This project is co-funded by

Horizon 2020

NICT National Institute of Information and Communications Technology

THOR

Photonics approaches for THz coms

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Context

Photomixers, Tx/Rx

Some systems

Project Exemples

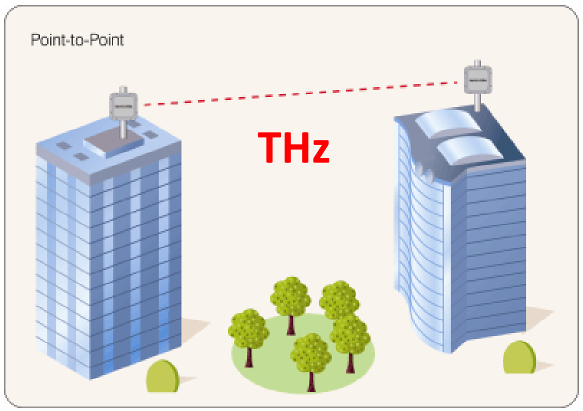
Conclusions/challenges

Massive data + Beyond 5G + urban cases: > 100 user/cell

Needs Tbps/cell + Fast cell-to-cell links!

Context

- Why using THz for coms?
- Point to point?



Fluidmesh.com

- Looking at Shannon

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

B: bandwidth

S/N = signal/noise

C = capacity (bit/s)

RADIO: Small B, High S/N (MIMO, RF performances)

THz: High Bandwidth, limited RF performances (power)

Photonics can help!

Main focus/challenge

Fixed points for THz **Tx**/**Rx**: optical fibers can be coupled to **deliver**/**collect** the BW to the antennas (concept of **RAU, Remote Antenna Unit**)

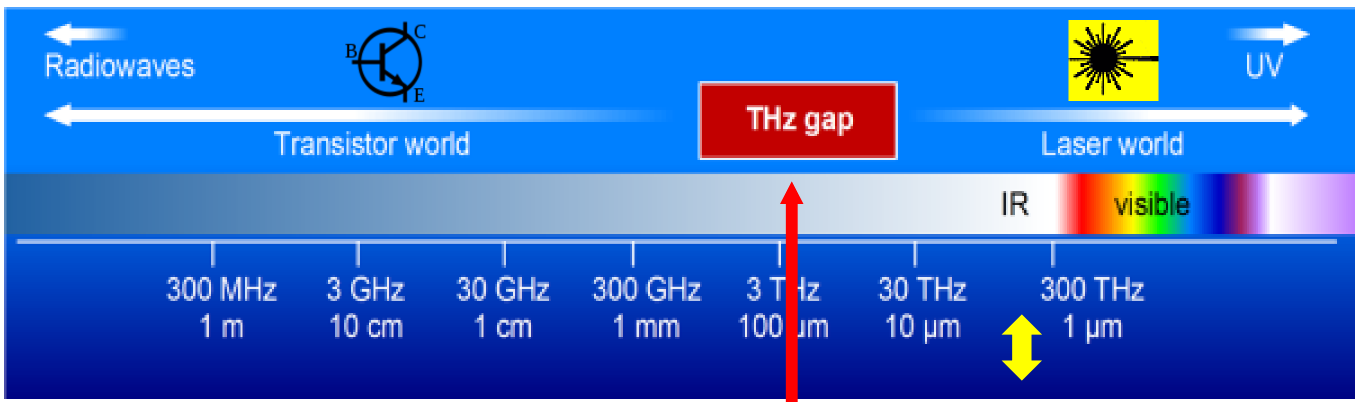
What source for Datacoms?

- **Sources**

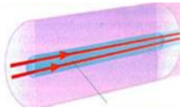
➢ Electronic sources:
- TMICs, Multiplication chains, RTD, transistors, diodes, TWTA …

Direct (not easy) or mixing (low power) for modulation
But active devices on the way

➢ Opto-electronics:
- Photodiodes, photoconductors
(tunable, very easy to modulated)
low power



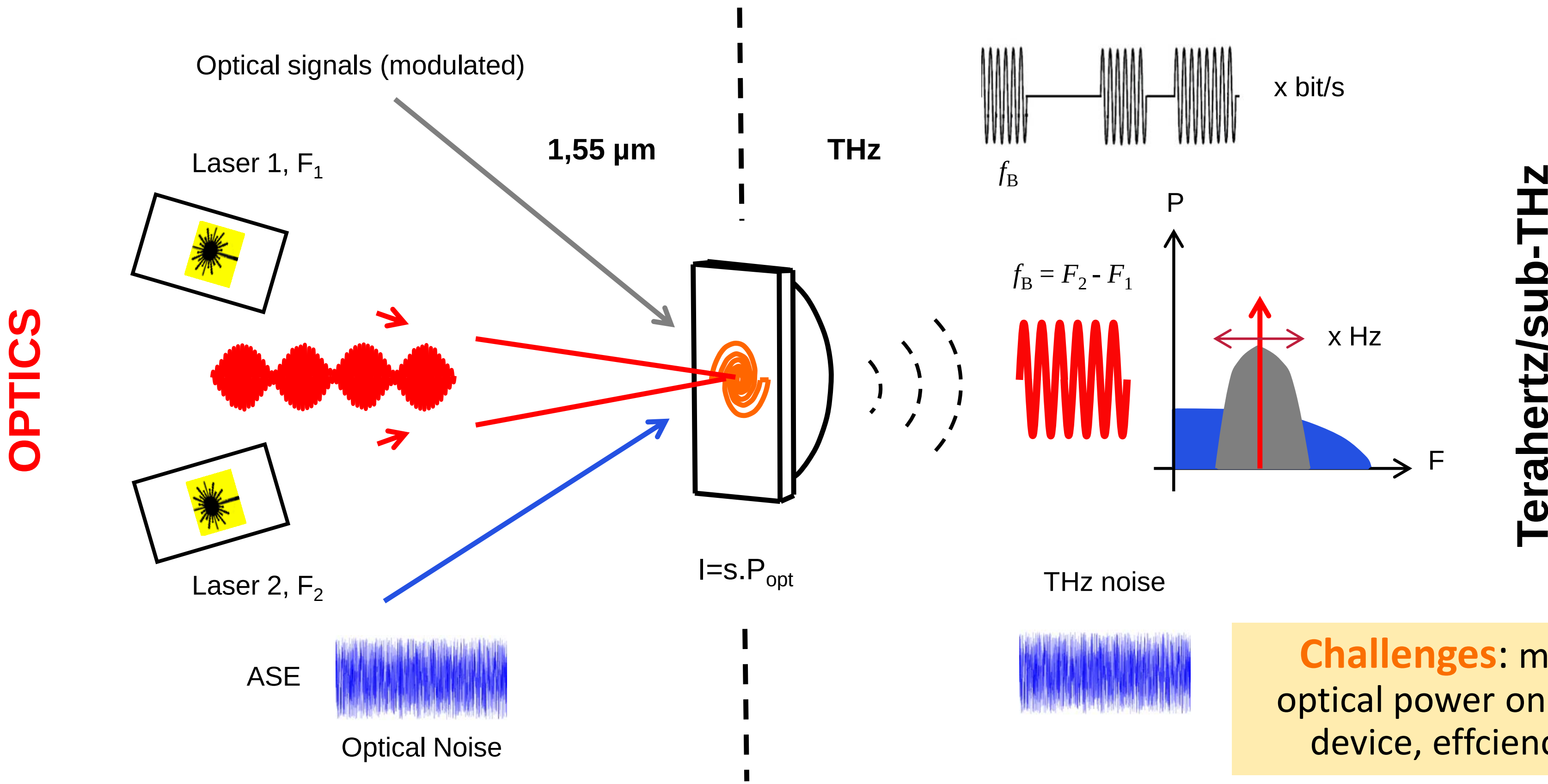
1 THz ⇔ 1 ps ⇔ 300 µm ⇔ 4,1 meV ⇔ 49 K


Optical fibers (1.55 µm)

➢ Direct generation
- QCL, non-linear optics, molecular lasers
(power = ok , but generally requires external modulation of the THz beam)

Photomixing

Photodiodes (UTC-PD, SiPho PD Ge, …) / Photoconductor (LT-GaAs, InGaAs, ErAs, …)

