CENTER FOR PHYSICAL SCIENCES AND TECHNOLOGY

A European Training Network

TERAOPTICS

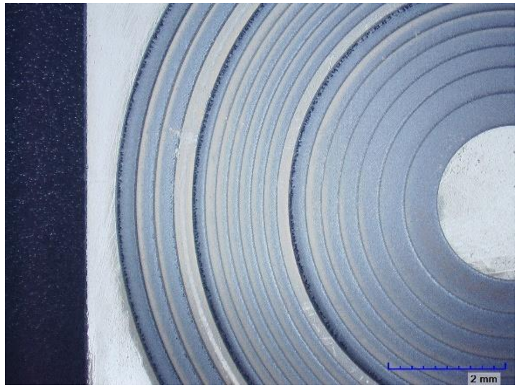
THz Atelier

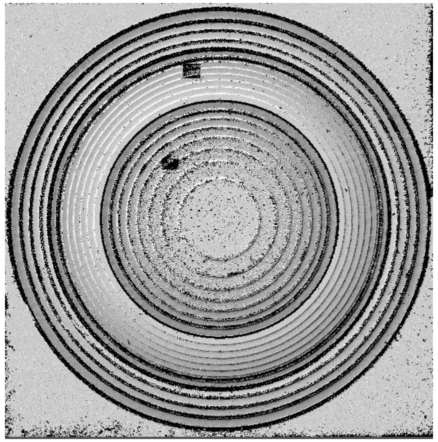
PHD Title: Diffractive Optics Integration with THz detectors and Emitters

Objective: The main objective of my PhD work is to develop high efficiency diffractive optics in order to replace refractive optics. The silicon-based multi-level phase-correcting Fresnel lenses as well as high-contrast-grating-type waveplates including antireflective structures for up to 1 THz are developed. Aiming to maintain compactness and robustness of the THz systems, In this project we will also develop solutions for on-chip integration of the diffractive optical elements and antireflective structures with the THz detectors and emitters. Using mask-less direct laser ablation technology, developing THz diffractive lenses and waveplates of silicon, allowing more sophisticated profiles with the increase of the component performance which makes the integration in compact THz systems possible.

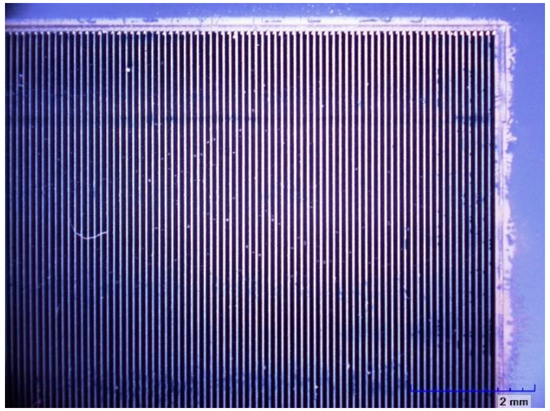
Diffractive optical elements (DOE's)

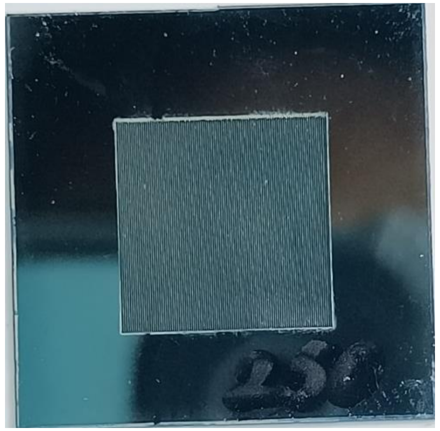
Hybrid Multi-phase Fresnel lens





High-contrast-grating-type waveplates





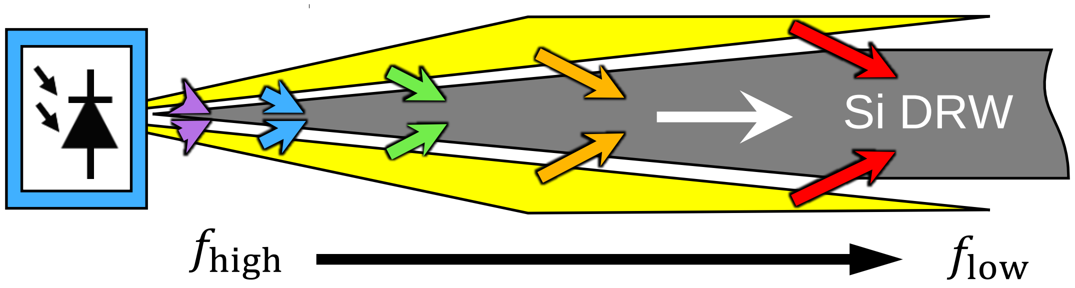
Ayyagari, Surya Revanth, Simonas Indrišiūnas, and Irmantas Kašalynas. "Hybrid Multi-Phase Fresnel Lenses on Silicon Wafers for Terahertz Frequencies." *IEEE Transactions on Terahertz Science and Technology* (2023).

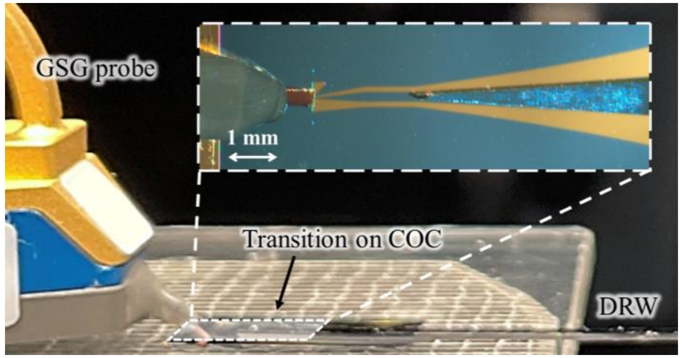
S. R. Ayyagari et al. "Broadband High-Contrast-Grating-Type Waveplates for the Terahertz Range" (submitted).

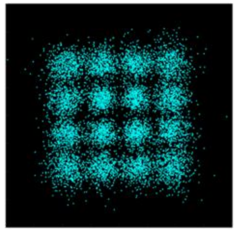
Ultra-wideband THz Interconnect

Shuya Iwamatsu, Universität Duisburg-Essen (shuya.Iwamatsu@uni-due.de)

- Development of ***ultra-wideband THz interconnect*** is a key to realizing ***THz integrated communication and spectroscopic sensing systems***







24 Gbps @80 GHz

↑ Ref. [1]

References

1. S. Iwamatsu, et al., Journal of Infrared, Millimeter, and Terahertz Waves, vol 44, pp. 532-550, 2023.
2. S. Iwamatsu, et al., Optics Letters, vol. 48, no. 23, pp.6275–6278, 2023.
3. S. Iwamatsu, et al., “THz Near-Field Imaging Sensor Using Integrated Substrateless Silicon Interferometer”, GeMiC, 2024. (To be presetned)

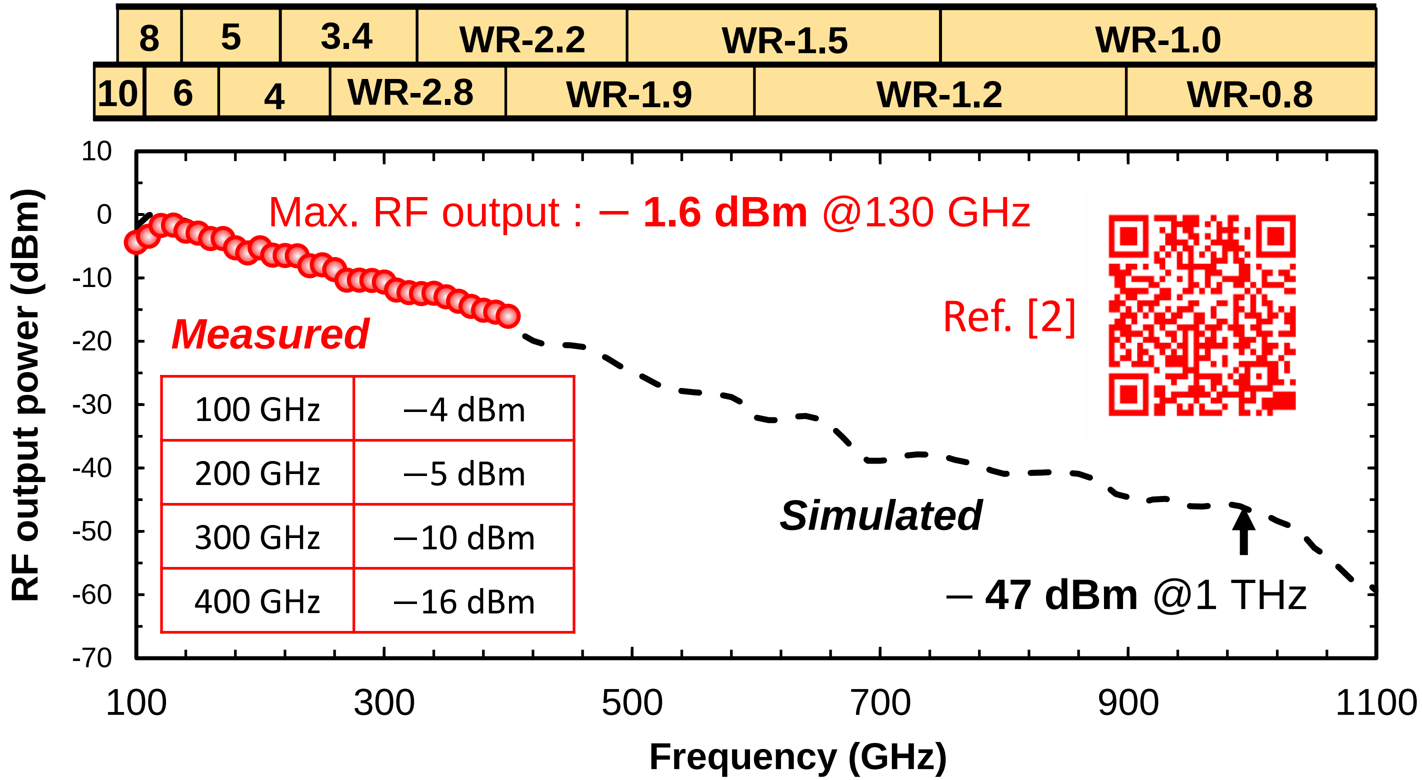
- ***A tapered-slot trasnsition*** enables ultra-wideband interconnection between InP-based THz uni-traveling-carrier photodiode (UTC-PDs) and Si-based dielectric rod waveguides (DRWs)
- Multi-band THz on-chip communications are demonstrated [1]

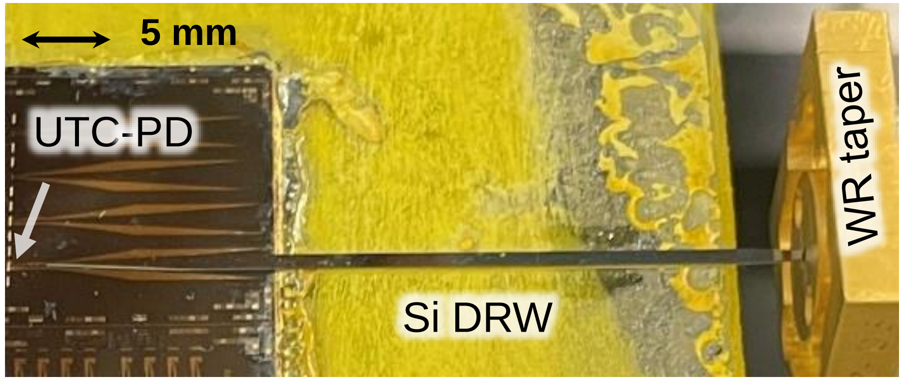
Ultra-wideband THz Interconnect

Shuya Iwamatsu, Universität Duisburg-Essen (shuya.Iwamatsu@uni-due.de)

2024 DUISBURG GeMiC German Microwave Conference

- ***An ultra-wideband THz photonic transmitter*** is developed using ***hybrid integrated InP-based UTC-PD with Si DRW through the tapered-slot transition*** [2]





References

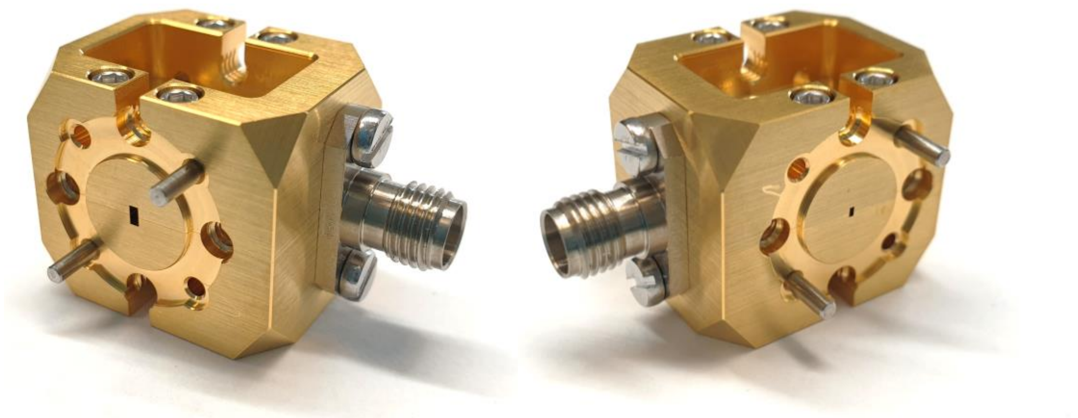
1. S. Iwamatsu, et al., Journal of Infrared, Millimeter, and Terahertz Waves, vol 44, pp. 532-550, 2023.
2. S. Iwamatsu, et al., Optics Letters, vol. 48, no. 23, pp.6275–6278, 2023.
3. S. Iwamatsu, et al., "THz Near-Field Imaging Sensor Using Integrated Substrateless Silicon Interferometer", GeMiC, 2024. (To be presetned)

UNIVERSITÄT DUISBURG ESSEN *Offen im Denken* LEAP WAVE MICROWAVE PHOTONICS uc3m Universidad Carlos III de Madrid TERAOPTICS A European Training Network TERAmeasure MARIE SFB/TRR 196 6GEM

Optically pumped THz mixer at 300 GHz

Javier Martinez Gil
Oleg Cojocari

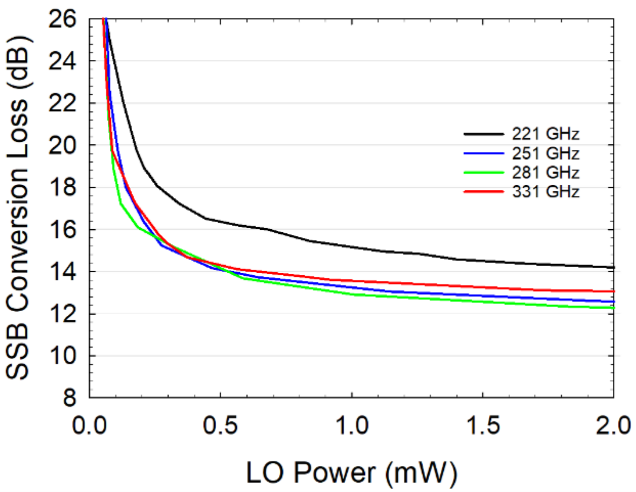
Mixer's main characteristics and performances

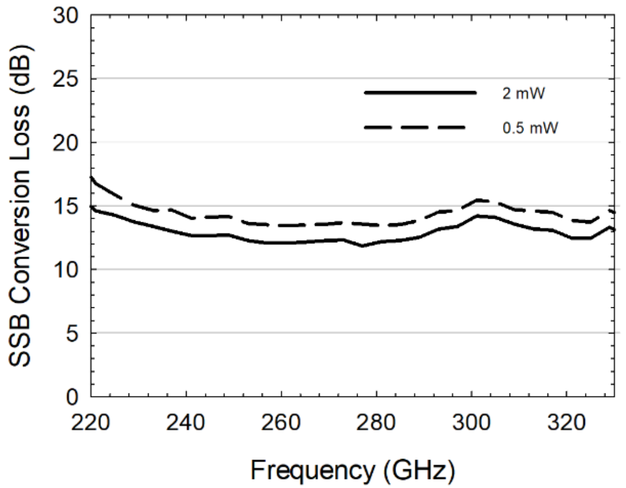


Fabricated block of the low barrier full-band WR3.4 mixer

Tech. Specifications	Min.	Typ.	Max.
LO Freq. (GHz)	110		165
LO Power (dBm)	-3	-1	2
RF Freq. (GHz)	220		330
RF Power (dBm)			-15
IF Freq. (GHz)	0		40
SSB Conversion Loss (dB)	12		15

