Packaging of Ultra-High-Speed Devices

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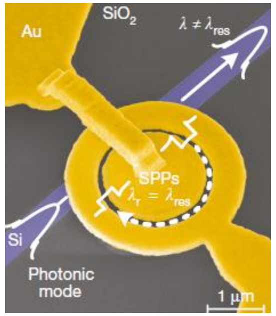
Content

- Our Plasmonic Technology
- Fiber coupling
- Integration Technologies
  - Chip-to-chip coupling
  - Flip-Chip bonding
    - Receiver TIA
    - Transmitter driver
    - RF ribbon bonding/PCB
  - Monolithic Integration

High-Speed Components in Networks

Devloping the critical components to enable operation at any frequency up to 500 GHz and beyond.

Modulators

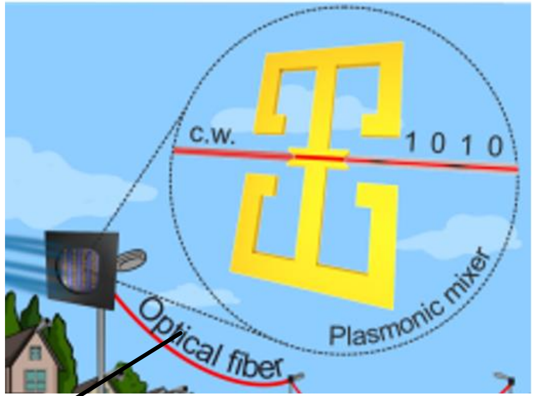


Nature 2018
Optica 2025

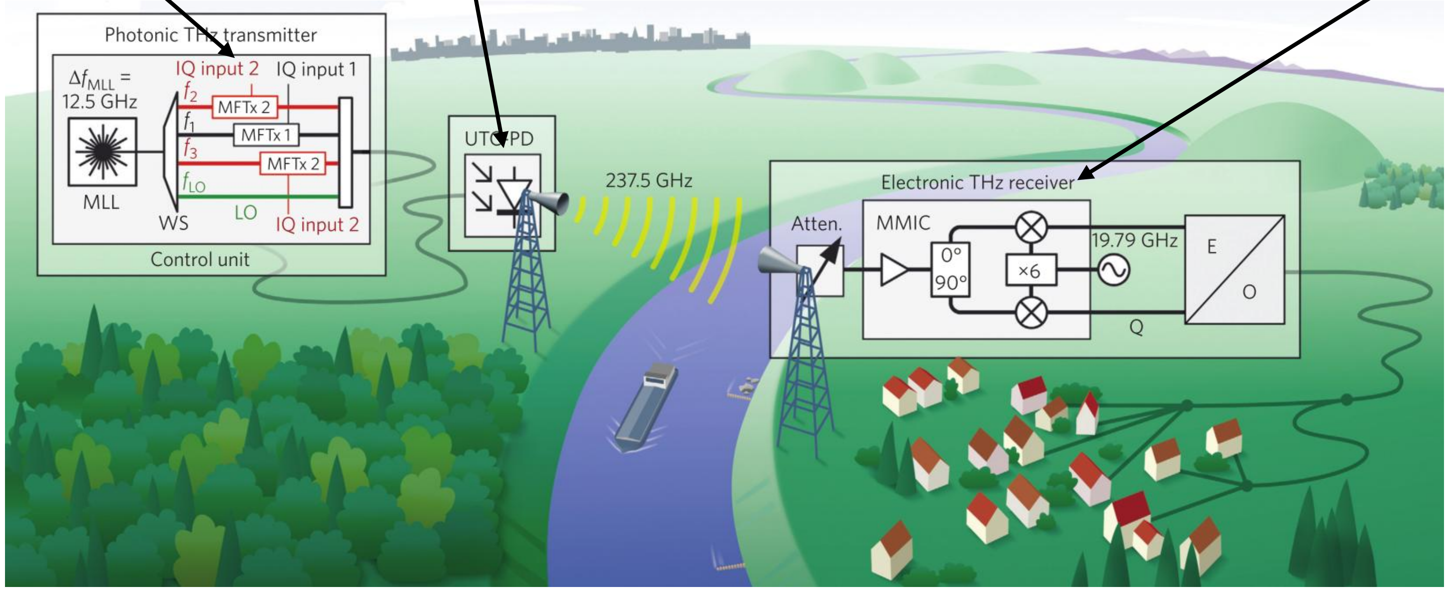
Fast & Efficient Photodiodes

Science 2023

THz Antenna

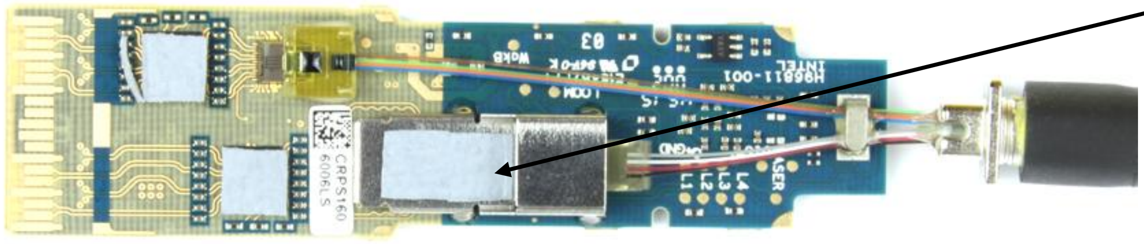


Nature Photonics 2018



Transceivers

Intel 100G silicon photonics transceivers



SYSTEMPlus CONSULTING

The dream: all the components on a single chip.

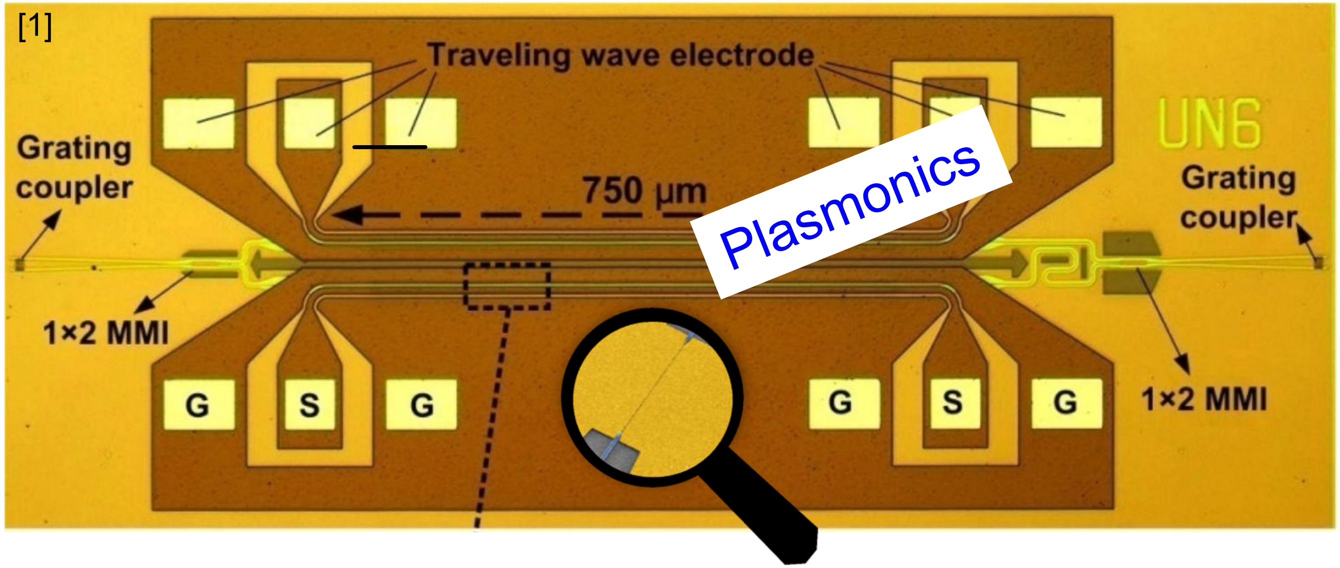
Transmitter
Main silicon die on which one finds:

- an InP lasers
- a Mach-Zehnder modulator to encode signals.
- other components to focus or isolate the signals.
- CMOS die chiplets to process data. Four-channel 25G optical Clock and Data Recovery (CDR) components

https://www.systemplus.fr/fr/reverse-costing-reports/intel-silicon-photonic-100g-psm4-qfsp28-transceiver/

Silicon Photonics

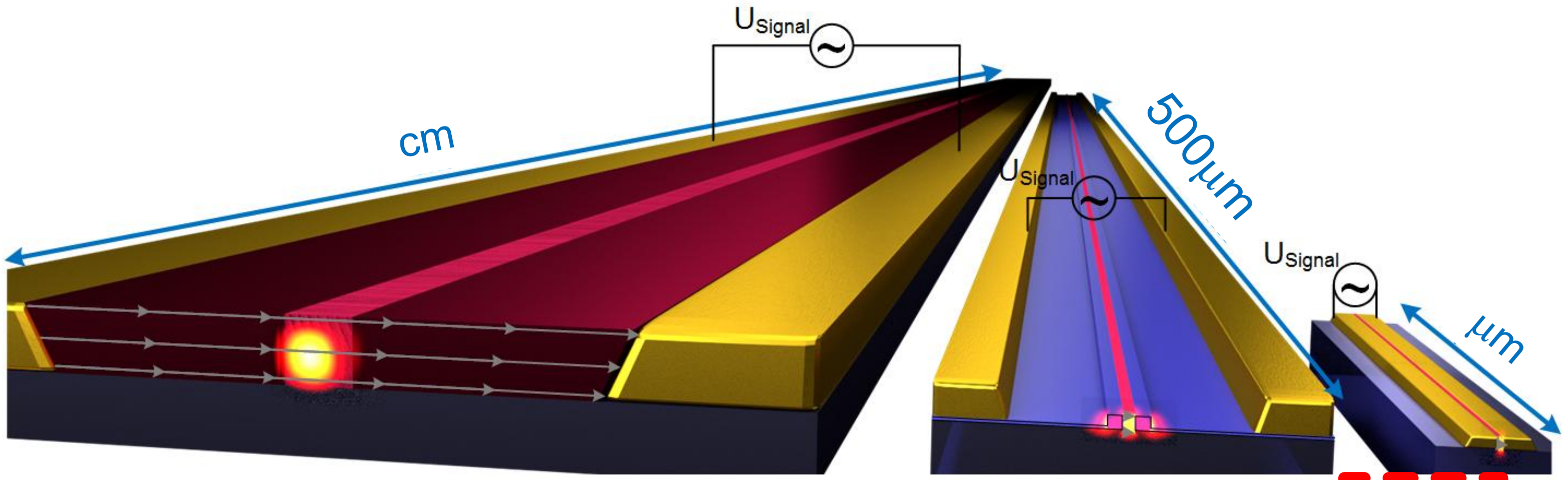
Photonic Approach of a modulator



Compact	~ mm [2]
High-speed	30 – 50 GHz [2]
Low drive voltage	~7 V [2]
Large-scale fabrication	SiP foundries

[1] Xiao, Xi, et al. "High-speed, low-loss silicon Mach–Zehnder modulators with doping optimization." *Optics express* 21.4 (2013)
[2] Li, Miaofeng, et al. "Silicon intensity Mach–Zehnder modulator for single lane 100 Gb/s applications." *Photonics Research* 6.2 (2018)

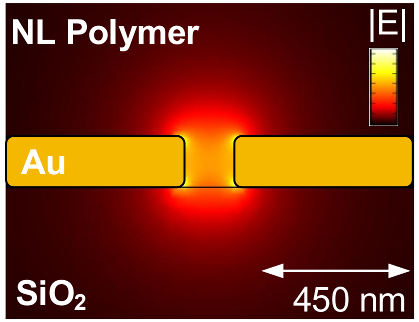
Plasmonic Modulators – Efficiency: The Footprint Advantage



Modulation in Phase Shifters $\Delta\varphi = k_0 \cdot \Delta n_{\mathrm{eff}} \cdot L = k_0 \cdot \frac{1}{2} n_0^3\, r \boxed{\frac{U_{\mathrm{signal}}}{\mathrm{w}}} \cdot \Gamma \cdot L$