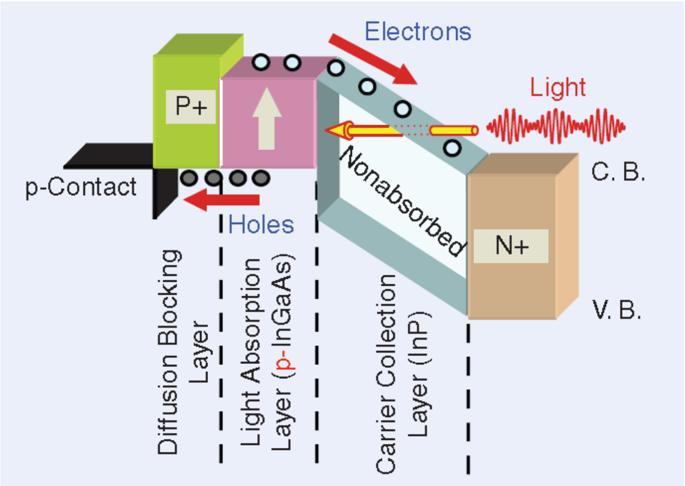


Challenges: max optical power on the device, effciency

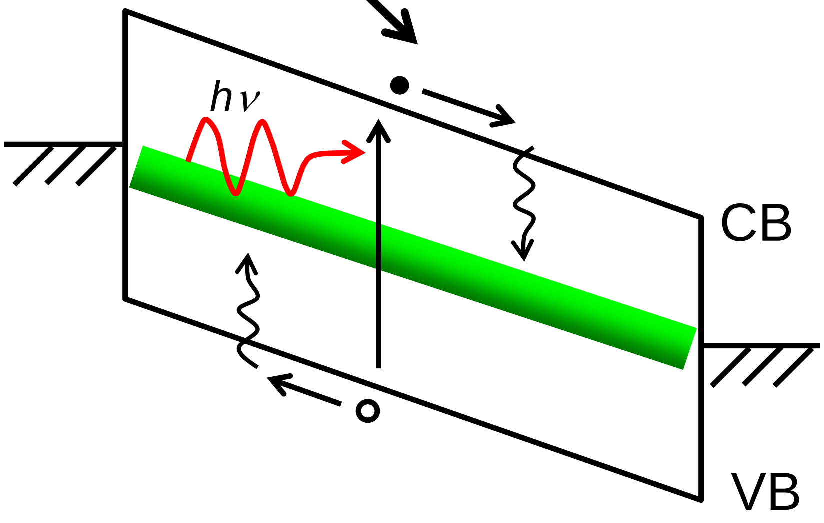
What is already used in optical fibers => THz can leveraged on that!!

The photonics emitter… the so called "photomixer"

2 families: **Photodiodes (ex. UTC-PD)** and **Photoconductors (PC)**

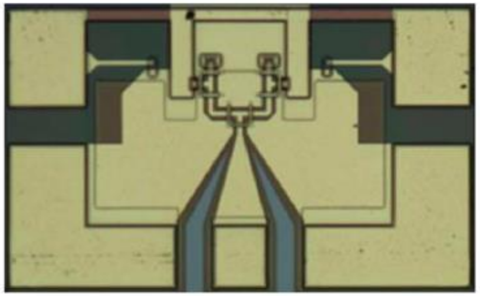


Uni-travelling carrier PD
UTC-PD, λ = 1.5 µm
p absorbing layer (not PIN)

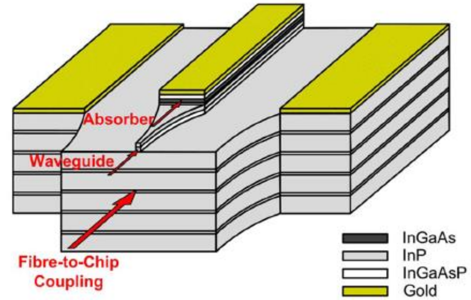


Most simple
Low-temperature grown GaAs PC
LTG-GaAs PC, λ = 0.8 µm / Short-carrier lifetime

Photomixing: results examples… photodiodes



[Song et al., IEEE MWCL (2012)]



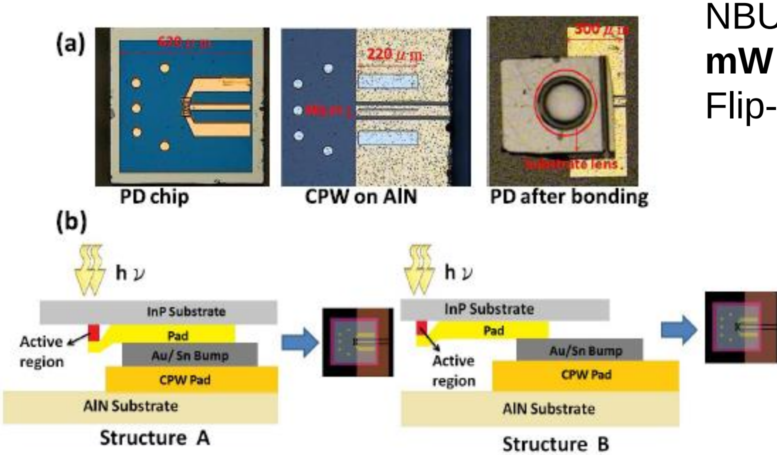
[Rouvalis et al., IEEE MTT (2012)]

TW-UTC: **110 µW** @ 300 GHz

2 × UTC-PD integrated (module):
1.2 mW @ 300 GHz
(20 mA/PD @ -3.9 V)

RCE-UTC-PD: **0.8 mW** @ 300 GHz

NBUTC-PD: **0.67 mW** @ 260 GHz
Flip-chip on AlN



P. Latzel IEEE TTST2017.

[Wun et al., IEEE PTL (2014)]

- Advantage of PM devices: the relative bandwidth.
- 1 device = compatible with multi-carrier THz emission

… ~ mW level (per device) is ok now

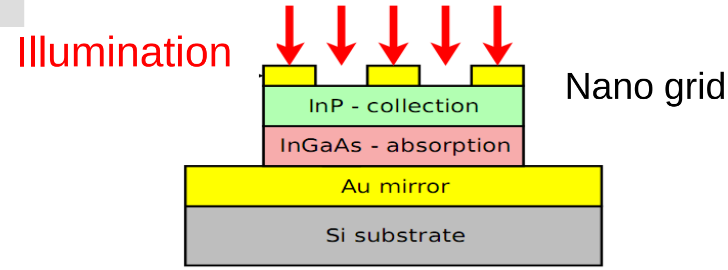
SoTA on UTC-PD: mW level, key point / optical driving power!

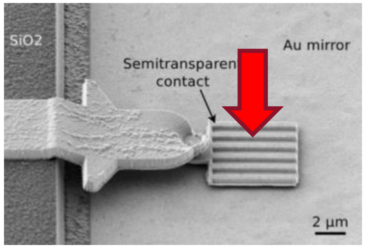
TABLE III
STATE OF THE ART OF POWER GENERATION AROUND 300 GHz USING SINGLE DEVICE PHOTODIODES

Ref.	f GHz	P_{RF} mW	R A/W	I_{dc} mA	r_{eff} Ω	M W^{-1}	PD *Type*
[29]	350	0.54	0.22	20	1.35	0.065	UTC *Packaged*
[18]	306	0.11	0.31	12	0.76	0.073	TWUTC *Planar antenna*
[20]	260	0.67	0.08	13	3.96	0.025	NBUTC *Flip-chiped, wafer-level*
This work	300	0.75	0.12	9.8	7.8	0.108	RCEUTC *Wafer-level*

[18] Rouvalis, E. et al. Opt. Express 18, 11105–10 (2010).
[20] J.M. Wun, et al. IEEE Photonics and Technology Letters, 26(4) :pp. 2462–2464, 2014
[29] A. Wakatsuki et al., 2008 33rd International Conference on Infrared, Millimeter and Terahertz Waves, Pasadena, CA, 2008, pp. 1-2. doi: 10.1109/ICIMW.2008.4665566

RCE-UTC: resonant cavity enhanced UTC-PD





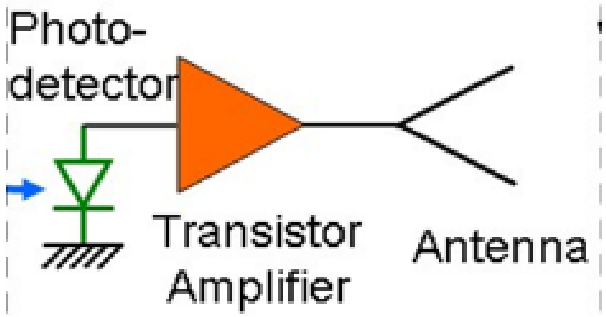
P. Latzel *et al.*, *IEEE Transactions on Terahertz Science and Technology*, vol. 7, no. 6, pp. 800-807, Nov. 2017.

Typical power from utc-pd output: now mW level, still need more!

-> arrays or ampl.

… but not enough… why not use amplifiers or arrays?

- Photodiode: simple devices, good for wide band modulation, limited power + low level of integration (if PD only)…



Or TWT!