Main characteristics of the presented low barrier mixer





Conversion loss of the mixer. Sweeping the LO power between 0.1 – 2 mW and over the WR3.4 band

Usage of the mixer in a wireless THz communication system

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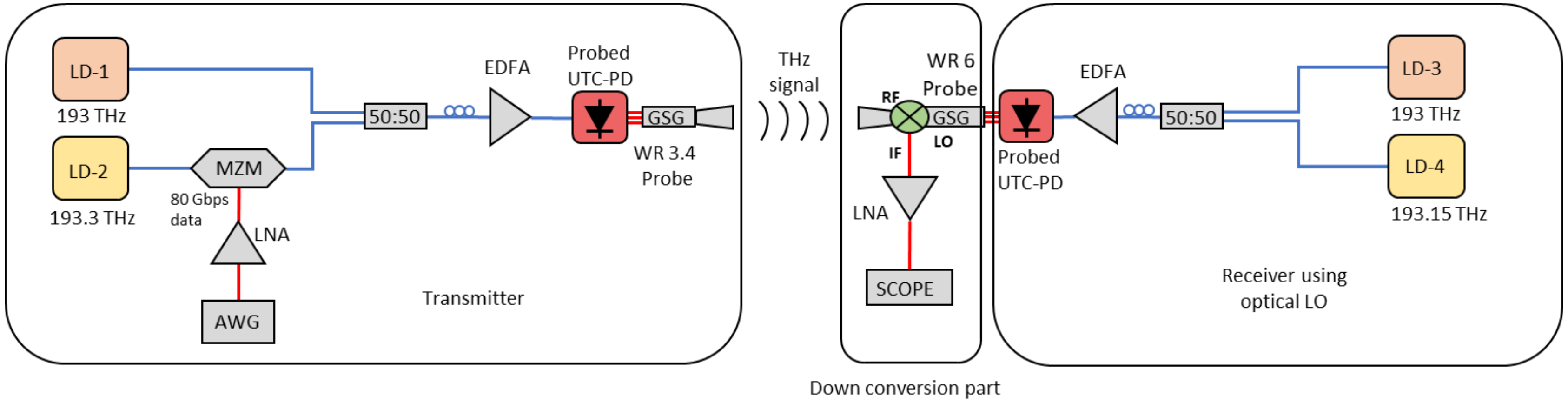
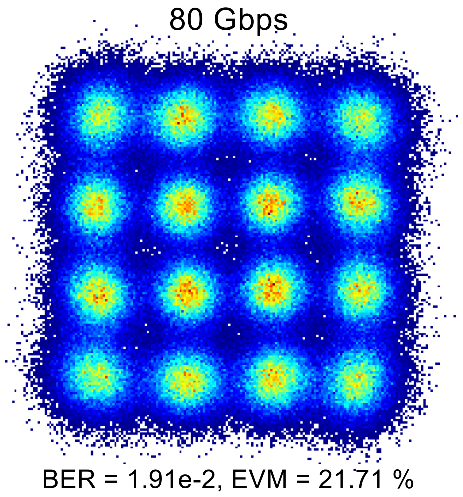


Optical THz wireless link. A photonic transmitter based on the beating of two lasers in a probed UTC photodiode, data is provided by modulating one of the laser's arm. After wireless transmission in the wireless channel, the signal is down-converted in IF using the sub-harmonic mixer. The receiver's LO signal is similar to the TX, using the beating of two lasers.



Constellation results of the 80 Gbps transmission link using different a mixer optically pumped. Performances obtained using InGaAs full-band mixer as a receiver, this mixer presents BER and EVM of 1.91e-2 and 21.71%.

Photonically pumped Integrated Schottky based heterodyne THz receiver using UTC-PD Power Combining.

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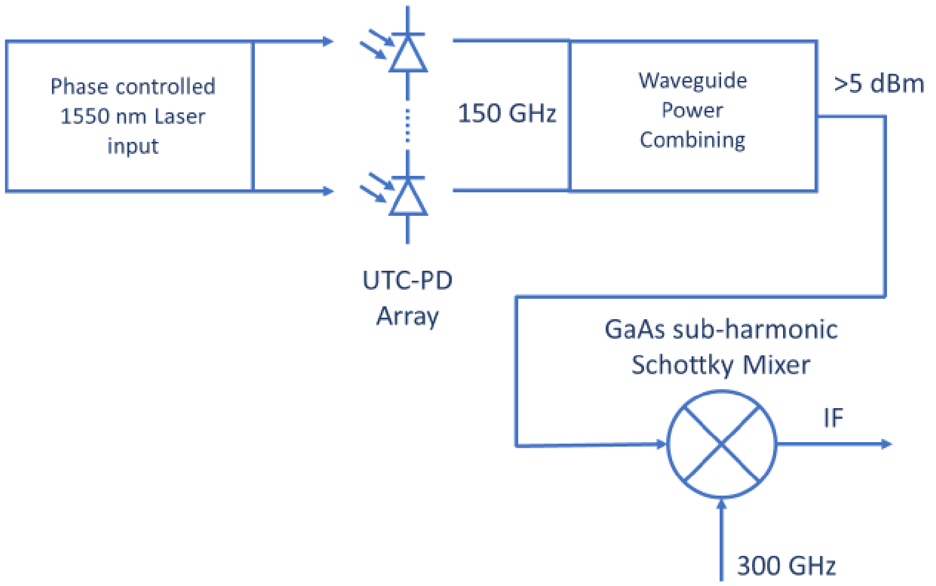
This project focuses on:

1. Developing a split-block (metallic block to house components split at the center of a WR waveguide) based integrated receiver housing Schottky mixer and the photonic local oscillator, working above 300 GHz.
2. Performing waveguide power combining of UTC-PDs to create a high-power LO source to pump a GaAs sub-harmonic Schottky mixer, with the aim of achieving comparable performance to those existing in the microwave regime.



Schematic of the receiver device working above 300 GHz using power combined UTC-PDs.

Workflow:

- Packaging of Uni-traveling-carrier photodiodes.
- Power combining using rectangular waveguides.
- Integration of Schottky Mixer and Photonic Local Oscillator

Applications in the field of:

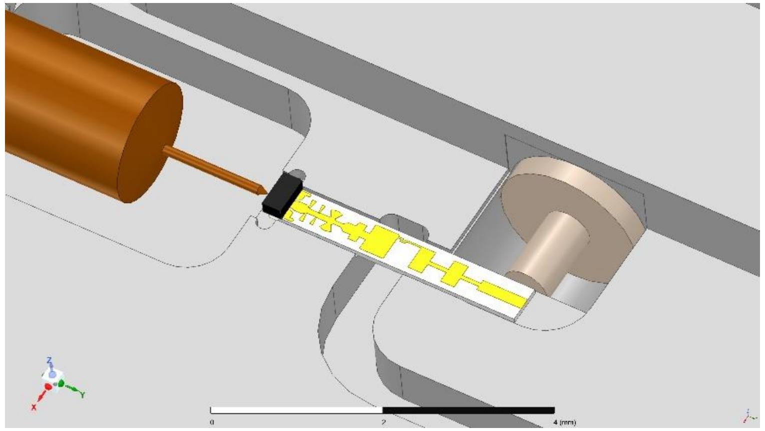
- Earth observation & Remote sensing.
- THz Astronomy.
- High-speed Communication.

ESR 11 – Himanshu Gohil

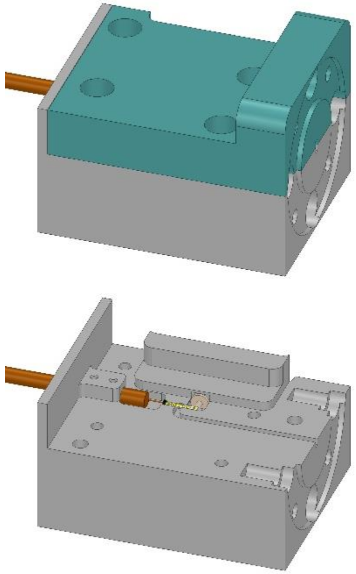
UKRI Science and Technology Facilities Council RAL Space

UCL

Project Highlights



Split-block design for UTC-PD integration showing quartz based mounting circuit and optical fibre coupling.

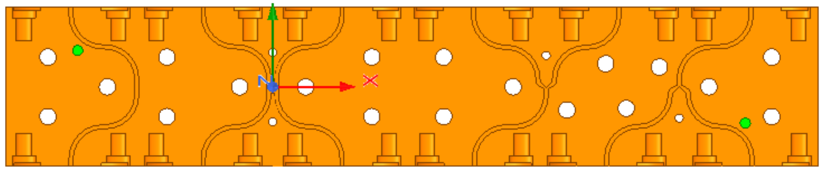


Packaging of Uni-traveling-carrier photodiodes using metallic split-blocks.

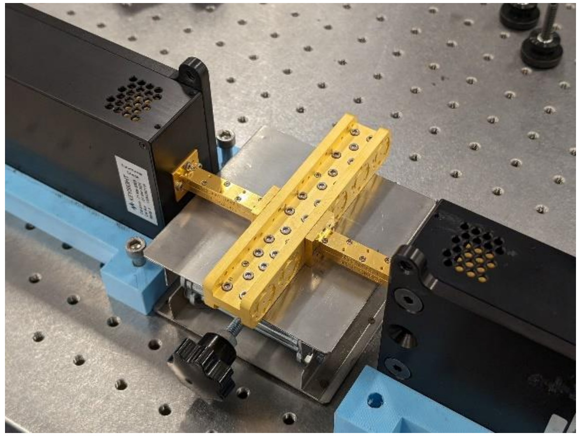
- GCPW to WR5 waveguide transition circuit based on quartz for photodiode integration
- Studying photodiode mounting using wire-bonding as well as flip-chip bonding.
- Employing Impedance Matching Circuit to maximize output power.

Rectangular waveguide based power combiners for multiplying UTC-PD power.

- Studying Hybrid as well as Branched coupler designs for optimal performance of Photonic LO.
- Manufactured using Precision CNC machining.



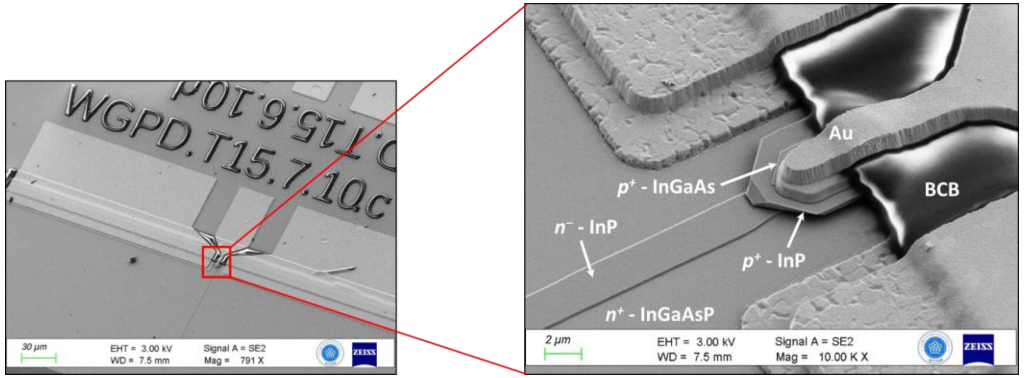
Multiple WR5 waveguide power combiner designs in a single block prototype.



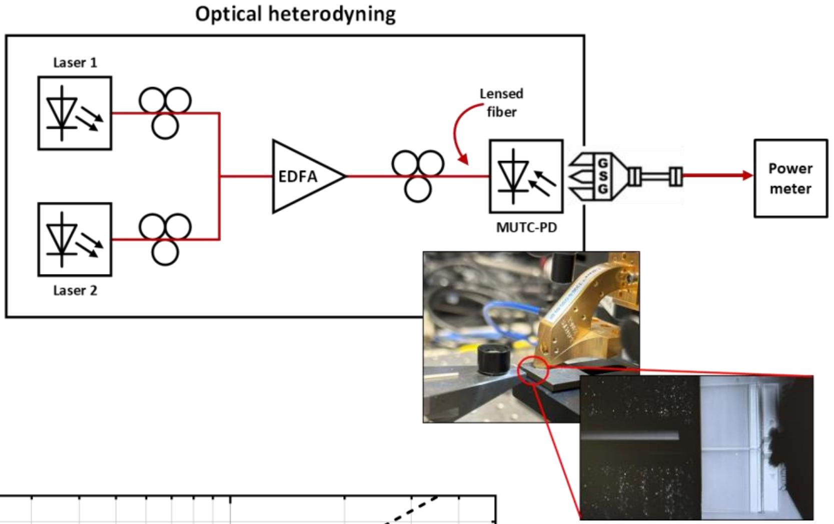
ESR 11 – Himanshu Gohil

Ultra-Broadband High Power THz MUTC-PDs

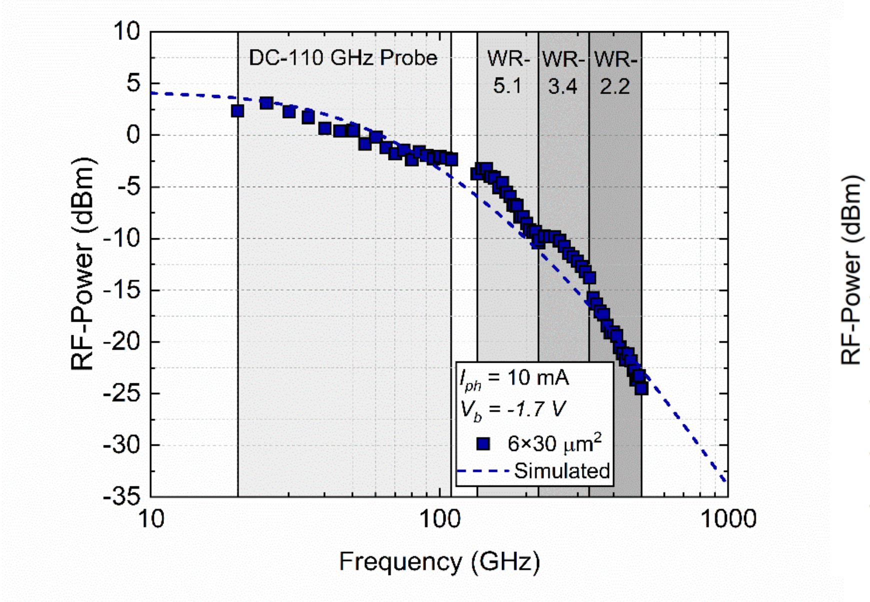
2024 DUISBURG GeMiC German Microwave Conference

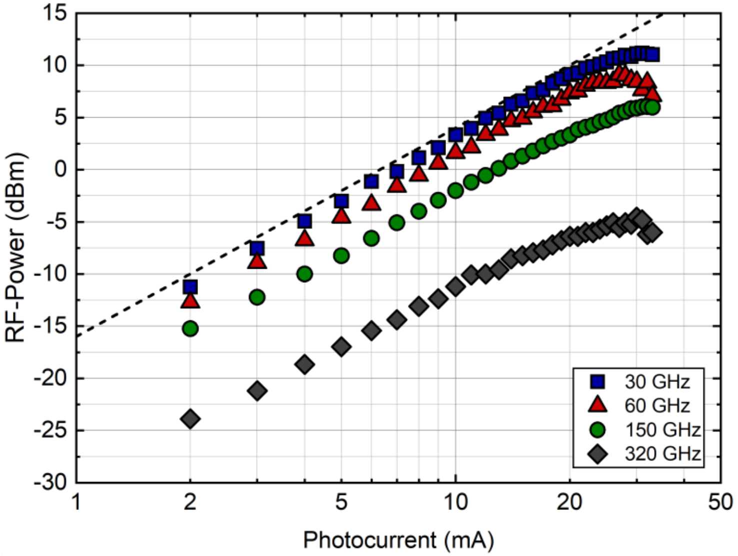


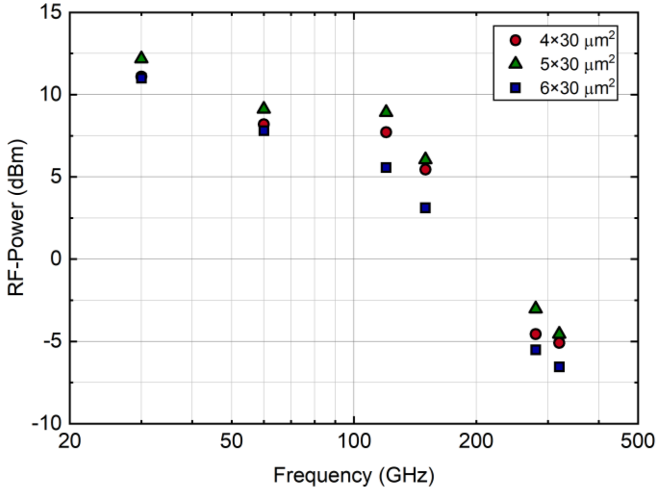
SEM images of a fabricated waveguide MUTC-PD.



