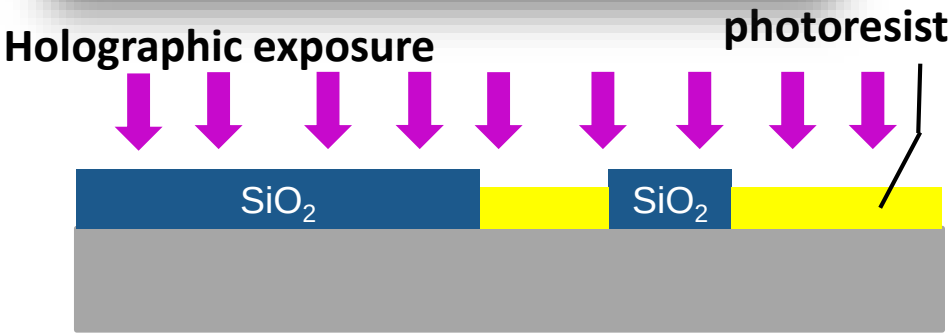




Holographic grating process

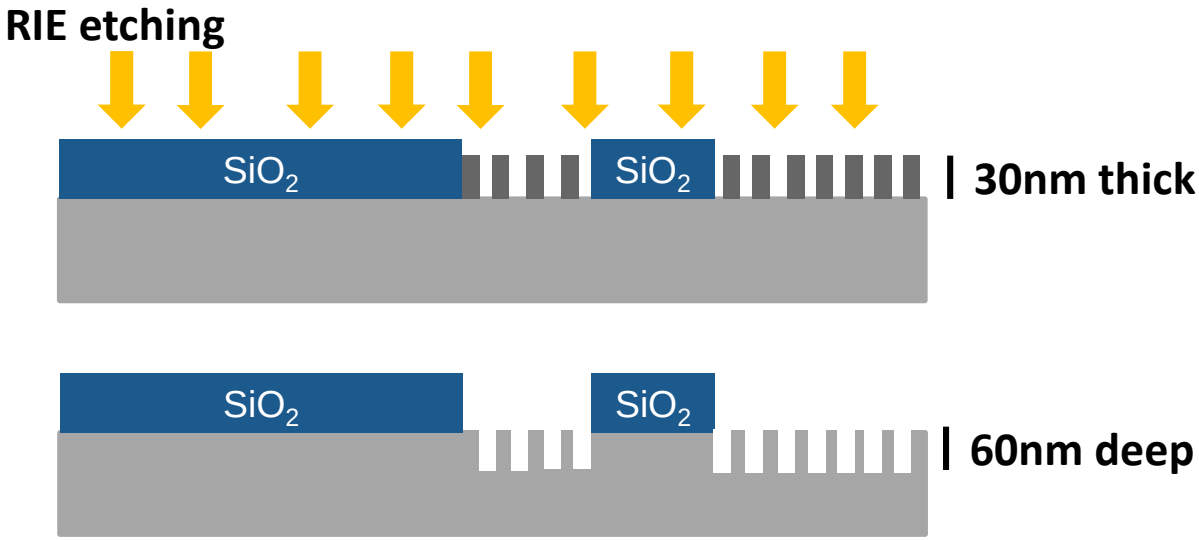




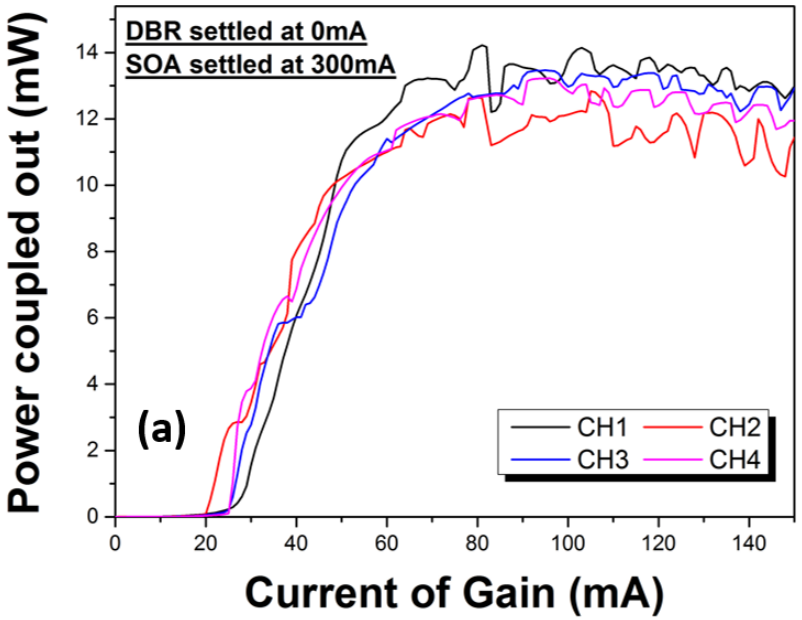


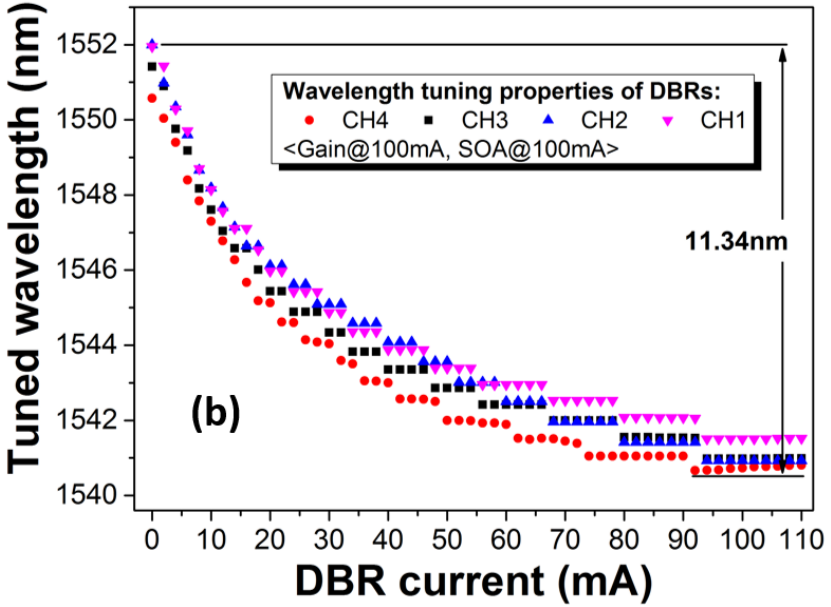
Advantages:

