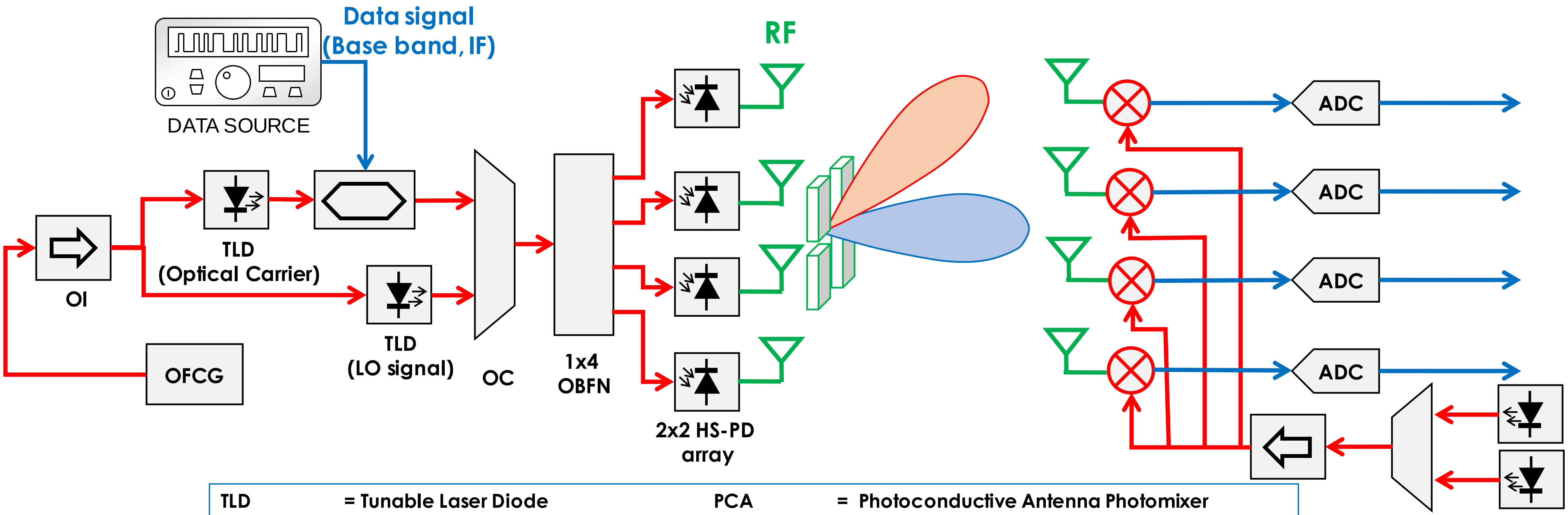
Session C

Photonics-enabled wireless transceivers

Novel photonic components for mmWave & THz communications

Guillermo Carpintero, Universidad Carlos III de Madrid (UC3M)

TERAWAY Microwave Photonics System Concept



TLD	= Tunable Laser Diode	PCA	= Photoconductive Antenna Photomixer
OBFN	= Optical Beam Forming Network	OLO	= Optical Local Oscillator
OC	= Optical Combiner		
OFCG	= Optical Frequency Comb Generator		
OI	= Optical Isolator		
HS-PD	= High-Speed Photodiode		

TERAWAY Challenge: Integrate as many components as possible on a Photonic Integrated Circuit (PIC)

TERAWAY Hybrid Integration Platforms

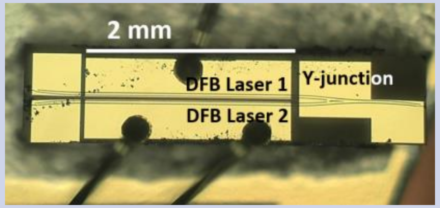
Building Block	InP	SiP	SiN	Polymer
Passive components	●●	●●	●●●	●●
Polarization components	●●	●●		●●●
Lasers	●●●	H	H	H
Phase modulators	●●●	P	●	●
Electro-Absorption modulators	●●●	●●		
Switches	●●●	●●	●	●●●
Optical Amplifiers	●●●	H	H	H
Detectors	●●●	H	H	H
Optical Isolators				H
RF and Microwave circuits	●	●	●	●●●

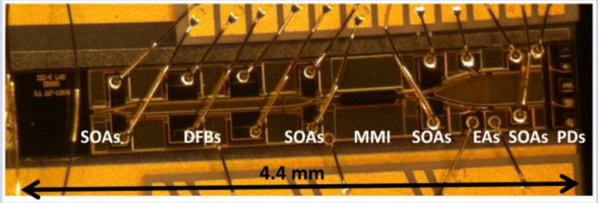
Performance	
●●●	Very good
●●	Good
●	Modest

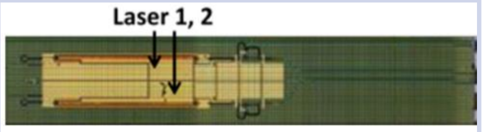
Fabrication technology	
H	Hybrid
P	Plasmonic

"JePPIX Roadmap 2018: The road to a multi-billion euro market in Integrated Photonics"

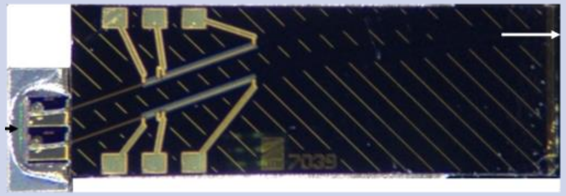
Integrated Microwave Photonics SotA







Polymer chip



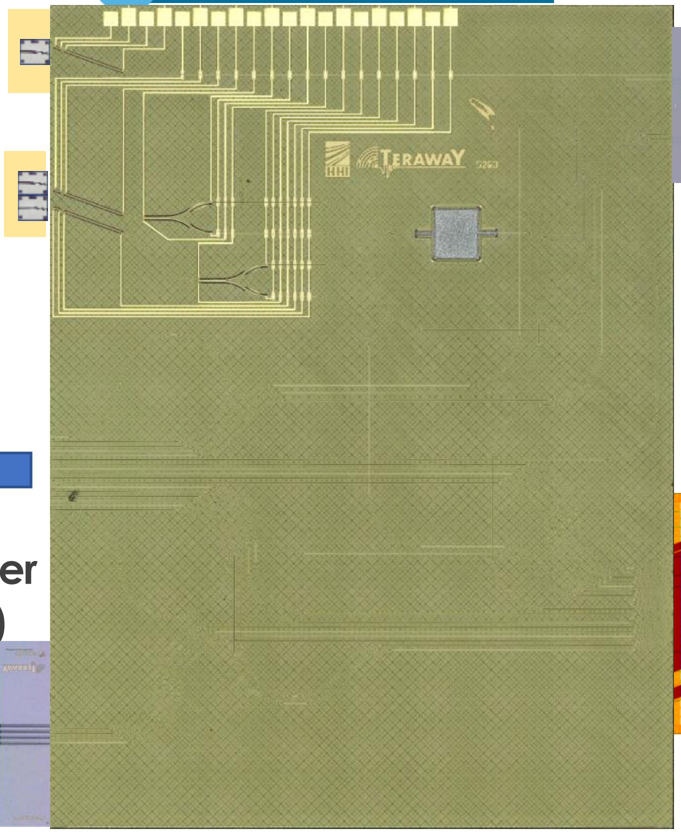
	2011	2014	2017	2018
Size	4 mm x 1 mm	4.4 mm x 0.7 mm		4 mm x 2 mm
Technology	Monolithic InP	Monolithic InP	Heterogeneous Si-InP	Hybrid Polymer-InP
Laser structure	DFB	DFB	Coupled Ring Resonator	DBR
Electrical LW	< 1 MHz	2 MHz	150 kHz	1,39 MHz
Tuning range	70 to 146 GHz	5 to 110 GHz	42 nm (1 to 112 GHz)	24 nm (1 GHz – 3 THz)
Tuning mechanism	Thermal (laser bias current)	Thermal (laser bias current)	Thermal heaters (Vernier effect)	Thermal heaters (Polymer DBR mirror)
	F. Van Dijk et al. "Monolithic dual wavelength DFB lasers for narrow linewidth heterodyne beat-note generation," IEEE Microwave Photonics (2011)	G. Carpintero et al "Microwave Photonic Integrated Circuits for Millimeter-Wave Wireless Communications" Journal of Lightwave Technology, 2014	J. Hulme et al "Fully integrated microwave frequency synthesizer on heterogeneous silicon-III/V" Optics Express, 2017	G. Carpintero et al "Wireless Data Transmission at Terahertz Carrier Waves Generated from a Hybrid InP-Polymer Dual Tunable DBR Laser Photonic Integrated Circuit" Scientific Reports 2018

TERAWAY Transmitter Module PIC

Module 2 - Tx

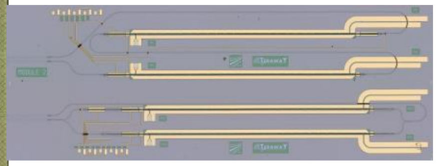
PolyBoard for tunable lasers, isolator and routing

Fabricated
Characterisation



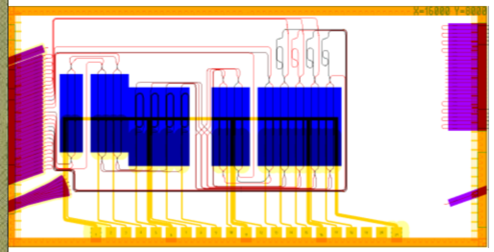
(17.1 x 25.7 mm)

InP modulator chip for generation of OFC and I/Q data modulation



Fabricated
Characterisation

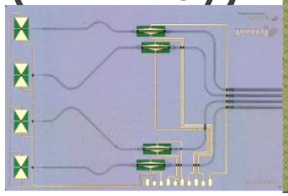
TriPleX 1x4 Optical Beam Forming Network



Fabricated
Characterized

To/from fiber array for monitoring, backup and alignment

InP THz emitter (1x4 Array)



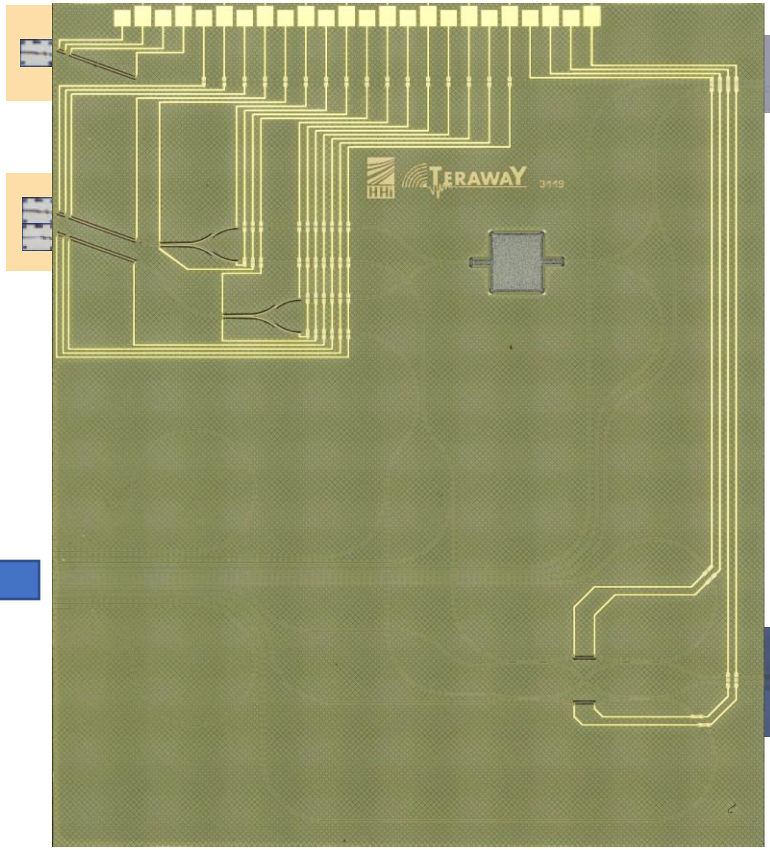
Fabricated
Characterisation

TERAWAY Receiver Module PIC

Module 2 - Rx

PolyBoard for tunable lasers, isolator and routing

Fabricated
Characterisation

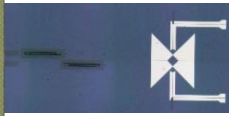


InP phase modulator chip for generation of OFC

Fabricated
Characterisation

To/from fiber array for monitoring, backup and alignment

InP THz I/Q receiver



Fabricated
Characterisation

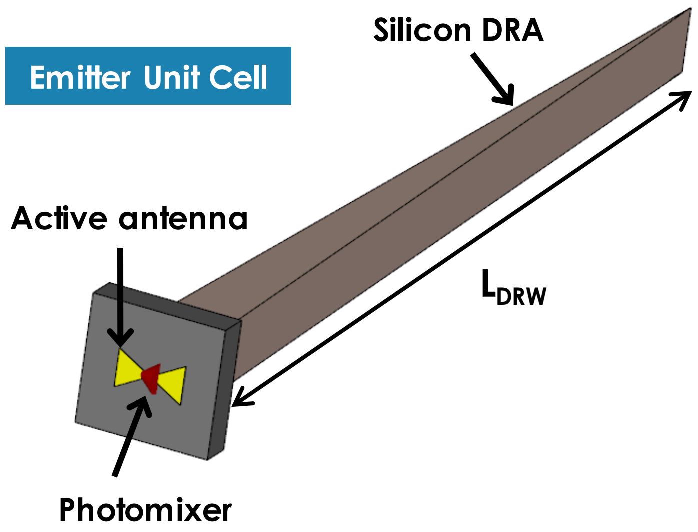
Fraunhofer Heinrich Hertz Institute

TERAWAY breakthrough developments (I)

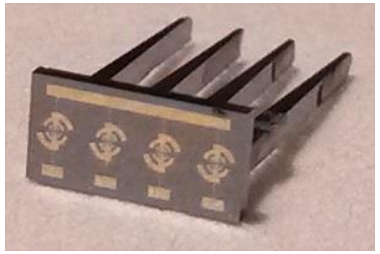
Integrated phase-array antenna

Dielectric Rod Antenna (DRA)

