UCL Electronic and Electrical Engineering
Photonics Group

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Applications des technologies photoniques pour l'accès aux domaines de fréquence THz

Cyril C. Renaud

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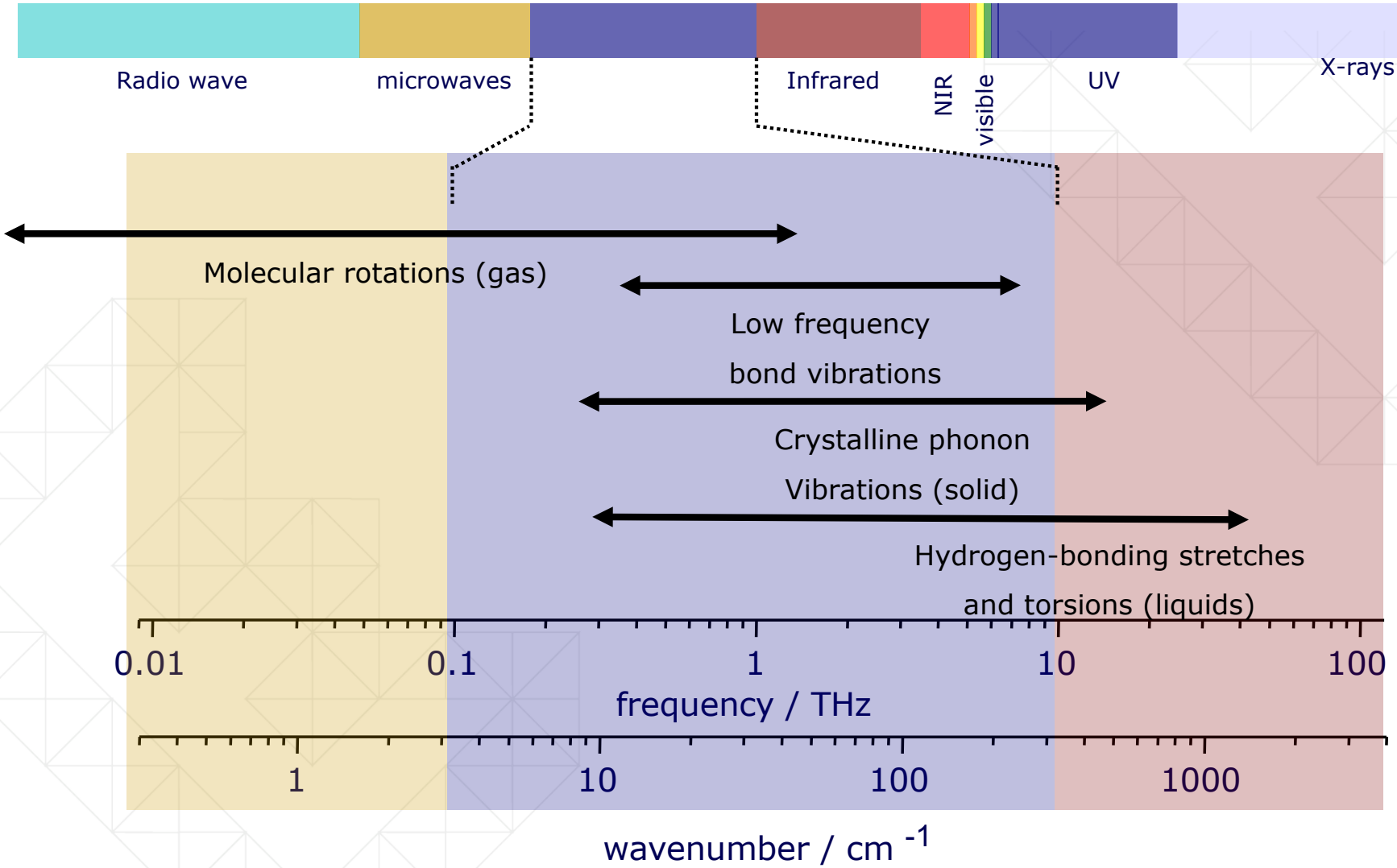
Terahertz : Spectral Region



$0.06 - 10$ THz or $2 - 300$ cm^{-1}

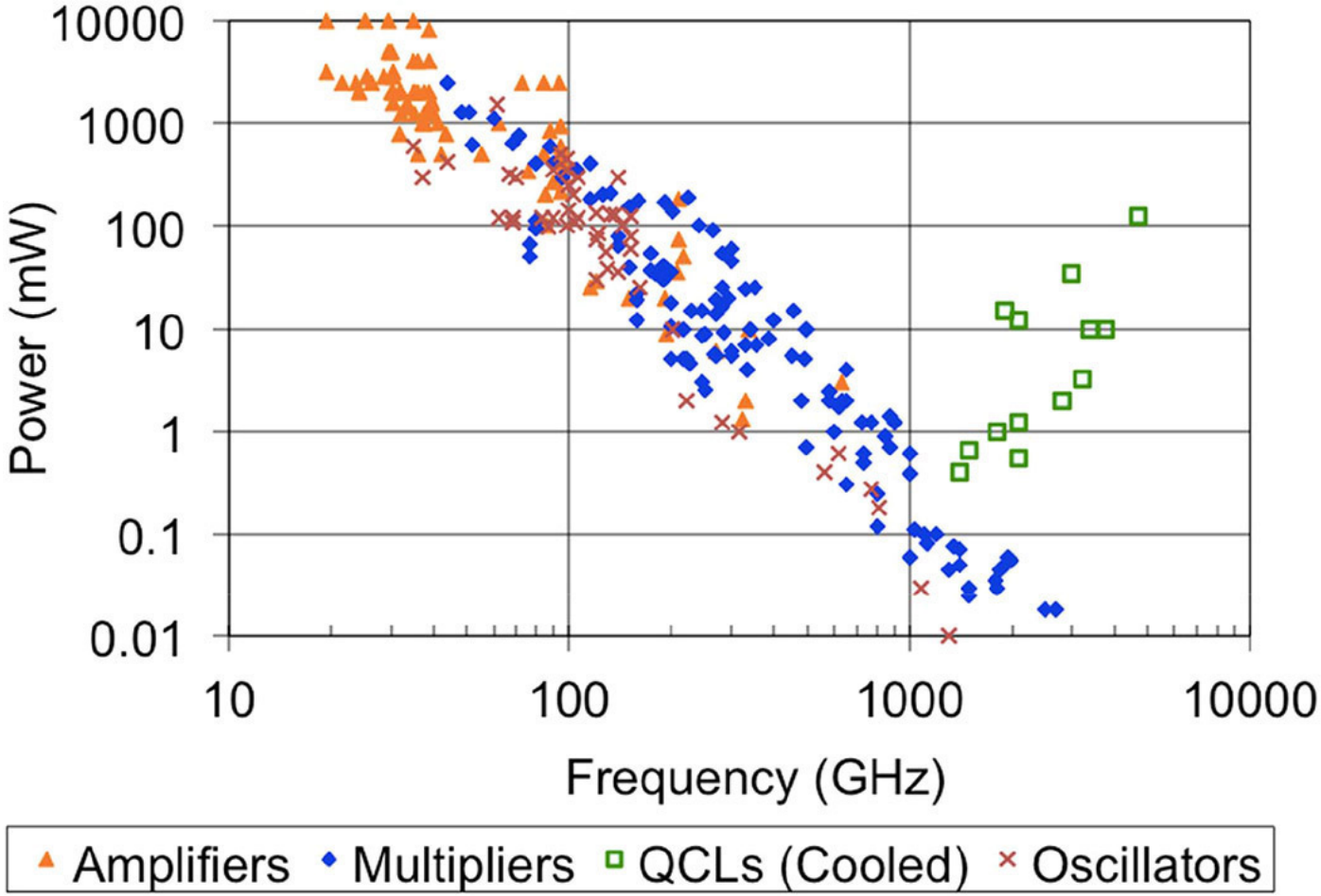
Why use the terahertz region?

- Non-invasive and non-destructive
- Rich in unique process information
- Real-time measurement
- Intrinsically “safe”
- Applicable to a wide range of processes
- Material Transparency

THz for applications (examples)

Imaging of skin tumours, teeth	Imaging of defects in pills, processors…	Security imaging	
Spectroscopy sensing for explosive and drugs	Atmosphere monitoring	Automotive paint quality	Artwork conservation and monitoring
High data rate wireless communication			

THz Sources



- Other sources include:
  - Synchrotron
  - Vacuum electronic (Gyro Devices multiple Watt output)
  - Intense laser based source

SS Dhillon, et al. “The 2017 terahertz science and technology roadmap,” [invited] Journal of Physics D: Applied Physics, vol.50, no. 4, pp 043001, 2017

Outline

- Typical photonic THz systems
- THz system photonic components
  - Emitters
  - Receivers
- Integration technologies
  - Hybrid vs monolithic
  - InP platform technology
  - Silicon platform technology
  - Photonics subsystems
  - An example of Electronic THz components
- Example of application: THz Communication
- Conclusion

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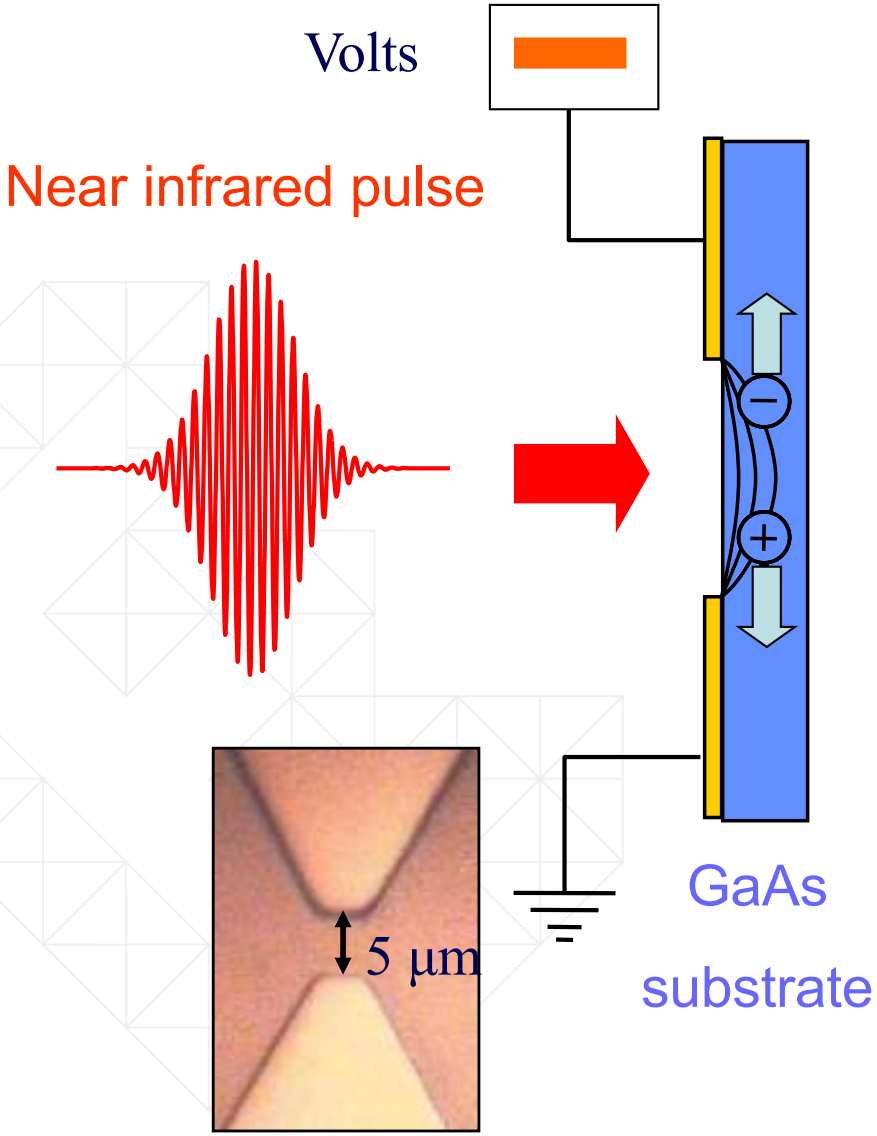
Typical Photonic THz Systems

Transmitter → THZ → Receiver

- Mode locked laser and photoconductive antenna
- Two lasers and a photomixer
- Might include:
  - Phase or amplitude modulation
  - Amplification

- Mode locked laser and photoconductive antenna
- Schottky diode based mixer or envelop detector
- Photonically pumped mixer?
- Might include amplification

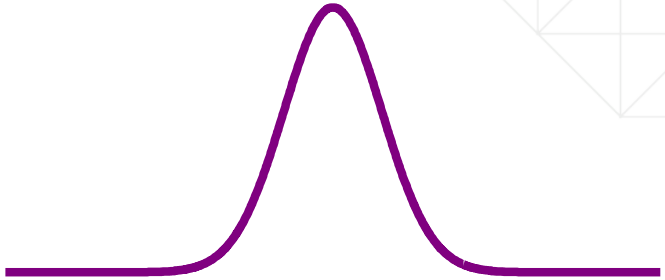
Photoconductive Generation of THz



Coherent Emission

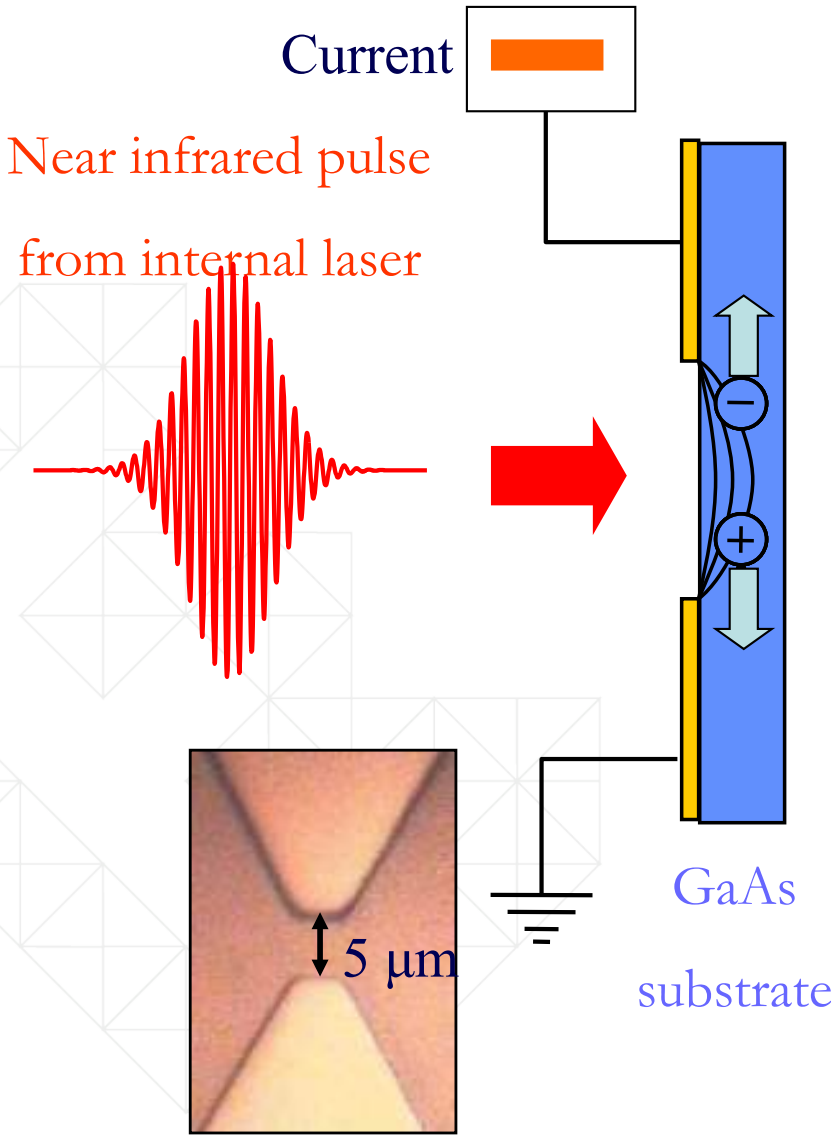
< 300 fs THz pulse <

40GHz – 4THz



THz pulse due to transient screening of bias filed by photo-injected charge

Photoconductive Detection of THz



Coherent Detection

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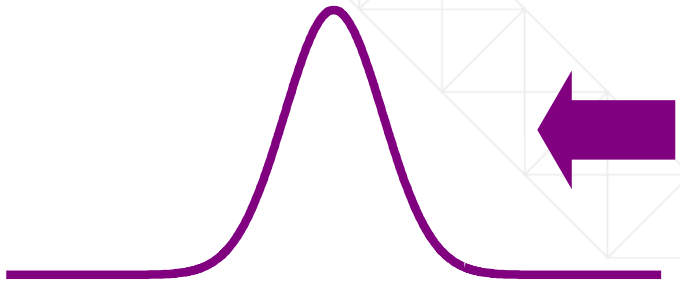
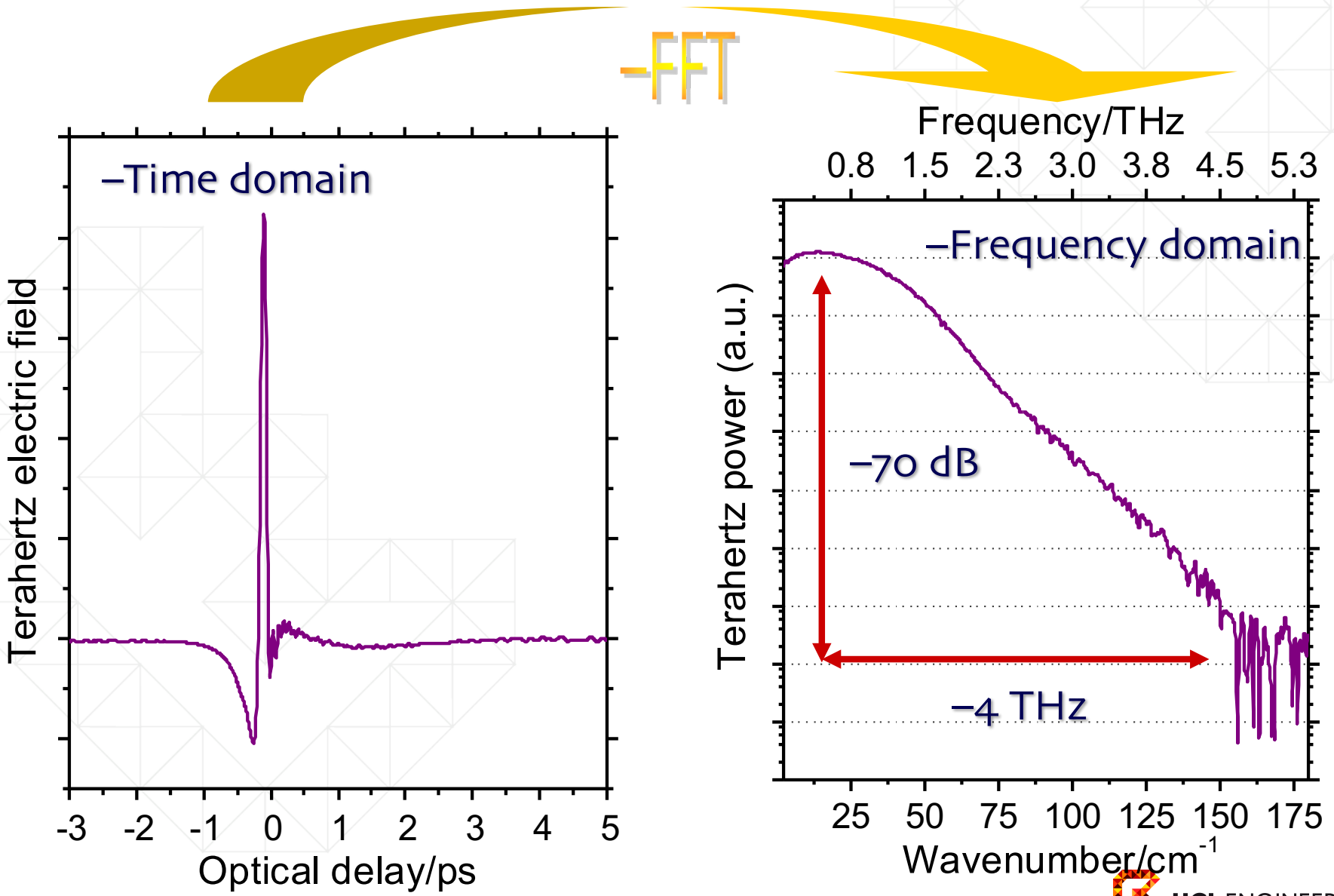


- THz pulse induces current by rectifying photogenerated (near Infrared) carriers, measure resulting current with ammeter – proportional amplitude & phase of THz wave
- Very low noise due to coherent, time gated detection



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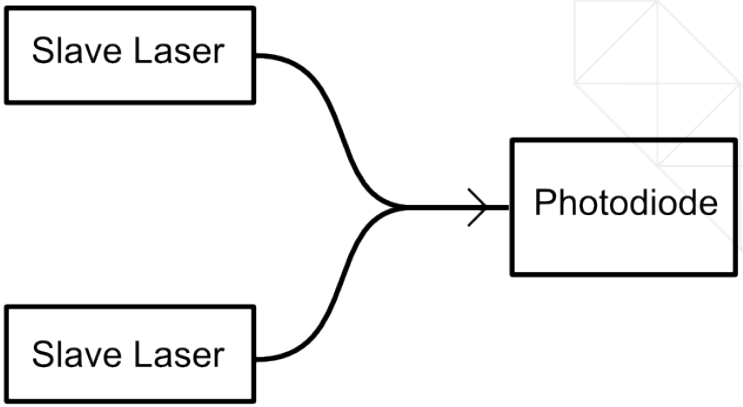
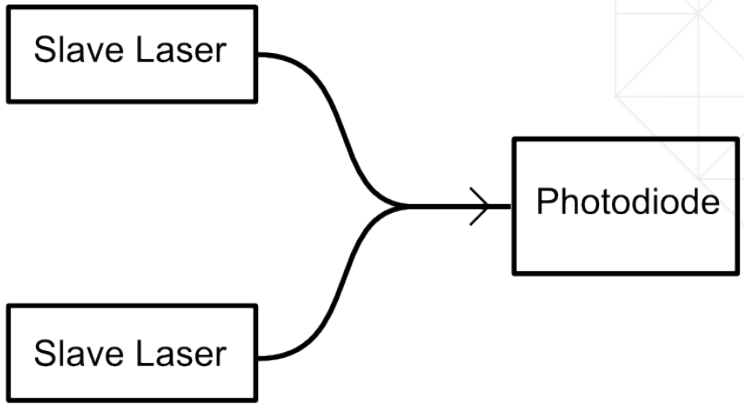
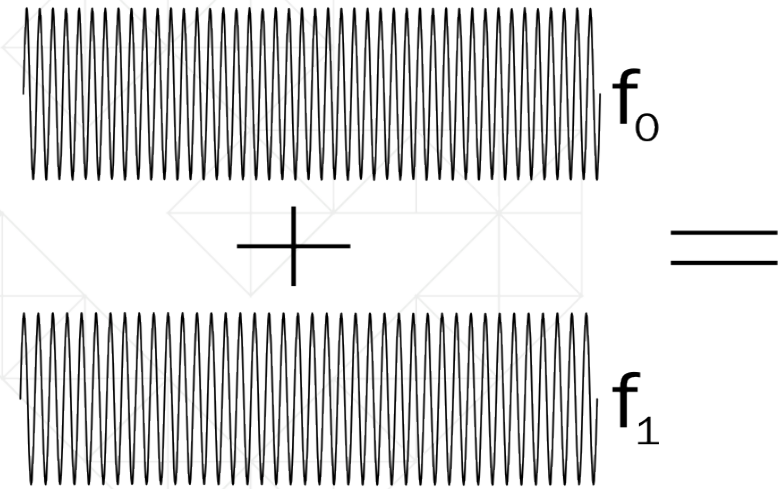
Photonic Synthesis



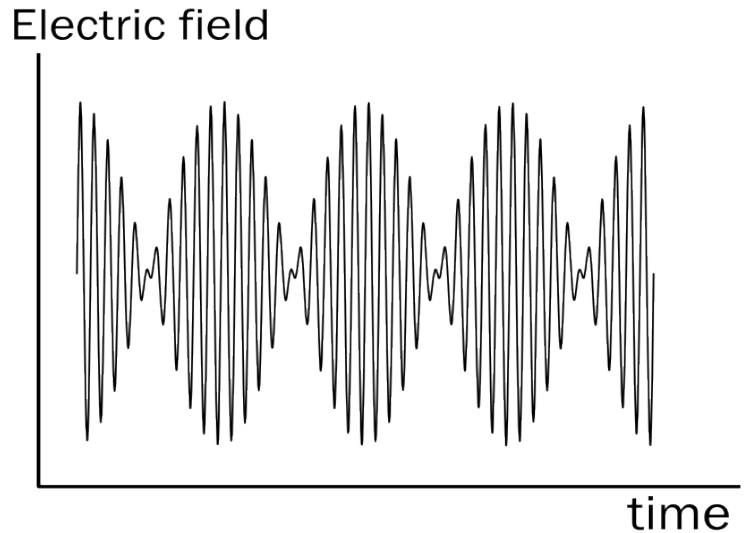
Photonic Synthesis



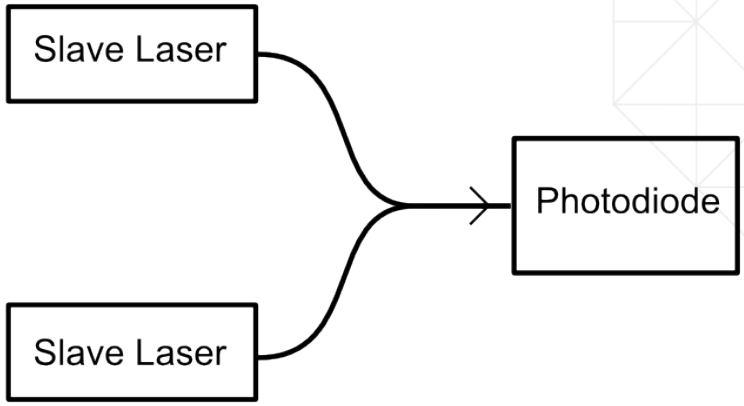
2 laser fields

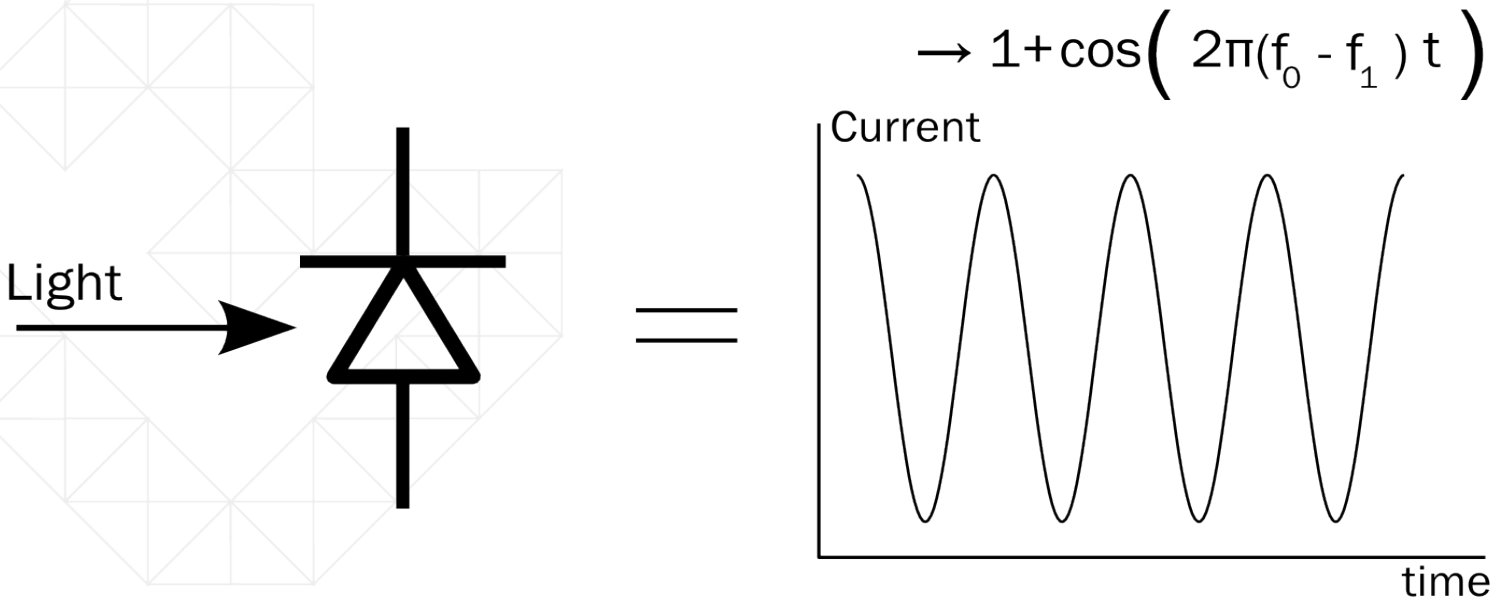


→ Beating at $(f_0-f_1)/2$



Photonic Synthesis





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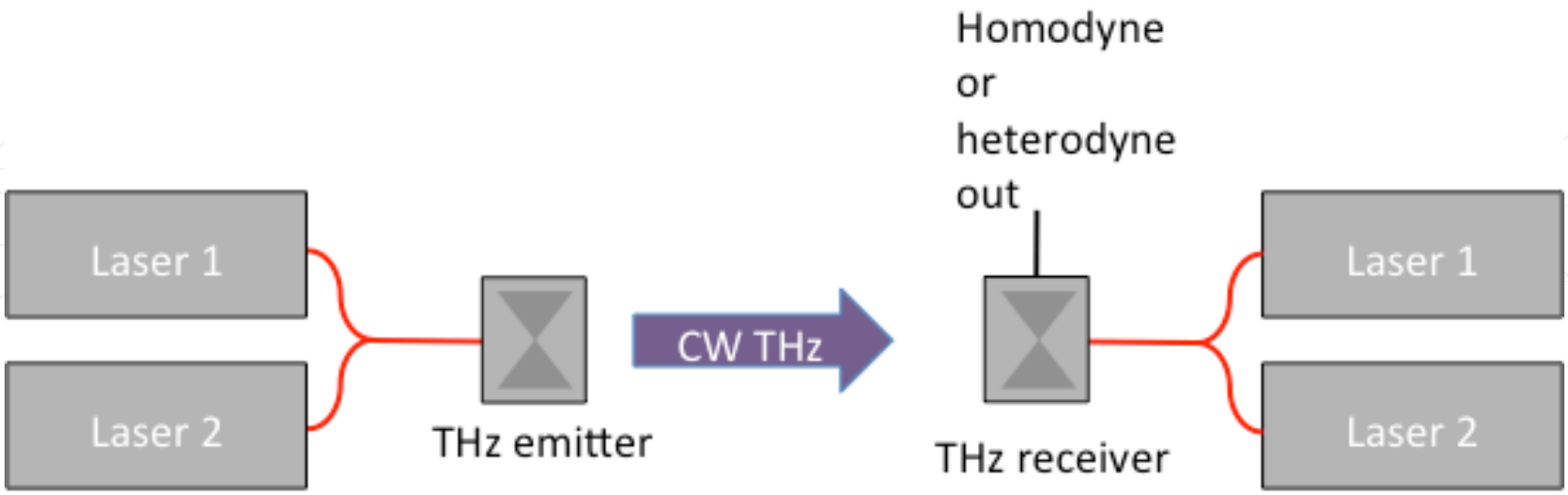
Typical CW system