RF Field

Plasmonics

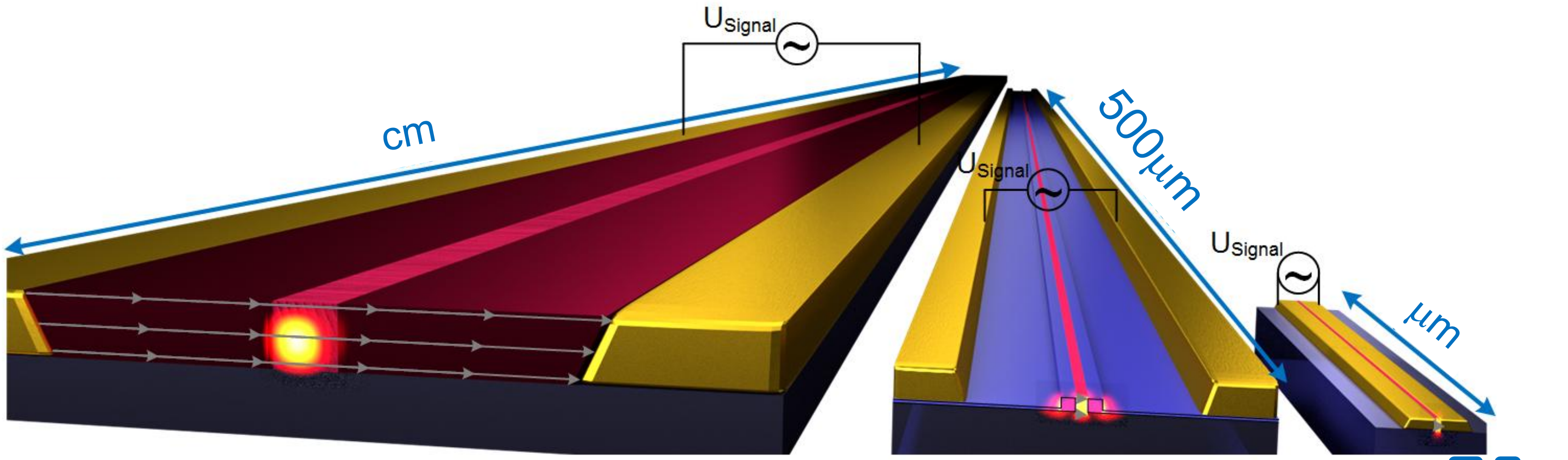


The plasmonic waveguide is smallest
→ Smallest voltage required

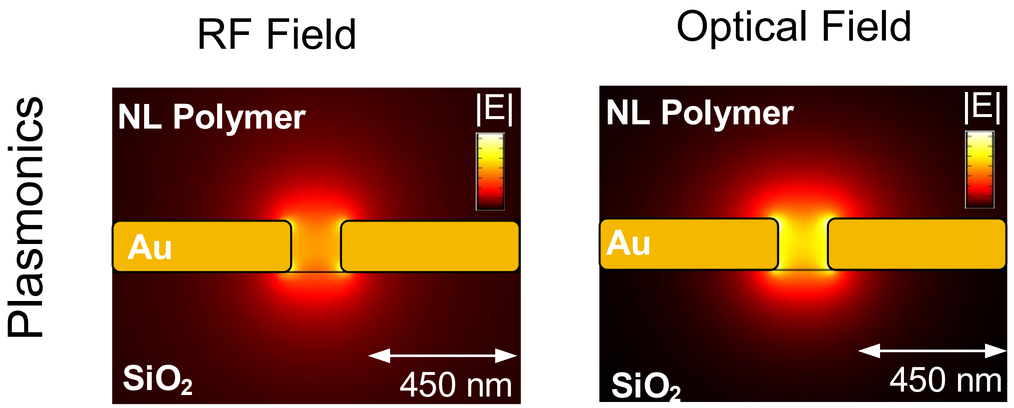
Factor 10!

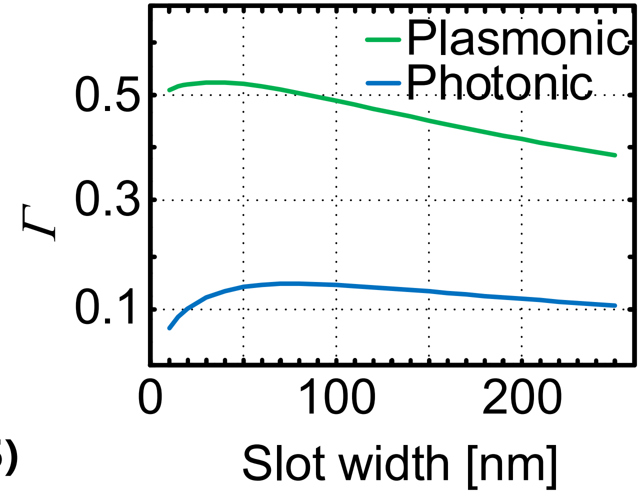
C. Haffner, W. Heni *et al. Nature Phot.*, **(2015)**

Plasmonic Modulators – Efficiency: The Plasmonic Confinement Advantage



Modulation in Phase Shifters $\Delta\varphi = k_0 \cdot \Delta n_{\text{eff}} \cdot L = k_0 \cdot \frac{1}{2} n_0^3\, r\, \frac{U_{\text{signal}}}{\text{w}} \cdot \boxed{\Gamma} \cdot L$

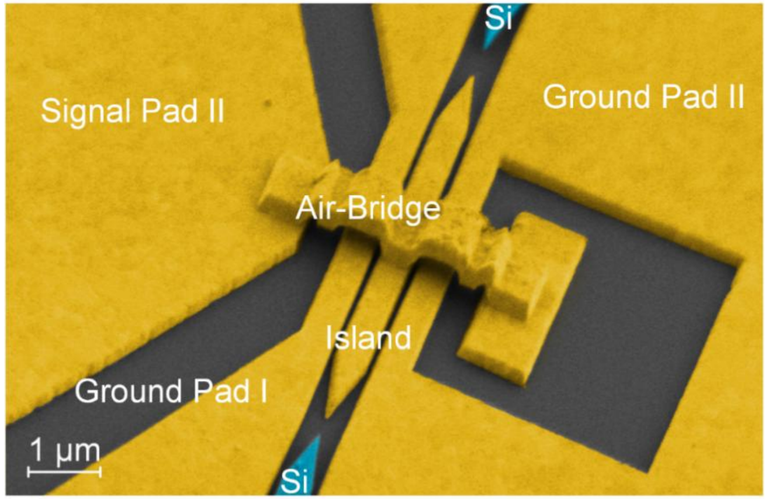




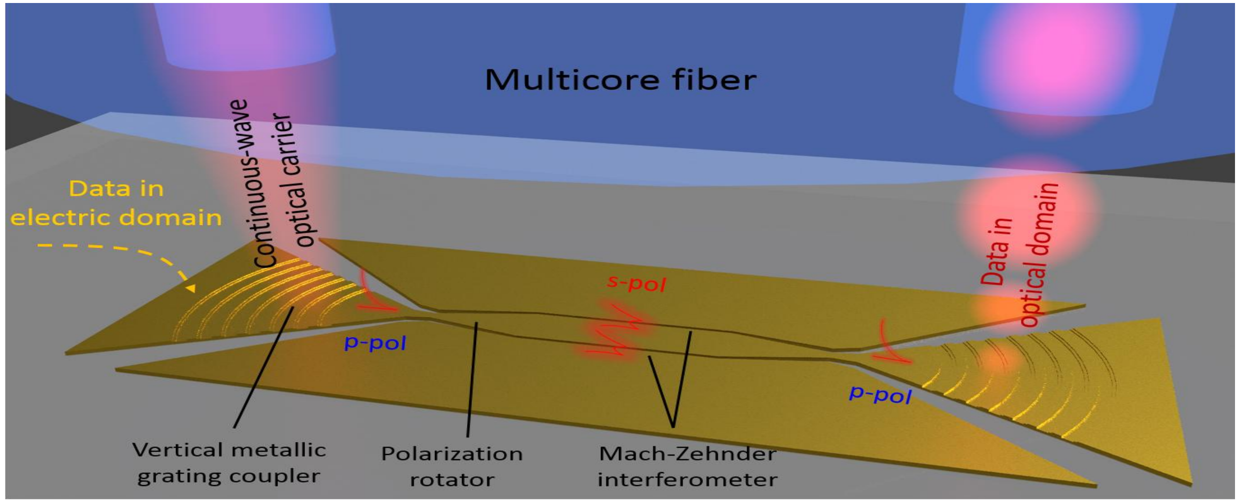
Factor 2-4!

C. Haffner, W. Heni *et al. Nature Phot.*, **(2015)**

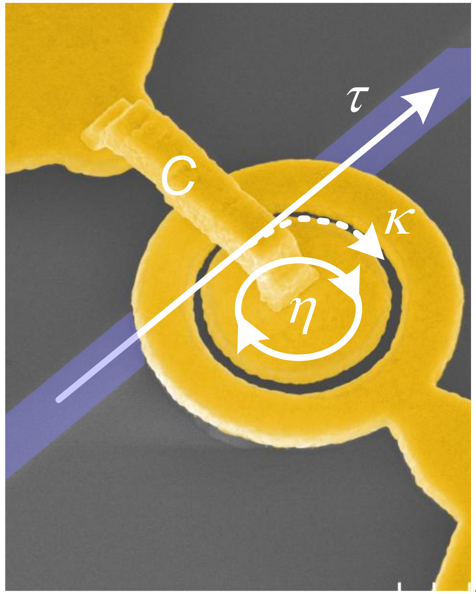
Plasmonic Modulators – the Footprint



Mach-Zehnder modulator in a waveguide: **10 μm length**, 8 dB Losses
Ref.: C. Haffner *et al., Nature Photonics, pp. 525-528, Aug. 2015.*

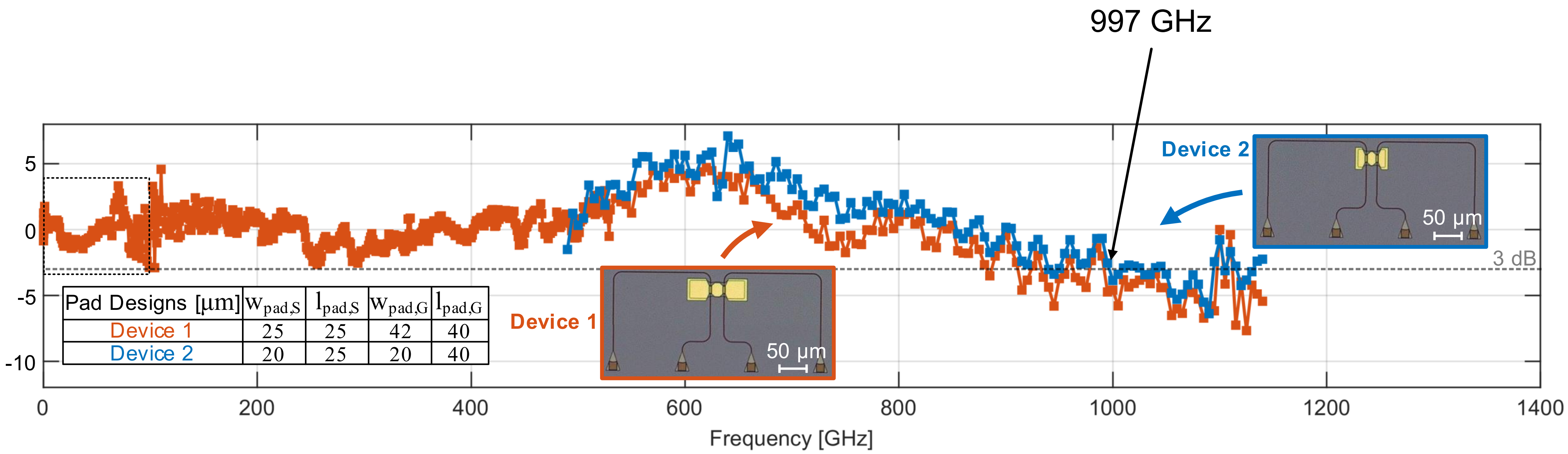


All metallic, **30 μm length**
Ref.: M. Ayata, *et al., Science, pp. 630-632, 2017.*



Ring modulator: **Radius 1.0 μm**; Device losses: 2.4 dB
Ref.: C. Haffner, *et al., "Low-loss plasmon-assisted electro-optic modulator," Nature, pp. 483-486, 2018.*