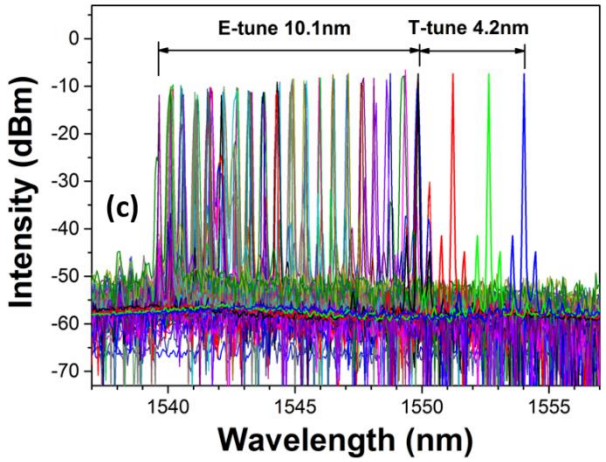
- Uniform gratings on selected area covers the whole wafer.
- Meet the demands of high yield fabrications with low cost and time saving.
- The quality of the process can be under control through identifying the photoresist morphology by SEM, without damage the structure on the wafer.

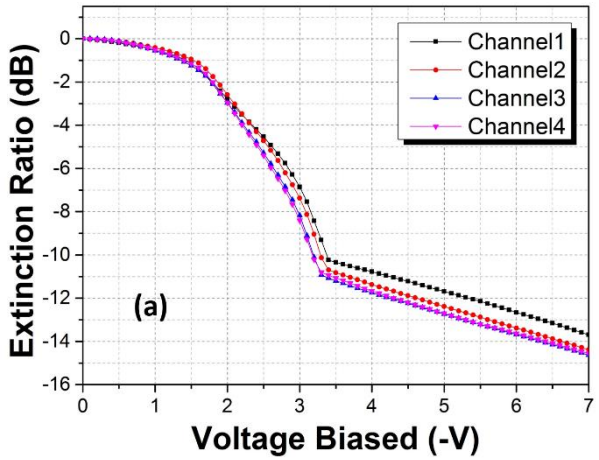


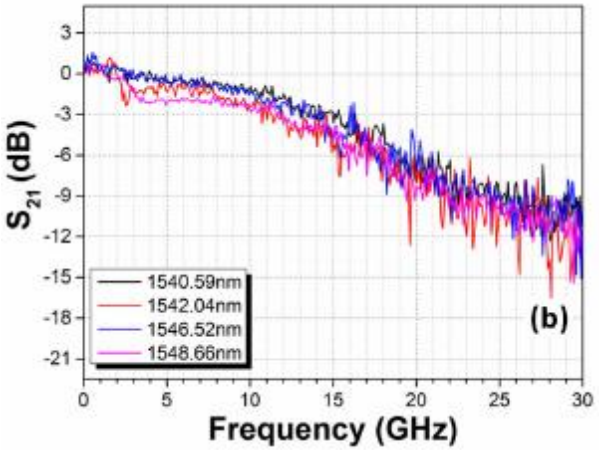
Device performance





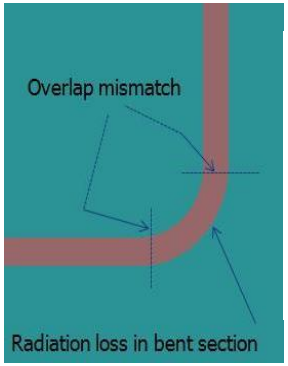




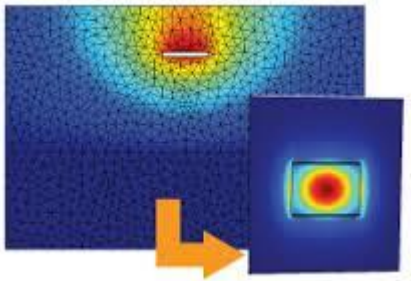


Software to design, analysis and optimization of the integrated optical waveguides

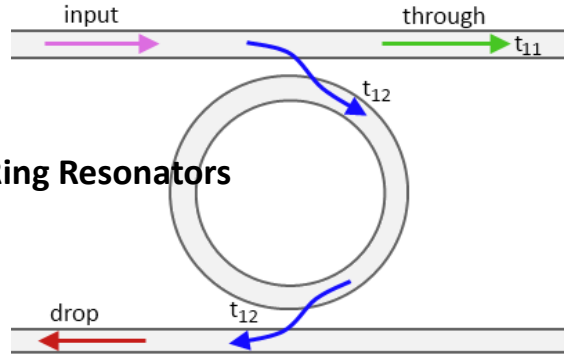
Propagation loss simulation in bend section



Mode Solutions



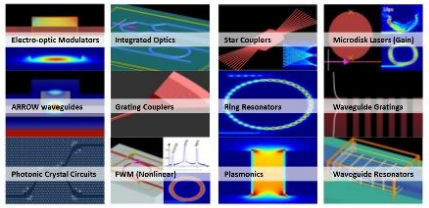
Analysis and optimization of integrated optical waveguides, components and fibers



