Future Outlook to Terahertz Communications

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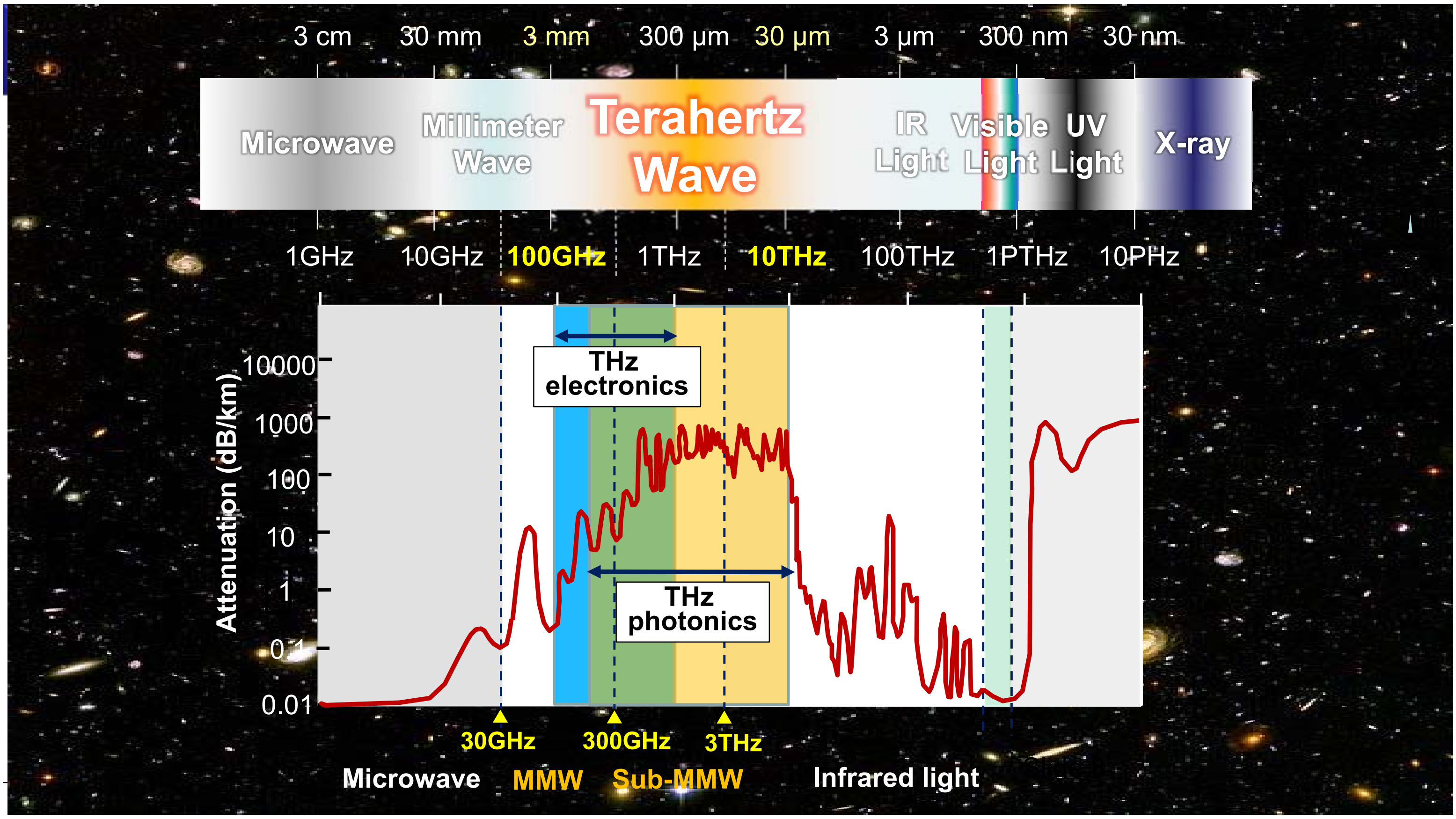
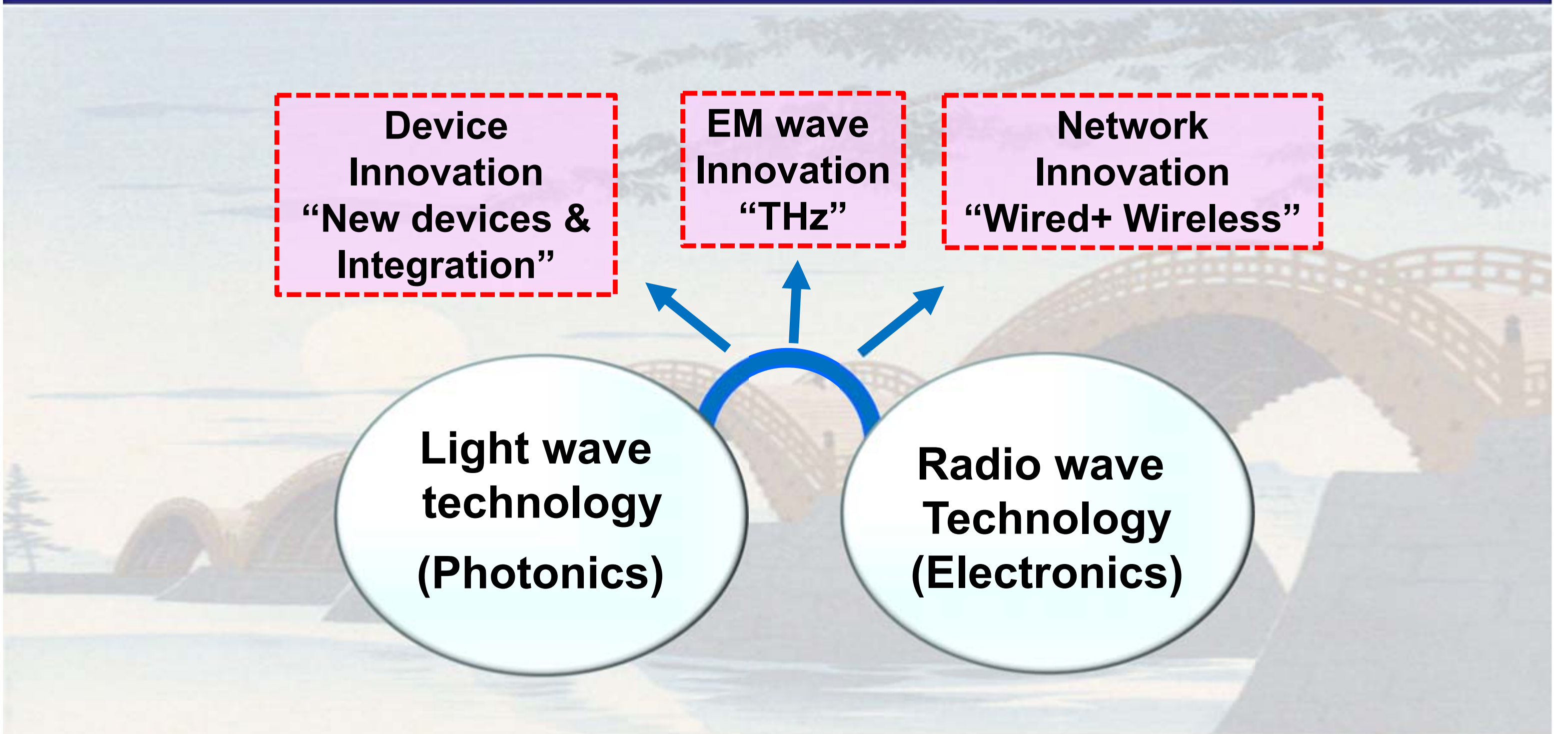
Outline

Review current status of THz communications research and discuss the future direction

1. ***State of the art***
   - ***selection of frequencies/bands***
   - ***transceiver and system technologies: photonics vs. electronics***
2. ***Future directions***
   - ***device technologies***
   - ***system integration technologies expectation for TERAWAY***

