ON-CHIP PHOTONICS ERBIUM-DOPED LASER FOR LIDAR APPLICATIONS

Integration of Amplifiers in Silicon Nitride Photonic Circuits

OFC *Photonic Devices for Novel Applications* – March 7th, 2023

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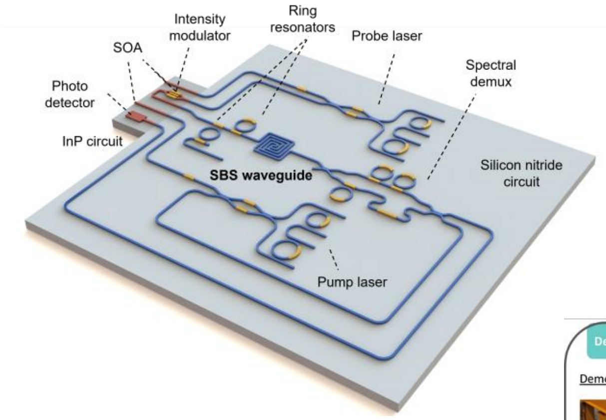
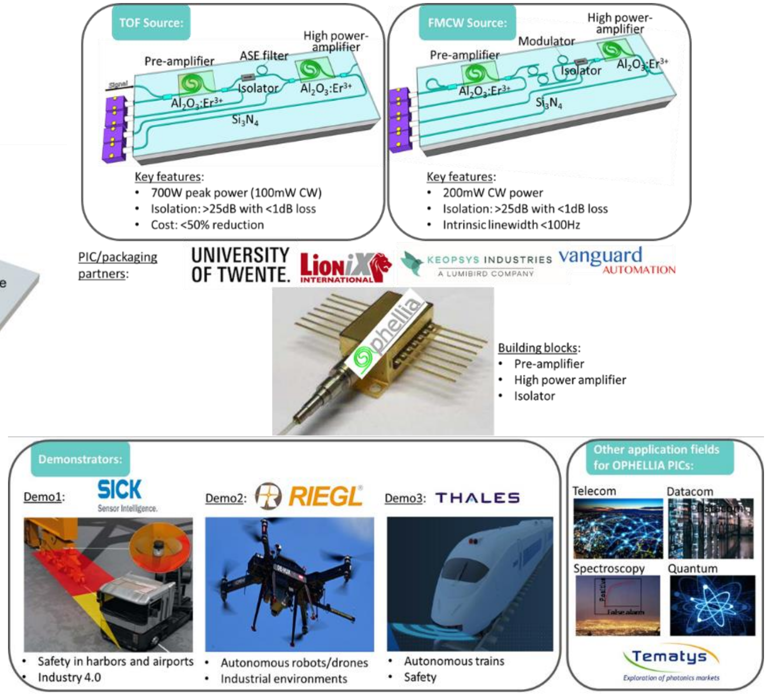
INTEGRATED PHOTONICS AT THE UNIVERSITY OF TWENTE

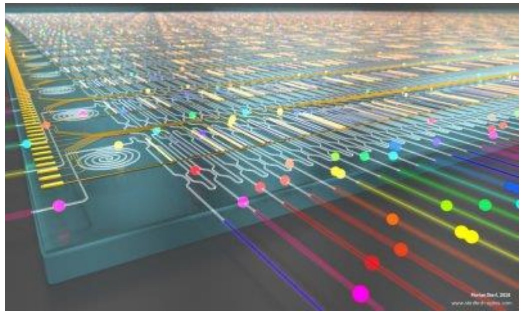
At the UT we carry out research in Integrated Photonics covering materials, devices and systems for different applications, including RF photonics, LiDAR, sensing and quantum technology



Brillouin gain in Si_3N_4



Integrated LIDAR systems



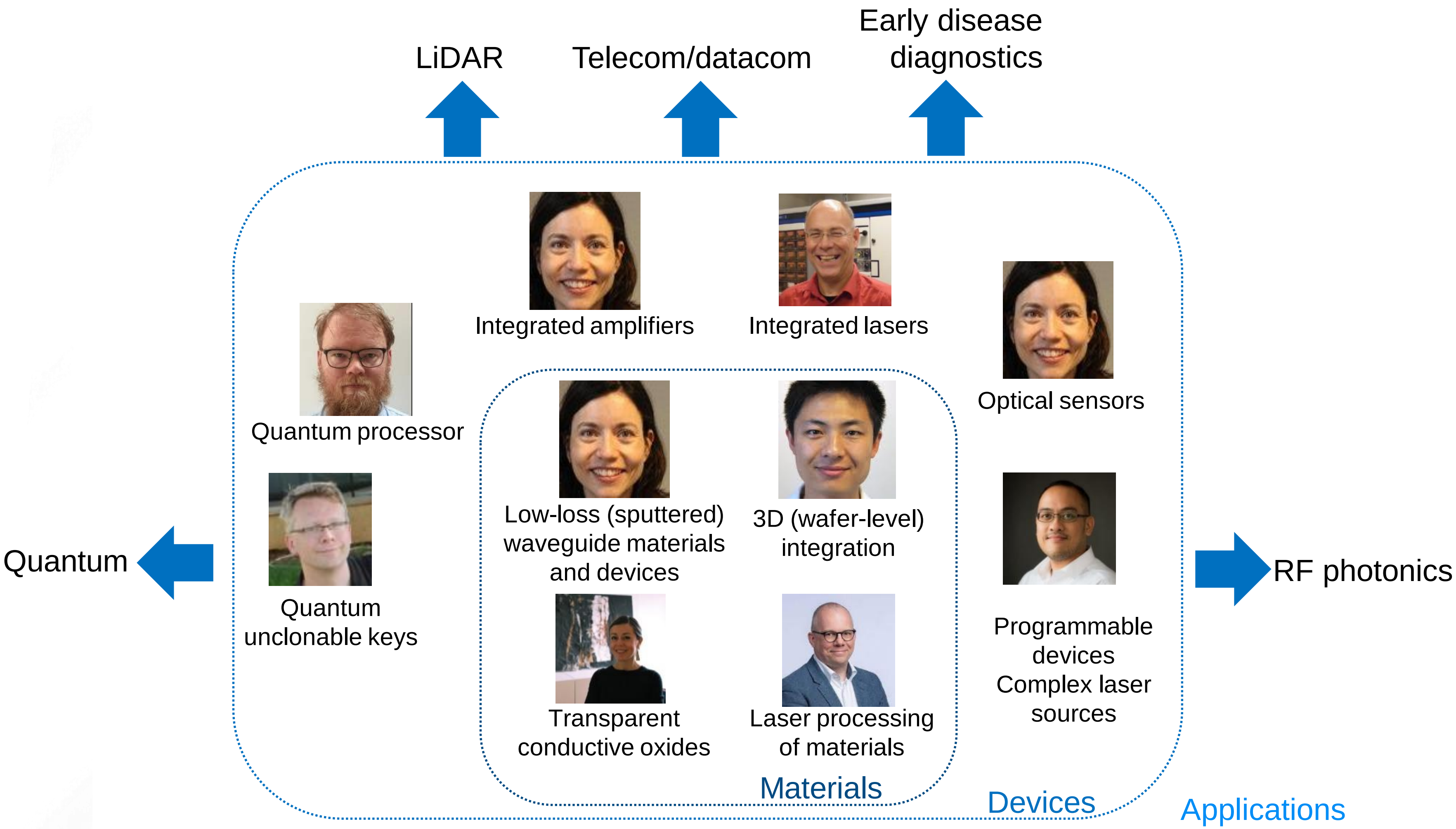
Quantum processing

MESA+ NANOLAB

MESA+ INSTITUTE

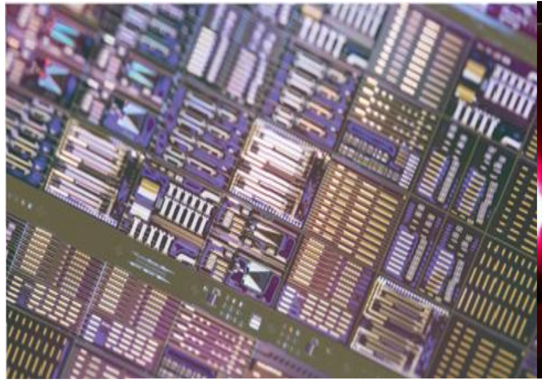
- 1250 m^2 Class 10,000 cleanroom
- 1000 m^2 of specialized equipment
- Deposition (PVD + CVD), lithography, e-beam, SEM, TEM, etching, dicing, annealing etc.

INTEGRATED PHOTONICS TWENTE

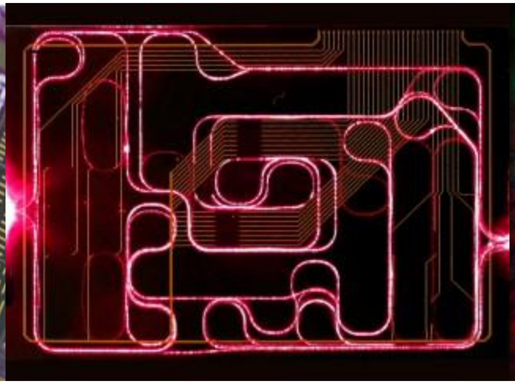


INTEGRATED PHOTONIC PLATFORMS

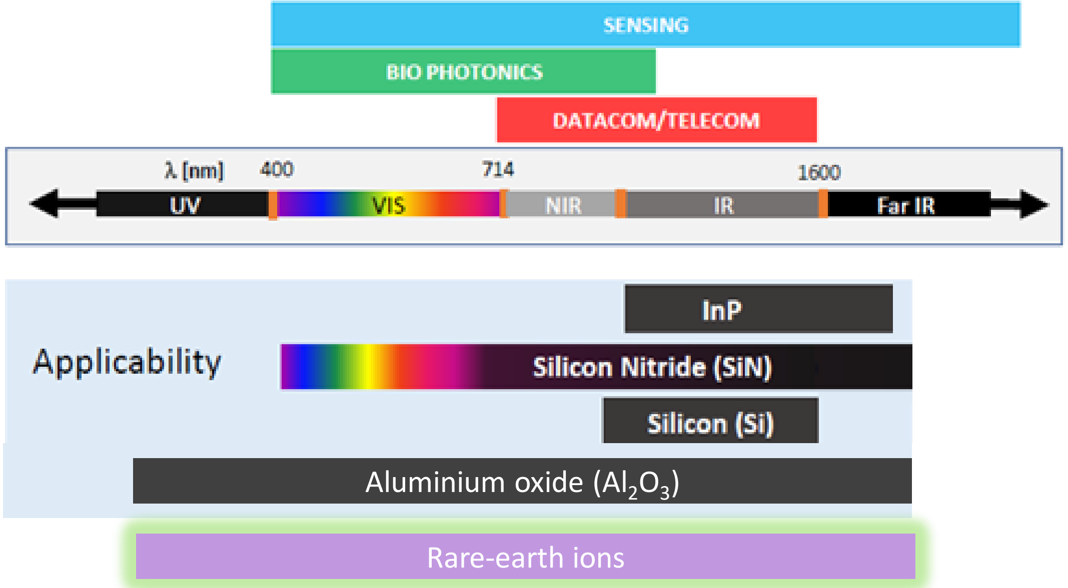
InP



SiN

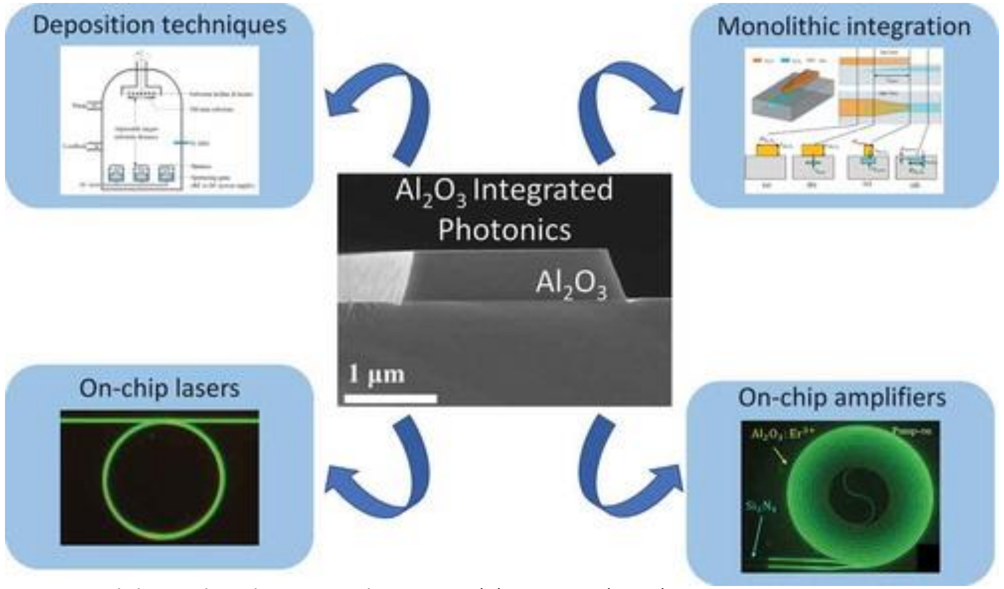


Si



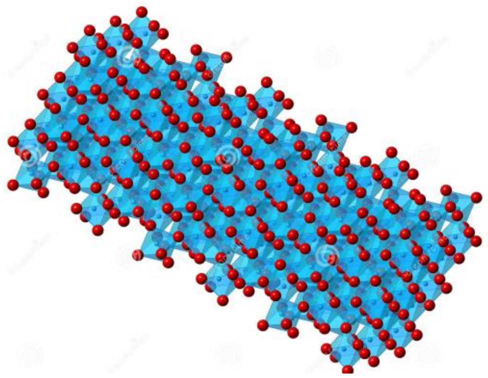
Al_2O_3 AS A PHOTONIC MATERIAL

- Large transparency window: UV-mid-IR
- Low propagation losses: 5 dB/m
- Moderate refractive index: ~1.72 @1550 nm
- Wafer level deposition
- High rare-earth ion solubility
- In the Nanolab→ RF reactive sputtering