The photodiodes/photoconductors could be a good « driver » of integrated amplifier, other active structures…

However, interconnexion losses using several technologies… to be investigated

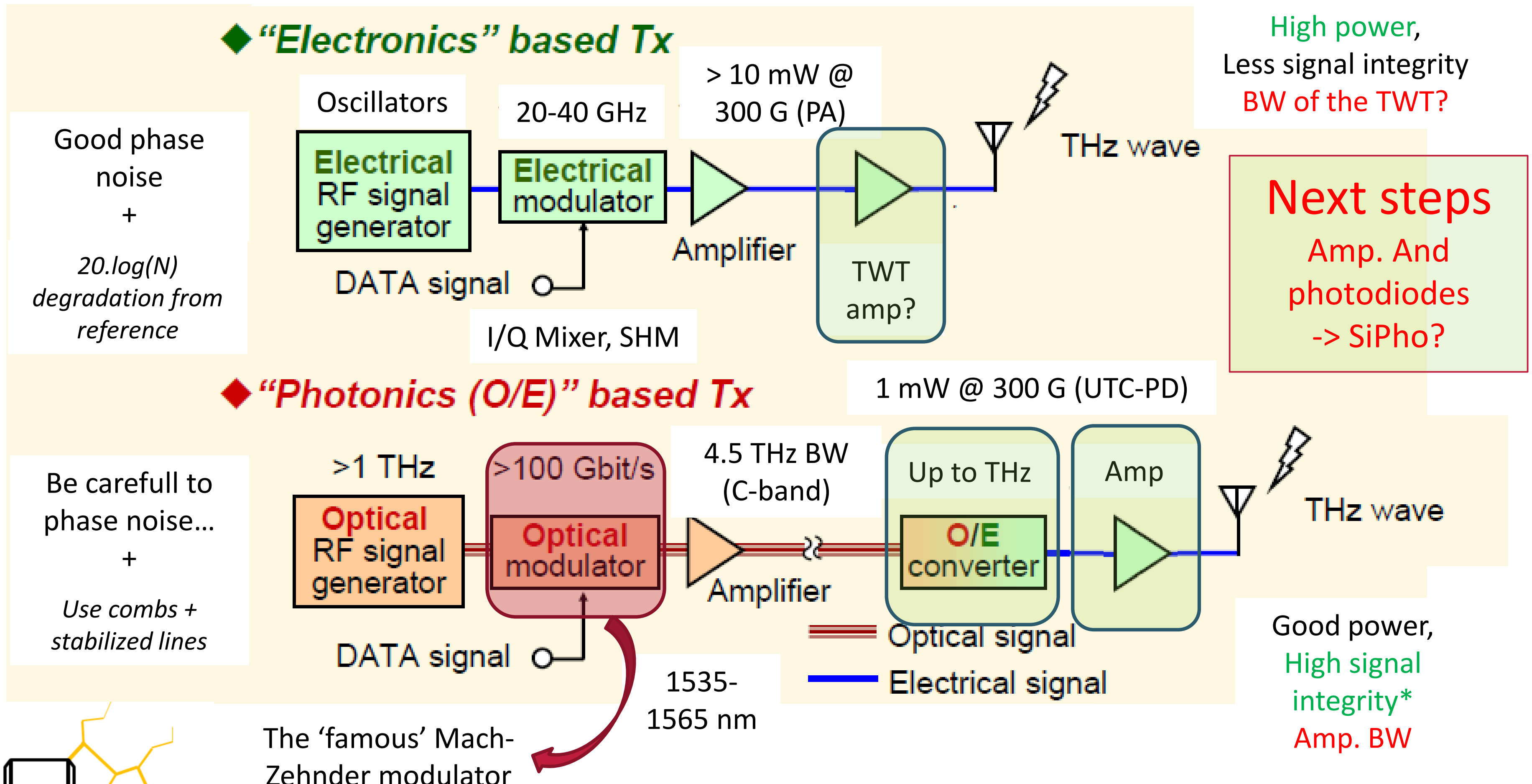
Future systems: integrated/co-designed

UTC−PD arrays

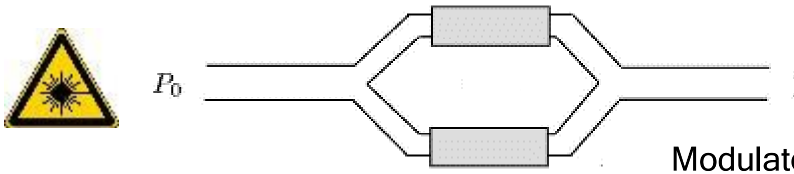
Challenges:
interconnections, integration of different technologies

Tx architecture: comparison

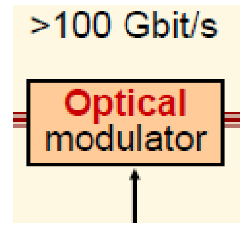
➢ Modified from IG THz study Group (15-10-0149-01)



Using photonics, efficient optical modulations



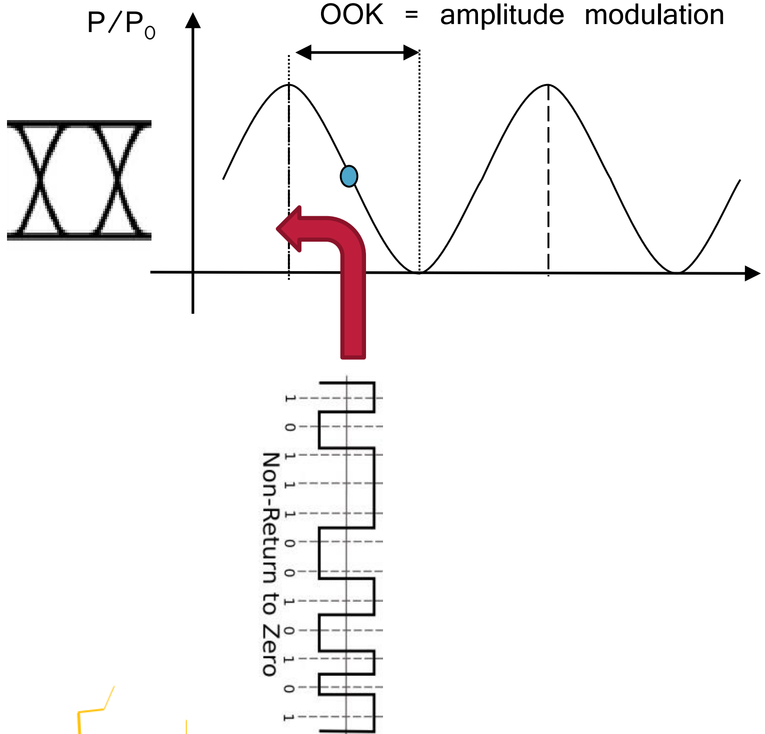
Modulated laser

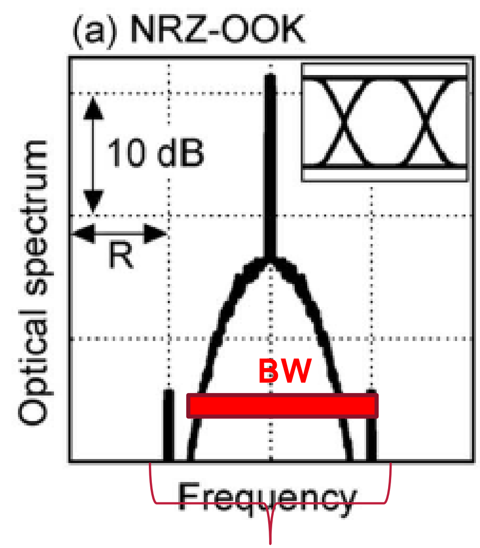


MACH ZEHNDER MODULATOR (MZM)

Discrete or integrated (SiPho PIC, …)