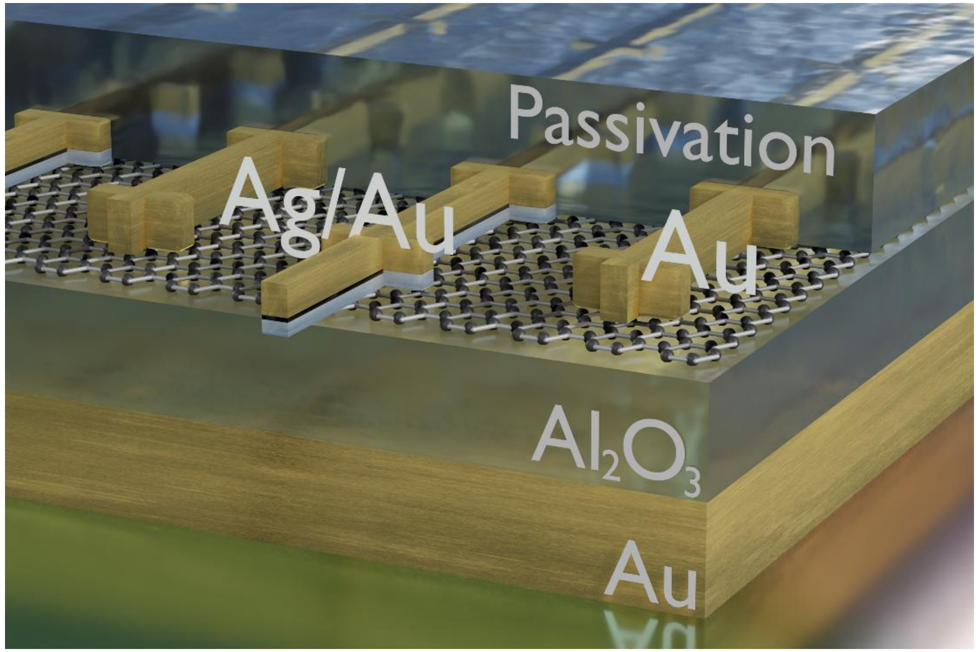
Plasmonic Modulators - Frequency Response



Pad Designs [µm]	$w_{pad,S}$	$l_{pad,S}$	$w_{pad,G}$	$l_{pad,G}$
Device 1	25	25	42	40
Device 2	20	25	20	40

ETH & Polariton: Y. Horst, et al."Ultra-wideband MHz to THz plasmonic EO modulator," Optica 12, 325-328 (March 2025).

Plasmonically (Metamaterial) Enhanced Graphene Photodetector



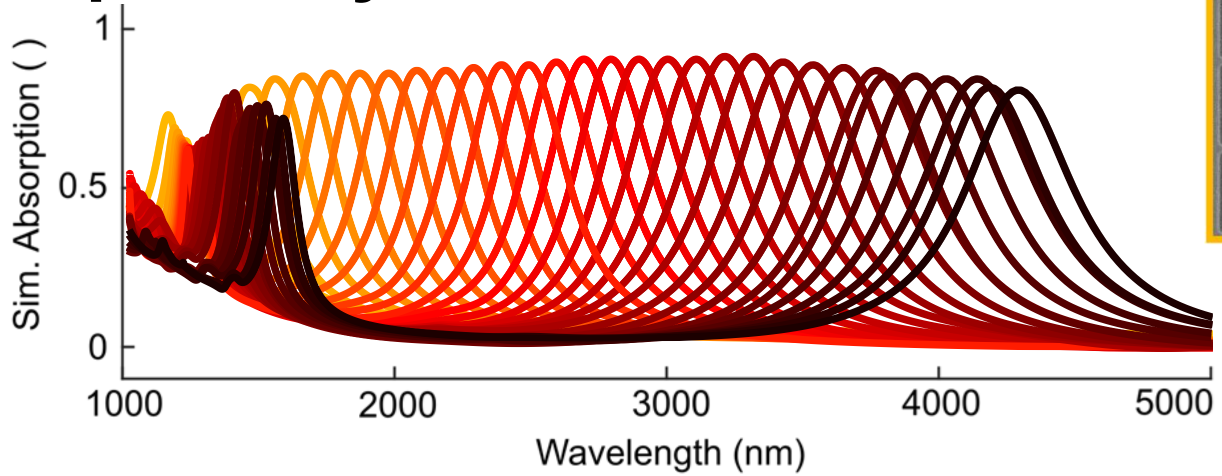
Main ideas of the stack:

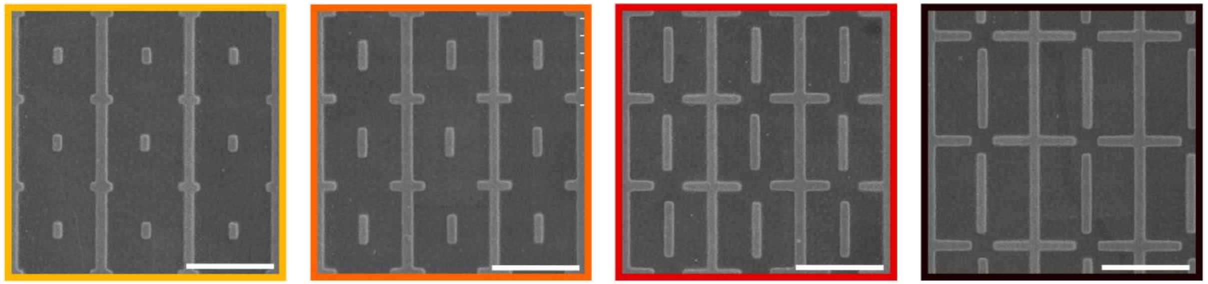
- Graphene in metamaterial perfect absorber stack → enhances absorption in graphene
- Alternating contact metals → p-n doping the graphene channel
- Dipole resonators are combined with contact lines → short carrier extraction pathways

S. M. Koepfli *et al.*, *"Metamaterial graphene photodetector with bandwidth exceeding 500 Gigahertz," Science, vol. 380, no. 6650, pp. 1169-1174, 2023, doi: doi:10.1126/science.adg801*

Institute of Electromagnetic Fields

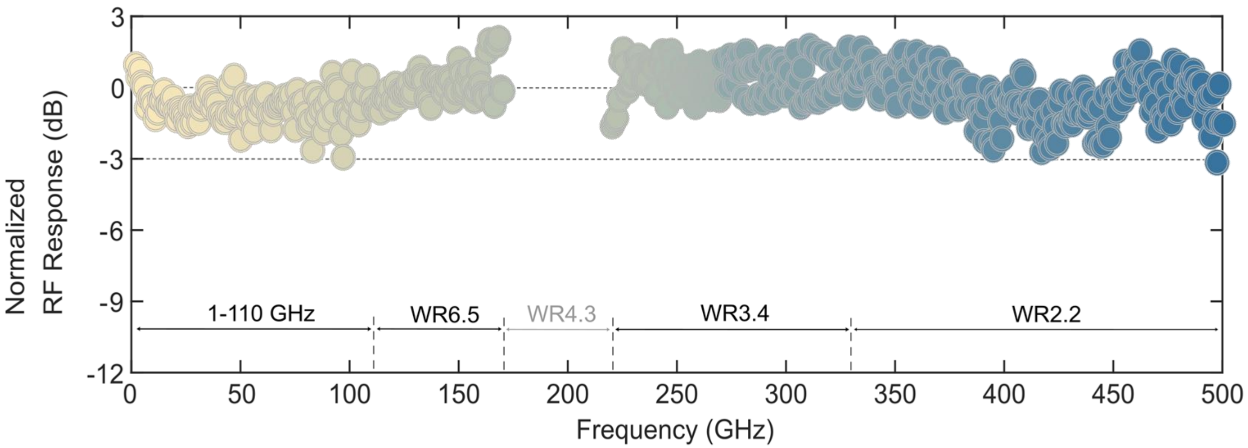
Spectrally Broadband





- Spectral adaptability across the infrared spectrum

Highest Speed Operation



- Flat frequency response from 2 to 500 GHz

→ World's fastest photodetector

S. M. Koepfli *et al.*, "*Metamaterial graphene photodetector with bandwidth exceeding 500 Gigahertz,*" *Science, 2023,*

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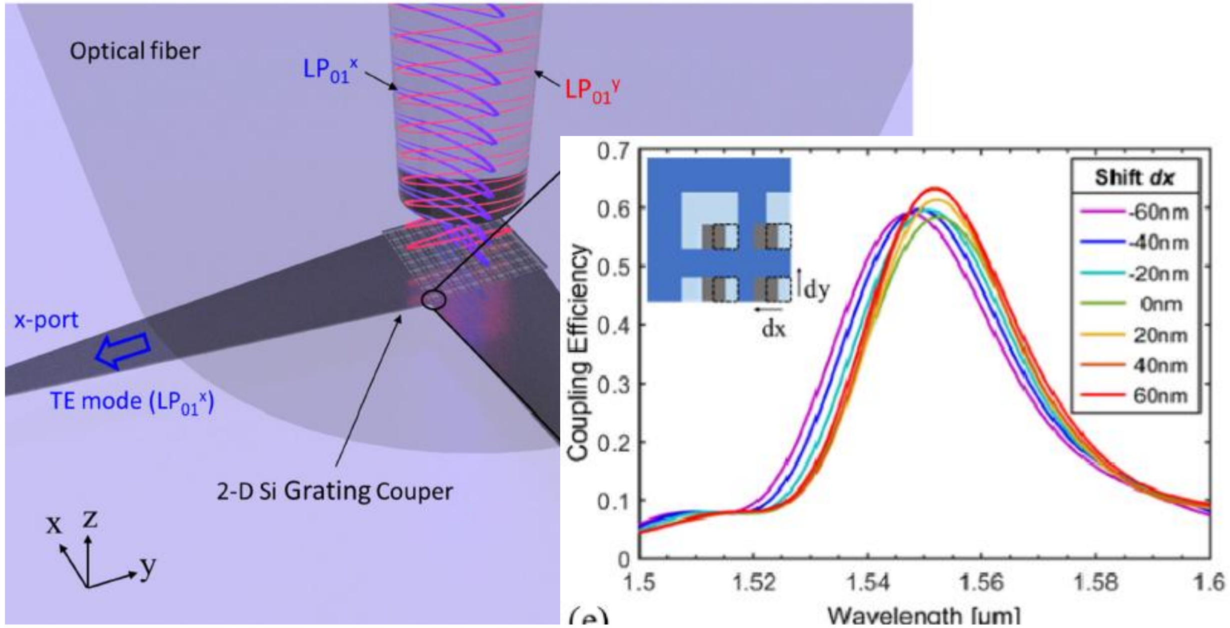
Fiber Coupling – Grating or Edge Coupling

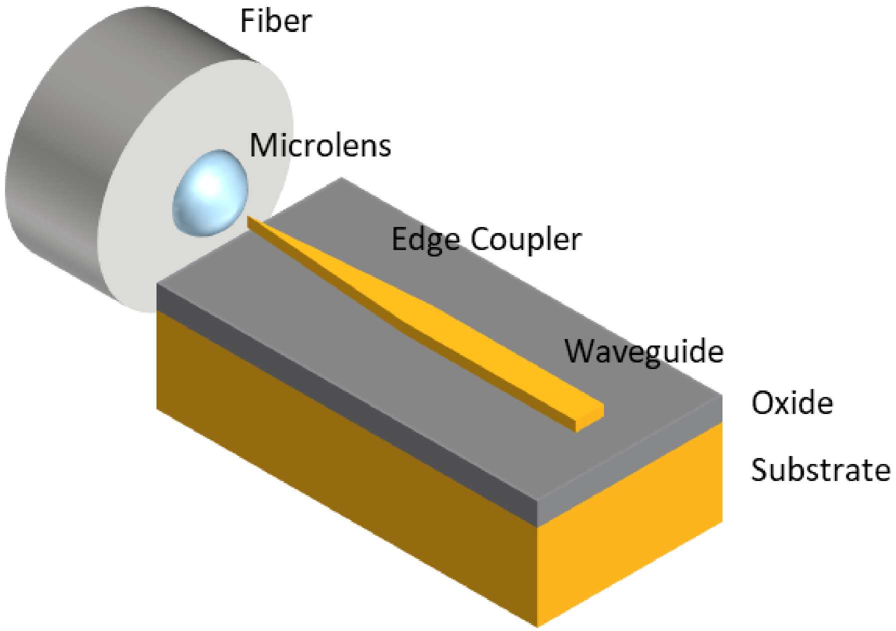
Grating Coupling



- Efficient characterization
- Fabrication is complicated, losses are large

T. Watanabe, Y. Fedoryshyn, and J. Leuthold, "2-D Grating Couplers for Vertical Fiber Coupling in Two Polarizations," IEEE Photonics Journal 11, 1-9 (2019).