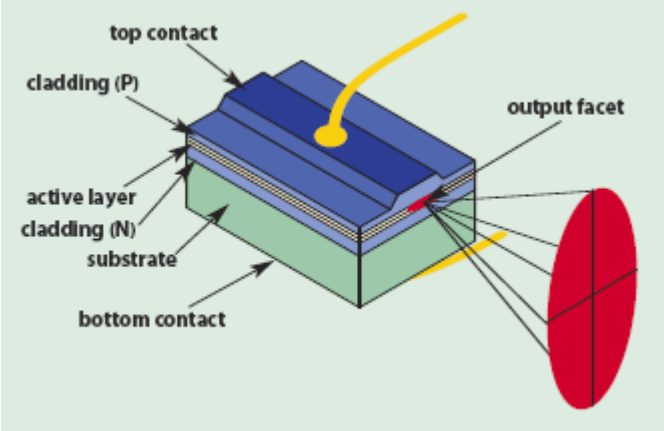
Ring Resonators

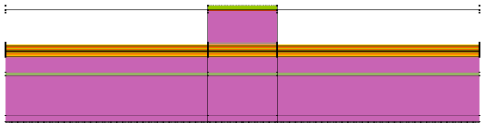
FDTD Solutions

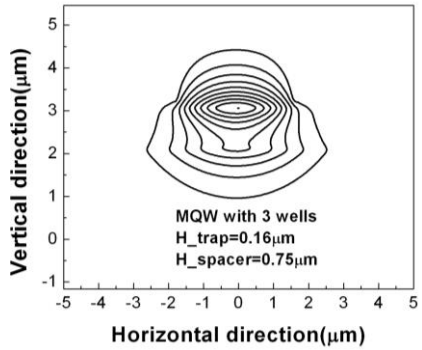
Applications: Integrated Optics

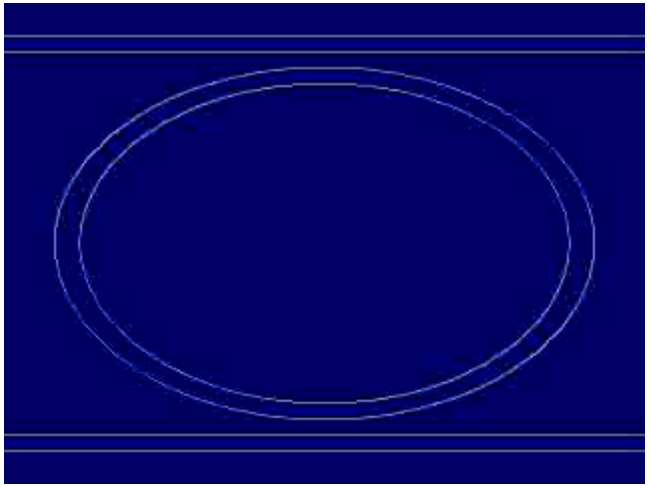


3D FDTD-method Maxwell solver for the design, analysis and optimization of nanophotonic devices, processes and materials









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What is silicon photonics

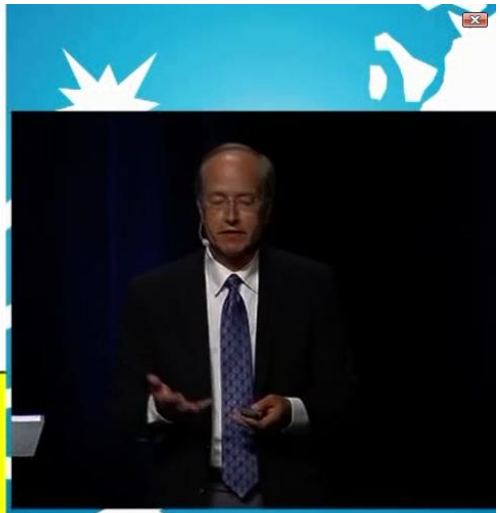
UCSB

What is Silicon Photonics?

- Making photonic integrated circuits on Silicon using CMOS process technology in a CMOS fab
- Merging photonics and CMOS

The issue is not InP or GaAs versus Si.
The issue is not VCSELs versus PICs
The issue is

1) Scaling photonics to high levels of integration with improved performance and better process control at low cost.
2) Wafer scale testing
3) Low cost packaging
4) WDM and scaling to >1 Tb/s
5) Solving electrical interconnect limits in Data centers, Supercomputers and ICs with higher capacity, lower cost optical interconnects