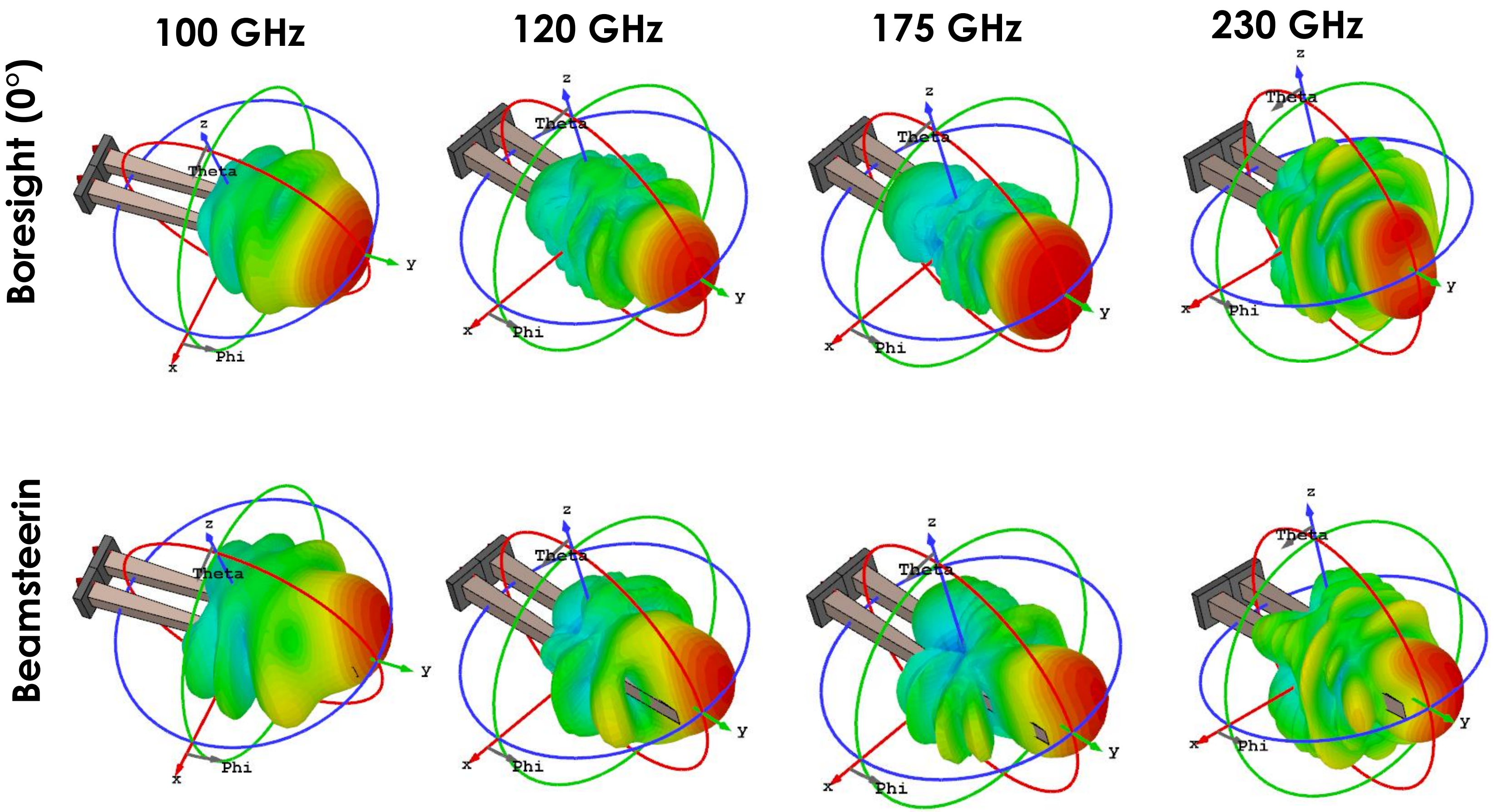
➢ Target freq. range 90 – 320 GHz



Prototype (1×4 DRA)



Radiation Patterns



Rivera-Lavado, *et al. J Infrared Milli Terahz Waves* **40,** 838–855 (2019)

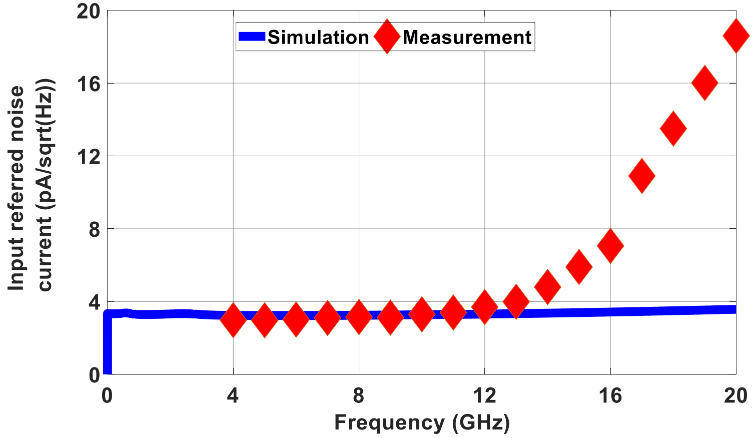
✓ Ultra-broadband radiation with beamsteering

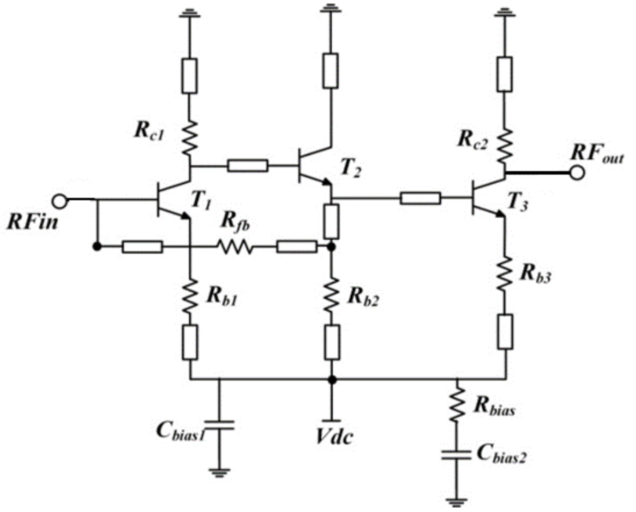
TERAWAY breakthrough developments (II)

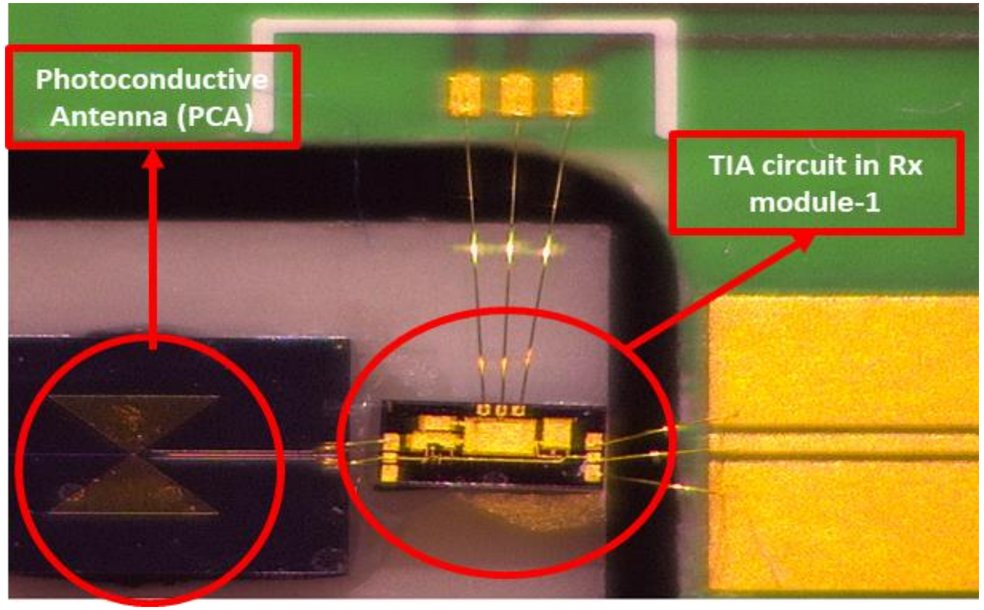
Photonic / Electronic co-integration

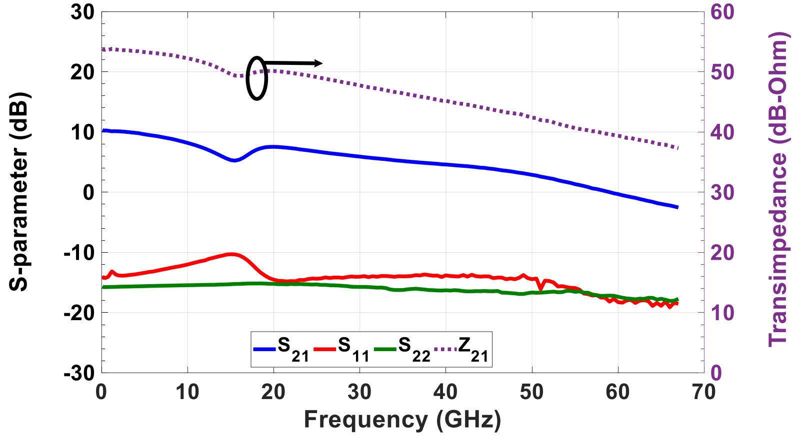
Electronic TIA: Key element for the photonic detection in combination with the novel waveguide-based PCAs

- Bandwidth > 10 GHz
- Measured current noise <3 pA/√Hz up to 10 GHz
- Specifications of Module-1 Rx are satisfied using the TIA
- New run for further reduction down to 1 pA/ √Hz









Summary

Hybrid integrated photonics-based millimeter- and Terahertz transmitter and receiver modules,

- Polymer widely tunable optical heterodyne source with integrated optical frequency comb generator with integrated optical isolator!
- SiN Optical Beamforming Network with piezo-electric actuators unlocking reduced power consumption beam-steering
- InP photomixer array with on-chip broadband antennas which include dielectric rod waveguide antennas unlocking beam-forming and beam-steering directly from the chip
- Co-integration of electronic transimpedance amplifiers (TIA) at receiver

- **Assembly and packaging challenges solved . . . addressed by the next speaker**

Terahertz technology for ultra-broadband and ultra-wideband operation of backhaul and fronthaul links in systems with SDN management of network and radio resources

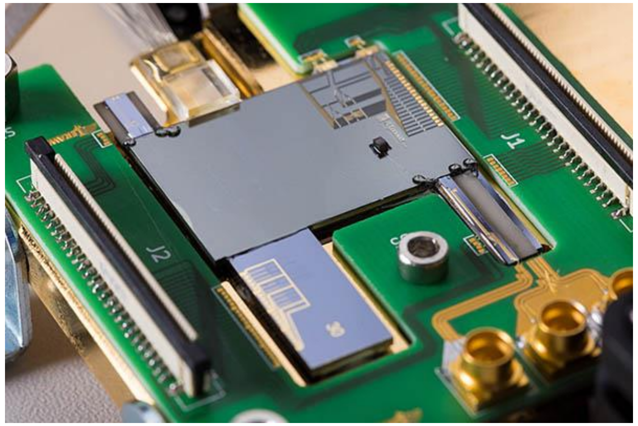
Funded by the Horizon 2020 Framework Programme of the European Union

H2020-ICT-2019-2
ICT-20-2019-2020: 5G Long Term Evolution
GA no: 871668
Starting date: 01.11.2019
Duration: 36 months

Website: https://ict-teraway.eu/

From concept to reality: Packaging of Photonics-enabled wireless transceivers

Zerihun Tegegne
PHIX



PHIX

PHIX Vision:

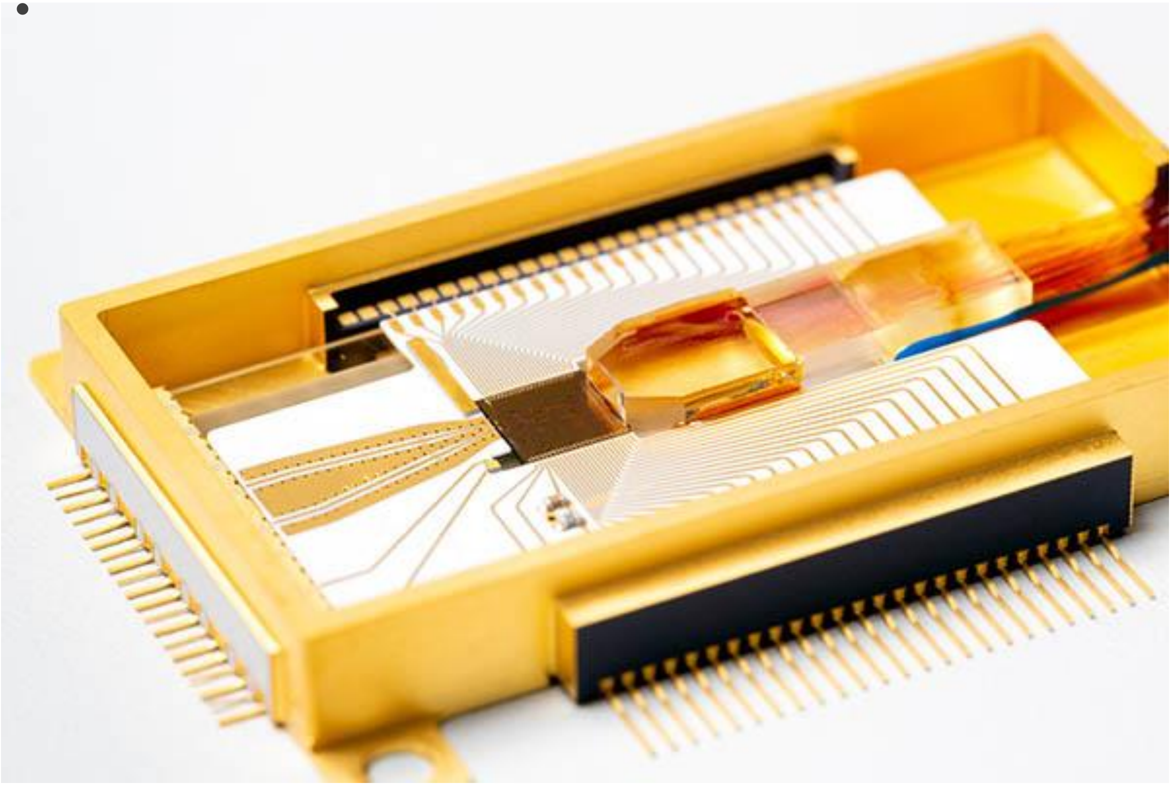
PHIX is to become a world leader foundry in packaging and assembly of Photonic Integrated Circuits (PIC's) by supplying PIC based components and modules in scalable production volumes.