OOK = amplitude modulation

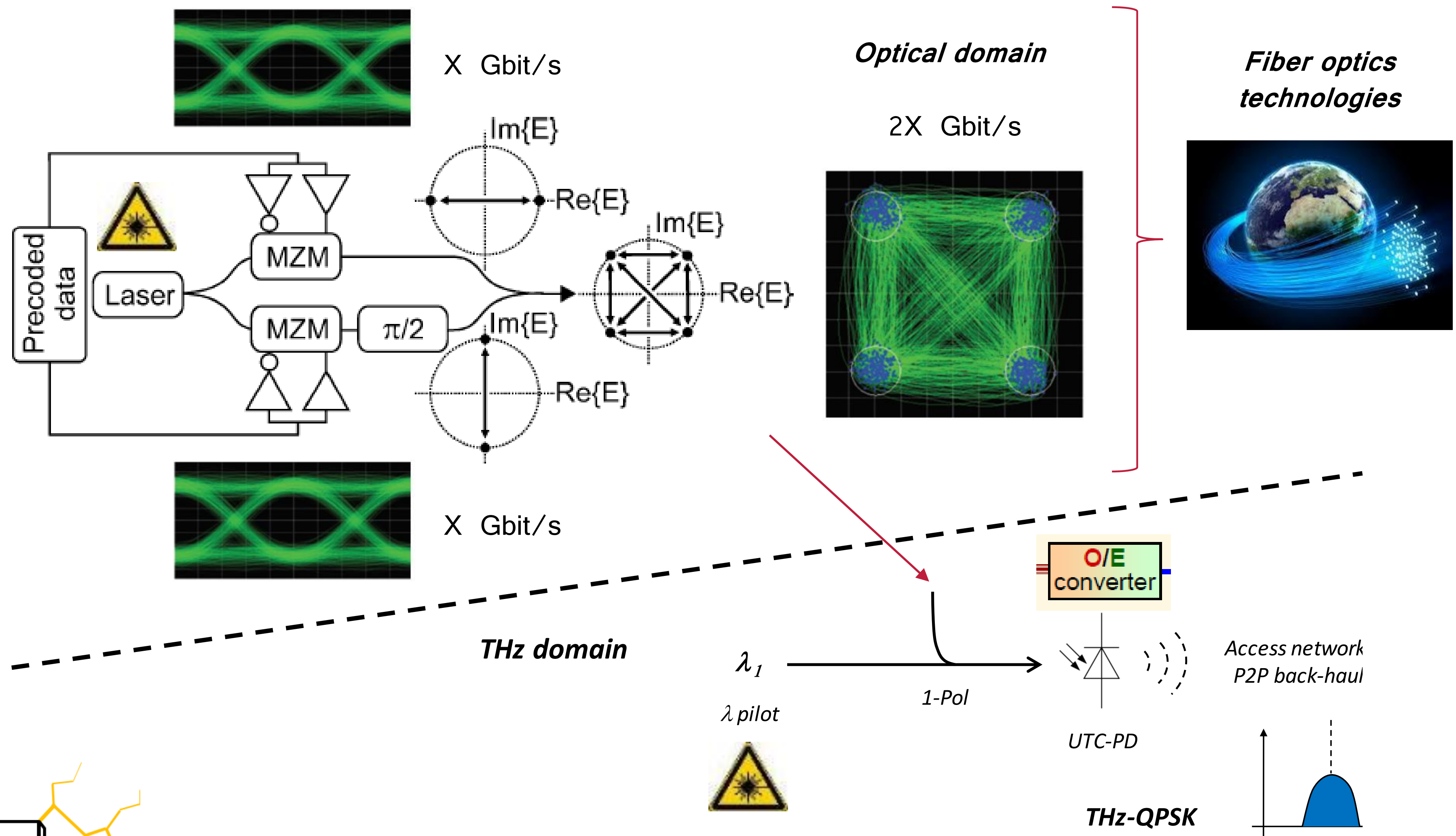




The spectrum

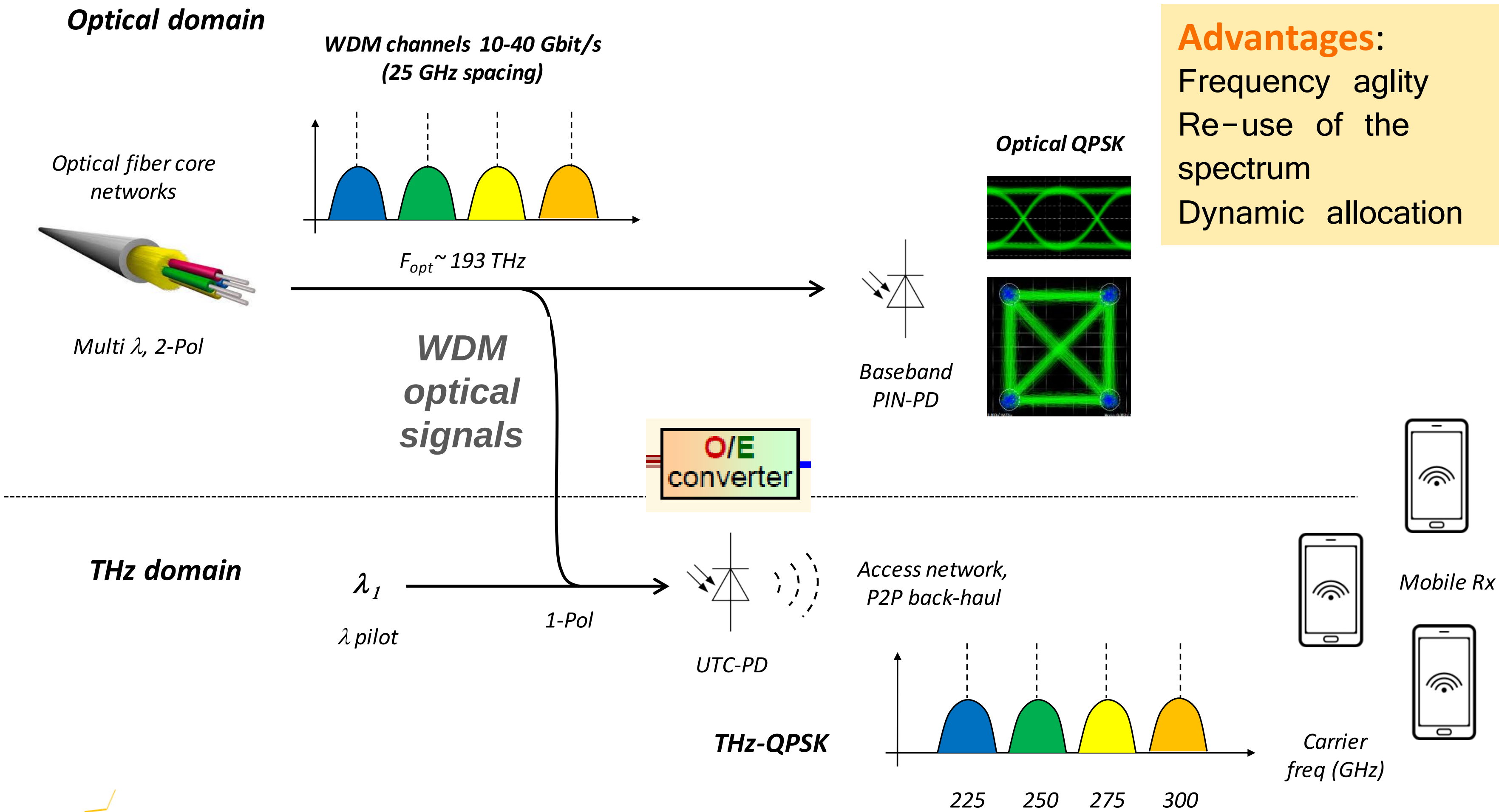
Spectral efficiency = Data-rate/BW

Combining I/Q at optical level then to THz



In a nutshell… what optics can do for wide-band THz …

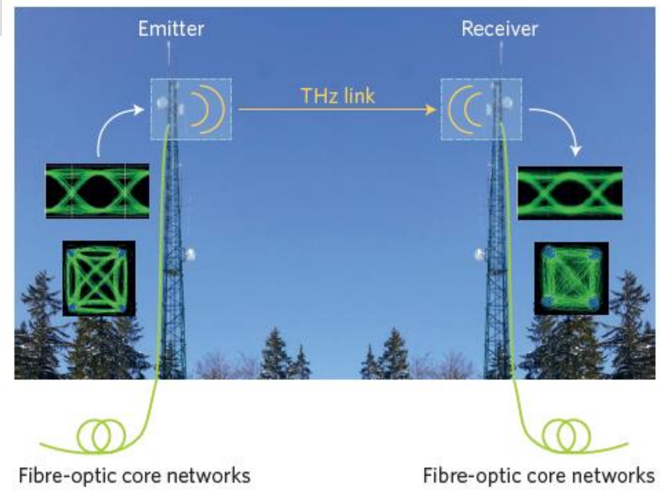
Advantages:
Frequency aglity
Re−use of the spectrum
Dynamic allocation



What about receiving: -> photonics?

- For a global THz system, we need **Tx AND Rx**.
- Up to now, photonic-driven Tx are combined with electronic Rx (Schottky).
- For a full **« optically transparent »** system, the Rx is to be done as well.

→ *Need to be investigated towards **« seamless integration »***



Less studies on photonics based Rx !

→ Optics -> THz -> Optics

- Use of UTC-PD as receivers (possible but structure has to be adapted)

E. Rouvalis, M.J. Fice, C.C. Renaud, and A.J. Seeds, "Millimeter-wave optoelectronic mixers based on uni-traveling carrier Photodiodes," IEEE Trans. Microw. Theory Techn., vol.60, no.3, pp.686–691, 2012.

32 dB conv. Gain @ 100 GHz

- Use of photoconductors (possible but devices to be optimized for 1.55 µm)

Peytavit *et al.*, Appl. Phys. Lett. **103**, 201107 (2013).