Edge Coupling

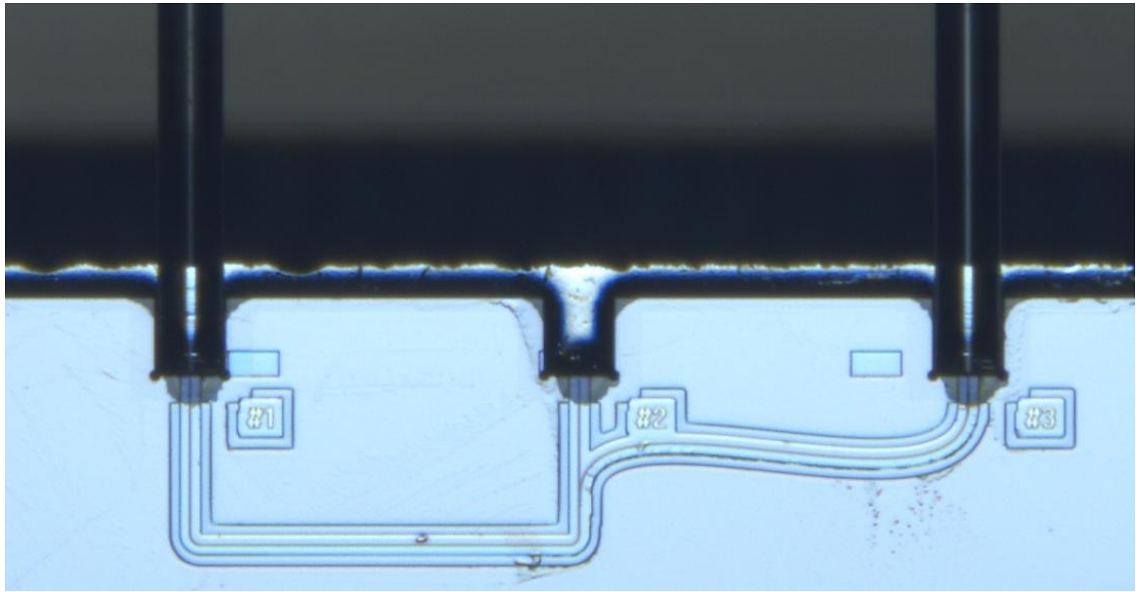


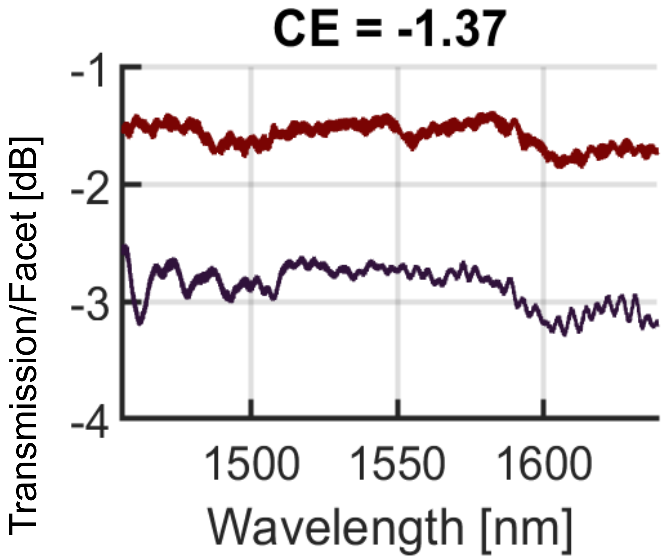
- Requires chip-level testing
- Mode-Adaptation needed (lenses, tapers)
- Losses are smaller

https://optics.ansys.com

Fiber Coupling – SMF with Lenses or UHNA?

- Fiber types:
  - SMF - large mode
  - UHNA - provides a better confinement and a better adaptation to small waveguide modes (Ultra-high Numerical Aperture)

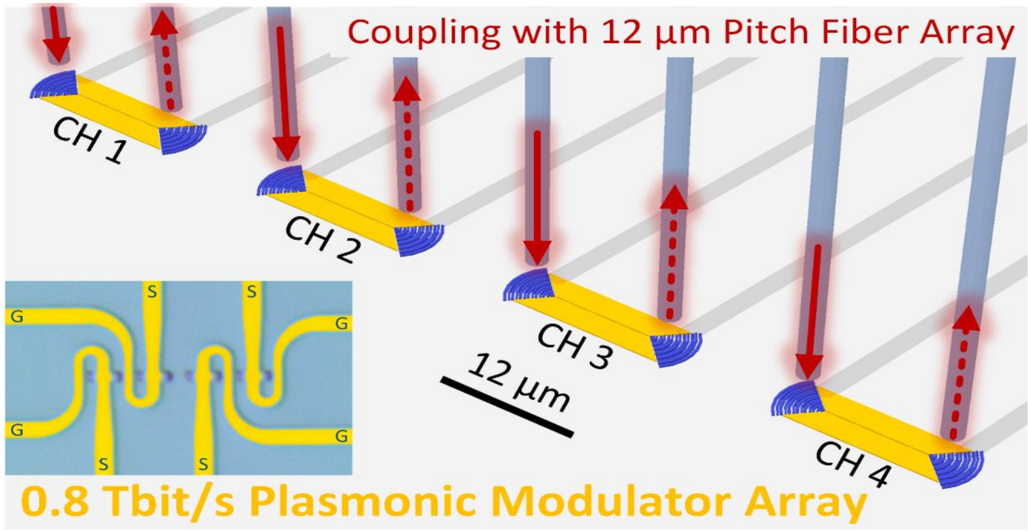




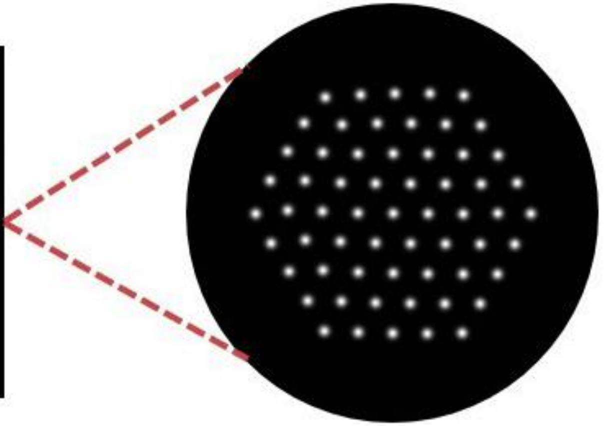
Fiber Coupling – Fiber Pitch

Challenge: Density of in-outputs!
Plasmonic provides it.
Standard fiber pitch is 125 um.

U. Koch *et al.*, *"Ultra-Compact Terabit Plasmonic Modulator Array," Journal of Lightwave Technology, March 2019.*



- Fiber types:
  - PROFA/Multicore (Pitch Reducing Optical Fiber Array)

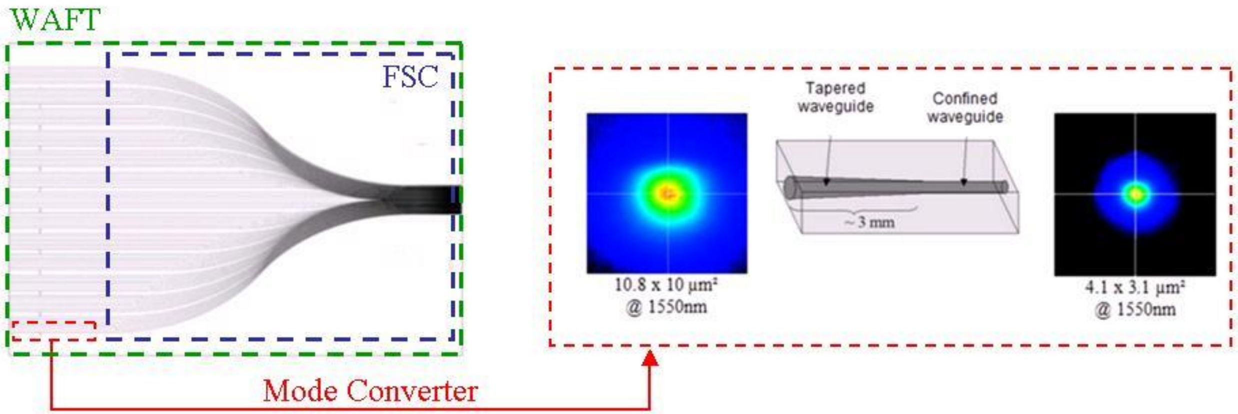


https://chiralphotonics.com/profa/

Fiber Coupling – Fiber Pitch

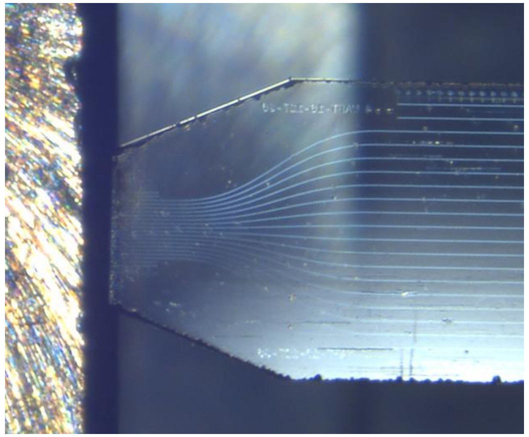
Challenge:

Low loss & high pitch

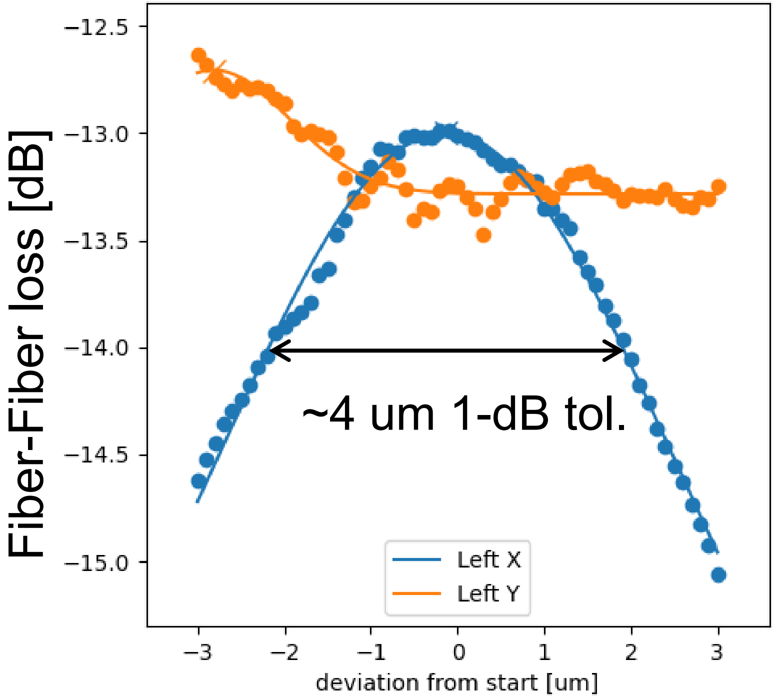


- Fiber types:
  - WAFT
    (Waveguide Array to Fiber Transposers)