Could be replaced by electronically driven Schottky receiver

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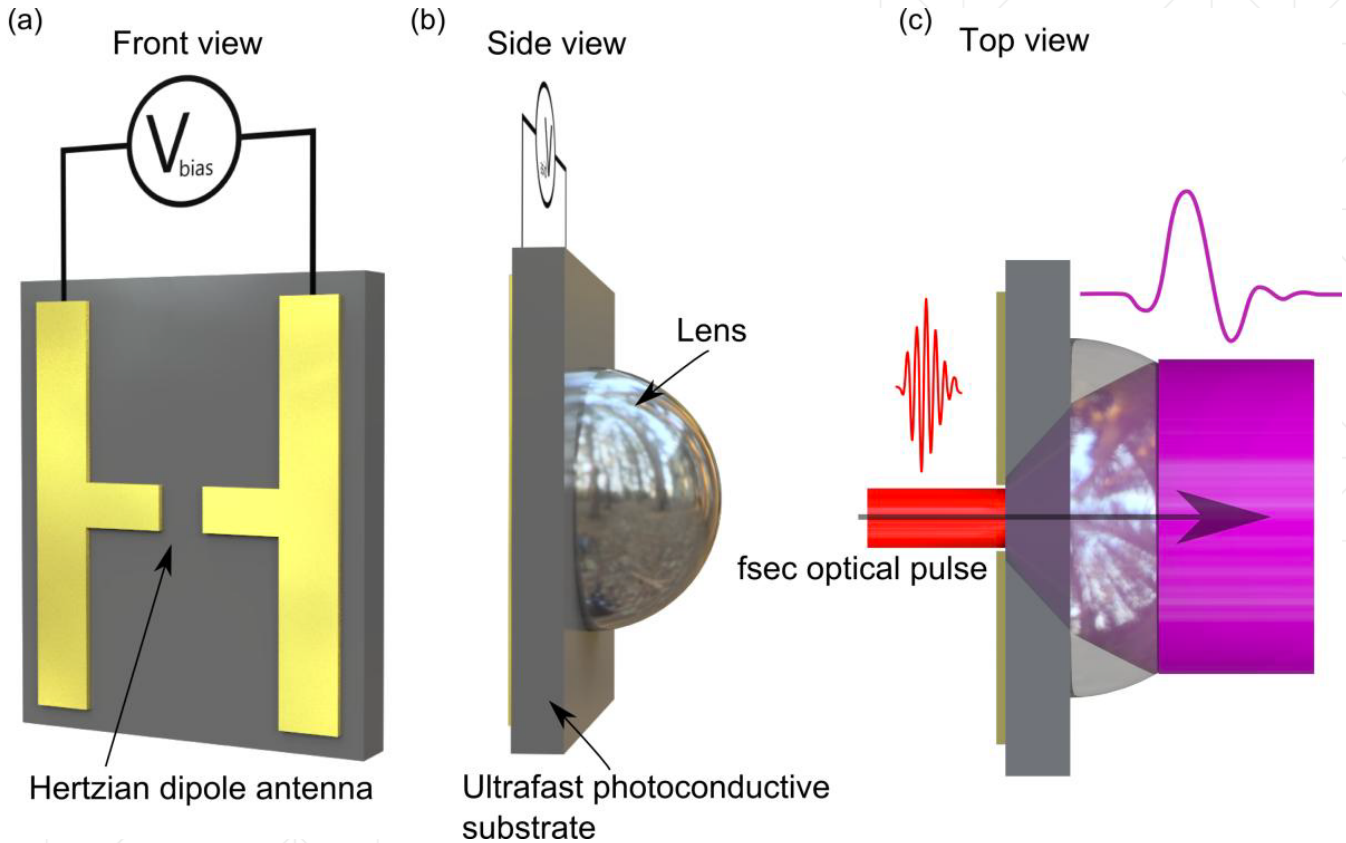
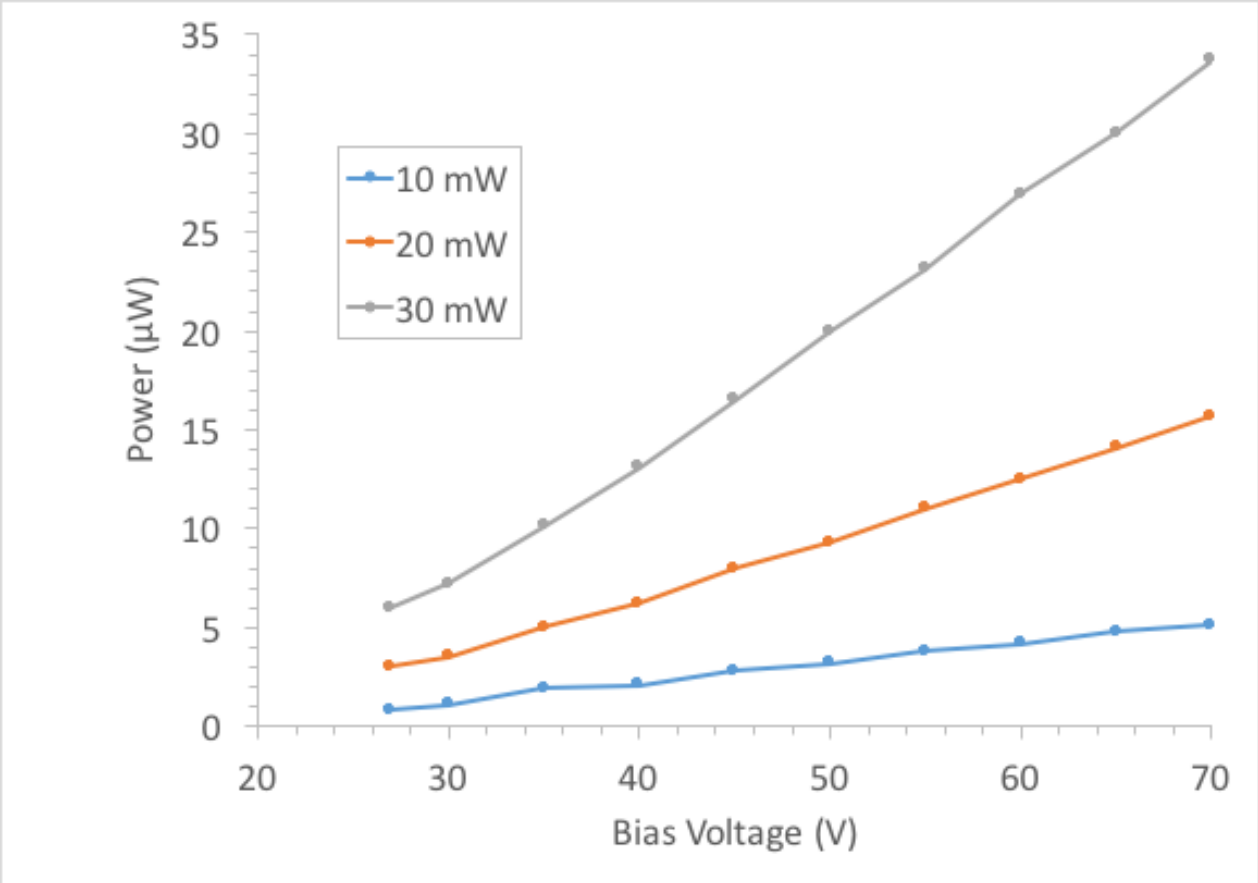
LT-GaAs Photoconductive antenna



- Could be used pulsed or CW as emitter or detector
- Semiconductor base so good candidate for integration
- Good detection sensitivity and emission power

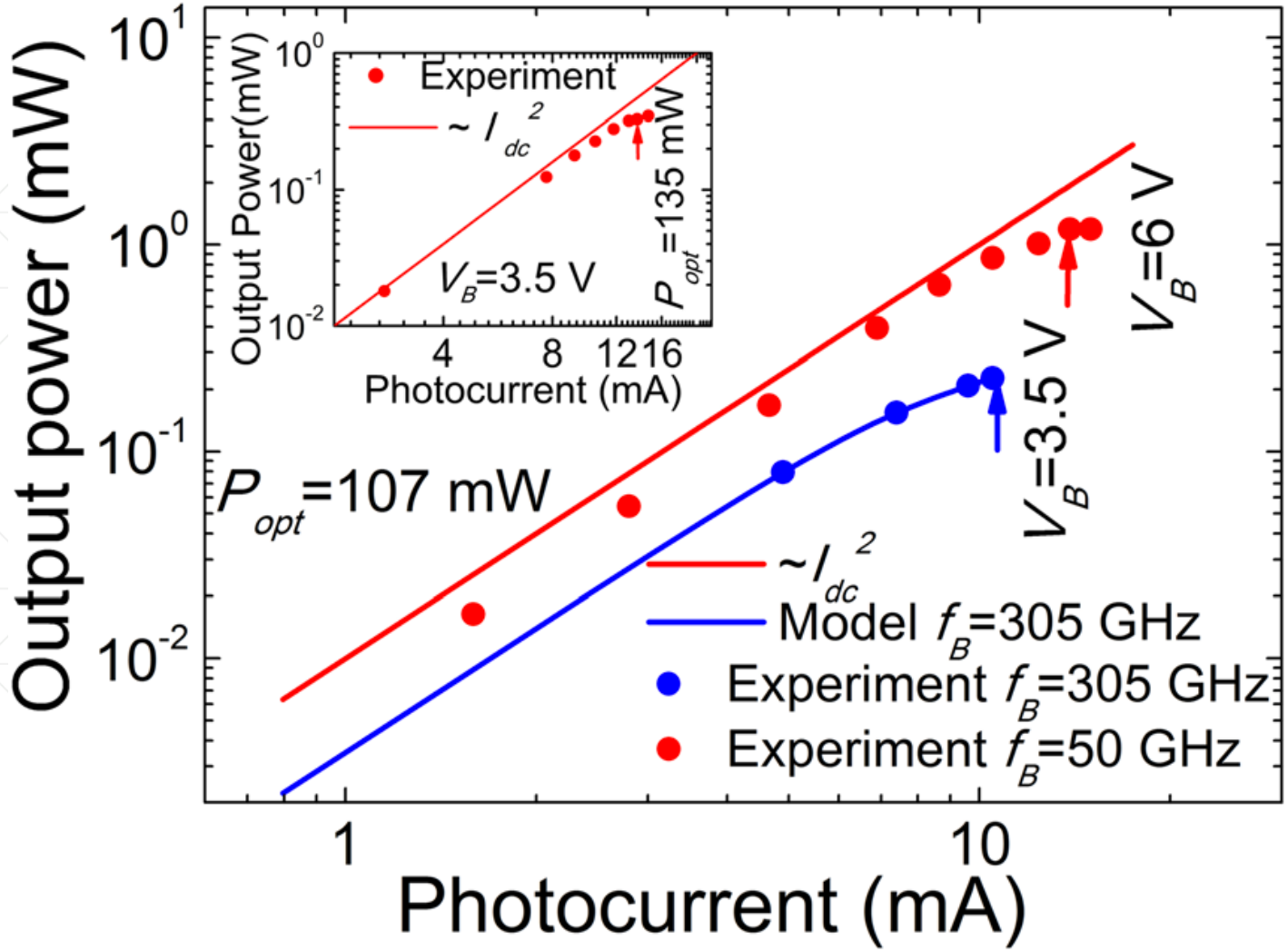
Typical power form photoconductive Switch

- Useful emitter for THz in pulse system
- Power of several μW at low optical excitation
- Good photoconductive detector
- GaAs offer good potential for integration



Photomixing in LT-GaAs

- Photomixing in LT-GaAs as also shown excellent results with power at 300 GHz of the order of 300 µW (University of Lilles)



E. Peytavit et al.

2013 38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)

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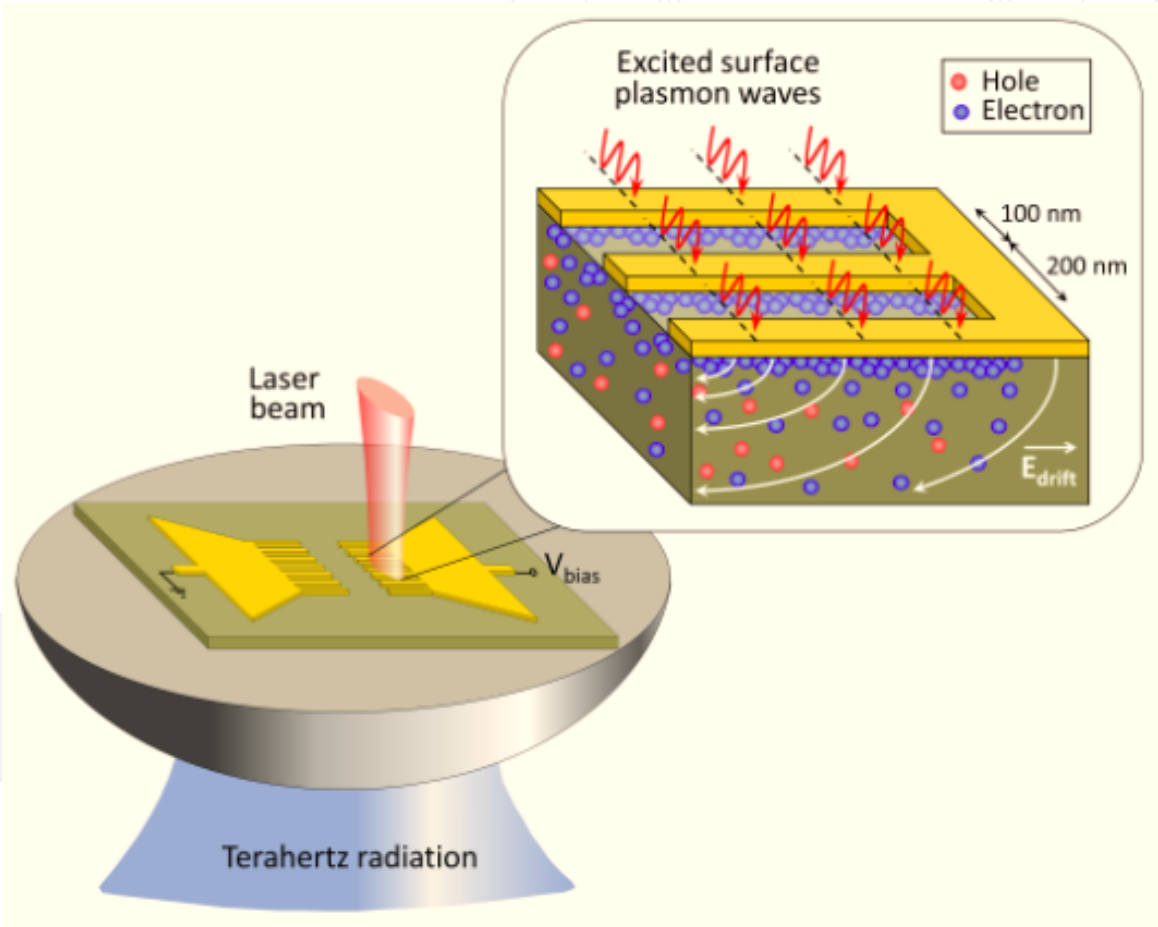
Plasmonic coupling for enhanced devices

- Enhanced performance in photoconductive antennae
- Enhanced number of carriers on a nanoscale layer (shorter transit time)
- 50 times more power emitted (UCLA)



C. W. Berry, N. Wang, M. R. Hashemi, M. Unlu, M. Jarrahi, "Significant Performance Enhancement in Photoconductive Terahertz Optoelectronics by Incorporating Plasmonic Contact Electrodes", *Nature Communications*, 4, 1622, 2013

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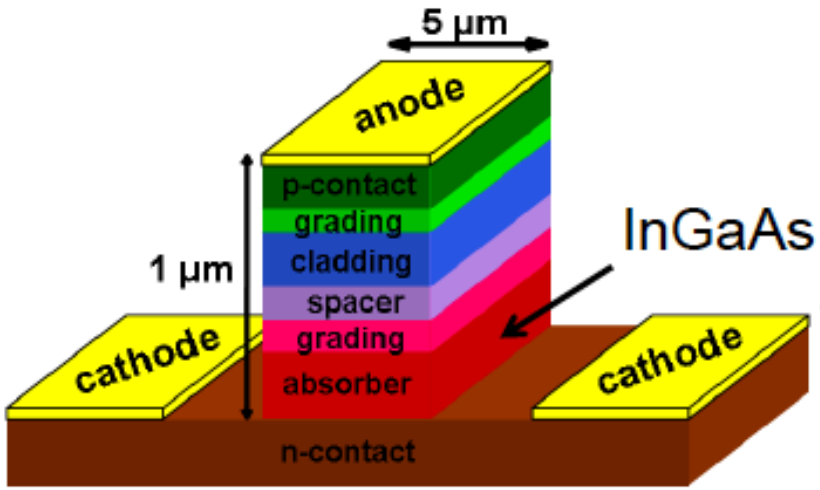
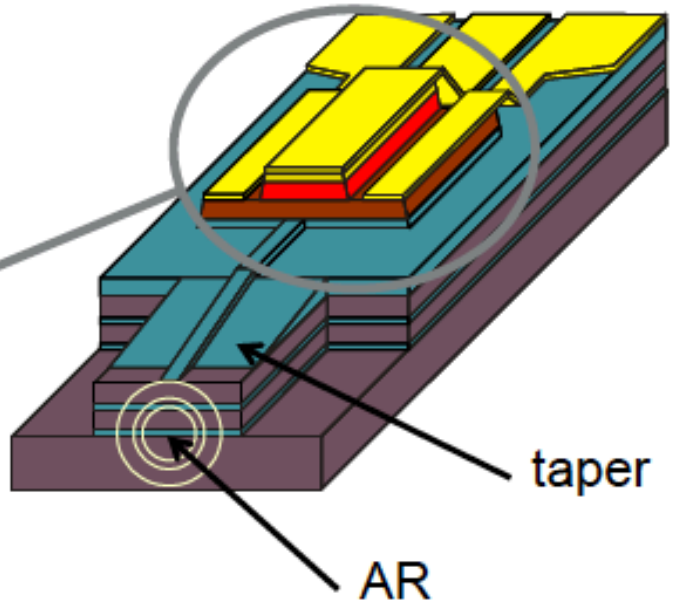
Photodetectors for photomixing

- Typical telecom photodiode could be used as photomixers

- Typical waveguide configuration as in Finisar high speed photodiodes could be used

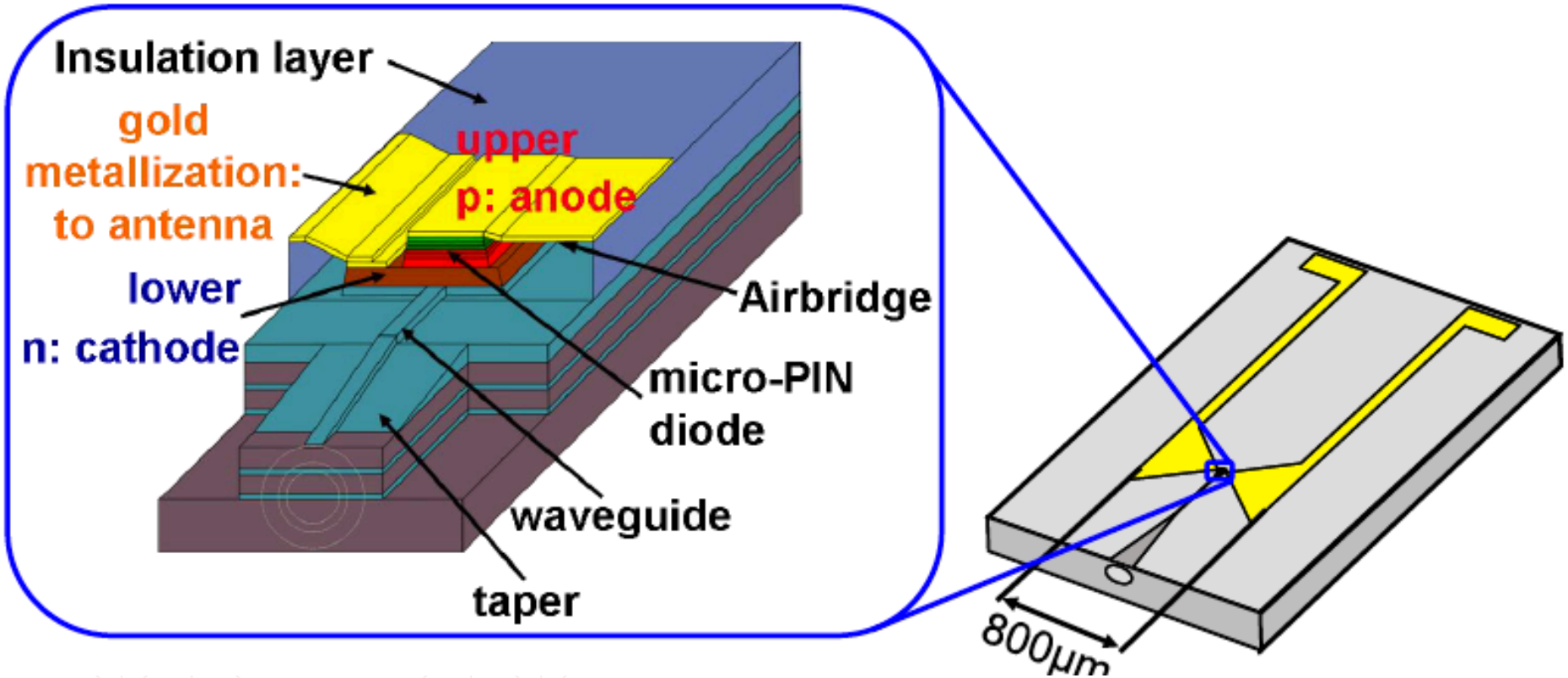


MOVPE growth on
semi-insulating InP-substrate

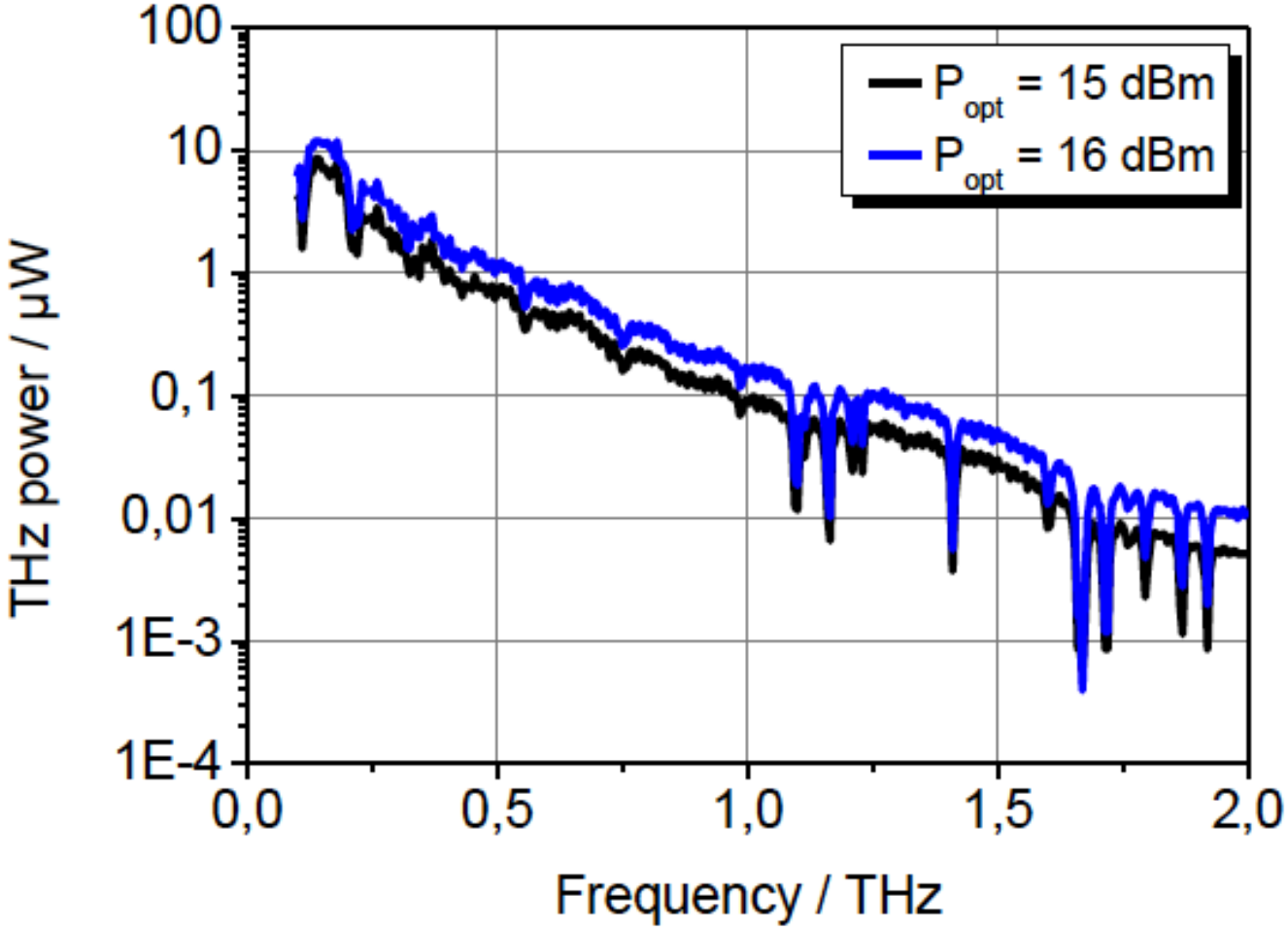


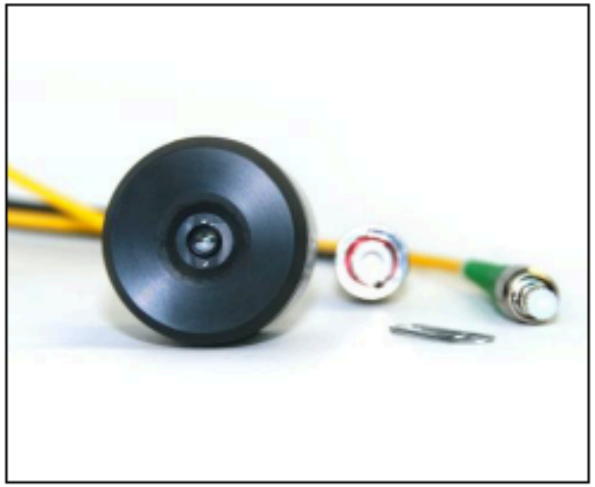
From photodiode to THz emitter

- Inserting the photodiode with a broadband or resonant antenna will make it a THz emitter



Typical output power (Toptica)





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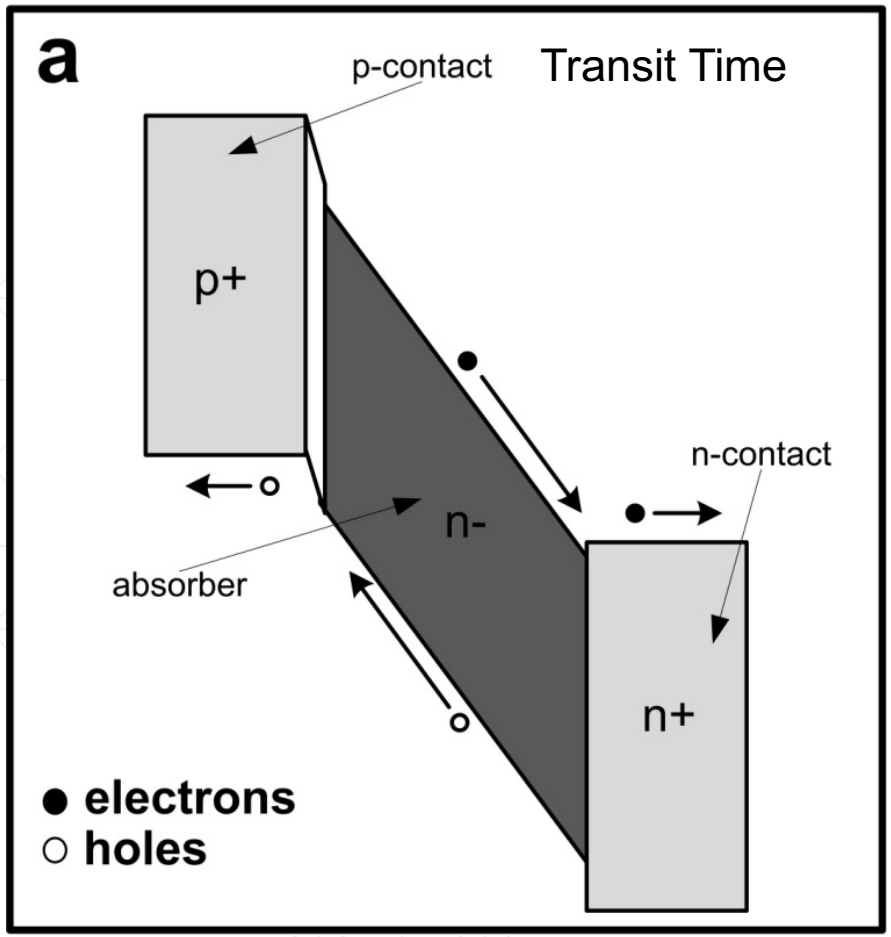
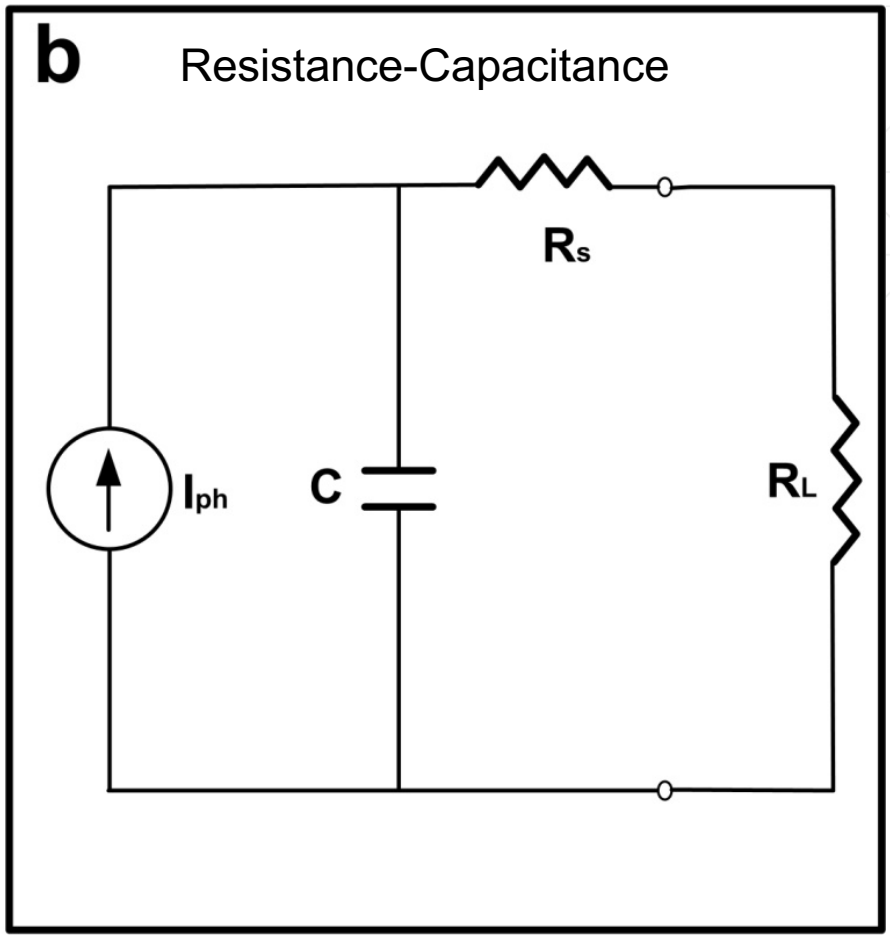
Frequency Limitations in p-i-n PDs