- Use of silicon-plasmonic based systems (works, overall efficiency has to be increased)

Silicon-plasmonic integrated circuits for terahertz signal generation and coherent detection

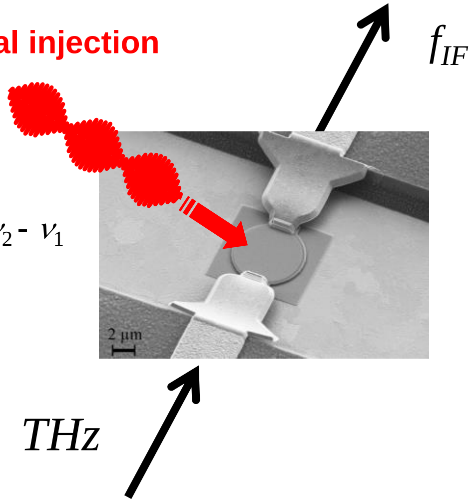
T. Harter[1,2*], S. Muehlbrandt[1,2], S. Ummethala[1,2], A. Schmid[1], S. Nellen[3], L. Hahn[2], W. Freude[1], C. Koos[1,2**]

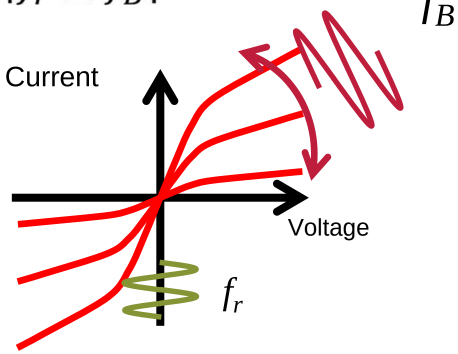
Examples. LT-GaAs & plasmonic-based

- ***Use photoconductive switches***

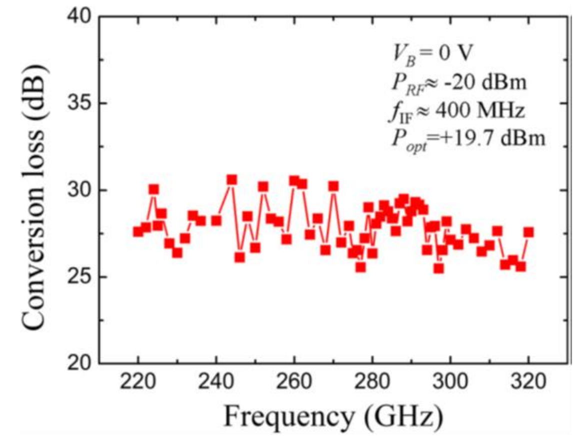
Peytavit *et al.*, Appl. Phys. Lett. **103**, 201107 (2013).

$$f_{IF} = |f_r \pm f_B|$$

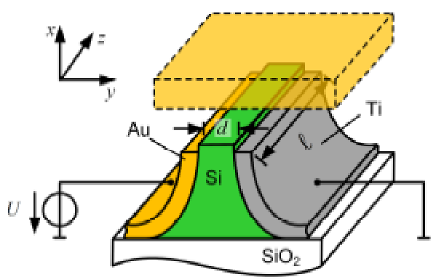




homodyne (f_{IF}=0) if $f_r = f_B$



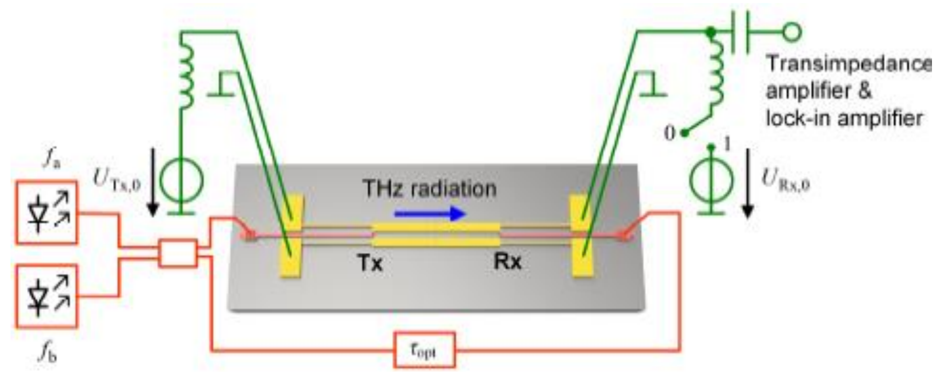
28 dB @ 300 GHz
Wideband, scalable beyond 1THz



O/T conversion using silicon
-55 dBm @ 300 GHz (Tx)

66 dB conv losses at Rx.

Silicon based



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Photonics: where could (should) it also be usefull??

- Beam steering, forming, switching? Arrays of 

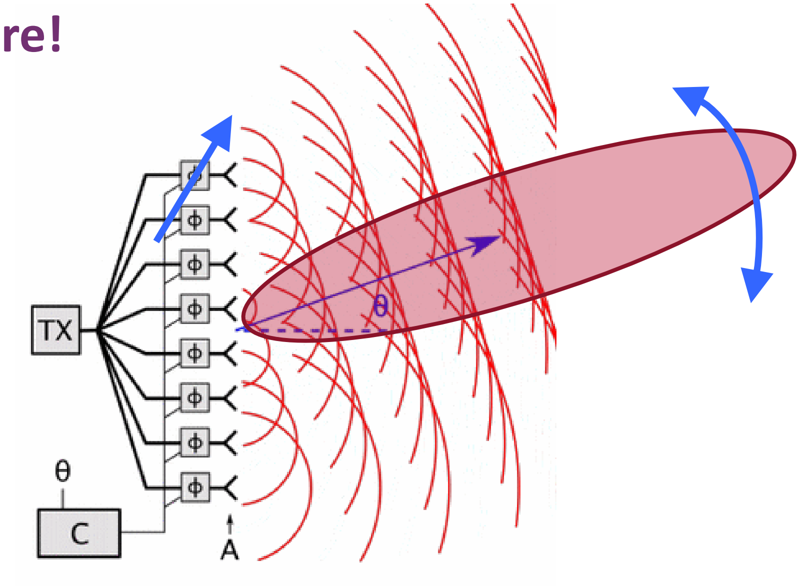
Indoor THz beam control, alignment of P2P links…

Optics can help here!

Easy to get multi-feed (low optical losses)

+

adjusting the relative phases



Beam forming phase delay in opt domain?

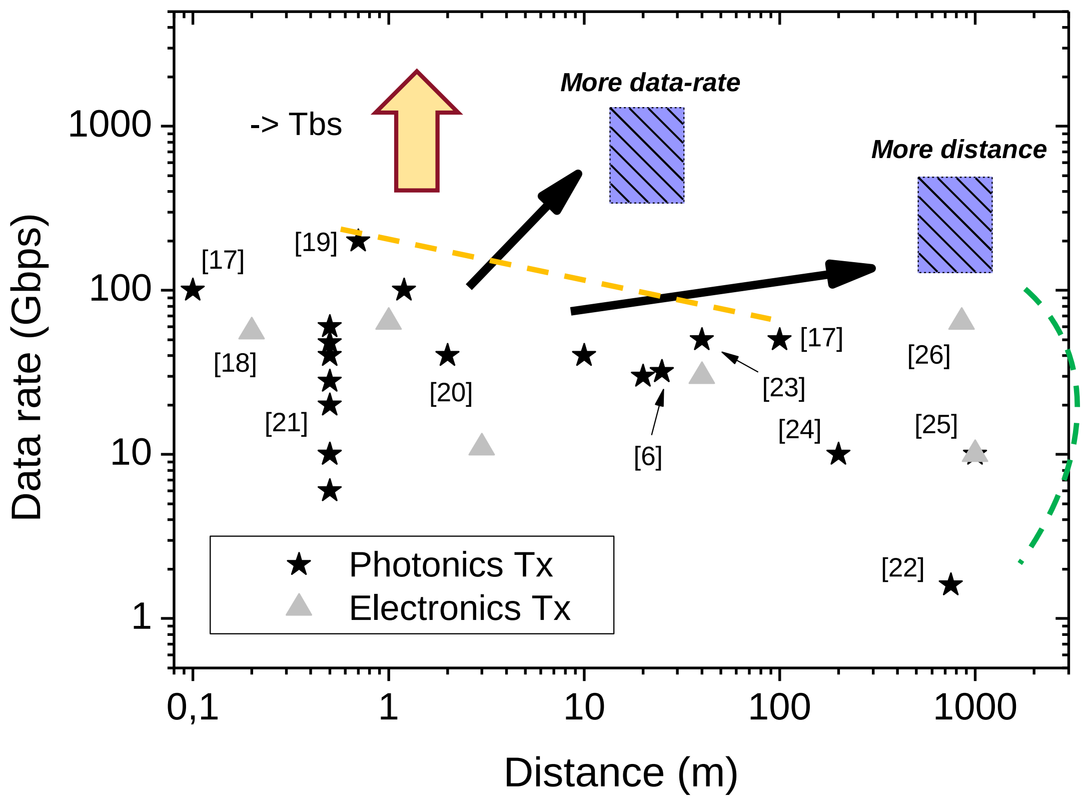
[Modified from Wikipedia]