WAFT

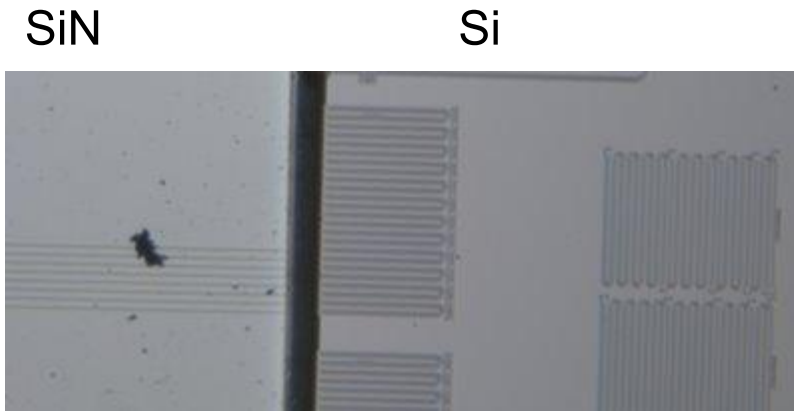


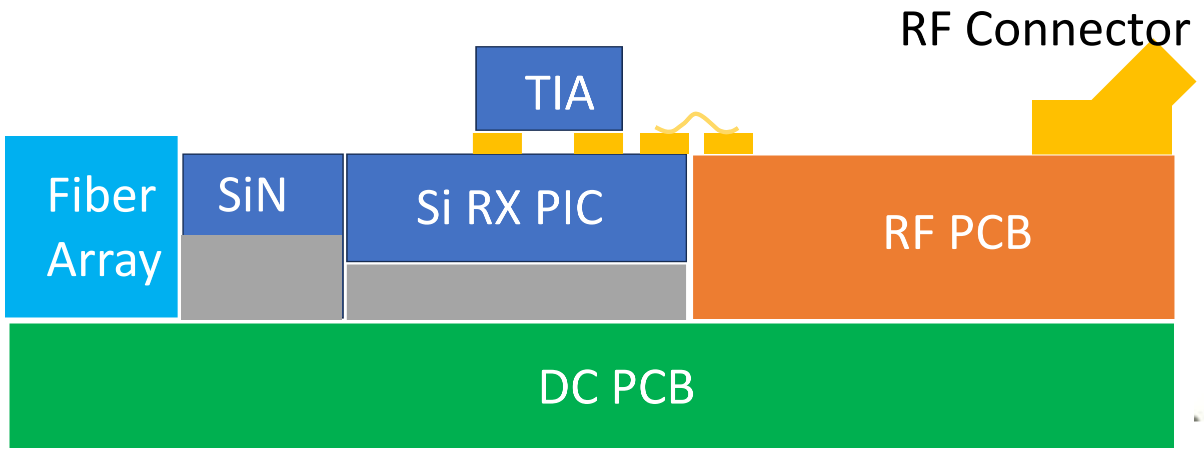
Alignement Tolerances

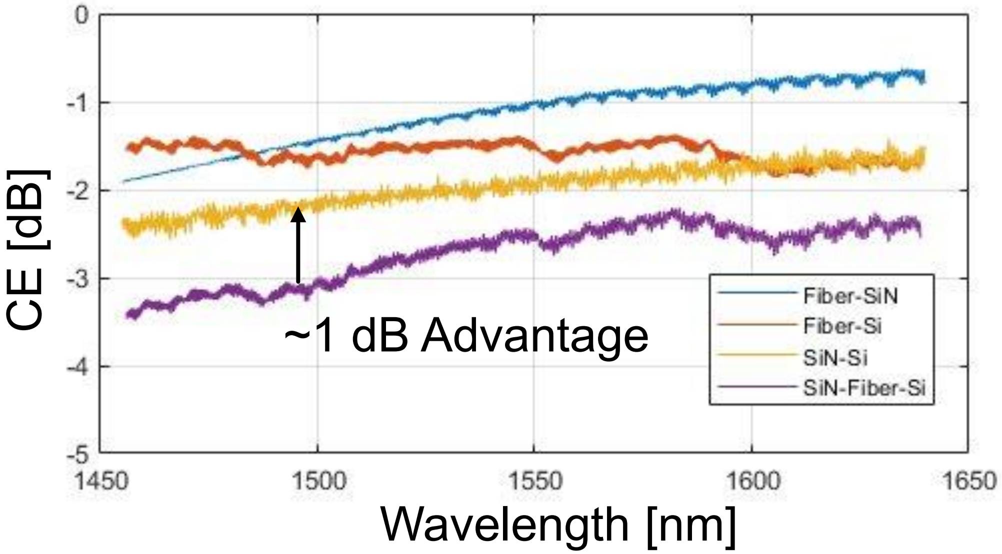


Chip-to-chip Coupling

- Silicon to Silicon Nitride
- Platform integration → Beamforming, RoF…
- MFD 2-4 um → better size match than fiber mode







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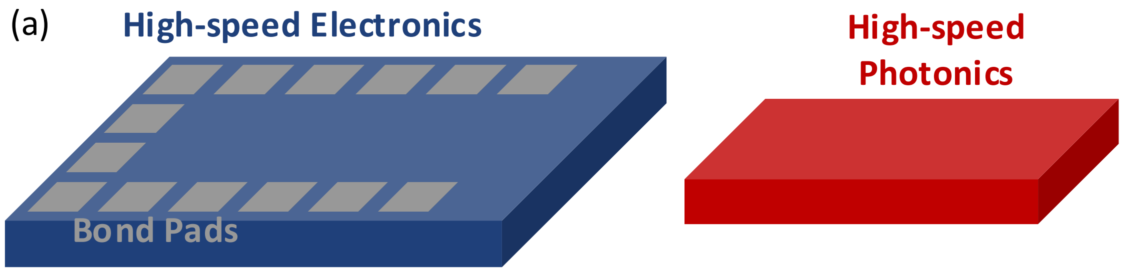
Co-integration Approaches of Electronics with Plasmonics

(a)

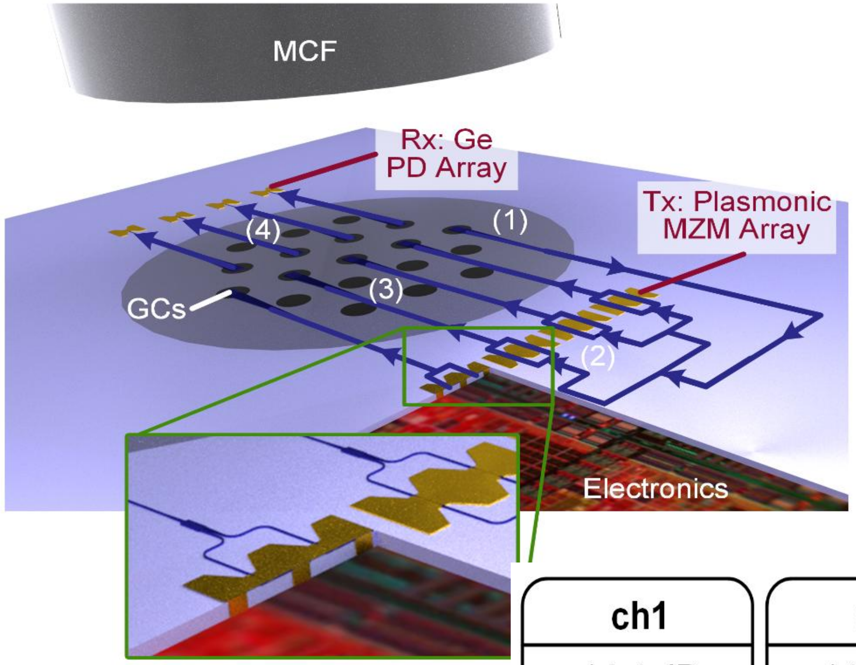


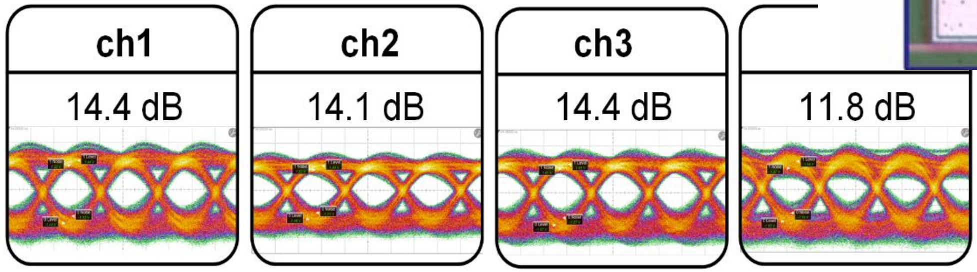
Separate chips

U. Koch, et. Al. , "Plasmonics—high-speed photonics for co-integration with electronics," Jap. J. of Appl. Phys. 60, SB0806 (2021).

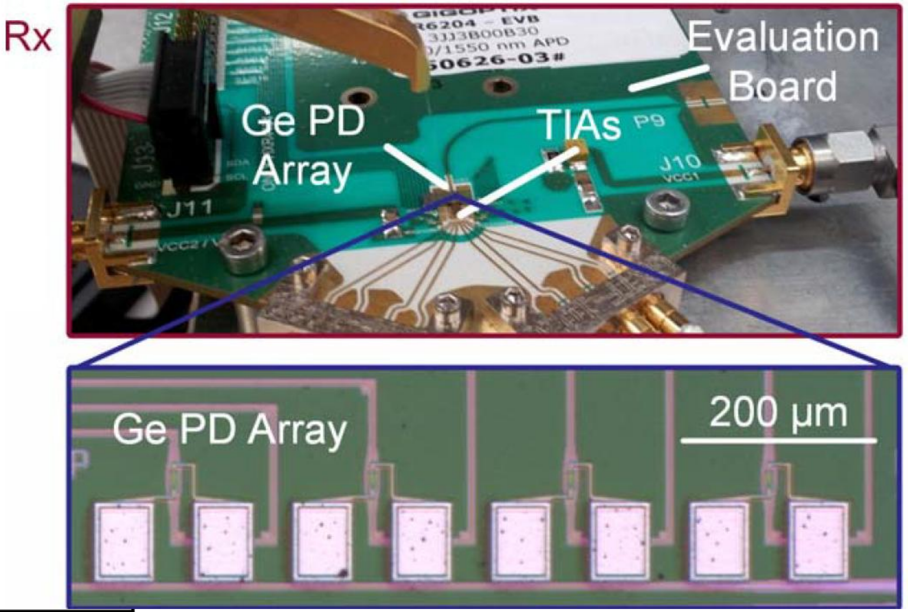
Interconnects: Arrays of Modulators & Detectors

Array of 4 modulators with 20 Gbit/s each.





Array of 4 PDs with 20 Gbit/s each.



C. Hoessbacher *et al., "Optical Interconnect Solution with Plasmonic Modulator and Ge Photodetector Array," IEEE Photonic Tech L, vol. 29, no. 21, pp. 1760 - 1763, Nov. 2017.*

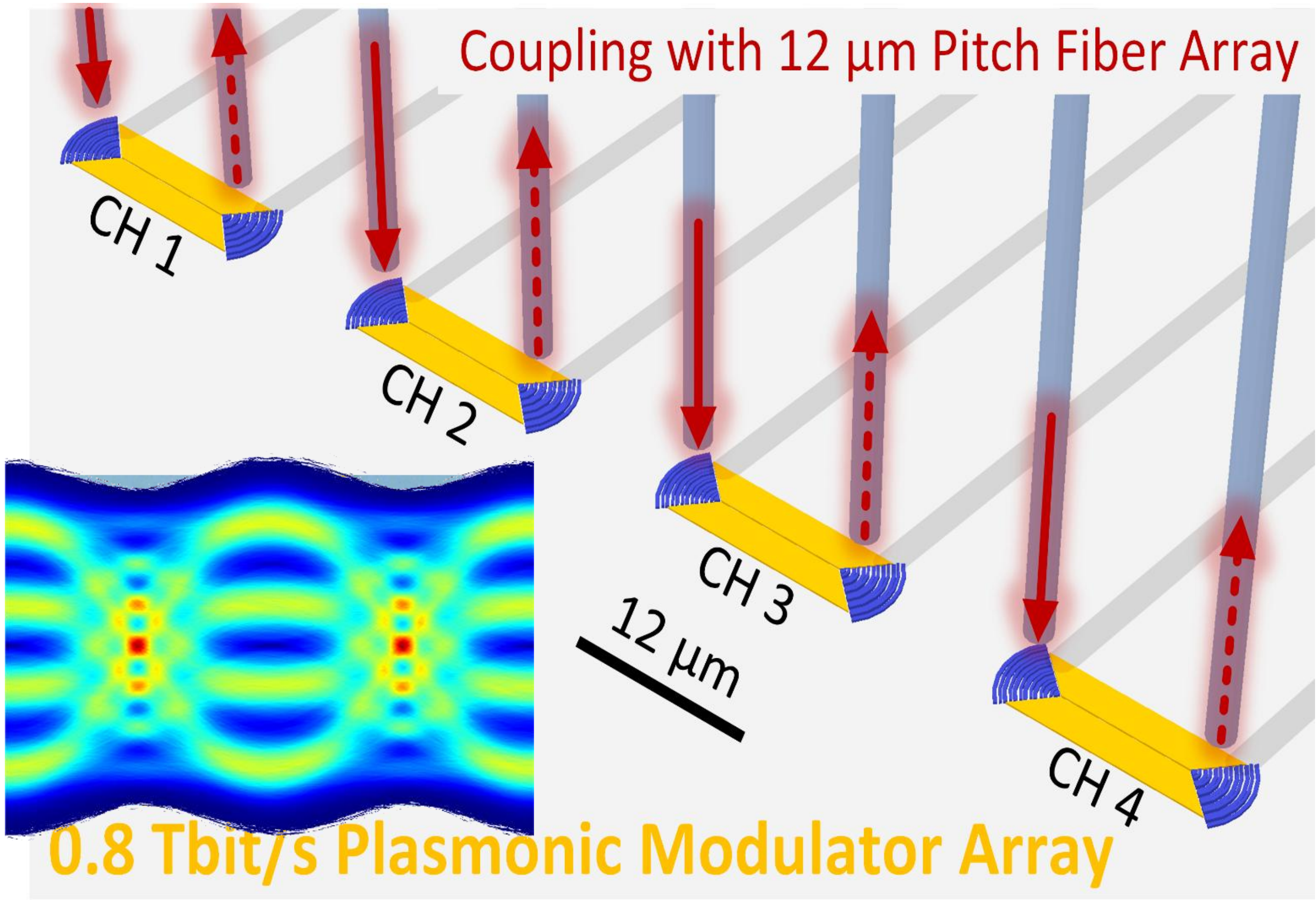
A Interconnect Solution with Tb/s Throughput