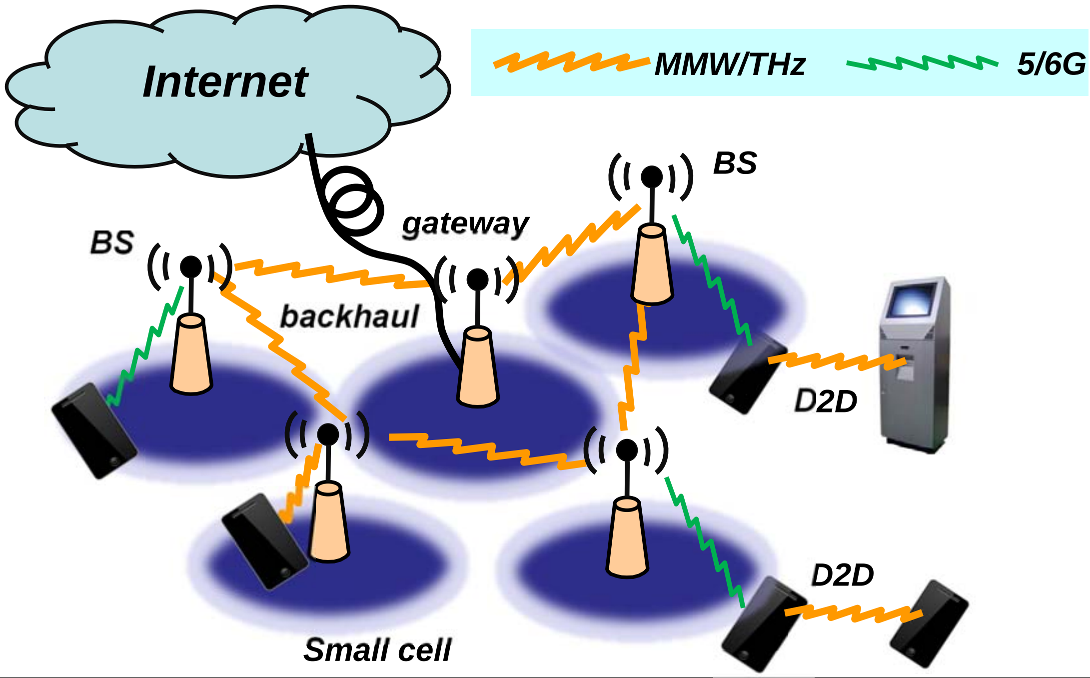


Bridging Light and Radio Waves



Network Innovation: Wireless Backhaul

Next Generation Mobile Network



International Consensus below 275 GHz

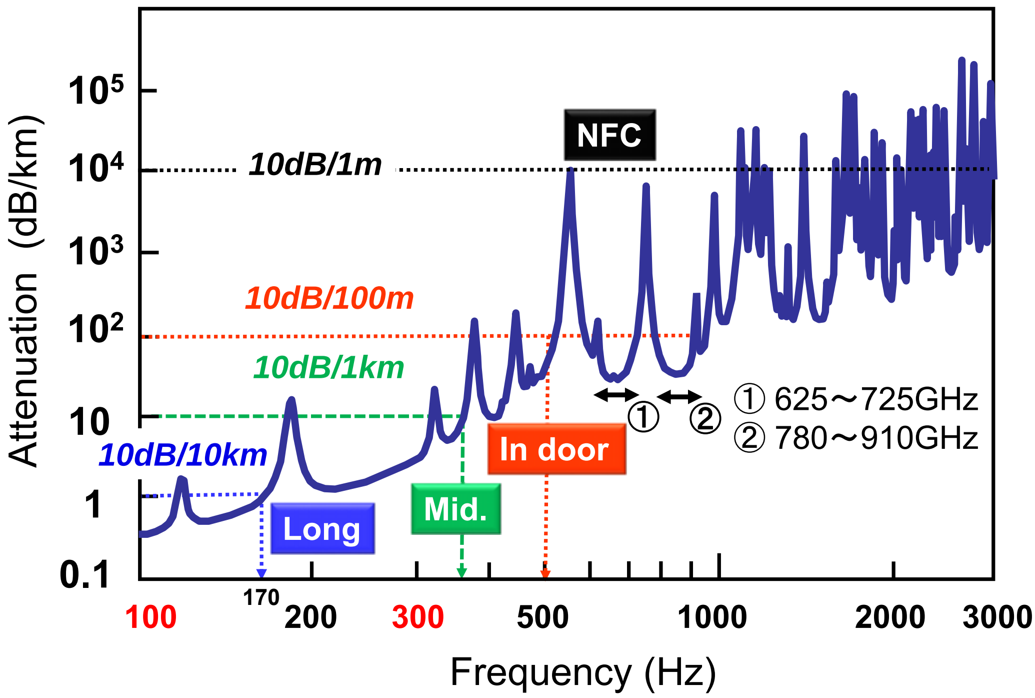
Prohibited Bands

Above 50GHz
52.4~50.4 GHz
52.6~54.25
86~92
100~102
109.5~111.8
114.25~116
148.5~151.5
164~167
182~185
190~191.8
200~209
226~231.5
250~252

Allocated for Fixed and Mobile

Frequency(GHz)	BW
102~109.5	7.5
111.8~114.25	2.45
122.25~123	0.75
130~134	4.0
141~148.5	7.5
151.5~164	12.5
167~174.8	7.8
191.8~200	8.2
209~226	17.0
232~235	3.0
238~241	3.0
252~275	23.0

Link Distance Determined by Attenuation

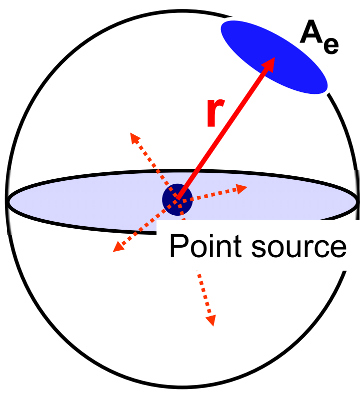


Another Loss: FSPL

Free-Space Propagation Loss (FSPL)

$$\Gamma = \left(\frac{4\pi r}{\lambda}\right)^2 = \left(\frac{4\pi f r}{c}\right)^2$$

Loss is proportional to square of frequency



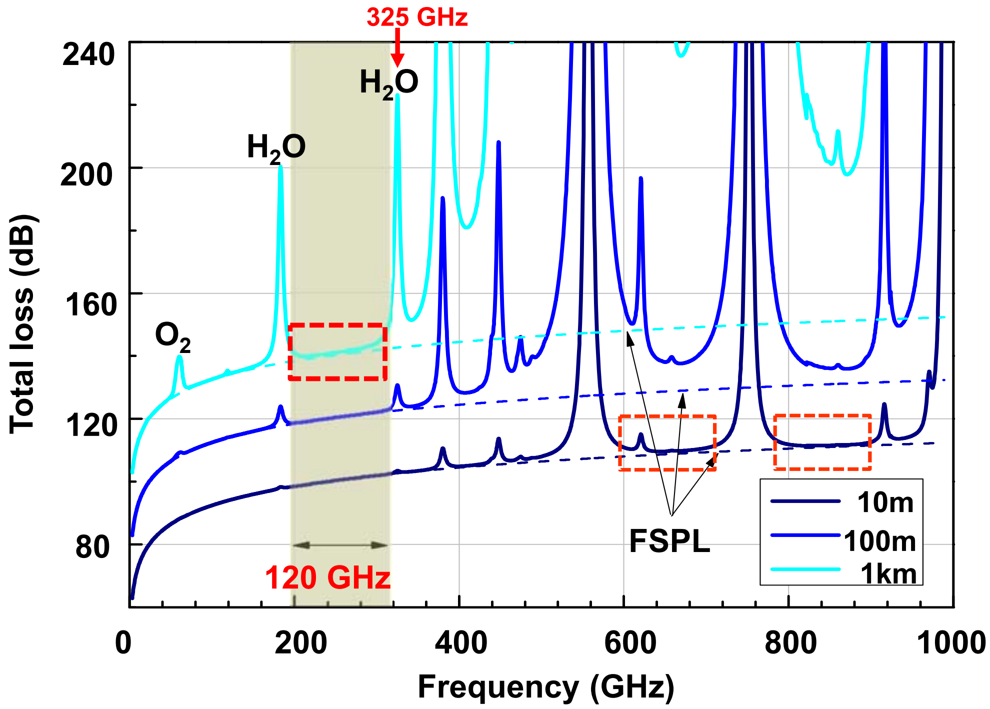
loss ∝ $4\pi r^2/A_e$

A_e: antenna aperture $= \lambda^2 G_a/4\pi$

G_a: antenna gain

The above equation is for the case when Ga = 1 (0 dBi)

Best Window at **200GHz~320GHz**



Results of WRC 2019 on THz Communications

Frequency (GHz)	Status in Radio Regulations
252-275 (23)	Allocation for land mobile and fixed service on a co-primary basis
275-296 (21) 306-313 (7) 318-333 (5) 356-450 (94)	**Identification for use for the implementation of land mobile and fixed service** according to FN 5.564A. No specific conditions are necessary to protect Earth exploration-satellite service (passive) applications.
296-306 (10) 313-318 (5) 318-356 (38)	may only be used by fixed and land mobile service applications when specific conditions **to ensure the protection of Earth exploration-satellite service** (passive) applications are determined in accordance with Resolution 731 (Rev.WRC-19).

Most Promising H Band for Beyond 5G

- **Window** determined by wave propagation
- **Standardized** in IEEE802.15
- **Identification** at WRC2019

☞ **252～296 GHz**
Center frequency：274 GHz
Bandwidth: 44 GHz

30 Gbit/s with ASK（OOK）
90 Gbit/s with PAM8
>100 Gbit/s with16QAM and 32QAM
>200 Gbit/s with 256QAM

State-of-the-art Semiconductor Electronics

Compound semiconductor (III/V)ICs

25nm InP HEMT, fmax=1.5THz,
(9-dB >1-THz amp)
GaN, fmax=0.58 THz
InP-GaAsSb DHBT, fmax=1.18 THz

Si-semiconductor ICs

CMOS bulk/SOI/FinFETs,
fmax≈300-450 GHz
(20nm~60nm node,
3nm applicable recently)
SiGe BiCMOS/SiGe HBT,
fmax ≈ 700GHz (100~150nm)

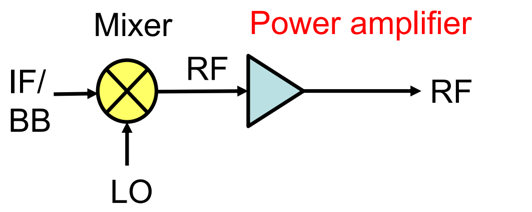
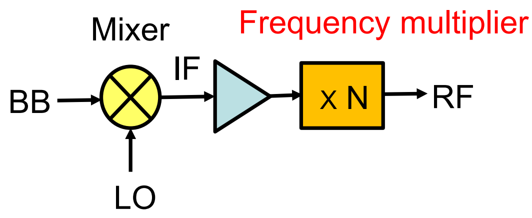
Heterogeneous integration

InP + SiGe
InP + SiC

Electronic-photonic integration

Optical modulator/optical waveguide/
Ge photodiode/ on Silicon

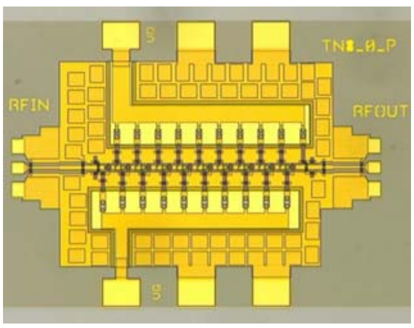
Different Approach: InP/GaAs vs. Si (@>300 GHz)

Material	Tr performance	Configuration of transmitter
InP/GaAs	$f_{RF} < f_{max}$	
Si	$f_{RF} > f_{max}$	

Capability of InP ICs: 1-THz Amplification

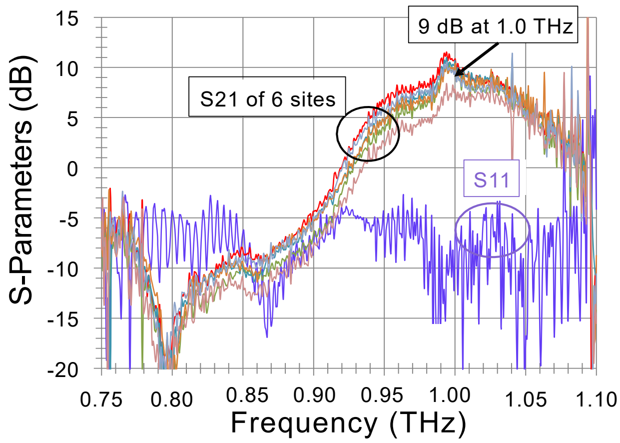
X. Mei, et al., "First Demonstration of Amplification at 1 THz using 25-nm InP High Electron Mobility Transistor Process," *IEEE Electron Dev. Lett.*, 36, pp. 327–329 (2015).