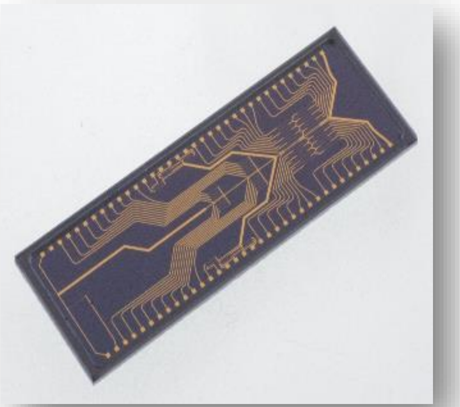
Outline

- Introduction
- Integration Trends for Photonics
- Photonics packaging challenges
- Optical Alignment Strategies (project specific)
- Integration and Packaging of TERAWY module -1
- Conclusion

A PIC by itself is not a product!

- **Optical interconnection** (fibers/free-space)
- **Electrical interconnection** (wire bonds/flip-chip)
- **Thermal management** (active/passive)
- **Mechanical support** (robust package)



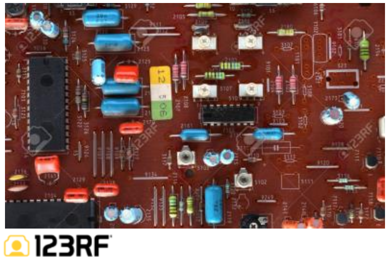


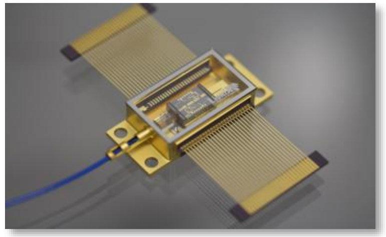
- Assembly is ~60-80% of the costs

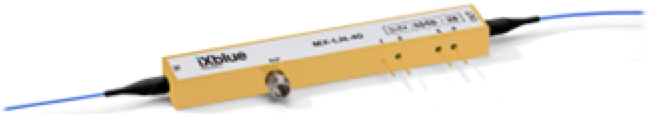
Photonics Integration Trends

Devices → Systems

Individually-packaged devices



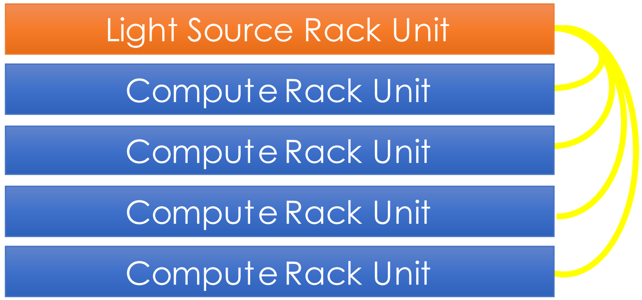




Every component (resistor, transistor, laser, PD, splitter, modulator) in its own package.

Circuit/system is built out of discrete components by connecting with discrete fibers, wires, flex or PCB traces

Integrated circuit in package with “hard parts” outside

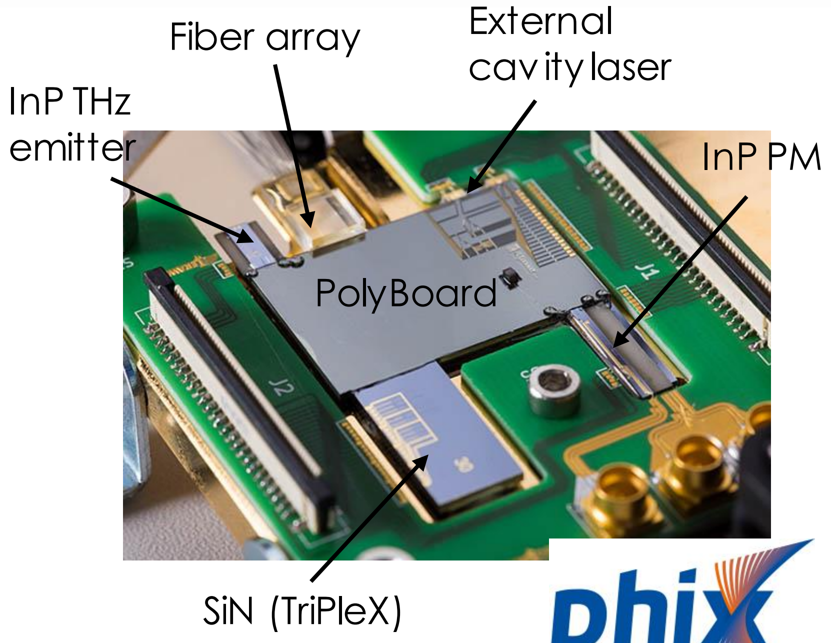


Components that can be monolithically integrated (resistors, transistors, splitter, modulators) are in one package or even one die.

Components with special requirements are kept separate (laser, extremely-cold photodetectors)

Everything in the package ((resistor, transistor, laser, PD, splitter, modulator)

TERAWAY: Hybrid integration of many discrete components of three different platform (InP, Polymer, SiN)



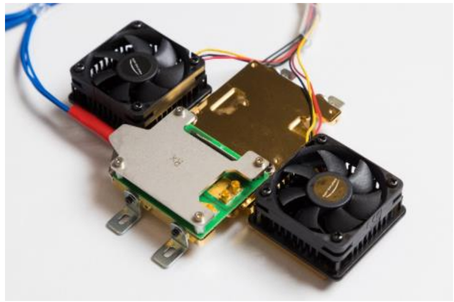
Photonics packaging challenges

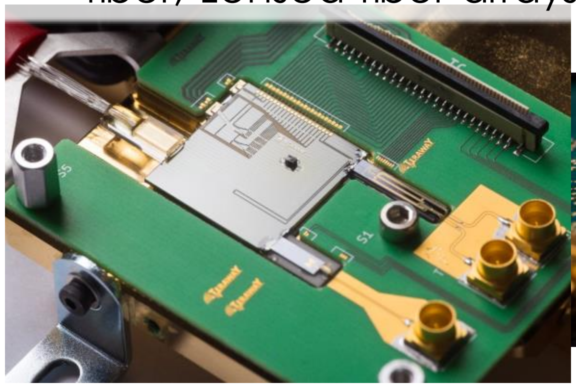
Hybrid assembly

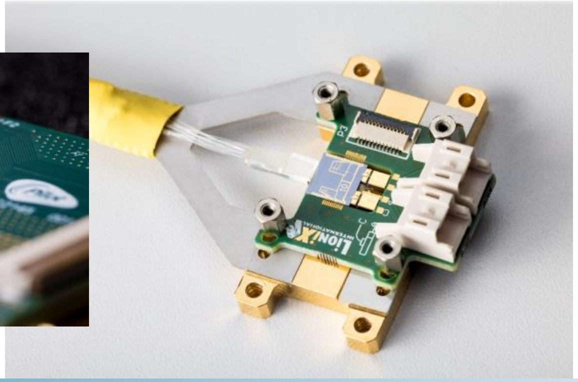
- Packaging of different components of diff. technological platforms (InP, Si, GaAs, LiNbO…) to enable a specific or multiple applications.
- No standard packaging process are available as optical interfacings are more specific (for electronics standard packaging options are available and can be reused
- High placement and alignment accuracy is needed (> x100 over electronic)
- Edge polishing might be required to expose the edge located waveguides
- Mode field diameters need to be match (by design or external SSC, UHNA fiber, Lensed fiber arrays) or accept higher losses

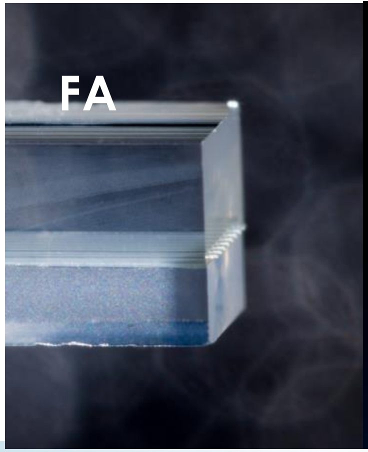
Thermal cooling subsystems

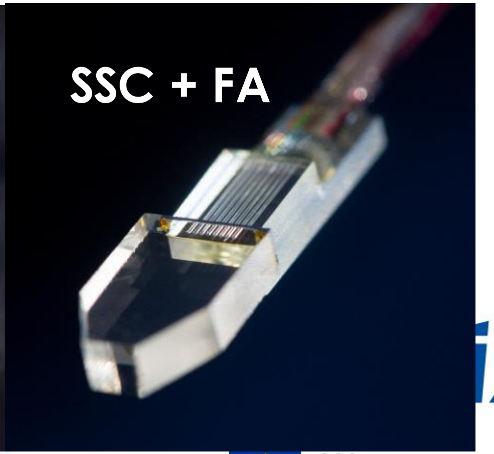
When TEC's reach their limit:
Massive cooling and electrical interconnections requirements





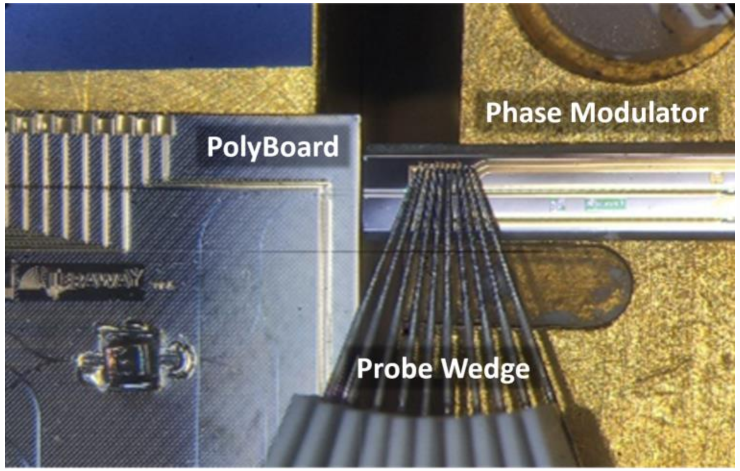






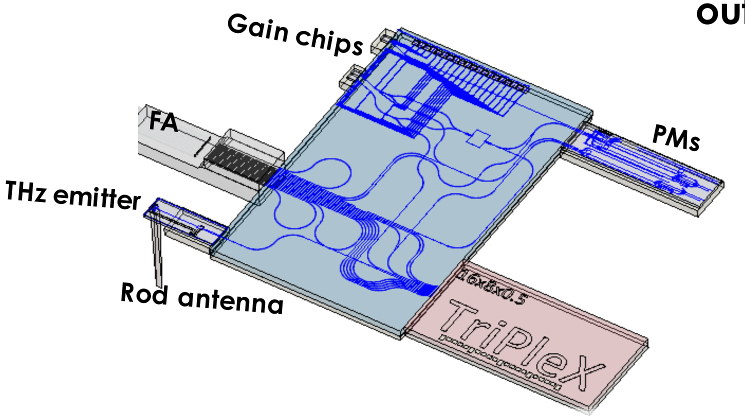
Optical alignment methods

Electro-Optical Active Alignment



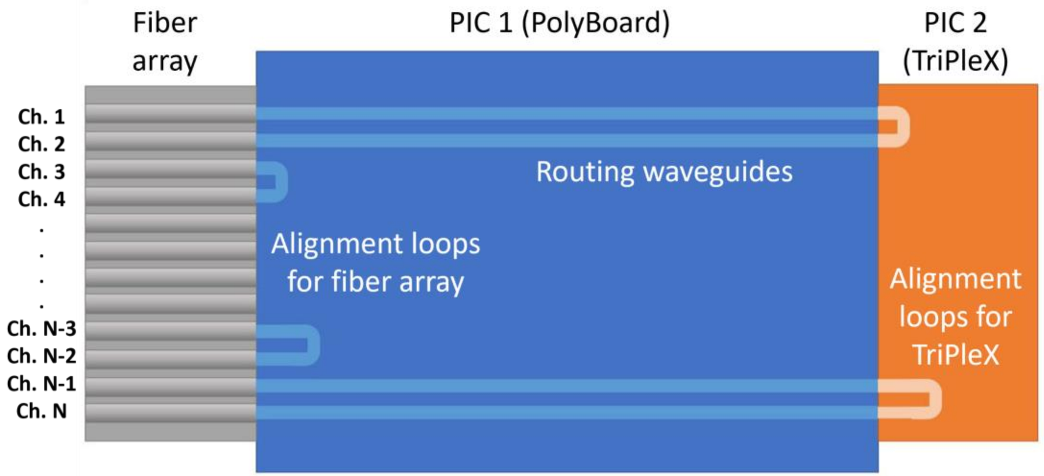
The chip-to chip alignment and integration is achieved by supplying electric power to the functional chips

1) Gain section chips to the PolyBoard
2) PM chips to the PolyBoard
3) InP THz emitter and receiver chips to PolyBoard



TERAWAY Mod.1 Tx

Loopback Active Alignment



- Alignment loop waveguides are used to align two chips.
- An external light is injected on one channel and the output is measured on the other

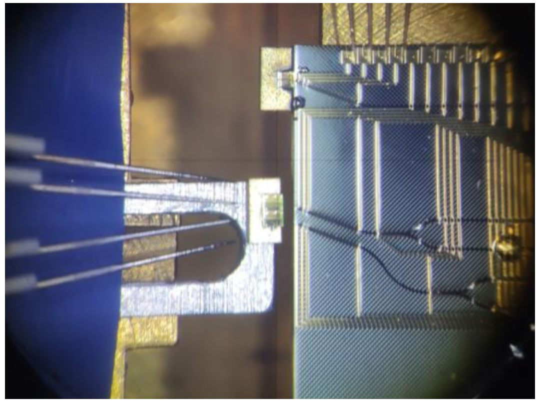
1) Fiber array to PolyBoard
2) Fiber array + PolyBoard to TriPleX chip