Footprint: 90 x 5 μm^2
→ could directly interface electronics
(no wirebonds, no lasers,…)

Power consumption: 10s of fJ/bit
→ capacitive loading

Speed: >100 GHz
e.g. 200 Gbit/s PAM4

15 dB fiber-to-fiber losses



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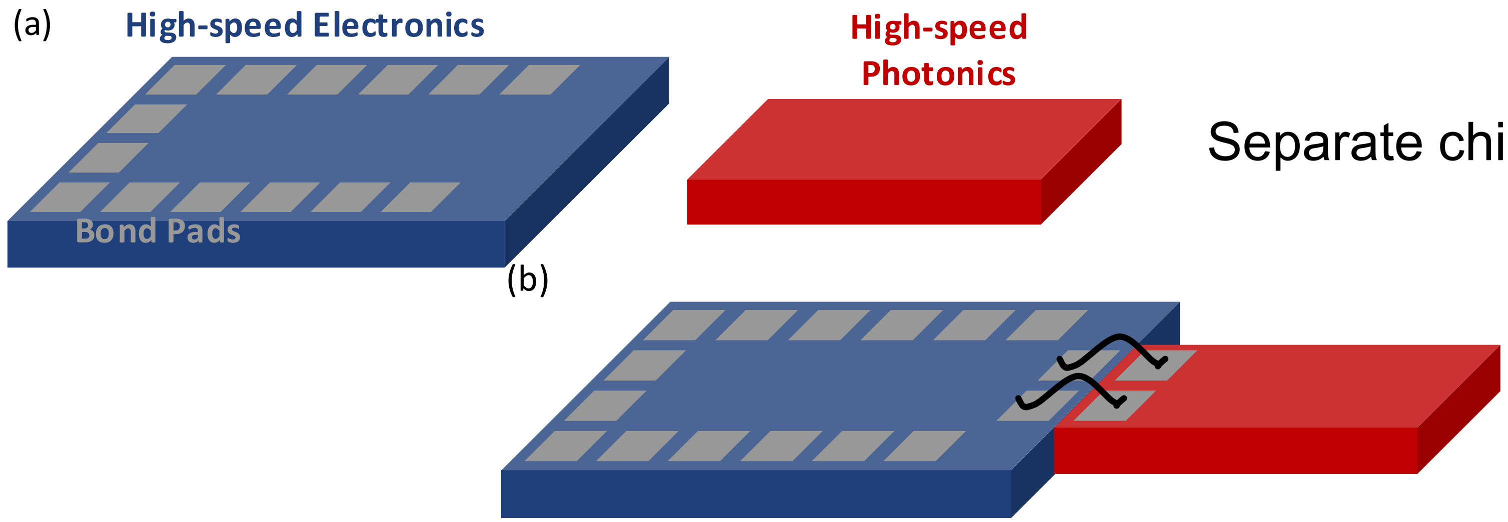
Co-integration Approaches of Electronics with Plasmonics

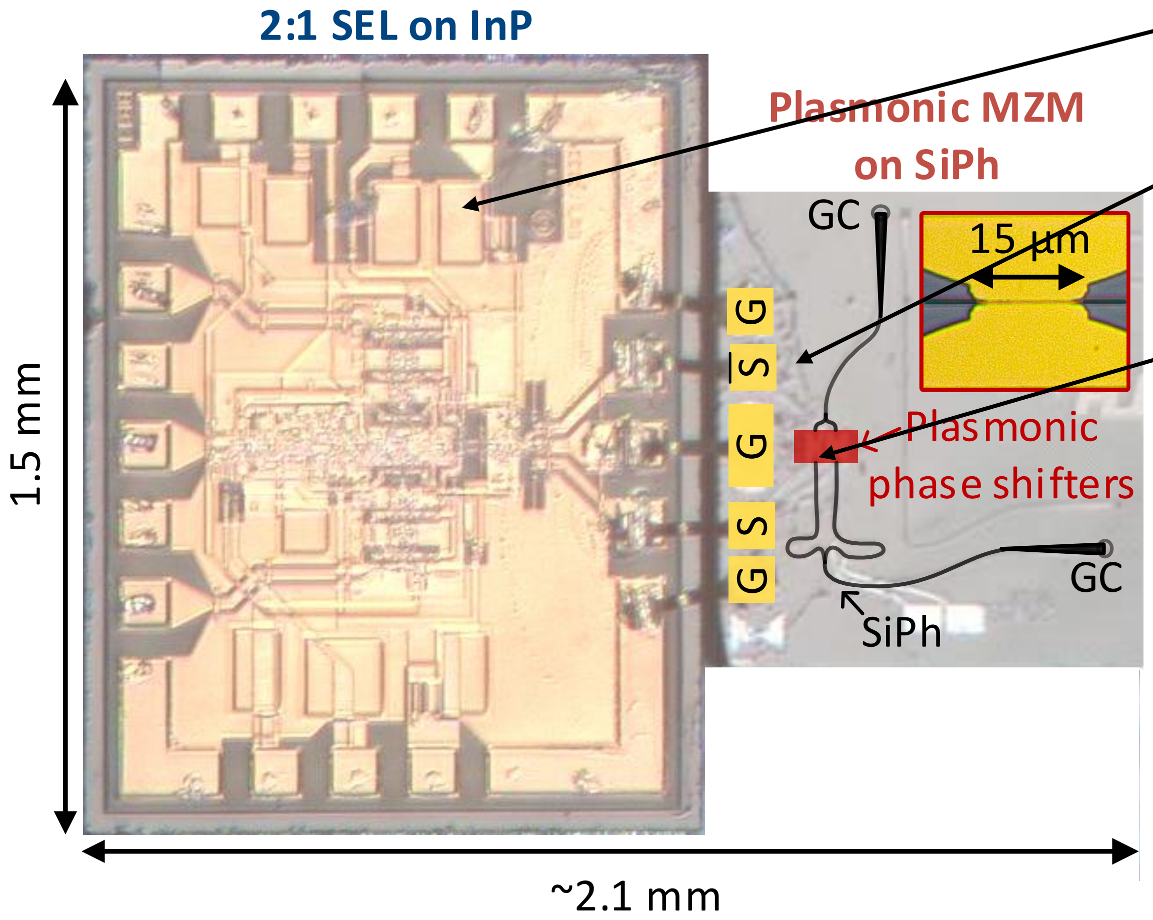


Separate chips

Bond-wire assembly

U. Koch, et. Al. , "Plasmonics—high-speed photonics for co-integration with electronics," Jap. J. of Appl. Phys. 60, SB0806 (2021).

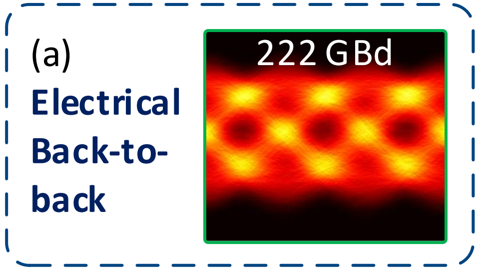
Bond-Wire Assembly of Electronics with Plasmonics

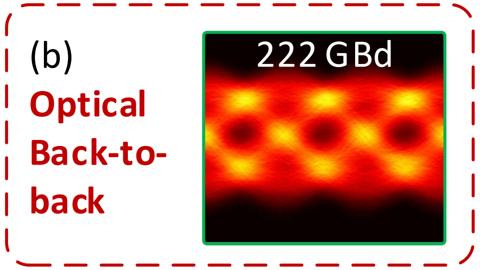


2:1 digital multiplexing selector in InP DHBT

Drives the modulator with a differential output voltage of 622 mV_{pp}

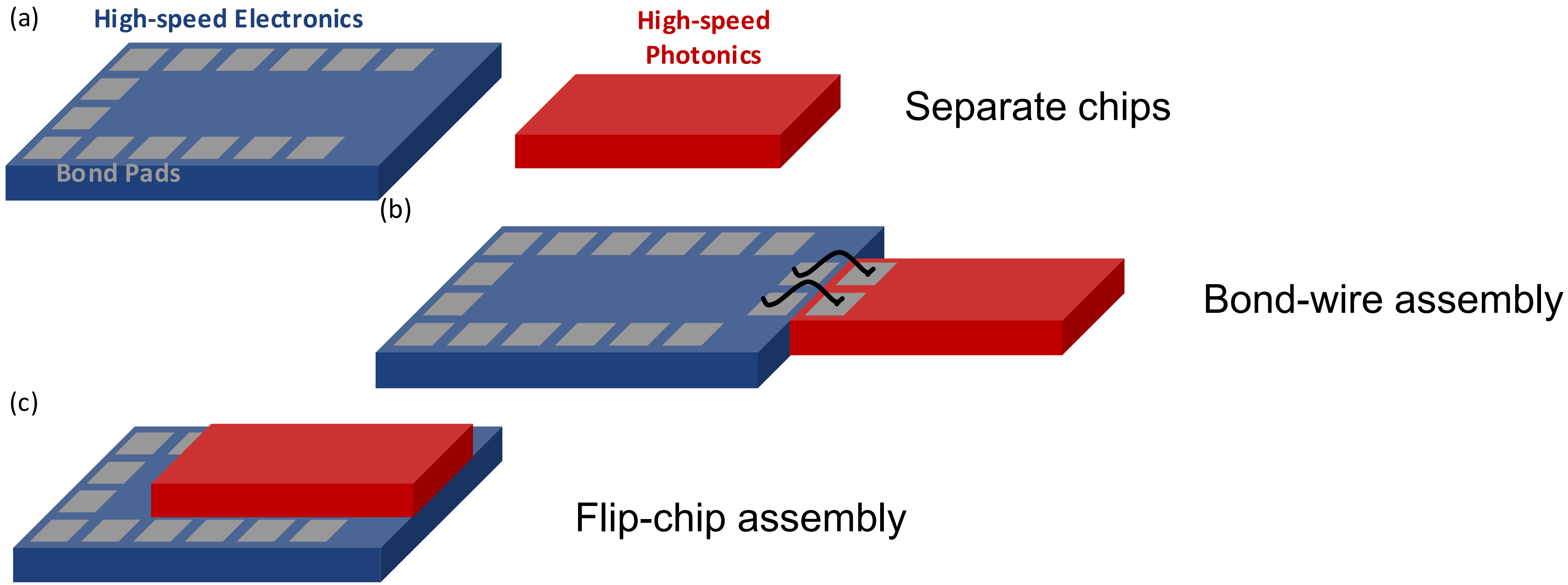
Plasmonic MZI





M. Haik, et. al., (ECOC'19), Dublin, Ireland, Sept. 2019.
W. Heni, et. al., Journal of Lightwave Technology 38, 2734-2739 (2020).

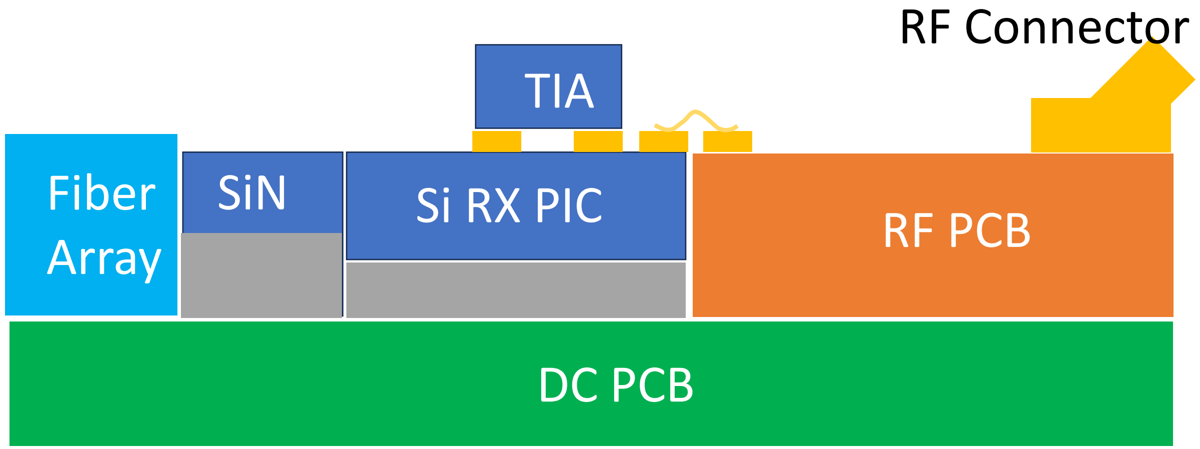
Co-integration Approaches of Electronics with Plasmonics



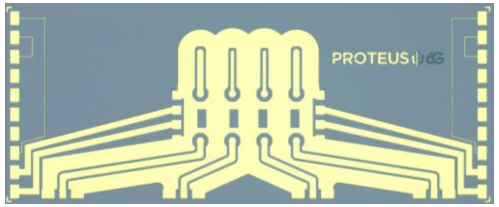
U. Koch, et. Al. , "Plasmonics—high-speed photonics for co-integration with electronics," Jap. J. of Appl. Phys. 60, SB0806 (2021).