Challenges: interconnections, array fab (yield), polarization control…

Should consider integrated optics (SiPho might help)

System-level demos

Photonics is pushing the data-rate



More compact systems for future…

So far, the compactness is not scaling for decrease of wavelenght…

Mastering simple schemes for Tx/Rx locking

Electronics is pulling the distance

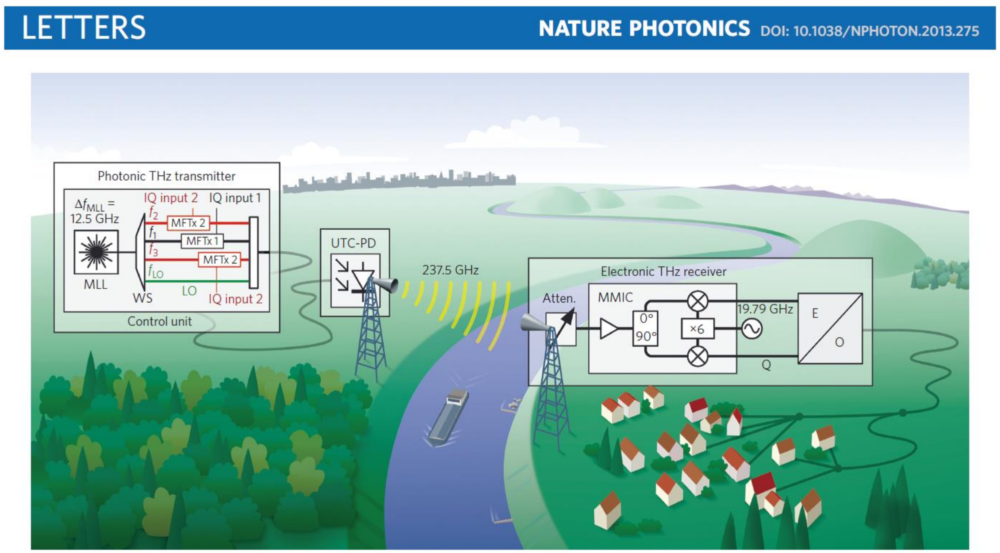
With moderately-sized antennas (ie not > 50 dBi);

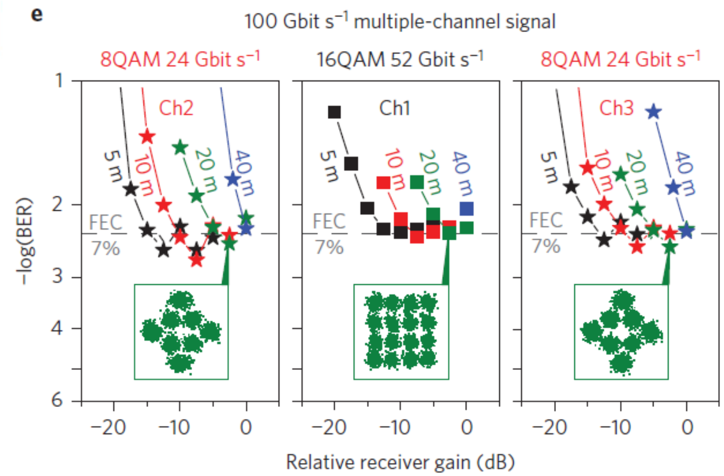
Highest schemes/complexity of mod. scheme: <u>photonic-based Tx usually</u>

Example 1/3

240 GHz band / 100 Gbit/s using several carriers

[23] S. Koening et al., Wireless sub-THz communication system with high data rate, Nature Photonics volume 7, pages 977–981 (2013), doi:10.1038/nphoton.2013.275





Photonic-based Tx (UTC-PD)

Solid-state Rx (electronic)

3 carriers in same emitter

(Not straightforward to do that in electronic, single device…)

'Off-line' DSP: meaning that signal is recorded, then processed

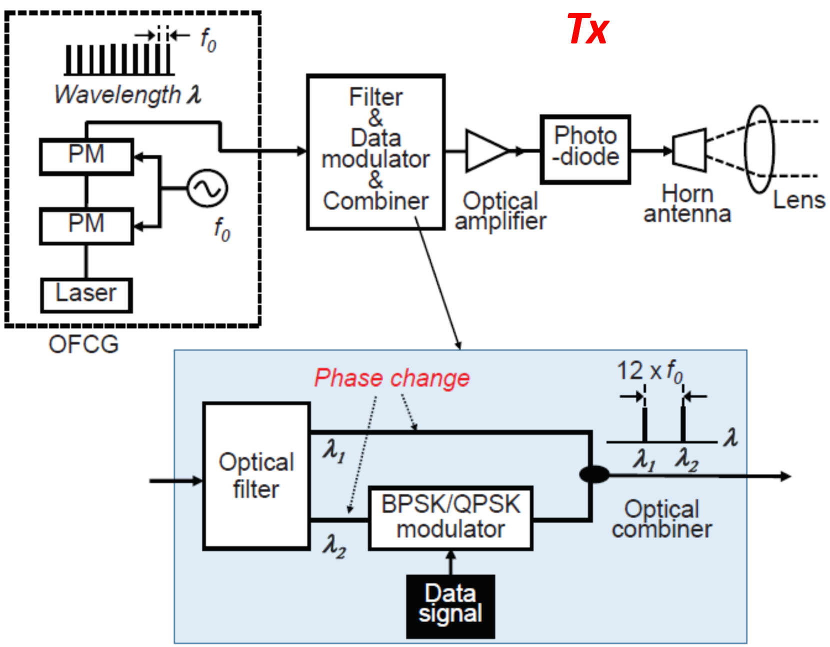
Future system with (almost) non latency should leverage on ASIC/real-time/FPGA capabilities

Example 2/3

300 GHz band, 100 Gbit/s, real-time, QPSK, 2016

[17] T. Nagatsuma et al., Real-time **100-Gbit/s QPSK transmission** using photonics-based 300-GHz-band wireless link, 2016 IEEE International Topical Meeting on Microwave Photonics (MWP), Long Beach, CA, 2016, pp. 27-30, doi: 10.1109/MWP.2016.7791277.