- mW THz output power levels of 6.1 dBm and −4.6 dBm at 150 GHz and 320 GHz, respectively
- High saturation current levels at around 30 mA at THz frequencies
- First time on-chip measurements up to 500 GHz
- Ultra-broadband MUTC-PDs with 500 GHz operational bandwidth







E. Abacıoğlu *et al.*, "500 GHz Operational Bandwidth MUTC-Photodiodes with Milliwatt Terahertz Output Power Levels," ECOC, Oct. 2023.

100 Gb/s and Beyond THz Communication Links

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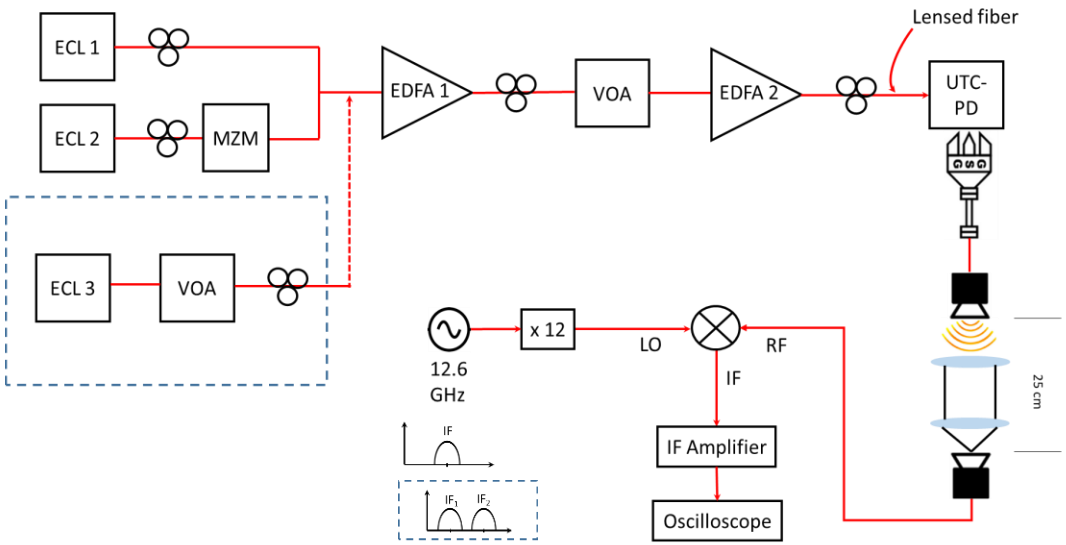
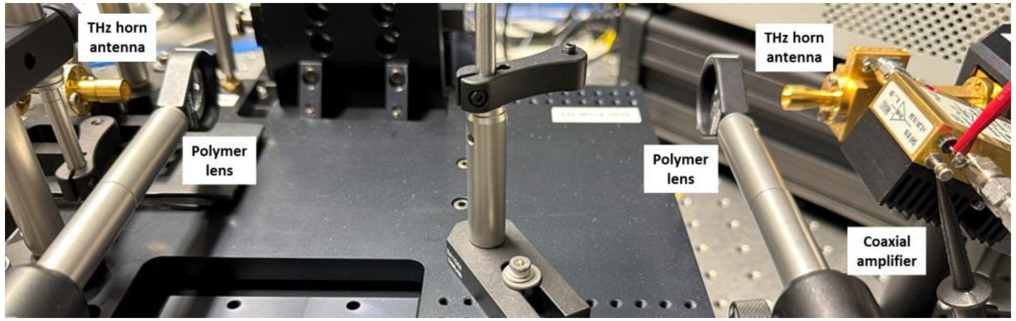
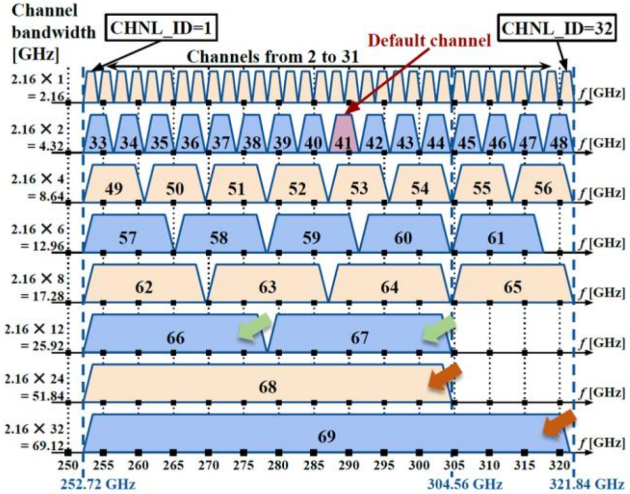
Single and multi-channel wireless communications





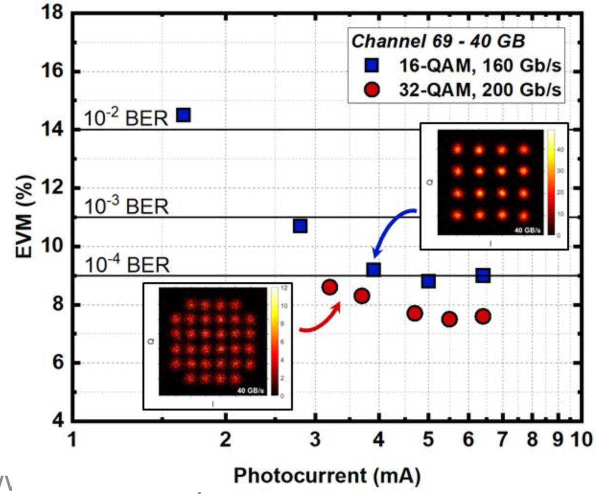
E. Abacıoğlu, A. S. Mohammed, J. Tebart, M. Grzeslo, T. Neerfeld, J. L. Fernández Estévez, G. Ducournau, and A. Stöhr, "100 Gbit/s IEEE 802.15.3d and Beyond THz Communication Links Using Broadband Waveguide-Integrated MUTC-Photodiodes," *IEEE Transactions on Terahertz Science and Technology*, in preparation.

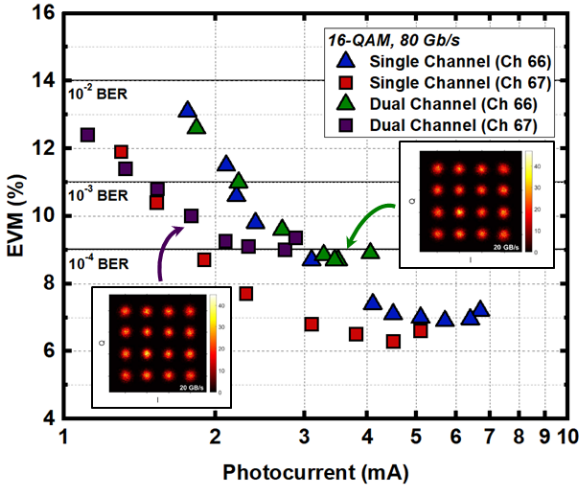
IEEE 802.15.3d channel plan



Petrov *et al.*, "First Standardization Efforts for Sub-Terahertz Band Communications toward 6G," doi: 10.1109/MCOM.001.2000273.

- First time on-chip measurements with highest data rate and lowest BER
- IEEE 802.15.3d compliant
- Showcase of PD linearity with 16-, 32-, 64-QAM modulation formats
- Record data rates of 200 Gbit/s for single channel at a carrier frequency of 280 GHz
- Dual channel measurements prove that two channels are supported at the same time in a single PD





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High-speed RF photonics transmitter for THz wireless communication systems

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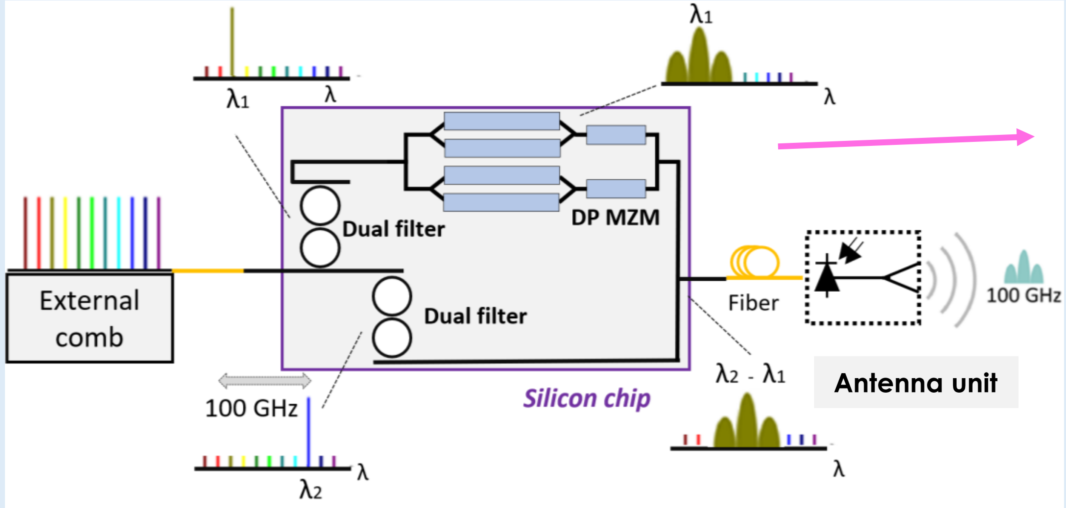
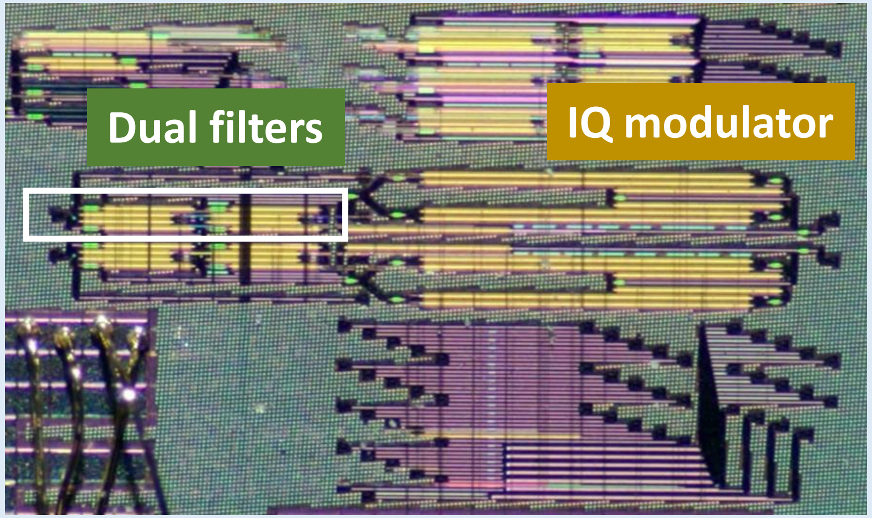
MARIE CURIE ACTIONS





Partners involved:

G.O.T.L.

Tower Semiconductor

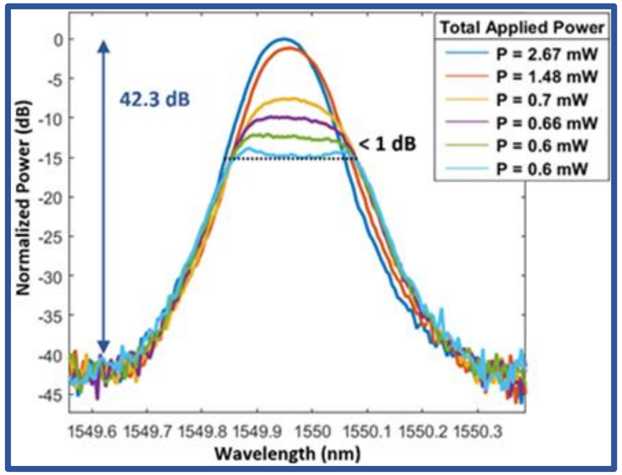
Where Analog and Value Meet

SYNOPSYS

Optical filtering

- Filters based on phase modulation
- FSR of 100 GHz
- Plasma dispersion and TO effect

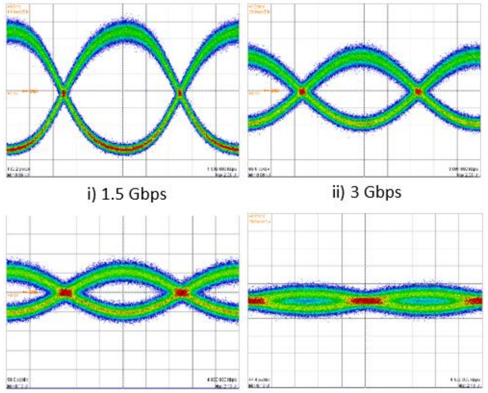
Dual filter



Single and dual filter performance				
Parameters	Single	Single	Dual	Units
Tuning mechanism	Thermo-optic	Plasma dispersion	Plasma dispersion	
Shape factor	0.22	0.28	0.27 – 0.66	
BW @-3dB	15	17.5	12.48	GHz
BW tunability	-	-	12.48 - 32.5	GHz
Extinction Ratio	18	17.5	42.3 - 30	dB
Q-factor	5000	5535.71	5961.5 - 4300	
Wavelength tuning	Full FSR	Full FSR	¼ Full FSR	
Tuning efficiency	0.02	0.44	0.005	nm/mW
Loss (for full FSR)	0.57	9.93	4.64	dB