Flip-Chip Bonding Receiver TIA

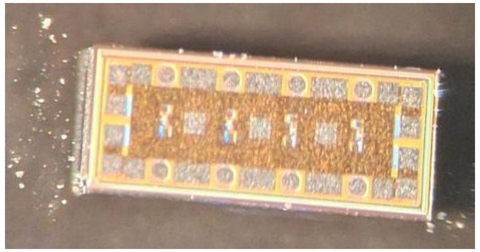
- >110 GHz 4-Channel in-house designed TIA
- Thermal budget 300 C
- 50 um pitch
- Power supply through PIC



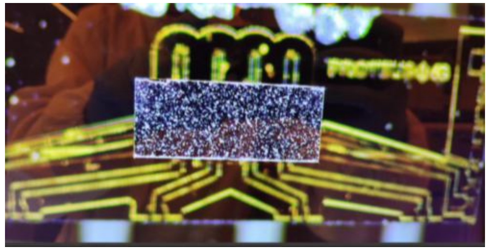
Test PIC



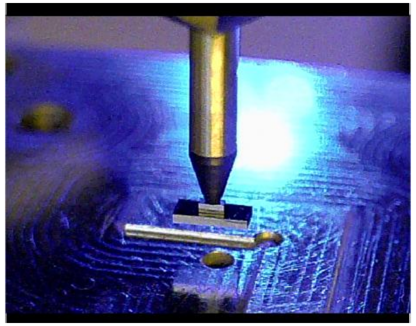
TIA



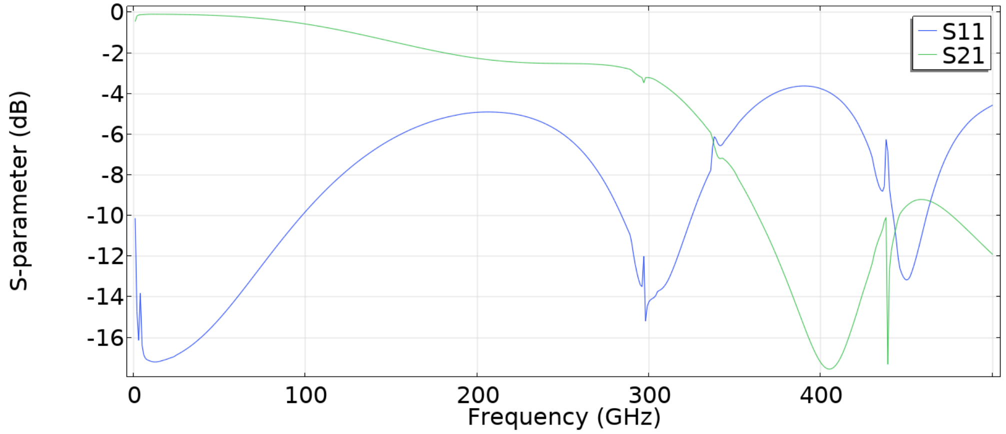
After Bonding*



Flip-Chip Process*



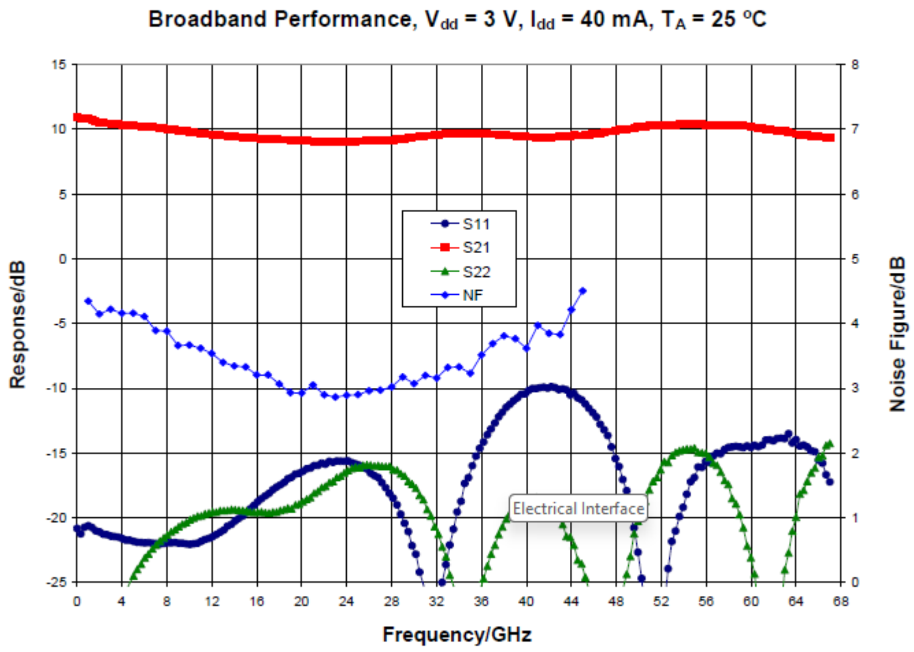
Simulated TIA Response



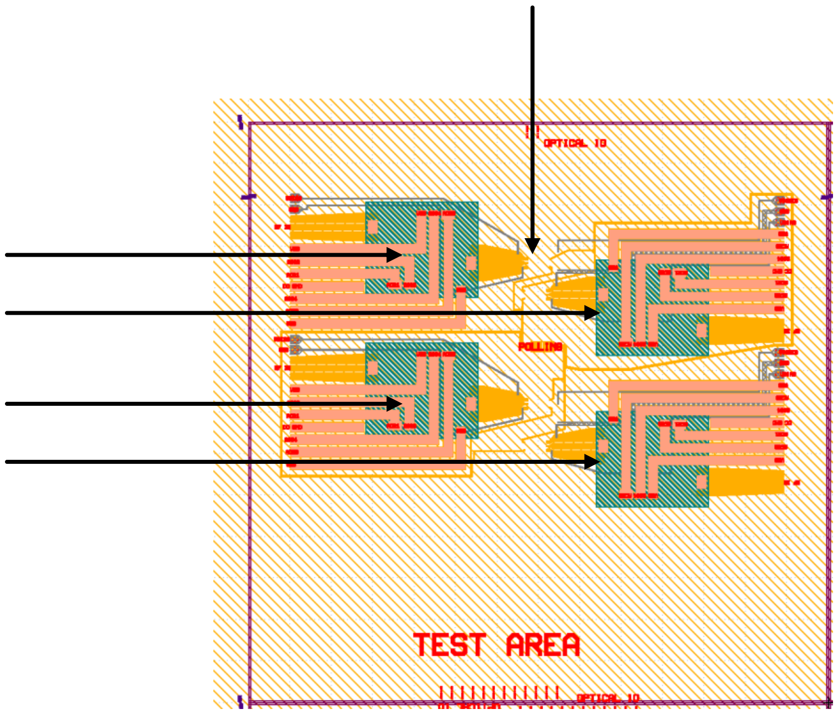
*Flip chip bonding by Picadvanced

Flip-Chip Bonding Transmitter Driver

- 70 GHz commercial driver
- 4 EIC on one PIC
- Thermal budget ~80C

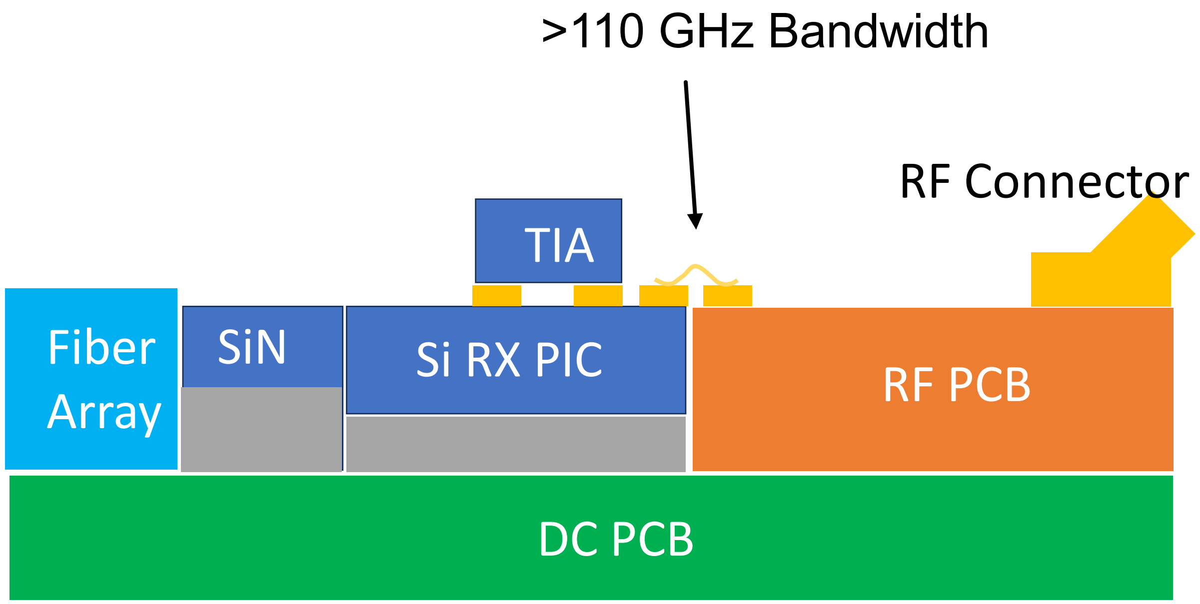


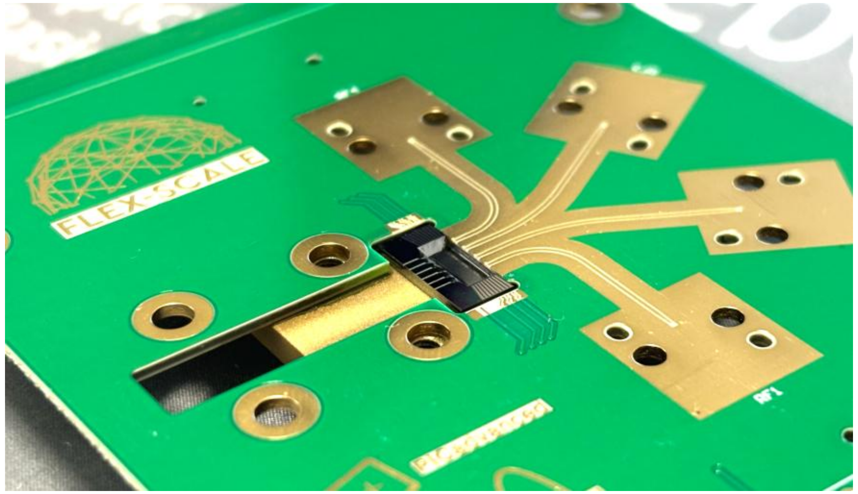
Plasmonic Modulator



RF Ribbon Bonding/PCB

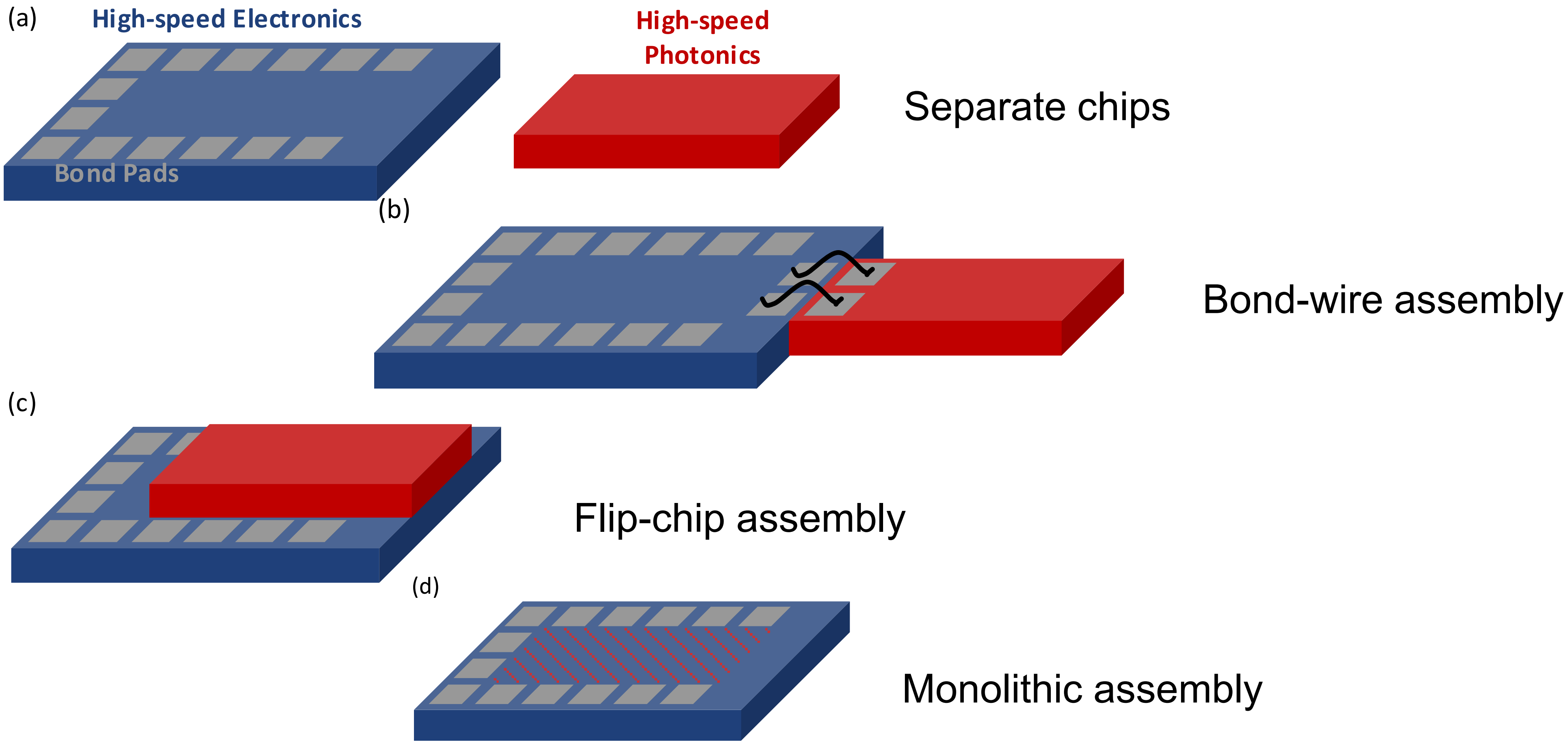
- 110 GHz RF PCB
- Short Au ribbon bonds for high bandwidth





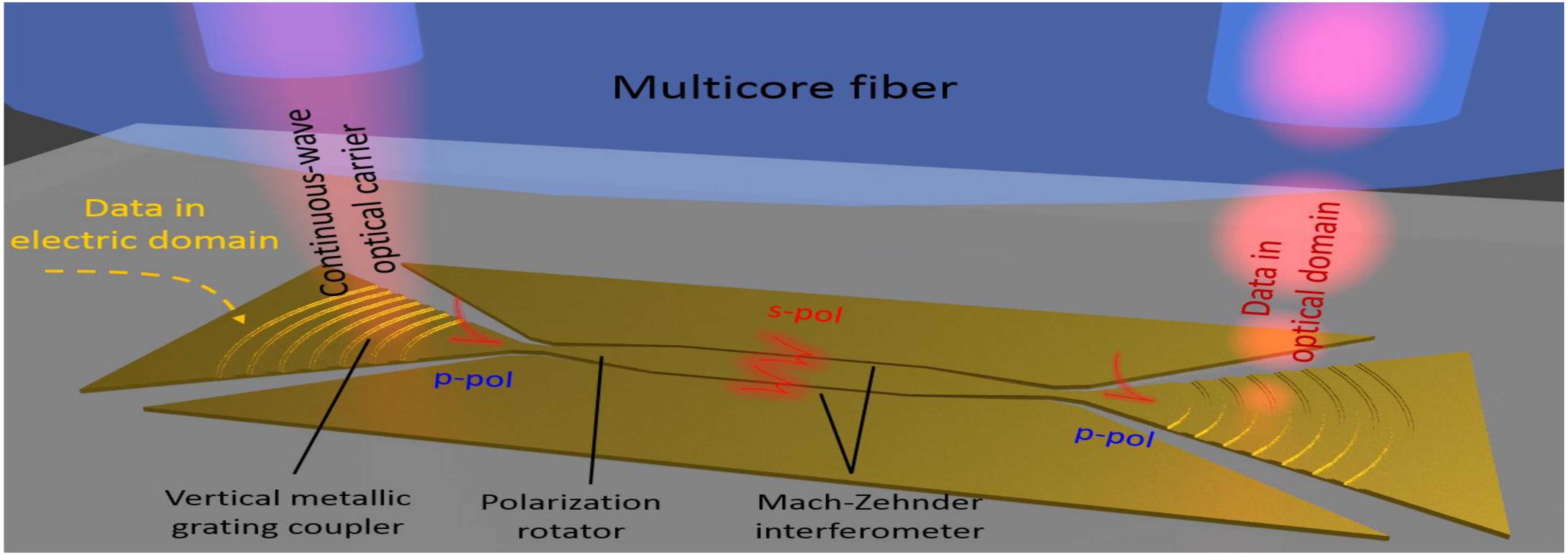
RF design by Polariton,
PCB and chip submount by Picadvanced

Co-integration Approaches of Electronics with Plasmonics



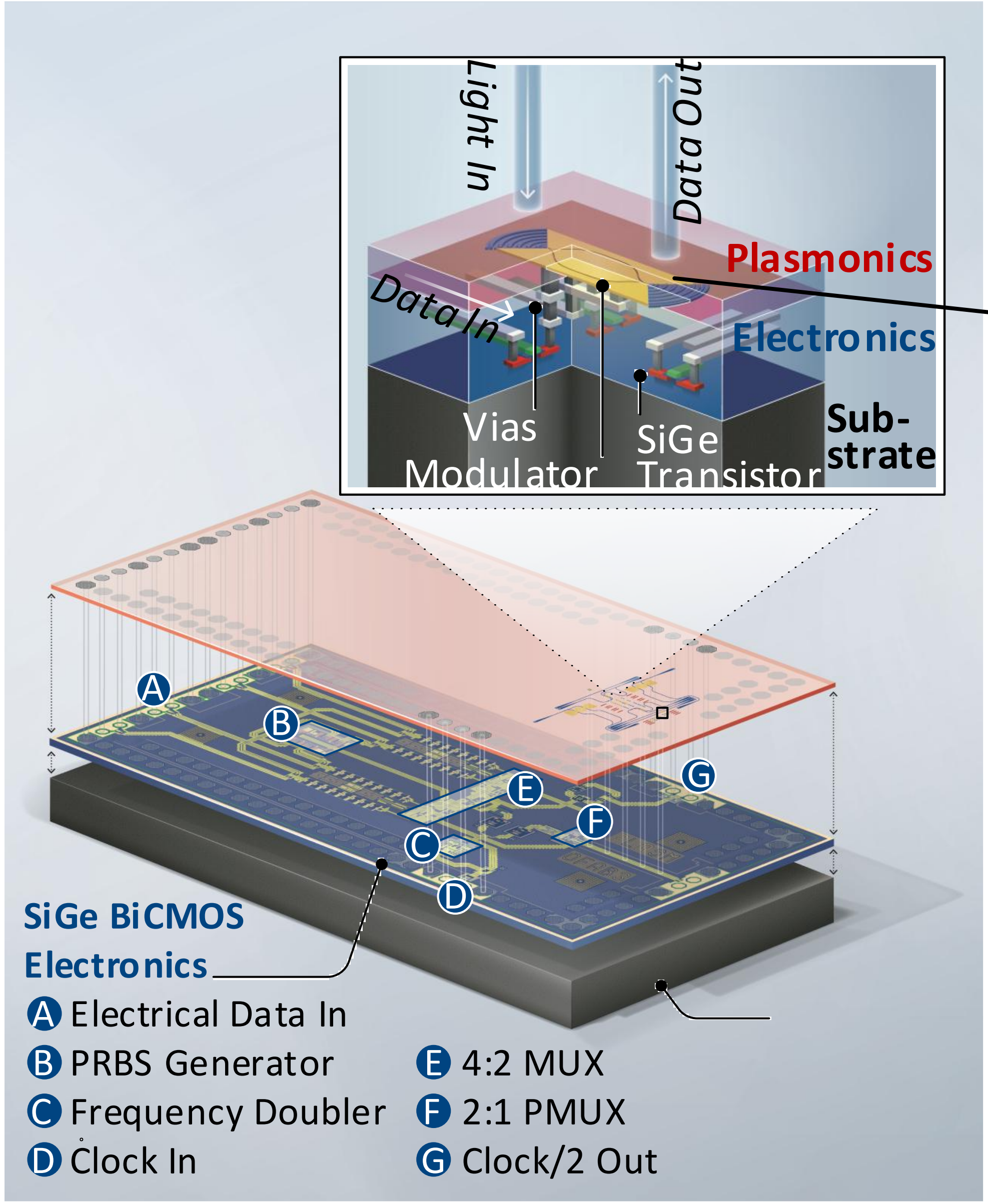