- **25-nm InP HEMT**
- **10-stage common source**
- **2-finger 8-μm wide devices**



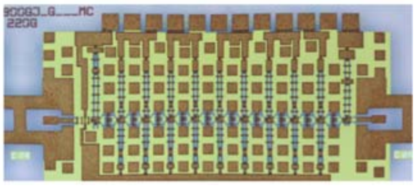
(Substrate thickness: 25μm)

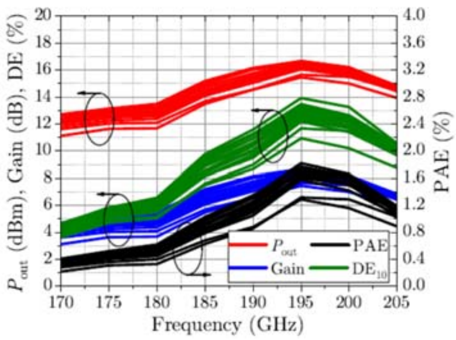
9 dB Gain demonstrated on wafer at 1 THz



Practical Amplifiers by Compound Semi

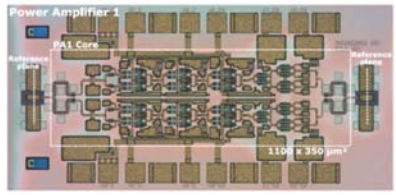
GaN G-band (140–220 GHz)

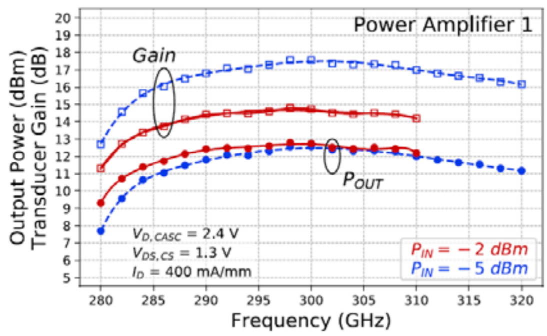




M. Ćwikliński et al., 2020 IEEE/MTT-S IMS.

InGaAs mHEMT 300 GHz

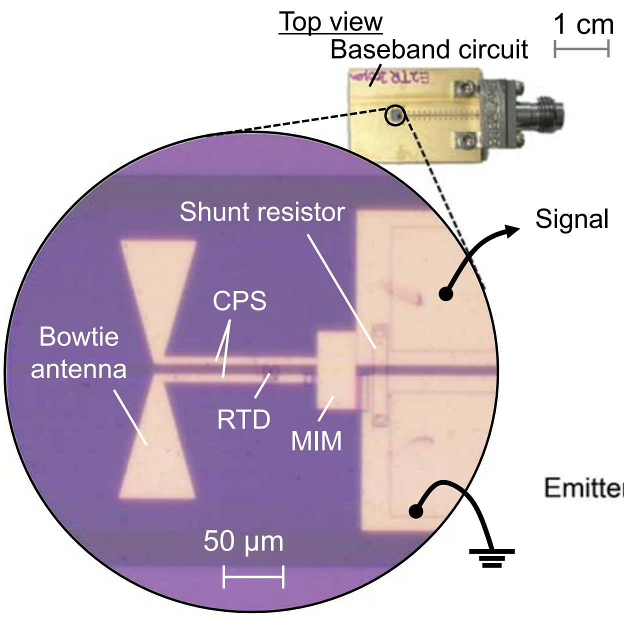


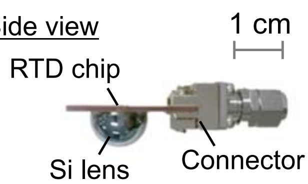


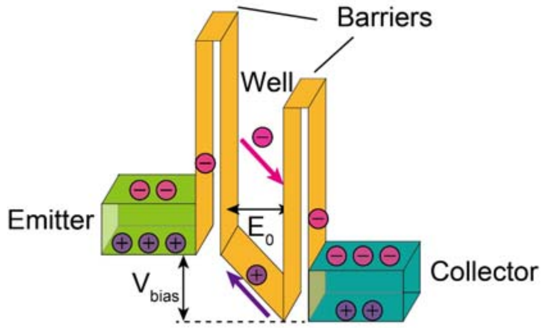
L. John et al., IEEE Trans. THz Science Tech., vol. 10, no. 3, pp. 309-320, 2020

Resonant Tunneling Diode "THz Dark Horse"

RTD: Resonant tunneling diode

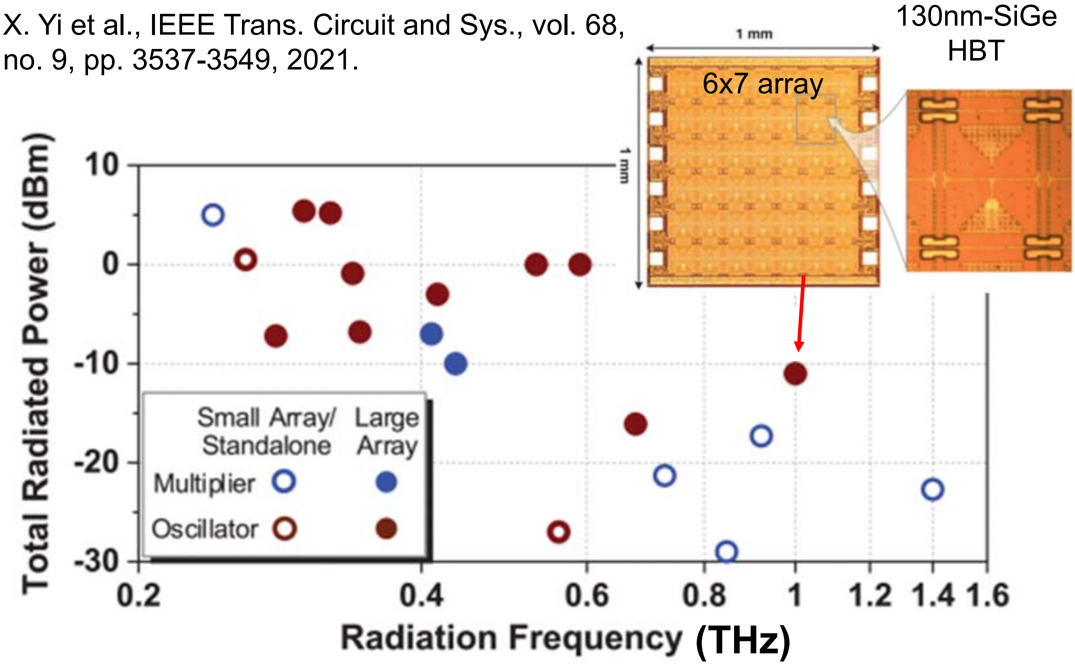






Si Way: Array Oscillators

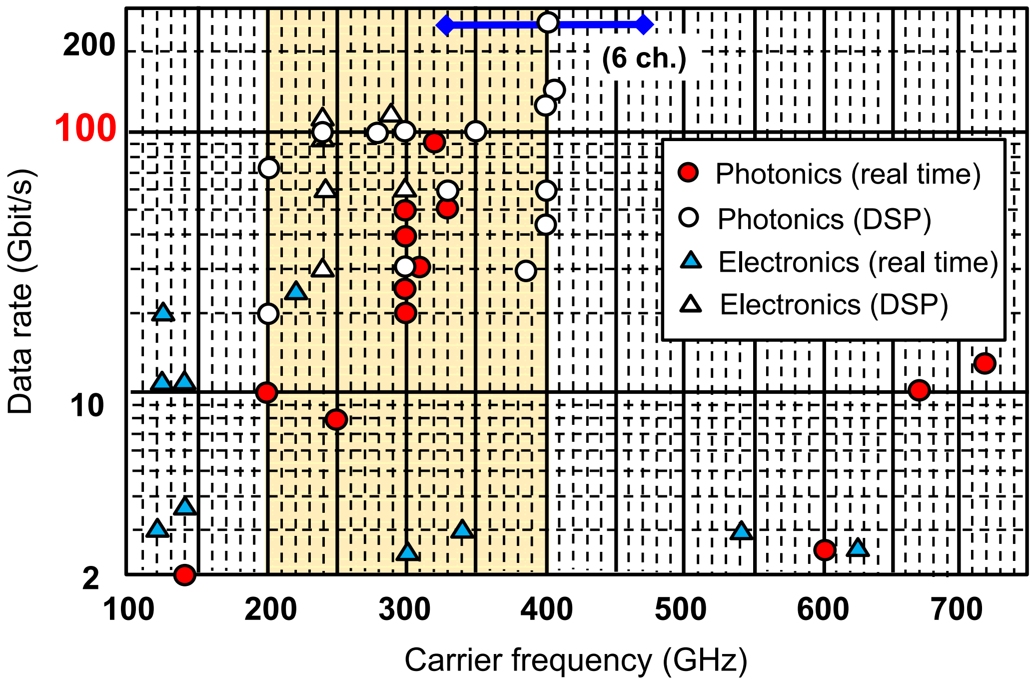
X. Yi et al., IEEE Trans. Circuit and Sys., vol. 68, no. 9, pp. 3537-3549, 2021.