Integration and Packaging of TERAWY module -1

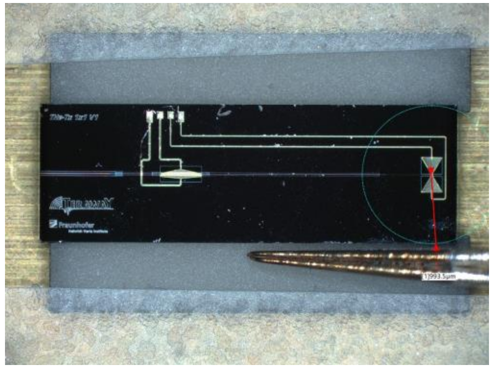
Hybrid photonics integration: Tx

<u>Electro-optical alignment technique applied</u>

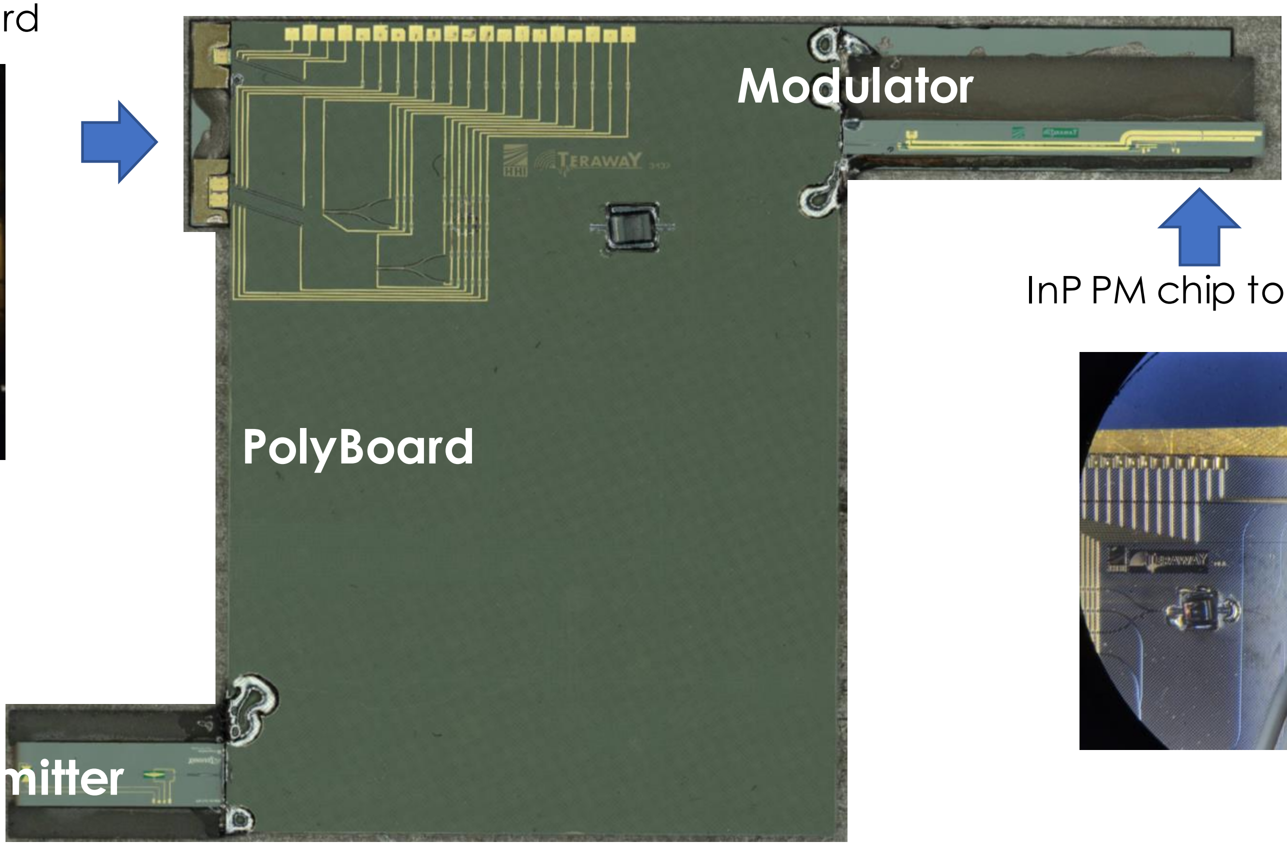
Gain section chips to the PolyBoard



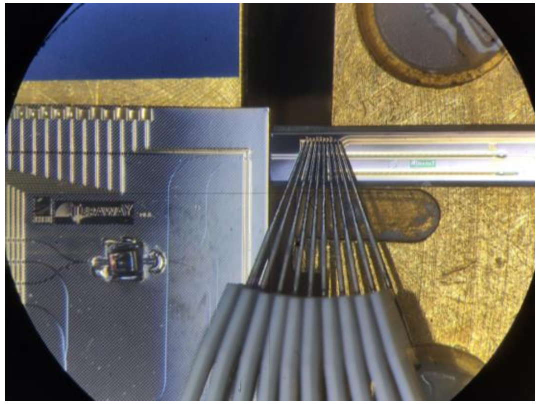
THz emitter chip to the PolyBoard



Tx hybrid PIC



InP PM chip to the PolyBoard



Index matching optical glue for chip –to – bonding

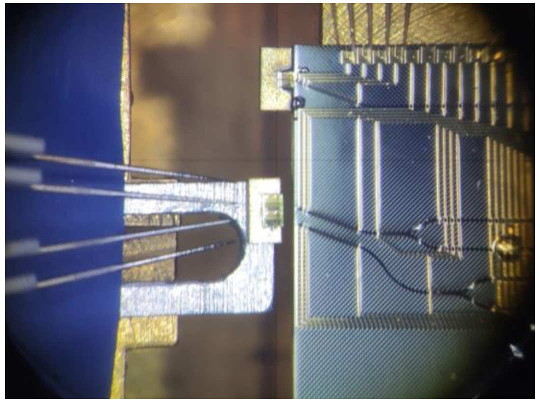
Fraunhofer HHI

Integration and Packaging of TERAWY module -1

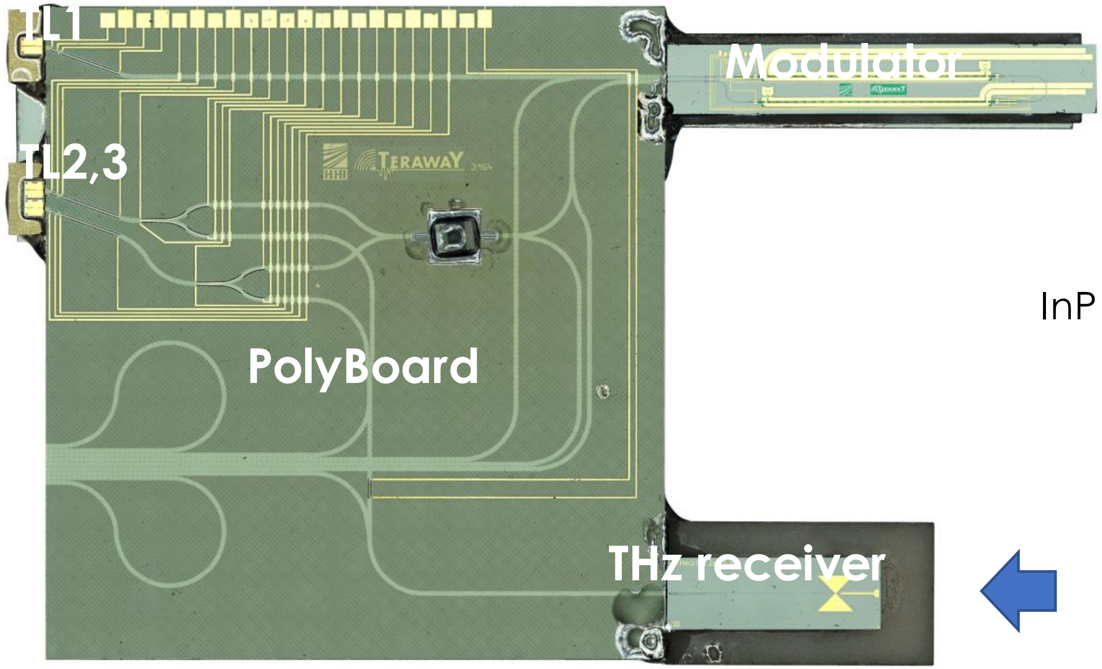
Hybrid photonics integration: Rx

Electro-optical alignment technique applied

Gain section chips to the PolyBoard

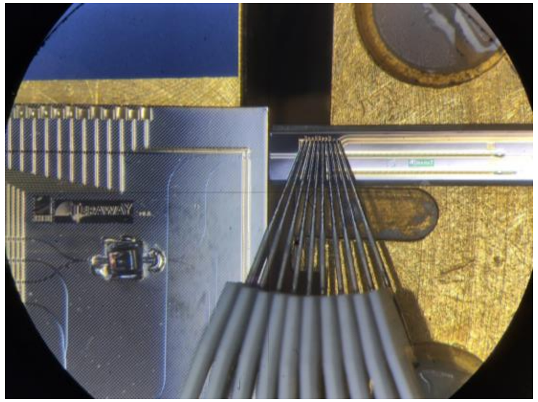


Rx hybrid PIC

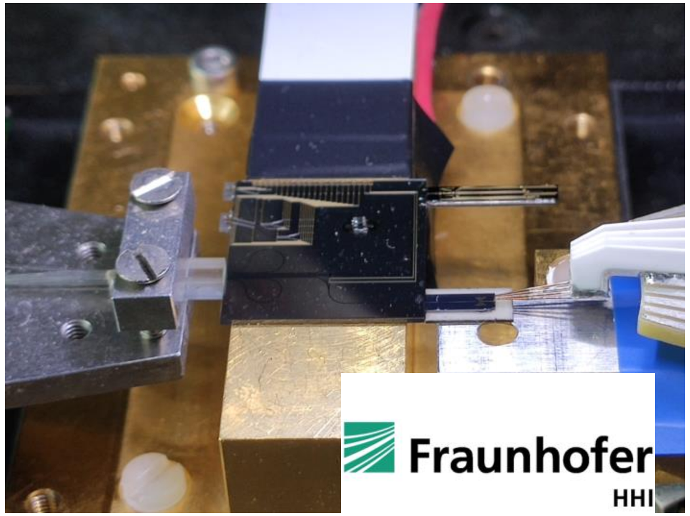


Index matching optical glue for chip –to – bonding

InP PM chip to the PolyBoard

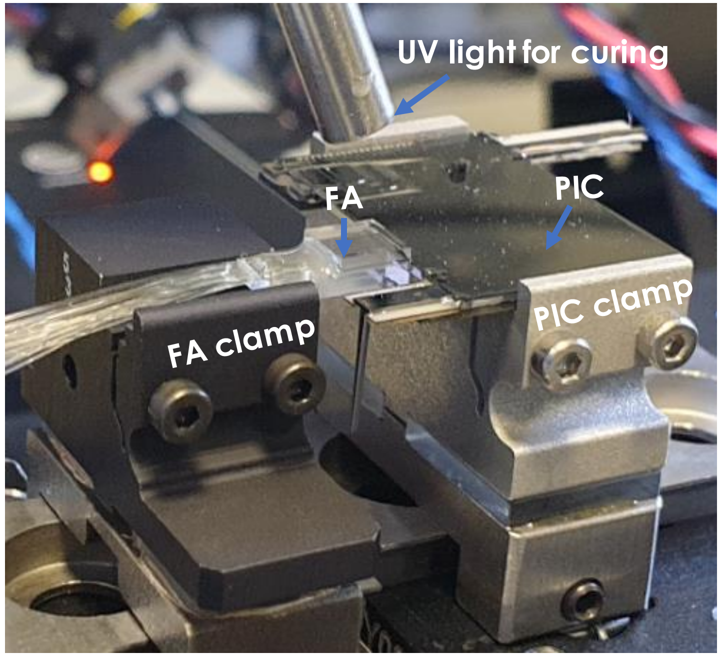


InP emitter/ receiver chips to the PolyBoard



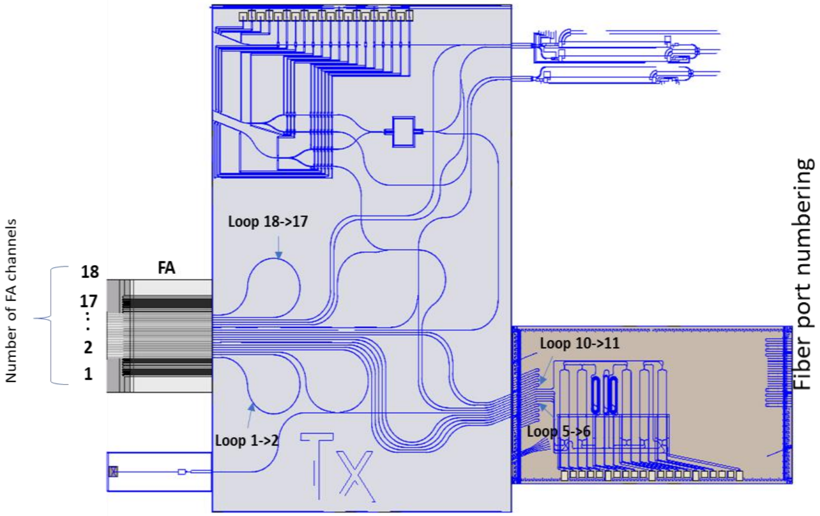
Integration and Packaging of TERAWY module -1