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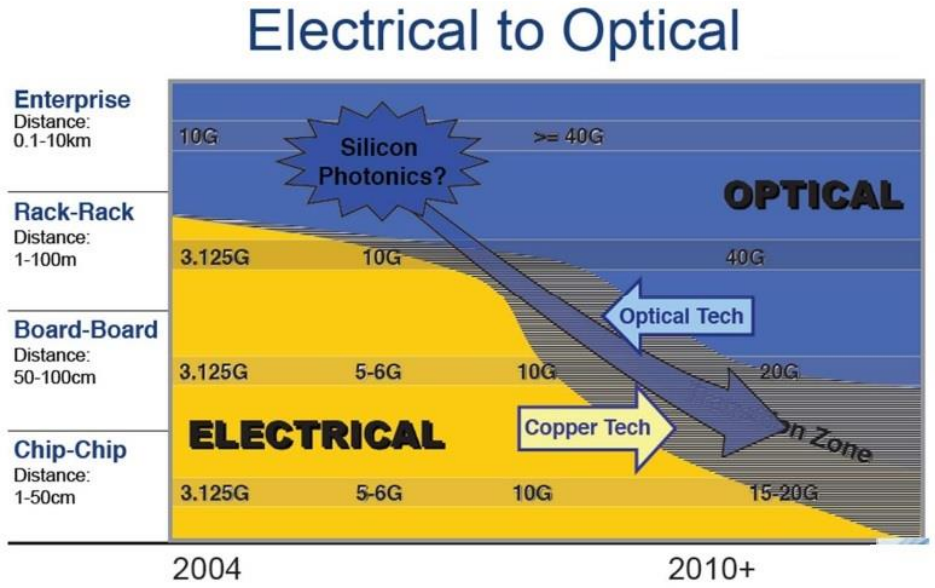
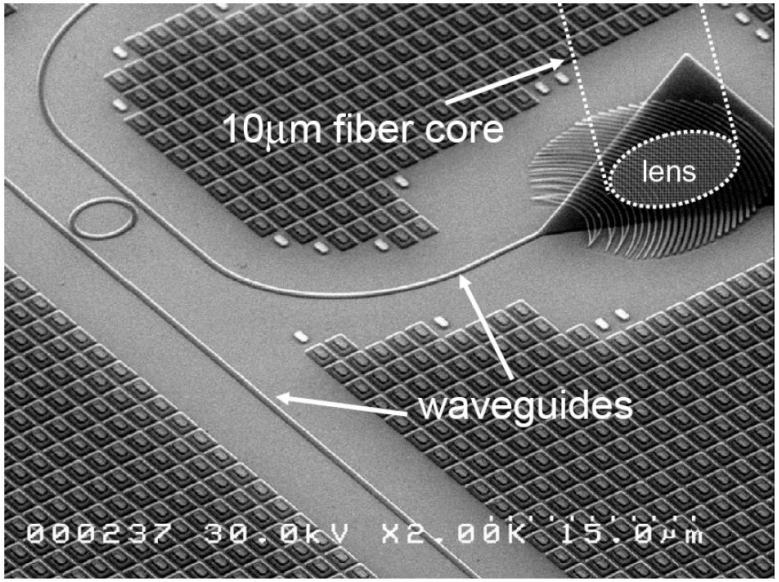
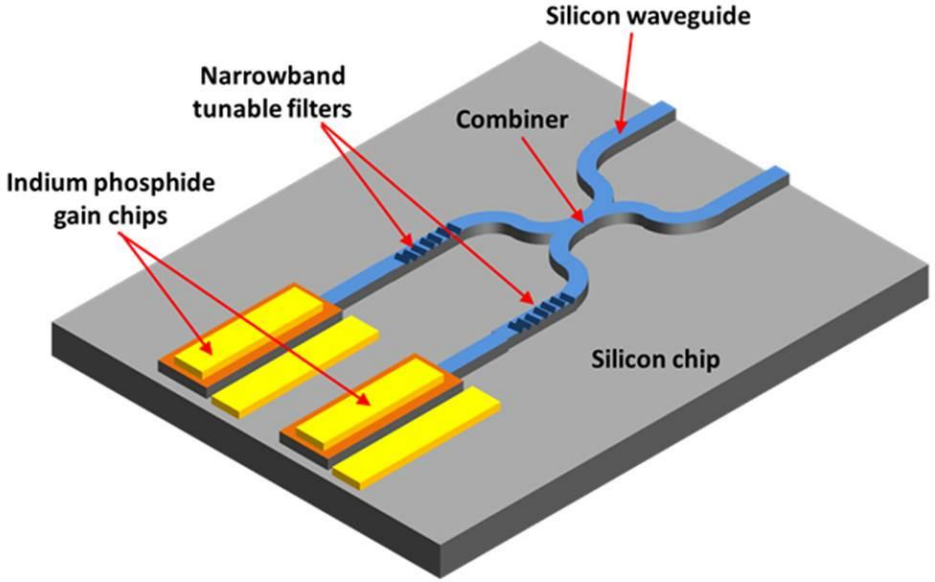
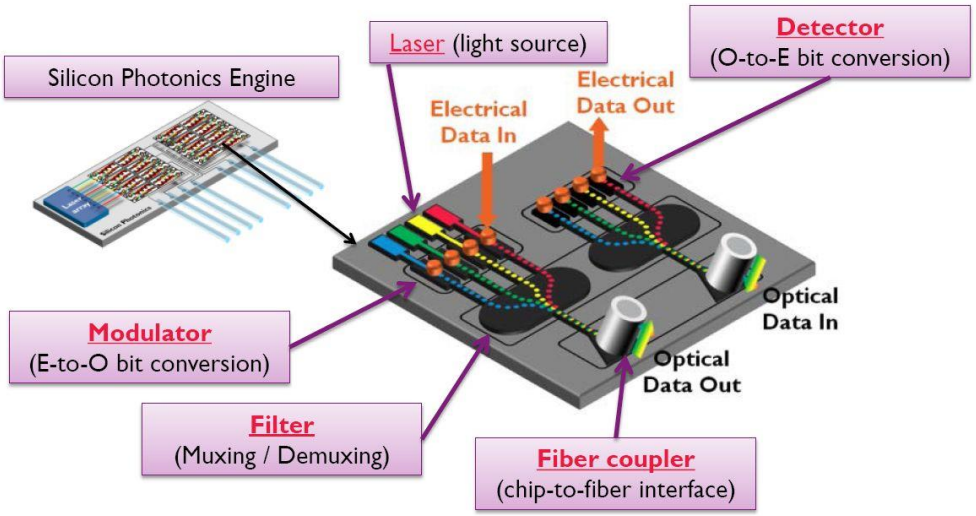
Silicon photonics -a solution to chip interconnects







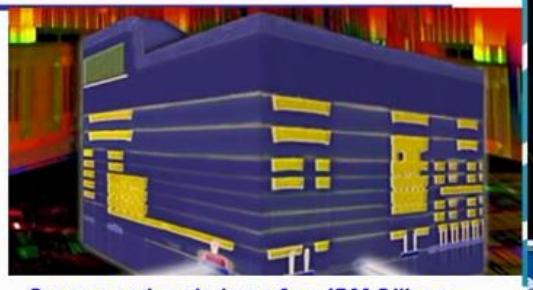


Why silicon photonics?

UCSB

Why Silicon Photonics?

- Integrate photonics with electronics
  - Same wafer
  - Bump bonding of silicon PIC with silicon IC
    - Same coefficient of thermal expansion
  - 3D stacking



Cross-sectional view of an IBM Silicon Nanophotonics chip combining optical and electrical circuits
Vlasov et al. IEDM postdeadline

- Reduce cost by going to larger diameter wafers (300 mm)
  - InP limited by wafer breakage to 100 mm diameter
- Reduce cost by sharing VLSI facility with electronics
- Improve yield by taking advantage of silicon process development
- Volume driver: Solve IC interconnect bottleneck (from 4 Tbps to 1 Pbps). Embedded transmitters/receivers on processors, memories, switches (see Intel/Altera commercialization slide)