Optical modulation

Single Mach Zehnder modulator



i) 1.5 Gbps ii) 3 Gbps iii) 4 Gbps iv) 4.5 Gbps

Photonic-based THz signal generation on InP/Polymer platform

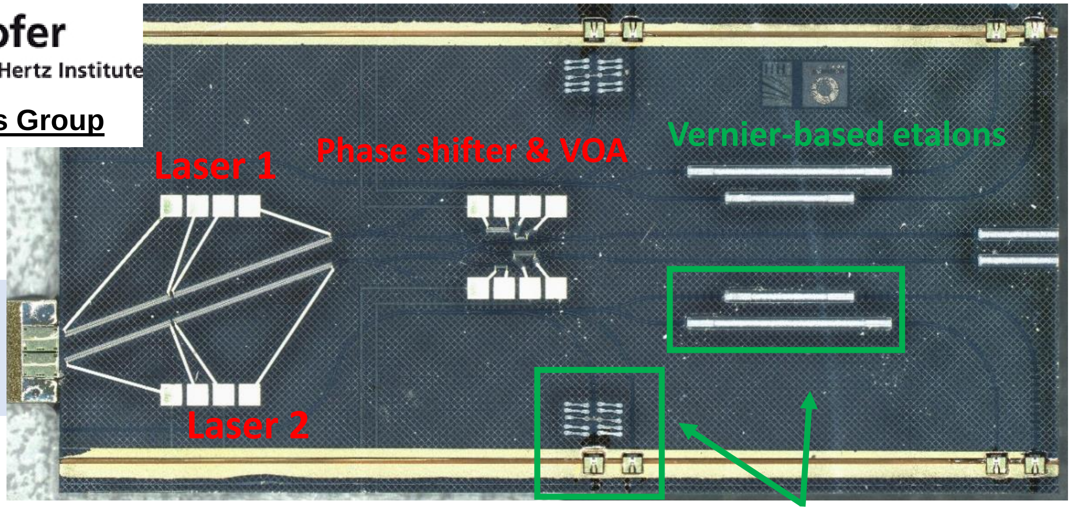
TERAmeasure

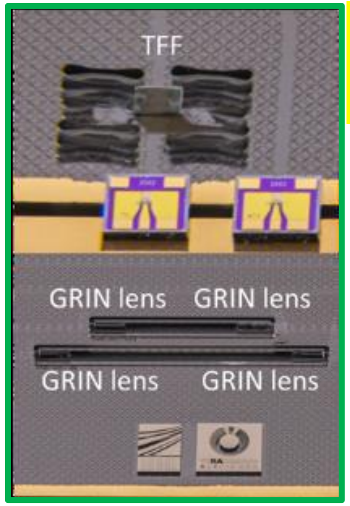
SCAN ME

Fraunhofer
Heinrich Hertz Institute

Hybrid PICs Group

InP
Gain chips





Grating & phase sections

On-chip power & wavelength meters

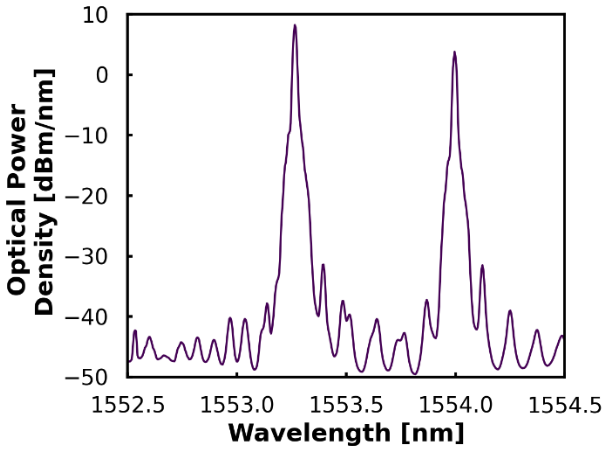
Polyboard

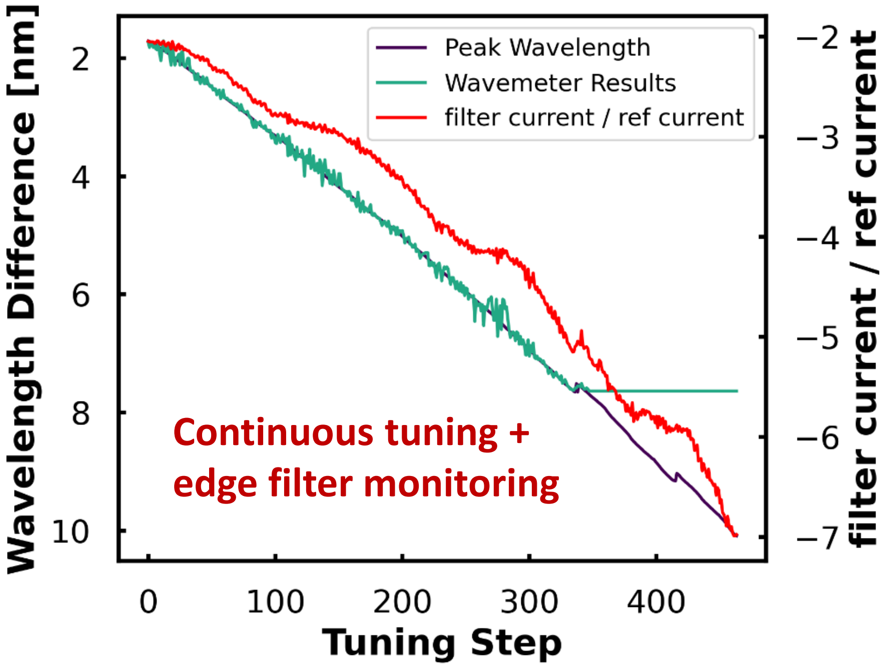
Focused Session on mm-Wave and THz Photonics
Tuesday, 16:30 in the Room "Tiger & Turtle"

- Integrated wavelength-meter based on **thin-film filters** (TFF)
- On-chip photodiodes (PD) for absolute wavelength and power measurements

Achieved:

1. **Continuous tuning: 4+ nm**
2. **Wavelength monitoring using the TFF**
3. **Power-monitoring PDs**





Note: Work conducted during the secondment at Fraunhofer HHI.

ELECTRONIC AND ELECTRICAL ENGINEERING DEPARTMENT

UCL

ESR7: Integrated UTC-PDs and SBDs for high sensitivity receivers

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956857.

Marie Skłodowska-Curie Actions

European Commission

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Why are optoelectronic THz receivers useful?

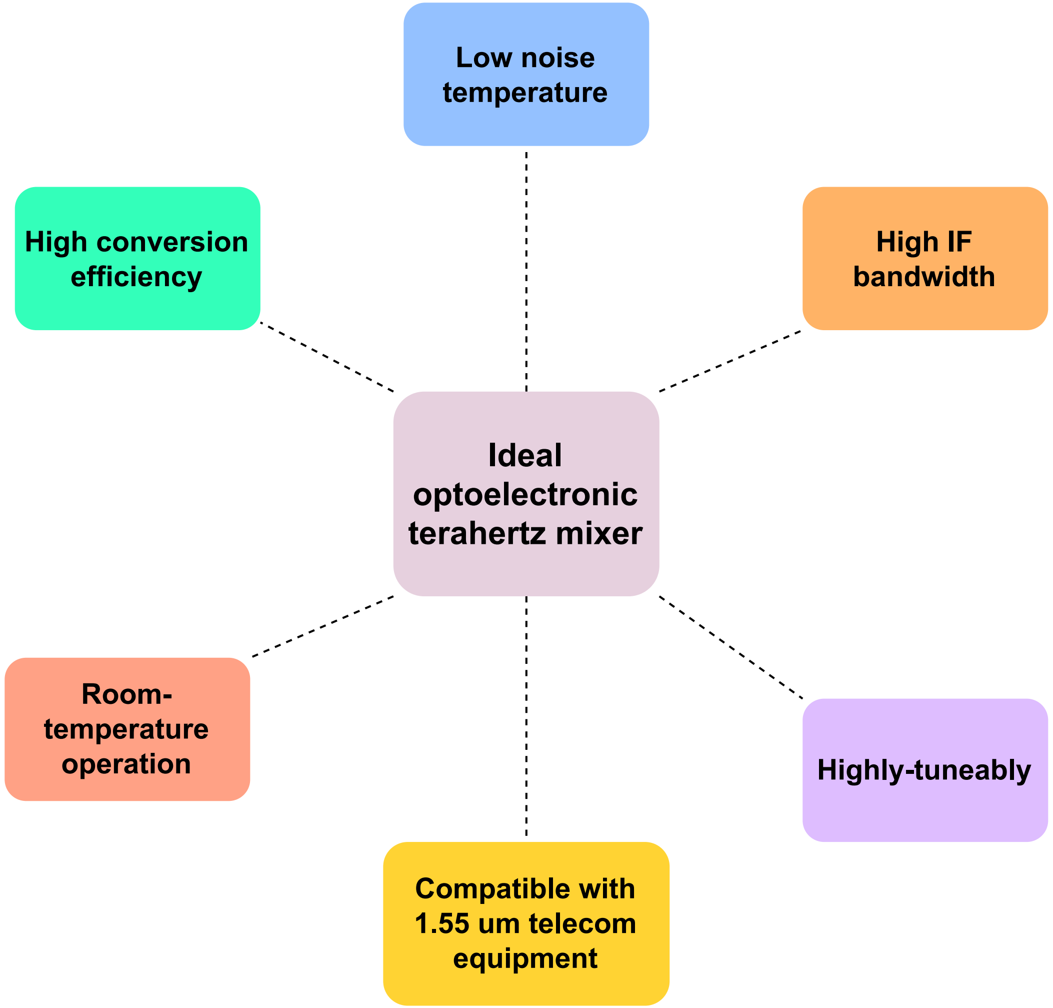
- LO can be distributed over long fibre links
- Reuse of mature 1.55 um telecom technology
- High-frequency tuneability and high LO purity

What are current optoelectronic mixers based on?

- GaAs/InGaAs photoconductors (LT-GaAs/InGaAs PC)
- Uni-travelling-carrier photodiodes (UTC-PD)

What is the main limitation?

- Conversion loss is significantly higher that electronic mixers.
- E.g. At 300 GHz a photoconductor would typically offer ~30-50 dB of conversion loss while a Schottky mixer <10 dB



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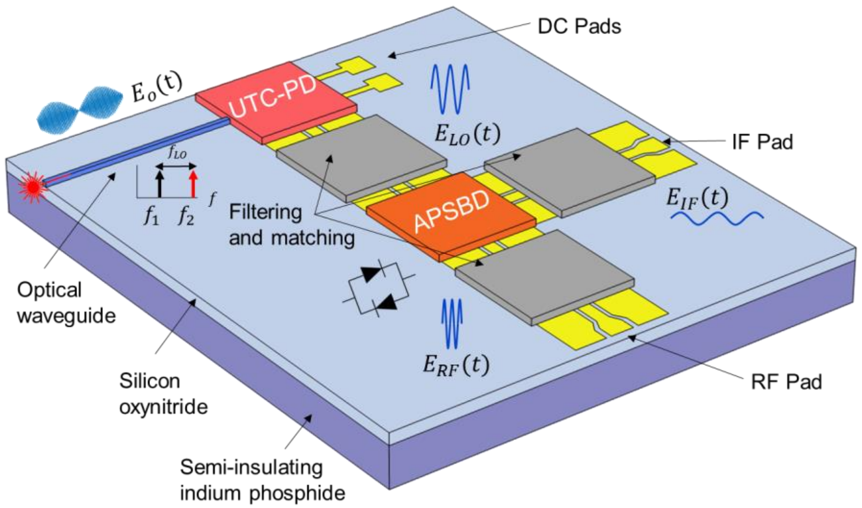
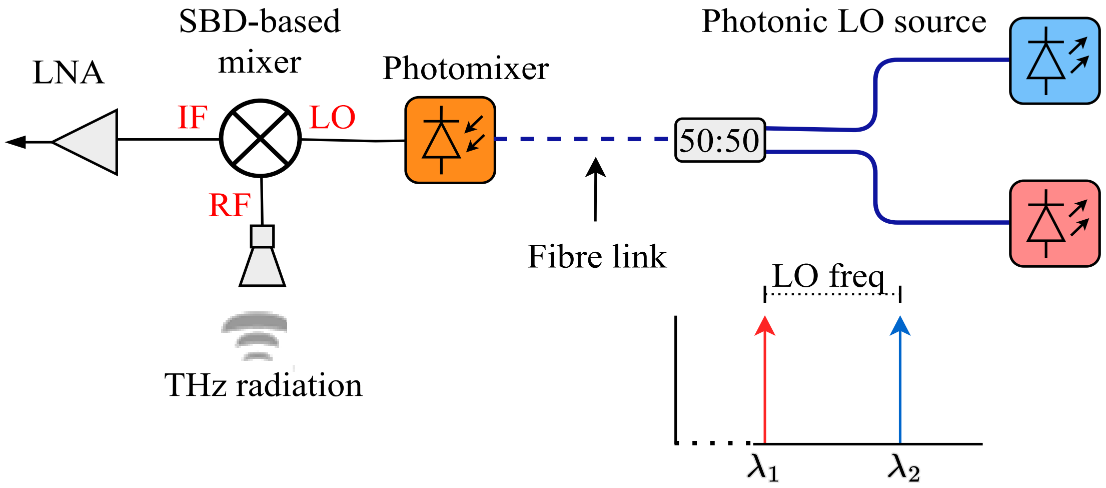
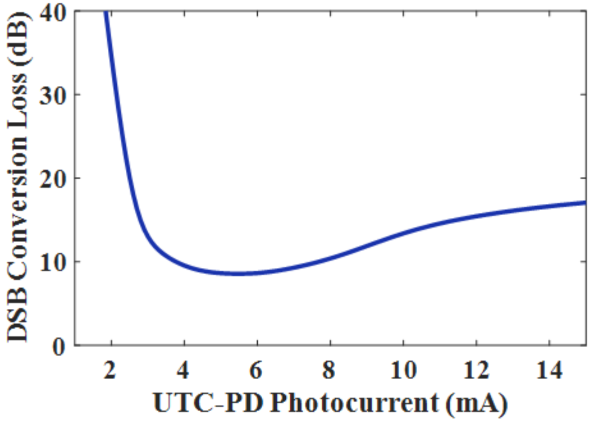
ESR7: Integrated UTC-PDs and SBDs for high sensitivity receivers

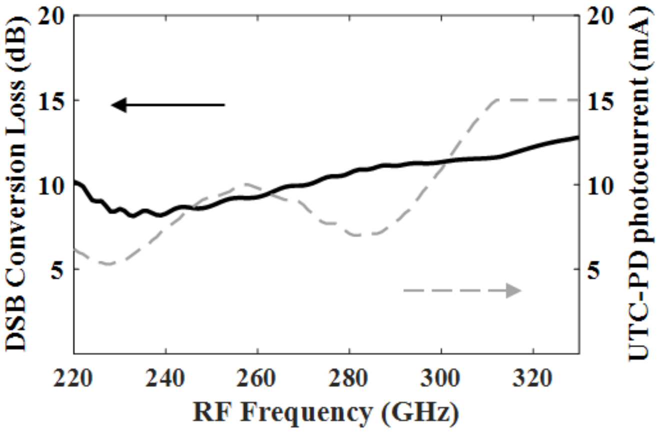
Iñigo Belio-Apaolaza

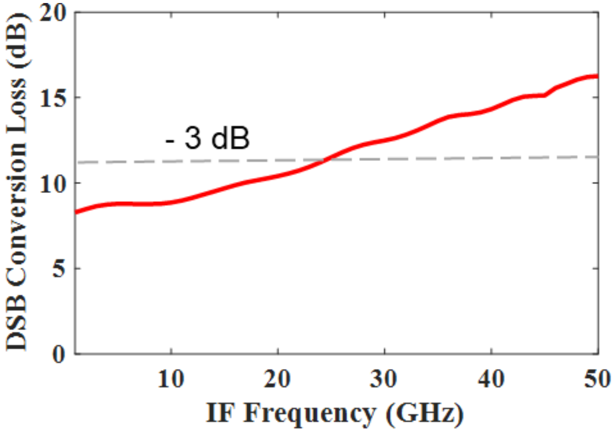
Terahertz optoelectronic receivers enabled by monolithic integration of SBDs and UTC-PDs