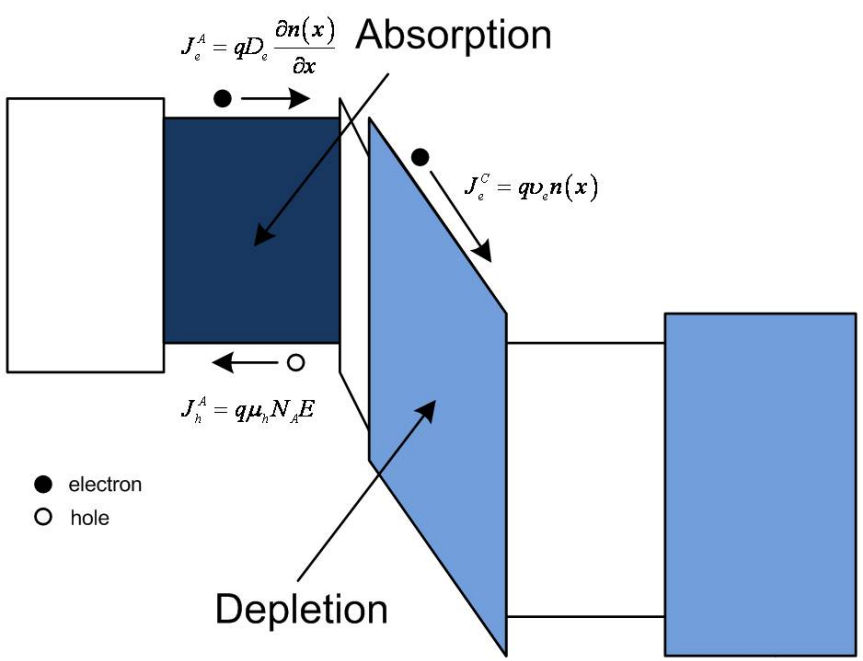
- **Main frequency limitations in p-i-n photodiodes**





Main Solutions

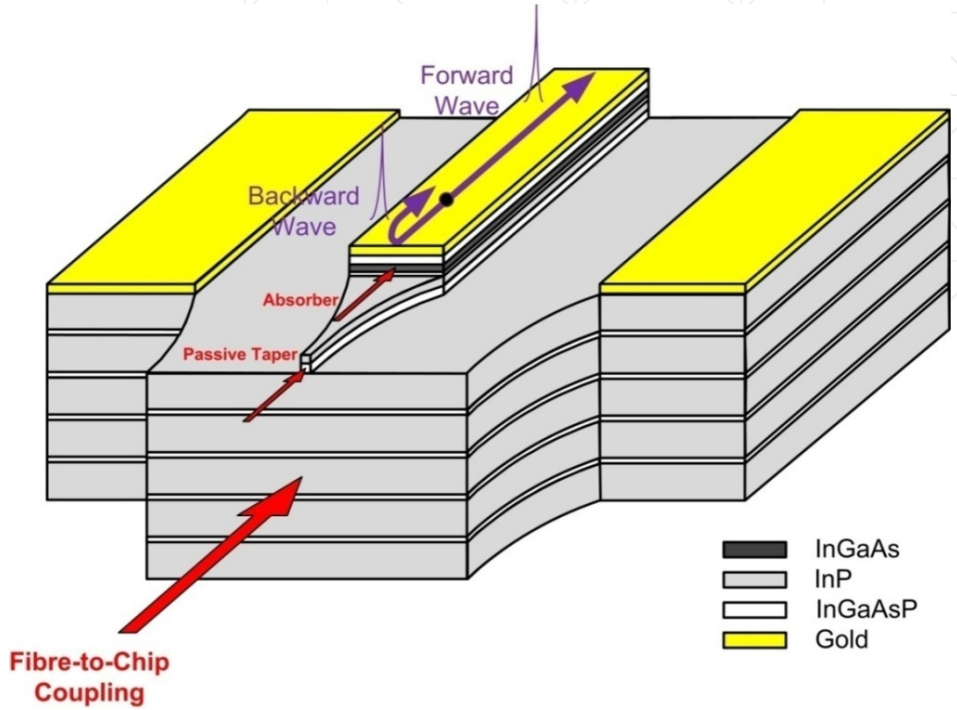
Uni – Travelling Carrier Photodiode



Faster transport – Hot electrons in the depletion region, no hole transport.

T. Ishibashi et al., *Jap. Journal of Applied Physics*, **36** (10), pp. 6263-6268, 1997.

Travelling Wave Photodiode



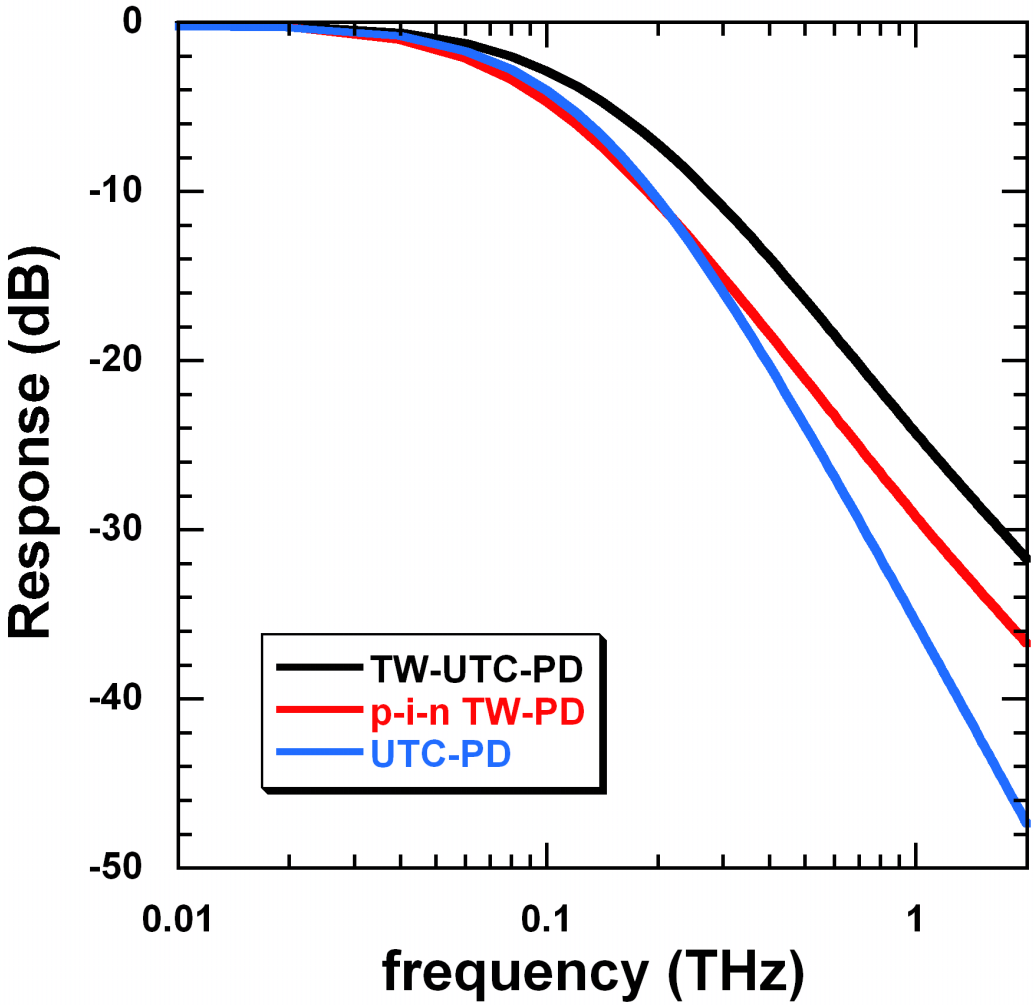
Travelling Wave Effects can achieve better response at high frequencies.

K. S. Giboney et al., *IEEE Trans. on Microwave Theory and Techniques*, **45** (8), pp. 1310-1319, 1997.

Comparison of different solutions

- Transmission Line Model combined with carrier transport was used to predict the frequency response of a 4×15 μm2 TW-UTC-PD.

- The device is compared to a vertically illuminated UTC-PD and a p-i-n TW-PD with the same active area dimensions and intrinsic layer thickness.



E. Rouvalis et al., *Optics Express*, **18** (11), pp. 11105-11110, 2010

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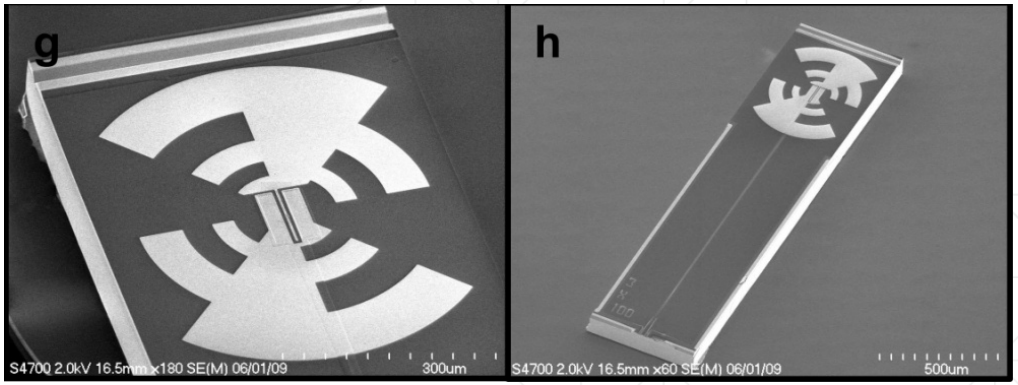
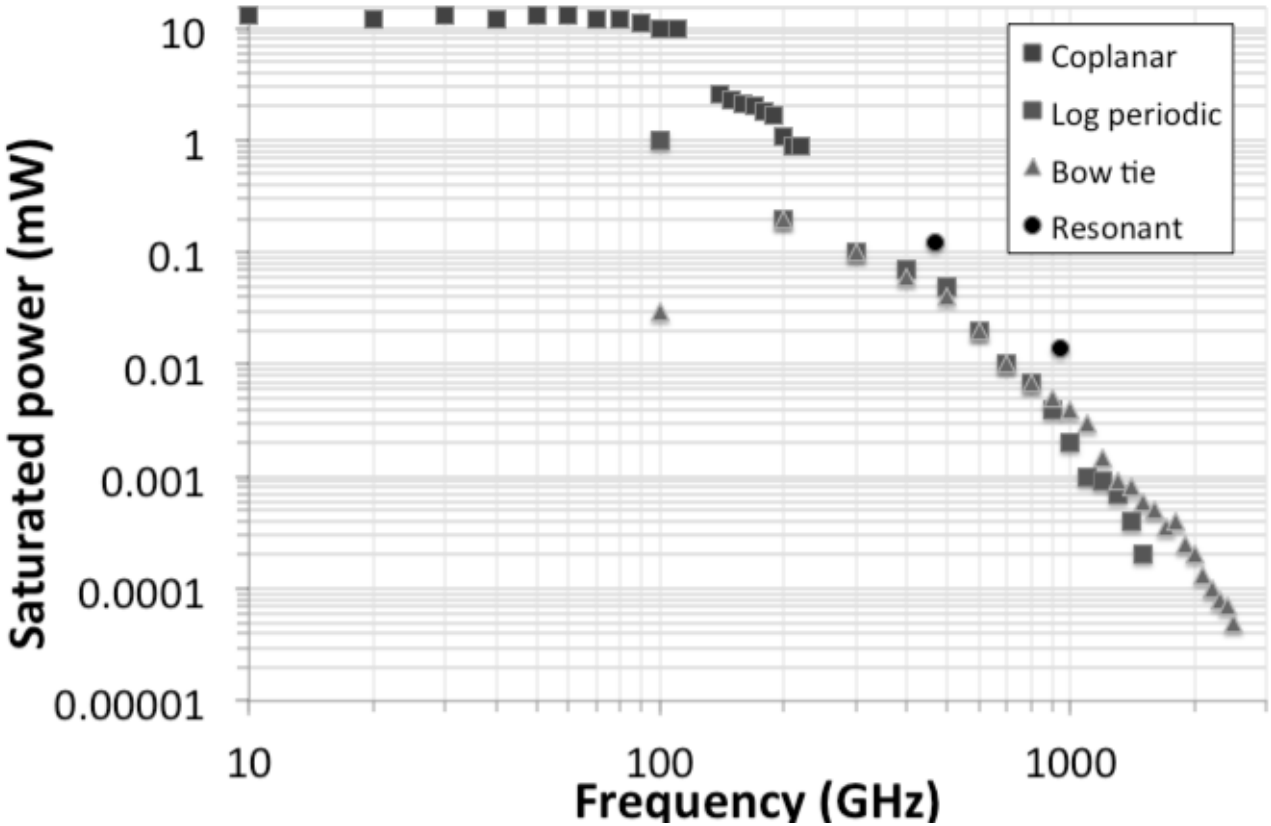
Performance summary

- Different configurations were measured

- Extracted power was ranging from >10 mW at 100 GHz to 45 nW at 2.3 THz.

- Resonant designs offered 1 mW at 200 GHz, >100 μW at 450 GHz and >10 μW at 900 GHz





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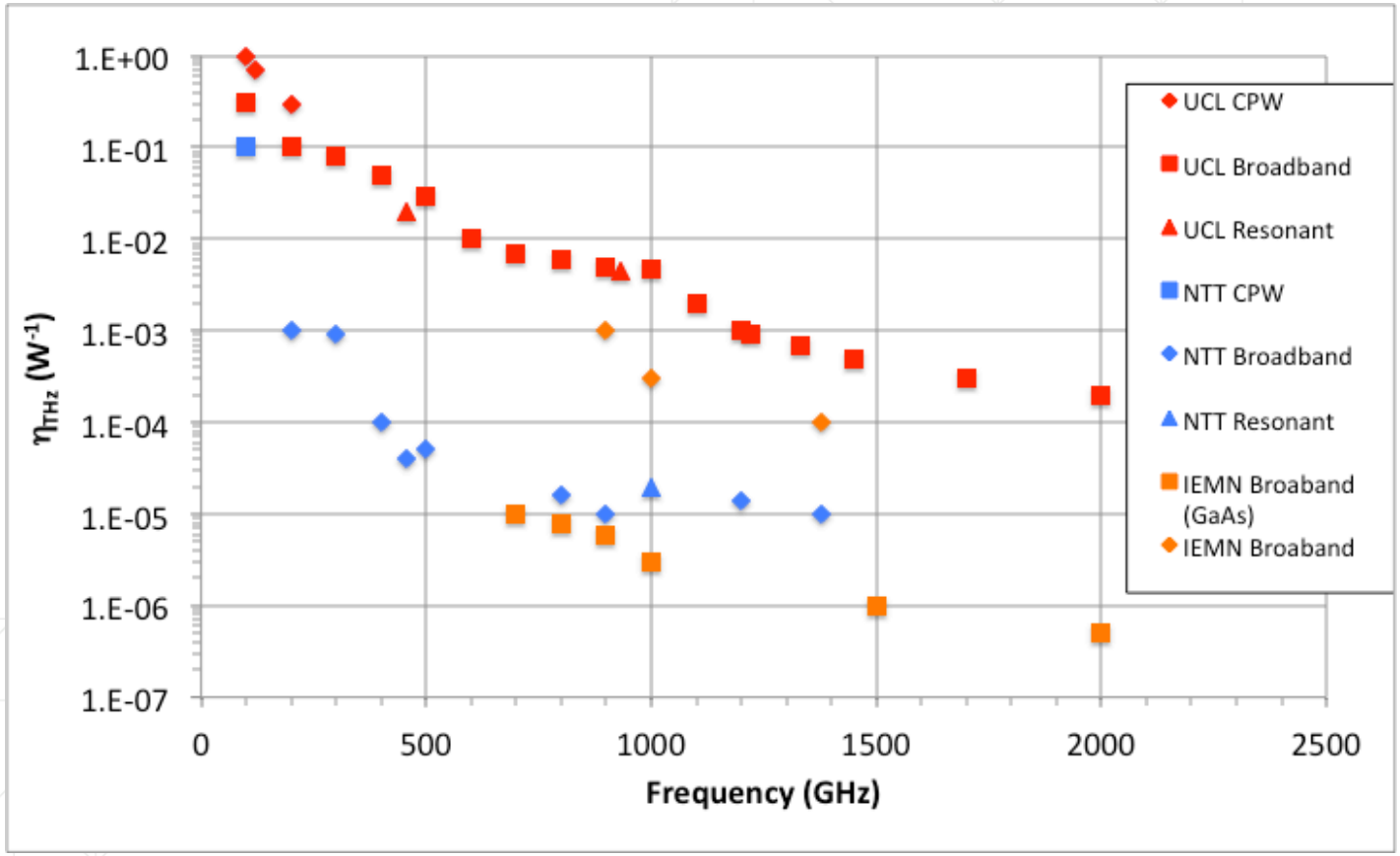
Efficiency as an emitter

- Key to the device is the efficiency of converting light into THz

- This is measured through a figure of merit (P_{THz}/P_{Opt}^2).

- The devices are an order of magnitude better than other photomixers.



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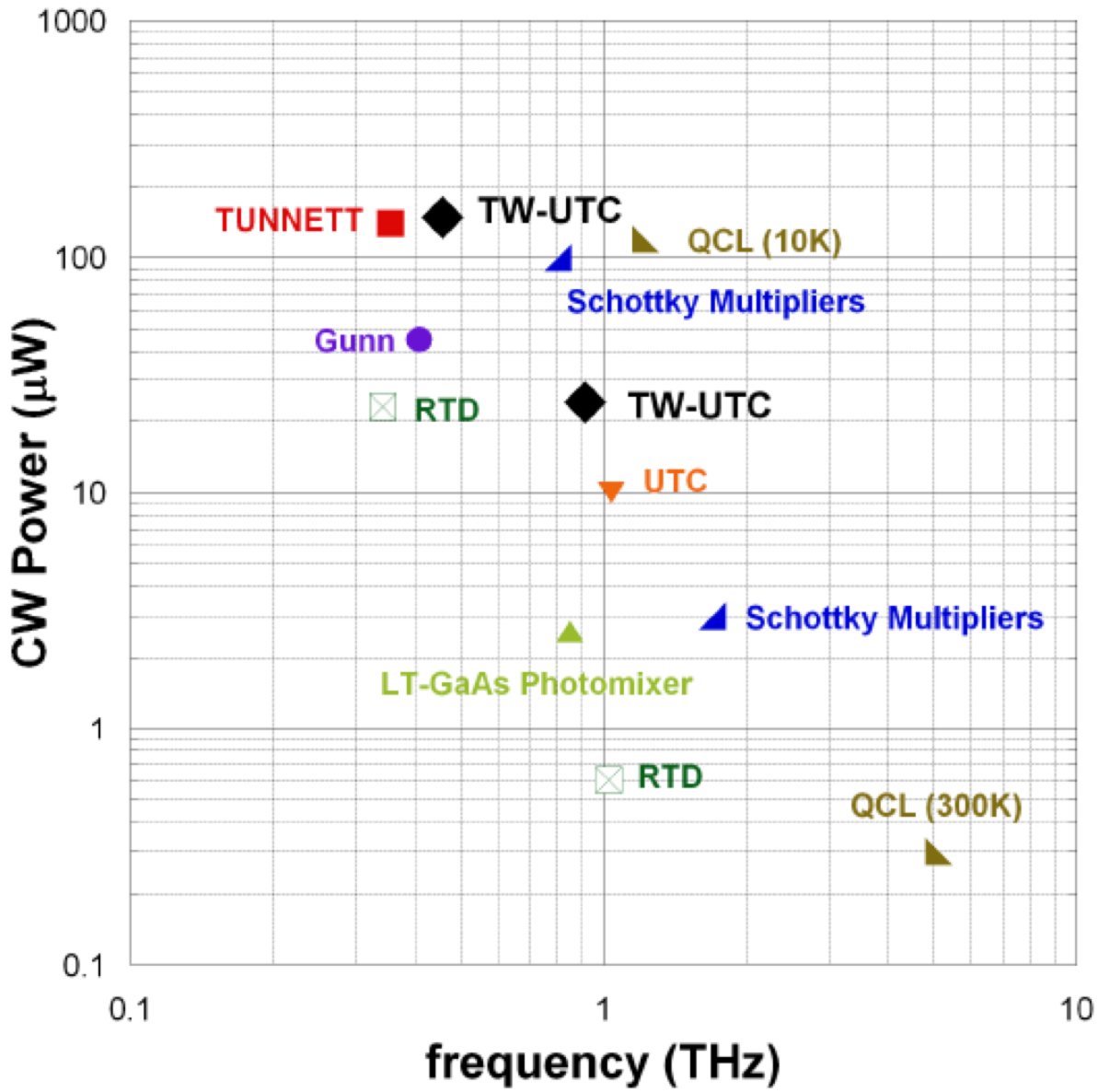
Comparison with other THz sources

- Another useful comparison is to other sources
- Again in term of power Photonic sources based on UTC-PDs compare well
- An other important parameter is that recently on an integrated chip at 100 GHz UTC-PD have emitted **100 µW** for **1 W** total electrical power consumption.



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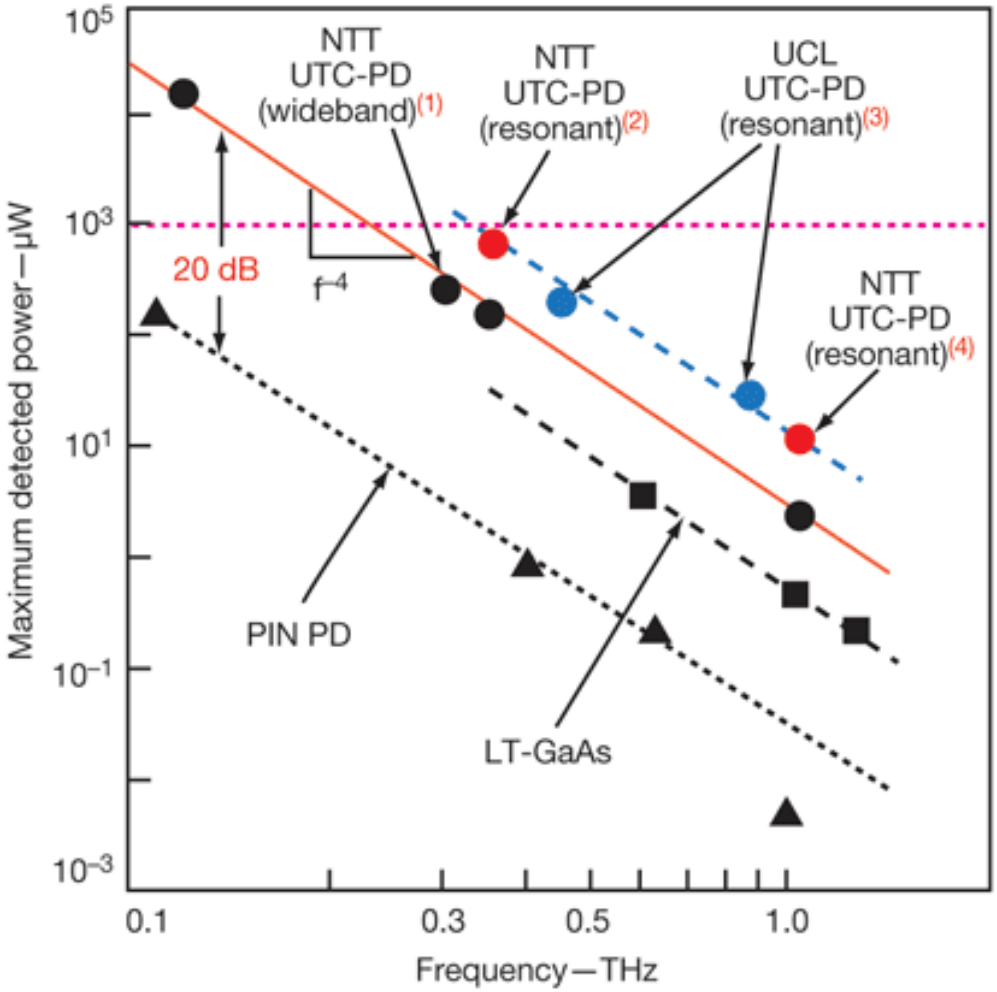
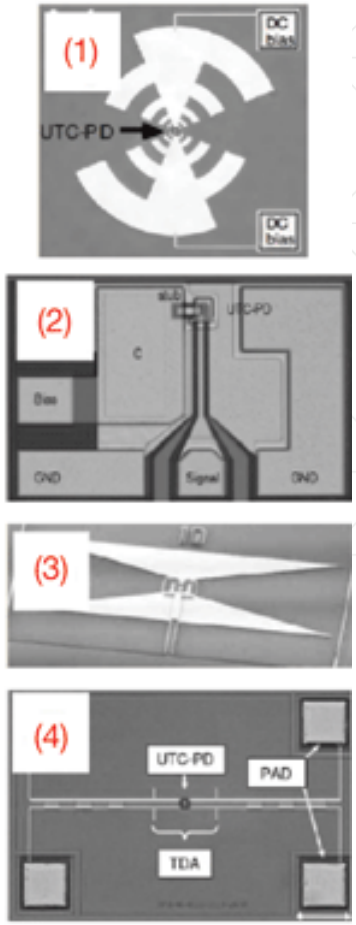
Comparison of photomixers



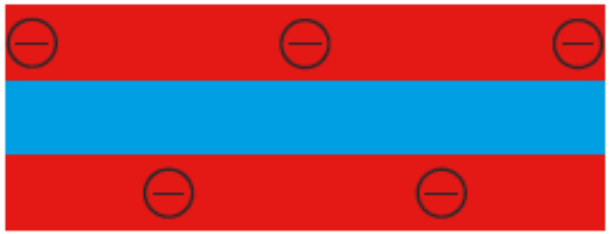


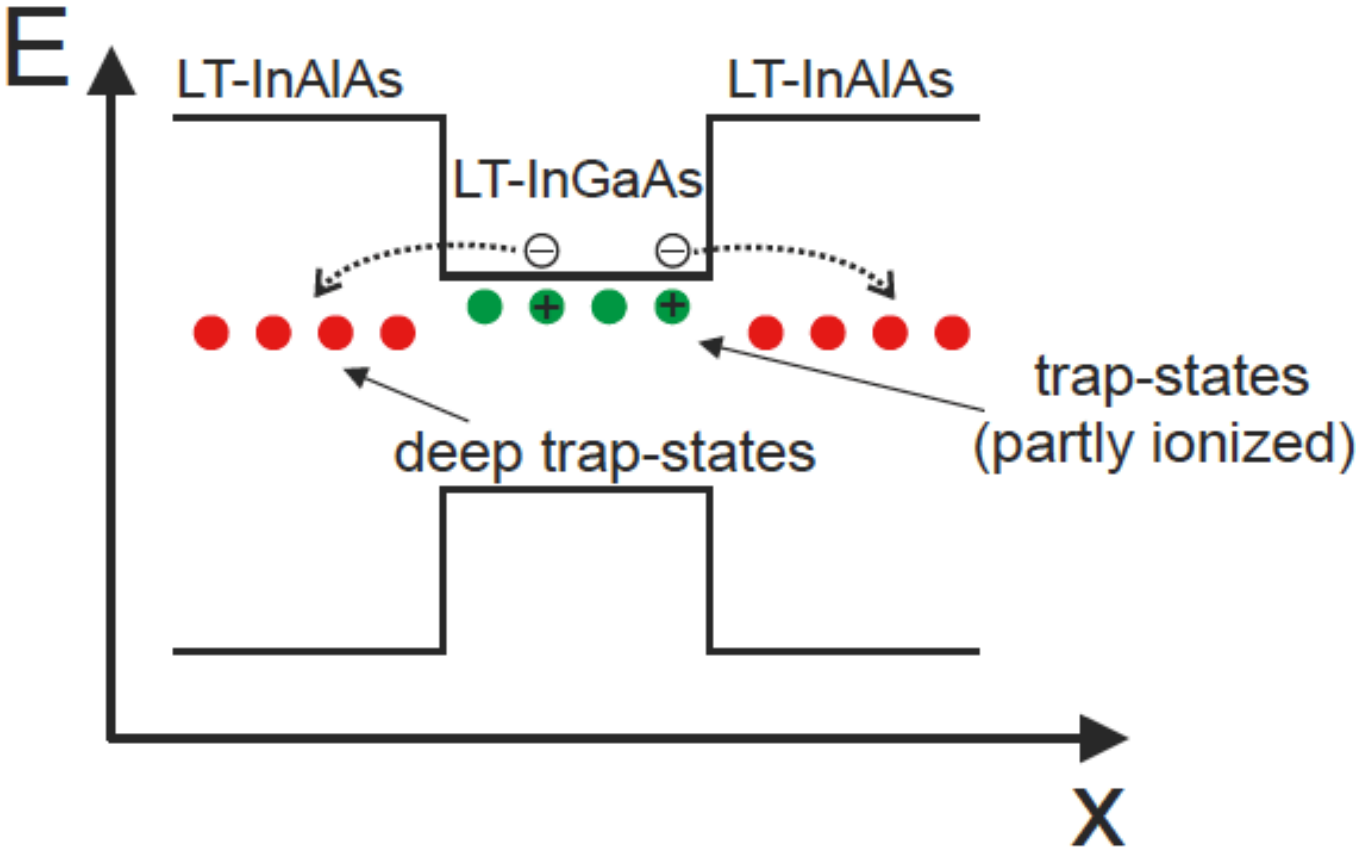
CLEO2016: Photomixer with plasmonic coupling with 17 mW output power

Photoconductive detector for 1.5 µm

	LTG-GaAs	LTG-InGaAs
Optical wavelength	800 nm	1550 nm
Short carrier lifetime	300 fs	600 fs
High mobility	> 100 Vs/cm^2	> 1000 Vs/cm^2
High dark resisitivity	10^5 Ω/sq.	10^2 Ω/sq.