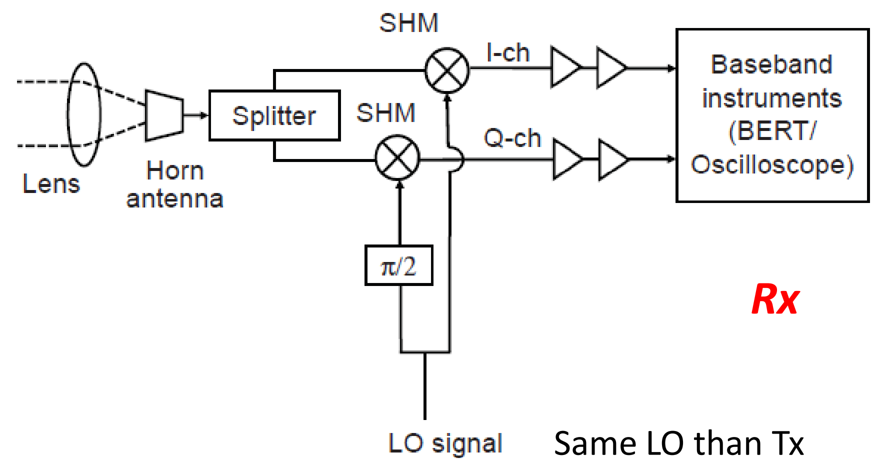
Tx



Optical comb, driven by reference F_0 => $12.F_0$

Phase noise of 300 GHz carrier = 20.log(12) + $Lc(F_0)$

Source = UTC-PD



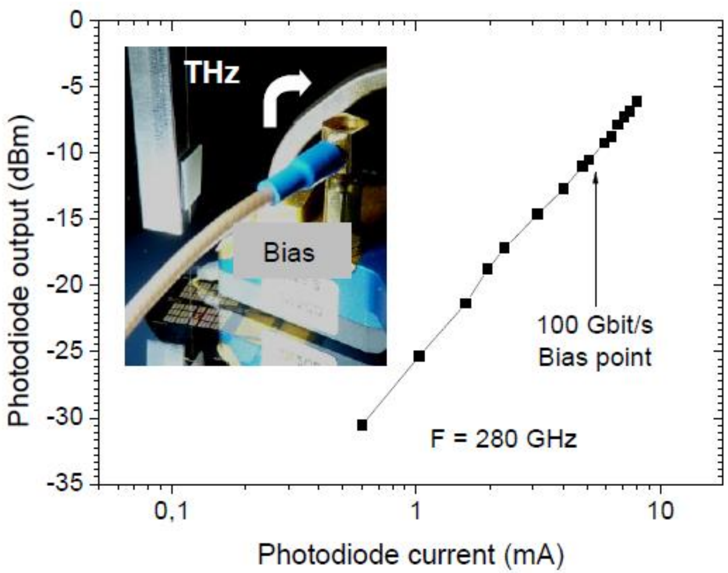
Rx

+ Need to correct relative phase fluctuations

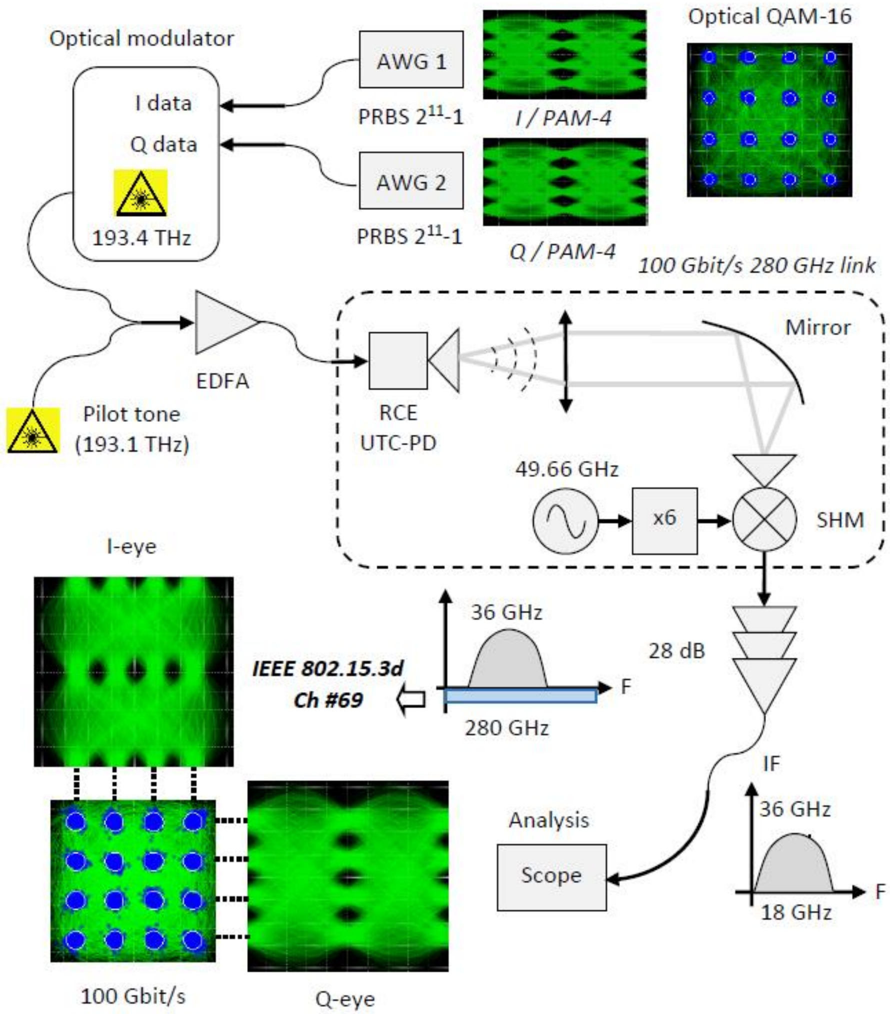
Same LO than Tx

300 GHz band single carrier, 100 Gbit/s, QAM-16 2018

Linear photomixer (UTC photodiode)



Single channel 100 Gbit/s transmission using III-V UTC-PD photodiodes for future IEEE 802.15.3d wireless links in the 300 GHz band



Open challenges

- Many approaches (in terms of devices, architectures, …)
- Photonics is an « enabler », a driving technology (enabling advanced tests thanks to high BW photodiodes + fiber technologies);
- Discrete approaches (initial) and discrete/integrated ones (actual)
- (III-V) photonics could be combined with active technologies (tackling the power issue).
- 'Urgent' need for unification of the performances evaluation/Metrology of THz com systems:
  - « Random sequences »: not always the same lenght (PRBS 2^x-1…)
  - Real-time or not?
  - Latency or not?
  - Power consumption of the system?

Next years THz coms R&D

*- High data-rate + distance (**POWER**)…*
- Compact integration of THz?
- Active devices (has to work with rain…)
- Energy efficiency
- Manipulation of THz signals
- Cost… to make THz bands a reality
Silicon industry (photonics & analog RF)

Example of on-going projects

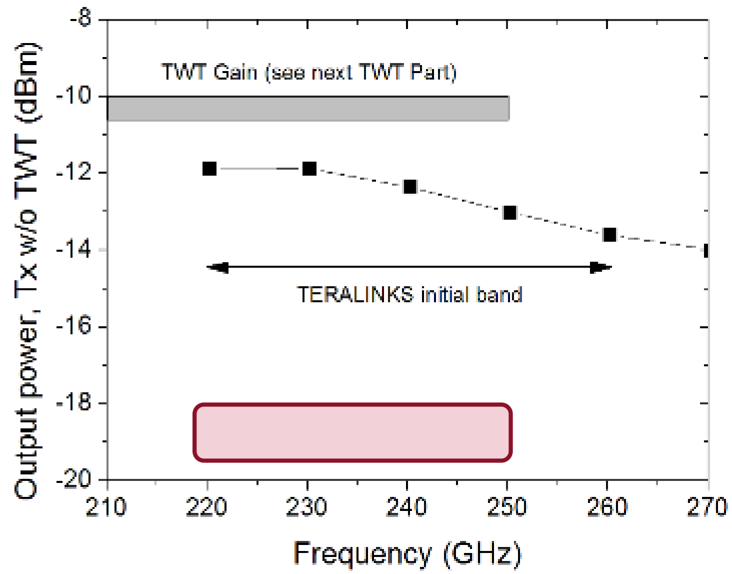
TERALINKS

Increase the range of THz links: combination of photonic approaches and TWTA

(TWTA: Prof. C. Paoloni)

Frequency	*220-260 GHz*
THz source	*up to1 mW / packaged*
TWT power amplifier	*Gain > 30 dB* *Power: 3-4 W*
Antenna	*50 dBi (high gain)* *> 20 dBi, beam-steering capable (indoor)*
Receiver (direct)	*Zero bias detector* *Schottky ~1 kV/W*
Rx bandwidth (GHz)	*40 GHz, including baseband amplifier*
Modulation	*ASK (real-time)* *40 Gbit/s*
Link budget (outdoor)	*140 dB (1 km)* *40 dB with 50 dBi antennas*