Required Data Rate for B5G/6G

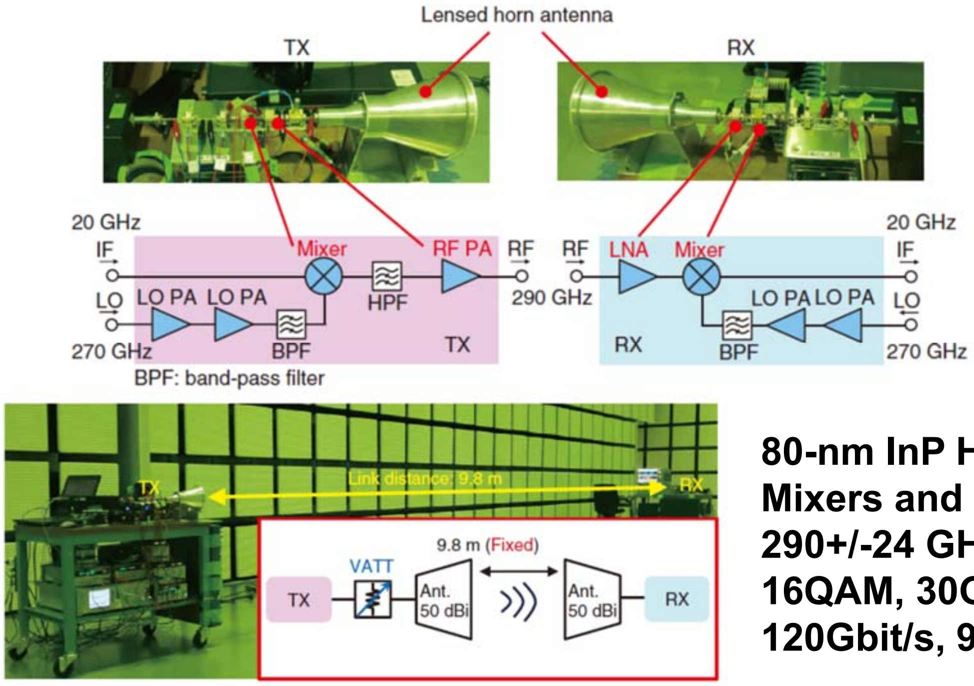
2000	2010	2020	2030
100M bit/s	1G bit/s	10G bit/s	**100G bit/s**
3G	LTE/4G	5G	**6G**

Recent Results: Carrier vs. Data Rate



300-GHz-band InP-HEMT ICs (NTT)

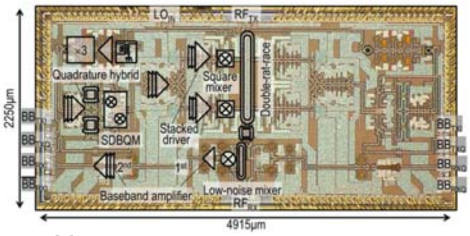
H. Hamada et al., NTT Technical Review, Vol. 19 ,No. 5, 74(2021).

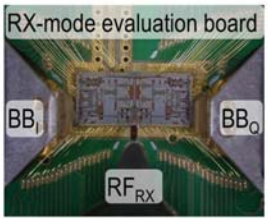


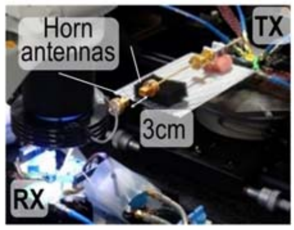
80-nm InP HEMT
Mixers and amplifiers
290+/-24 GHz
16QAM, 30Gbaud
120Gbit/s, 9.8 m

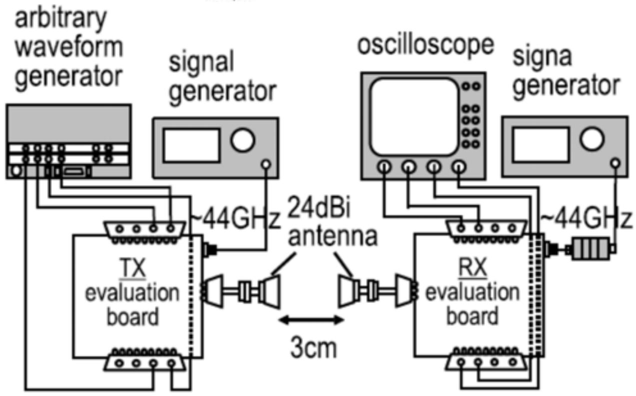
300-GHz-band Si-CMOS ICs (Hiroshima U.)

M. Fujishima et al., IEICE Electronics Express, Vol.18, No.8, 1–7, 2021.

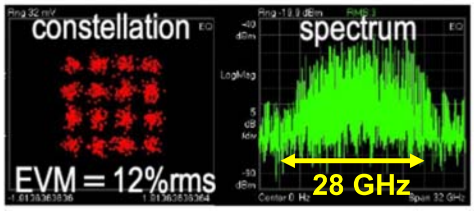






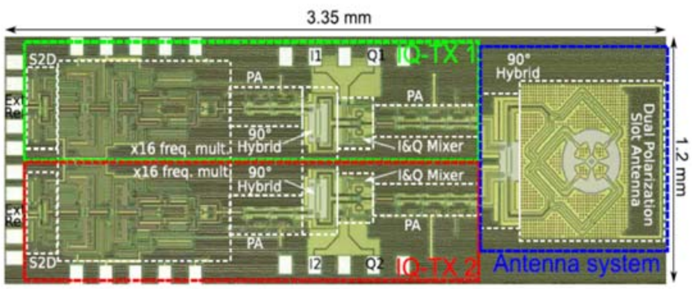


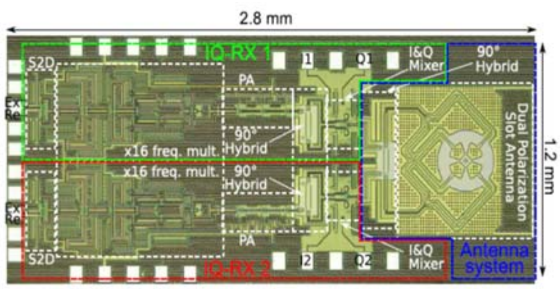
Carrier Frequency	265.68GHz Ch66 in 802.15.3d
Modulation	16QAM
Symbol Rate	20GBaud
Output Power	-1.6dBm
Power Consumption	1.79W



16QAM, 20 Gbaud, 80 Gbit/s, 3 cm

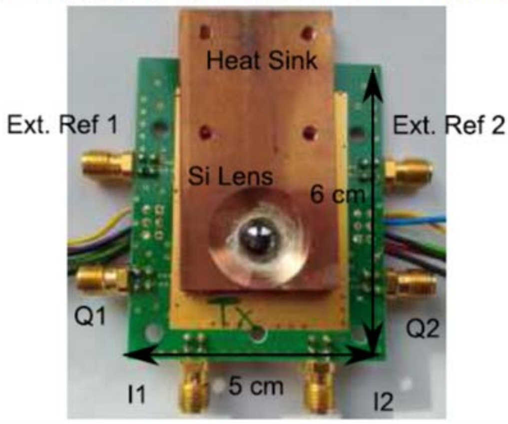
240-GHz-band SiGe HBT ICs(U. Wuppertal)





110 Gbit/s (QPSK+ **pol. Mux**)

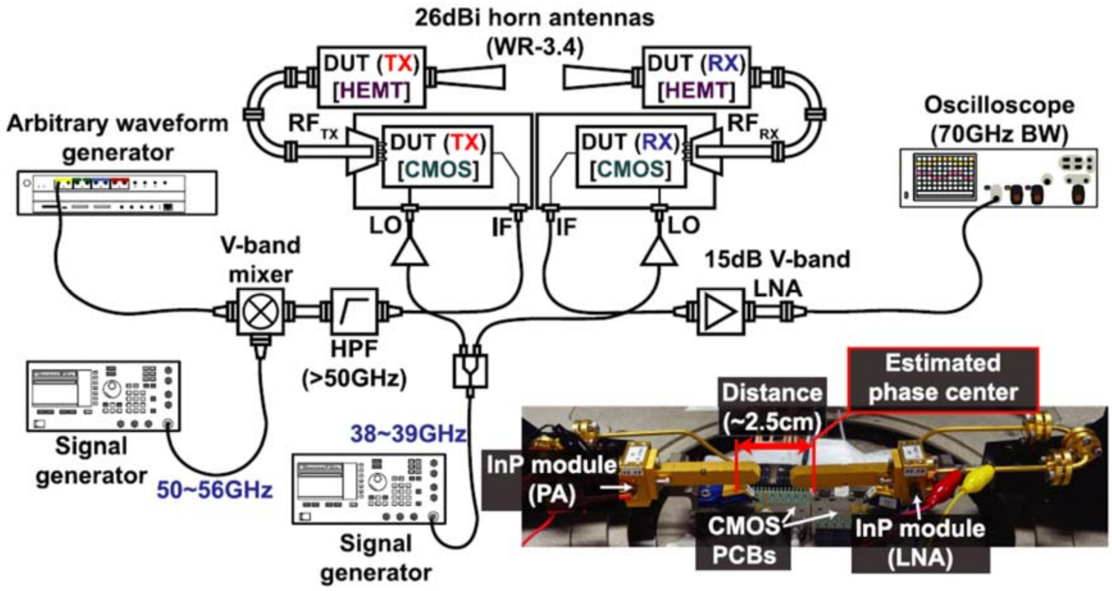
P. Rodríguez-Vázquez et al., "A QPSK 110-Gb/s Polarization-Diversity MIMO Wireless Link With a 220–255 GHz Tunable LO in a SiGe HBT Technology," IEEE Trans. MTT, pp. 3834-3851, September 2020.