InGaAs/InAlAs Heterostructure





LT-InGaAs:Be / InAlAs heterostucture

- LT-InAlAs has higher bandgap and is isolating
- contains deep trap-states

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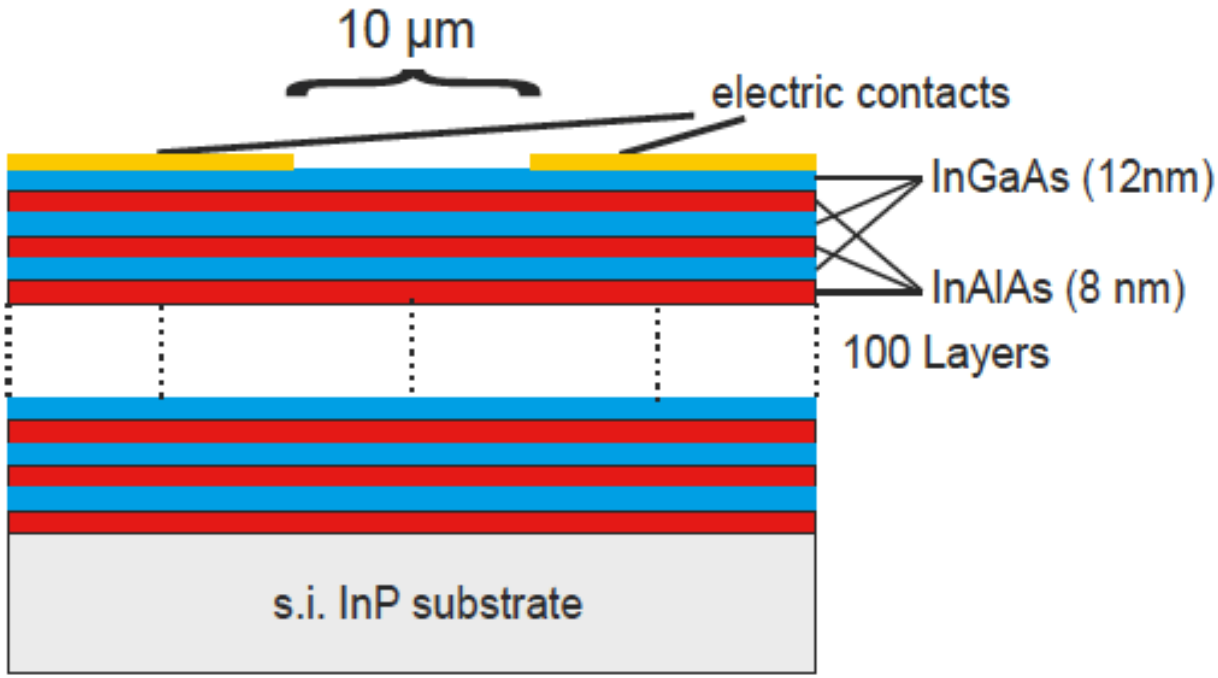
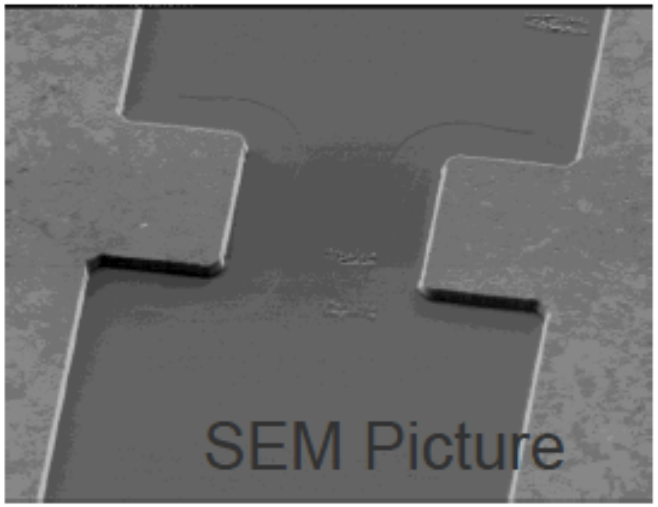
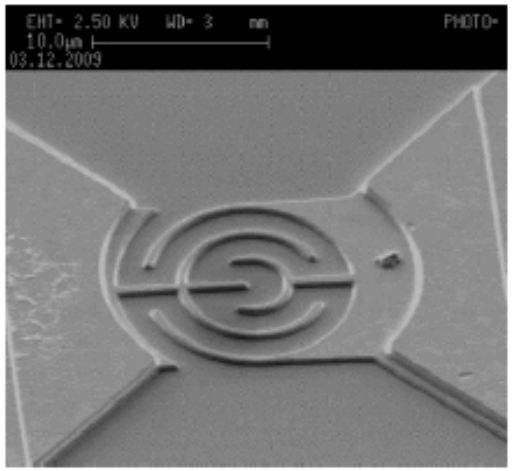
Multilayer solution





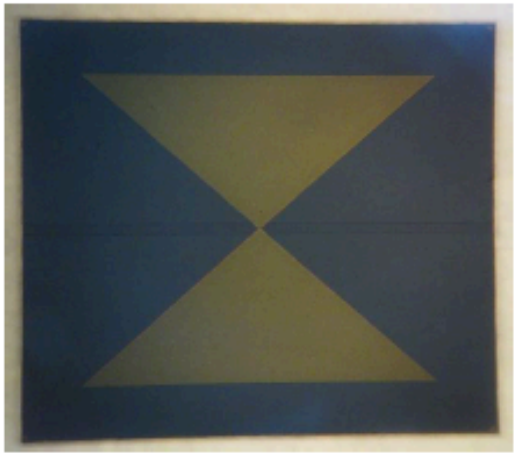
Multilayer PC-antenna with planar deposited contacts

Receiver Setup



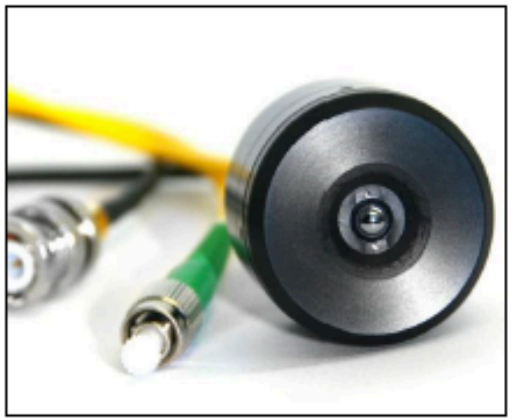
Photomixer

- Interdigitated fingers
- Radius: 5 µm



Antennae

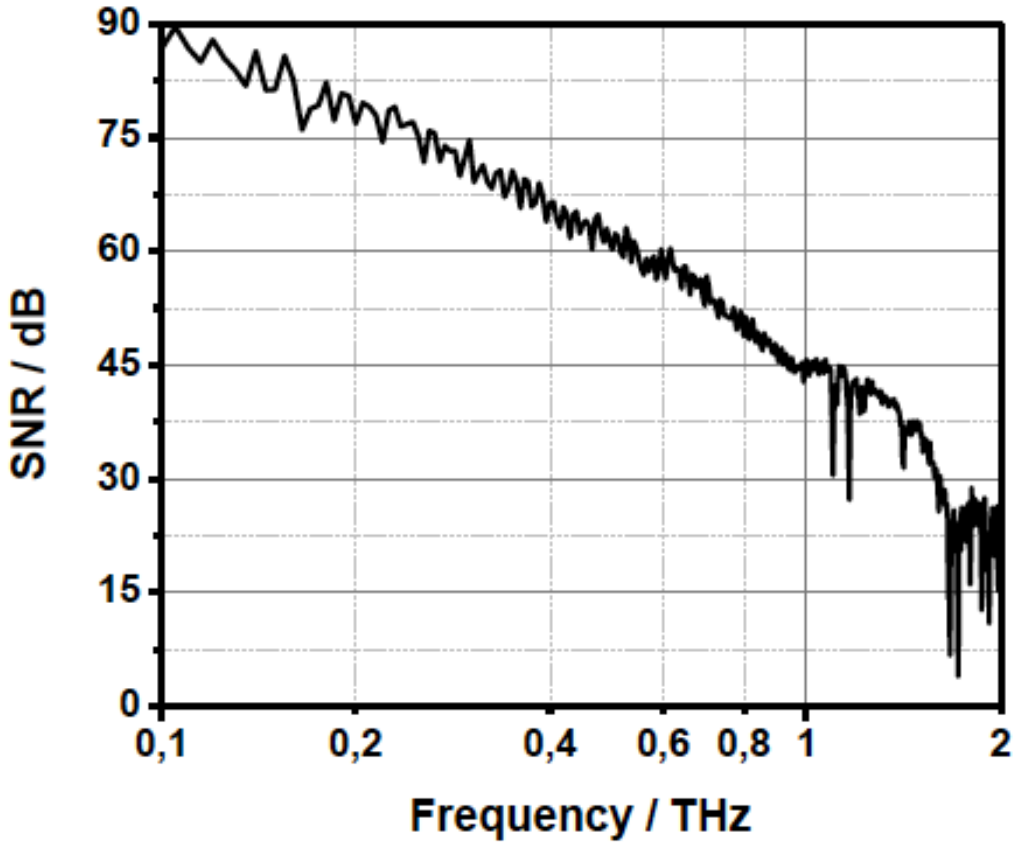
- Bow Tie
- Impedance : ~ 70 Ω
- Bandbreite: ~ 3 THz



Module:

- Fiber coupled
- Robust

Performances



	SNR*
100 GHz	90 dB
1 THz	45 dB
2 THz	20 dB

* 200 ms integration time

- Best performance of 1.5µm photomixing CW THz systems
- 15dB gap to 800nm system @ 1THz

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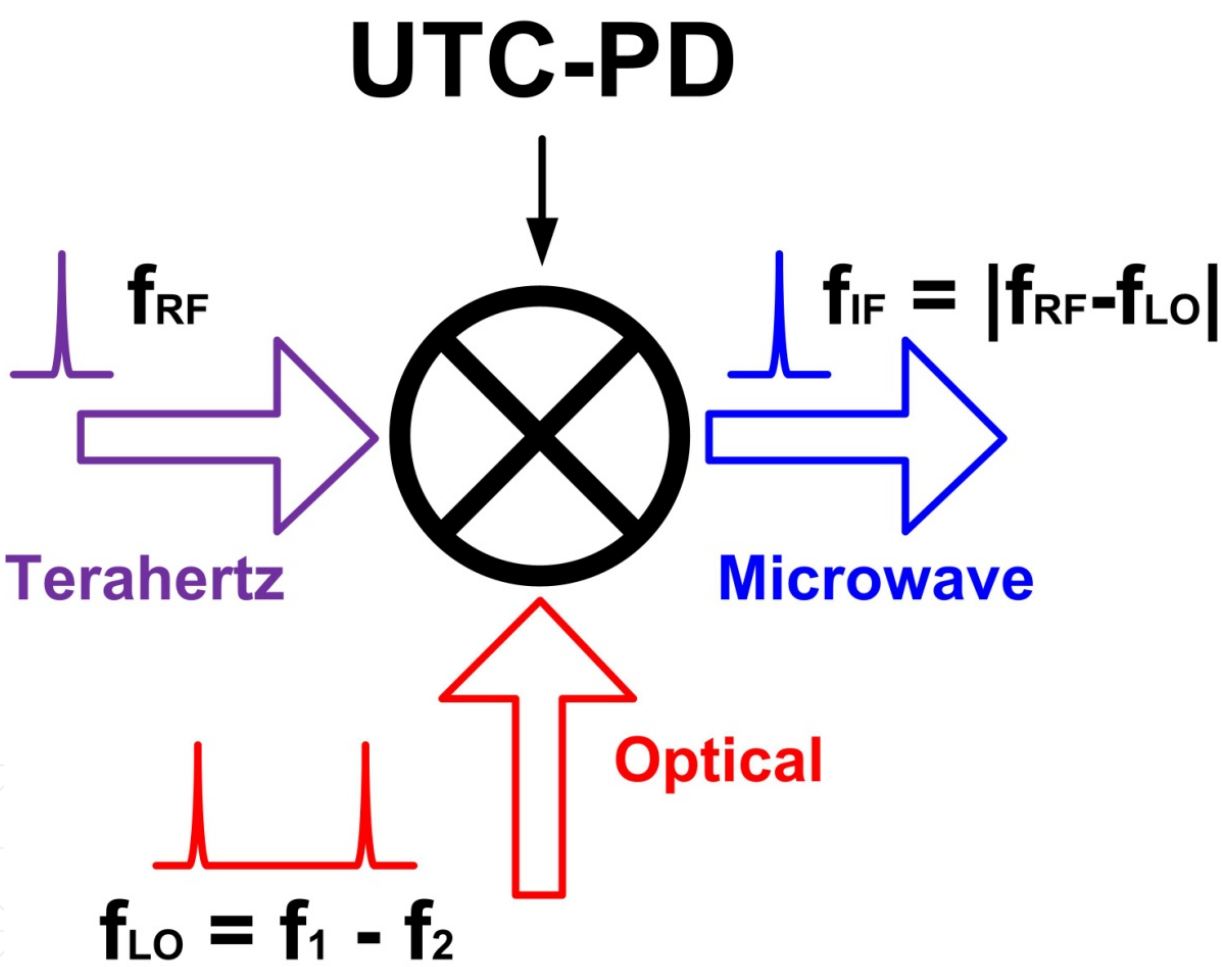
Optoelectronic Detection

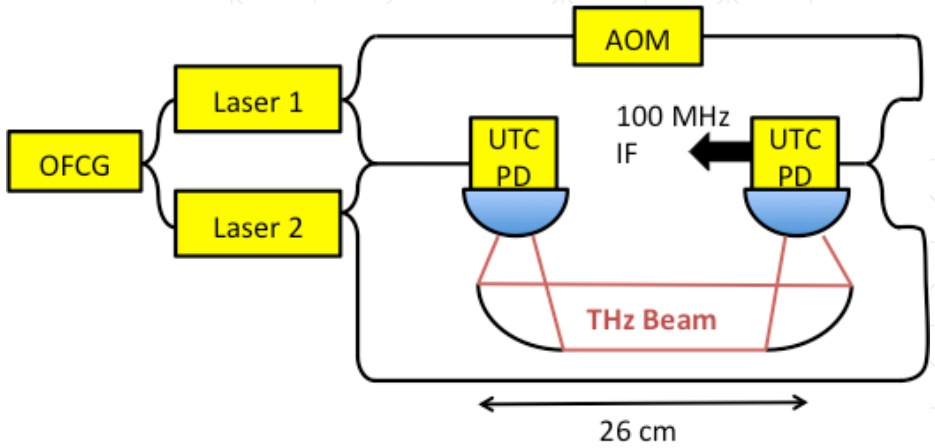
- Coherent detection is required for high spectral resolution.
- Current electronic mixers (Schottky, SIS, HEB) require a tuneable Local Oscillator (LO).
- Employing an ***Optoelectronic Mixer*** allows for the LO to be distributed.
  LO is transferred through an optical fibre.
- Using the same device as a detector may enable ***integrated on-chip spectroscopy***.

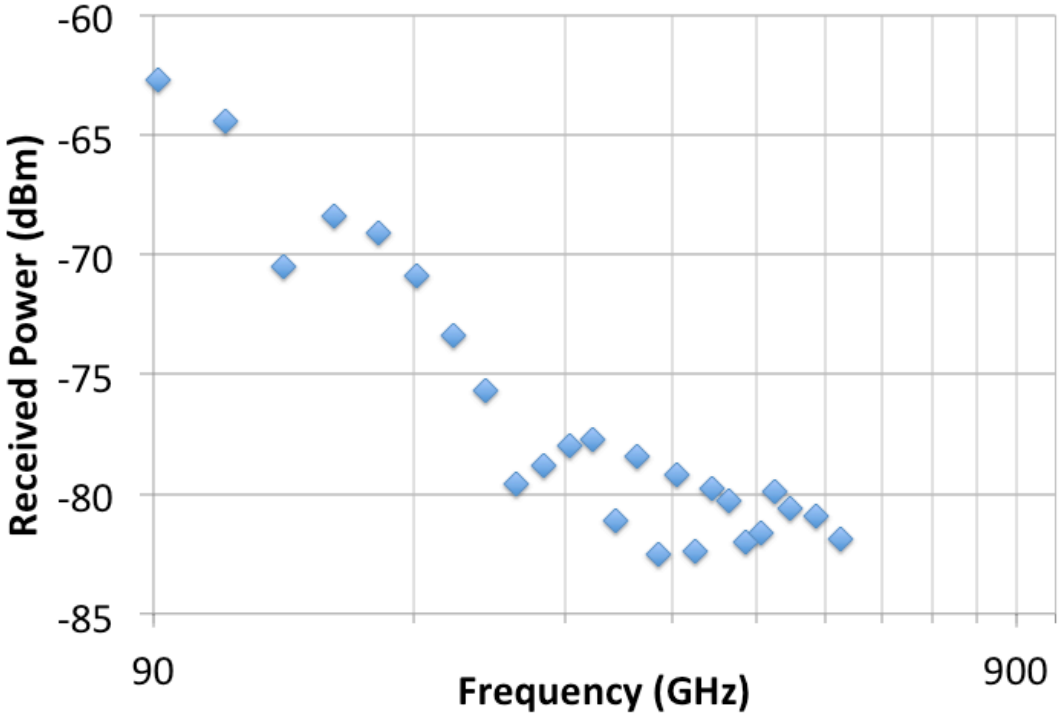


M. J. Fice, E. Rouvalis, L. Ponnampalam, C. C. Renaud, and A. J. Seeds, "Telecommunications technology-based terahertz sources," *Electronics Letters*, **46** (26), 2010 *(invited paper, Special issue on Terahertz Technology)*

Mixing results

- First tests done with UTCs emitters and detector
- Received power in the aperture was ranging after propagation from -62 dBm at 90 GHz to -83 dBm at 550 GHz
- Noise floor in 100 Hz BW was at -83 dBm
- Record breaking bandwidth of detection from UTC-PD (550 GHz)
- Limited by power emitted and ASE beat noise from the source





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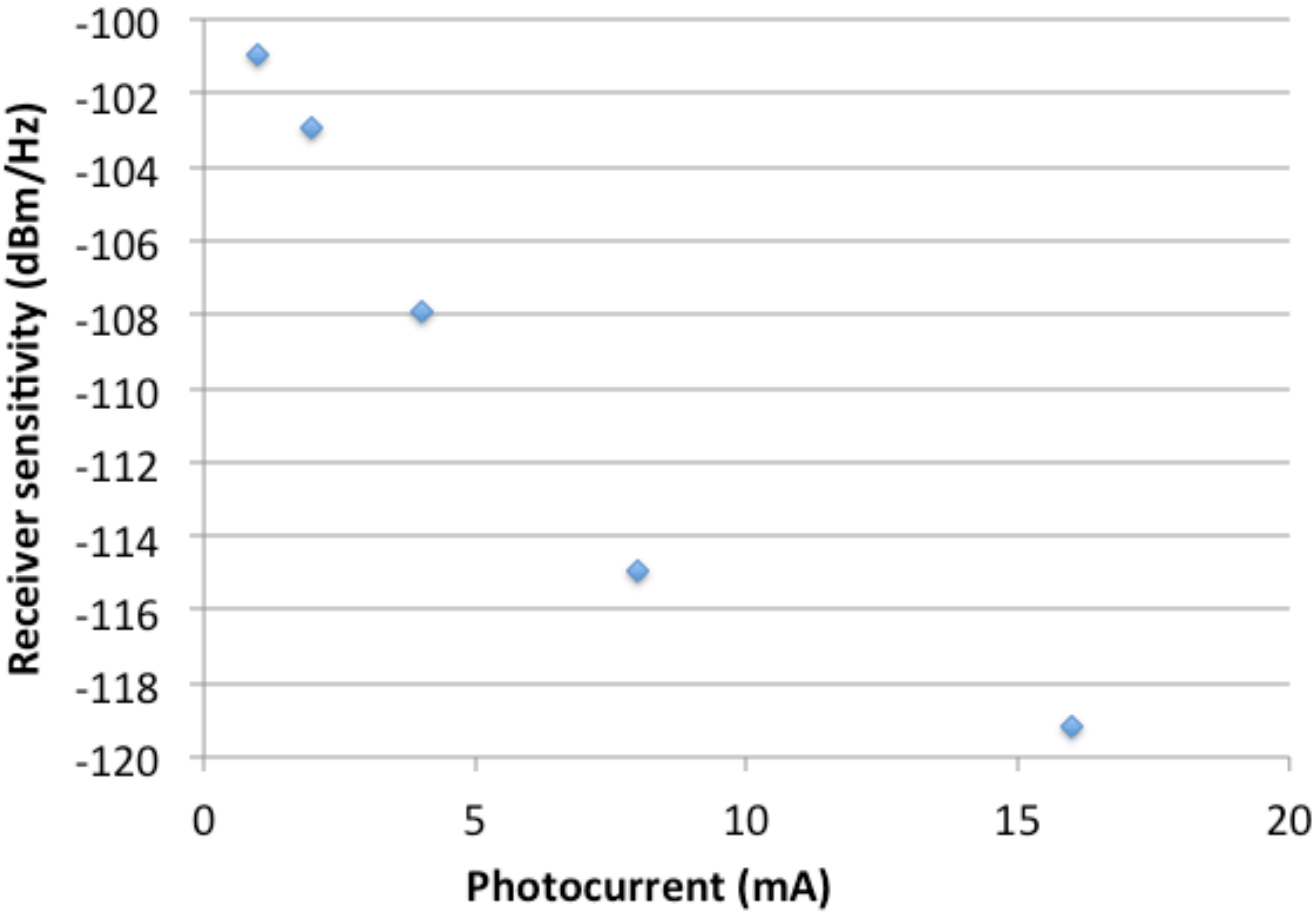
Mixing results

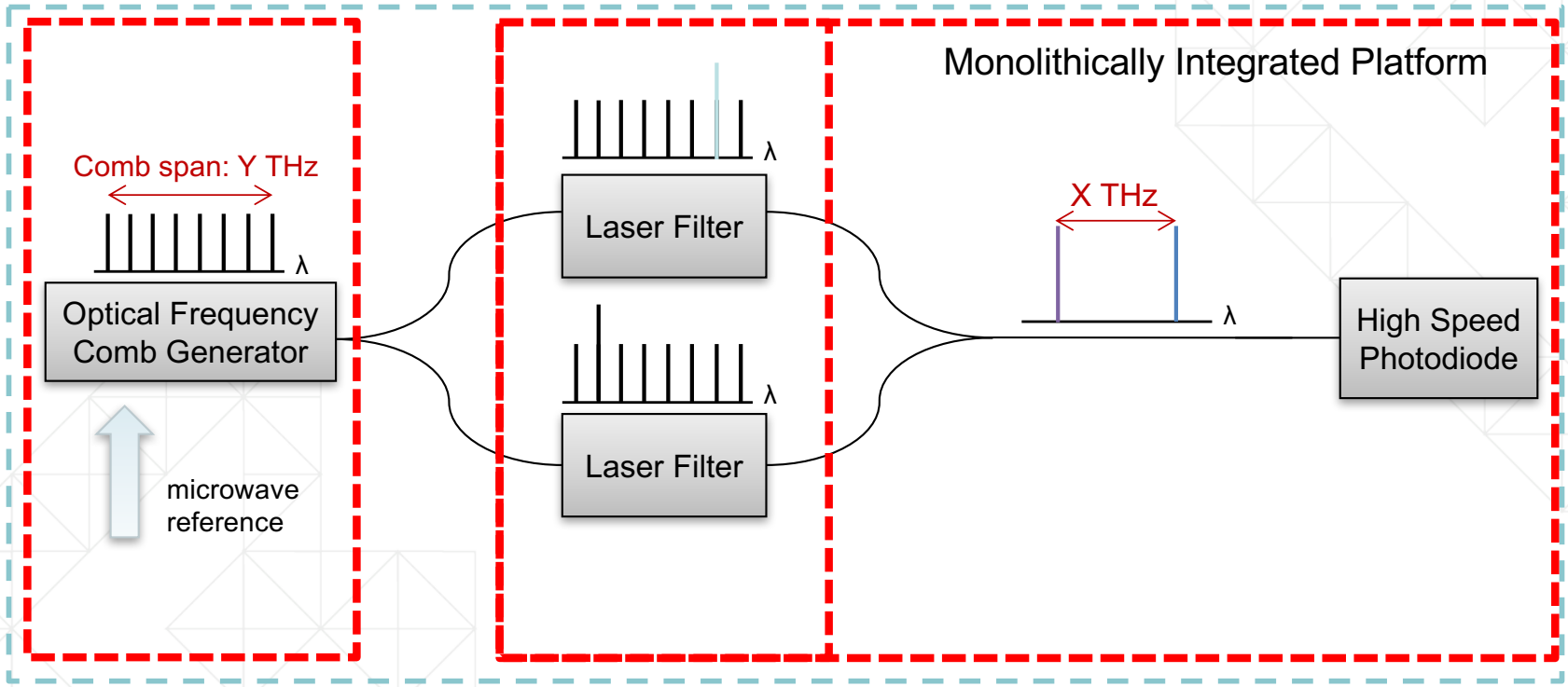
- Sensitivity was measured to be -95 dBm/Hz
- Limited by ASE noise from the source.
- THz communication ✗
- THz spectroscopy ✔
- With optimal source and detector (from previous results) -119 dBm/Hz



Outline

- Typical photonic THz systems
- THz system photonic components
  - Emitters
  - Receivers
- Integration technologies
  - Hybrid vs monolithic
  - InP platform technology
  - Silicon platform technology
  - Photonics subsystems
  - An example of Electronic THz components
- Example of application: THz Communication
- Conclusion

Example system to be integrated



- Generated signal can be continuously tuned in range between GHz (comb line spacing) and THz (comb span)
- Phase locked lasers offer functionality of narrow bandwidth, tuneable filtering and amplification
- PD to convert signal for optical to electrical domain

- One package and one TEC
- No inter-element coupling losses
- Compact and small system footprint
- Generic integration to improve reliability and yield

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Hybrid or monolithic

- Hybrid

  ✓ Vast choice of base materials (e.g. silicon)
  ✓ Lower losses
  ✓ Optimised active components

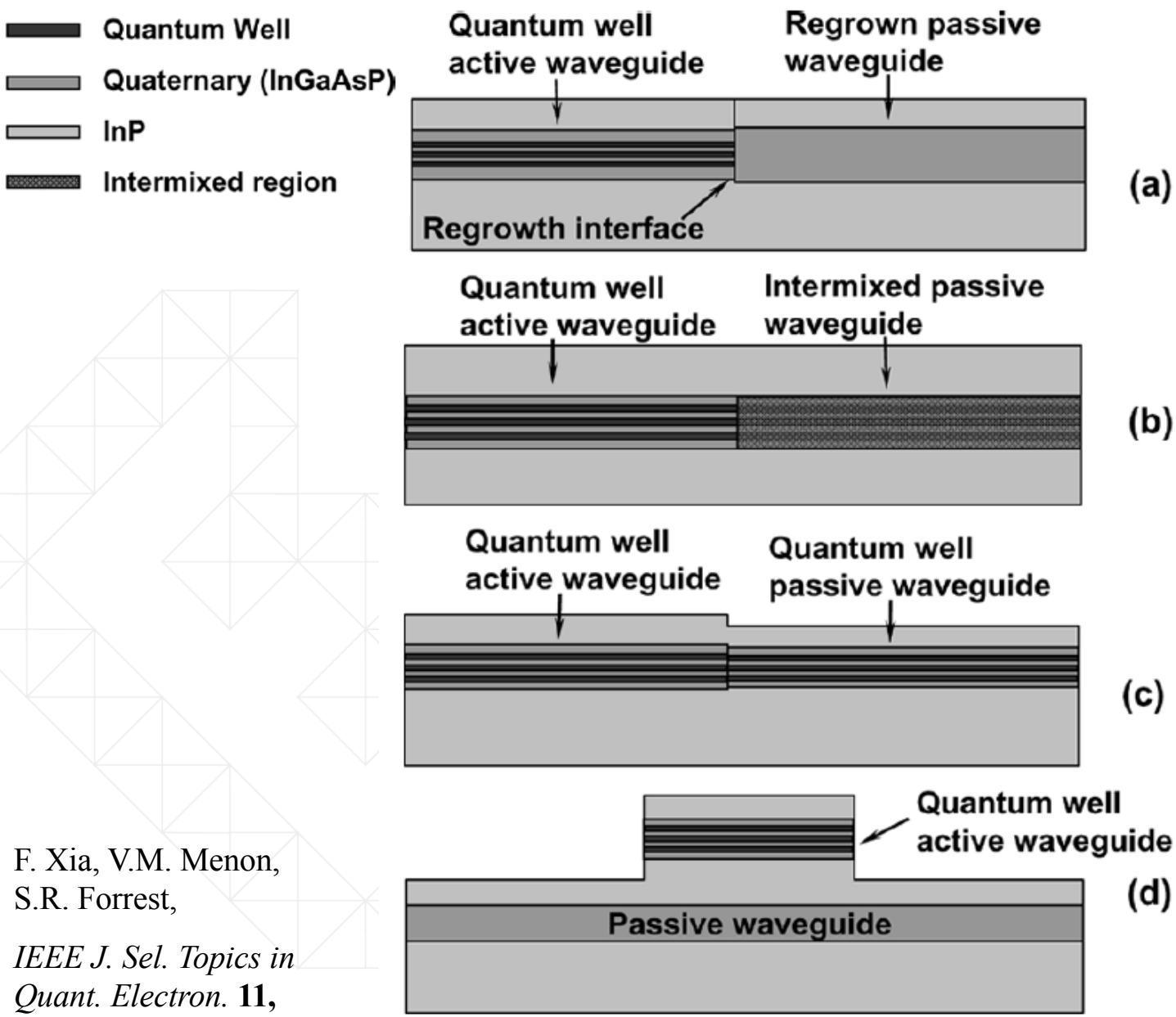
  ✖ Coupling losses
  ✖ Yield
  ✖ Assembly cost

- Monolithic

  ✓ Low coupling loss
  ✓ Lower assembly cost
  ✓ Maximum compactness

  ✖ Propagation losses
  ✖ Compromise on active components
  ✖ Complexity of design

Monolithic integration concepts



F. Xia, V.M. Menon, S.R. Forrest,

IEEE J. Sel. Topics in Quant. Electron. **11,** 17 (2005).