[Review: Hendriks et. al. , Advances in Physics: X, 6 (1), 1833753 (2021)

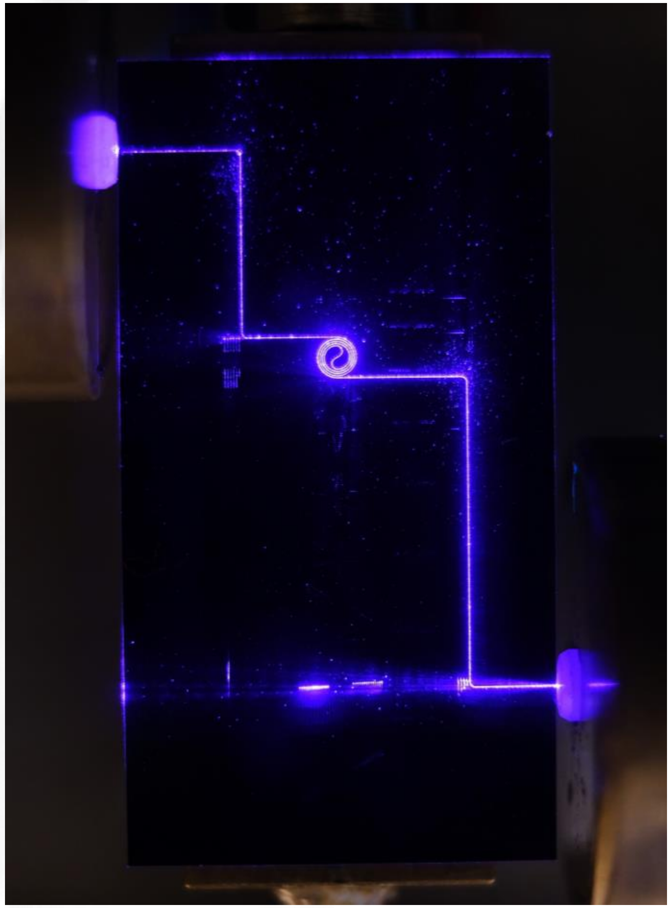
- Rich history in photonics
- Naturally occurring in crystalline state as corundum, forming popular gems such as ruby and sapphire



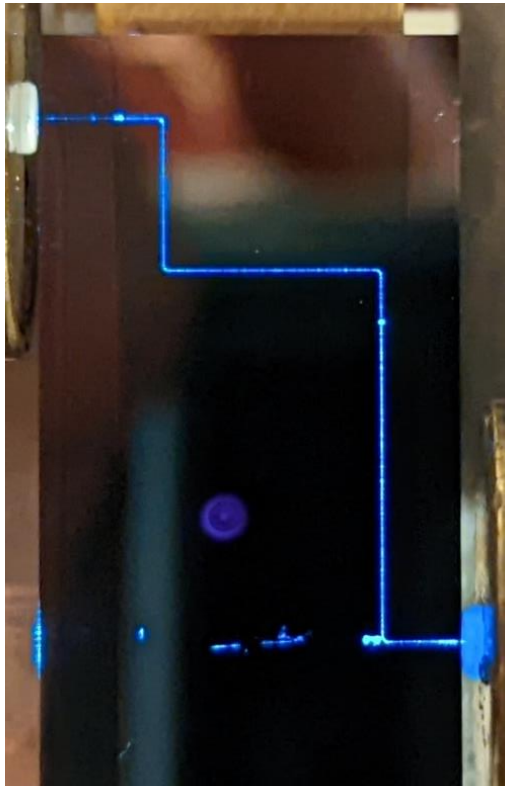
BROADBAND WAVEGUIDE TRANSPARENCY

Commercialized as foundry service via Aluvia Photonics

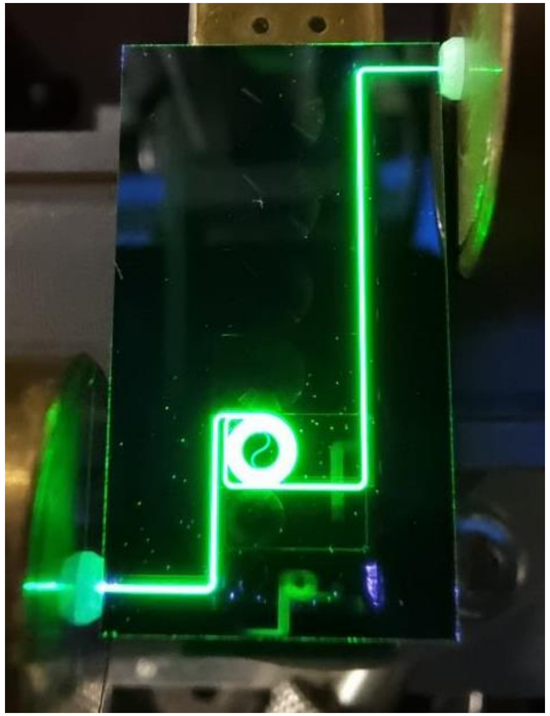
1.4 dB/cm losses measured at 405 nm

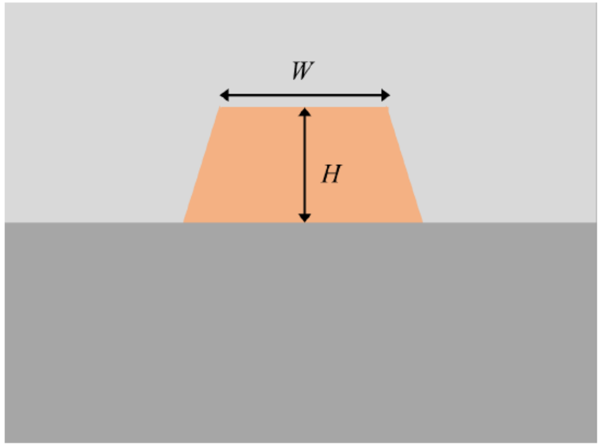


405 nm transmission



980 nm pumped $Al_2O_3:Er^{3+}$



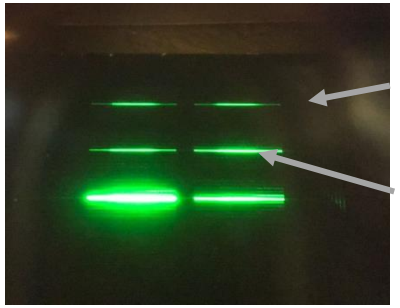


632 nm alignment

PAST WORKS IN ACTIVE / PASSIVE INTEGRATION

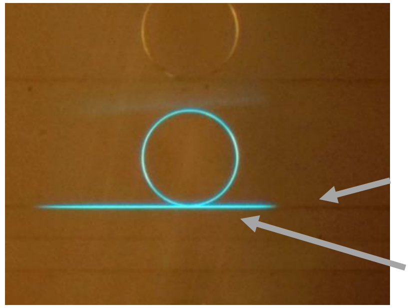
Double layer

A stack of two (or more) independent photonic layers interconnected by vertical adiabatic or resonant couplers



Single layer

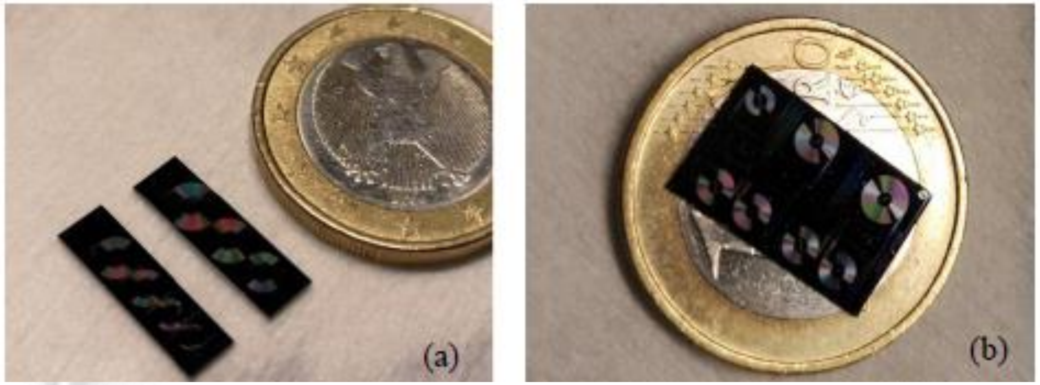
Single passive photonic layer with incrustations of active gain material (photonics damascene process)
→ seamless transitions between layers

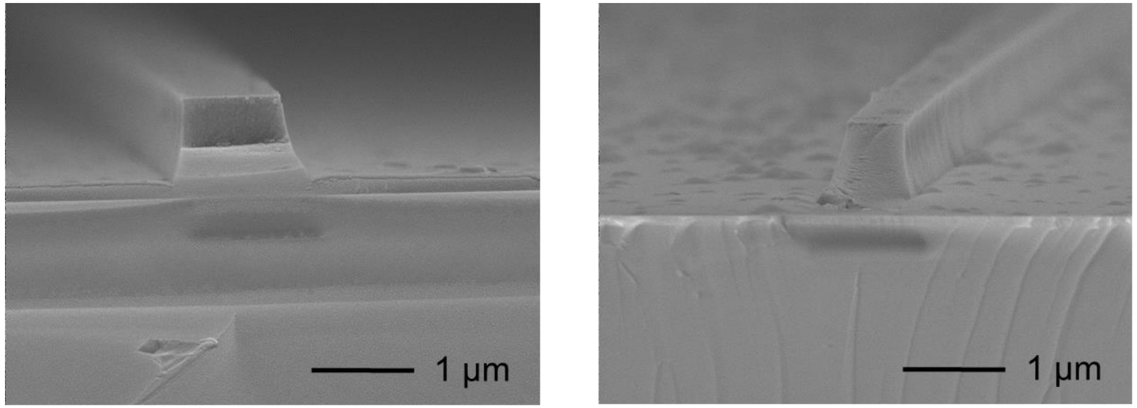


[J. Mu, et. al. "Monolithic Integration of Al_2O_3 and Si_3N_4 Toward Double-Layer Active-Passive Platform," IEEE J. Selec. Top. Quant. Electron. 25, 8200911 (2019)]

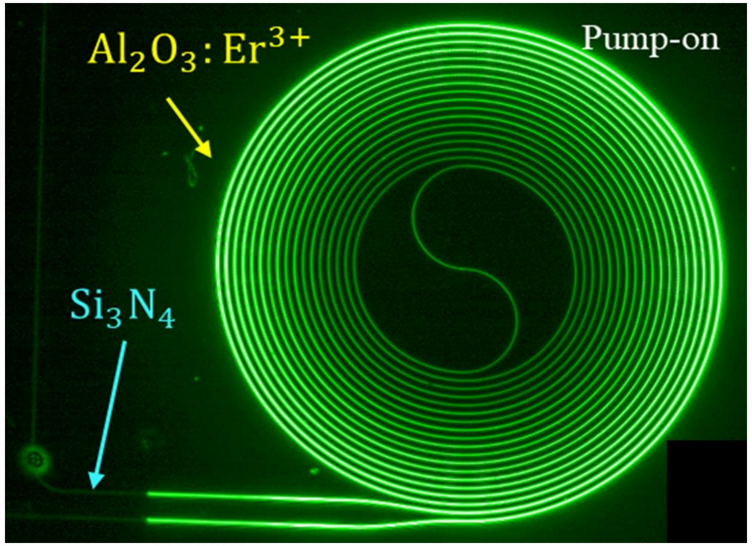
[C. I. van Emmerik, et. al., "Single-layer active-passive Al_2O_3 photonic integration platform," Opt. Mater. Express 8, 3049-3054 (2018)]