U. Koch, et. Al. , "Plasmonics—high-speed photonics for co-integration with electronics," Jap. J. of Appl. Phys. 60, SB0806 (2021).

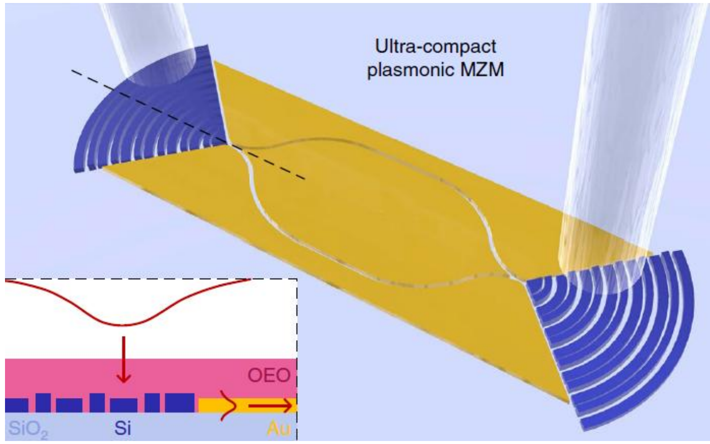
Plasmonic Modulators – A Platform to go Everywhere



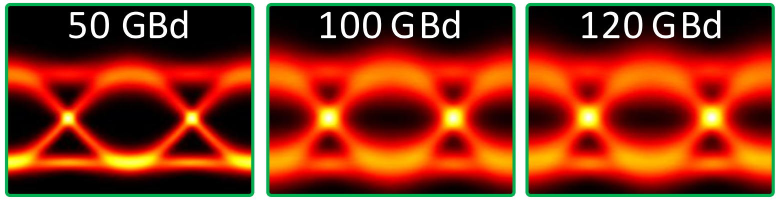
All metallic, **30 μm length**
Ref.: M. Ayata, *et al., Science, pp. 630-632, 2017.*

Monolithic Electronic-plasmonic High-speed Transmitter





Silicon-plasmonic MZM



SNR = 13.14 dB SNR = 8.14 dB SNR = 7.20 dB

U. Koch, et. al. "A monolithic bipolar CMOS electronic–plasmonic high-speed transmitter,« Nature Electronics 3, 338–345 (2020).

Summary

Plasmonic devices offer

- Highest bandwidths – yet, to take advantage a high-speed bonding or integration technology is needed.
- A most compact footprint – yet, to take advantage a low-loss, low pitch coupling to fibers is needed.

Potential solutions to fiber coupling

- UHNA-WAFT would be needed
- Bonding technologies must be developed that are able to handle >>100 GHz

The expertise from **Swiss PIC** meets a relevant need!