300-GHz-band InP-CMOS Hybrid (Titech･NTT)

I. Abdo et al., IEICE Electronics Express, Vol.18, No.17, pp.1–4 (2021).

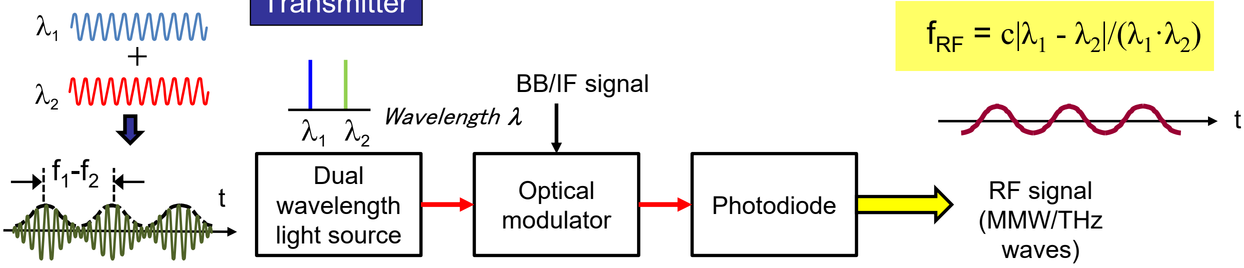
278-304GHz: 56 Gbit/s (16QAM)



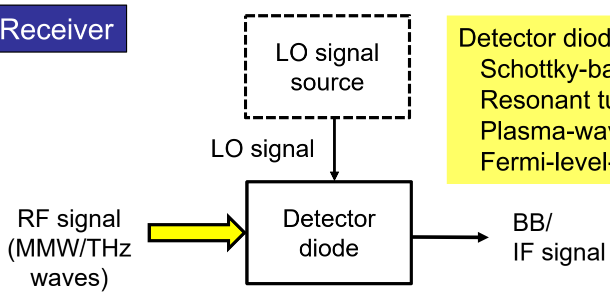
Basic Configuration: Photonics for CW Transmitters

Transmitter

$f_{RF} = c|\lambda_1 - \lambda_2|/(\lambda_1 \cdot \lambda_2)$



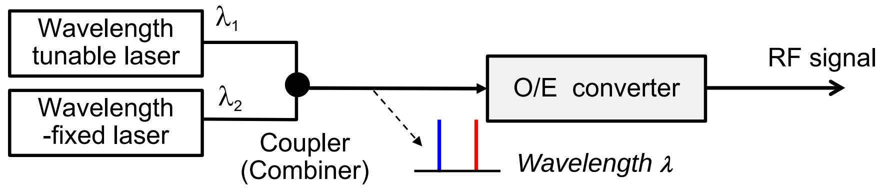
Receiver



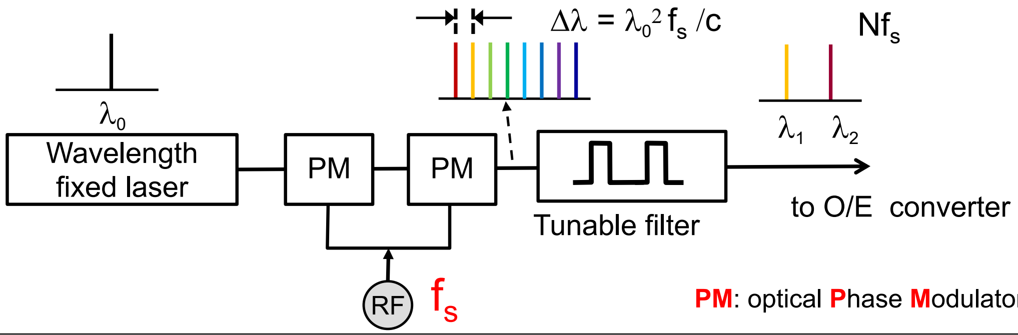
Detector diode
- Schottky-barrier diode (SBD)
- Resonant tunneling diode (RTD)
- Plasma-wave detector (FET)
- Fermi-level-managed barrier diode (FMBD)

CW Optical MM/THz-wave Sources

Basic scheme



Highly Coherent Sources using *Optical Frequency Comb*

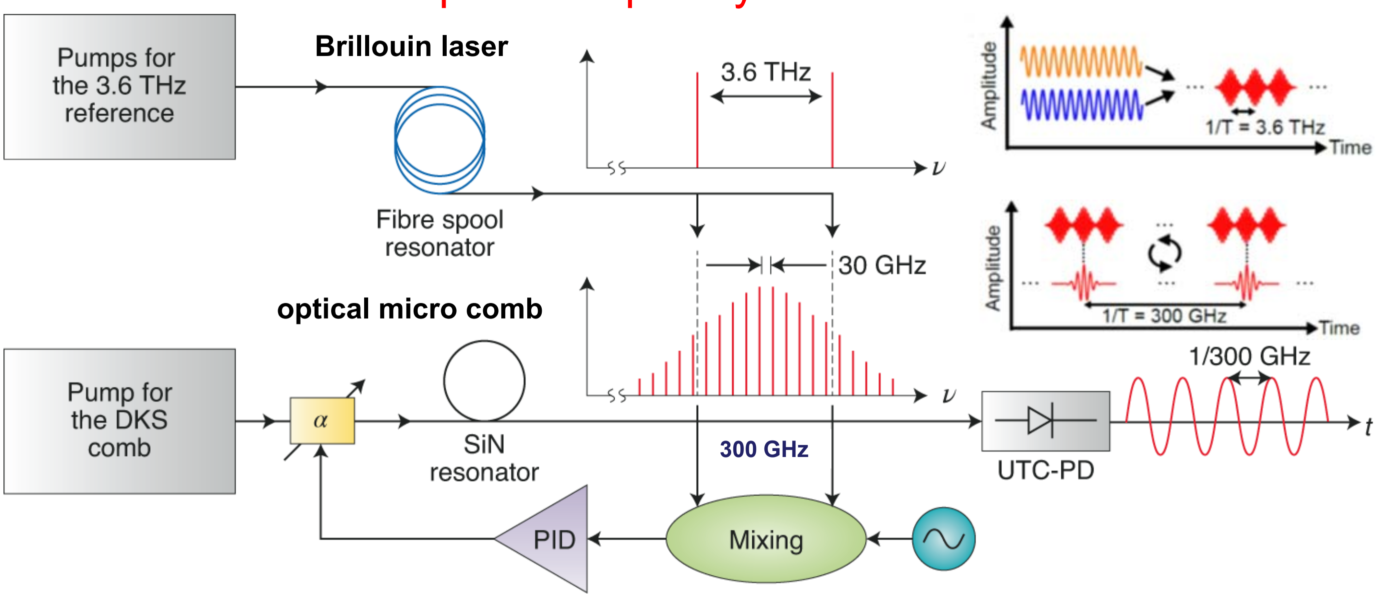


PM: optical **P**hase **M**odulator

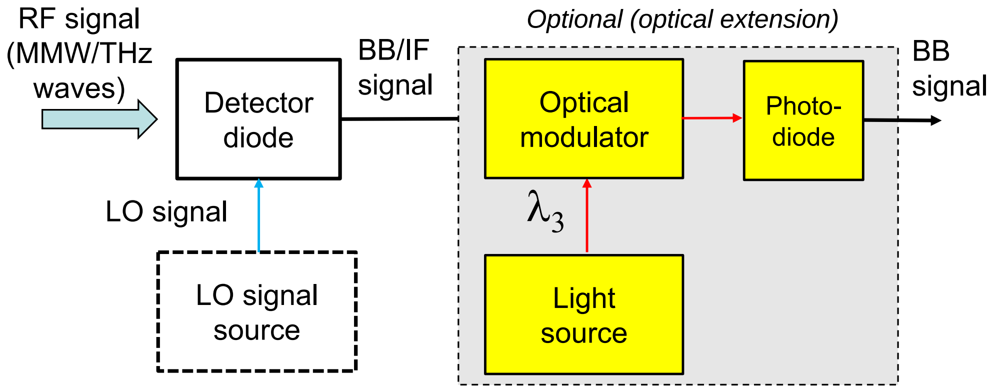
Ultra-low Phase Noise Optical Signal Generation

T. Tetsumoto, T Nagatsuma et al., "Optically referenced 300 GHz millimetre-wave oscillator," Nature Photonics, 2021.

"optical frequency division"



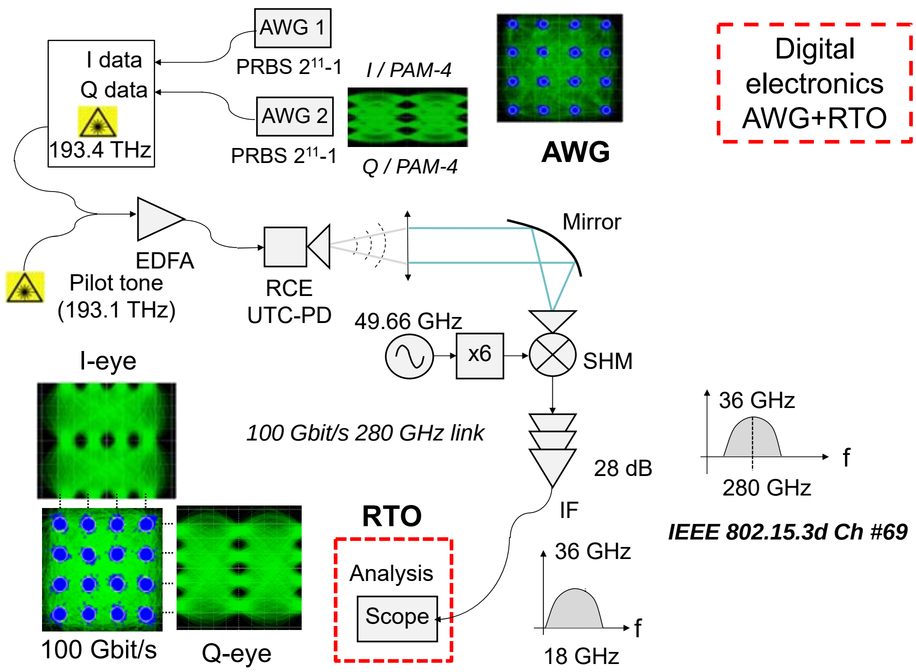
Typical Receiver Configurations



Detector diode
- Schottky-barrier diode (SBD)
- Resonant tunneling diode (RTD)
- Plasma-wave detector (FET)
- Fermi-level-managed barrier diode (FMBD)