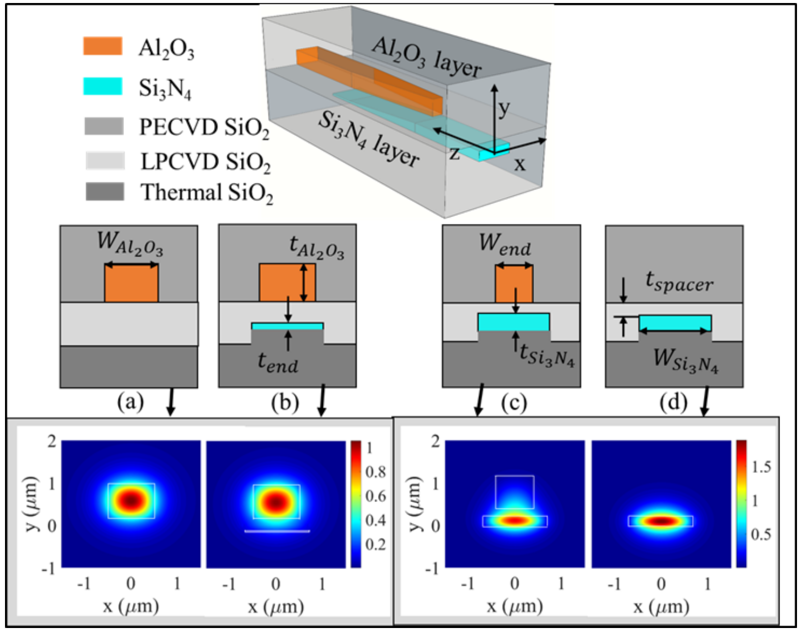
ACTIVE PASSIVE INTEGRATION TECHNOLOGIES
MONOLITHIC INTEGRATION: $RE^{3+}:Al_2O_3$ ON Si_3N_4





~20 dB net gain from Si_3N_4 to Si_3N_4



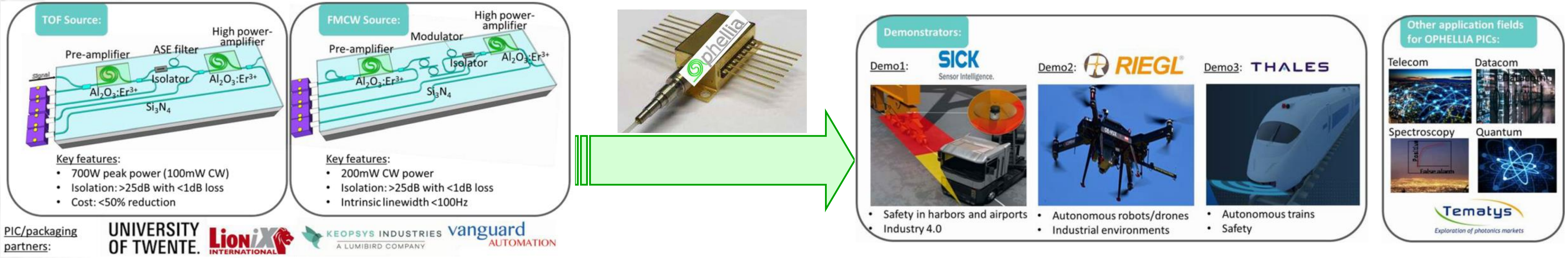


[J. Mu, et. al., "High-gain waveguide amplifiers in Si_3N_4 technology via double-layer monolithic integration," Photon. Res. 8, 1634-1641 (2020)]


Unlimited power!
*@ 1550 NM

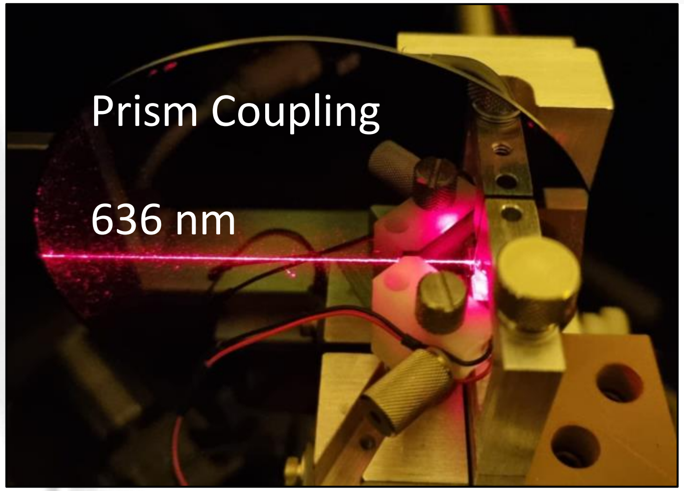
OPHELLIA WORK PACKAGES

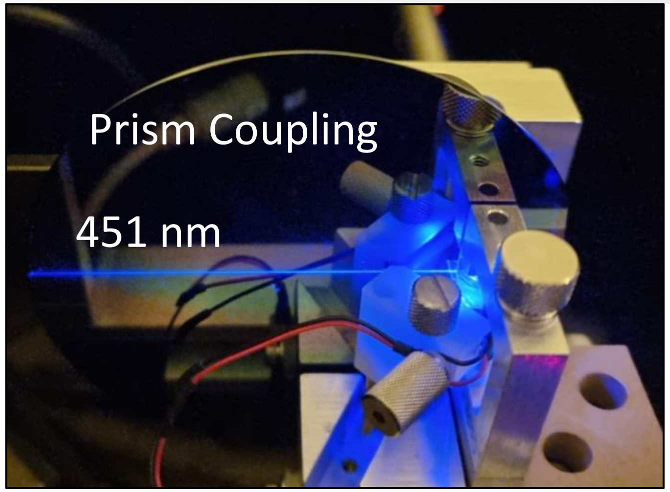
- Passive circuitry design and fabrication (TriPleX)
- Gain material development
- Microlens printing
- Photonic packaging
- End-user testing



[(a)]PIC: Photonic integrated circuit [(b)]TOF: Time of flight [(c)]FMCW: Frequency-modulated continuous-wave [(d)]LiDAR: Light detection and ranging

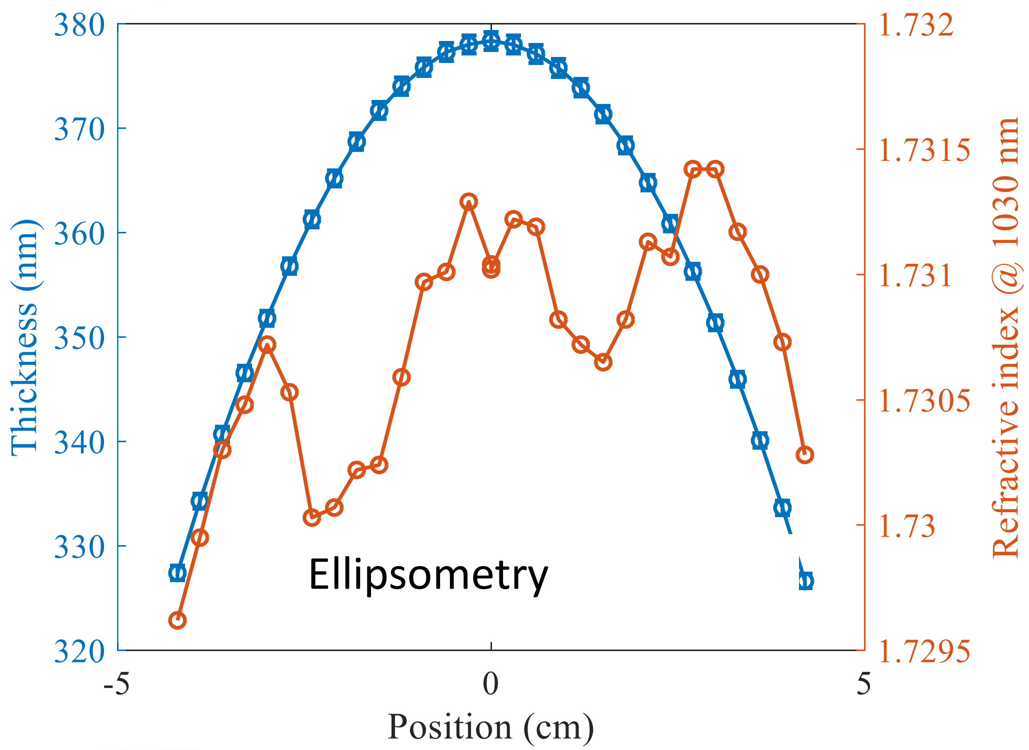
$Al_2O_3:Er^{3+}$ Process Flow – CMOS Compatibility – Films, Waveguides & Chips

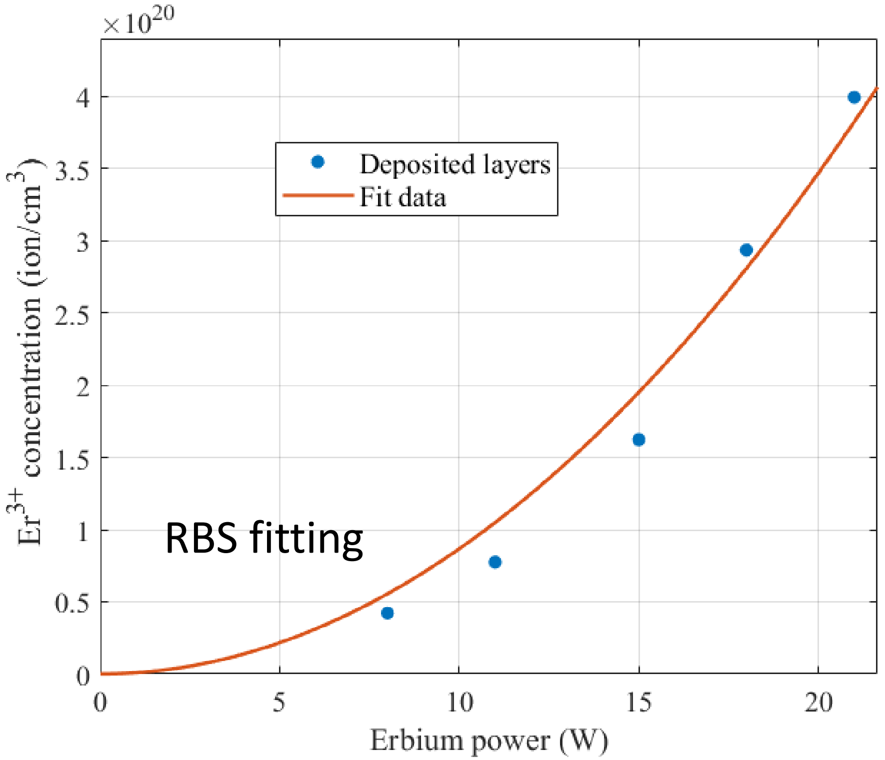




Flexible, scalable, repeatable processing using reactive sputtering

T (°C)	760
Er Power (W)	18
Expected concentration (x10^{20} ion/m^3)	2.93
n (@ 1030 nm)	1.7389
Losses @ 377 nm (dB/cm)	21.94 ± 0.43
Losses @ 403 nm (dB/cm)	2.66 ± 0.07
Losses @ 451 nm (dB/cm)	3.57 ± 0.52
Losses @ 521 nm (dB/cm)	18.42 ± 0.38
Losses @ 636 nm (dB/cm)	0.97 ± 0.11
Losses @ 978nm (dB/cm)	3.00 ± 0.05