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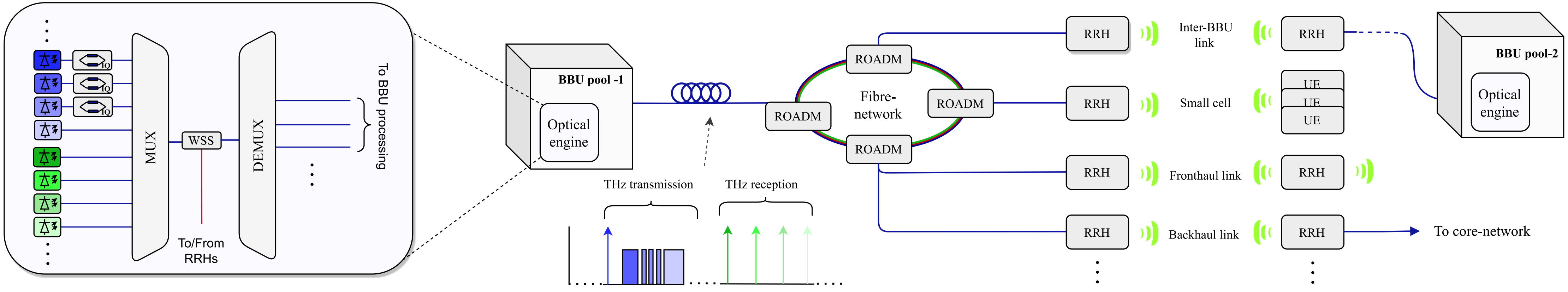
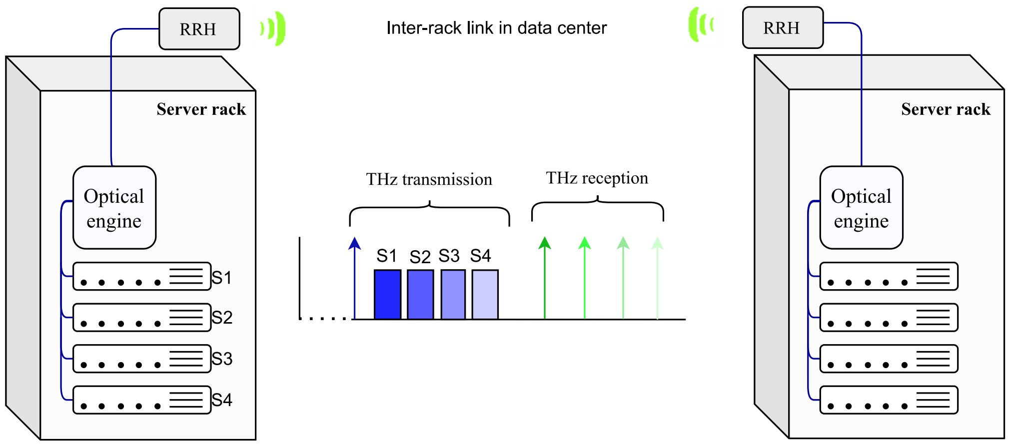
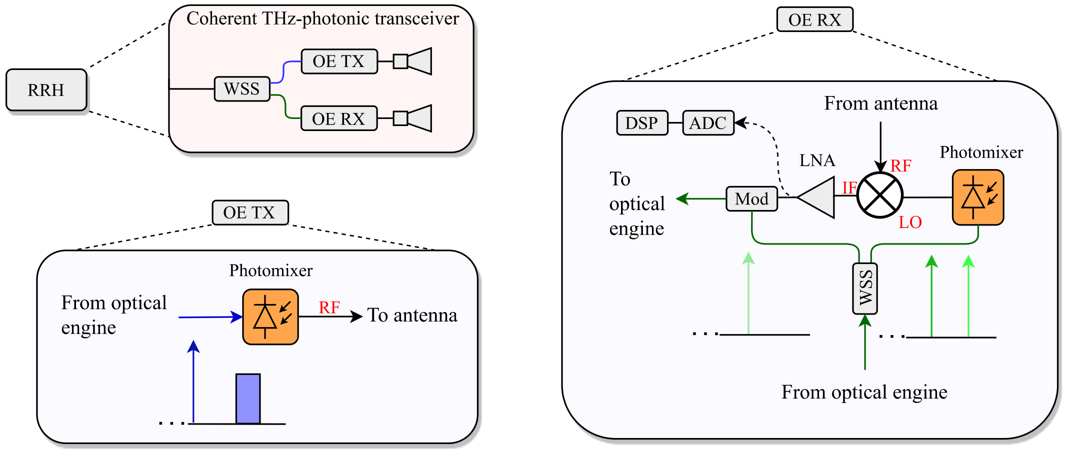
ESR7: Integrated UTC-PDs and SBDs for high sensitivity receivers
Iñigo Belio-Apaolaza

Use case: Terahertz wireless communications in 6G networks and data centers







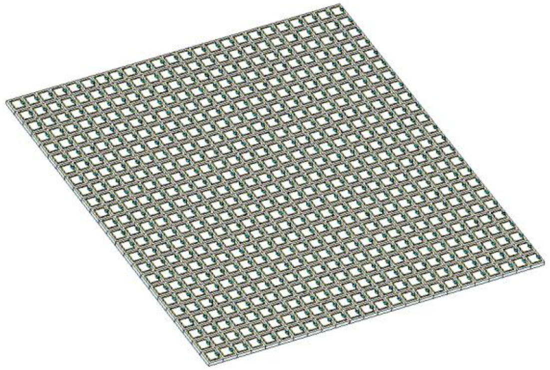
Photonics systems for THz spectroscopy and THz imaging

Krishna Kumar, DAS Photonics, Valencia, Spain, 46022
Early-Stage Researcher – 15 (TERAOPTICS ITN)

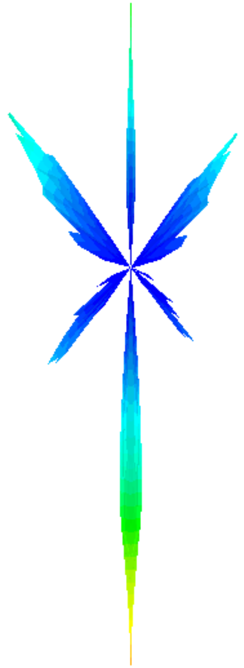
AIM: Development of an optically mediated multi-frequency and beam steerable terahertz source tool.

Phase change metamaterial based active THz beam steering

- Square shaped split ring resonator with VO2 patch
- Active THz phase shifter
- Active THz beam switching with reduced phase modulation range
- Plane wave beam steering at fixed frequency
- Gaussian wave beam steering at fixed frequency
- Inverse design optimization in MATLAB
- Development of THz beam steering device and its characterization



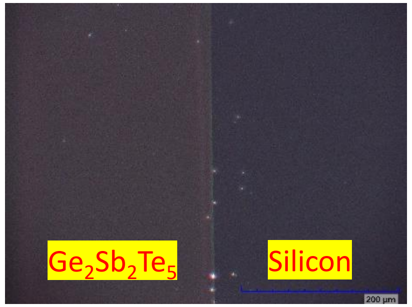
VO_2 incorporated tunable antenna array



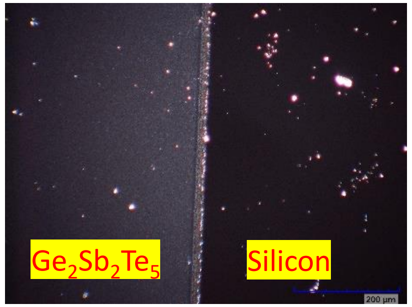
Far-field radiation pattern

Investigation of novel chalcogenide THz phase change materials

- Material investigated: $\mathbf{Ge_2Sb_2Te_6}$, $\mathbf{Ge_2Sb_2Te_5}$ and $\mathbf{Sb_2Se_3}$
- THz-time domain spectroscopy of chalcogenide phase change materials
- Optical properties extraction (complex permittivity and conductivity)
- Raman spectra of PCMs
- X-Ray diffraction of PCMs
- Application of PCMs in THz beam steering



Amorphous



Crystalline

THz beam steering

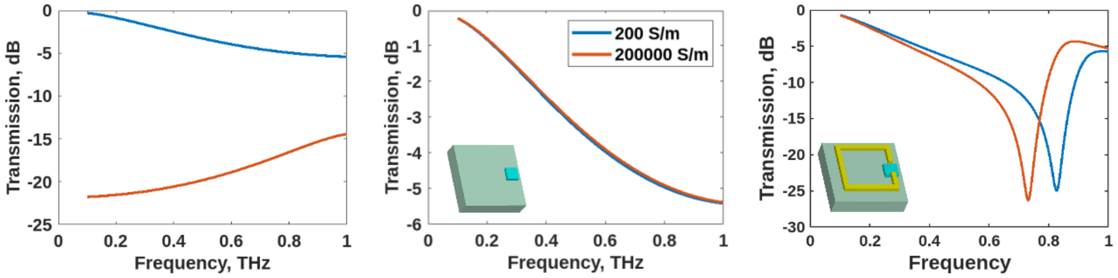


Figure 1 THz transmission through VO_2 integrated meta-atoms with VO_2 undergoing metal-to-insulator transition: (a) meta-atom integrated with thin-film (b) meta-atom integrated with a small patch (c) meta-atom comprised of square-shaped Aluminum (yellow) split ring, on top of VO_2 patch (cyan) deposited on Silicon substrate (light cyan) THz resonator, the transmission amplitude under metal-to-insulator transition demonstrate a frequency shift of 0.095 THz that corresponds to a phase modulation range of approximately 120°.

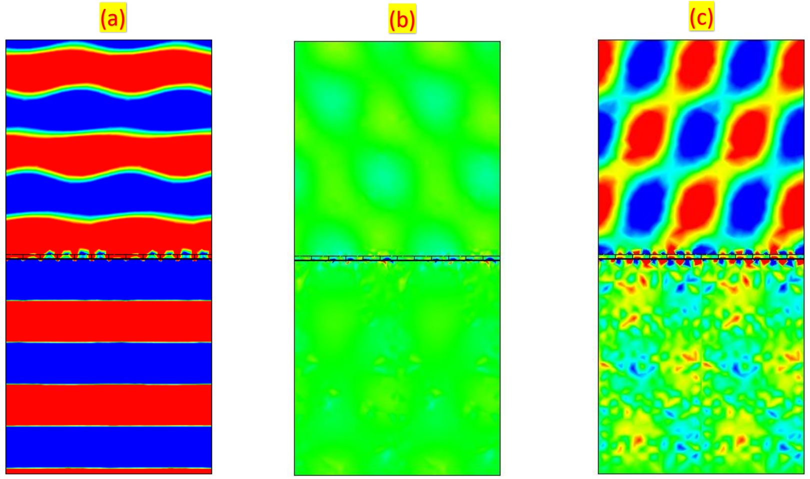


Figure 2 Supercell under plane wave excitation; (a) X-component, (b) Y component and (c) Z-component of the electric field. A supercell composed of 6 unit-cells were illuminated with normal incidence plane wave. The phase gradient designed to steer only X-polarized beam in the XZ-plane (c).

PCM characterization

- **PCMs investigated: $Ge_3Sb_2Te_6$, $Ge_2Sb_2Te_5$ and Sb_2Se_3**

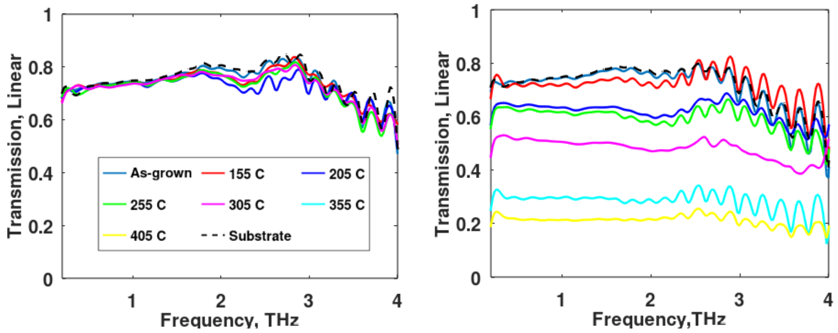


Figure 1 Transmission spectra of (a) 70nm thin Sb_2Se_3 PCM and (b) 104 nm thin $Ge_3Sb_2Te_6$ PCM both deposited on 625 (±25) µm Silicon substrate. The samples were annealed at several different temperatures. The decrease in the transmission of $Ge_3Sb_2Te_6$ PCM suggests the formation of cubic and hexagonal phases upon annealing.

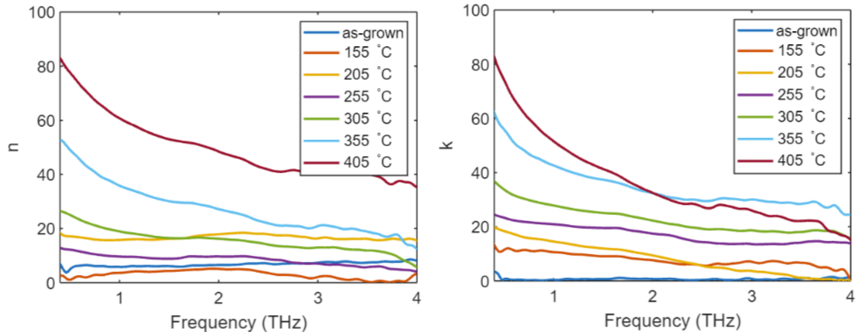


Figure 2 Complex refractive index of 100 nm thin $Ge_3Sb_2Te_6$ phase change material at different annealing temperature. (Left) The real part of the complex refractive index increases as the annealing temperature increases. (Right) The imaginary part of the complex refractive index corresponds to absorption in the PCM. It also grows when the annealing temperature rises, but less comparative to the real part of the refractive index.

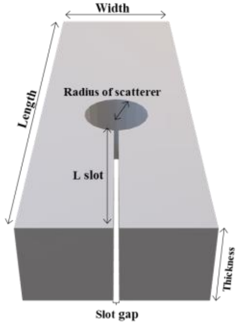
Silicon microstructures for THz interfacing and High- resolution imaging

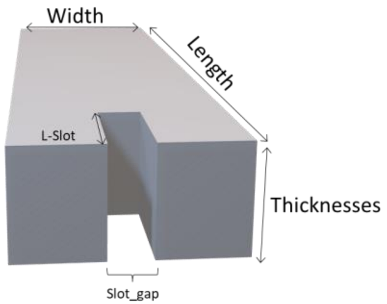
Ashish Kumar, UC3M , Madrid, Spain.
Early- stage researcher-6 (Teraoptics ITN)

Aim: Design silicon microstructure and passive component for the THz sensing, spectroscopy and high-resolution imaging.

All dielectric slot-terminated Silicon microstructures:

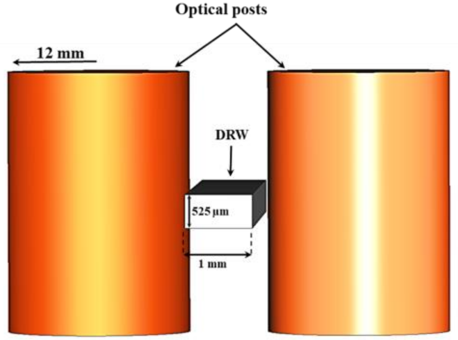
- Design and characterization of silicon slot-termination waveguide.
- Slot- termination coupling with free space and waveguide.
- Evanescent- wave interaction for sensing.
- THz high-resolution imaging with high confined radiating slot aperture.
- Integration of quasi-optics to waveguide via slot-waveguides.
- Slot-tips and low-index material for THz high-gain antennas.





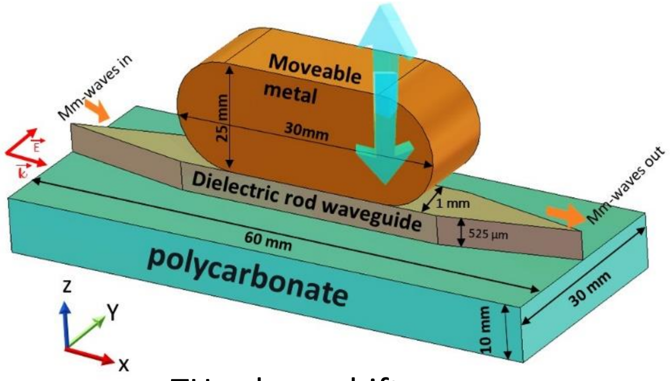
All dielectric Passive components design :

- THz waveguide polarizer.
- THz high-pass filter for waveguide.
- THz phase shifter.



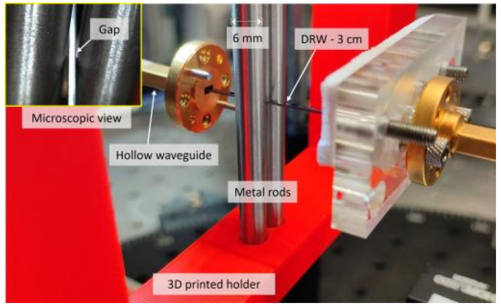
THz waveguide polarizer

[A. Kumar *et al*., *2022 47th (IRMMW-THz)*, Delft, Netherlands, 2022]



THz phase shifter

[A. Kumar *et al*.,,"*2023 IMS 2023*, San Diego, CA, USA, 2023]



High-Pass Filter

[A. Kumar *et al*., *APROPOS*, FTMC, Lithuania 2022]

Silicon Waveguide to Hollow Metallic Waveguide Coupling using a Quarter-Wave Dielectric Slot Waveguide

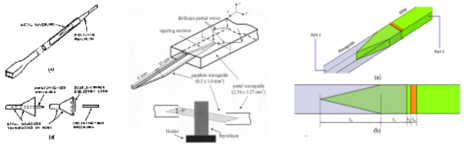
Ashish Kumar[1], Mushin Ali[2] , Daniel Headland[1], Guillermo Carpintero[1]

[1] Optoelectronics and Laser Technology Group (GOTL), University Carlos III of Madrid, 28911 Madrid, Spain.

[2] Leapwave Technologies Madrid, Spain.

Terahertz feeding

- **Free-space beam ➔** high feeding loss.
- Hollow waveguide provides **compact** ,**port access** and **calibration** [1].
  - Currently linear tapered is utilized for coupling to hollow waveguide and dielectric rod waveguide

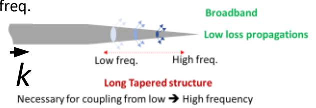


[2] [3] [4]

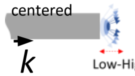
Long tapered provides major drawback in terms of accidentally interference, damage blind like MMIC or Monopole probes

Quarter-wave slot waveguide

Long tapered – radiation center moves along freq.