69

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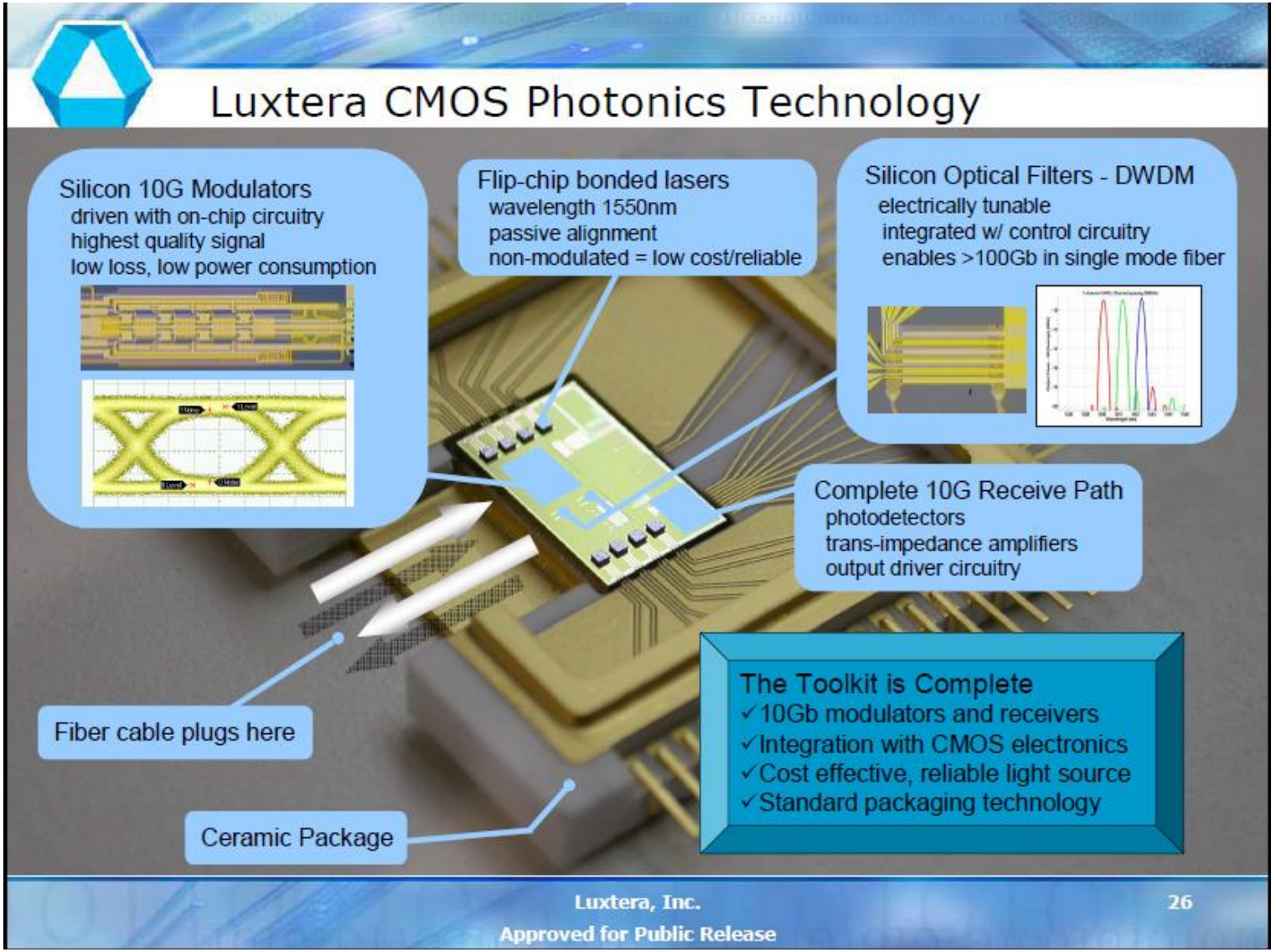
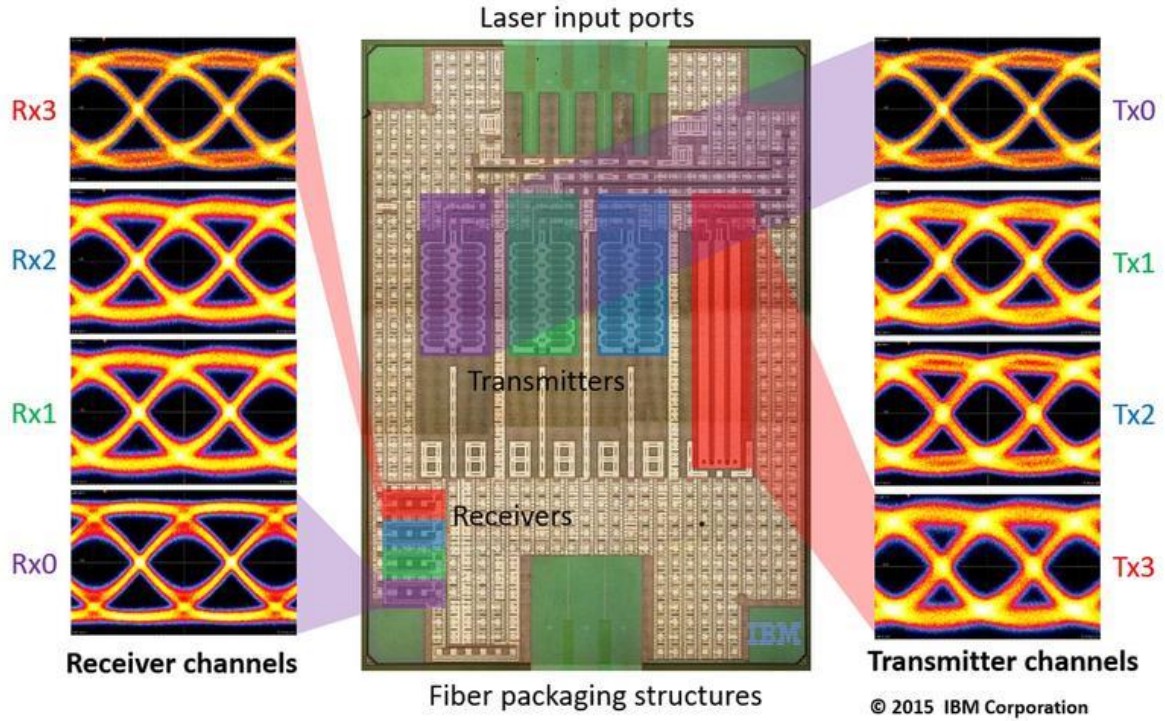
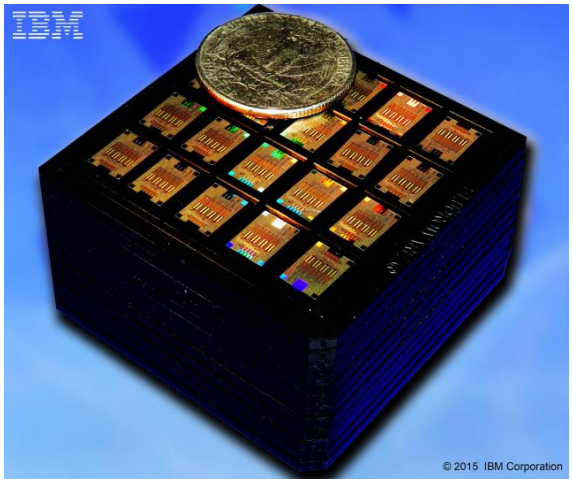
Integrated optics future-with CMOS process