r & heater

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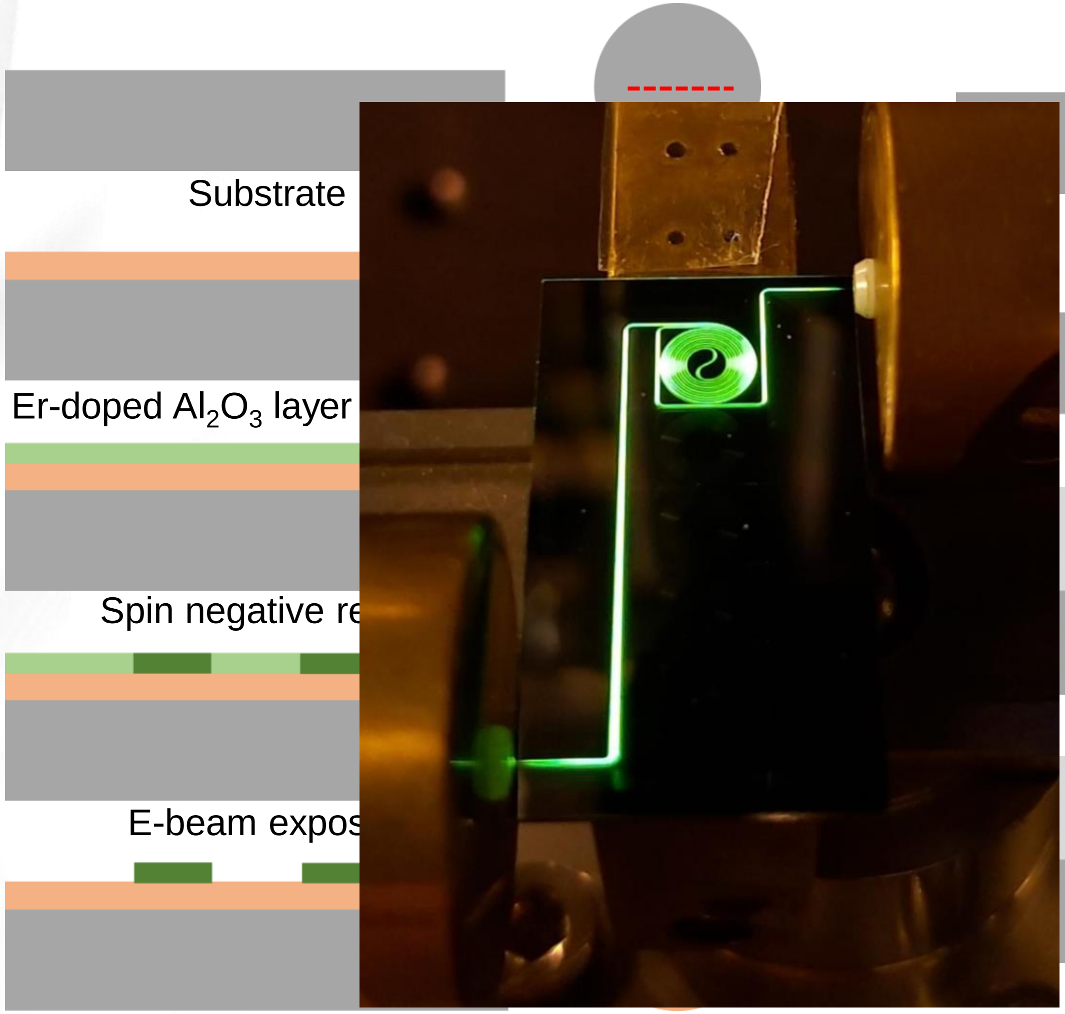
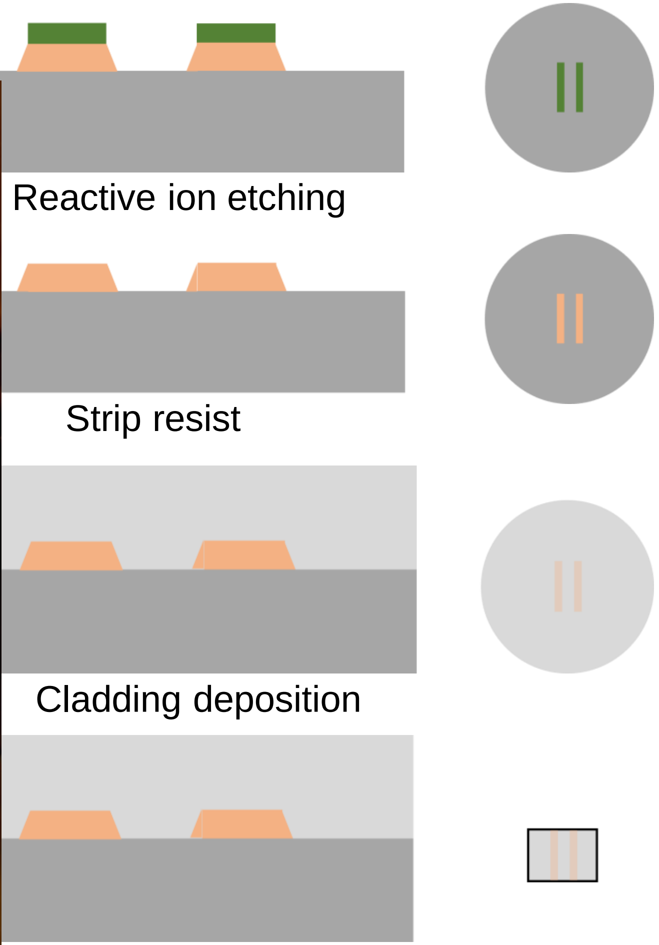
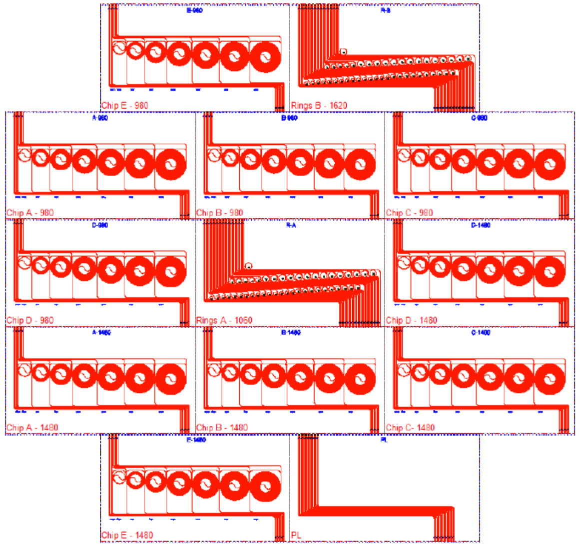
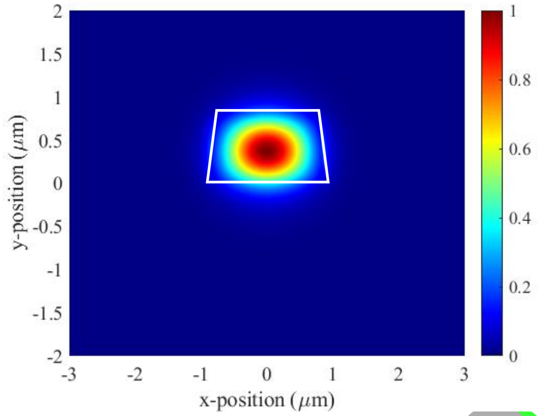
Fabrication of $Al_2O_3:Er^{3+}$ Channel Waveguide Amplifiers