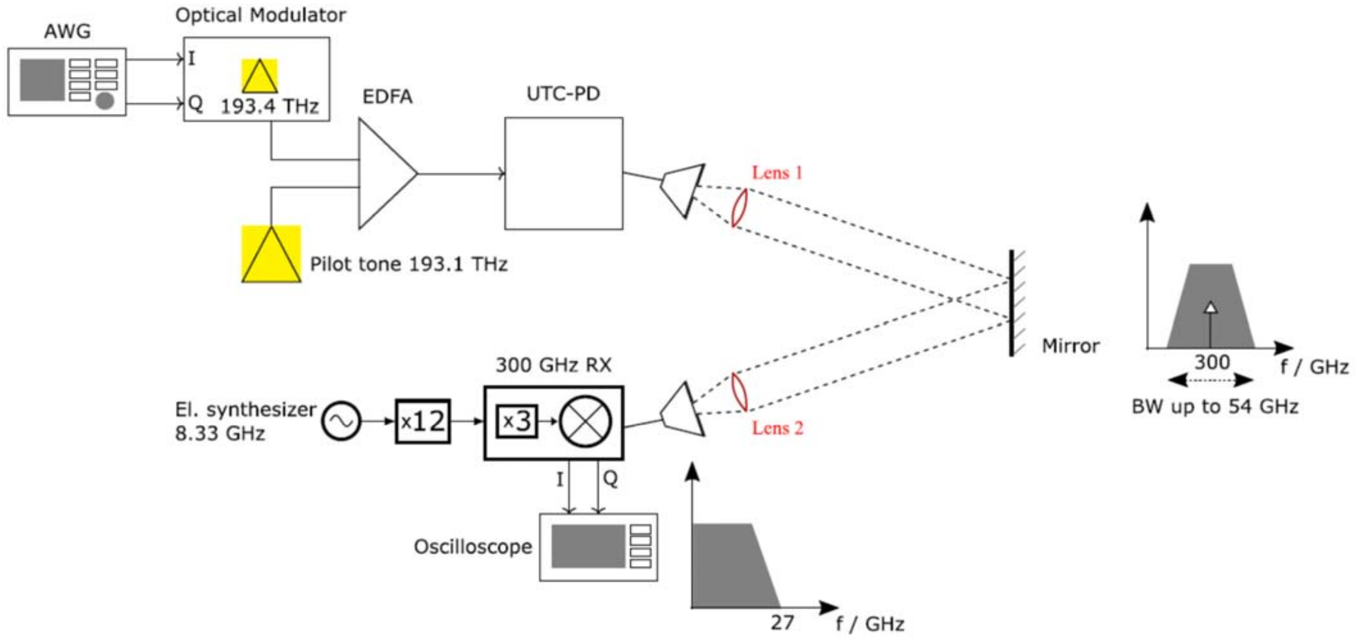
Free-running Transmitter and Heterodyne Receiver

V. K. Chinni *et al.*, *Electron. Lett.*, 54, 10, pp. 638-640, March 2018.



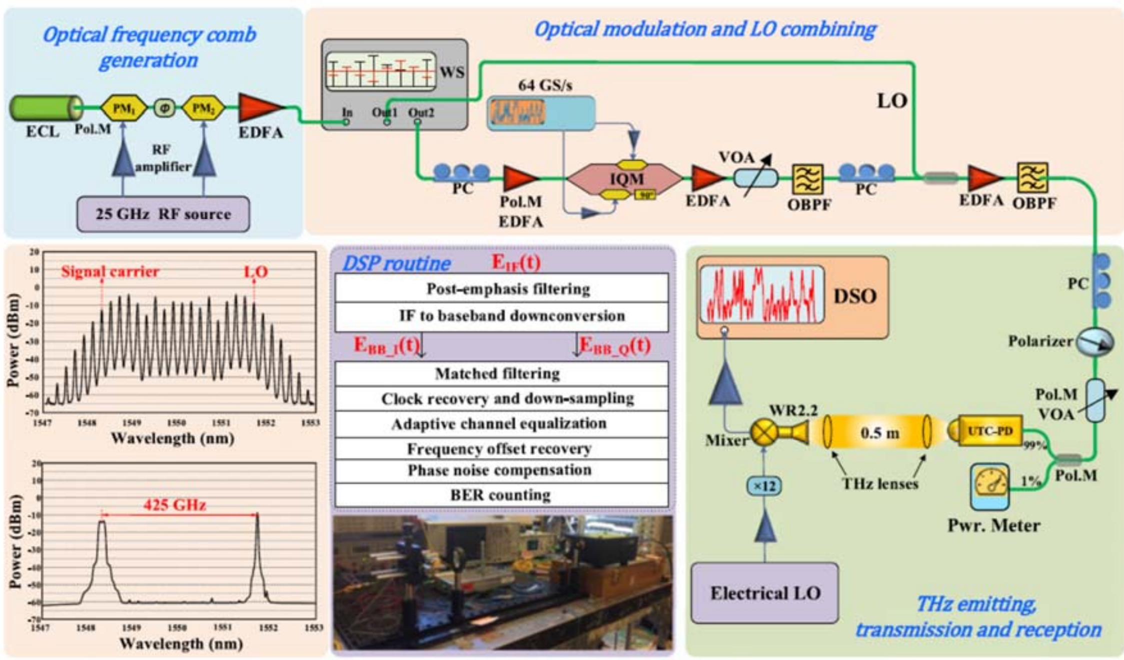
Free-running Transmitter and Direct I/Q Receiver

I. Dan *et al*., *Trans. Terahertz Science Tech*., **10**, 3, pp. 271-281, May, 2020.



Frequency-stabilized Transmitter and Heterodyne Receiver

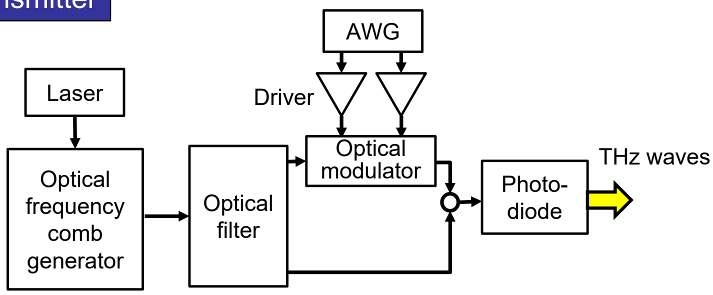
S. Jia *et al*., J. Lightw. Technol., **36**, 2, pp. 610-616, Jan. 2018.



Frequency-stabilized Transmitter and Direct I/Q Receiver

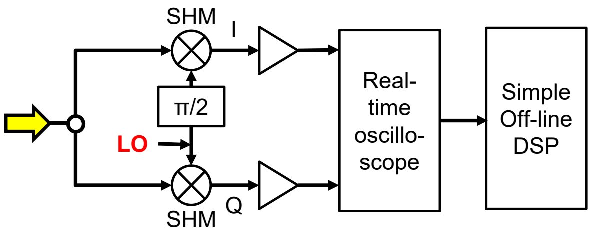
T. Nagatsuma *et al*., URSI AT-AP-RASC2022, Tu-D01-PM2-1, May 2022.

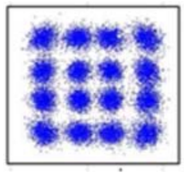
Transmitter



Receiver

SHM: sub-harmonic mixer pumped by frequency multiplier
LO = 26.5 GHz **x 6** = 159 GHz RF = 318 GHz (26.5 GHz x 12)





32 Gbaud/16 QAM
128 Gbit/s

Standard Simplest Off-line DSP

I/Q

↓

Resample

↓

Adaptive FIR filter

↓

Carrier frequency offset compensation (CFOC)

↓

Carrier phase estimation (CPE)

↓

Differential decoding

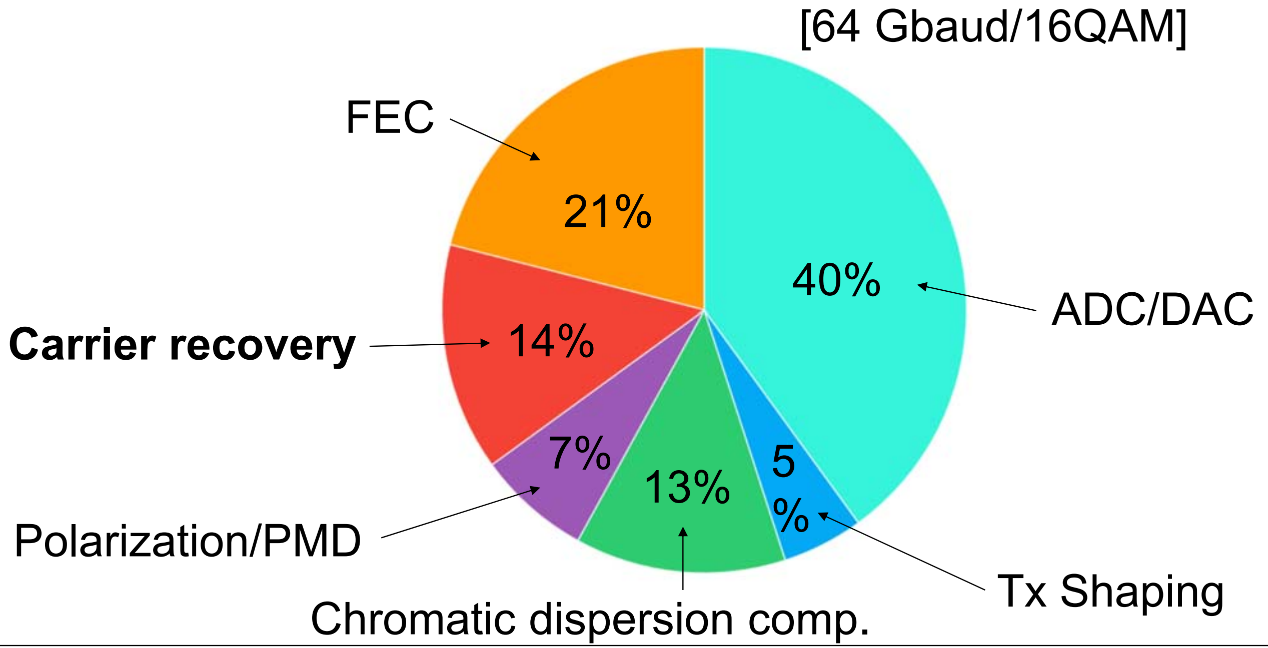
↓

BER

Can we eliminate this??