Si Nanophotonics with CMOS process



Fully integrated wavelength multiplexed silicon photonics chip

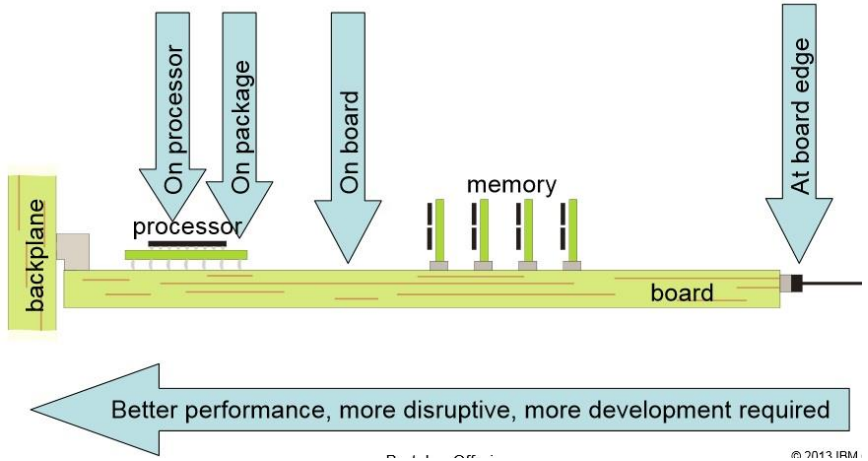


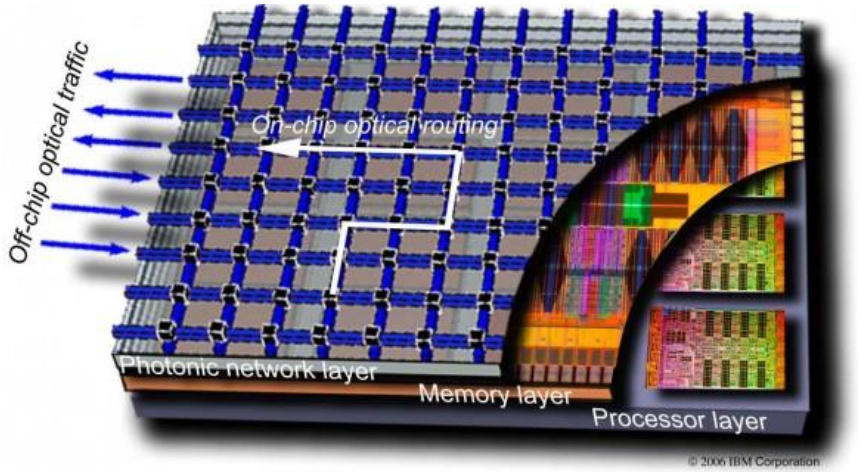


http://arstechnica.co.uk/information-technology/2015/05/ibm-demos-first-fully-integrated-monolithic-silicon-photonics-chip/

The point where electro-optical conversion takes place moves closer to the processor

– Card edge optics → Board-level optics → Optics on processor package





Attachments

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Electronics and Nanoscale Engineering: James Watt Nanofabrication Centre

Vistec VB6

Süss MA6 optical lith

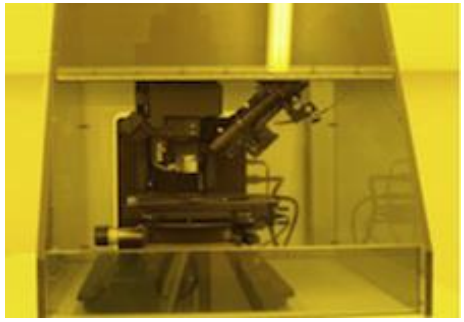
- 750 m^2 cleanroom - quasi-industrial operation
- 13 technicians + 4 PhD research technologists
- Part of EPSRC III-V National Facility
- Kelvin Rutherford – venture with STFC
- Preferred partner status with DSTL
- Commercial access through Kelvin NanoTechnology

10 RIE / PECVD

4 Metal dep tools

4 SEMs: Hitachi S4700

Veeco: AFMs



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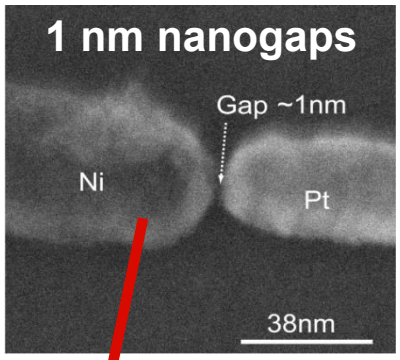
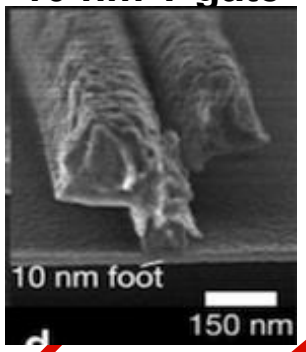
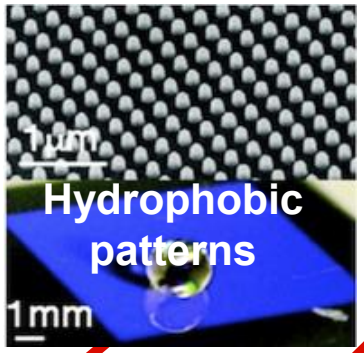
Nanotechnology at Glasgow