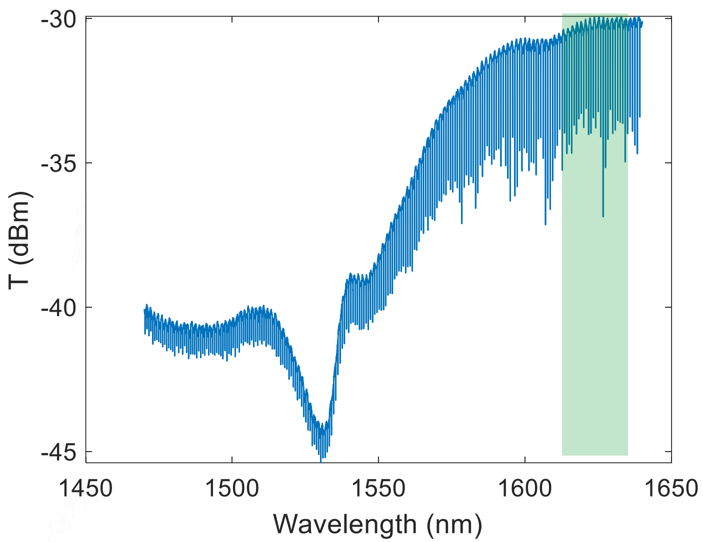


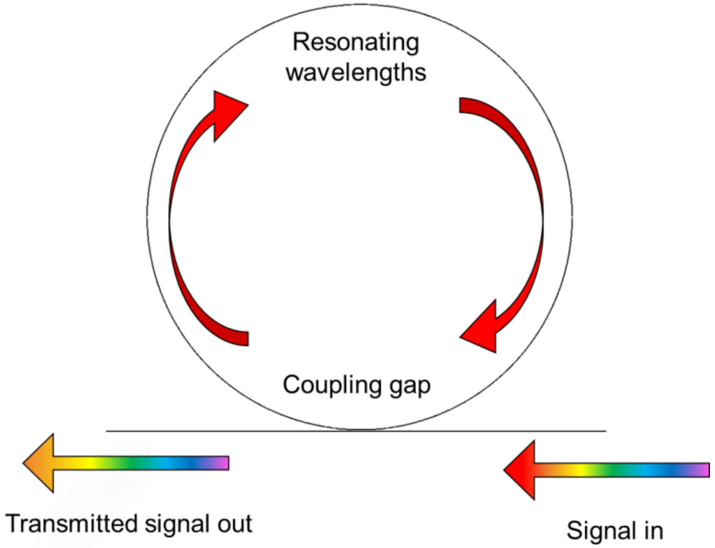
*single layer designs

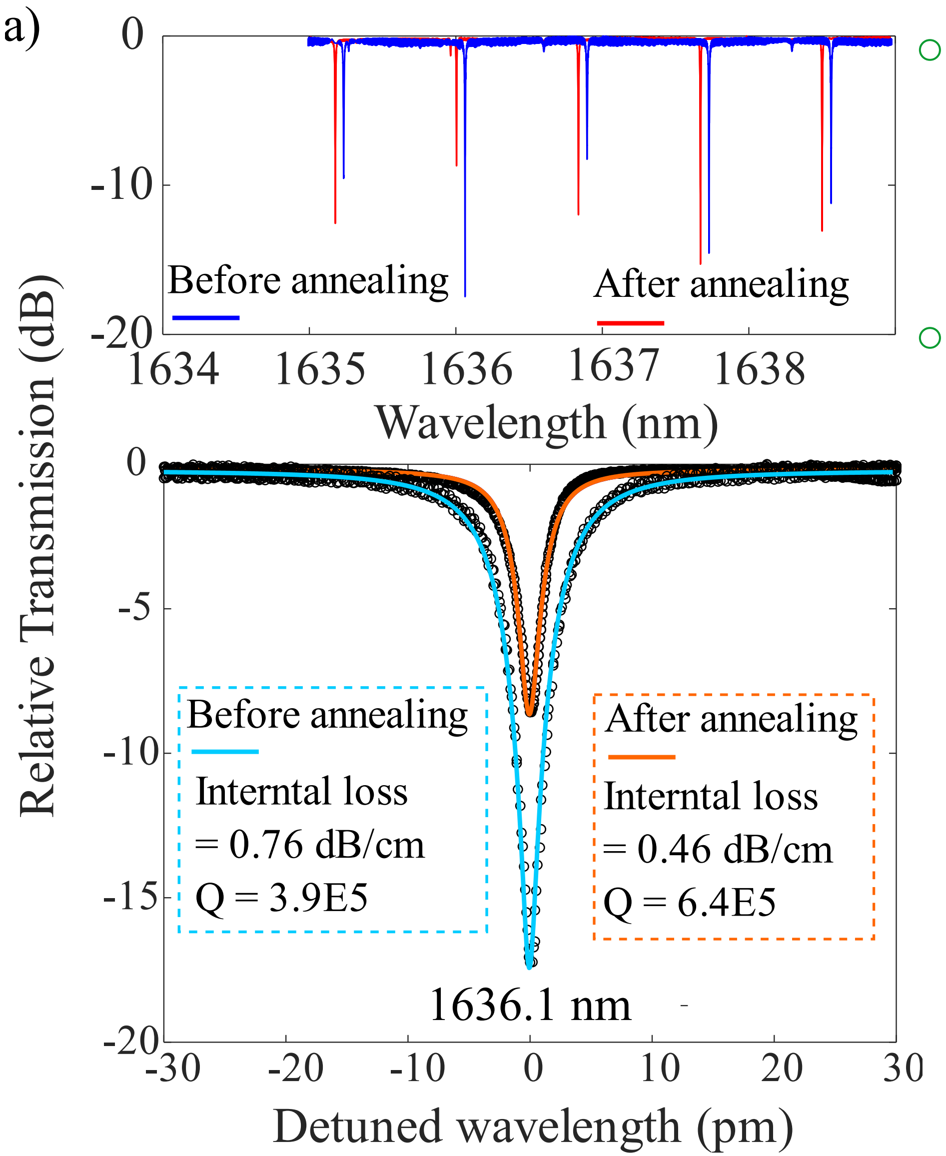




Propagation Loss – Effects of Annealing



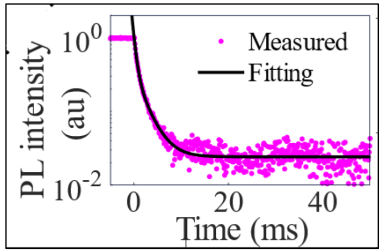


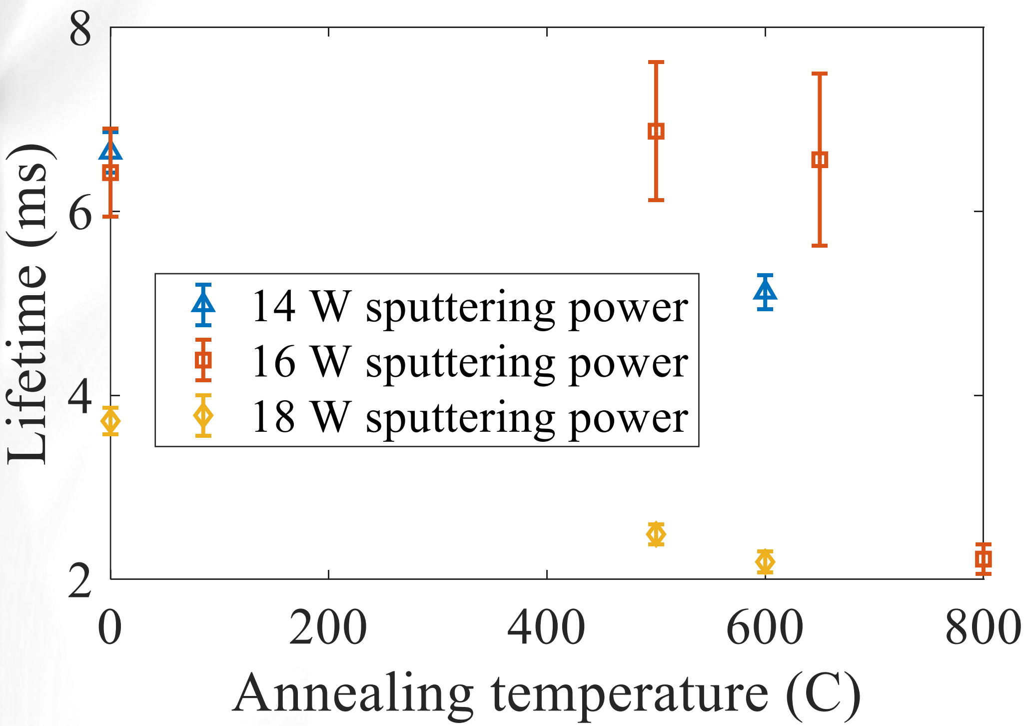


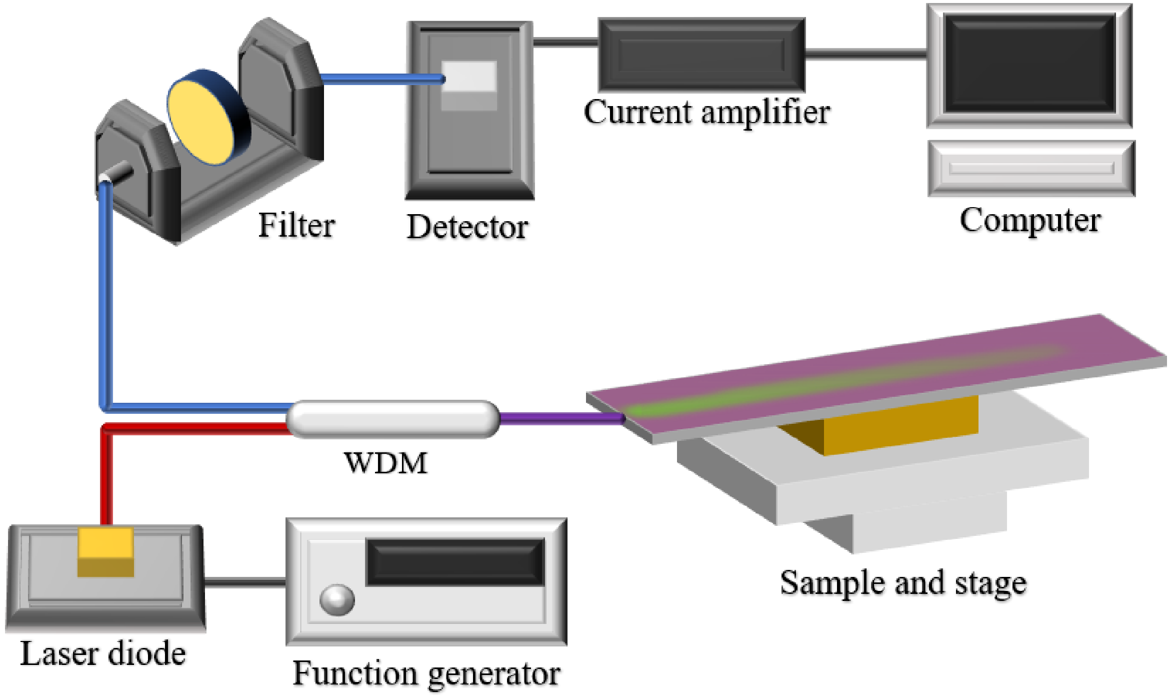
- Ring resonator measurements used for propagation loss measurements
- Annealing at 500 °C decreases losses by 0.3 dB/cm

PHOTOLUMINESCENT DECAY TIME VS ANNEALING

- Lifetime shown to vary with concentration and annealing temperatures
- Lifetime decrease with annealing accompanied by decrease in losses, and change in pump absorption, indicative of a change in the quenched ion fraction

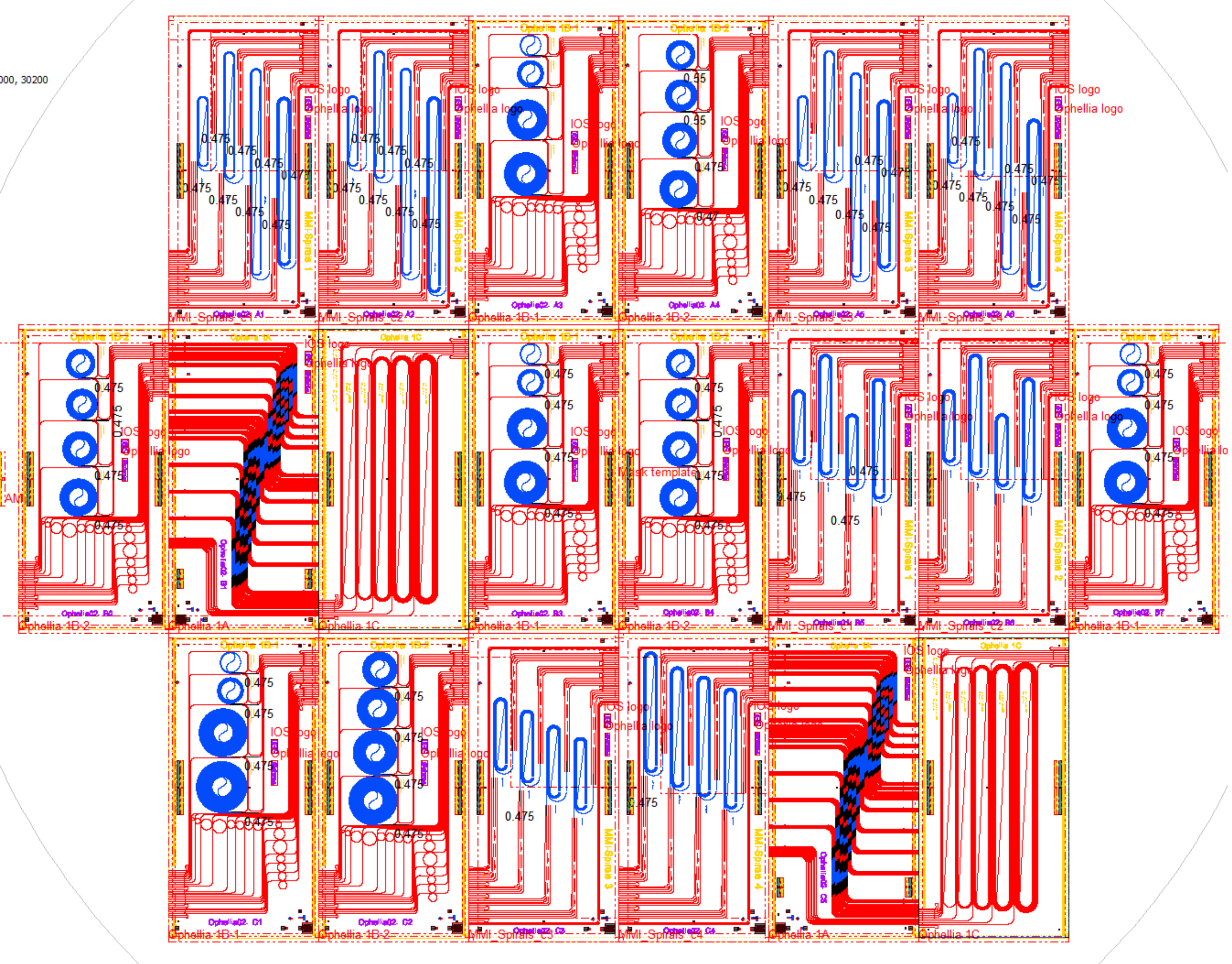






*Concentrations from 1.5 – 3.0 × 10^{20} ions/cm^3

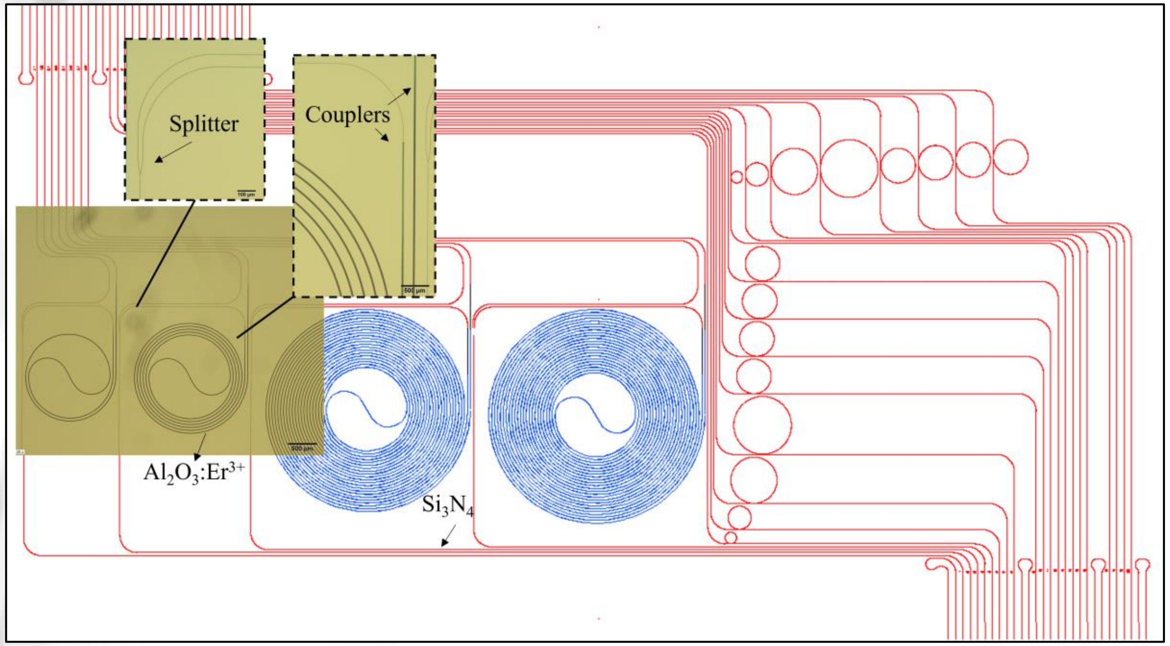
Al_2O_3-Si_3N_4 AMPLIFIER – WAFER LAYOUT