- **Loopback active alignment technique used:**

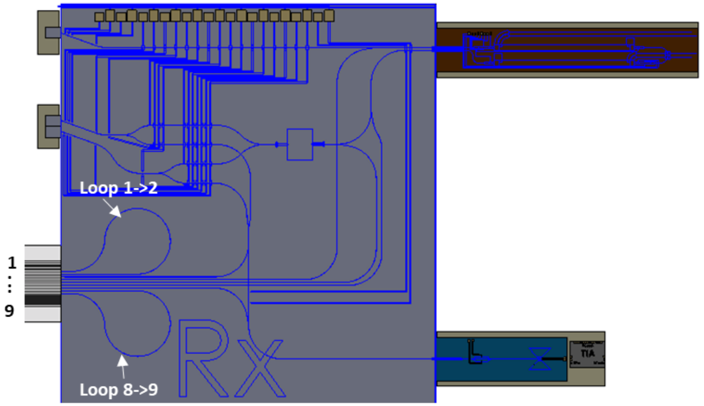


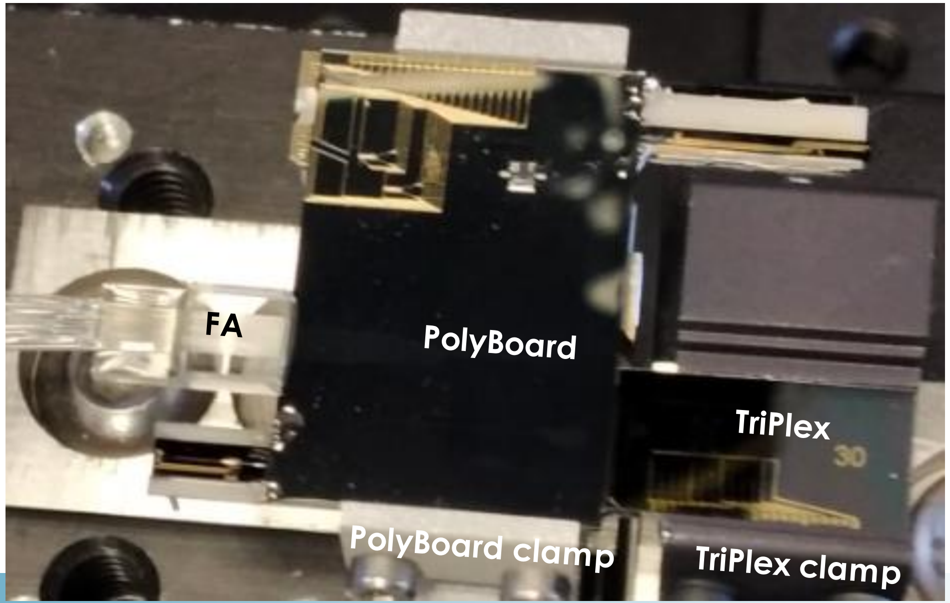
Fiber array to PolyBoard

Tx hybrid PIC



Rx hybrid PIC



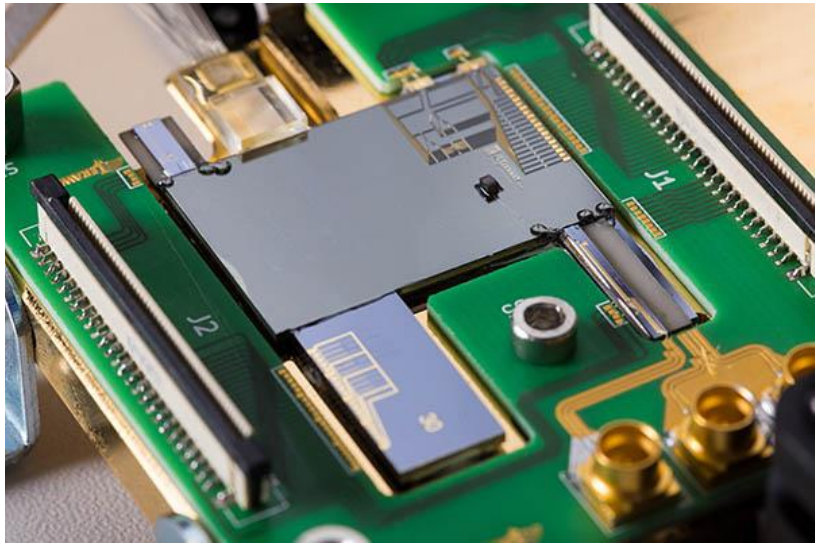


TriPleX chip to PolyBoard

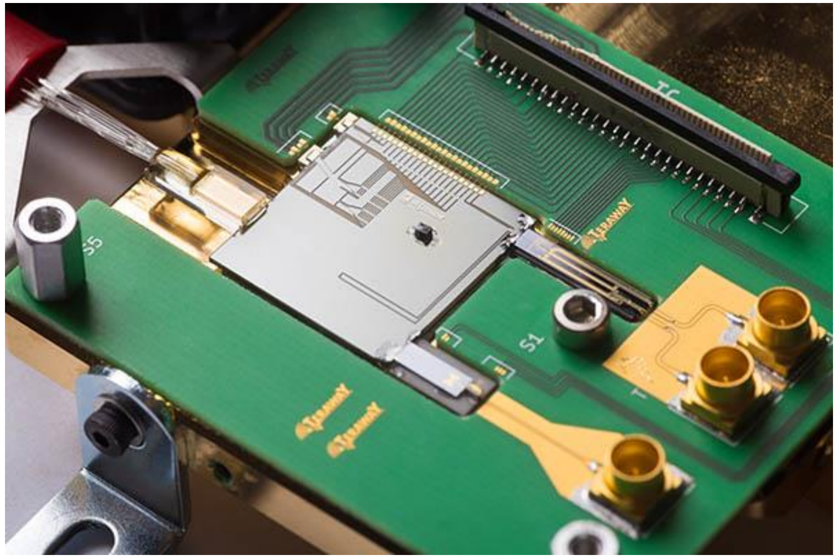
Integration and Packaging of TERAWY module -1

Mechanical assembly and Electrical interconnections

Tx



Rx

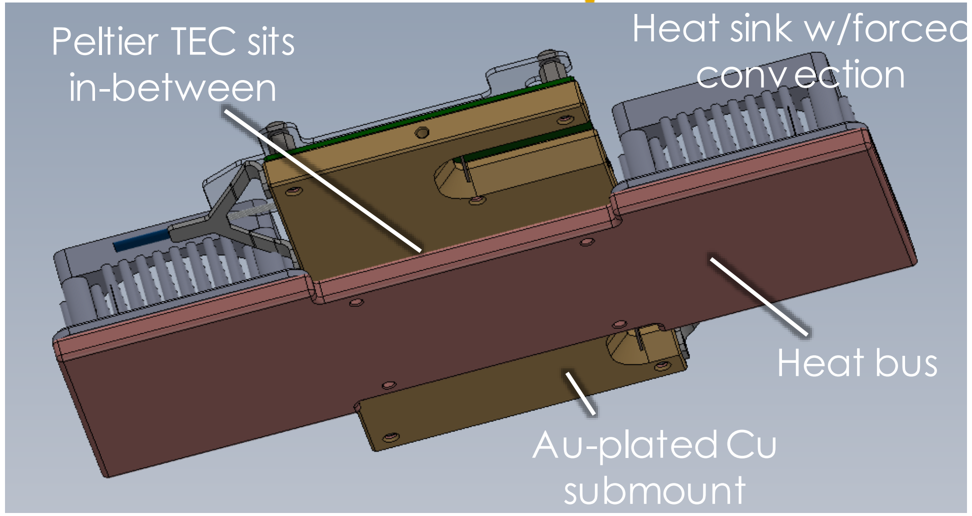


- The required electrical board and mechanical carrier are designed and manufacture
- The PCB and the preassembled optical subassemblies are assembled onto Au plated Cu mount using thermal conductive glue
- The required electrical interconnections via wire boning is performed

Integration and Packaging of TERAWY module -1

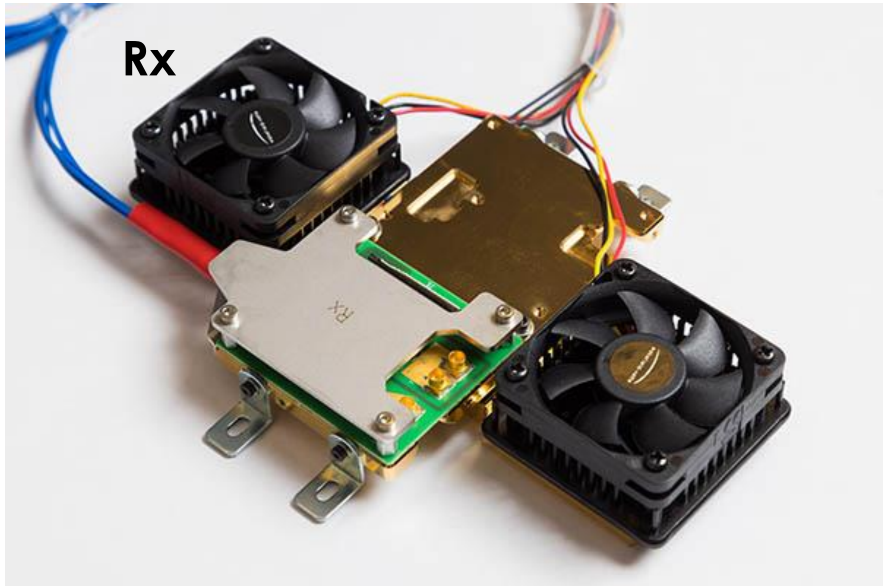
Thermal management subsystems

- The adequate thermal management subsystem is designed and integrated to the optical module
- The cooling system comprises:
  - Thermoelectric cooler (TEC): directly attached to the optical module
  - Heat spreader (bus): which is bonded to the hot side of the TEC
  - Fan driv en heat sink (forced conv ection) placed at both ends of the heat spreader



Tx

Rx



Conclusion

- TERAWAY project demonstrates the integration of three different photonics platforms (PolyBoard, InP, SiN) that enables to build THz wireless transceivers
- Electronics packaging is very matured, and it has well defined standards. Whereas there is no any standard for photonics packaging due to:
  - The optical interfacings are more specific.
  - Edge polishing might be required to located waveguides.
  - Requires high placement and alignment accuracy.
  - Requires massive cooling system

Thank you for your attention!

For more info, visit TERAWAY website: ict-teraway.eu/

Funded by the Horizon 2020 Framework Programme of the European Union under under G.A No 871668 and it is an initiative of the Photonics Public Private Partnership

Funded by the Horizon 2020 Framework Programme of the European Union

H2020-ICT-2019-2
ICT-20-2019-2020: 5G Long Term Evolution
GA no: 871668
Starting date: 01.11.2019
Duration: 36 months

Website: https://ict-teraway.eu/

Experimental results for mmWave and beyond wireless systems based on photonic techniques

Dr. Nikolaos K. Lyras

Photonics Communications Research Laboratory (PCRL), ICCS/NTUA

National Technical University of Athens

TERAWAY Concept-Sum-up

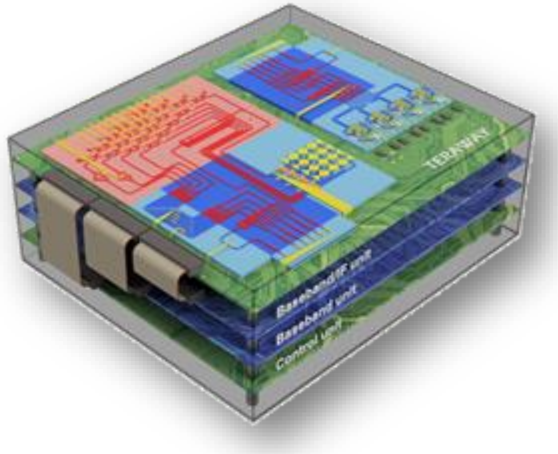
A new disruptive generation of photonic-enabled THz transceivers for high-capacity BH and FH links in B5G networks

Vision - Concept

"enabling industrialization of THz wireless communication technology"

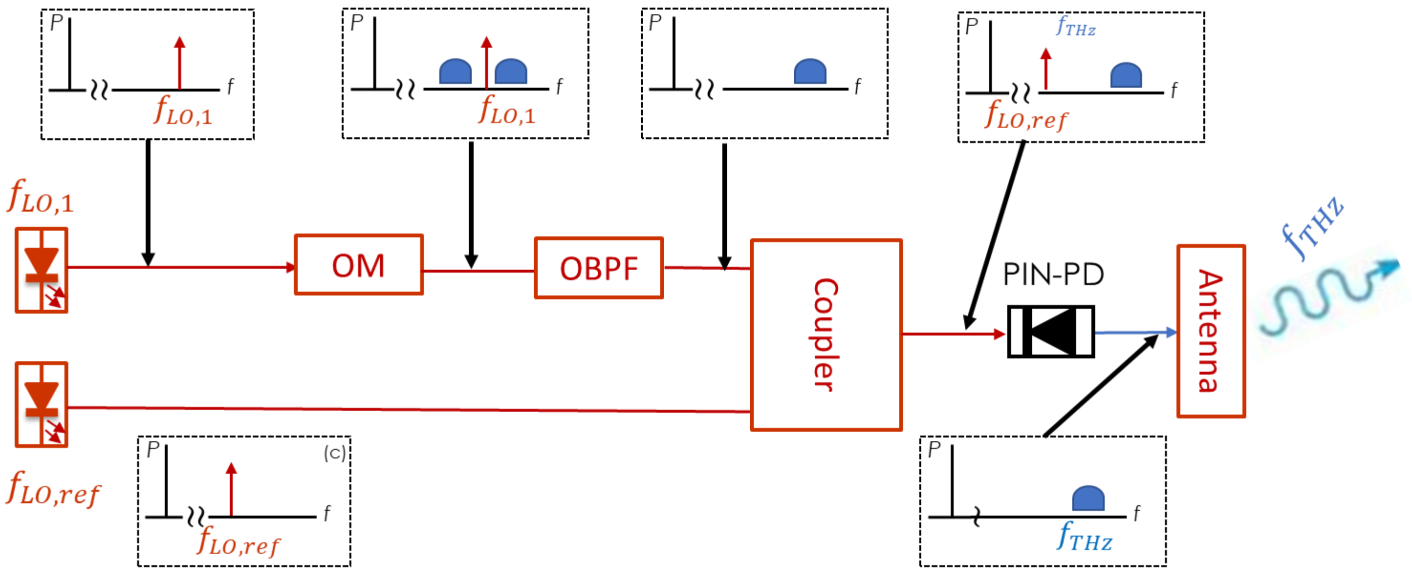
Development of photonic-enabled transceivers for wireless communication systems operating across the W- (92-114.5 GHz), D- (130-174.8 GHz) and THz (252 – 322 GHz) bands

- **Multi-channel, ultra-wide band transmitters**: Generation/emission and of THz/W/D signals with selectable symbol rate and high bandwidth.
- **Multi-channel, ultra-wide band receivers**: Detection of THz/W/D band signals and their direct down-conversion to baseband/IF.
- **Integration of the prototypes inside a functional network system of high-flexibility and efficiency:** New network management platforms (based on SDN) and an extended control hierarchy to perform the management of the network and radio resources.