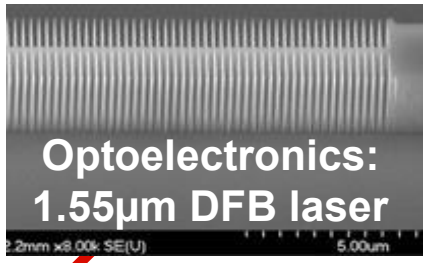
1 nm nanogaps



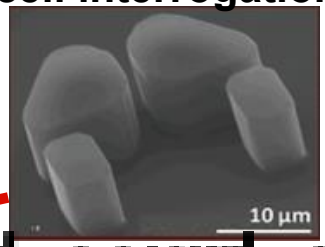
Nanoelectronics:
10 nm T-gate



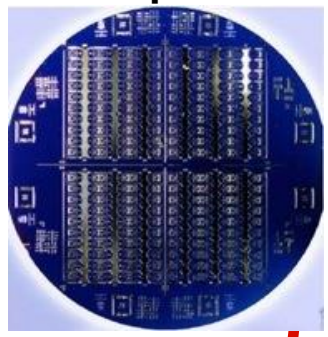




Healthcare: STEM cell interrogation

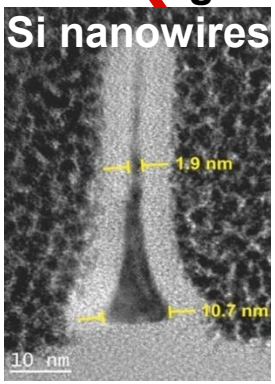


Manufacture:
AFM probes

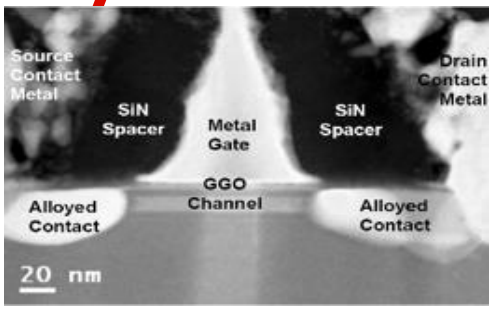


10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} metres

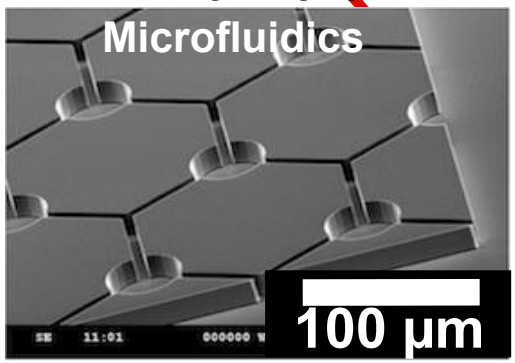
Sensing:
Si nanowires



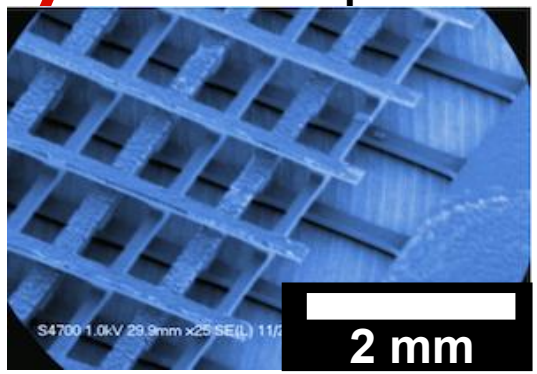
III-V CMOS



Environment:
Microfluidics



MEMS: THz optics



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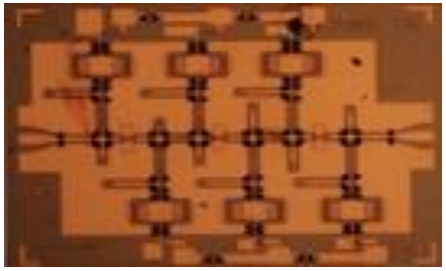
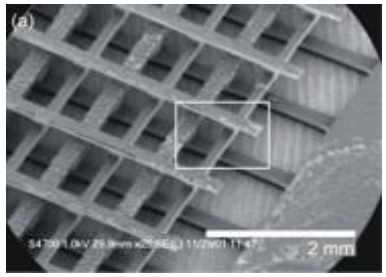
Nanotechnology Applications