Increase in DSP Power Dissipation

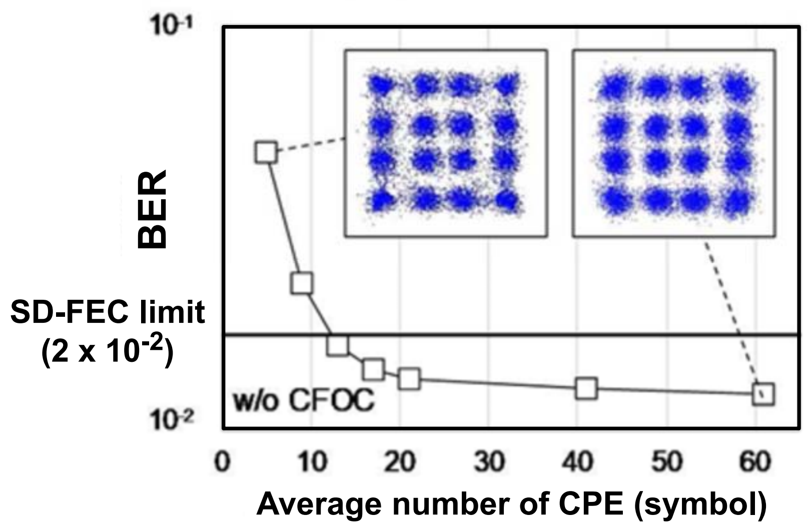
T. Kupfer et al., "Optimizing Power Consumption of a Coherent DSP for Metro and Data Center Interconnects," Th3G.2, OFC2017.



Effect of CFOC & CPE

CFOC: Carrier frequency offset compensation

CPE: Carrier phase estimation

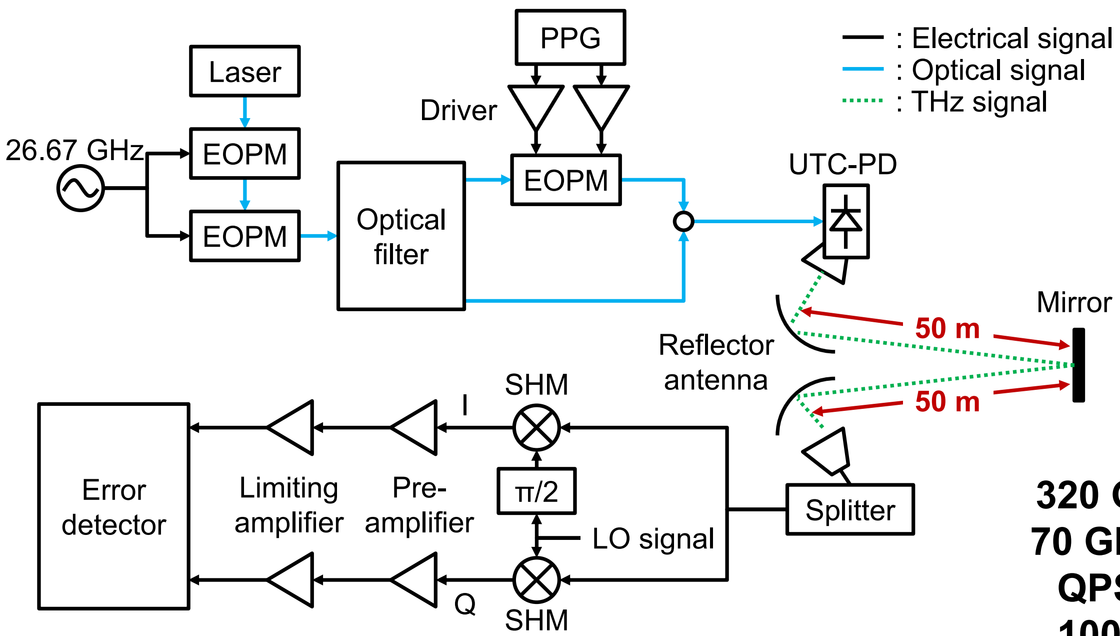


CFOC is not necessary!!

Link Distance Challenge/SISO

Carrier	Data rate	Distance	Ref.
125 GHz (18GHz)	10 Gbit/s (OOK/real time)	5.8 km	A. Hirata et al., ICWITS 2010
240 GHz	64 Gbit/s (QPSK/off line)	850 m	I. Kallfass et al., J. IRMMW/THz, 2015
320 GHz	**70 Gbit/s (QPSK real time)**	**100 m**	**K. Iwamoto et al., MTSA 2017**
300 GHz	**100 Gbit/s (QPSK /off line)**	**110 m**	**T. Harter et al., ECOC 2018**
300 GHz	44 Gbit/s (QPSK /off line)	1 km	C. Castro et al., IWMTS 2020

QPSK 100-m Transmission at 320GHz (OU)

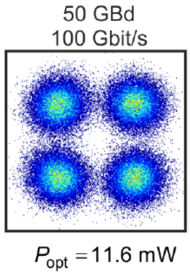


EOPM : Electro-Optic Phase Modulator, PPG : Pulse Pattern Generator

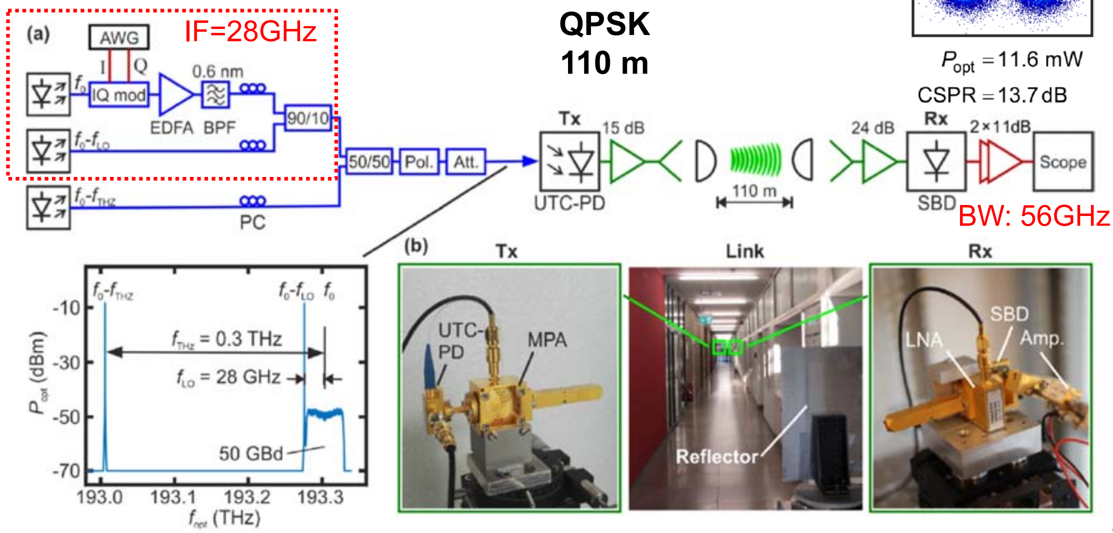
320 GHz
70 Gbit/s
QPSK
100 m

QPSK 100-m Transmission at 300 GHz (KIT)

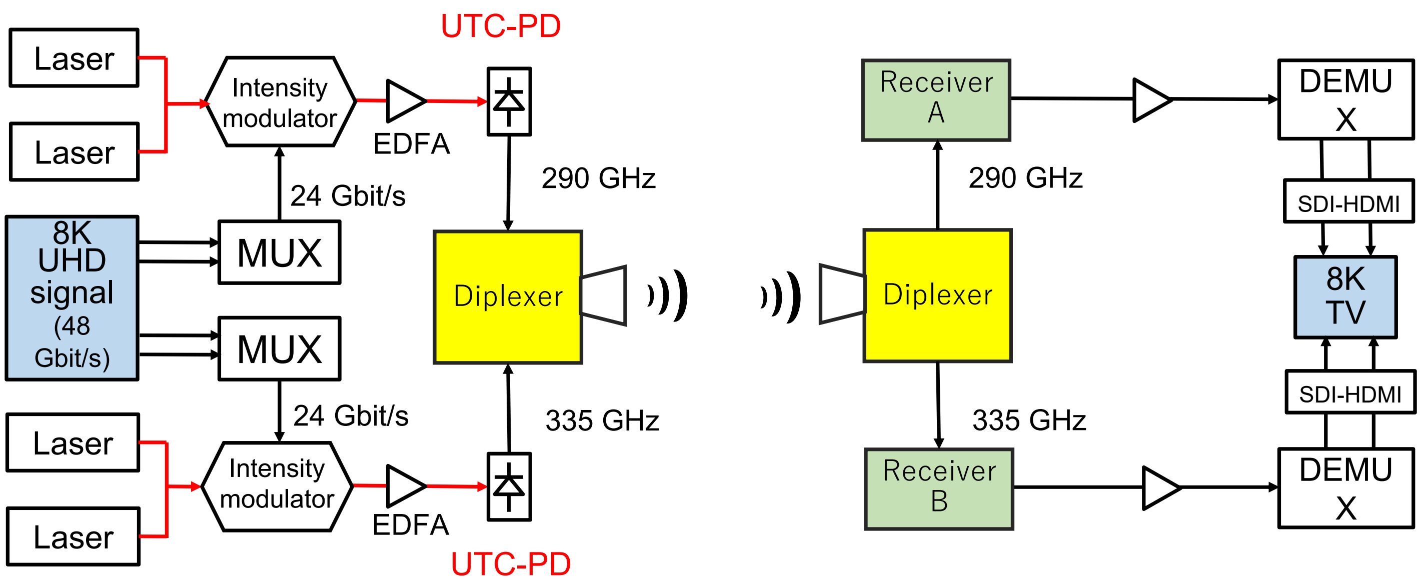
T. Harter et al., "110-m THz Wireless Transmission at 100 Gbit/s Using a Kramers-Kronig Schottky Barrier Diode Receiver," ECOC)2018, September 2018.