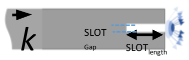


Truncated rods localization is well centered



Matching negatively impacted as no smooth index transition

Modal index of the dielectric slot waveguide is tailored with slot gap.

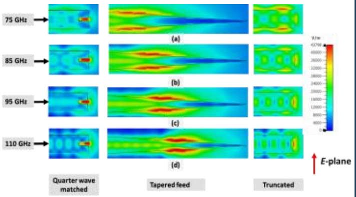


free-space interface cancel with those from the input to the slot-guide section

Low reflection to matched frequency band (75-110 GHz) smooth index transition

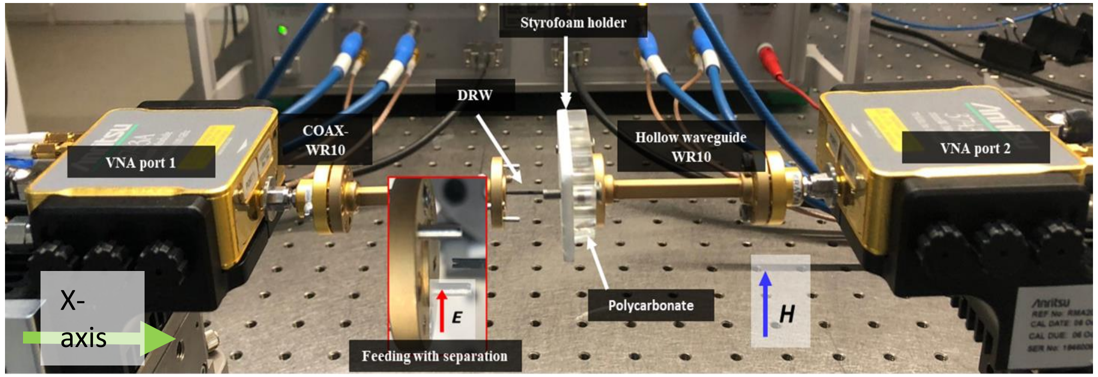
E-field analysis

- Quarter-wave matched slot waveguide has fix radiation center.
- Tapered has different radiation center for different frequency.



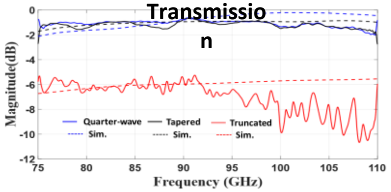
Experimental

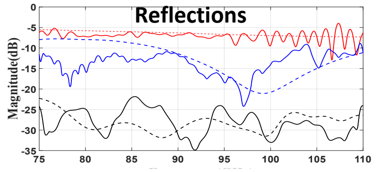
Hollow waveguide were excited with desired polarization



VNA port -1 ➔W1coax➔WR10➔DRW ➔ foam ➔WR10➔W1coax➔VNA port-2

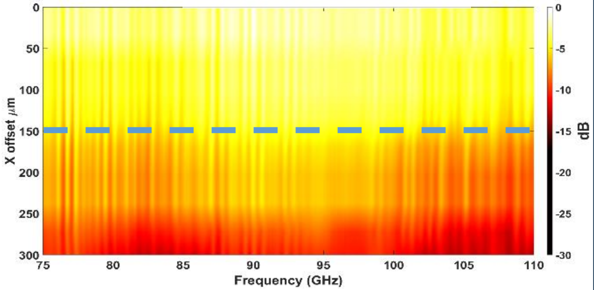
Results





Measured and Simulation response

Off-set coupling 150 µm < -5 dB loss.



Contactless Quarter-wave slot WG -WR coupling

References

1) T. W. Crowe ,et.al, *International Conference on Infrared, Millimeter, and Terahertz Waves*, Dec. 2011.
2) C. H. Chandler, *Journal of Applied Physics*, vol. 20, no. 12, pp. 1188–1192, Dec. 1949.
3) D. Lioubtchenko,et.al, *IEEE Microw. Wirel. Compon. Lett.*, vol. 11, 2001.
4) H. Zhu *et al.*, *IEEE Trans. Terahertz Sci. Technol.*, vol. 10, 2020.

Acknowledgements

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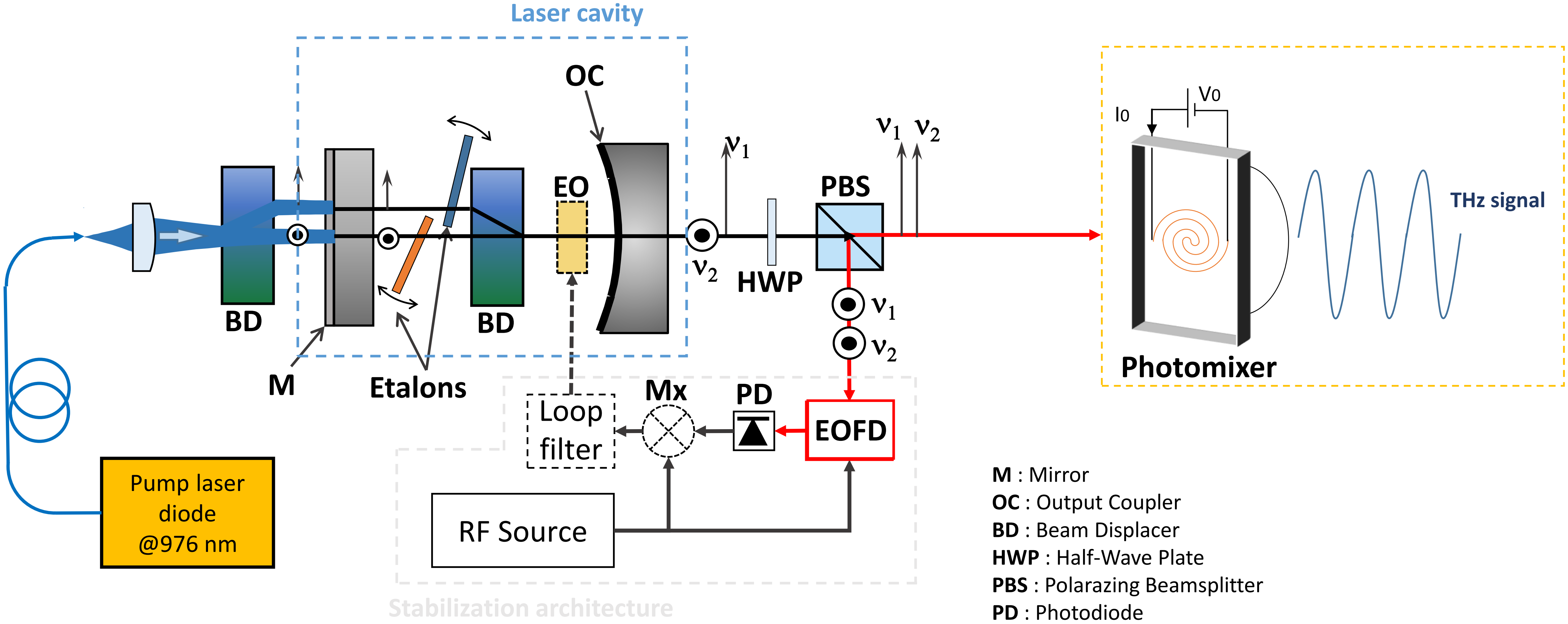
LEAP WAVE

2023 International Topical Meeting on Microwave Photonics (MWP), Nanjing, China, 2023, pp. 1-4, doi: 10.1109/MWP58203.2023.10416634.

Perspective: Frequency stabilized tunable dual-frequency solid-state laser



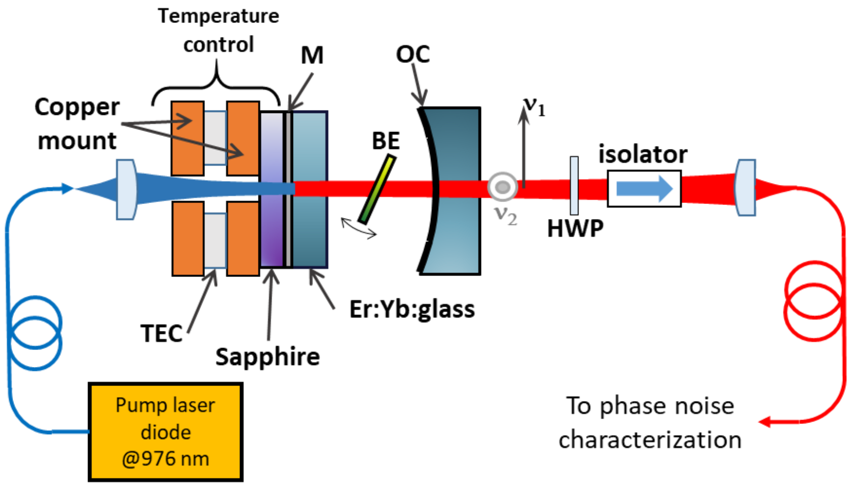
M : Mirror
OC : Output Coupler
BD : Beam Displacer
HWP : Half-Wave Plate
PBS : Polarazing Beamsplitter
PD : Photodiode
Mx : Mixer
EOFD : Electro-Optical Frequency Downconverter.

Laser cavity development part 1: Thermal effect study in Er:Yb:glass

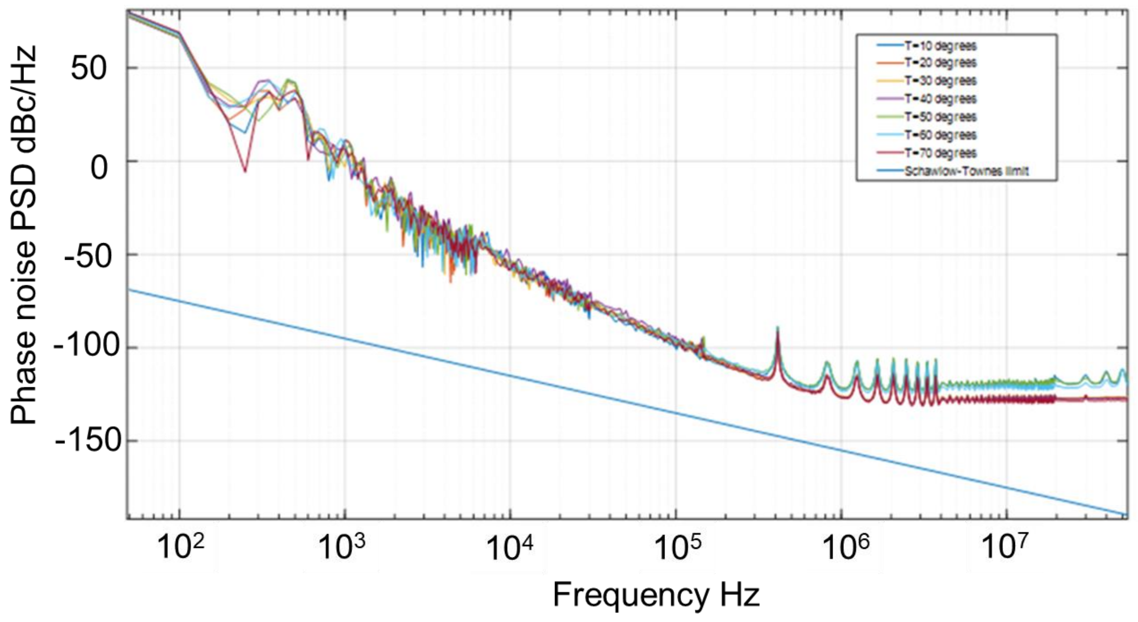
This configuration was made to observe:

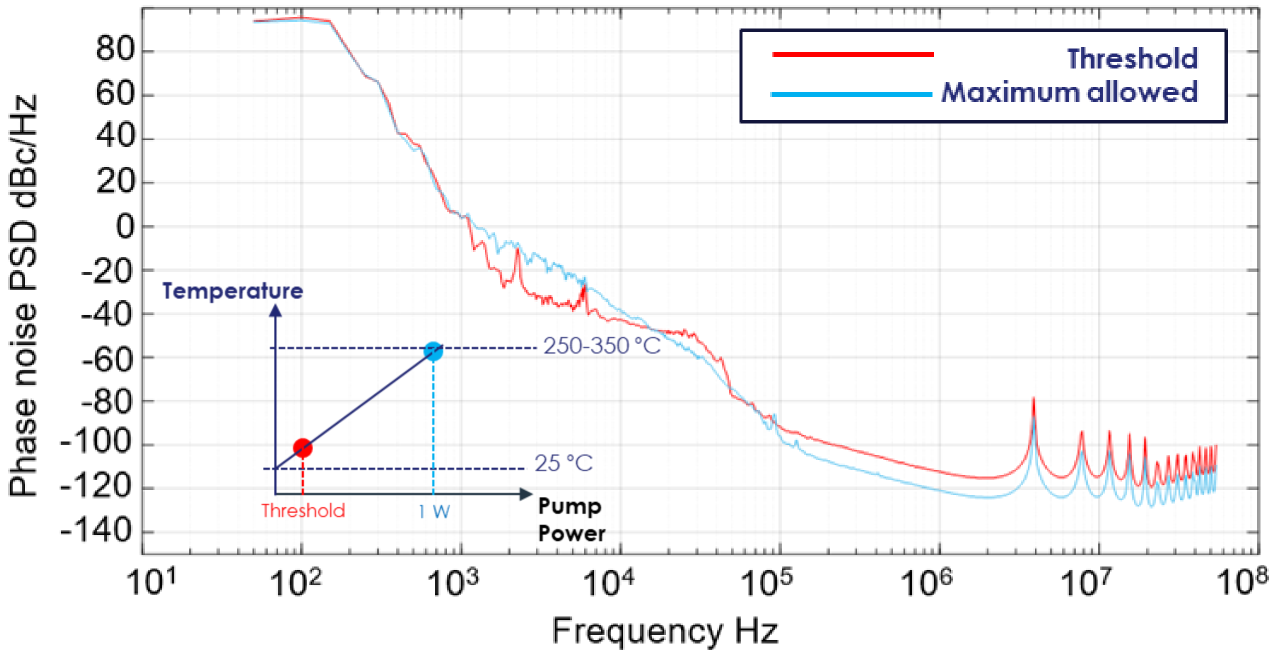
(I) How thermo-refractive noise and the thermal expansion effect impact into the phase noise behaviour of the Er:Yb:phosphate laser.