Defence & Security



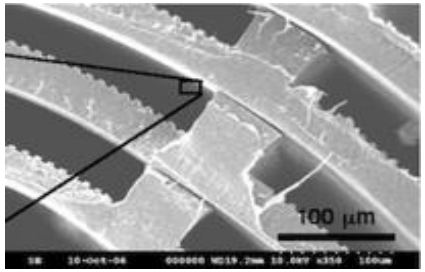
MMICs: 183 GHz LNA

MIR QC laser counter measures

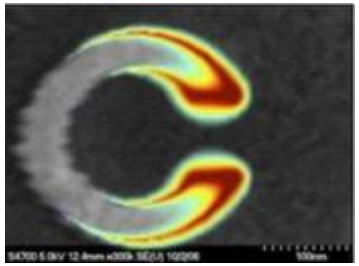


THz / mm-wave optics

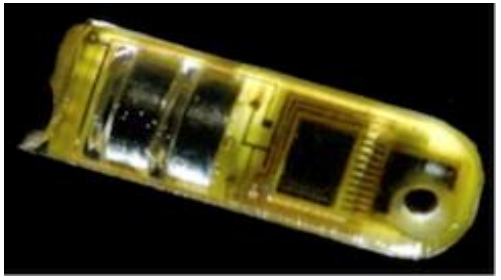
Healthcare



Medical scaffolds



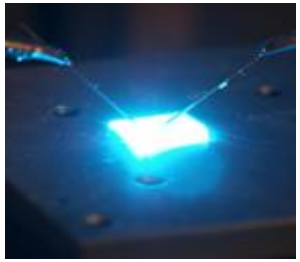
Plasmon sensors for cancer detection



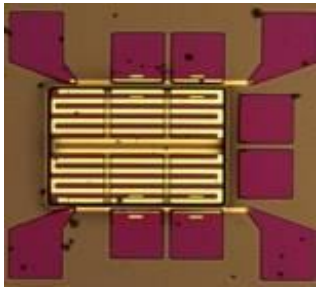
Lab-on-a-pill

Energy

PV cells

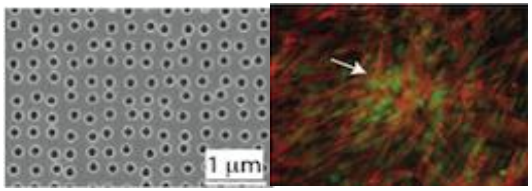


GaN white light LEDs

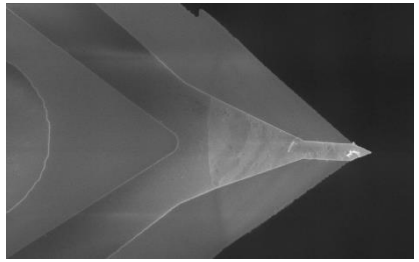


TE energy harvesting

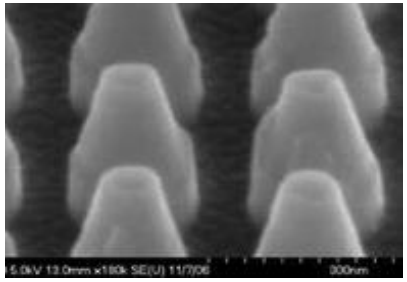
Nanoscience



Directed STEM cell growth

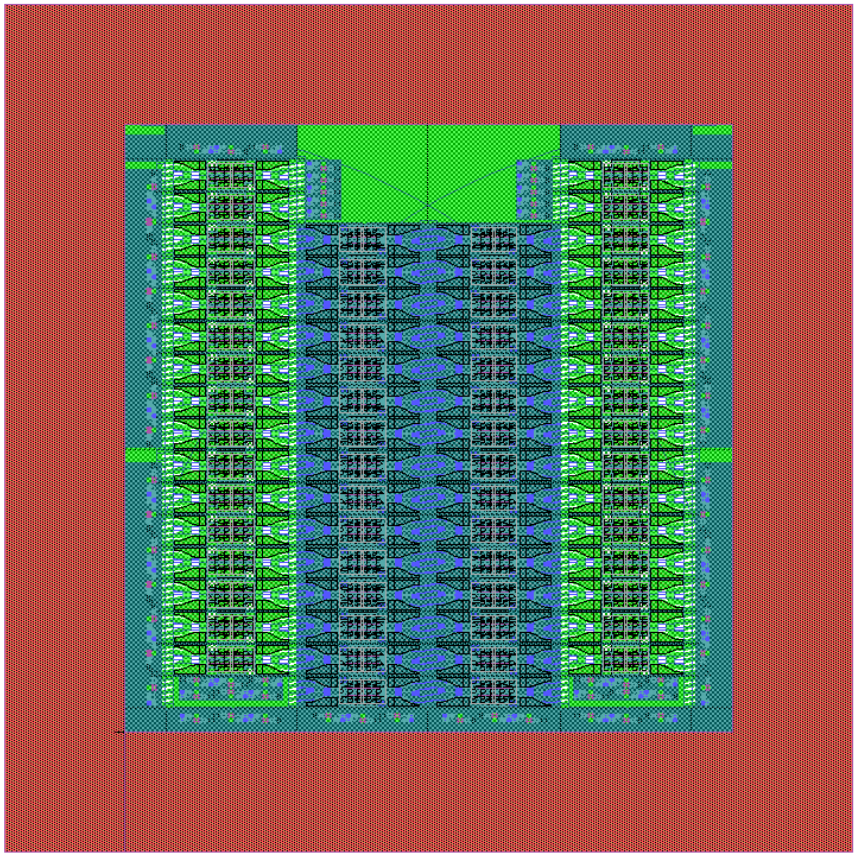


Electrochemical AFM

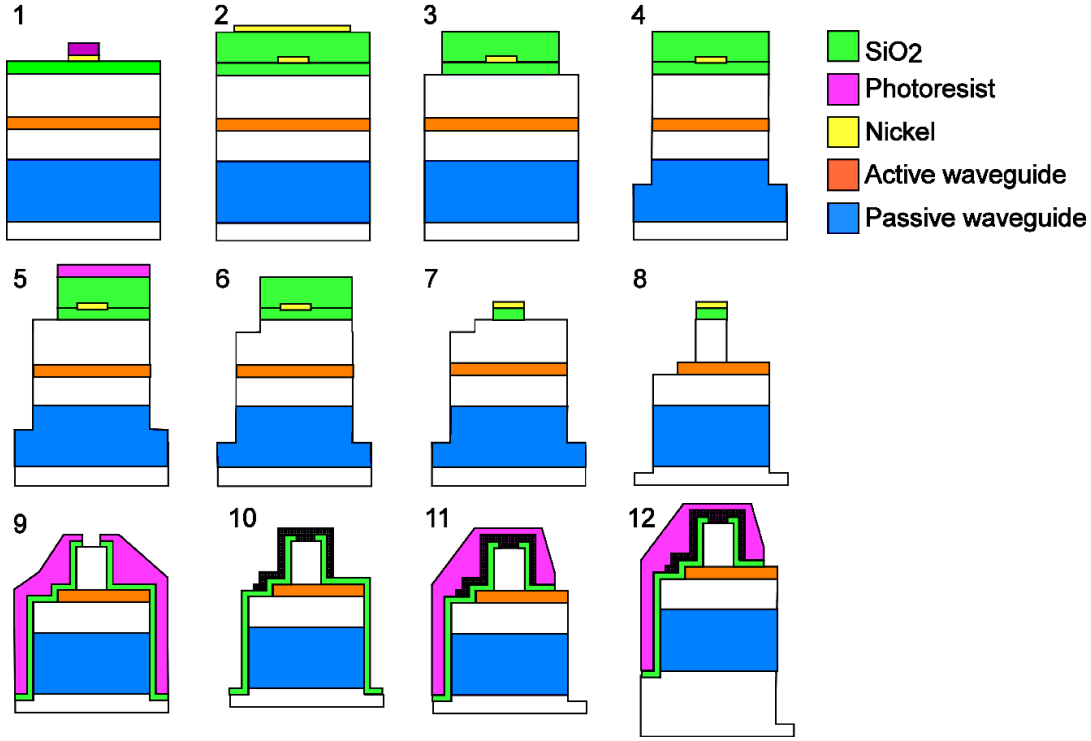


Magnetic rock sensors

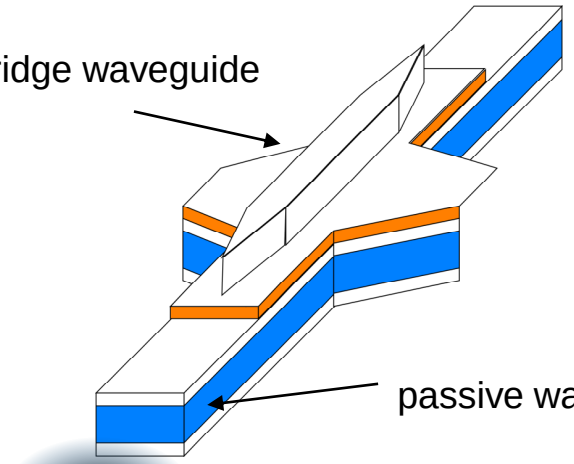
PIC mask and fabrication processes



deep etch active contact
surface self-aligned window



SOA active ridge waveguide



passive waveguide

University of Glasgow

Fabrication process of the RWG DFB laser buried by BCB polymers