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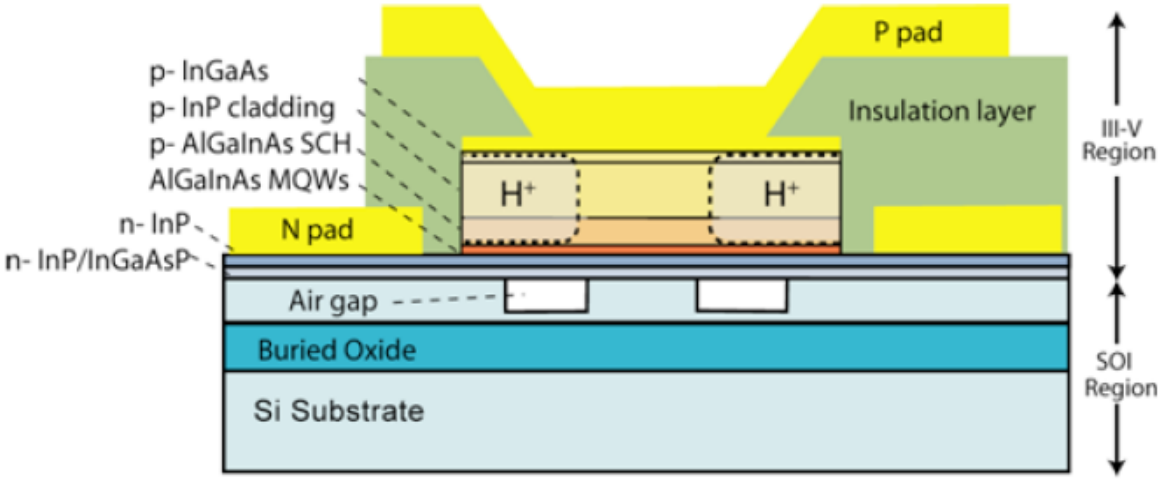
Hybrid integration

- III-V material and Silicon are not lattice matched
- Silicon offer better performances in electronic devices and passive optical components
- Integration of both technology is key
- Current work is mostly on hybrid technology where both photonic and electronic platform are bonded on each other

Univ. of California Santa Barbara – prof. Bowers group



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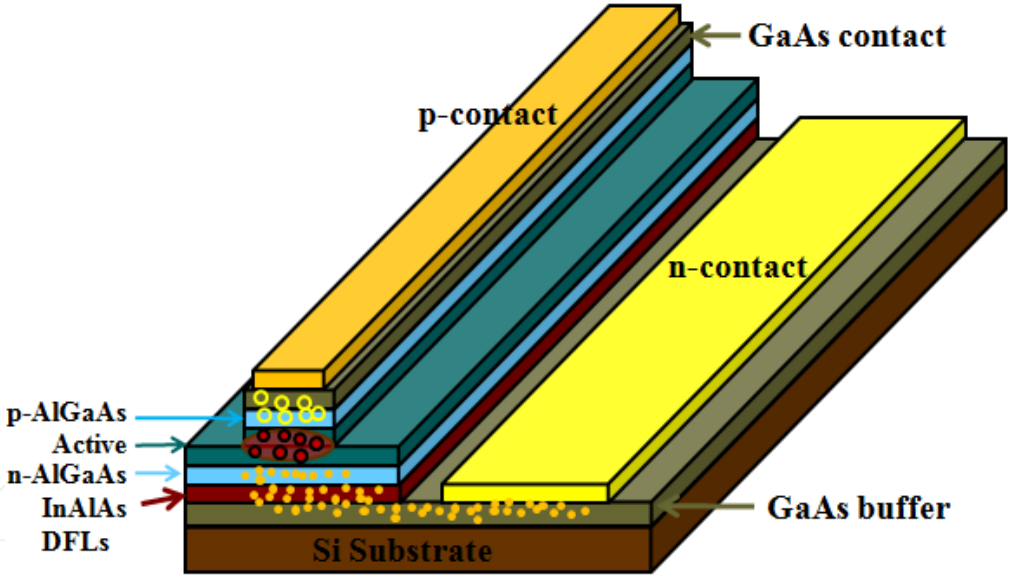
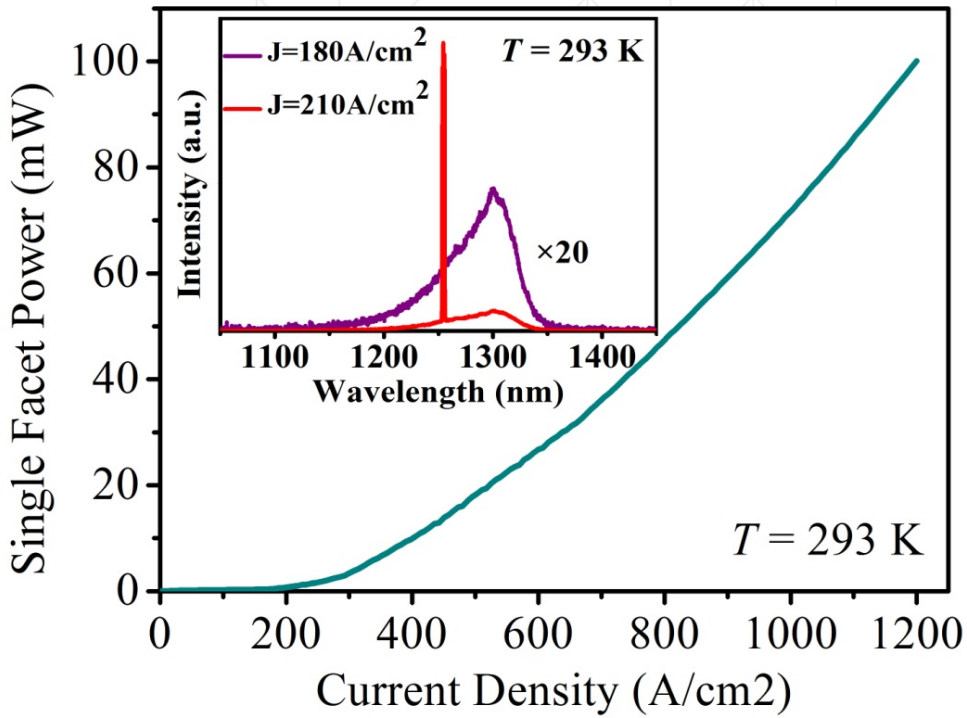
1300-nm InAs/GaAs QD lasers on Si





- The ridges were etched down to 200 nm below the active region for an improved carrier confinement.
- Ti/Pt/Au and InGe/Au were deposited on the p-GaAs contacting layer and the exposed n-GaAs buffer layer, respectively.
- As cleaved devices of 3 mm in length and 50 μm in wide were mounted and wire bonded on ceramic tiles to enable testing. No facet coating is applied.

Generic integration

Goal:

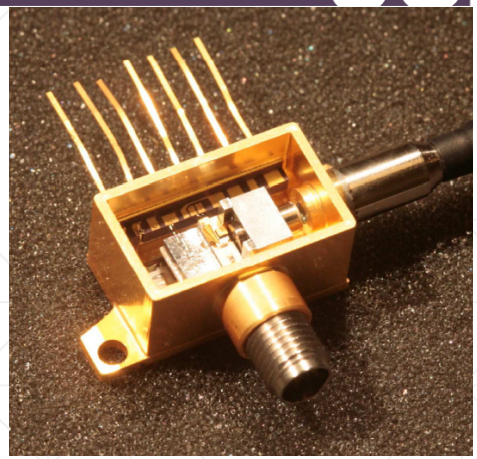
Reducing development time and cost of Photonic Integrated Circuits

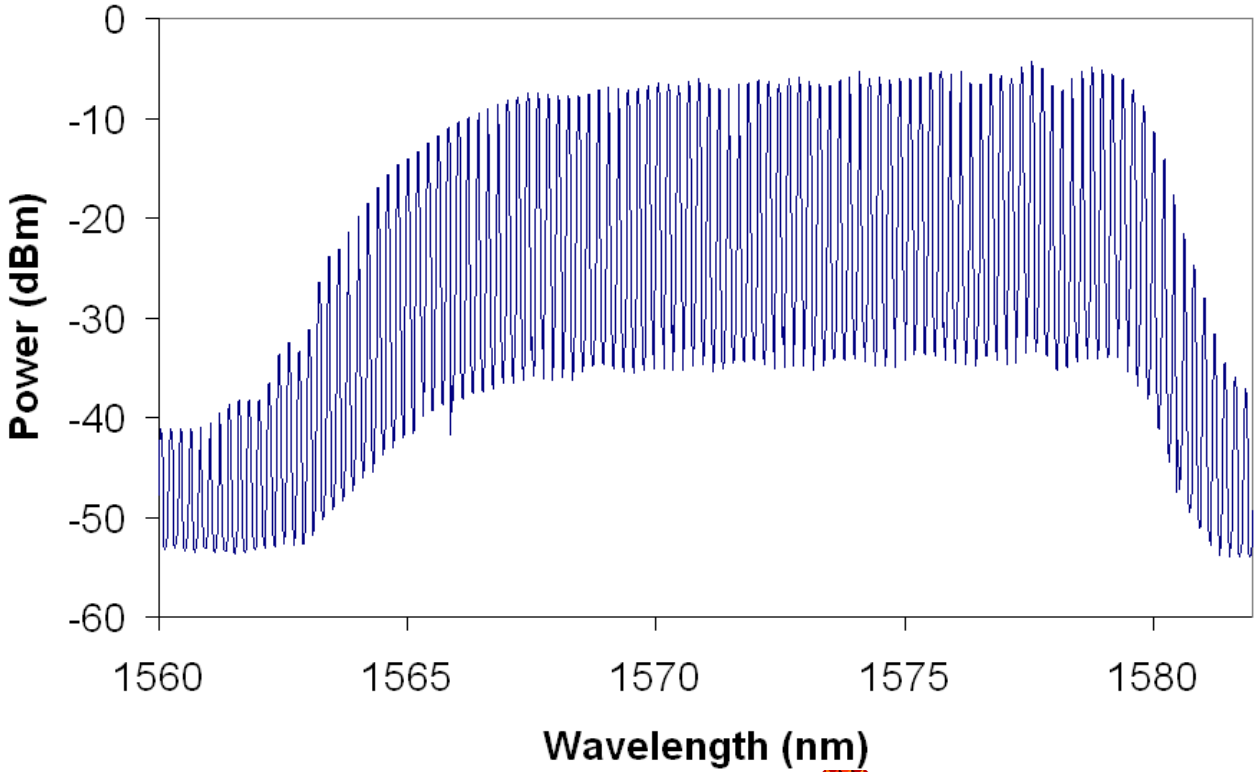
- Sharing development cost and time using standardised circuit components
  - Software design kits for correct and accurate design
  - Separate component design from circuit design
    - Allows for focussing on circuit design
    - Manufacturer focuses on component

- Sharing fabrication cost
  - Multi-Project Wafer (MPW) runs

QD Mode Locked Laser

- FP laser with a quantum-dash gain medium, fabricated at III-V lab
- Butterfly package with an isolator and a V- connector for biasing and modulation
- Threshold current : 20mA
- Power : > 20mW at 400mA gain current
- Optical Spectrum :
  - Line spacing : 24.5GHz (1715mm long cavity)
  - 3dB span : 1.6THz





U. Rafailov, M. A. Cataluna & W. Sibbett Nature Photonics 1, 395 - 401 (2007)

III-V lab

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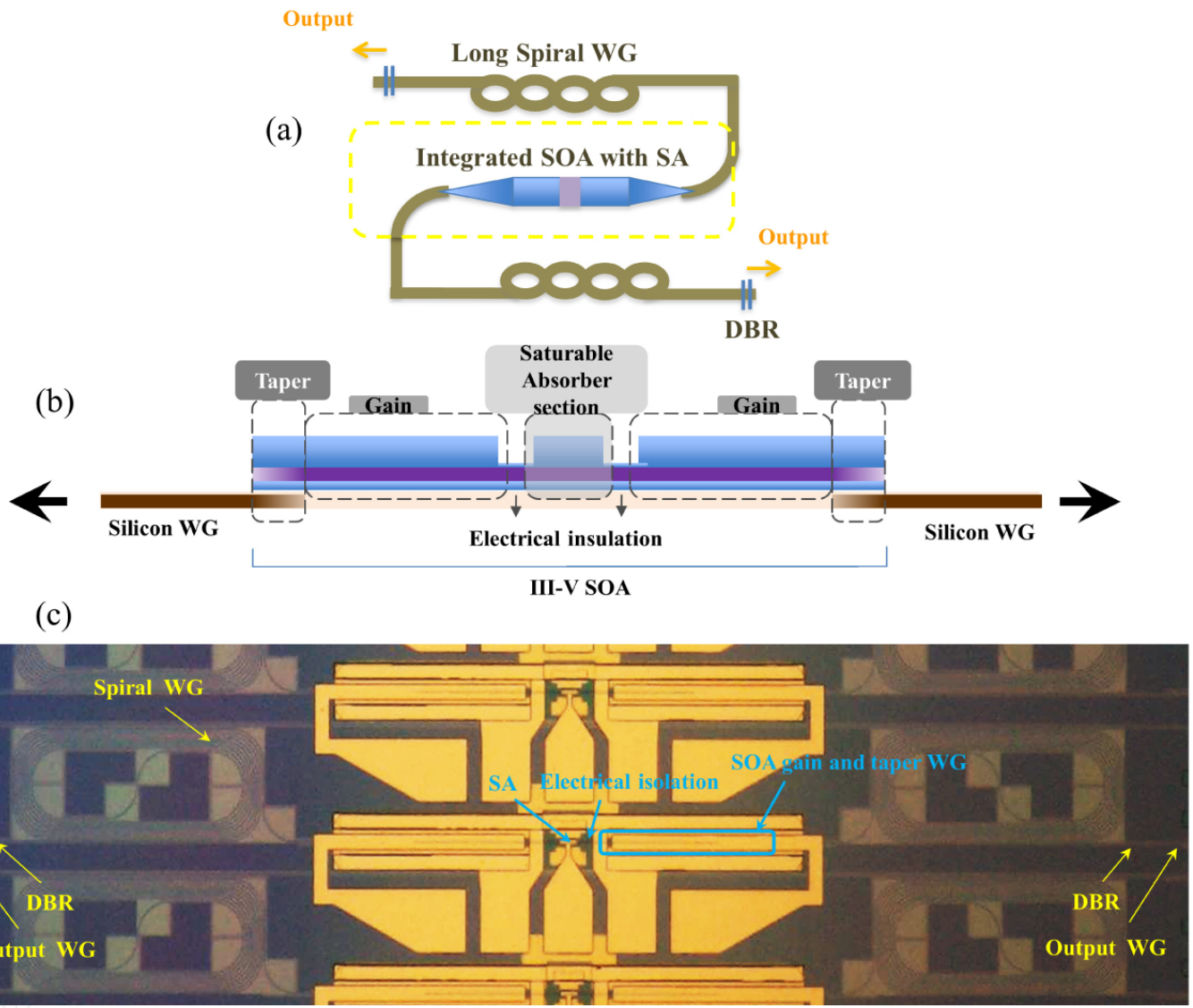
Integrated Mode Locked Laser on Silicon

- Longer cavity and lower repetition rate: 4.7 GHz
- Efficient integrated source
- 1.5 ps pulses



S. Keyvaninia et al. Opt. Express 23, 3221-3229 (2015)

Monolithic Re-circulating OFCG

- PIC was fabricated within generic foundry
- Each PIC contains 3 rings, and comb lines are expected to be spaced by 6 GHz to 10 GHz
- Comb lines are generated through successive modulation of the reference laser in an amplified recirculating loop
- Flat comb lines can be generated by adjustment of the modulation frequency and loop gain

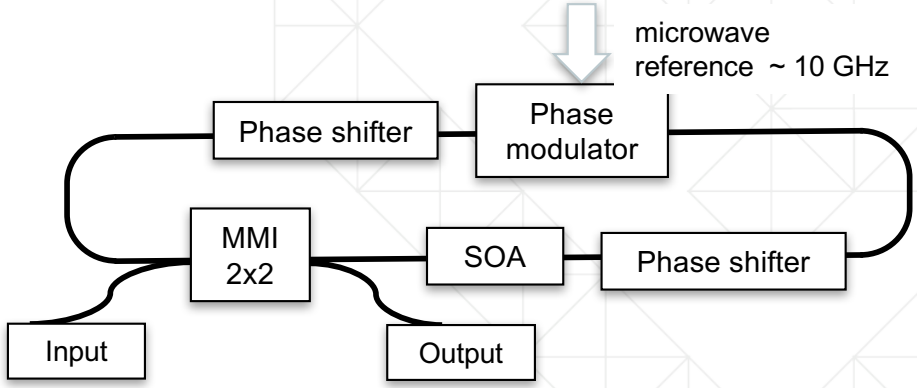


Fig. Schematic of the re-circulating loop OFCG

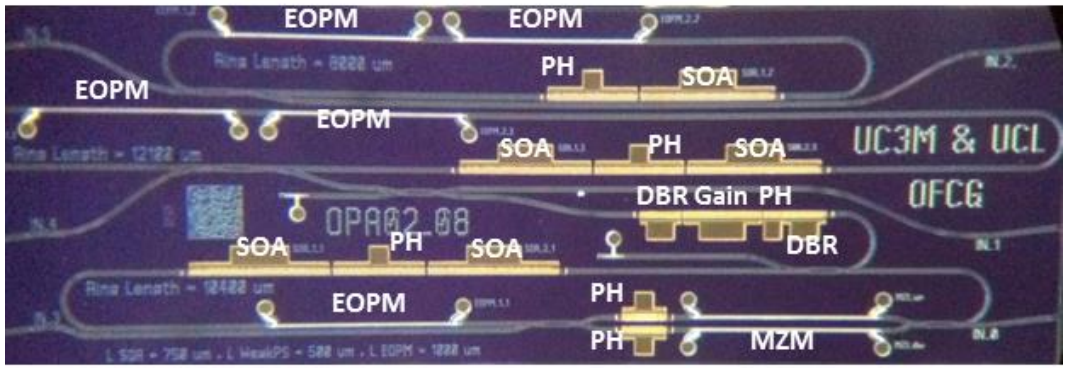
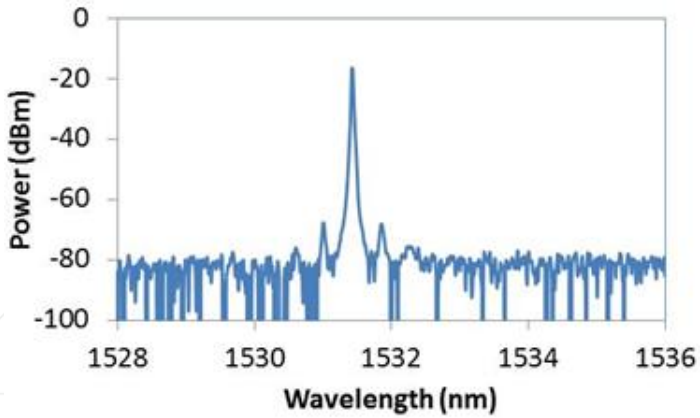


Fig. Fabricated OFCG PIC photograph. Dimensions 2 x 6 mm

General performances



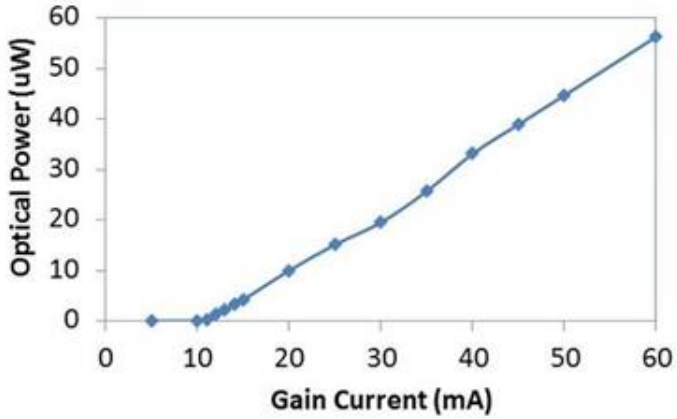


Fig. DBR Characteristics

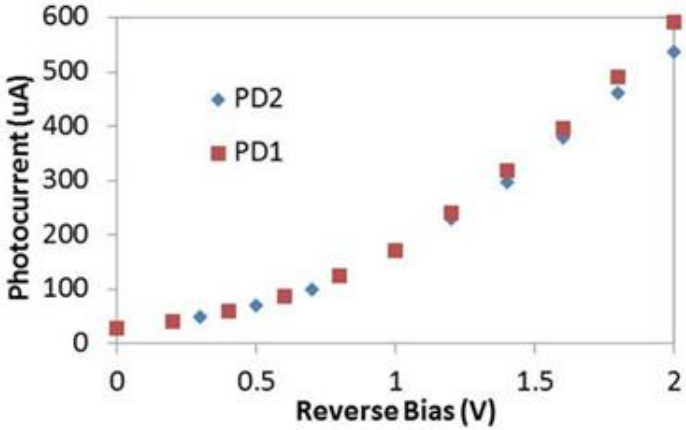


Fig. Photodiode Characteristics (Estimated responsivity of 0.8A/W)

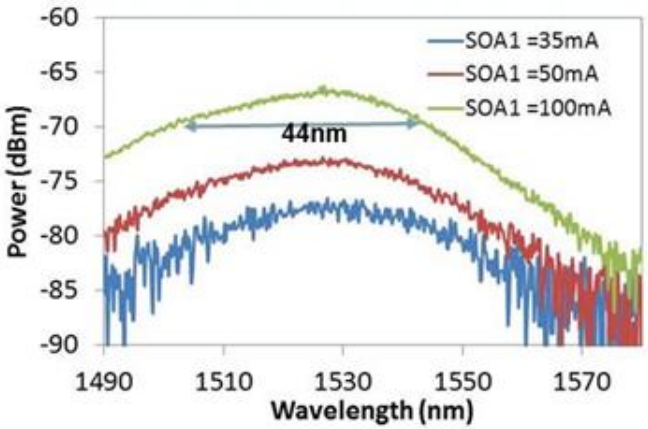
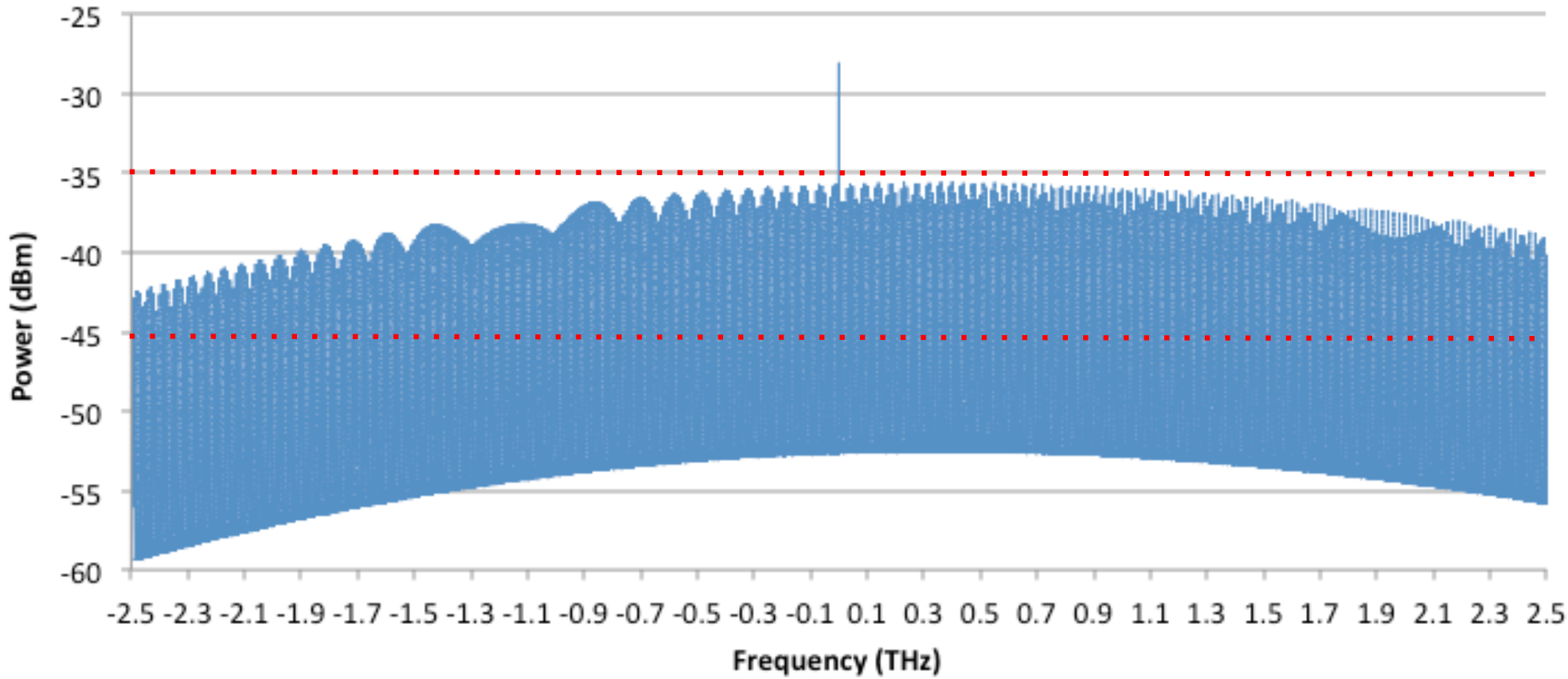


Fig. ASE spectrum of the SOA

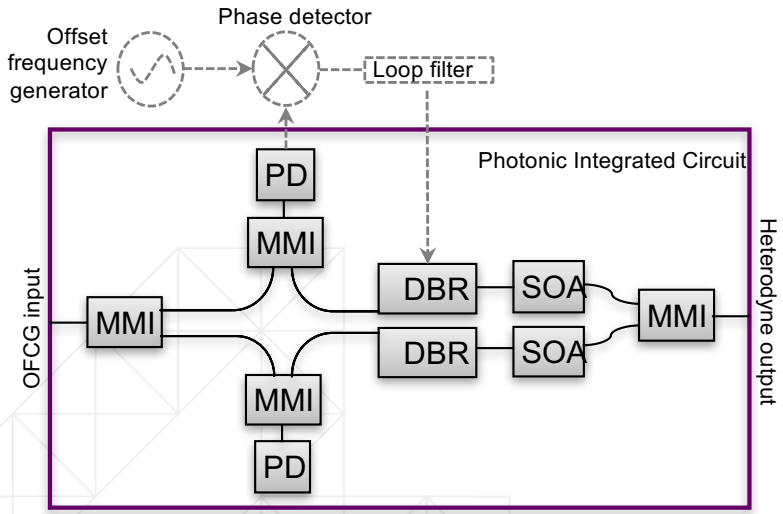
comb spectrum



- The cavity/comb spacing is 10 GHz
- Being monolithic allows for better cavity control and no issues with super-modes.
- The span of the gain is above 5 THz

OPLL – Generic foundry PIC

InP-based widely tuneable and high purity THz source based on heterodyne principle



The following elements are included on single Photonic Integrated Circuit (PIC):

- Tunable lasers – four section DBR for extended tuneability.
- Passive optical waveguides and MMI couplers
- PIN photodetectors
- Semiconductor Optical Amplifiers
- Electro-Optic Phase Modulator

- Demonstrated heterodyne signal from 50 GHz to 3 THz with 10 dBm optical power

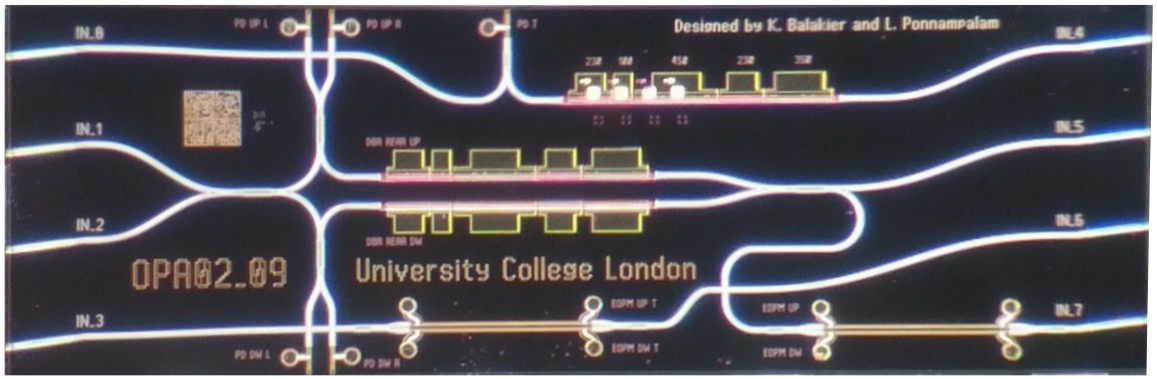


Fig. Fabricated PIC photograph. Dimensions 2 x 6 mm

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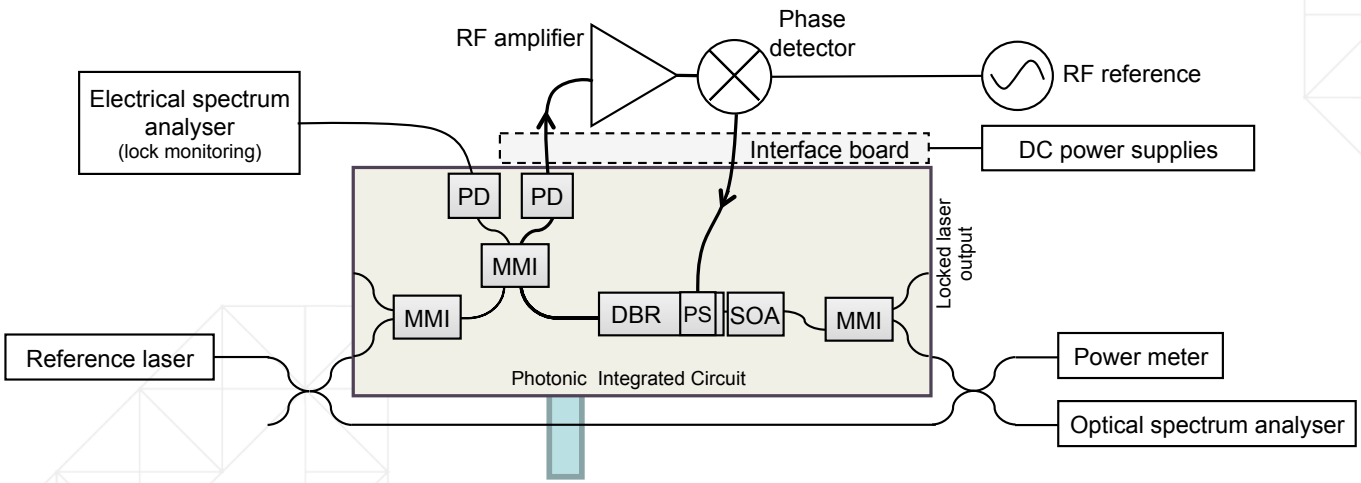
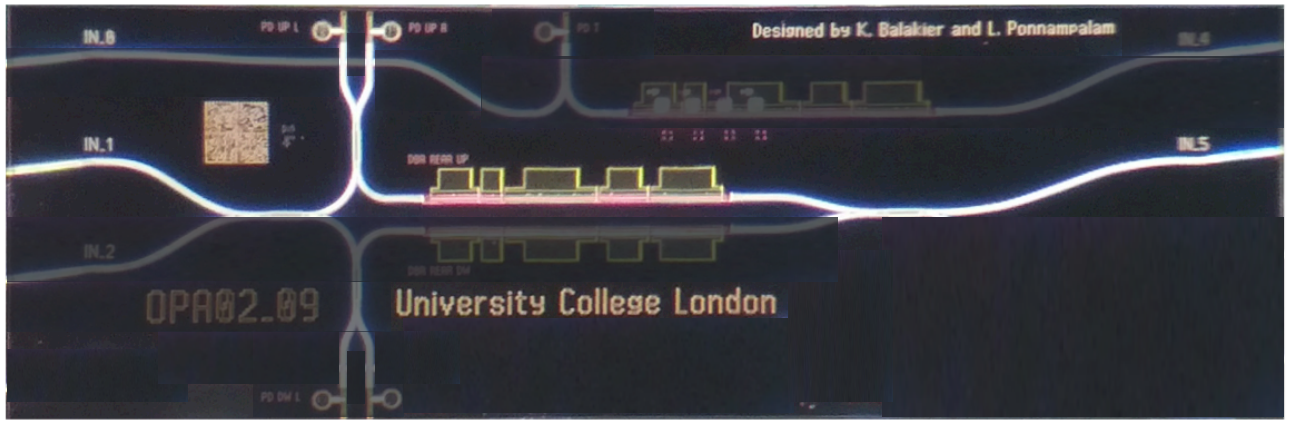
OPLL Design and Demonstration