(II) How the thermal effect of pumping affects the phase noise



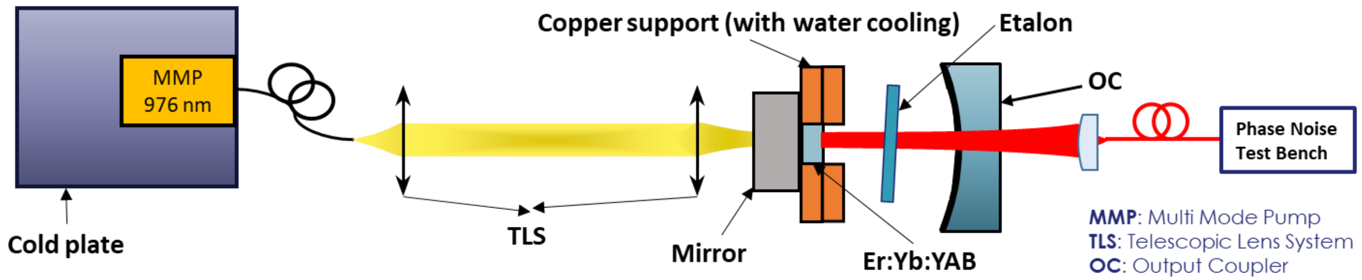
TEC: Thermoelectric cooler
M: Mirror
BE: Birrefrigent Etalon
HWP: Half-Wave plate

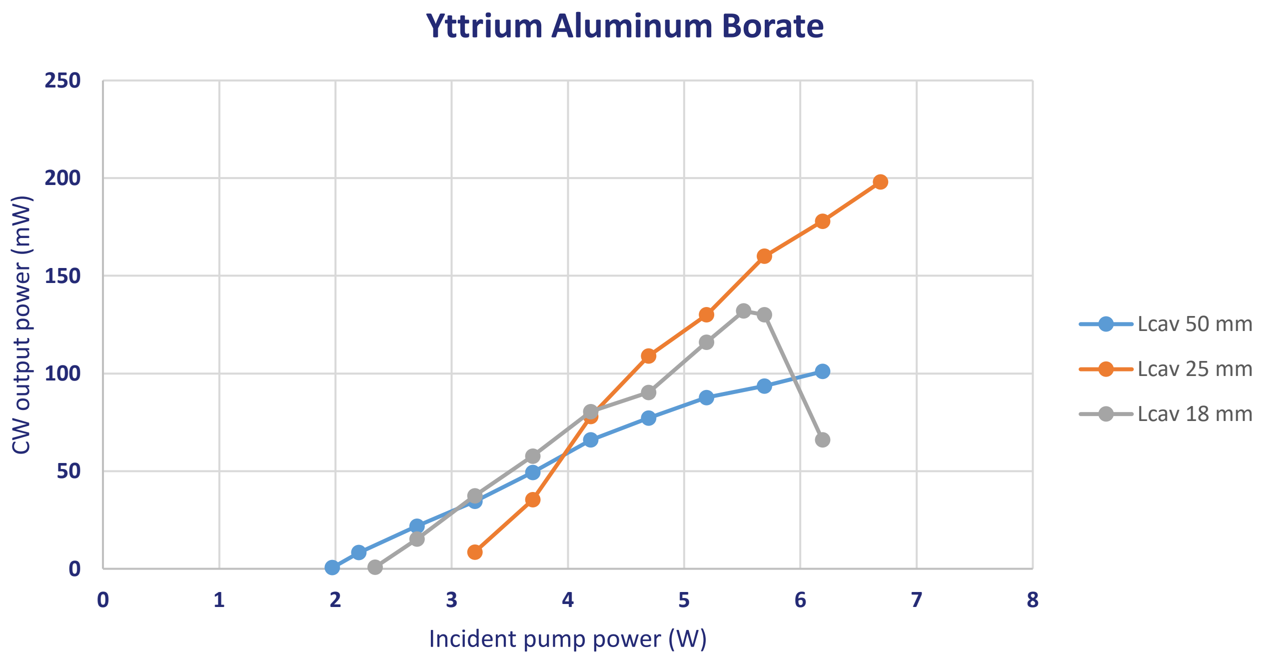


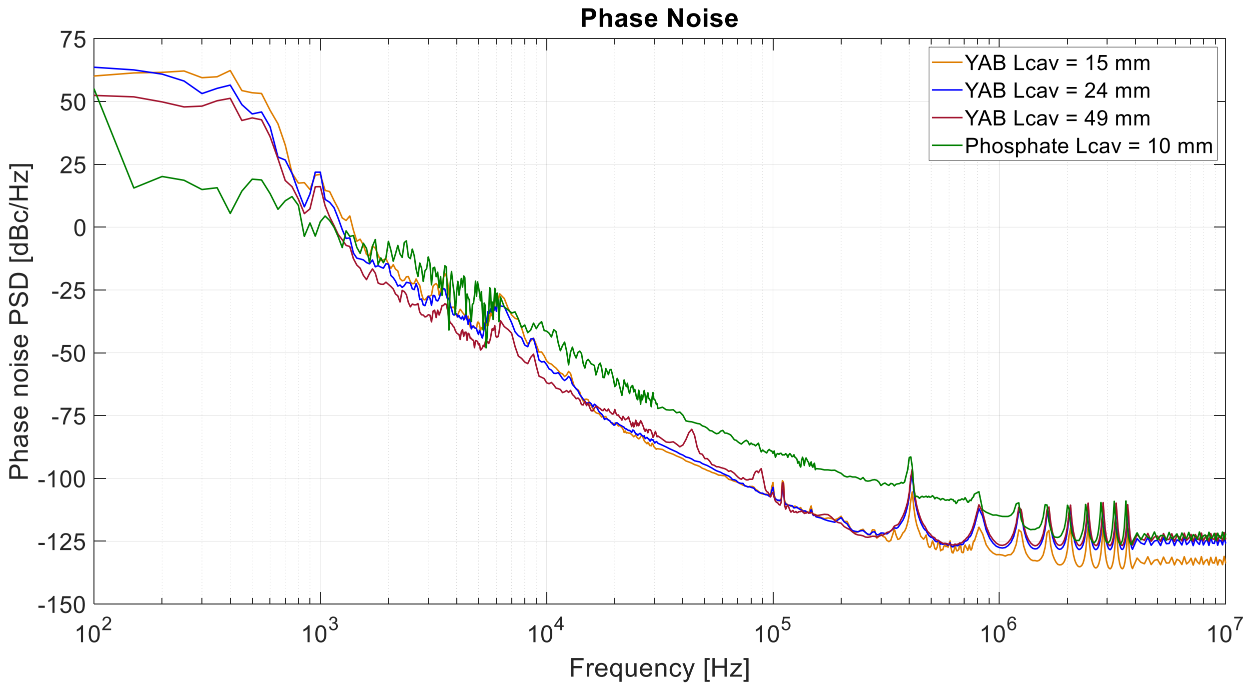


Laser cavity development part 2: New Er:Yb doped material

With this new doped material we were able to test a new Er:Yb laser performance thanks to its higher thermal conductivity, expecting a significant phase noise lever due to its better temperature distribution

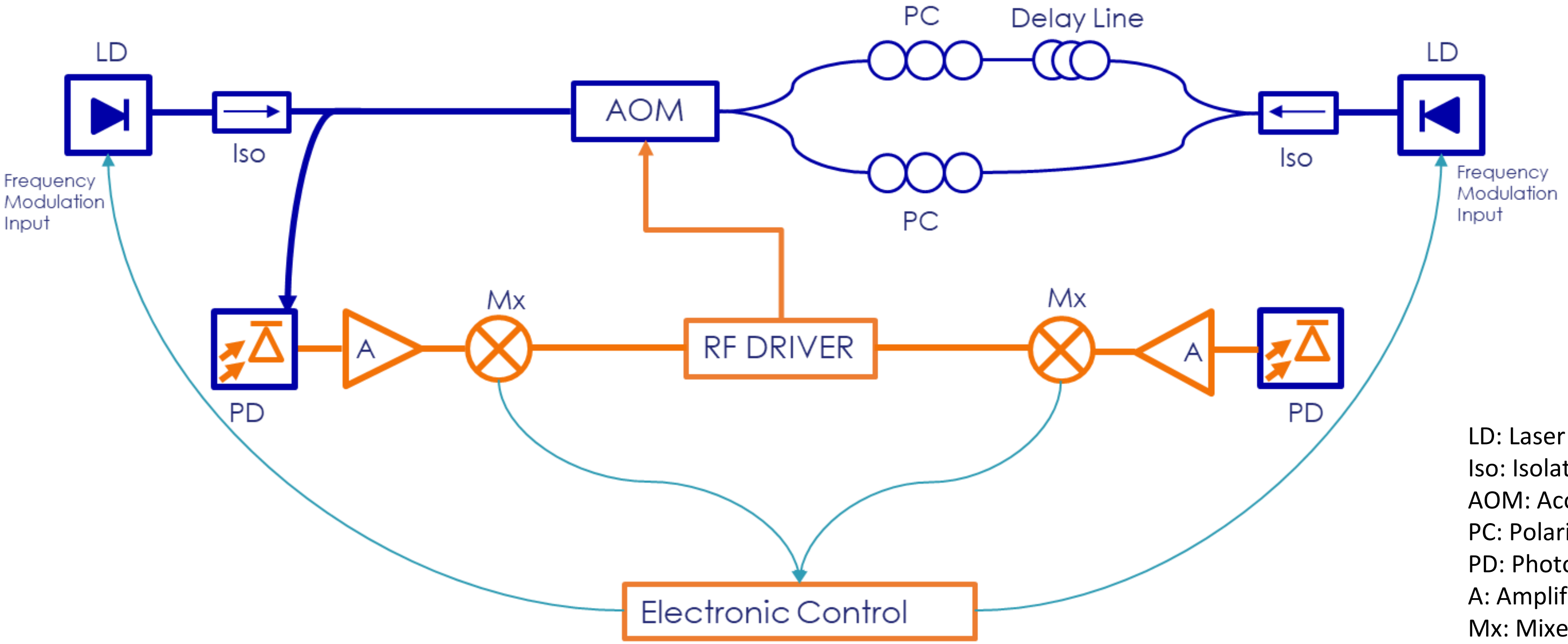






In parallel with laser cavity study, a stabilization arquitecture is being developed, using for that two different semi-conductor lasers that will be locked in frequency using next scheme:

Stabilization arquitecture

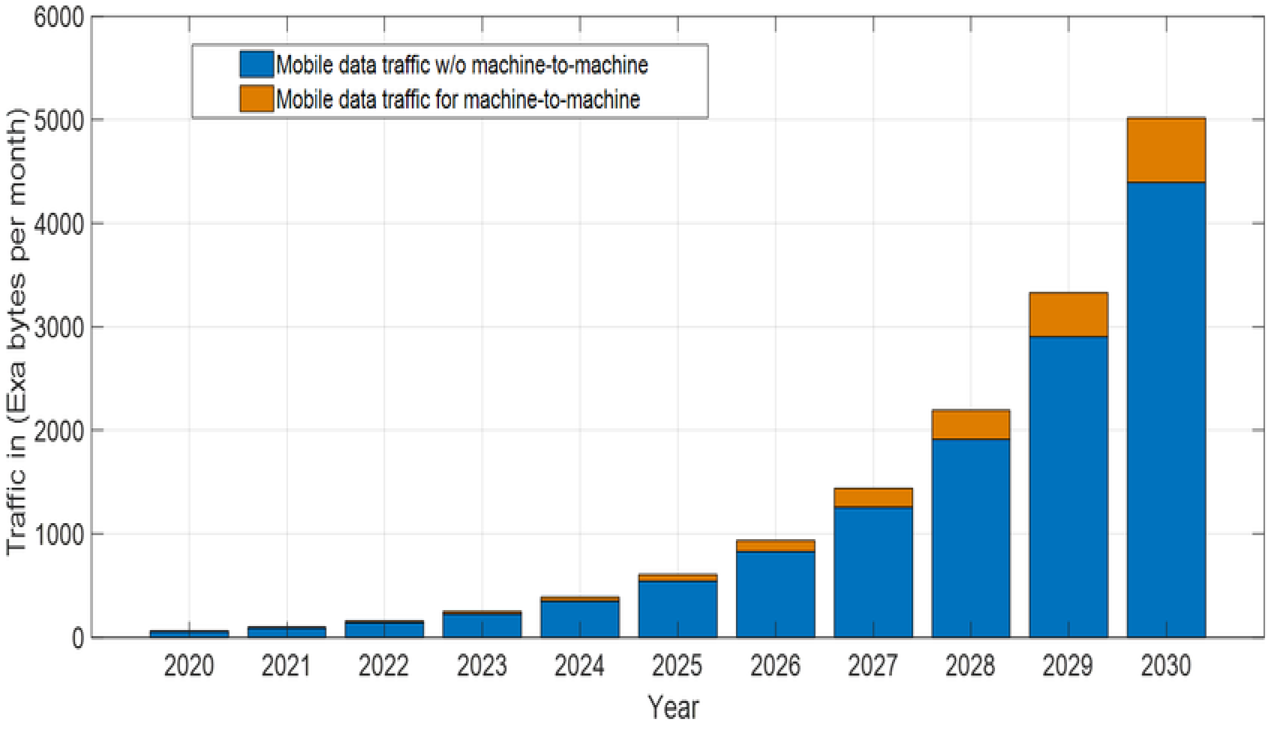


LD: Laser diode
Iso: Isolator
AOM: Acoustic-Optical Modulator
PC: Polarization Controller
PD: Photodiode
A: Amplifier
Mx: Mixer

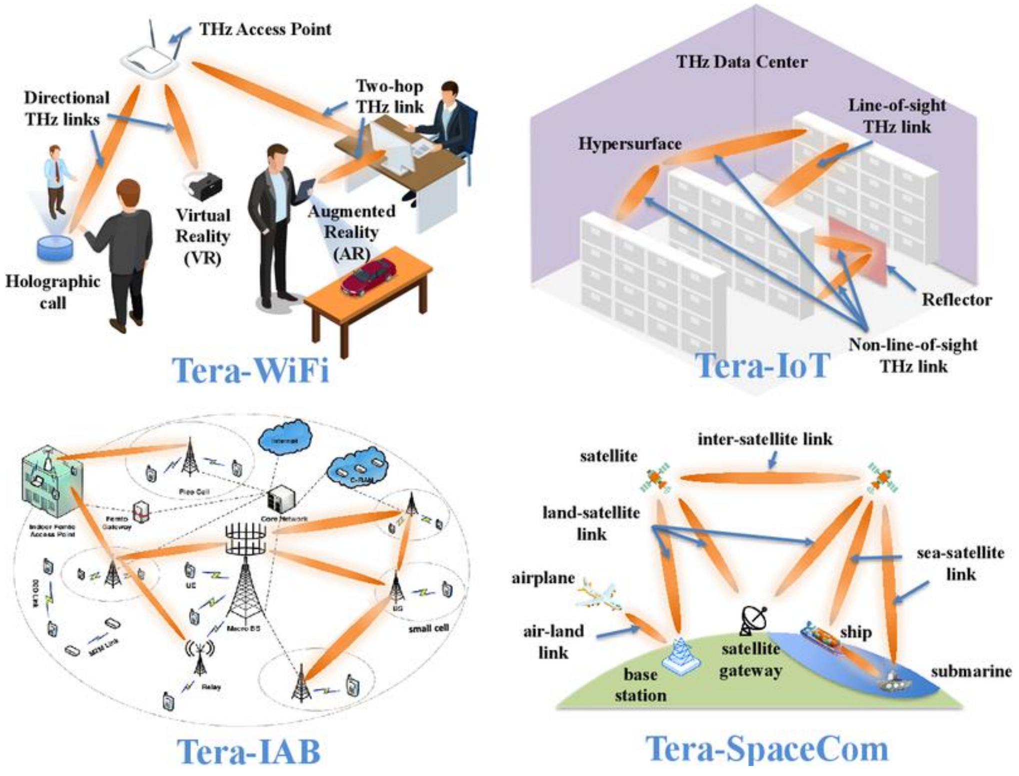
These lasers in development, are promising to be exploited in many practical applications such as high performance THz communications, high sensitivity THZ spectroscopy, but also in other fields of photonic sensing such as coherent lidars and fiber sensors, where the ultra-low optical phase noise and the dual-frequency operation will offer an improvement of performances and functionalities

Metasurfaces to improve antenna beam profiles at 300 GHz

Global mobile data traffic forecast for the period 2020 to 2030 [1]



Future of THz communications [2]



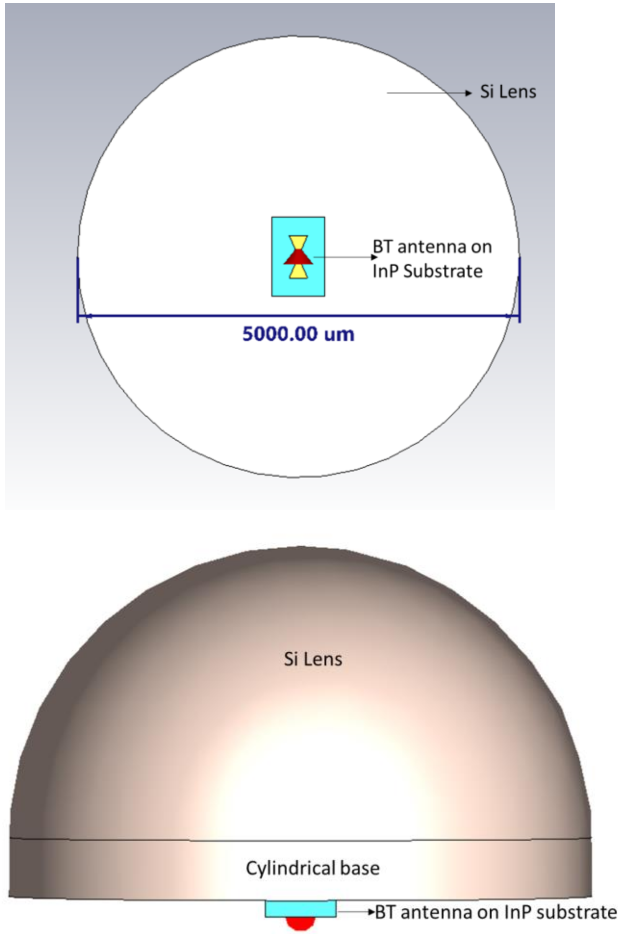
[1] Union, I. IMT traffic estimates for the years 2020 to 2030. Rep. ITU 2015,2370. Available online: https://www.itu.int/pub/R-REP-M.2370 (accessed on 20 January 2023).
[2] Chong Han, Yongzhi Wu, Zhi Chen, and Xudong Wang “Terahertz Communications (TeraCom): Challenges and Impact on 6G Wireless Systems“.