Photonics



30 GHz of BW combining power and efficient modulation (thanks to optically driven sources)

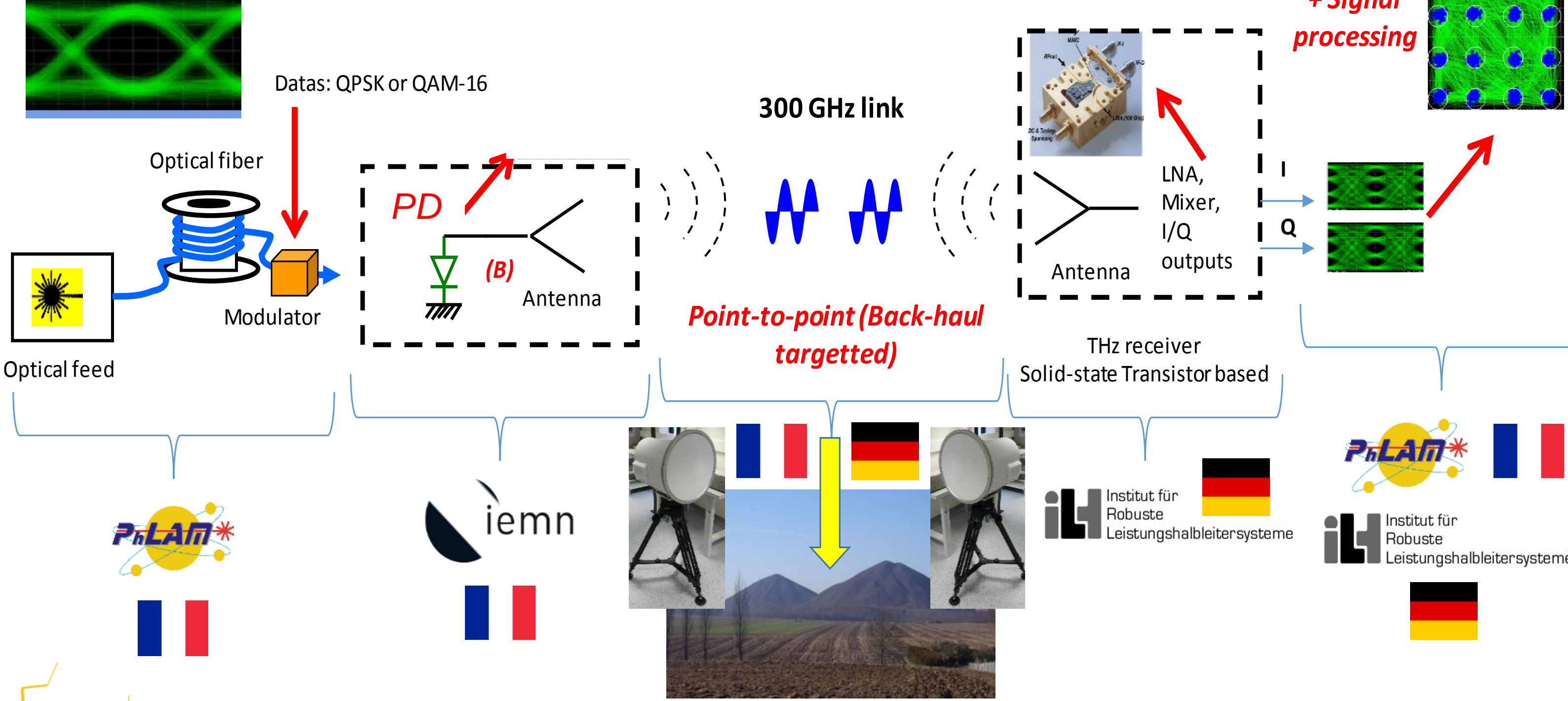
Example of on-going projects

TERASONIC Project

Increase the range of THz links: combination of photonic approaches and electronic based

FR-Prof. G. Ducournau
DE-Prof. I. Kallfass

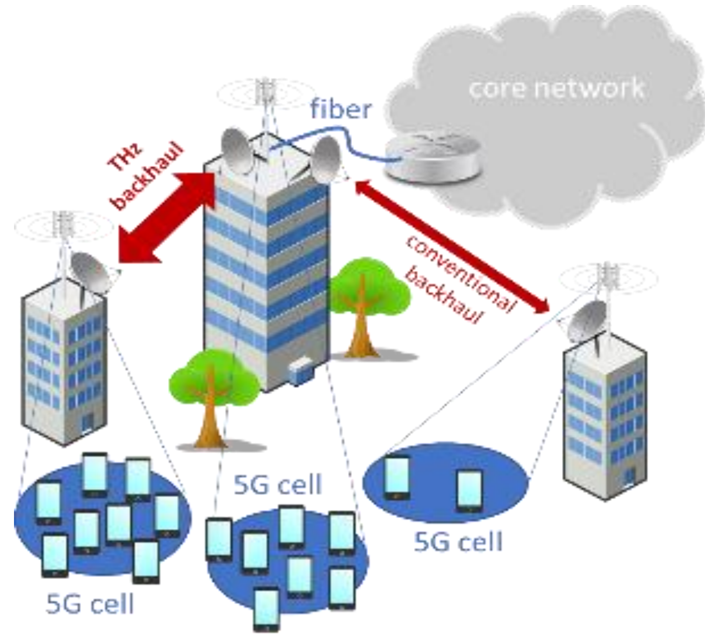
TERASONIC: Beyond 100 Gbit/s using combined technologies



ThorProject.eu

Example of on-going projects

Point to point transmission system thanks to up conversion of E/V-band MODEMs

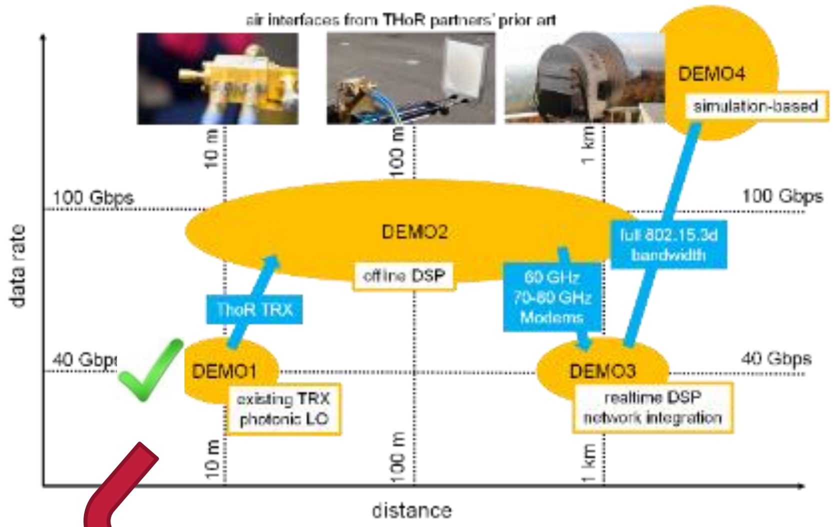


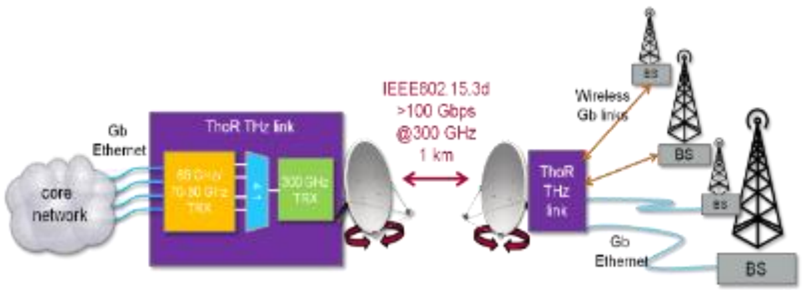
Super heterodyne architecture:

- *Photonic (LO): low phase noise*
- *Solid-state devices: wideband up-conversion to THz bands*
- *Tube amplifier to reach km-range*

Example of on-going projects

ThorProject.eu





DEMO-1 validated in Nov. 2018 by merging skills of Japanese and European teams

https://www.youtube.com/watch?v=U1zatU6Gfbk

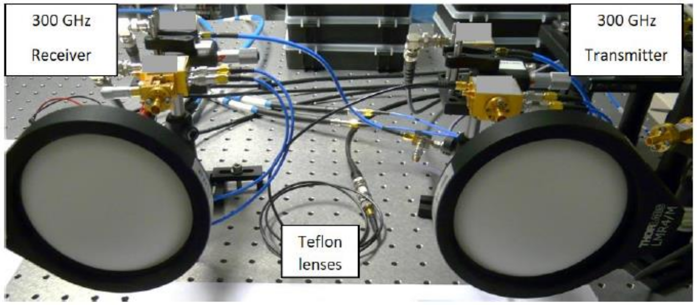
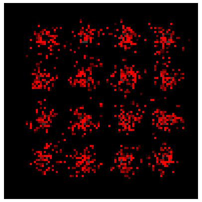
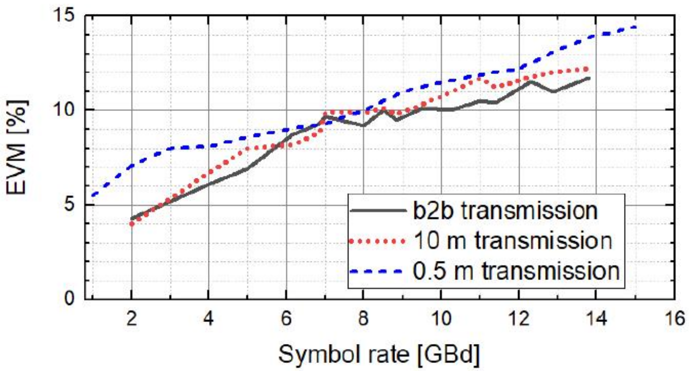


Fig. 6. Setup of the 10 m transmission using collimating dielectric lenses.



16QAM / 56 Gbps data-rate transmission.

DEMO 2 and 3: increase the range using TWT



Thus… a huge space for research and industrial opportunities

Use the photonics: bandwidth OK, BUT… need power… photonics to be combined with active devices.

If limited power/distance + compact/density required (kiosk, data-center) => simple links using SiPho is possible (decrease the cost + industrial foundries in Europe available!)

Arrays of Photonic devices has to be investigated: smart solution for beam-steering

Photonics = technological enabler (driver)=> has to be used where it is relevant:

- bandwidth and signal integrity, seamless connection with optical waves
- integrated with electronic devices (silicon for mass, III-V or TWT for dedicated scenarios?)
- frequency invariant photomixing process: high purity carriers to drive electronic-based systems

Every system also need integration! Need to think about THz generic interconnexions…

Ackowledgment

- THz photonics group, IEMN: J.F. Lampin, E. Peytavit, M. Vanvolleghem, F. Pavanello, P. Latzel, S. Bretin, M. Billet, …
- IEMN MBE team and charac. Center S. Lépilliet, …
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