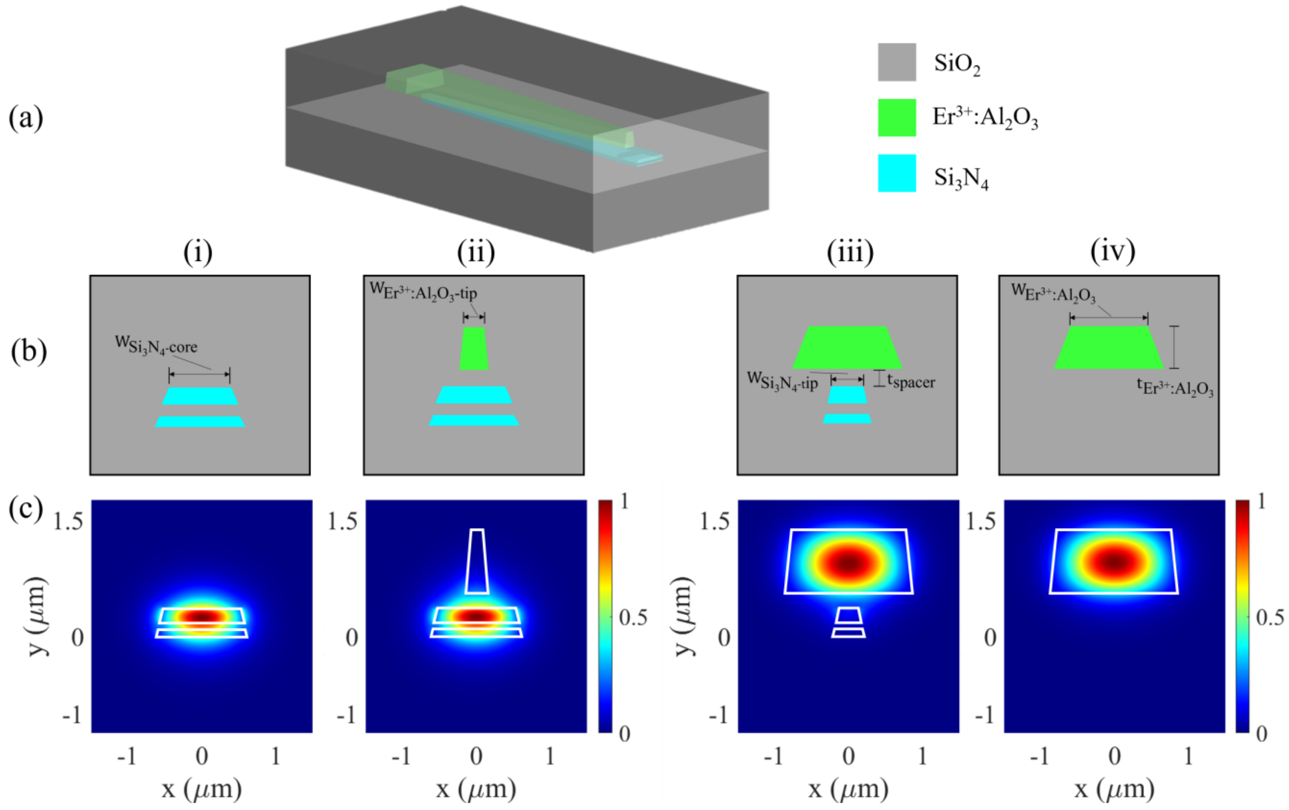
Location	Description	Width (µm)	Lengths (cm)
A1	Amplifier w/ straight	1.6	3.59, 6.12, 9.59, 12.92
A2	Amplifier w/ straight	1.6	3.59, 6.11, 9.59, 14.91
A3	Amplifier w/ reference Si3N4 wg	1.3	0.99, 3.19, 10.94, 12.88
A4	Amplifier w/ reference Si3N4 wg	1.3	4.48, 5.88, 7.44, 9.13
A5	Amplifier w/ straight	1.75	3.59, 6.11, 9.61, 12.96
A6	Amplifier w/ straight	1.9	3.55, 6.07, 9.51, 12.84
B0	Amplifier w/ reference Si3N4 wg	1.75	4.48, 5.88, 7.44, 9.13
B1	Adiabatic couplers + test directional couplers	1.3, 1.6	n/a
B2	Inverted strip loaded spirals	n/a	n/a
B3	Amplifier w/ reference Si3N4 wg	1.6	0.99, 3.19, 10.94, 12.88
B4	Amplifier w/ reference Si3N4 wg	1.6	4.48, 5.88, 7.44, 9.13
B5	Amplifier w/ MMI	1.6	5.92, 9.42, 5.92, 9.42
B6	Amplifier w/ MMI	1.6	5.92, 9.42, 5.91, 9.41
B7	Amplifier w/ reference Si3N4 wg	1.9	0.99, 3.19, 10.94, 12.88
C1	Amplifier w/ reference Si3N4 wg	1.6	0.99, 3.19, 17.18, 19.44
C2	Amplifier w/ reference Si3N4 wg	1.3	7.44, 10.94, 13.89, 17.13
C3	Amplifier w/ DC	1.6	5.91, 5.91, 5.96, 5.96
C4	Amplifier w/ DC	1.6	9.38, 9.38, 9.34, 9.34
C5	Adiabatic couplers + test directional couplers	1.75, 1.9	n/a
C6	Inverted strip loaded spirals	n/a	n/a

MULTI-LAYER INTEGRATION – CHIP LAYOUT

- Cross-section and chip layout
  - Si_3N_4 input
  - 50/50 splitter
  - Reference branch
  - Si_3N_4 – Al_2O_3 coupler + amplifier



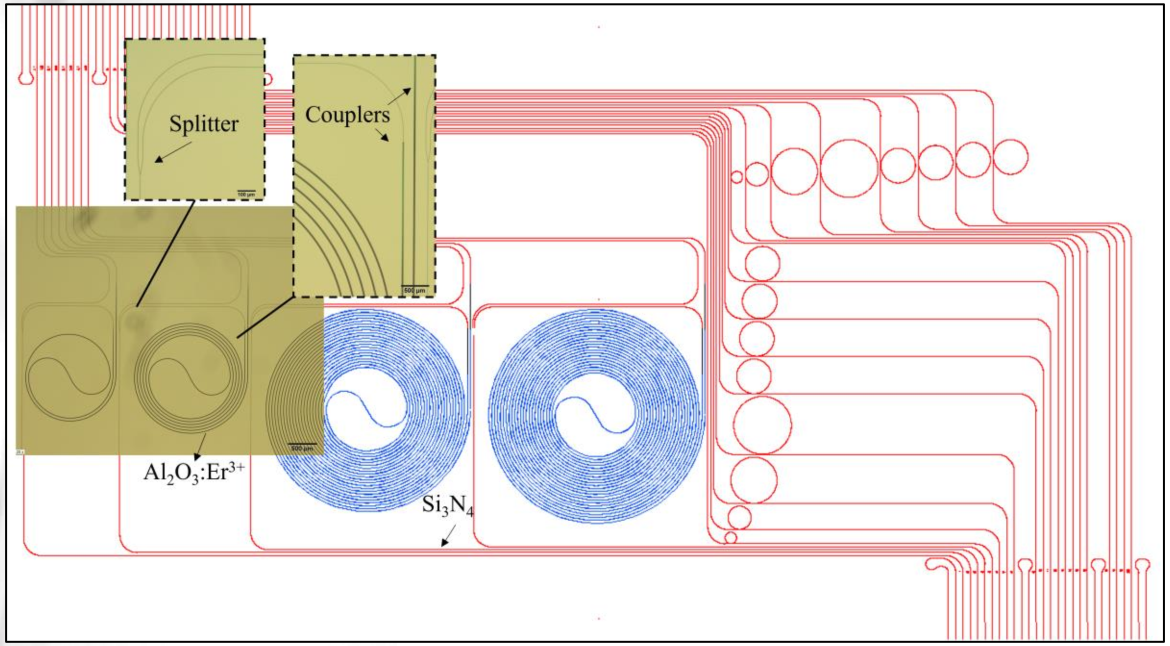
Vertical adiabatic taper – Passive / Active coupling



Al_2O_3-Si_3N_4 AMPLIFIERS – REFERENCE BRANCH GAIN MEASUREMENT

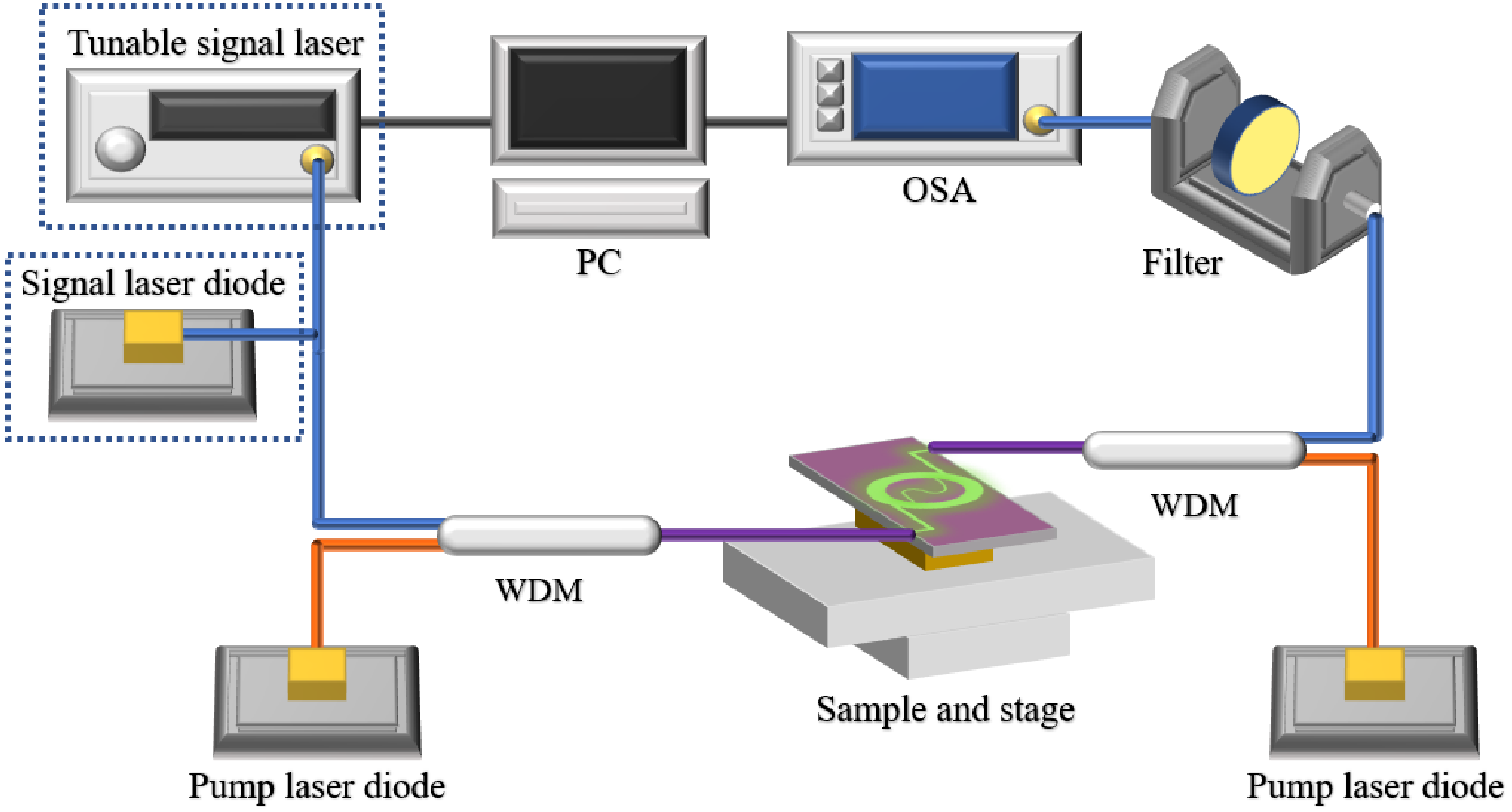
- Gain with reference branch method
  - Active-passive integration
  - Passive Si_3N_4 reference branch
  - All on-chip losses are considered
    - No need of individual characterization of losses

T_{on} → Pump on, signal on in amplifier branch
T_{bon} → Pump on, signal off in amplifier branch
T_{ref} → Pump off, signal on in reference branch



$$g_{global} = 10 * log_{10}\left(\frac{10^{T_{on}/10} - 10^{T_{bon}/10}}{10^{T_{ref}/10}}\right)$$

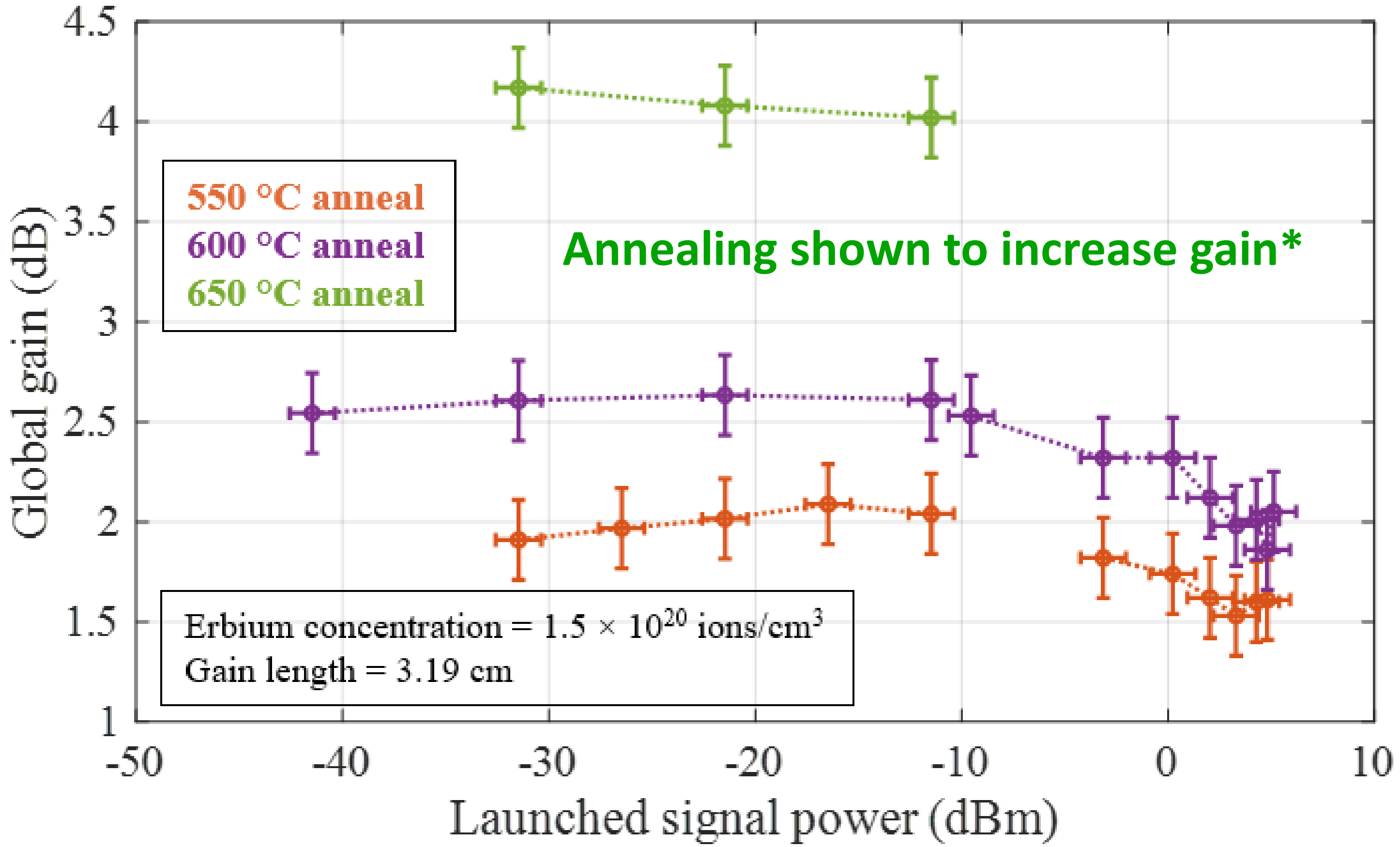
Amplifier Measurements – Double Side Pumping Setup