TERAWAY: Photonic-based Up-conversion

Photonic components for the generation and emission of mmWave/ THz signals



- Two optical carriers $f_{Lo,1}$, $f_{Lo,\mathrm{ref}}$ are generated by tunable laser sources.
- The frequency of the emitted RF THz signal equal to $f_{THz} = |f_{LO,1} - f_{LO,fre}|$.
- The first optical carrier is modulated and filtered
- The beating of the modulated optical carrier with the reference optical carrier on the high bandwidth PD will generate the modulated RF-THz signal.
- The modulated RF-THz signal is coupled and emitted by an antenna

Changing the frequency difference between two optical carriers

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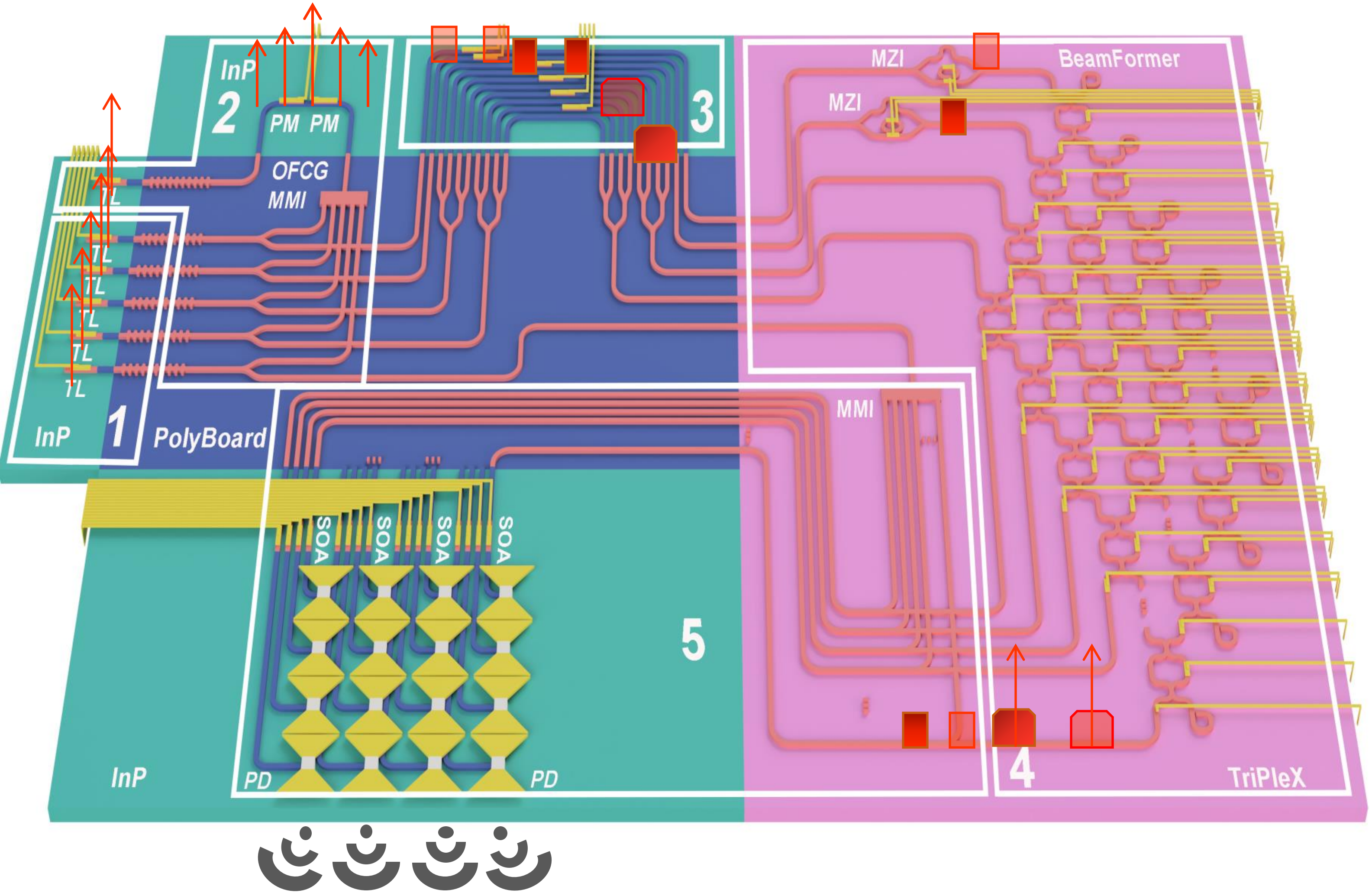
Seamless selection of the emitted signal frequency

TERAWAY Transmitter (Tx)

Hybrid photonics-based platform for **ultra-wideband signal generation and emission**



1. Optical carrier generation unit

Free selection of the emission wavelength (10 nm ~ 1 THz) • **Tunable Lasers (TLs)**

2. Optical phase locking unit

Injection of an Optical Frequency Comb (OFC) back to the TL cavities

3. Optical modulation unit

- **Phase Modulators (PMs):** Low-capacity channels
- **IQ Modulators:** High-capacity channels

4. Optical multi-beamforming & filtering unit

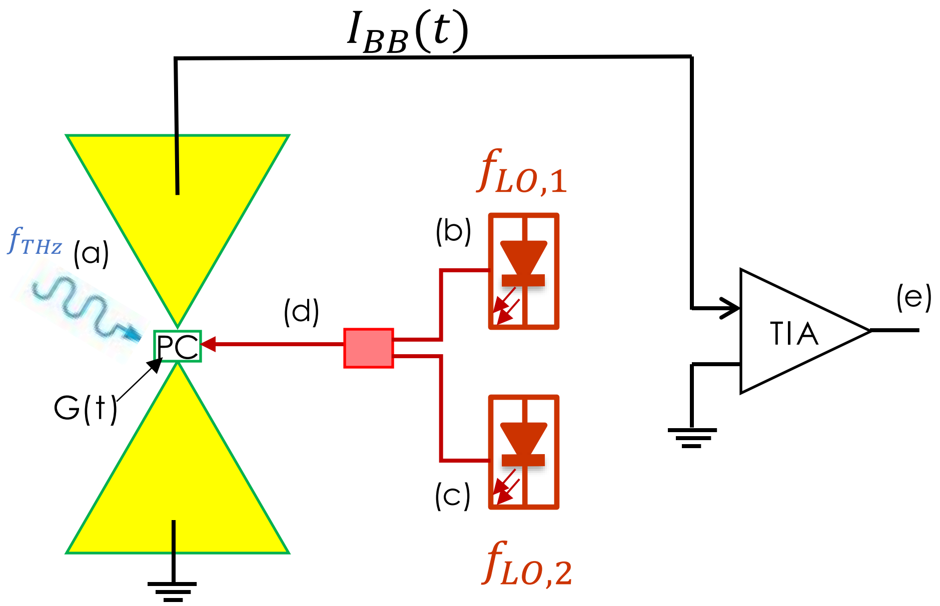
Independent steering of transmitted wireless beams

5. Optical amplification, frequency up-conversion and wireless emission unit

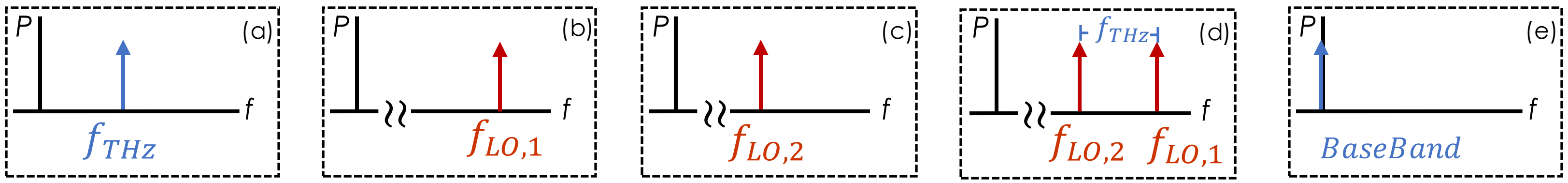
- **Semiconductor optical amplifiers (SOAs)**
- **PIN-PDs**, as photonic mixer
- **Broadband Antennas**

TERAWAY: Photoconductive Down-converter

Photonic components to convert mmWave/ THz signals to baseband/IF



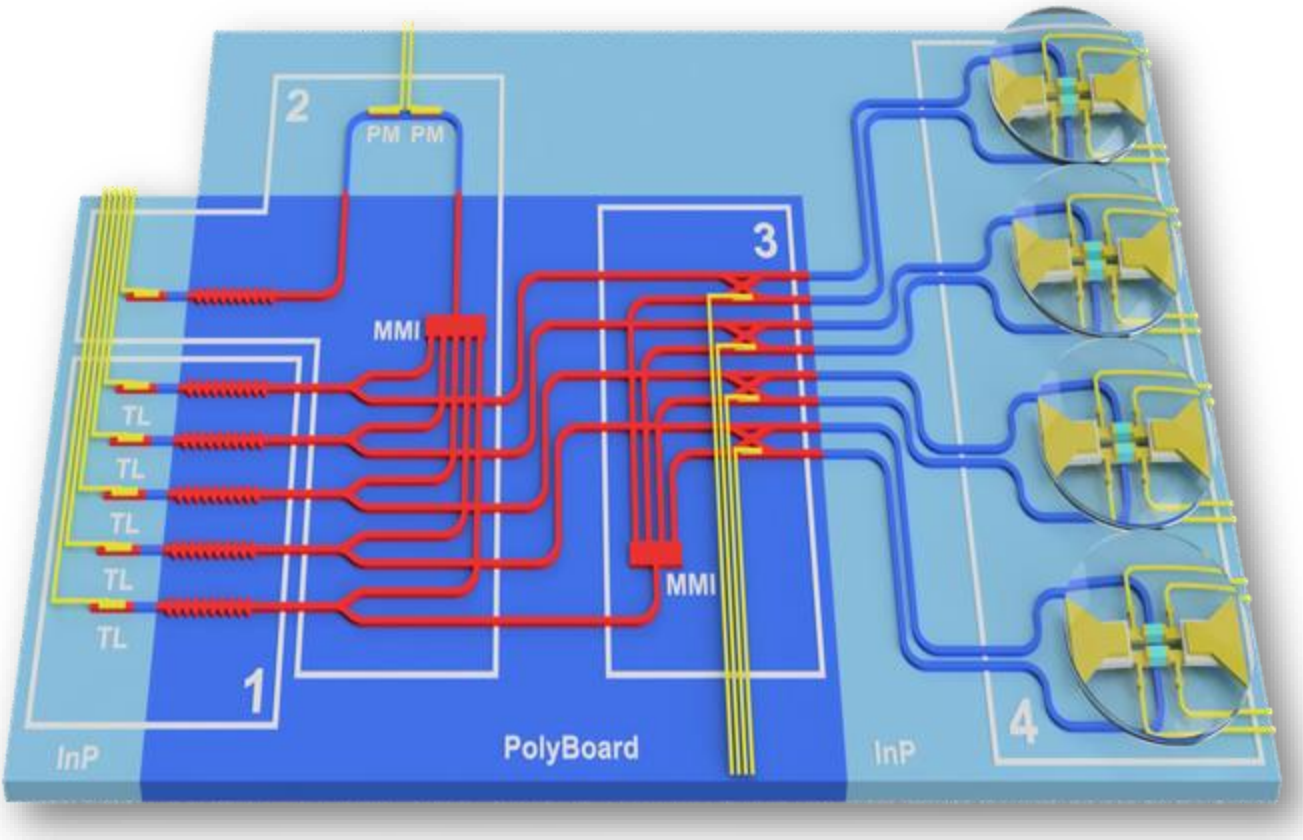
- The THz signal (f_{THz}) is received by an antenna with a photoconductor (PC) between the antenna feed points (Picture a)
- Two unmodulated optical carriers $f_{Lo,1}$, $f_{Lo,2}$ are generated by tunable laser sources (Pictures b, c)
- The photoconductance G(t) is modulated at frequency equal to $f_{Lo} = |f_{LO,1} - f_{LO,2}|$ (Picture d)
- Changing the frequency difference between the two optical carriers we can down-convert the THz signal directly to baseband or to an IF. If f_Lo=f_THz, the generated current, I_BB(t), is baseband (Picture e)



TERAWAY Receiver (Rx)

Hybrid photonics-based platform for **ultra-wideband signal detection and reception**

TERAWAY Receiver (Rx)



1. **Optical carrier generation unit**
   Same as transmitter (Tx)
2. **Optical frequency comb generator unit**
   Same as transmitter (Tx)
3. **Optical combining and phase shift unit**
   Introduction of 90° phase difference between copies of the same optical carrier
4. **Wireless detection and IQ photonic mixing unit**
   - Broadband Antennas and photoconductive elements for down-conversion to the baseband/IF
   - Low-noise and high bandwidth TIAs

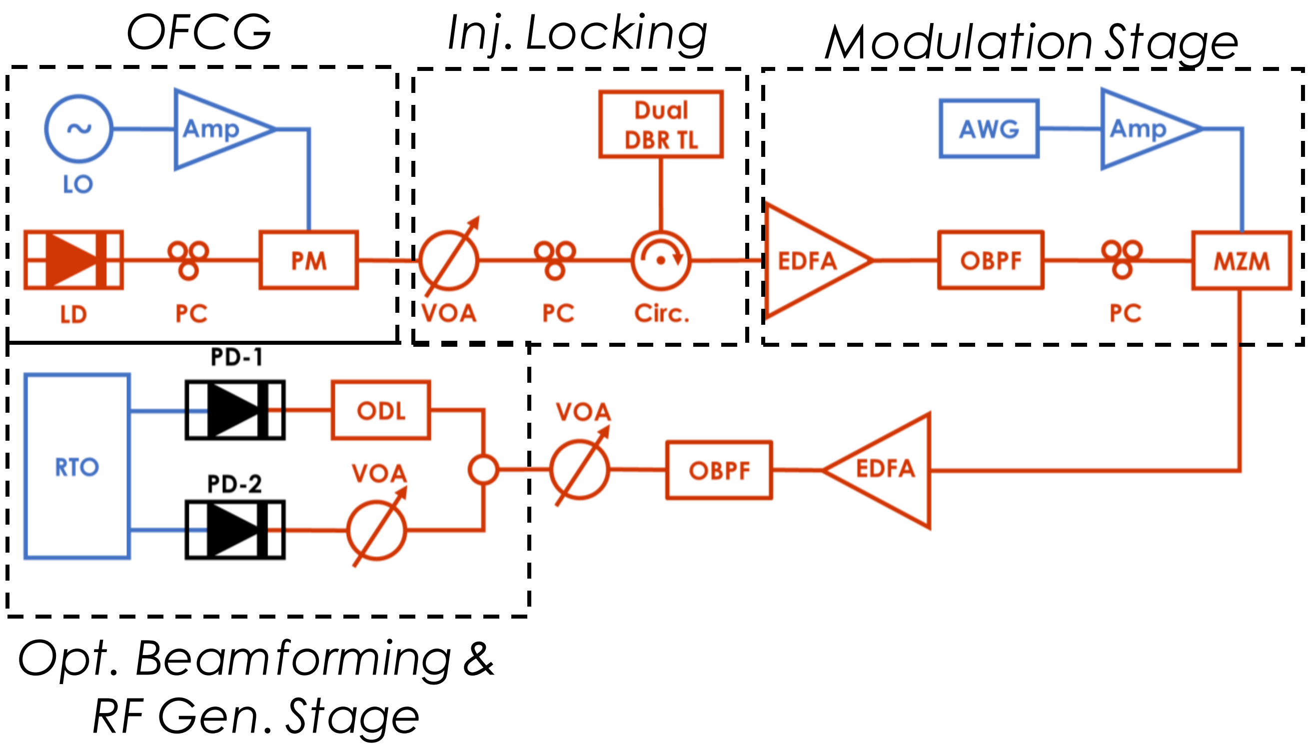
Experimental set up: External photonic components