- Demonstration of an OPLL here on one arm.
- Use of a simple type I OPLL circuit with off the shelf components
- Loop delay is 1.7 ns
- Bandwidth is 1.2 GHz
- Continuous tuning of offset from 4 to 12 GHz (widest reported)

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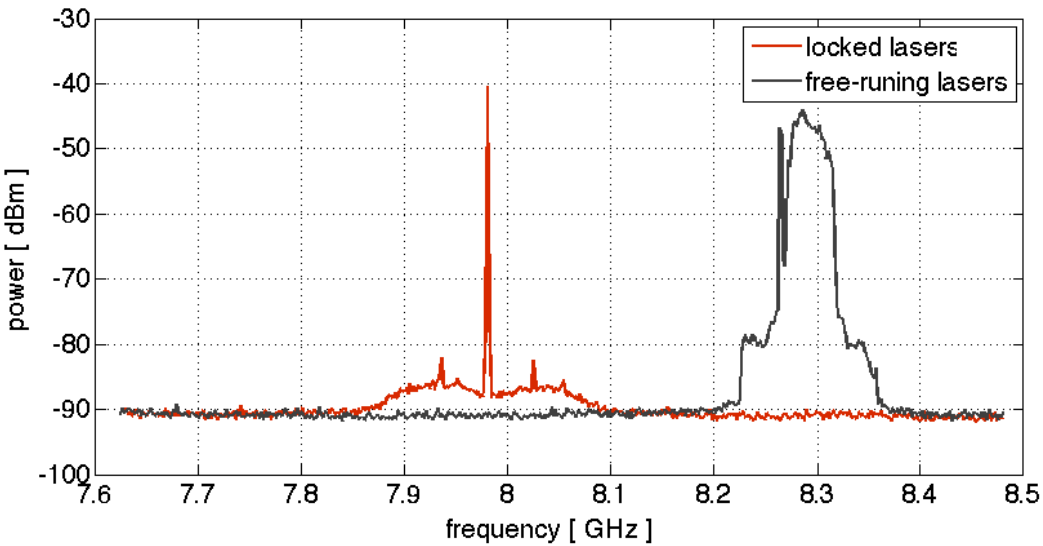
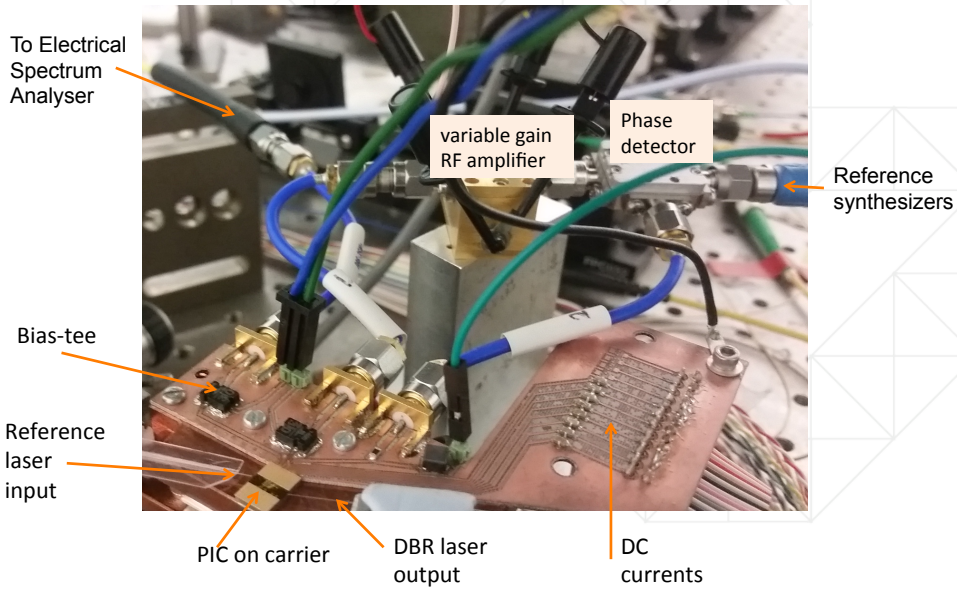
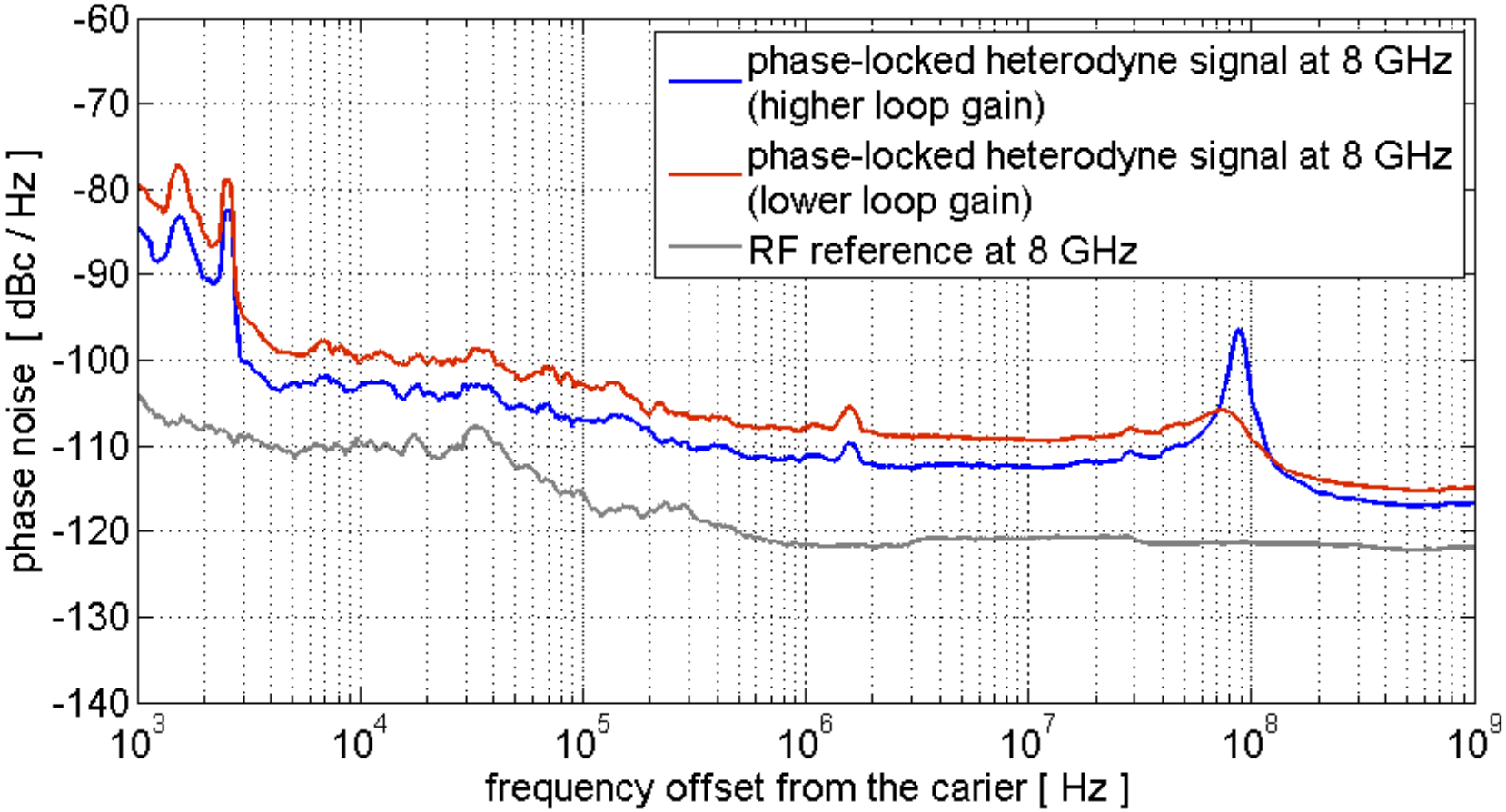
OPLL Locking results





- Successful locking was demonstrated from 4 to12 GHz offset
- Wavelength was rapidly tuned between different set of injection lines from a optical comb with up to 3 THz tuning
- Continuous tuning is 8 GHz

OPLL current design stage



- Phase noise at -100 dBc/Hz at 10 kHz offset
- Corresponds to a phase variance of 0.012 Rad^2 (Best reported performances with a PIC to date)
- Extrapolated linewidth <10Hz

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Laser/UTC-PD Integration

UCL

"Integrated photonic transceivers at sub-terahertz wave range for ultra-wideband wireless communications"

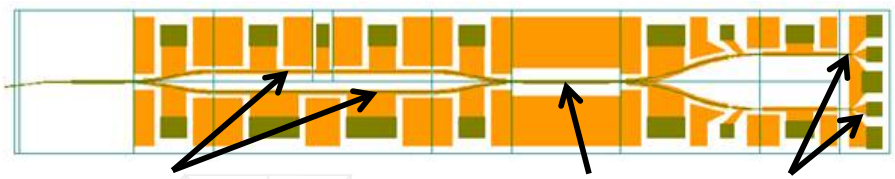

Fig. PIC mask layout

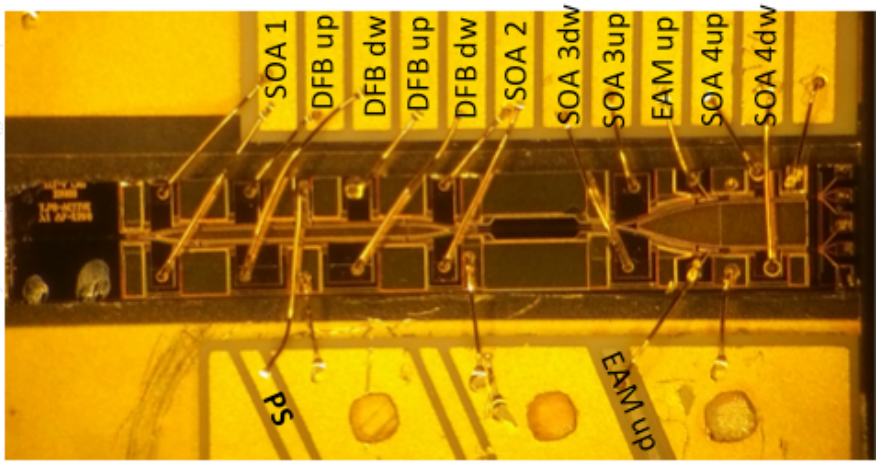

Fig. Fabricated PIC and carrier

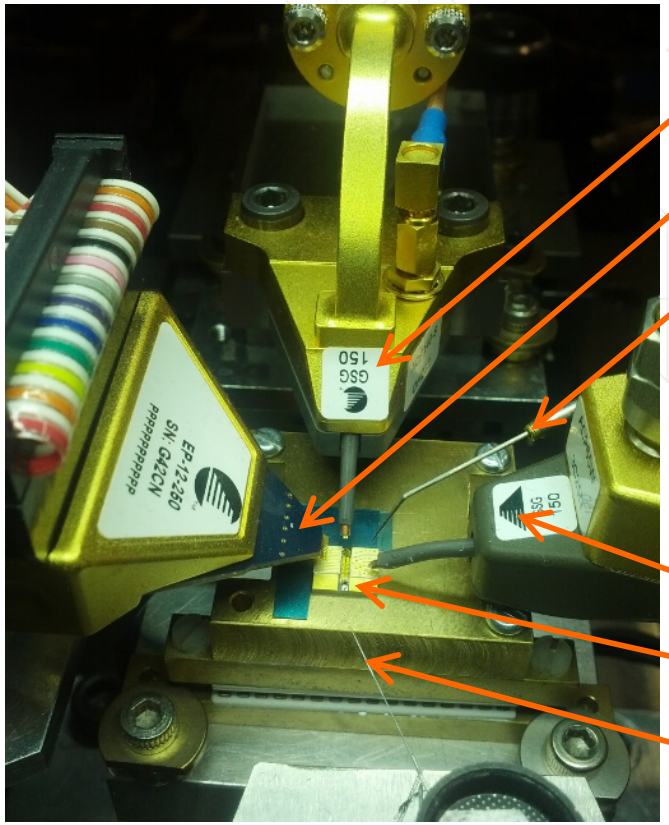

Fig. Measurement assembly

iPHOS www.iphos-project.eu

III-V lab

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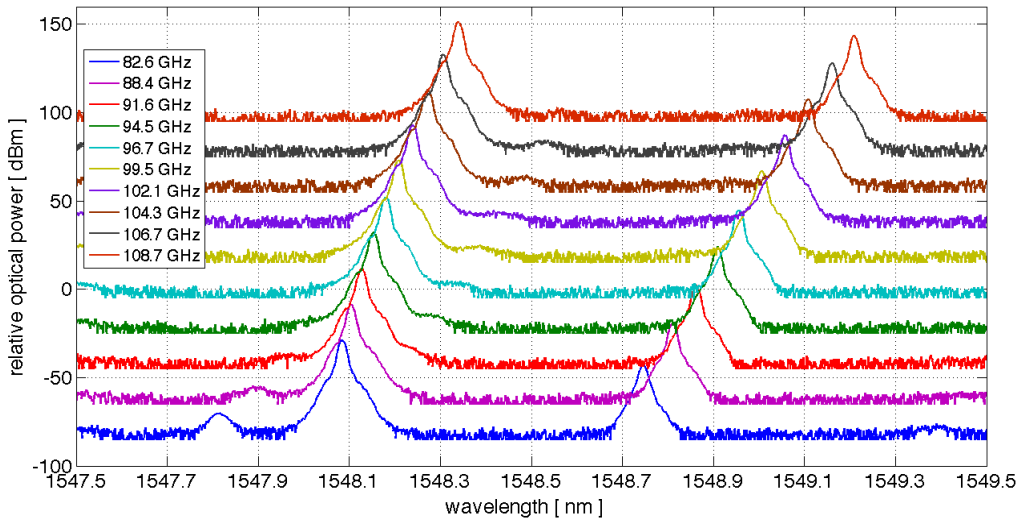
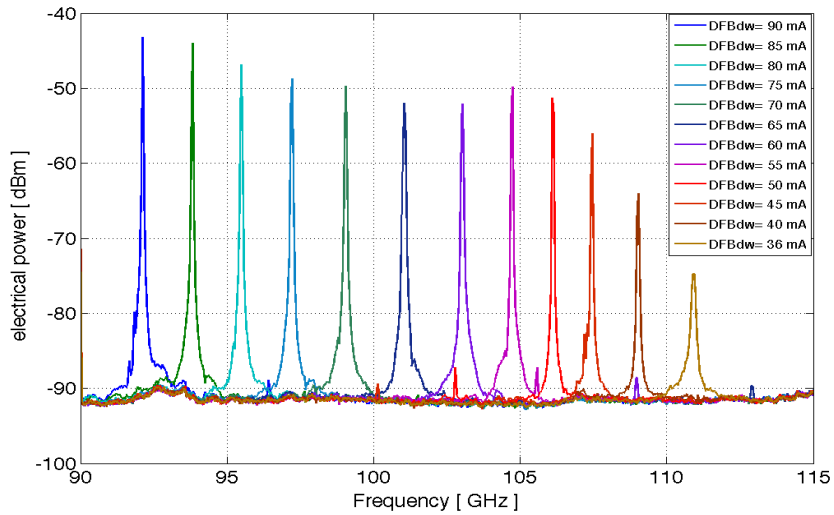
Laser/UTC-PD Integration

Optical spectra:



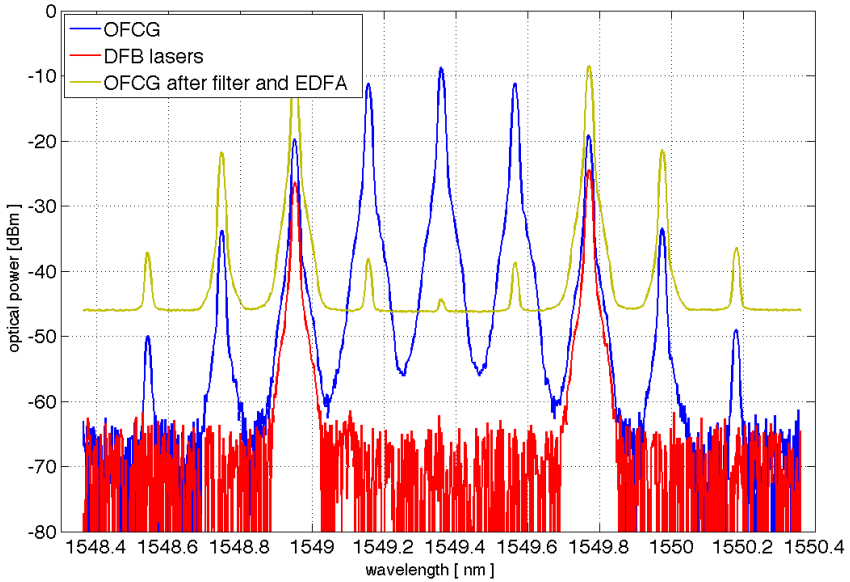
Electrical spectra:

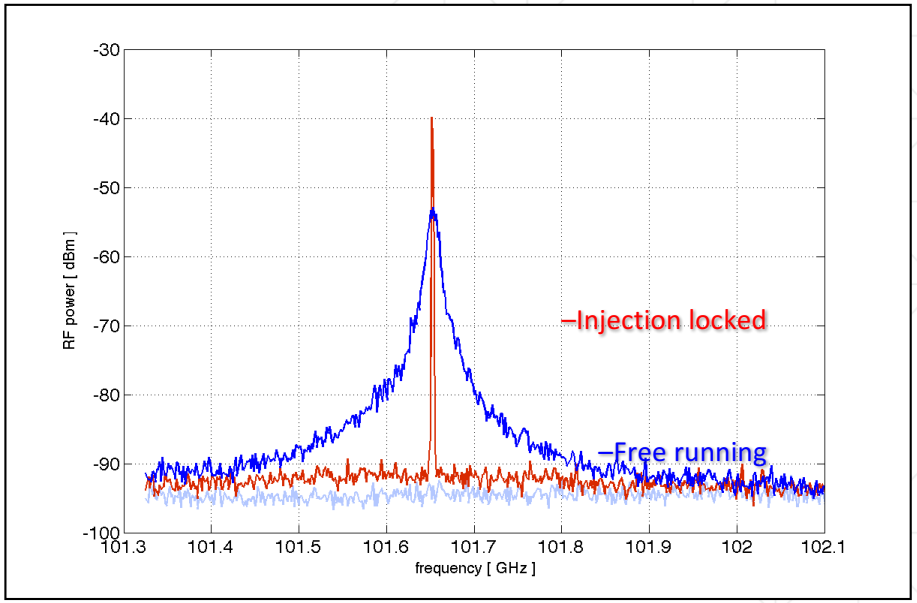


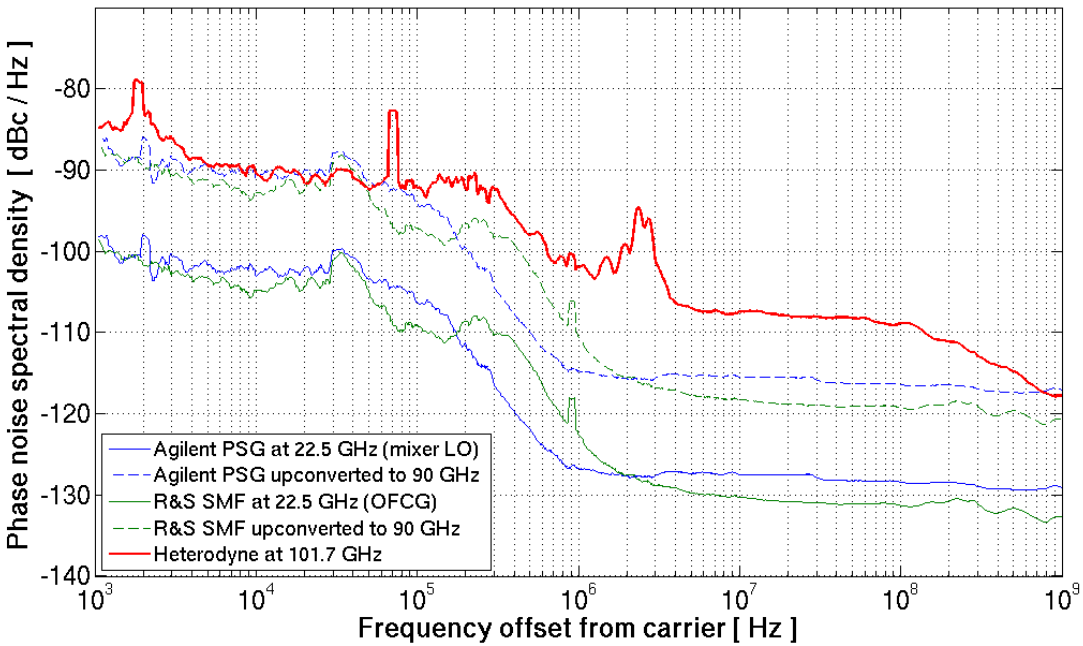
- DFB laser FWHM linewidth:~ 2-3 MHz
- DFB laser phase section tuning sensitivity of 1,45 GHz/mA
- Detected electrical power **-10 dBm** at **100 GHz** from on-chip photodiode (-2.5 V bias, 8.7 mA photocurrent).

- Total power consumption of the chip (with TEC): **1W**
- Millimetre signal tuning range from 60 to 120 GHz

Injection locking results







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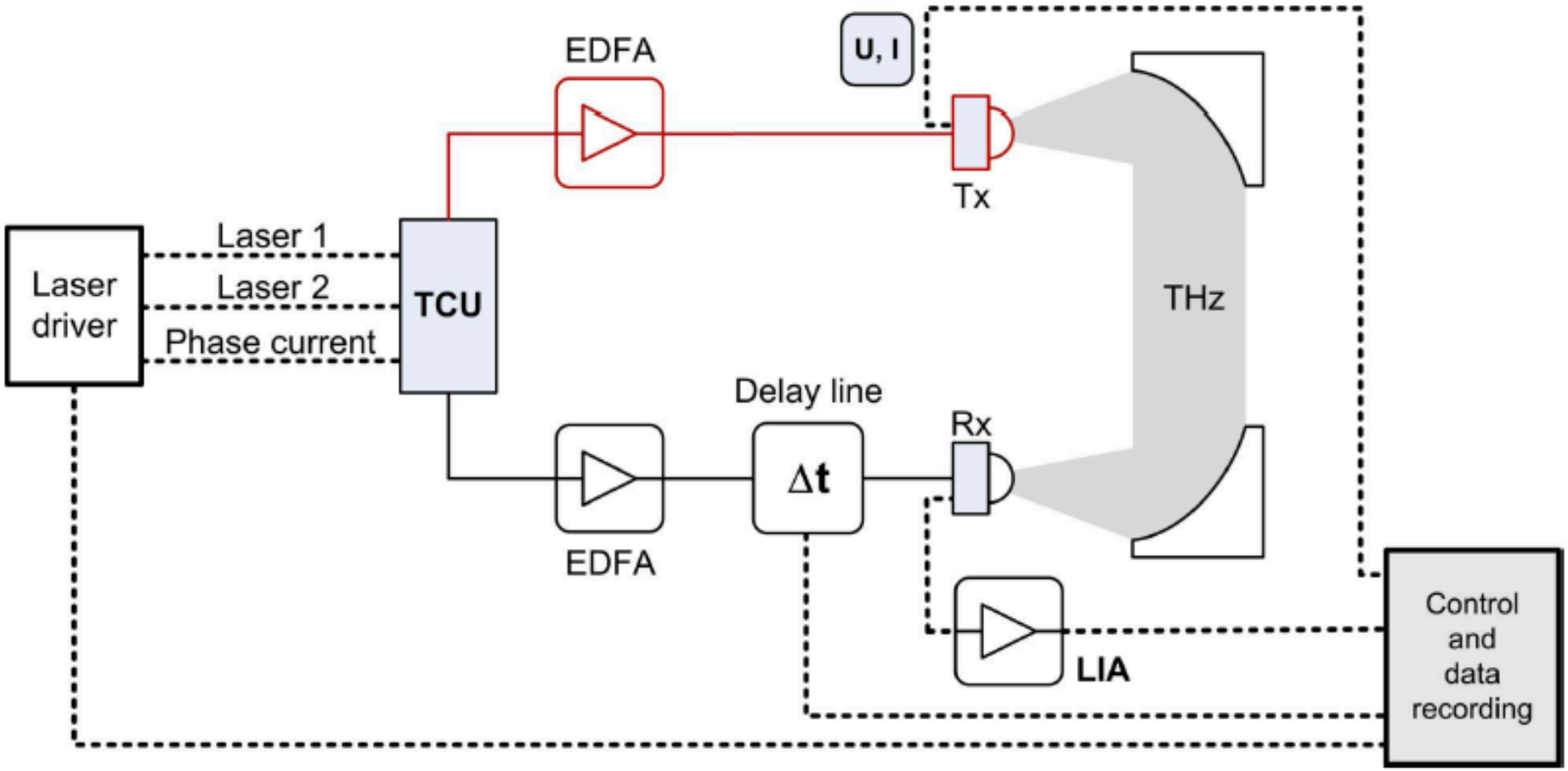
CW THz spectrometer Integrated source



Fraunhofer
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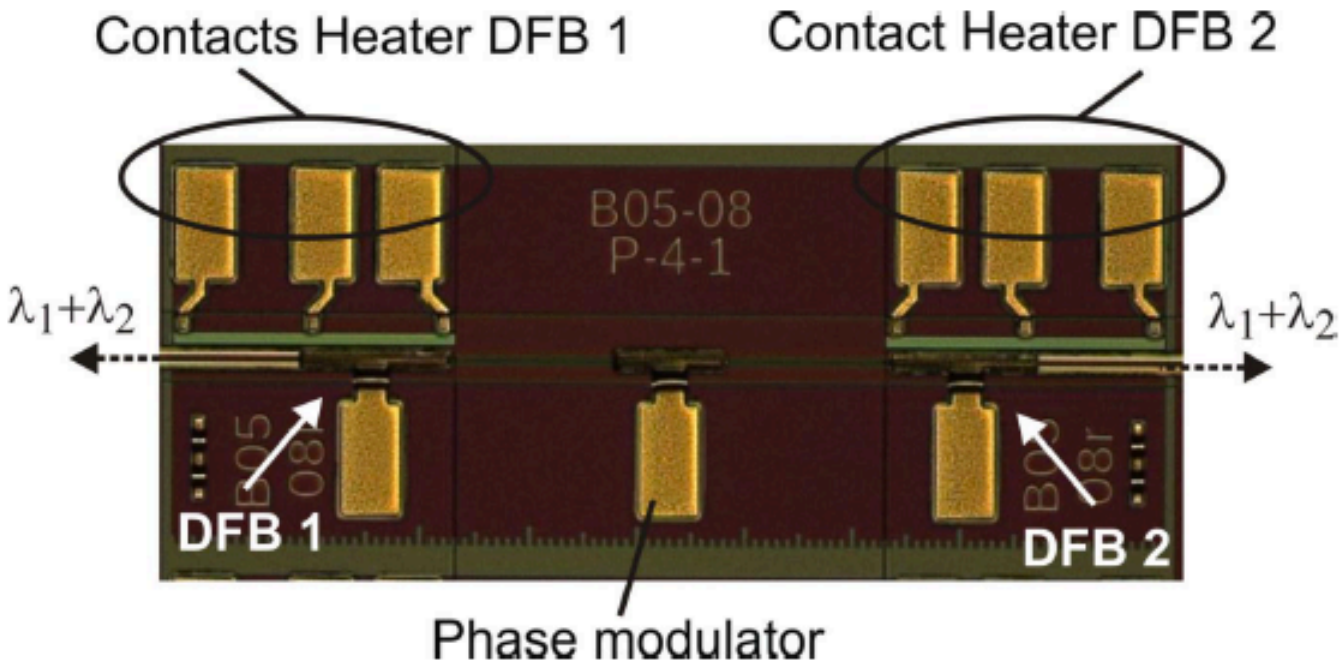
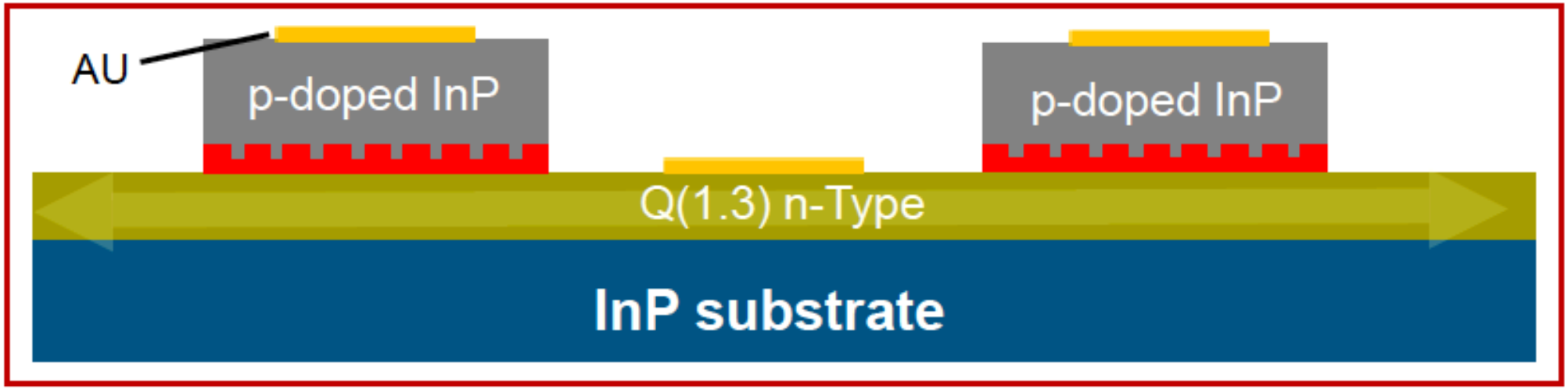
Integrated dual laser source