- 1480 nm pumping used to avoid additional ETU in comparison to 980 nm for **high signal powers**
- **2 Concentrations measured** including varying widths and lengths of amplifiers

Al_2O_3-Si_3N_4 Amplifiers – Low Concentration (~1.5 x 10^{20} ions/cm^3)

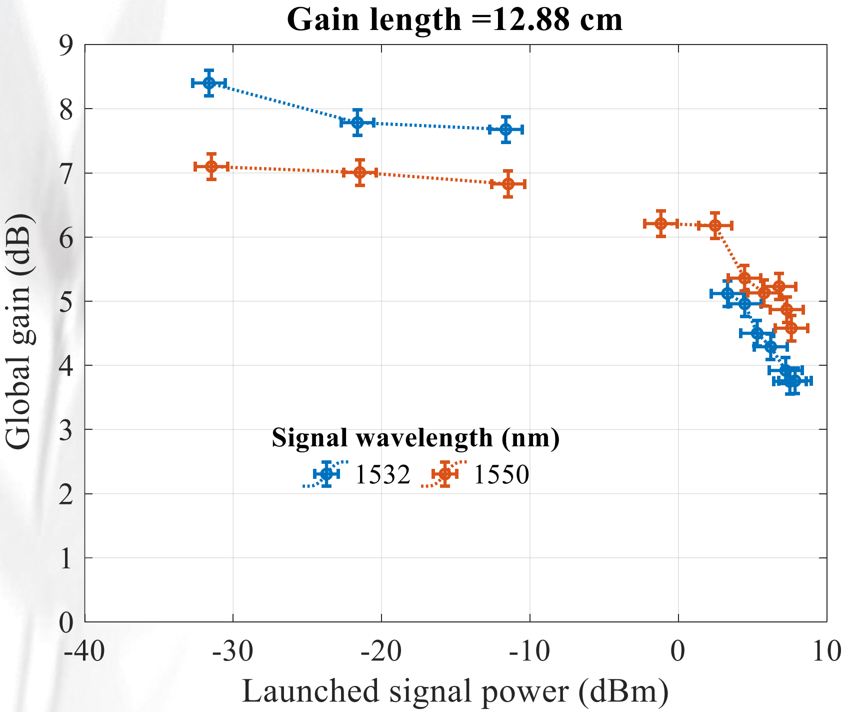
On-chip pump power (~240 mW)

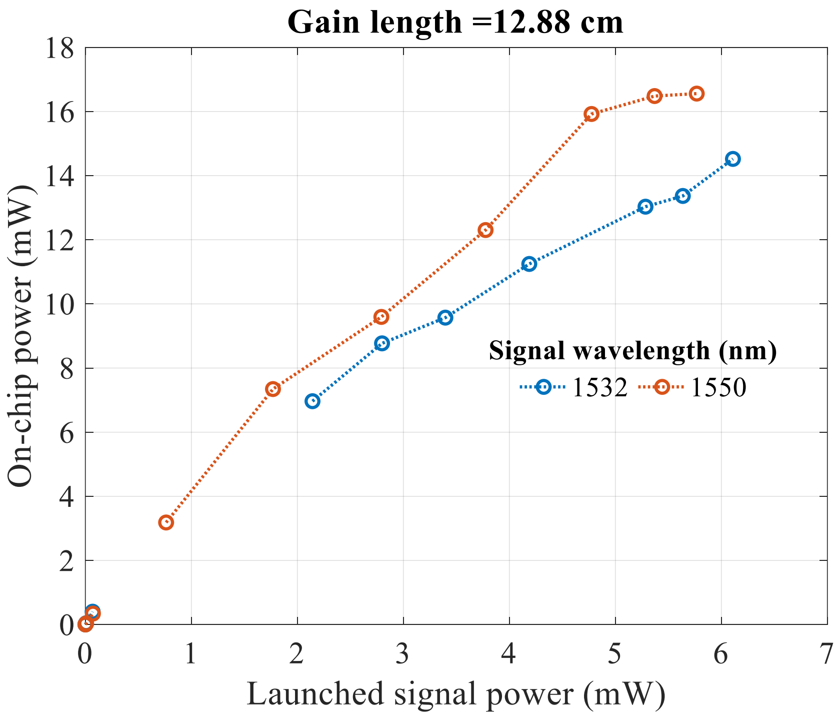


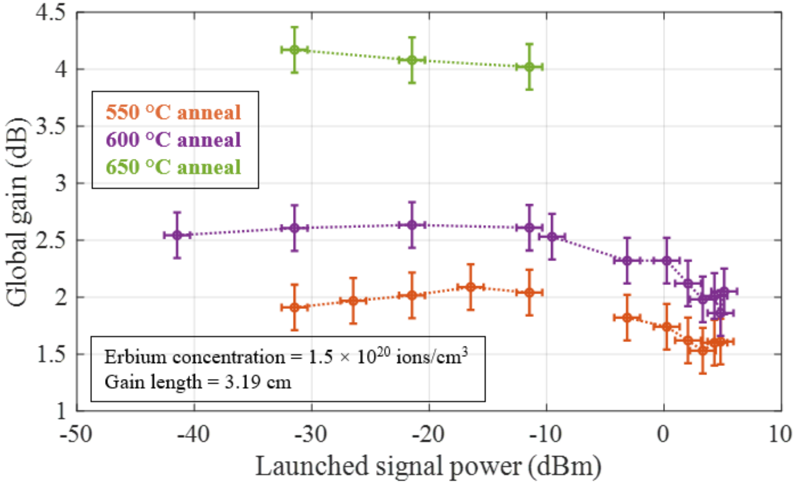
***variable optimum temperature depending on concentration**

Al_2O_3-Si_3N_4 Amplifiers – Low Concentration (~1.5×10^{20} ions/cm^3)

Width = 1.9 µm & annealing 600°C





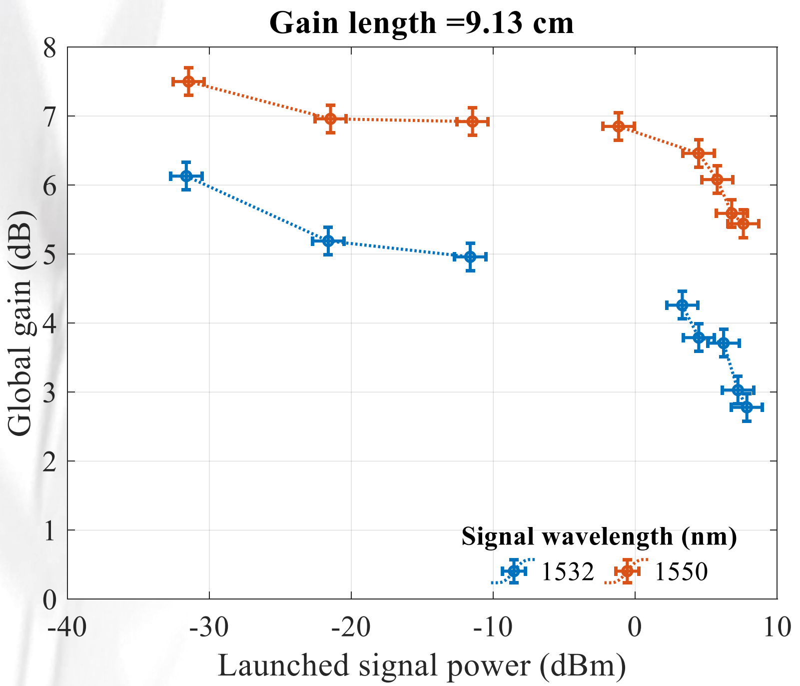


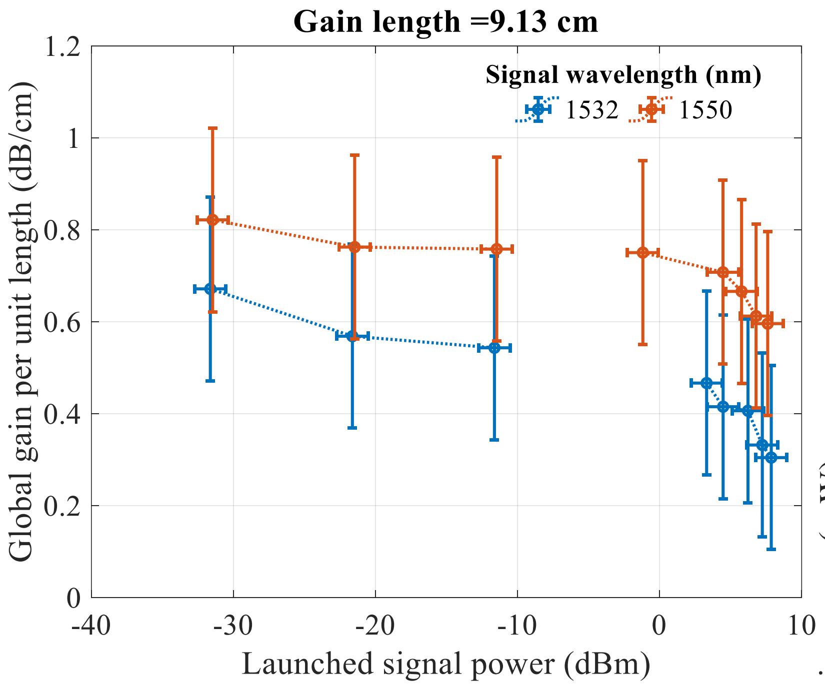
Small signal and high signal (~6 dBm launched signal power) gain demonstrated at 1532 and 1550 nm

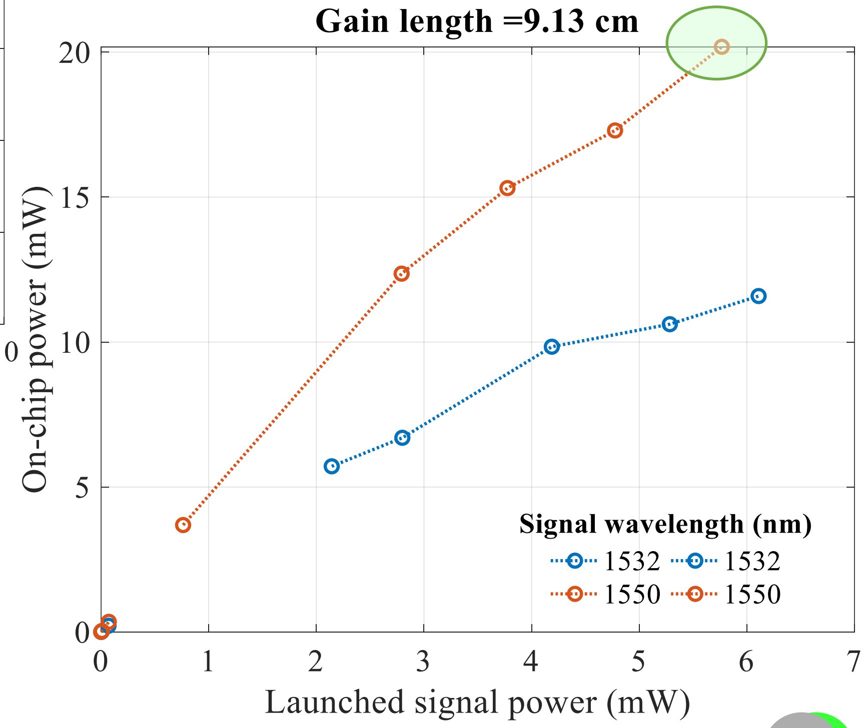
On-chip pump power (~240 mW)

Al_2O_3-Si_3N_4 Amplifiers – Low Concentration (~2.5 x 10^{20} ions/cm^3)