Experimental Validation of TERAWAY photonic technology: Injection locking & Beamforming

Experimental validating of TERAWAY functionalities and photonic concept:

- ❑ Proof of concept of all-optical generation of mmWave signals including **injection locking**, **optical modulation** and **optical beamforming**

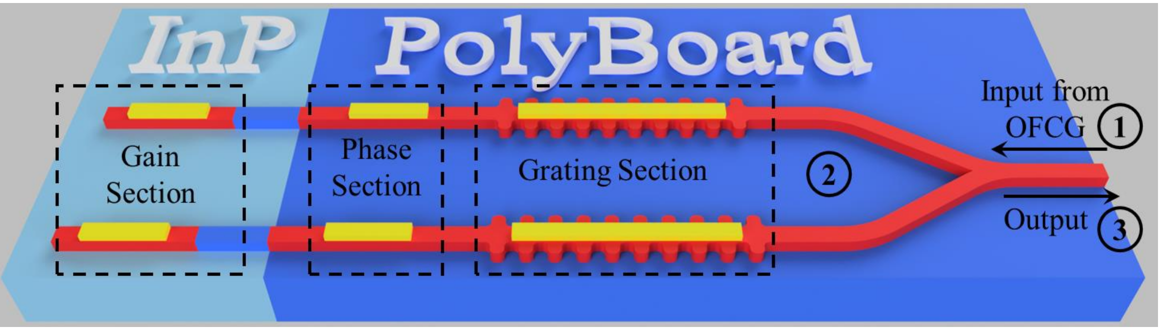
Experimental setup schematic



- ➢ **Injection locking** performed through dual DBR laser PIC provided by HHI
- ➢ Proof-of-concept **beamforming** using optical delay line to inject true time delay
- ➢ Central frequency up to 60 GHz (limited by bandwidth of PD)

External photonic components: Injection locking (I)

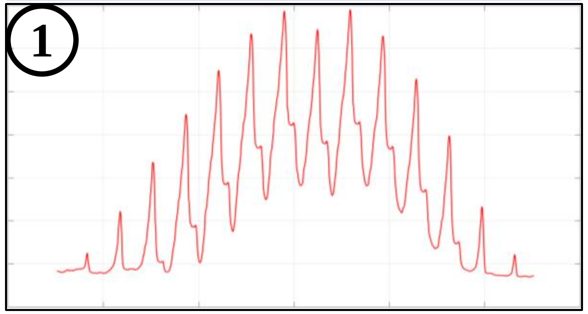
Hybrid Dual DBR PIC schematic



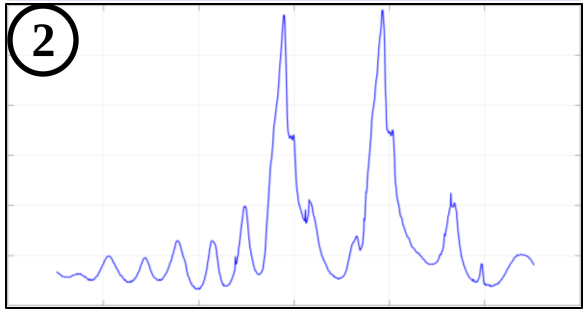
- ✓ Independent tuning of the two cavities
- ✓ >18 nm wavelength tunability per each laser
- ✓ Precise tuning and SMSR > 35dB enabling pure RF signal generation in different frequencies

- ➢ **Phase locking process**: Output wavelengths of PIC in free-running mode, coinciding with desired tones of the OFC

Optical frequency comb

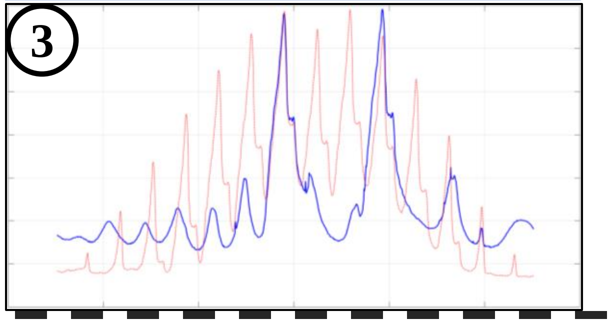


Free-running laser output

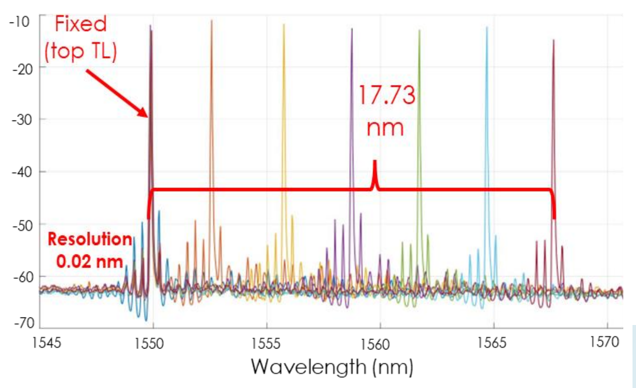


Injection locking process

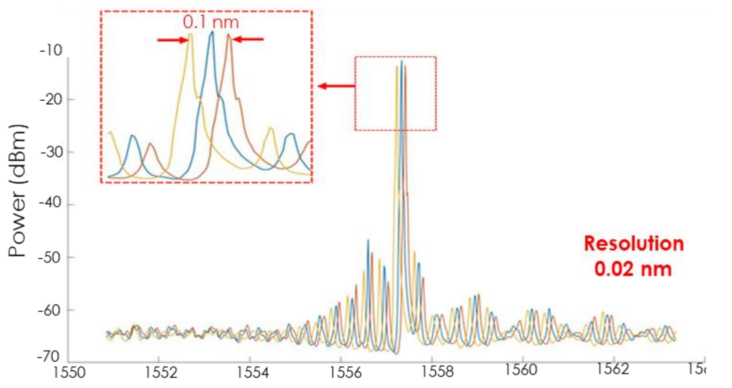
Superimposed spectra



Coarse tuning (Grating section)



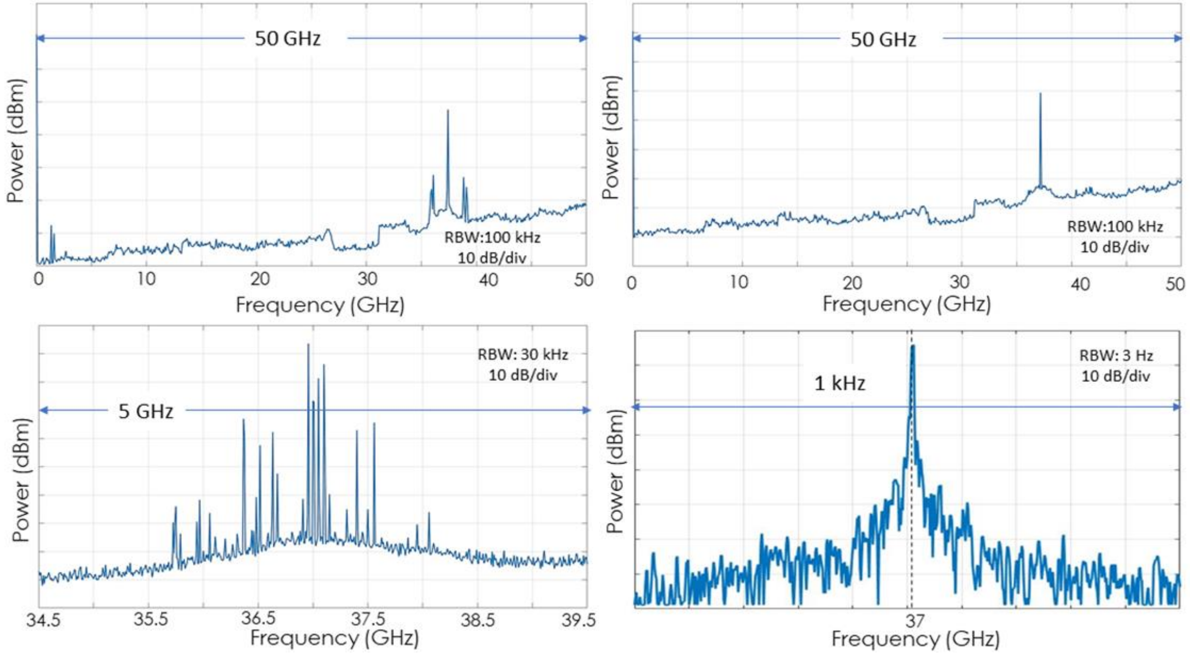
Fine tuning (Grating section)



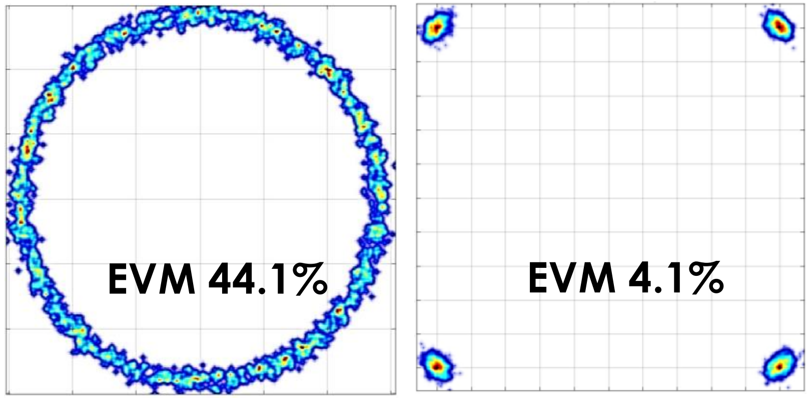
External photonic components: Injection locking (II)

- DSP chain implemented at the receiver
- Generated mmWave tone (injection locking)
  - ✓ **High purity** (negligible phase noise), **no frequency drift**
- Comparison of constellation diagrams at the receiver after DSP processing
  - ✓ **Significant EVM improvement** in phase locked operation
  - ✓ Seamless transitions between mmWave frequencies

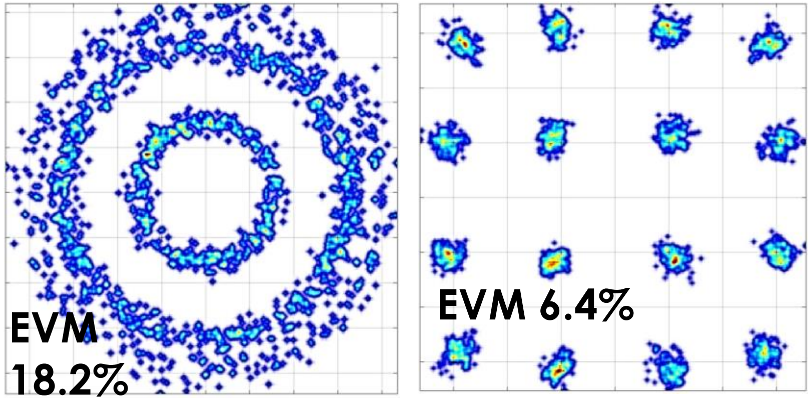
Free-running operation	Phase locked operation



Free-running operation	Phase locked operation



QPSK 0.5 GBaud – 60 GHz

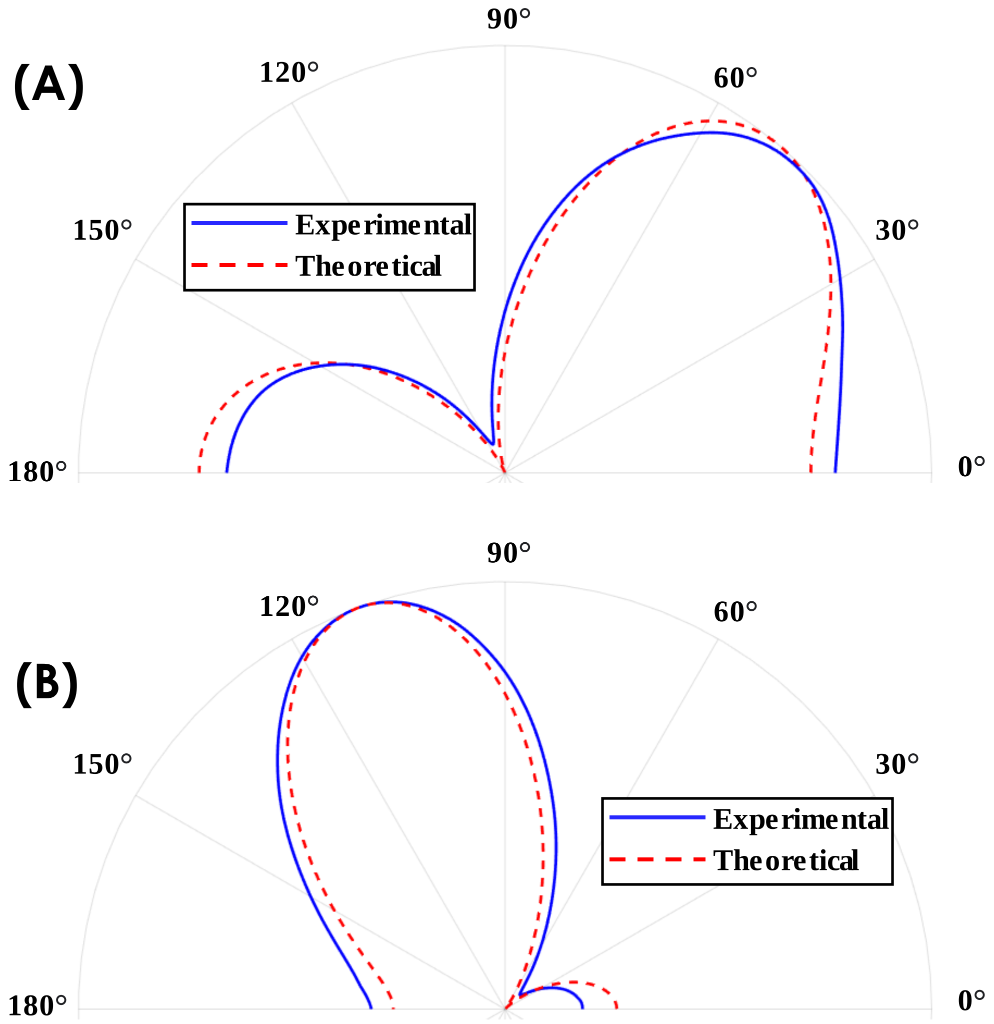


16-QAM 0.5 GBaud – 39 GHz

External photonic components: Beamforming

- Proof-of-concept beamforming of a 2 AE array using optical delay line to set the relative phase difference
- λ/2 spacing between AEs
- Signals acquired and stored at the oscilloscope for offline processing (extraction of the radiation pattern)
- Figures showing
  - **A)** QPSK signal at 60 GHz frequency directed at 50° compared to the theoretical
  - **B)** 16-QAM signal at 39 GHz frequency directed at 100° compared to the theoretical
- Wider main lobes with suppressed side lobes caused by slight amplitude imbalance between paths
- Slight angle deviation at the 60 GHz case, due to resolution of ODL