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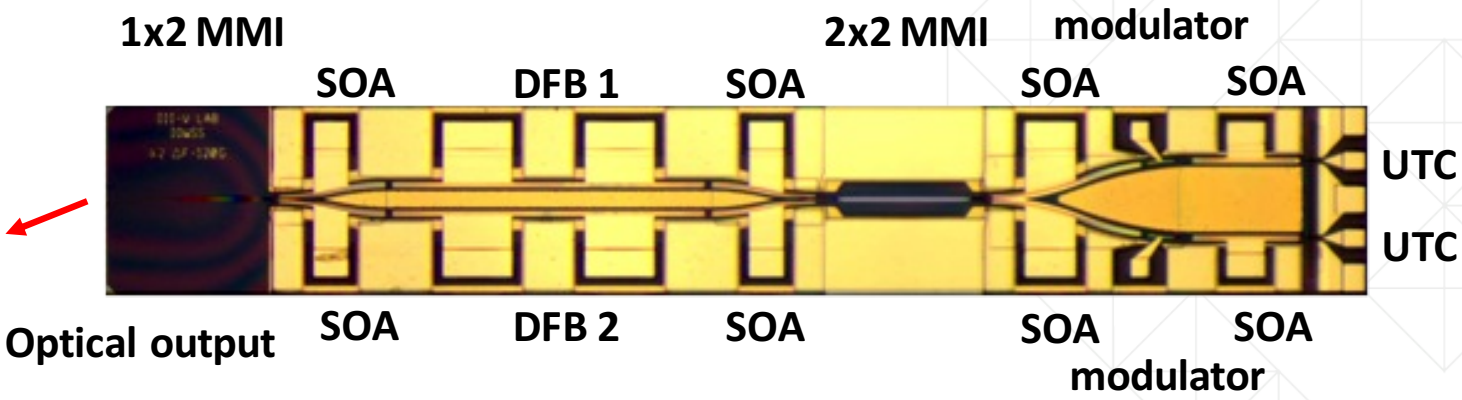
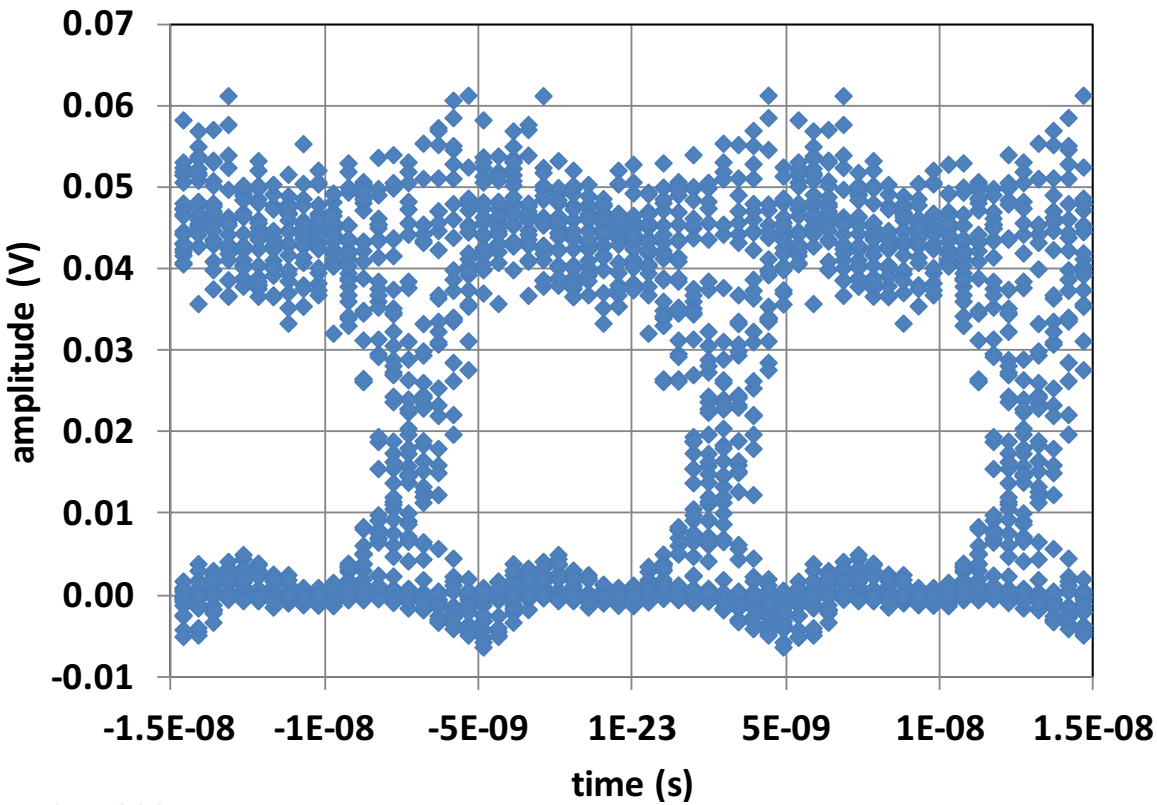
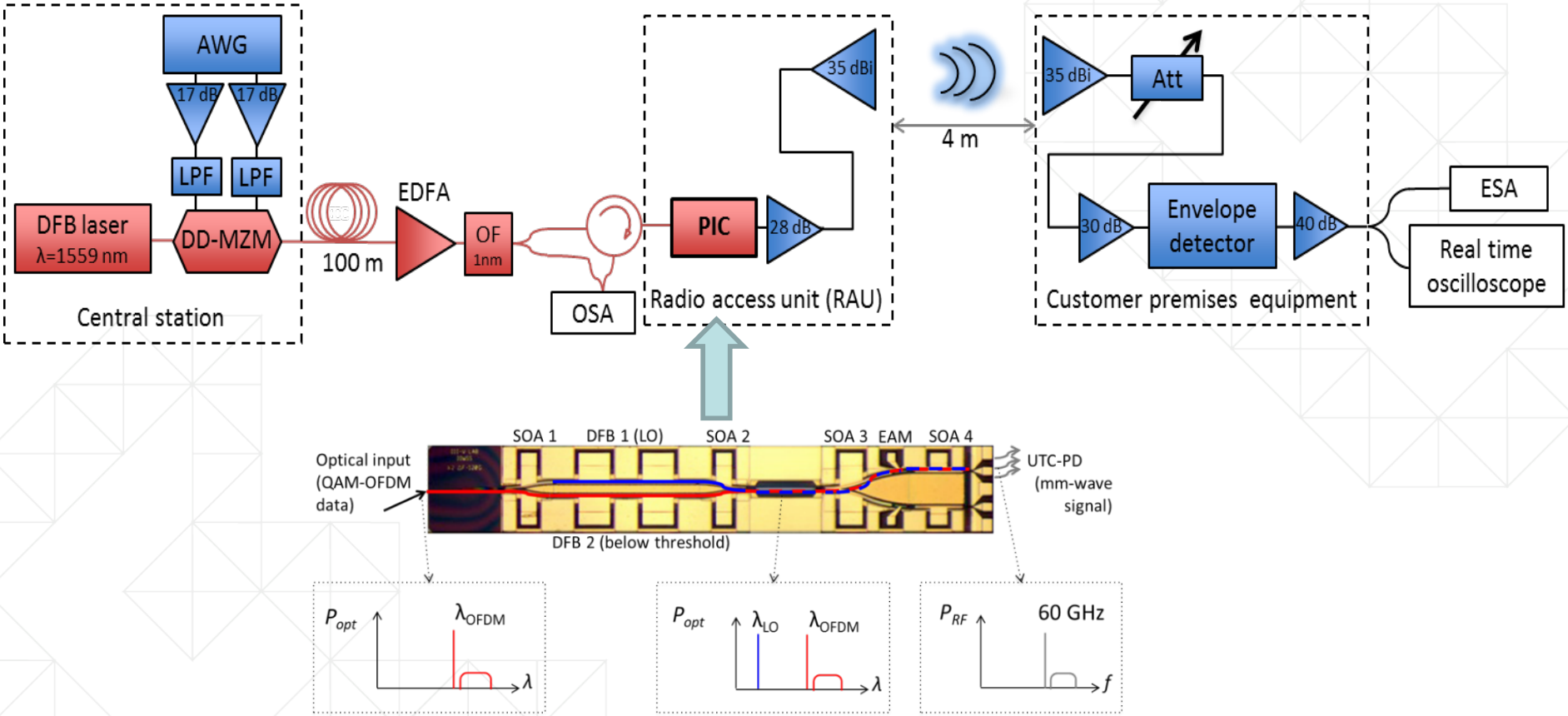
Potential for integration





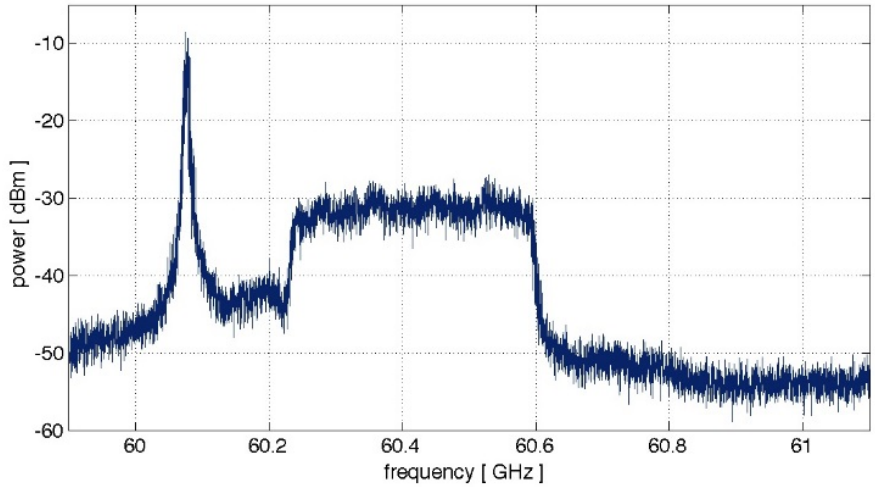
- 100 Mbit/s OOK demonstrated across a few meters.

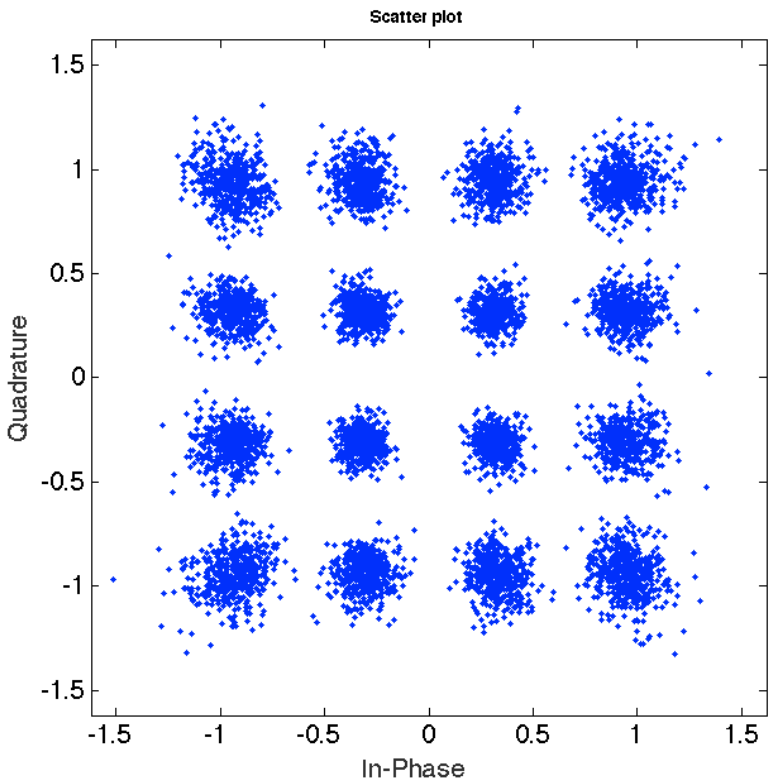
Use of the PIC as a RAU



- The laboratory experimental setup was based on a **PIC on Carrier** delivered by III-V (iPHOS design).
- Due to space limitation in Lab demonstration the signal received was attenuated.
- Sets of modulations were investigated. Chosen report is on **16 QAM OFDM, 1.2 Gb/s** data rate

Link performances





- Full demonstration of downlink operation with potential transmission up to 1 km (no attenuation at receiver, 43 dBi antenna and 15 dBm out of emitter)
- BER better than the FEC limit (1.27 10^{-4})
- Spacing between carrier and data is necessary to reduce signal-subcarrier beat interference.
- Demonstration of up to 10.8 Gb/s with 9x380 MHz bandwidth channels.

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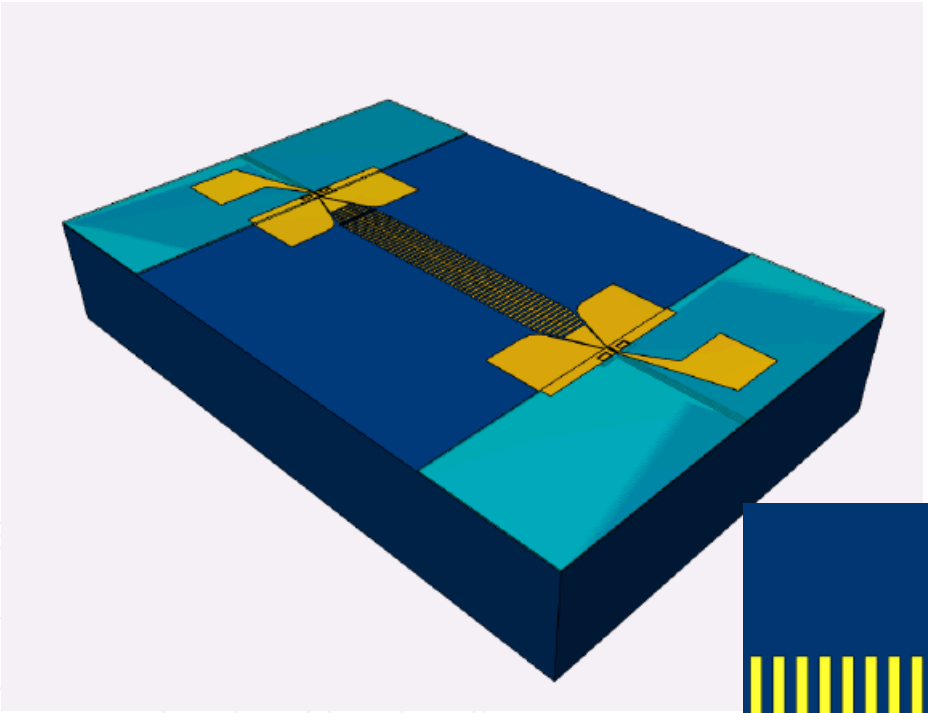
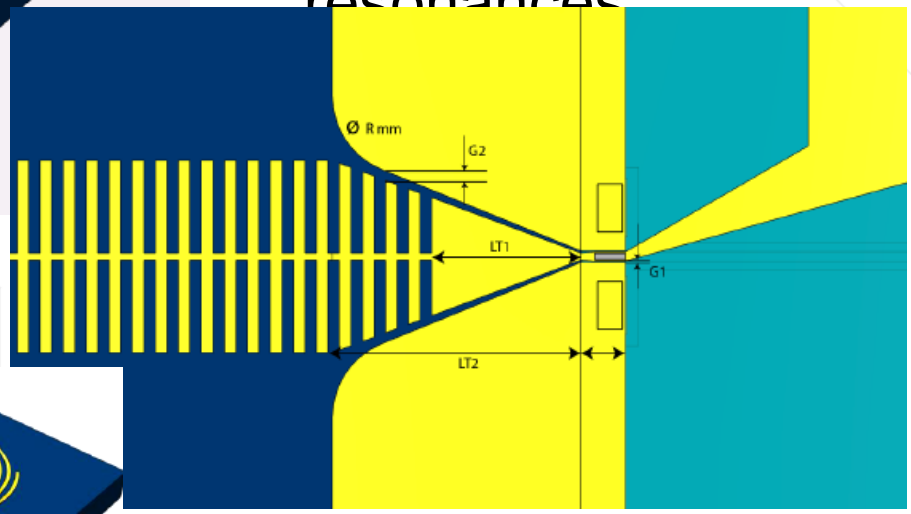
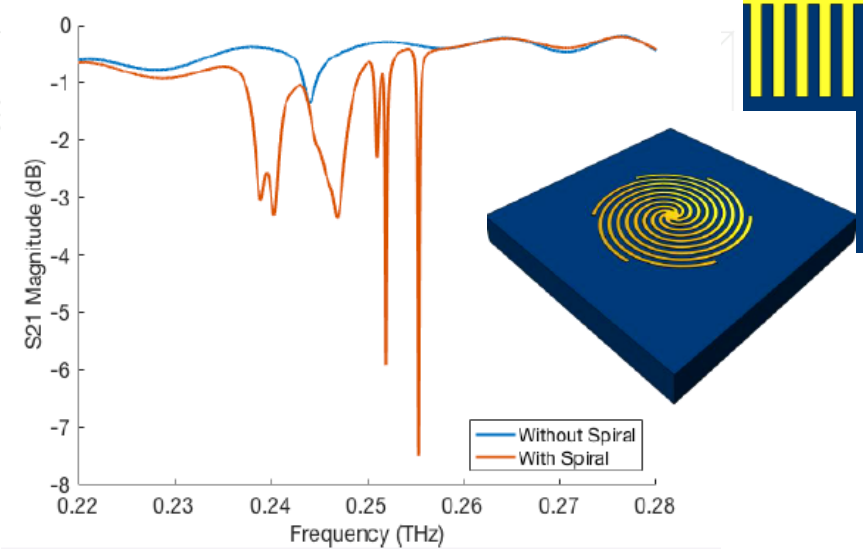
Lab on Chip UTC based sensor



- Development of Spoof Plasmonic waveguides and resonators
- UTC as emitter and receiver
- Enhanced sensitivity and contrast for detection of resonances





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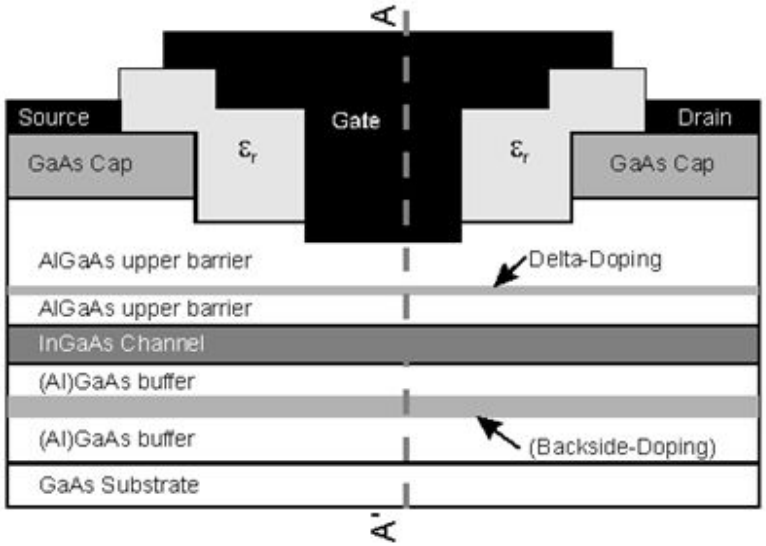
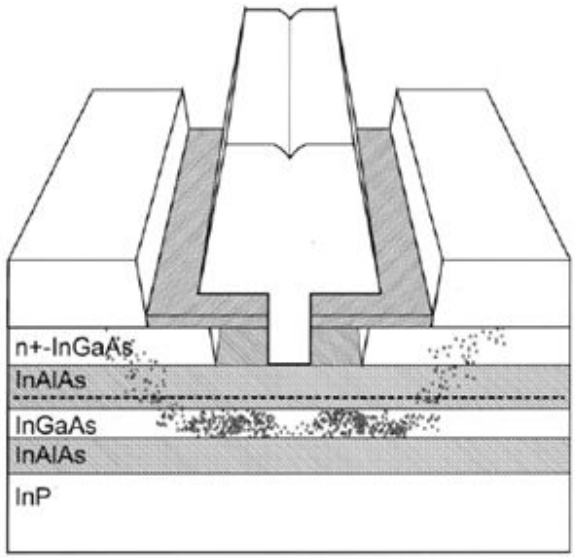
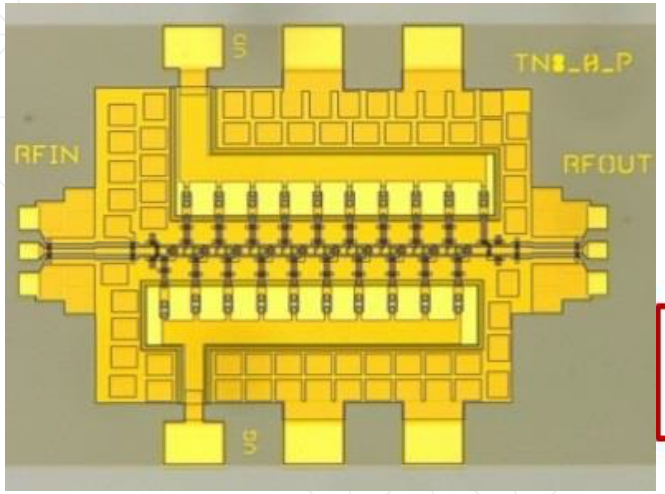
Electronic components: InP HEMTs



GaAs-based HEMT

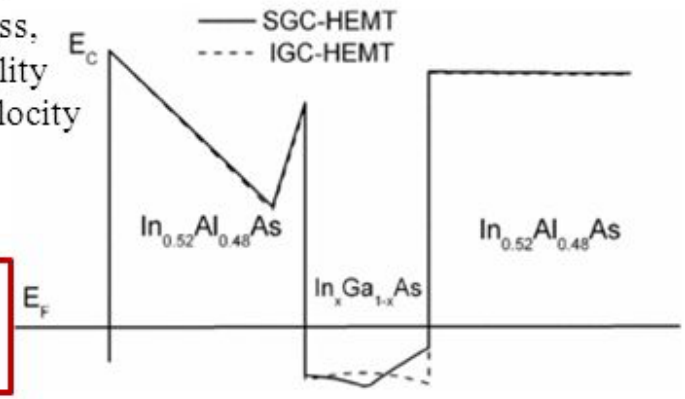


InP-based HEMT



e^- in InP-based HEMT:

- lower effective mass, hence higher mobility
- High saturation velocity
- High electron concentration



InP-based HEMTs
Higher Speed !

W. R. Deal, "Demonstration of a 0.48 THz Amplifier Module Using InP HEMT Transistors ," IEEE Microwave and Wireless Components Letters 20, 289-291 (2010)

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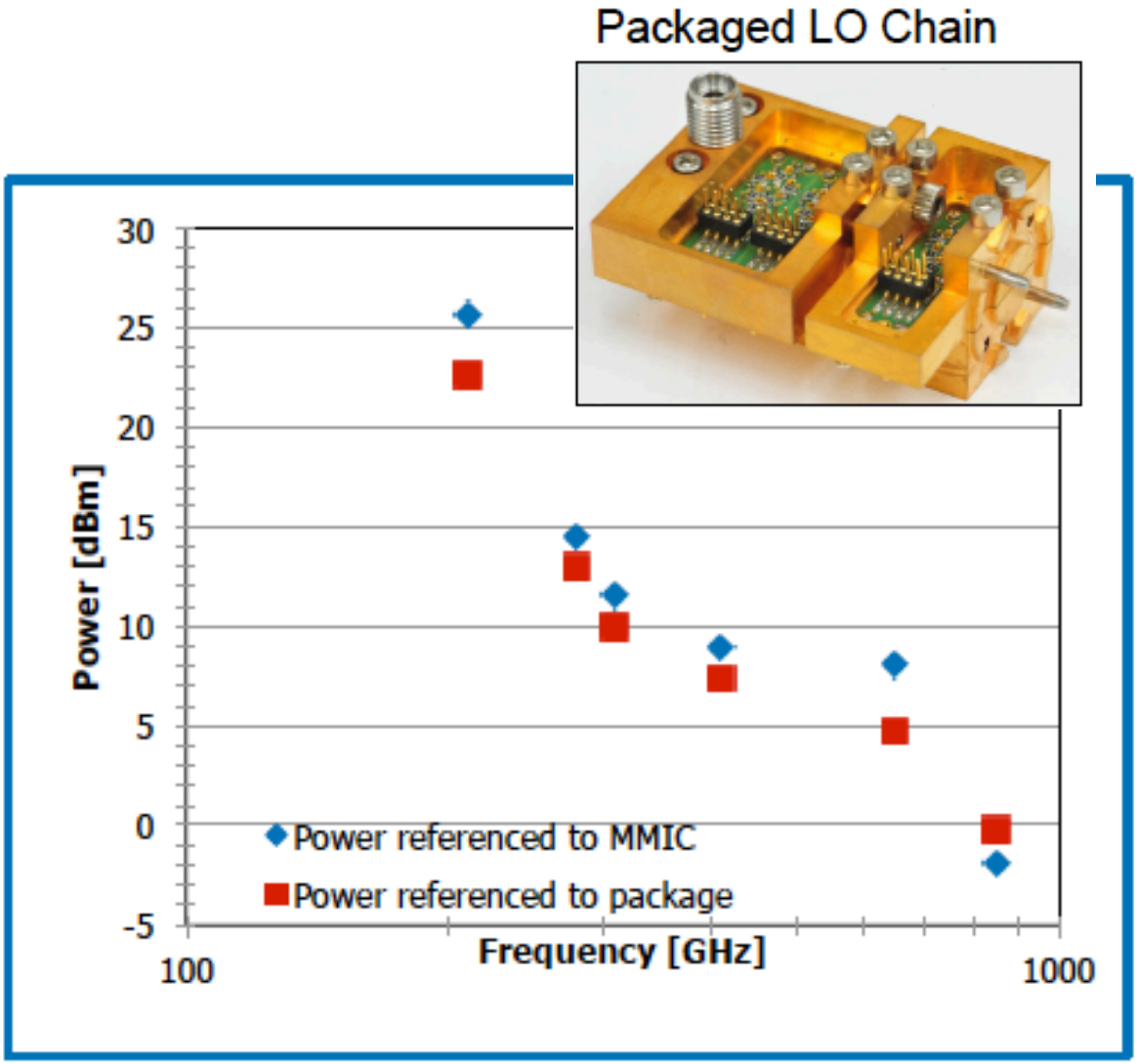
Performances up to 1 THz



- Strong emitters up to almost 1 THz
- Not broadly tuneable but high power and high level of integration
- Oscillator quality similar to best photonic solution
- Relatively complex system with amplifiers and multipliers

NORTHROP GRUMMAN

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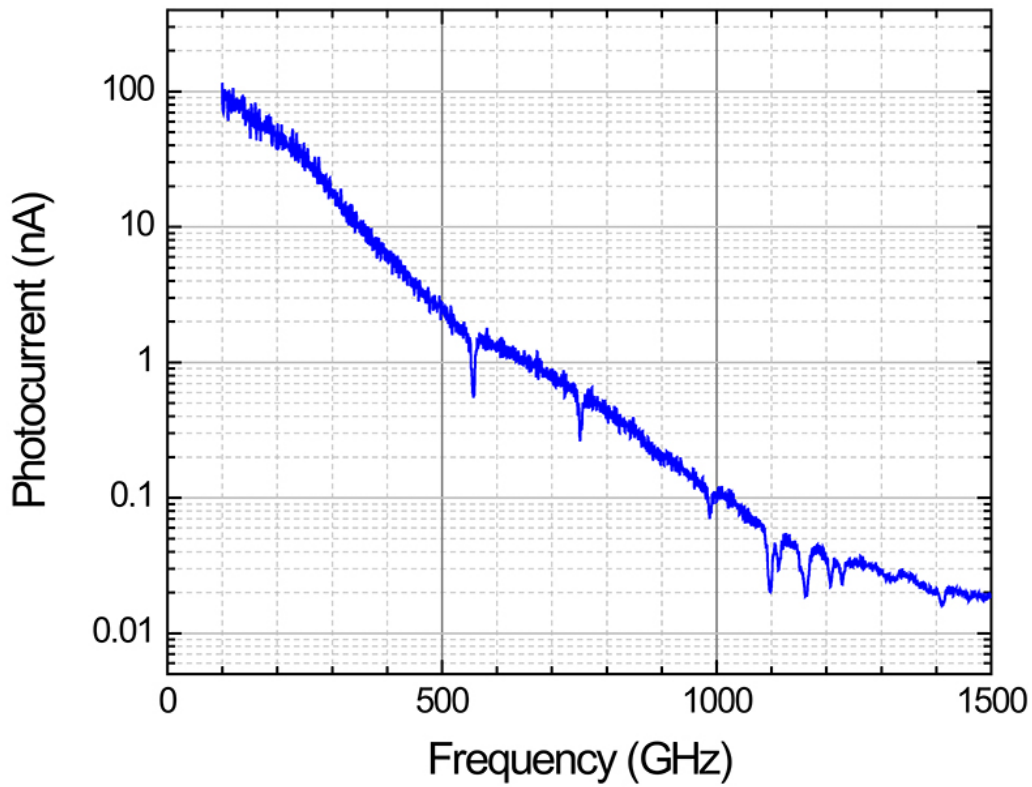
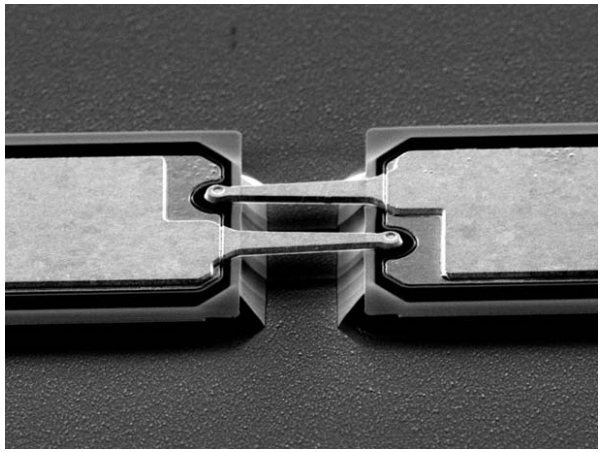
Schottky diode for THz detection