Challenges

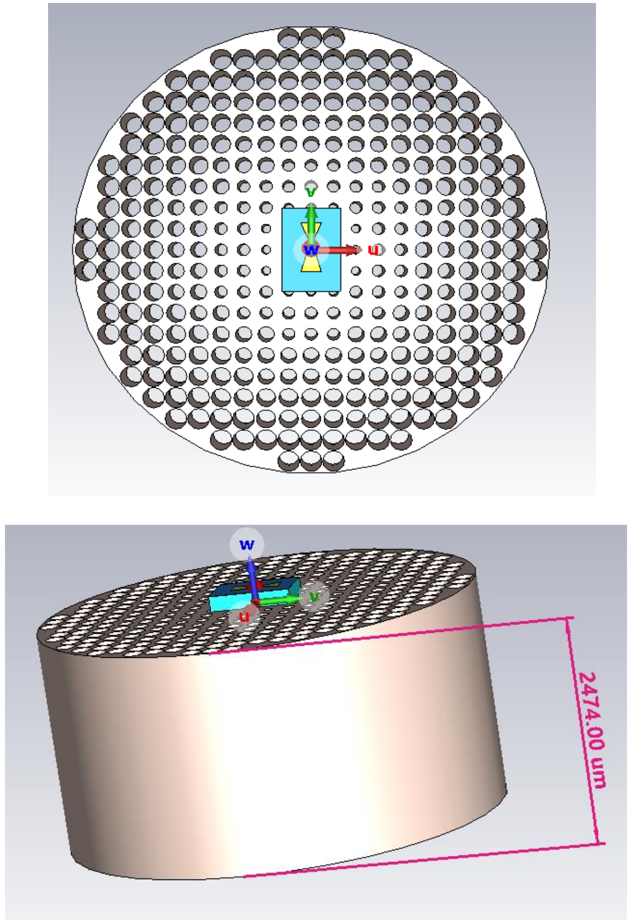
- Lower Bandwidth
- Low Antenna Gain
- Huge device size

Solutions

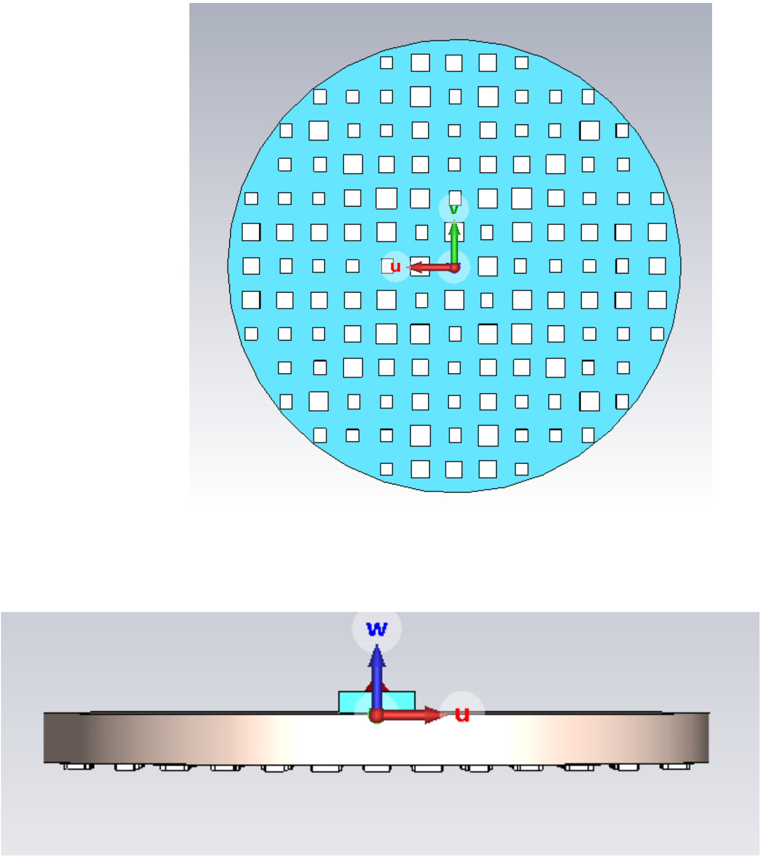
- THz Frequency band
- High Gain Lens
- Planar MTS Lens



Bowtie antenna integrated Silicon hemispherical lens



Bowtie antenna integrated Perforated Silicon lens



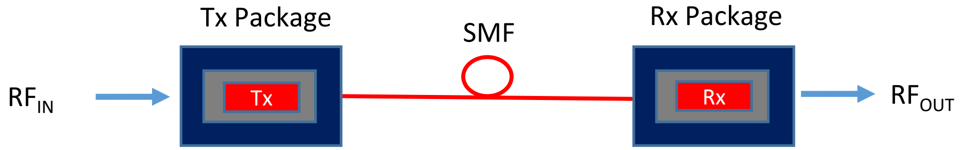
Bowtie antenna integrated Metalens

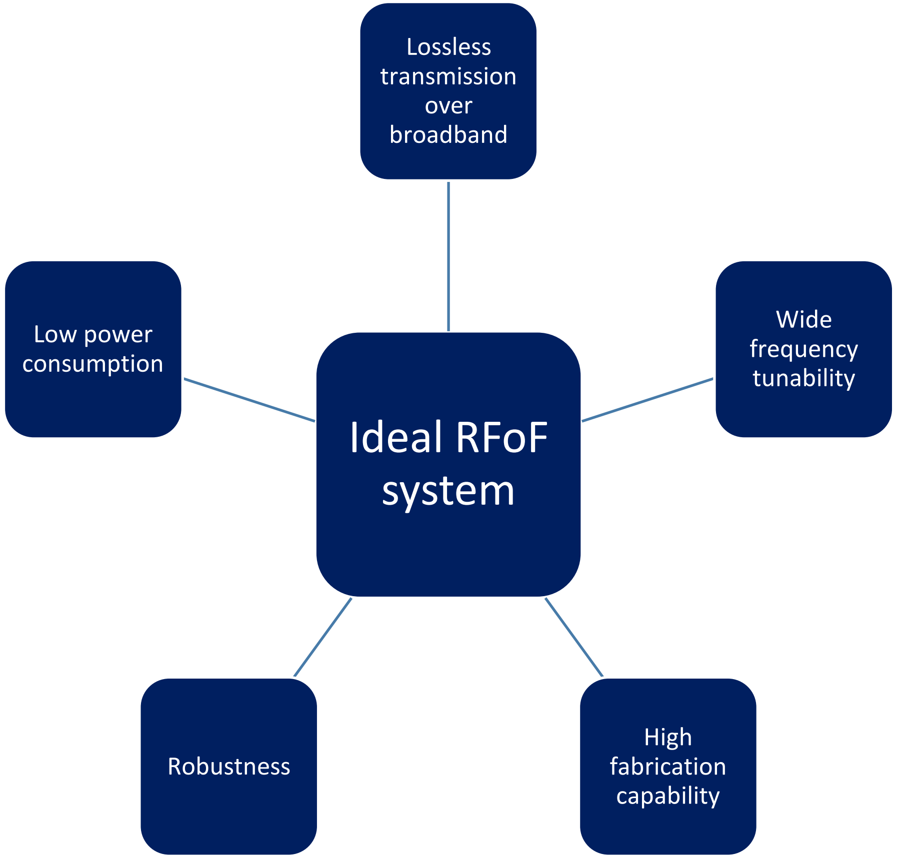
Project Highlights – ESR 14

Low Power Consumption and Low Phase Noise Broadband RFoF Links

Objective: Developing new optical methods for low-phase noise reference signal generation and its fiber-optic transmission to remote sites.

- Developing such a system is crucial for various applications covering space applications, test & measurement, and communications.
- An RFoF system incorporating novel transmitter and receiver modules has been implemented. The system features low power consumption and low phase noise over a broadband.





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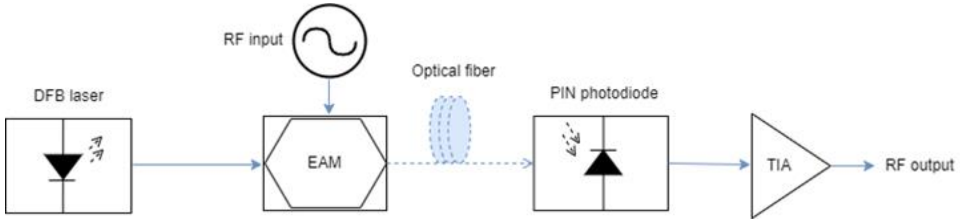
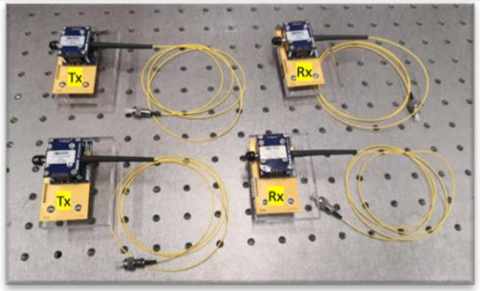
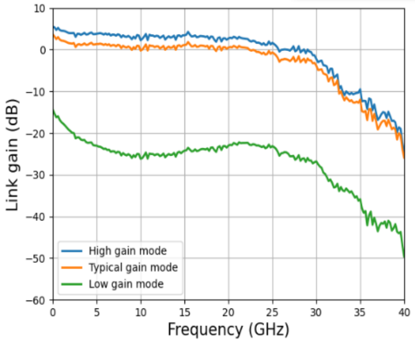
Project Highlights – ESR 14

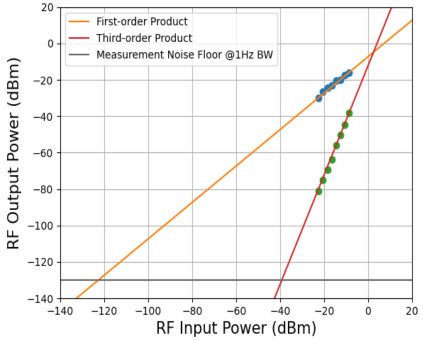


- Transmitter module using a 1.31 µm uncooled electro-absorptive modulated laser (EML) and a receiver module using a high-frequency 1.31 µm photoreceiver (PR).
- The EML benefits from a large bandwidth, low driving requirements and compact size.
- The utilized EML offers uncooled operation in the operating temperature range of 20°C to 70°C, meaning the elimination of the thermo-electric cooler (TEC). Therefore, the power consumption of the system is reduced remarkably, and a power consumption of less than 1 W has been achieved for the whole RFoF system.
- The receiver module comprises a 1.31 µm PIN photodiode and a gain-controllable transimpedence amplifier (TIA).

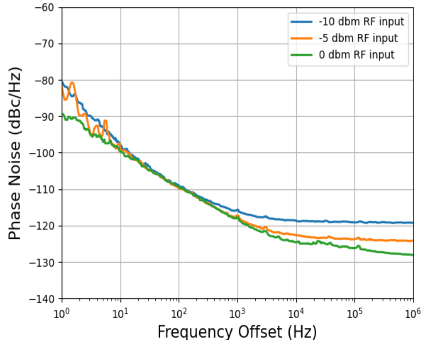




Link gain > 0dB up to 30 GHz



SFDR ≈ 90 dBc @30 GHz



Phase noise ≈ -120 dBc/Hz >10 kHz

Project Title: Towards smart THz integration leveraging silicon passive functions

Main Goal:

Develop Novel techniques for THz-integrated components and Devices utilizing topological Photonics.

1. We expanded the frequency range of our design beyond the commonly used 300 GHz threshold within the terahertz community's familiar territory.
2. We use ideas from *Topological photonics* for our device designs.
3. Our Perspective scaling of Topological protection to tune the functionality of Passive devices.

ESR 4
Abdu Subahan Mohammed
ULIL

THz group IEMN ULIL

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This project has received funding from the European Union's Horizon 2020 and the research and innovation programme under the Marie skłodowska-Curie grant agreement No 956857

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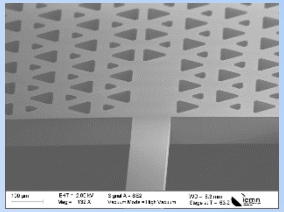
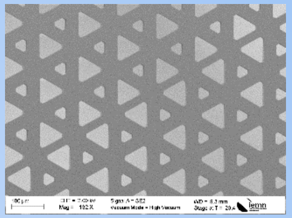
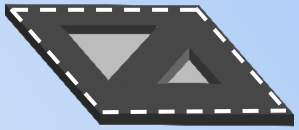
Our Designs and Outcomes

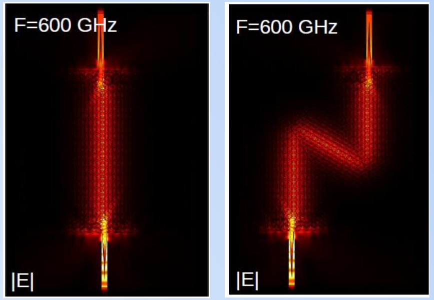
THz topological Waveguides





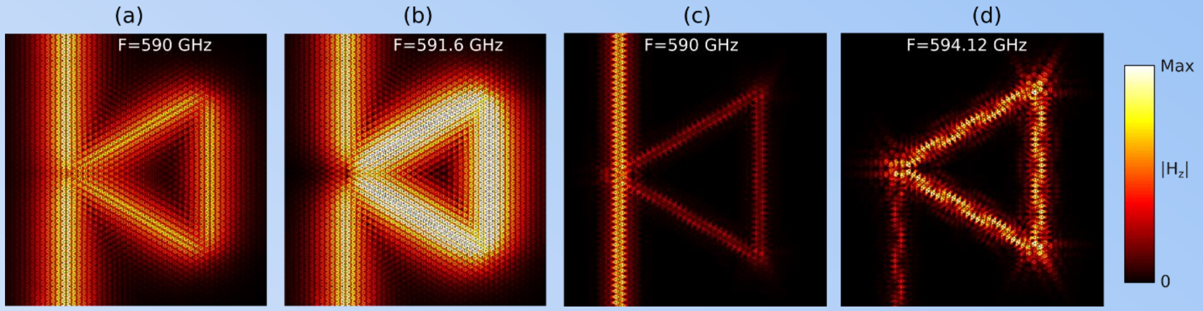


Design of THz topological Straight and bent waveguides at 600 GHz



The Electric field in the Valley photonic crystals designed.

THz topological Resonators



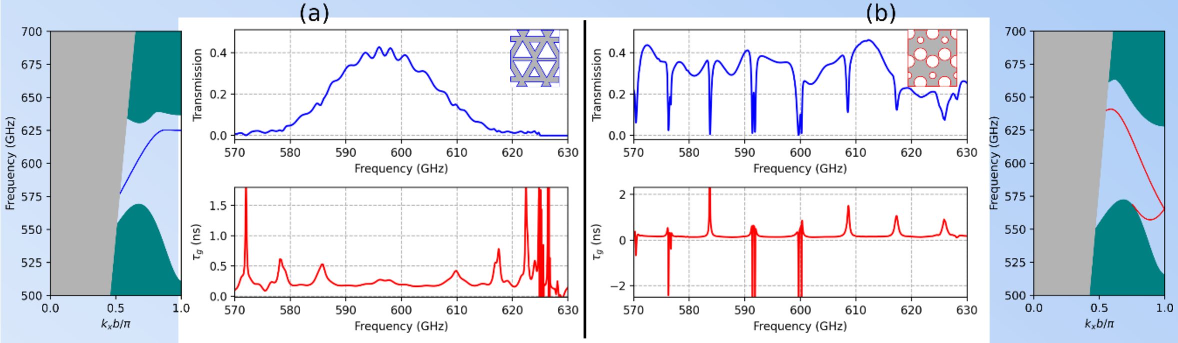


Fig. : Electric field Simulation and Band diagrams, transmission spectra (top) and group delay (bottom) computed through the full 3D membranal devices with single-cavity resonators, for circular holes and zig-zag interface (a), and triangular holes and bearded interface (b). In each case, the band diagram of the interface is plotted, with the light cone in grey and lattice bulk modes in green.

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