Width = 1.75 µm & annealing 550°C



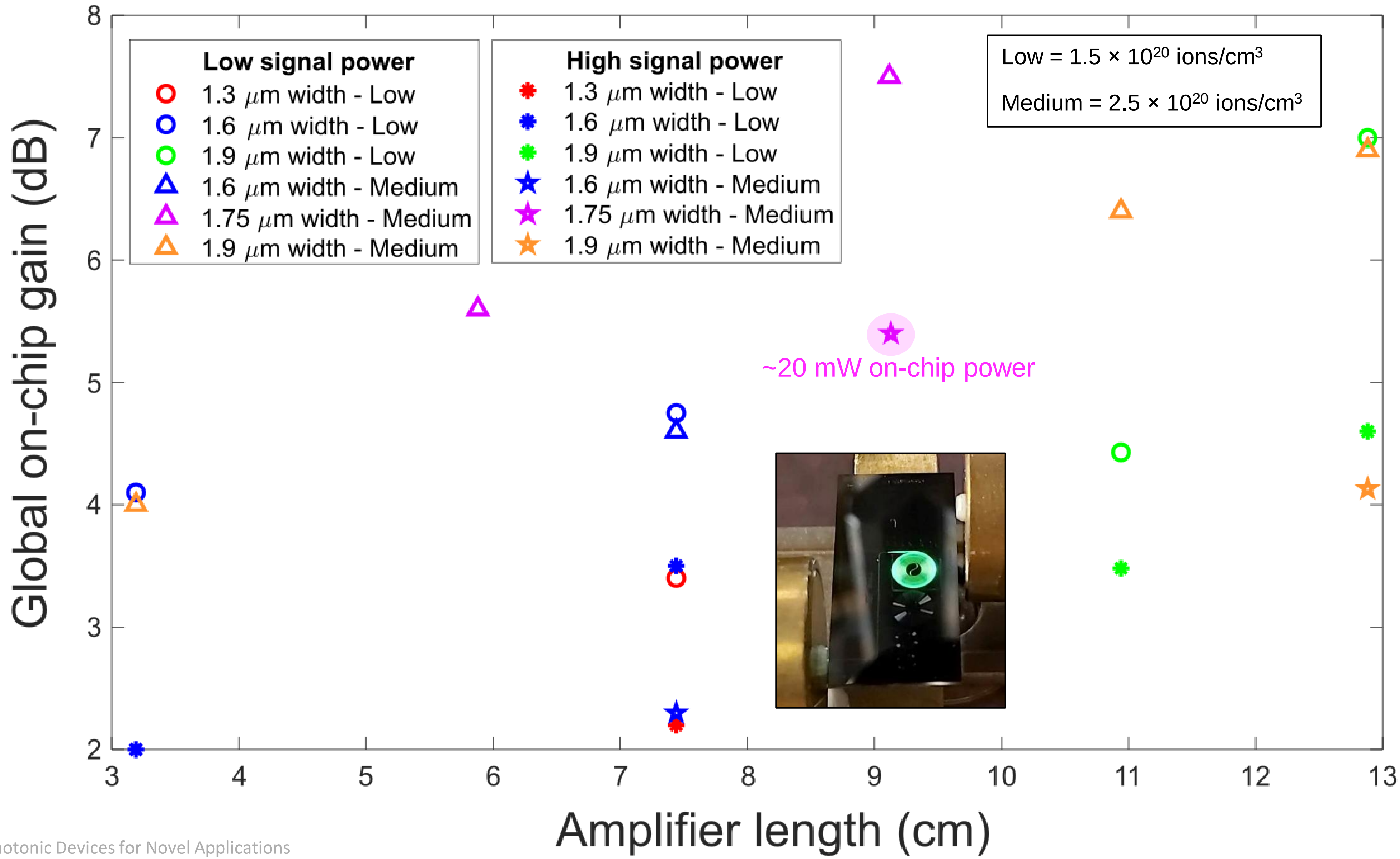




= ~14.6 dBm – Comparable to output power of commercial EDFA

On-chip pump power (~240 mW)

GAIN SUMMARY – VARIOUS LENGTHS, WIDTHS, CONCENTRATIONS & SIGNAL POWERS



STATE OF THE ART COMPARISON

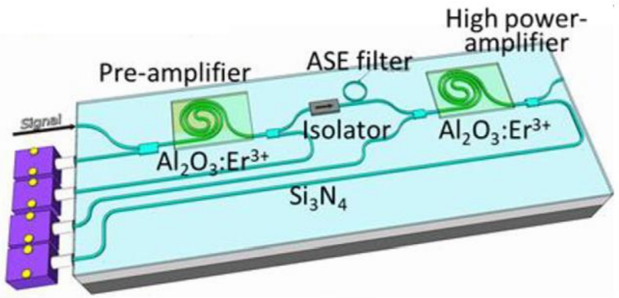
Material	Fabrication method	On-chip net gain (dB)	On-chip signal power (dBm)	Gain / unit length (dB/cm)	Length (cm)	Erbium Concentration ($\times 10^{20}$ cm^{-3})	Ref
Er^{3+} : Al_2O_3	Sputtering	17.0	14.7	1.5	12.0	3.9	This work
Er^{3+} : Al_2O_3	Sputtering	20.0	4.0	1.5	12.9	1.9	Twente
Er^{3+} : Al_2O_3	Sputtering	9.3	-30.0	2.0	5.40	1.2	Twente
Er^{3+} :Yb^{3+} : Al_2O_3	Sputtering	4.3	-8.5	1.4	3.00	1.5	McMaster
Er^{3+} : TeO_2	Sputtering	14.0	13.0	2.8	5.0	2.2	LPC
Er^{3+} : $LiNbO_3$	Czochralski	18.0	0.0	5.0	3.6	1.9	SKL
Er^{3+} : Si_3N_4	Ion implantation	30.0	21.6	1.4	21	3.25	EPFL
				Multi-layer integration			
Si_3N_4 / Er^{3+} : Al_2O_3	Sputtering	7.5	13.0	0.8	9.1	2.5	This work
Si_3N_4 / Er^{3+} : Al_2O_3	Sputtering	18.1	2.7	1.3	10	1.65	Twente
Si_3N_4 / Er^{3+} : TeO_2	Sputtering	5.0	<-1.0	1.3	6.7	2.5	McMaster
Si_3N_4 / Er^{3+} : Al_2O_3	ALD	0.4	-20	20.0	0.16	~20	Aalto
				III / V Active materials			
Si / III-V	Epitaxy	27.0	17.5	185.7	0.145	N/A	IMEC
Si_3N_4 / III/V	Epitaxy	8.8	14.0	121.7	0.115	N/A	IMEC
$LiNbO_3$/ III/V	Epitaxy	11.8	< 5.0	N/A	N/A	N/A	IMEC
				Erbium doped fibers			
Er-doped fiber	N/A	> 19.0	13.0	N/A	N/A	N/A	Amonics
Er-doped fiber	N/A	> 30.0	> 20.0	N/A	N/A	N/A	Thorlabs

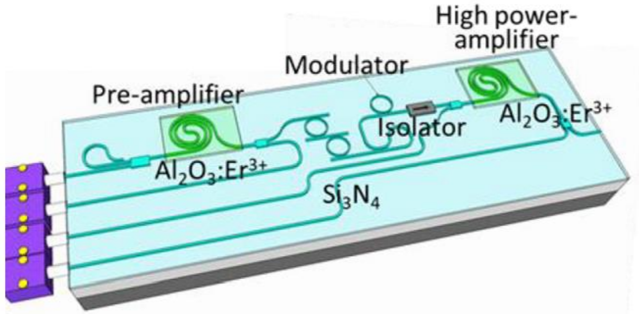
STATE OF THE ART COMPARISON

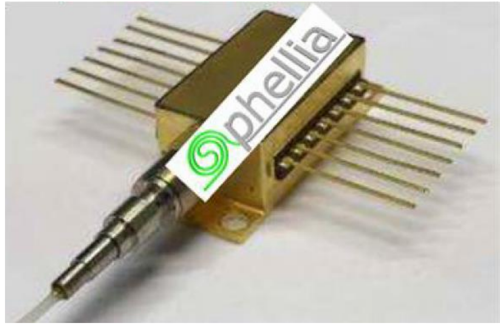
Material	Fabrication method	On-chip net gain (dB)	On-chip signal power (dBm)	Gain / unit length (dB/cm)	Length (cm)	Erbium Concentration ($\times 10^{20}$ cm^{-3})	Ref
Er^{3+} : Al_2O_3	Sputtering	17.0	**14.7**	1.5	12.0	3.9	**This work**
Er^{3+} : Al_2O_3	Sputtering	20.0	4.0	1.5	12.9	1.9	Twente
Er^{3+} : Al_2O_3	Sputtering	9.3	-30.0	2.0	5.40	1.2	Twente
Er^{3+} :Yb^{3+} : Al_2O_3	Sputtering	4.3	-8.5	1.4	3.00	1.5	McMaster
Er^{3+} : TeO_2	Sputtering	14.0	13.0	2.8	5.0	2.2	LPC
Er^{3+} : $LiNbO_3$	Czochralski	18.0	0.0	5.0	3.6	1.9	SKL
Er^{3+} : Si_3N_4	Ion implantation	30.0	**21.6**	1.4	21	3.25	EPFL
			Multi-layer integration				
Si_3N_4 / Er^{3+} : Al_2O_3	Sputtering	7.5	**13.0**	0.8	9.1	2.5	**This work**
Si_3N_4 / Er^{3+} : Al_2O_3	Sputtering	18.1	2.7	1.3	10	1.65	Twente
Si_3N_4 / Er^{3+} : TeO_2	Sputtering	5.0	<-1.0	1.3	6.7	2.5	McMaster
Si_3N_4 / Er^{3+} : Al_2O_3	ALD	0.4	-20	20.0	0.16	~20	Aalto
			III / V Active materials				
Si / III-V	Epitaxy	27.0	**17.5**	185.7	0.145	N/A	IMEC
Si_3N_4 / III/V	Epitaxy	8.8	14.0	121.7	0.115	N/A	IMEC
$LiNbO_3$/ III/V	Epitaxy	11.8	< 5.0	N/A	N/A	N/A	IMEC
			Erbium doped fibers				
Er-doped fiber	N/A	> 19.0	**13.0**	N/A	N/A	N/A	Amonics
Er-doped fiber	N/A	> 30.0	> 20.0	N/A	N/A	N/A	Thorlabs

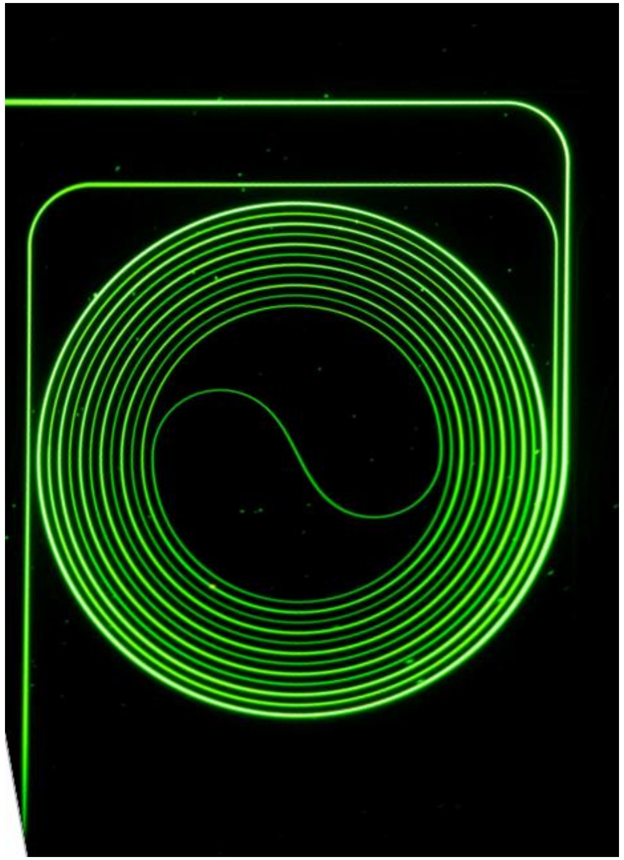
FUTURE WORK

- Multi-layer integration with silicon nitride resonator cavities for laser demonstration
- Systematic study of lengths and widths
- Investigate quenching and absorption/emission cross sections
- Polish facets to reduce coupling losses
- Package devices with fiber array
- Maximize high power signal gain to achieve 50+mW on-chip









FINAL ACKNOWLEDGMENTS & GENERAL INFORMATION







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Topic(s): ICT-37-2020 - Advancing photonics technologies and application driven photonics components and the innovation ecosystem

Call for proposal: H2020-ICT-2020-2

Funding Scheme: RIA - Research and Innovation action

More information:

https://lidar-ophellia.eu

https://cordis.europa.eu/project/id/101017136

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CHEERS, THANK YOU!

Thank you for your attention! Happy to take questions.