Specifications	High Responsivity	High Bandwidth
Concept	Zero-bias Schottky diode	
Terahertz bandwidth	50 – 1500 GHz	
Noise-equivalent power	7 pW/sqrt(Hz) @ 100 GHz 100 pW/sqrt(Hz) @ 1 THz	70 pW/sqrt(Hz) @ 100 GHz 1000 pW/sqrt(Hz) @ 1 THz
Responsivity	25000 V/W @ 100 GHz 2000 V/W @ 1 THz	250 V/W @ 100 GHz 20 V/W @ 1 THz





TOPTICA PHOTONICS

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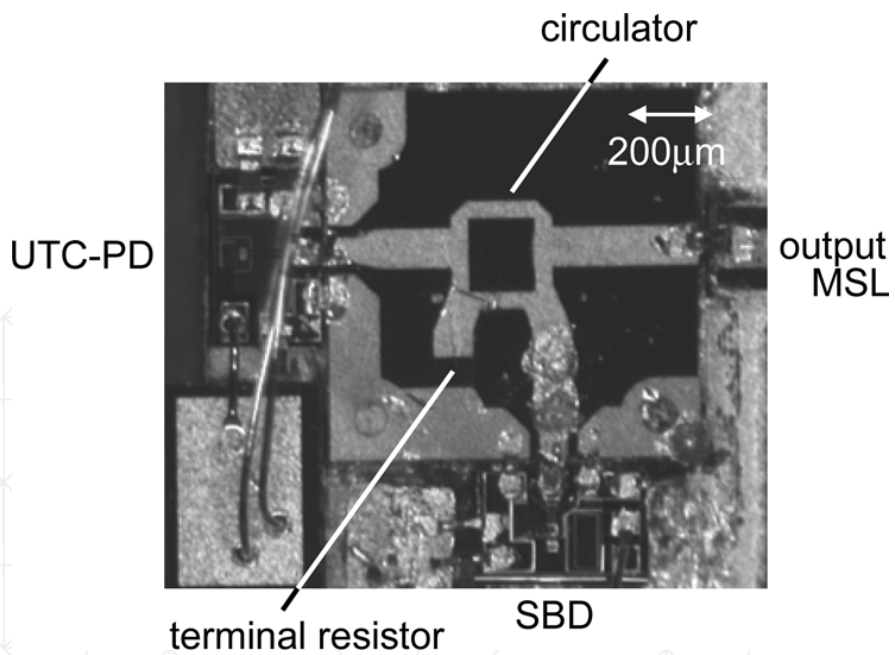
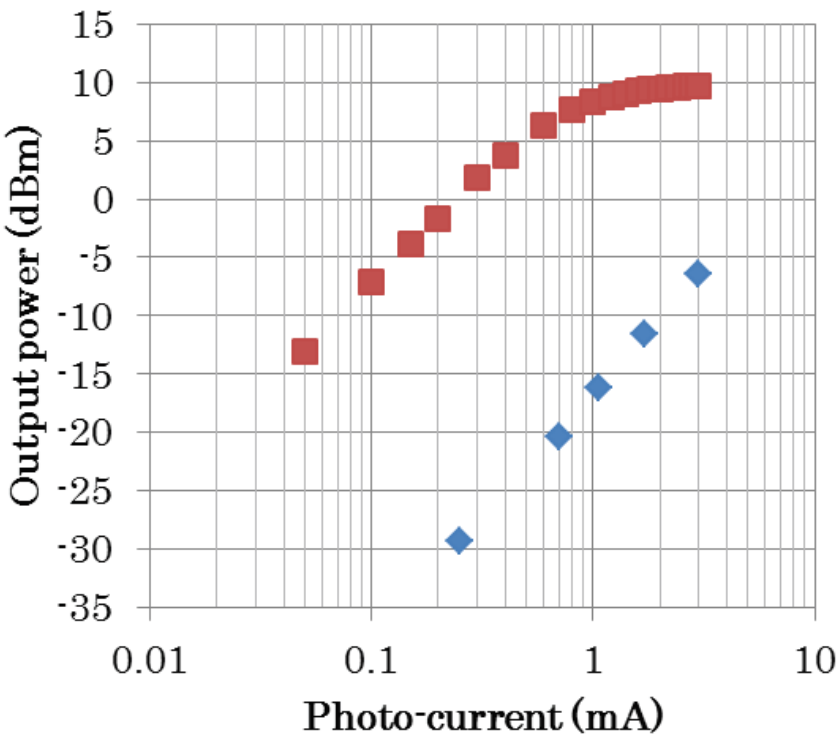
Hybrid UTC integration

- Hybrid integration has been done with both HEMT InP amplifier and InP Schottky mixer





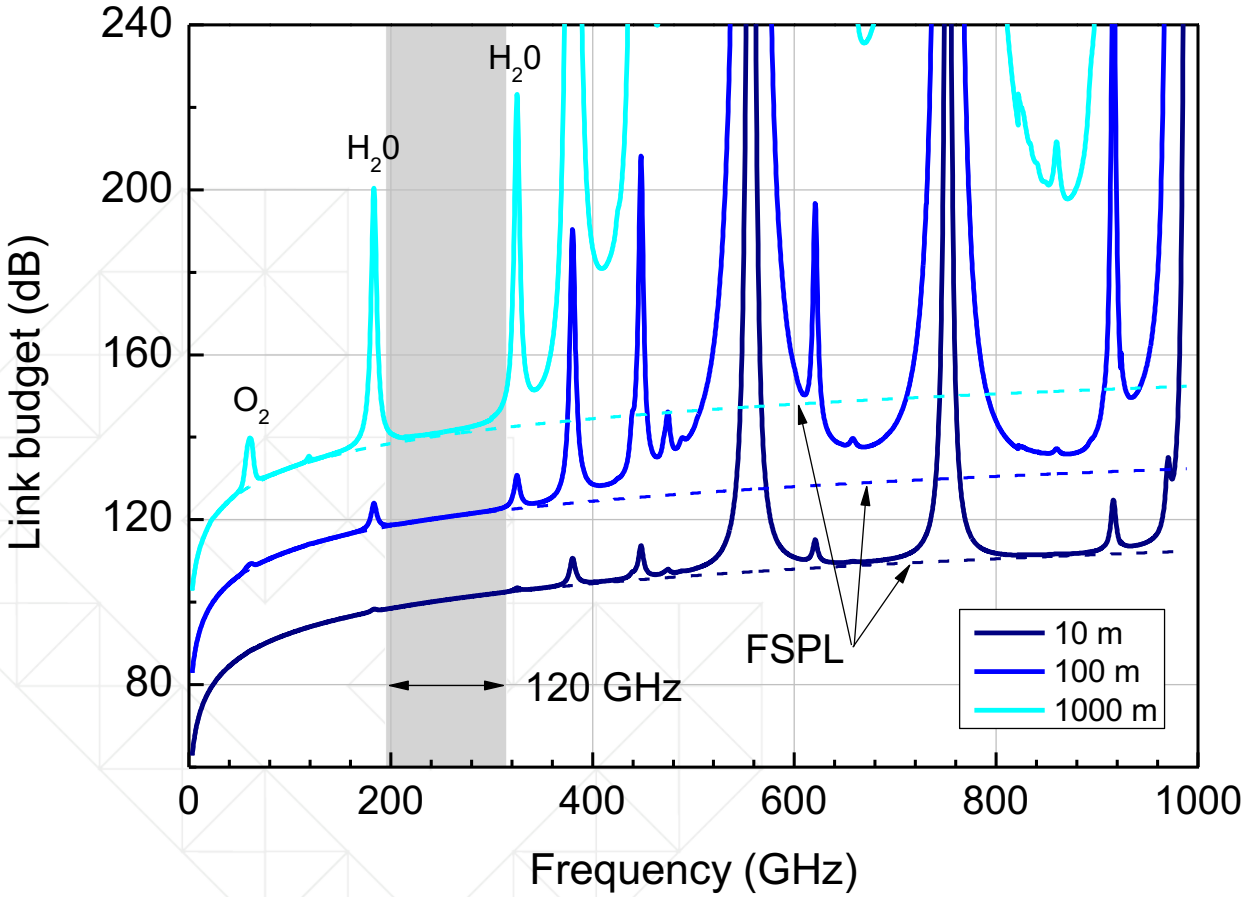
Umezawa, T. *et al.*, "High conversion gain, low power consumption W-band photoreceiver integrated with UTC-PD and InP-PHEMT amplifier," presented at IEEE Topical Meeting in Microwave Photonics, Paphos Cyprus, 2015

Hiroshi Ito et al., "Sub-Terahertz Transceiver Module Integrating Uni-Traveling-Carrier Photodiode, Schottky Barrier Diode, and Planar Circulator Circuit,", J. of Lightwave Technologies 28, 3599-3605 (2010)

Outline

- Typical photonic THz systems
- THz system photonic components
  - Emitters
  - Receivers
- Integration technologies
  - Hybrid vs monolithic
  - InP platform technology
  - Silicon platform technology
  - Photonics subsystems
  - An example of Electronic THz components
- Example of application: THz Communication
- Conclusion

THz Atmospheric Transmission



- Licensed applications below ~300 GHz
  - Limited available unallocated spectrum below ~300 GHz: 3.5 GHz in ISM bands at 61.25 GHz, 122.5 GHz and 245 GHz
- Large available unallocated bandwidth above 300 GHz despite water absorption, especially around 350GHz

T. Nagatsuma, G. Ducournau, and C. C. Renaud, "Advances in terahertz communications accelerated by photonics," **[invited]** *Nature Photonics (Review)*, vol. 10, no. 6, pp. 371–379, 2016.

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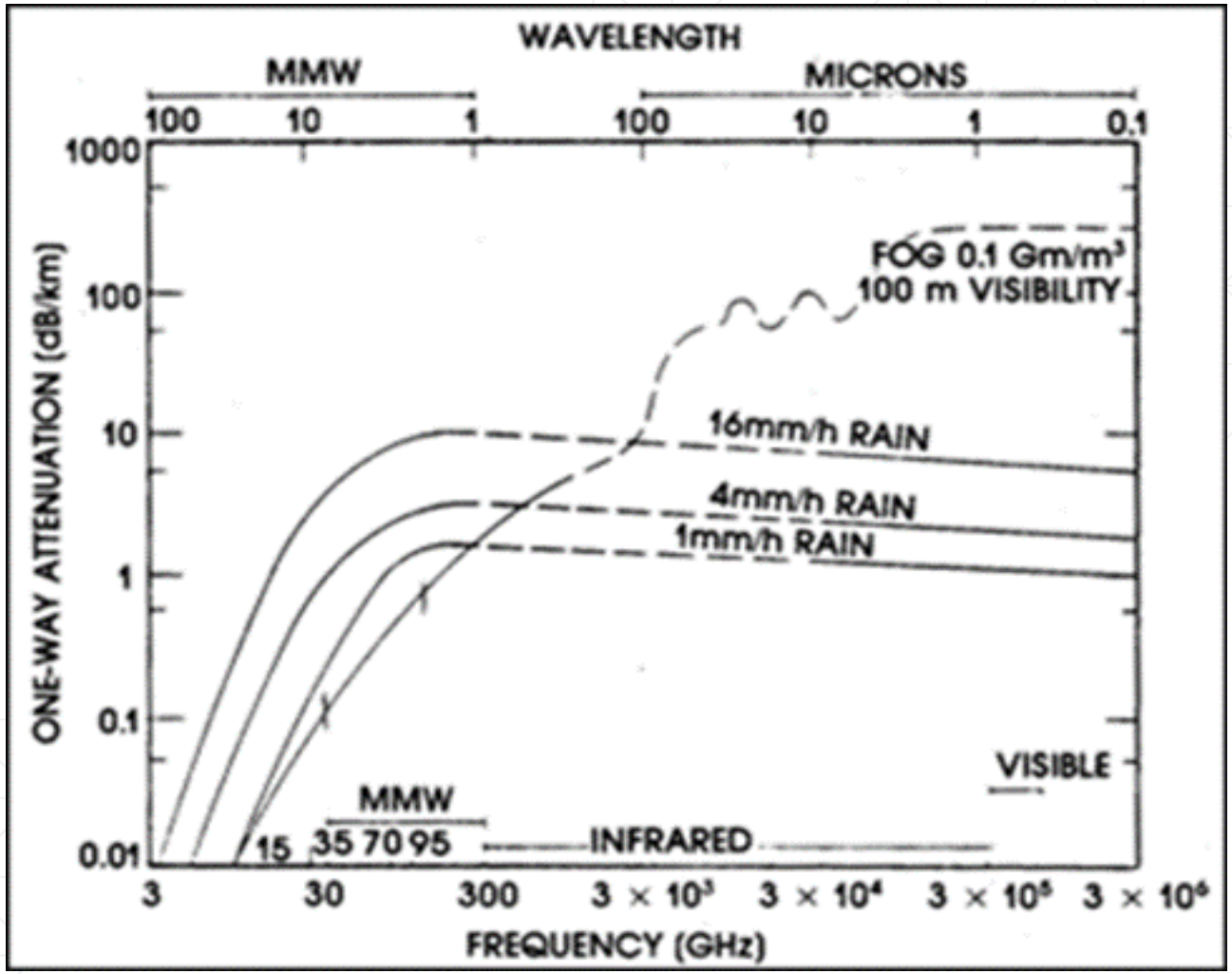
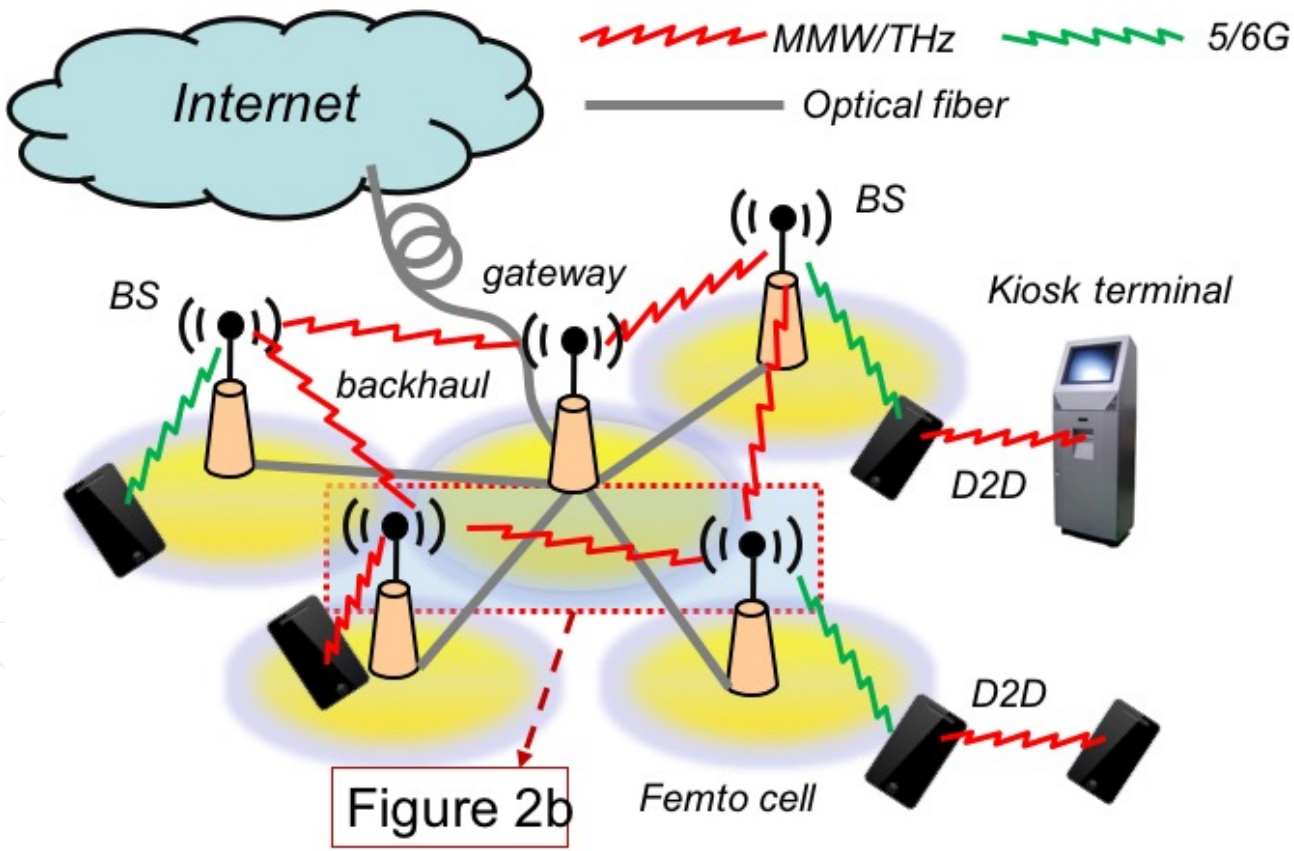
Rain and fog absorption across frequencies

- Rain absorption is relatively flat from 100 GHz to visible light (few dB better)
- Fog however is quite different with visible light 2 orders of magnitude higher in losses compared to 300 GHz



C. E. B. Nicholas C. Currie, *Principles and Applications of Millimetre Wave Radar*. Norwood, MA: Artech House, 1987

THz wireless link



- Best achieved performances are:
  - up to 200 Gbit/s with FEC and offline processing at 100 GHz carrier and 0.5 m transmission
  - Up to 1 km transmission at 10 Gbit/s (real time) at 120 GHz carrier

On full electronic solution (MMIC): 64 Gbit/s, 240 GHz carrier, 850 m transmission

T. Nagatsuma, G. Ducournau, and C. C. Renaud, "Advances in terahertz communications accelerated by photonics," **[invited]** *Nature Photonics (Review)*, vol. 10, no. 6, pp. 371–379, 2016.

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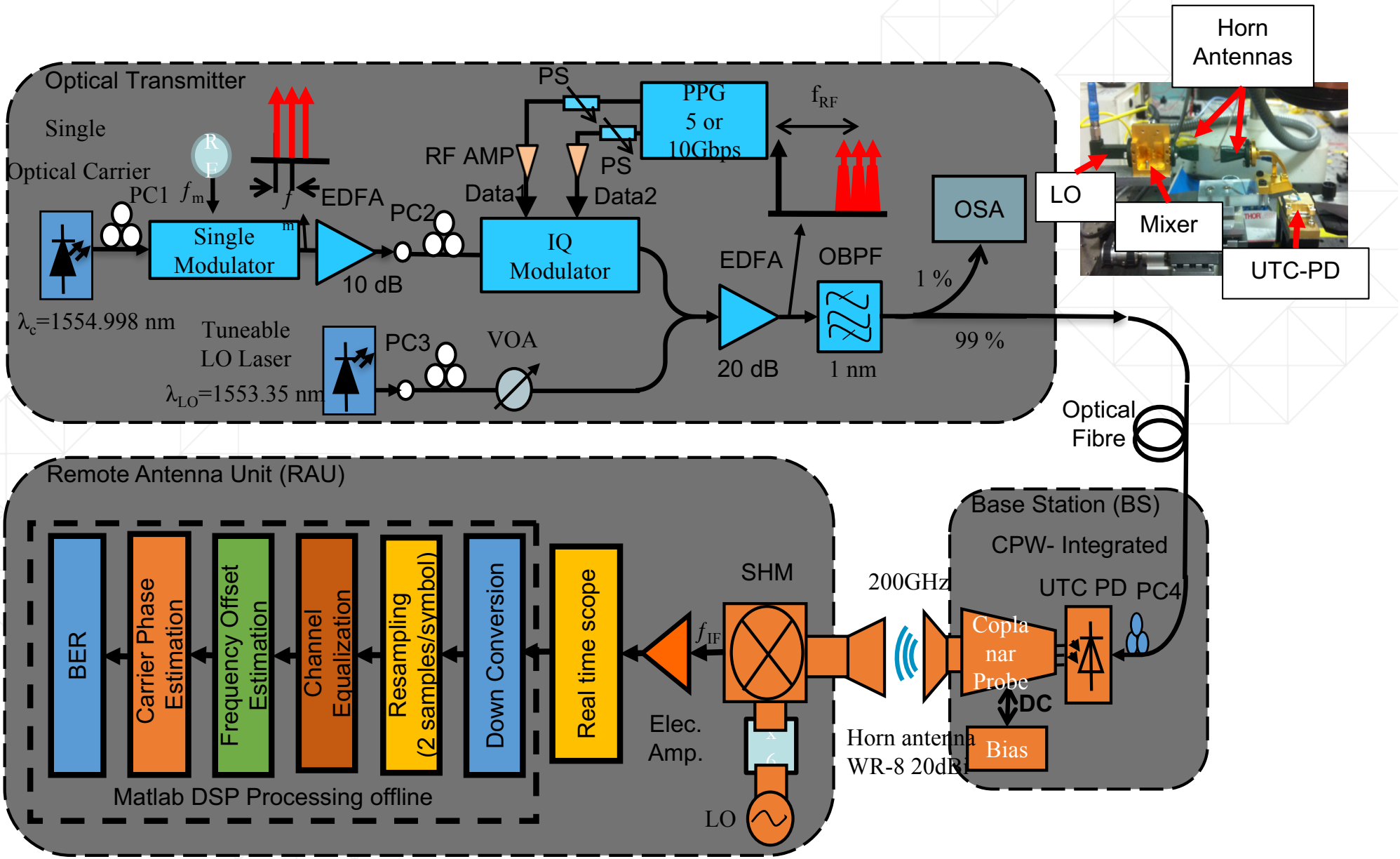
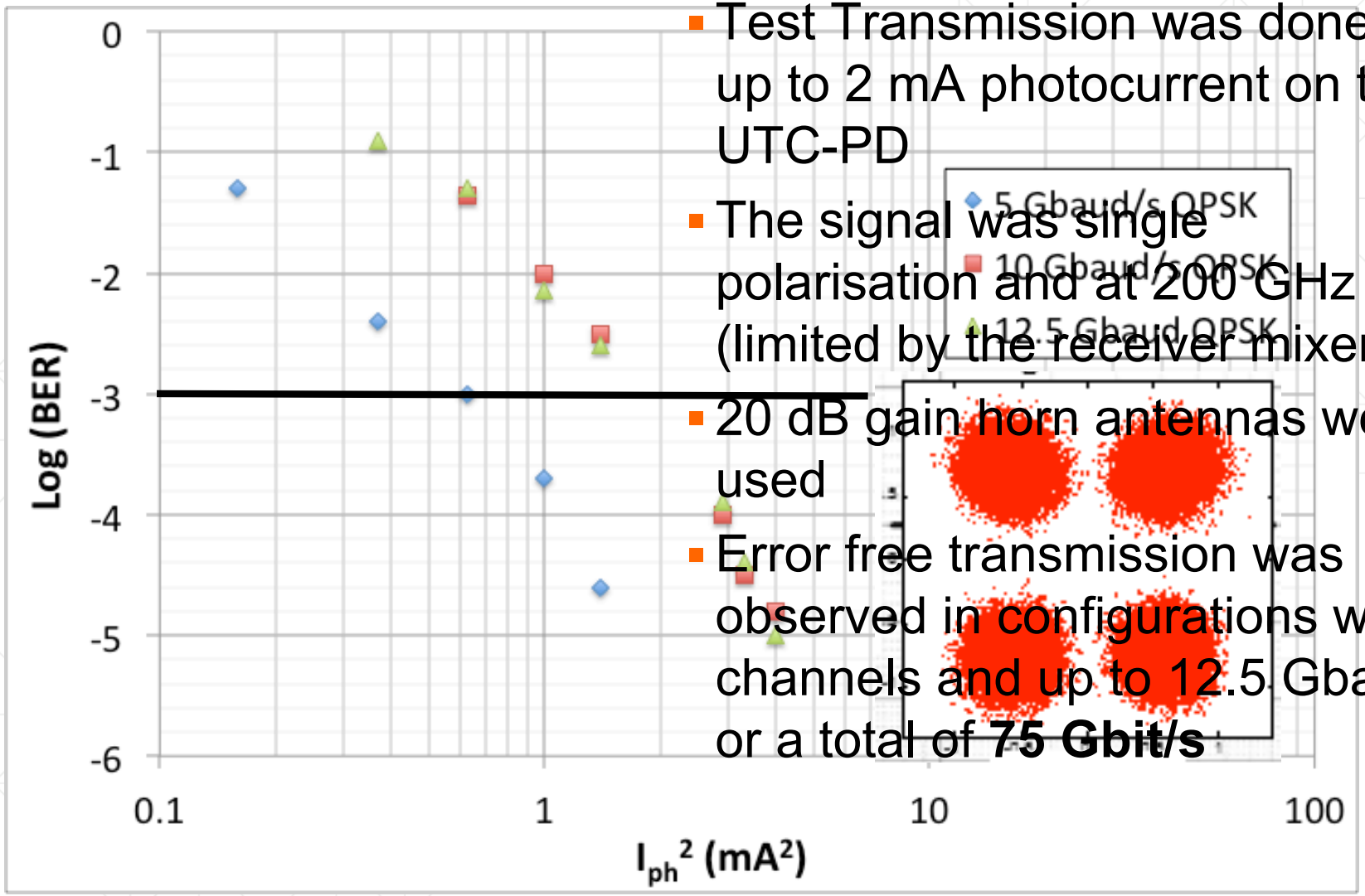
Example of a transmission system

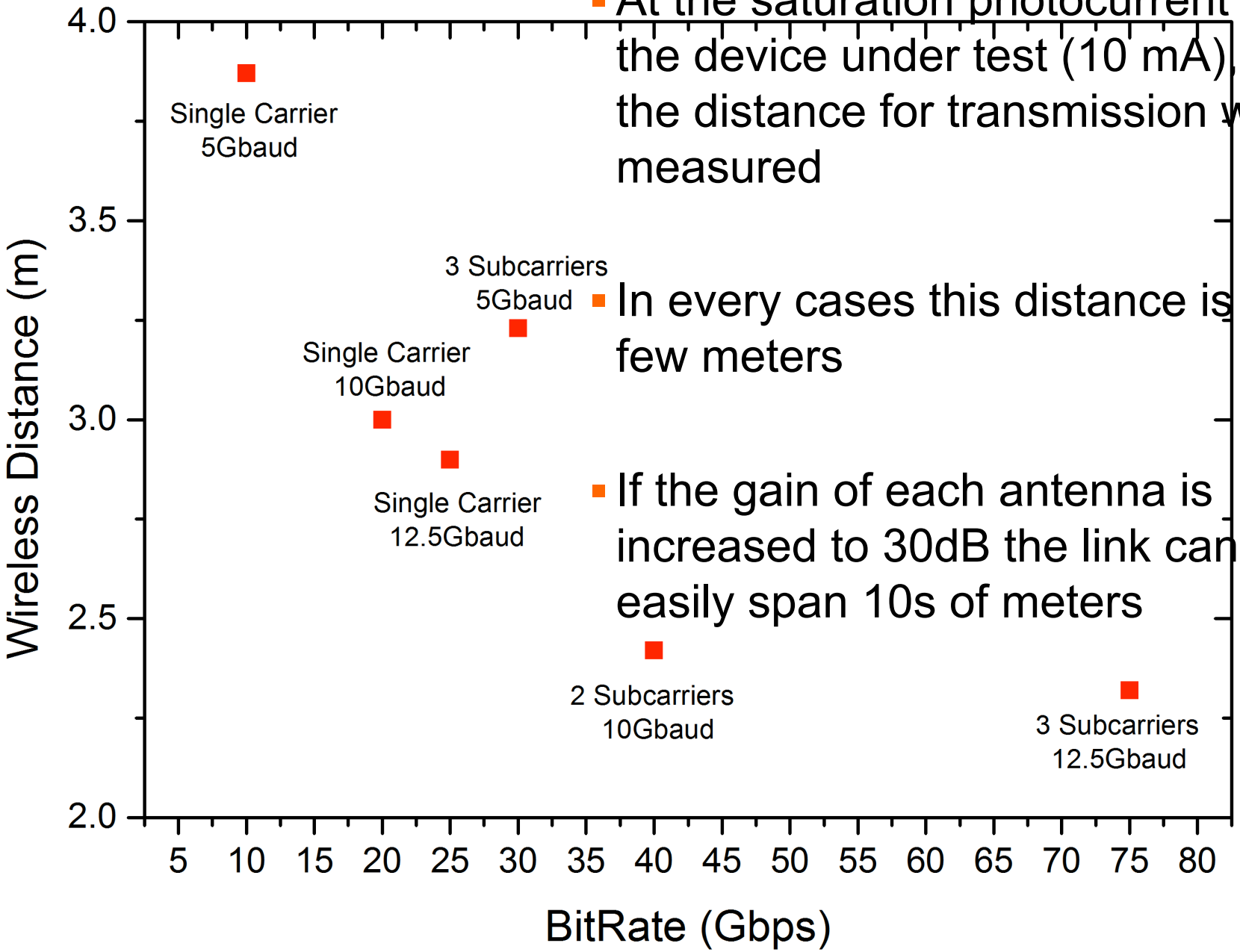


Experimental results



- Test Transmission was done with up to 2 mA photocurrent on the UTC-PD
- The signal was single polarisation and at 200 GHz (limited by the receiver mixer)
- 20 dB gain horn antennas were used
- Error free transmission was observed in configurations with 3 channels and up to 12.5 Gbaud/s or a total of **75 Gbit/s**

Distances of transmission



- At the saturation photocurrent for the device under test (10 mA), the distance for transmission was measured
- In every cases this distance is a few meters
- If the gain of each antenna is increased to 30dB the link can easily span 10s of meters

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Summary and Conclusion

- Photonic is an attractive solution for THz offering broad tuning and competitive power compared to electronic solutions

- Integration of photonic systems is progressing

- Integrated system showing performances necessary for coherent photonic millimetre wave and THz system have been demonstrated

- Highlights: Full heterodyne sources up to 1THz, 100 μW output power from a single heterodyne chip with <1W consumption, <10Hz linewidth demonstrated.

- Questions for the future:
  - What is the right balance in a hybrid system?
  - Higher power?
  - Efficient receivers?
  - integration with other technologies

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Acknowledgement

iPHOS
www.iphos-project.eu

COTS
Coherent Terahertz Systems

Information Society Technologies

SEVENTH FRAMEWORK PROGRAMME

EPSRC Engineering and Physical Sciences Research Council

III-V lab

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