Radiation patterns (Experimental vs Theoretical)

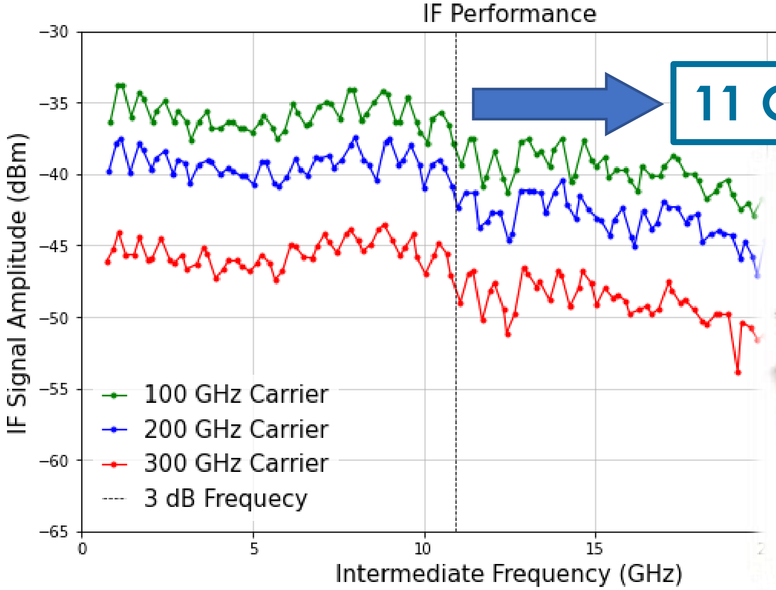


Photonic-Enabled mmW and THz Link

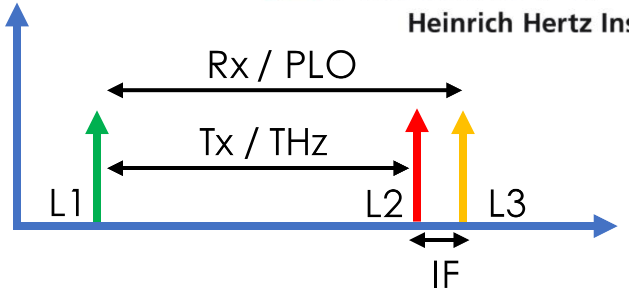
InP photomixer for THz generation and detection

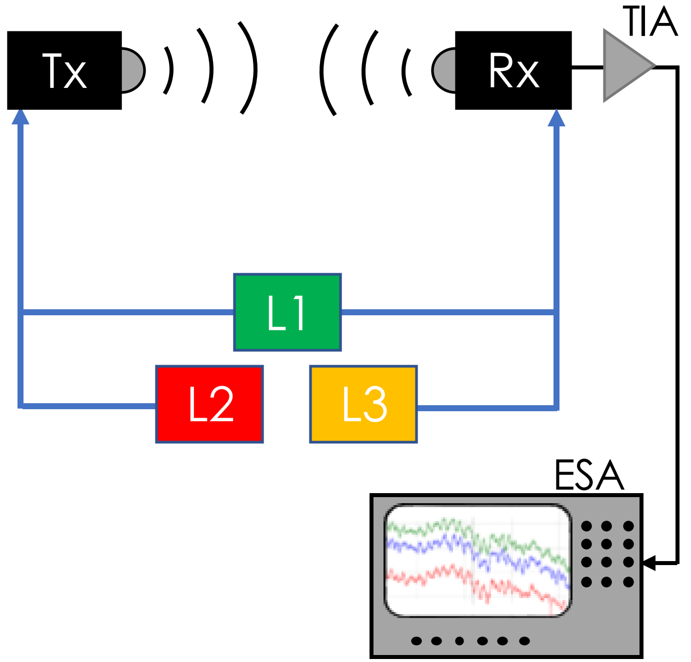
Opto-electronic conversion using photomixing

- Transmitter:
  → Conversion of an optical beat to mmW/THz:
  $$f_{THz} = |f_{L1} - f_{L2}|$$
- Receiver:
  → Generation of a photonic local oscillator PLO:
  $$f_{PLO} = |f_{L1} - f_{L3}|$$
  → Down-conversion to intermediate frequency IF
  $$f_{IF} = |f_{THz} - f_{PLO}| = |f_{L2} - f_{L3}|$$



11 GHz IF bandwidth …and rising!



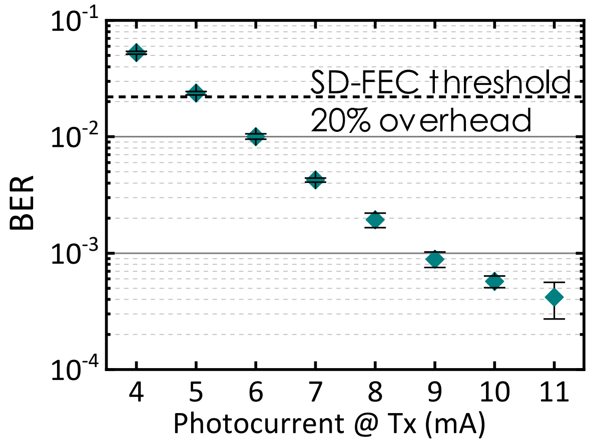


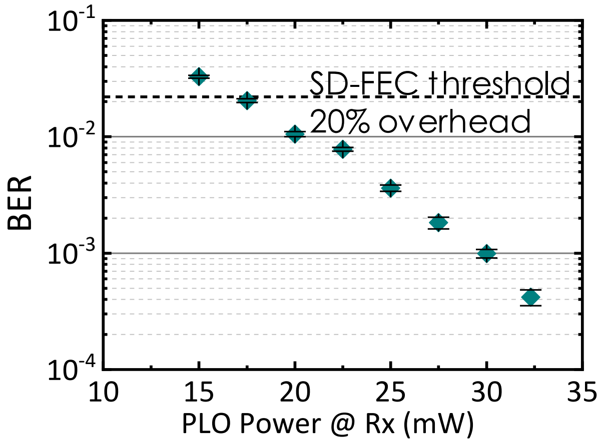
Photonic-Enabled mmW and THz Link

InP photomixer for THz communication

1m-link with pigtailed Tx and Rx

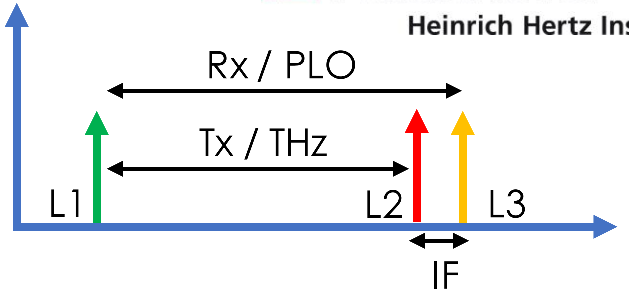
- 120 GHz carrier frequency
- 2 Gbaud QPSK
- 8 GHz intermediate frequency

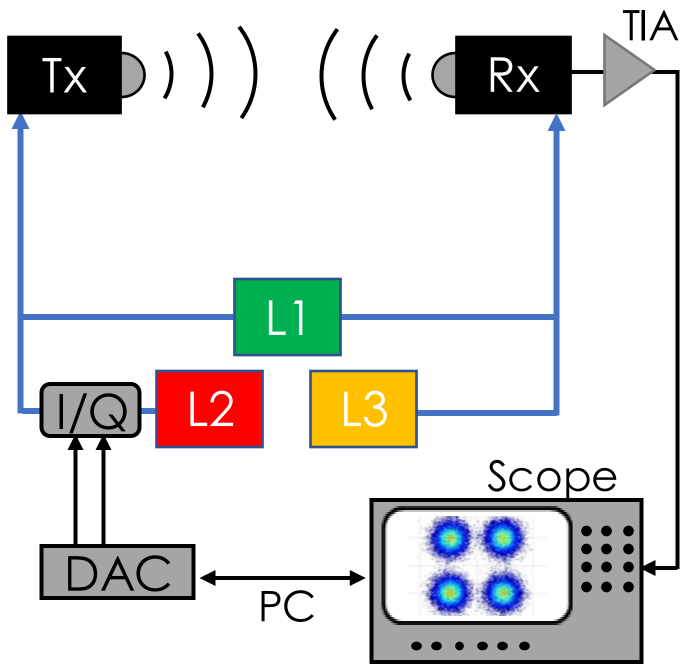




Purely photonic THz communication link

Achieved up to 8 Gbit/s with QPSK





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Photonic-Enabled mmW and THz Link

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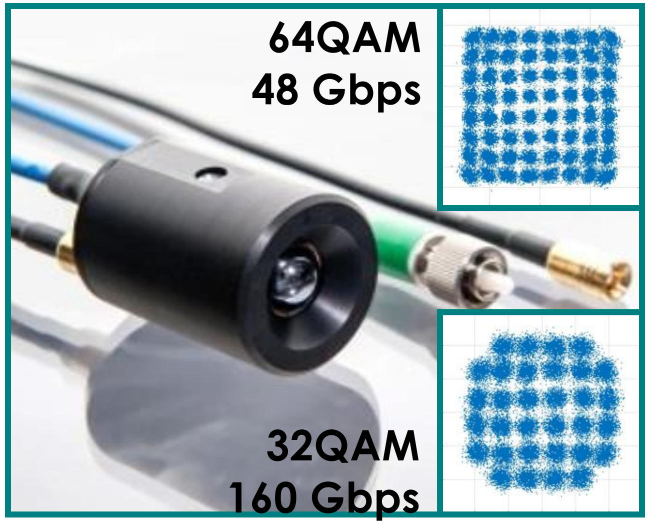
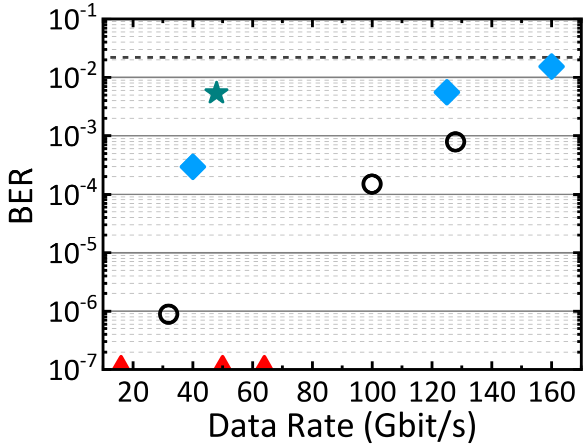
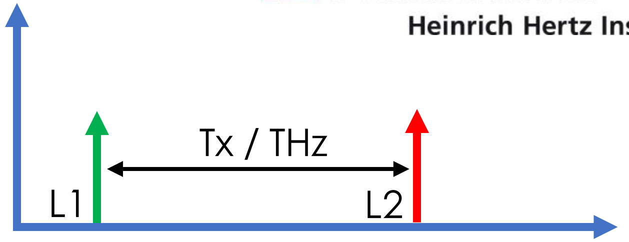
InP photomixer for THz communication

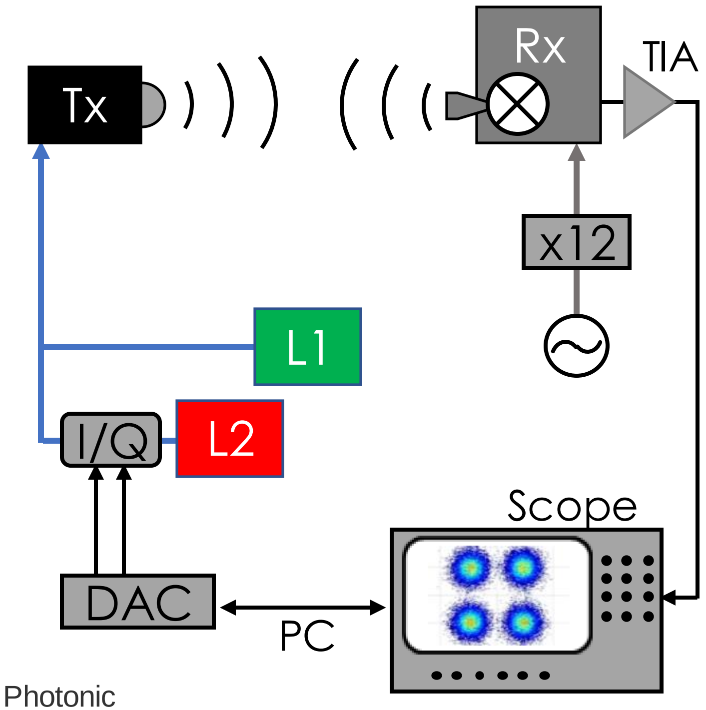
Link with photonic Tx and electronic Rx

- 300 GHz carrier frequency
- 32 Gbaud 32QAM
- 8 Gbaud 64QAM









Photonic THz emitter
Electronic THz receiver

Achieved up to
160 Gbit/s with 32QAM

S. Nellen *et al.*, "Coherent Wireless Link at 300 GHz with 160 Gbit/s Enabled by a Photonic Transmitter," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2022.3160096.

Conclusion/Next Steps

- ❑ Photonic components and concepts assisting on the exploitation of the full potential of THz technology towards the B5G Era
- ❑ Significant steps on the development of ultrawideband photonic-enabled THz transceivers operating seamlessly in W/D and THz band

Next Steps

- ❑ Integration of photonic techniques including injection locking with the THz emitter and receiver modules (ICCS-HHI joint experiment)
- ❑ Real time operation integration with ICOM's BBU(ICCS/ICOM)
- ❑ Experimental validation of TERAWAY prototypes and photonic technology
- ❑ Integration and experimental validation of TERAWAY transport and network technology

Thank you for your attention ! TERAWAY

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