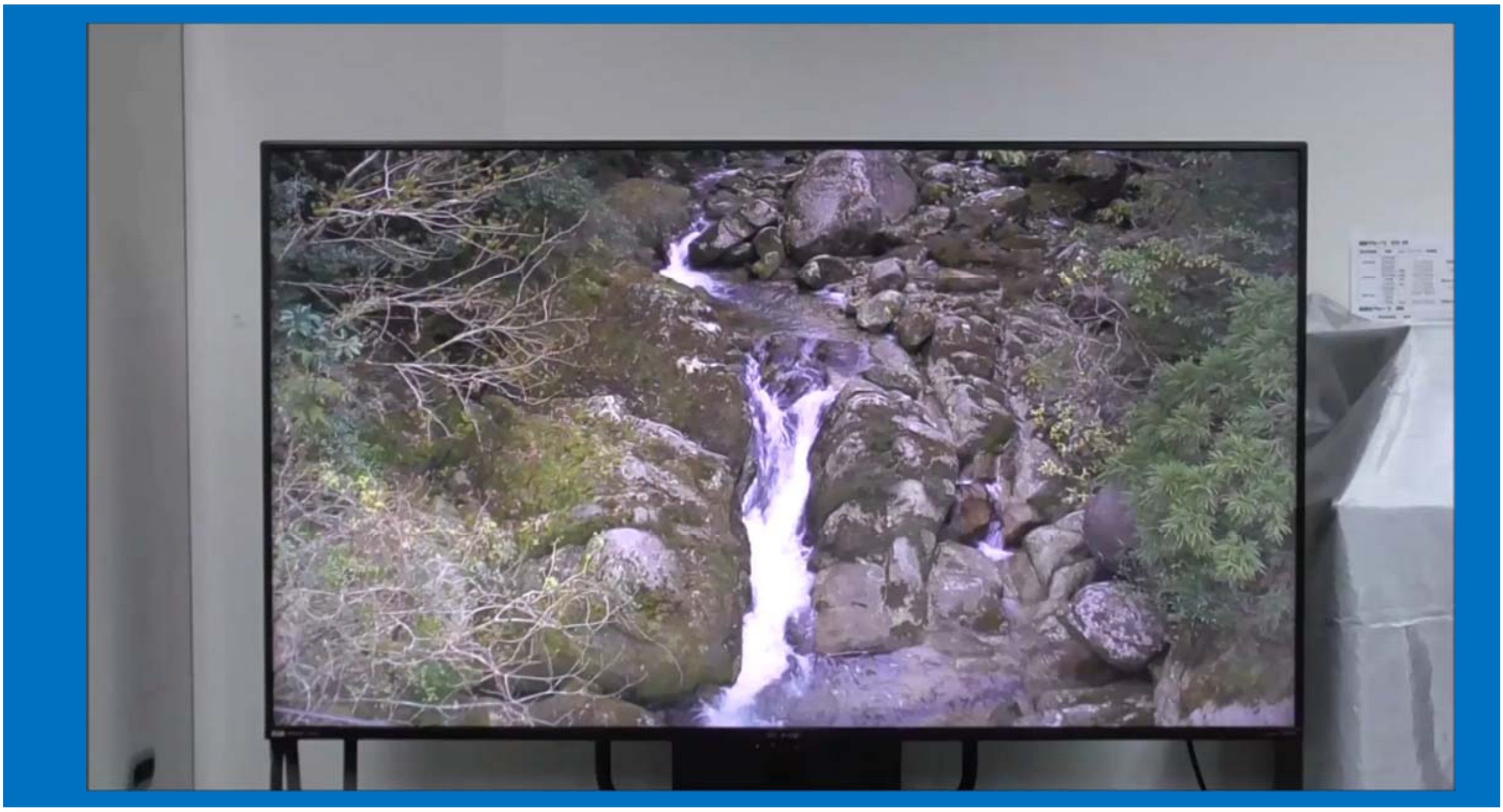


300 GHz
100 Gbit/s
QPSK
110 m



Full 8K Ultra-HDTV Transmission: 48 Gbit/s





We are ready for preparation towards 6G

- 100 Gbit/s has been achieved by using 200-400GHz carriers (G and H bands).
- Most of them utilize photonics technologies, which has led frontend of THz communications research.
  Now, electronics have been catching up with photonics.
- Over-200-Gbit/s has been reported by using multi-channels based on photonics.
- D-band (110-170GHz) is also promising in terms of device maturity.

Outline

Review current status of THz communications research and discuss the future direction

1. *State of the art*
   - *selection of frequencies/bands*
   - *transceiver and system technologies: photonics vs. electronics*

2. ***Future directions***
   - ***device technologies***
   - ***system integration technologies expectation for TERAWAY***

Technical Issues and Challenges

･Components

Transmitter output power increase
thermal management of devices
power combiners

Receiver sensitivity increase
low-barrier diodes, etc.
THz optical modulators

Phased arrays (phase shifter problems) and antennas

Phase noise reduction of oscillators

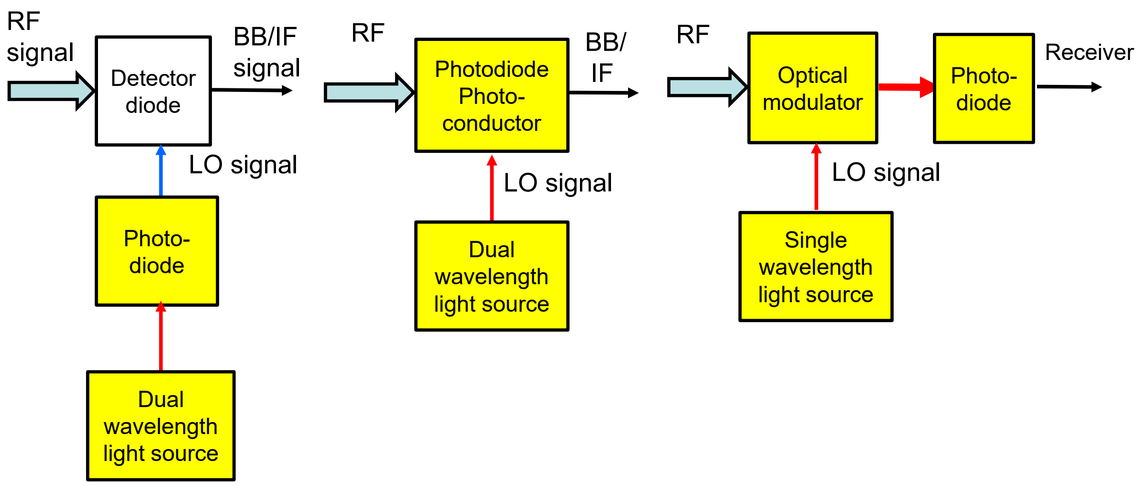
･Integration and packaging

Platform: hollow waveguide, dielectric waveguide
Electronics-photonics integration

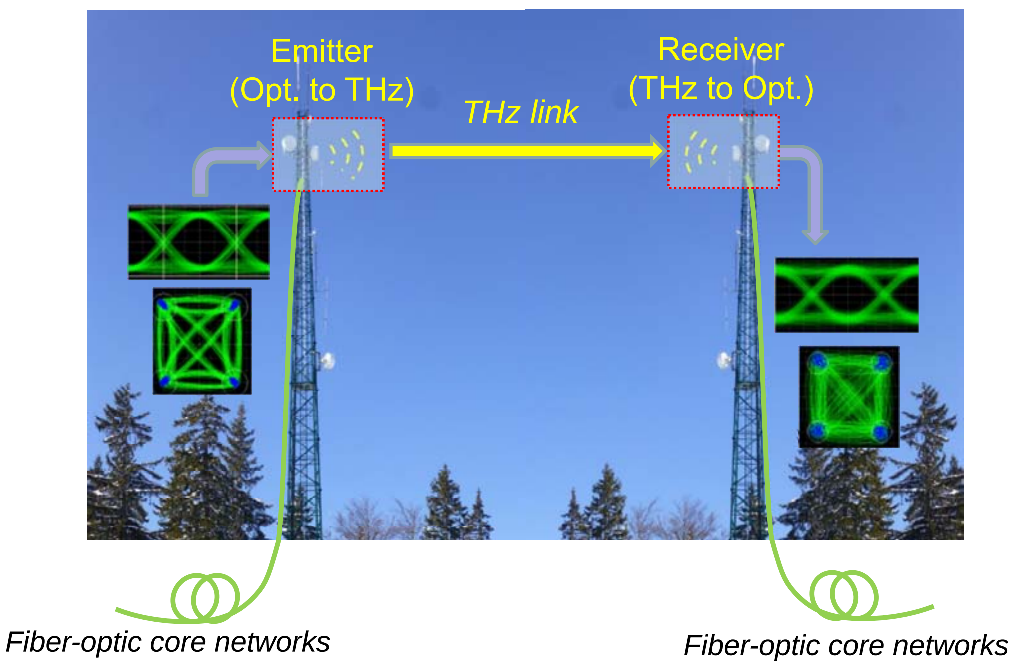
Photonics-based Receivers

Photonics is required more in receivers.

(I) Photonic LO type (II) Photonic receiver type (III) Optical output type



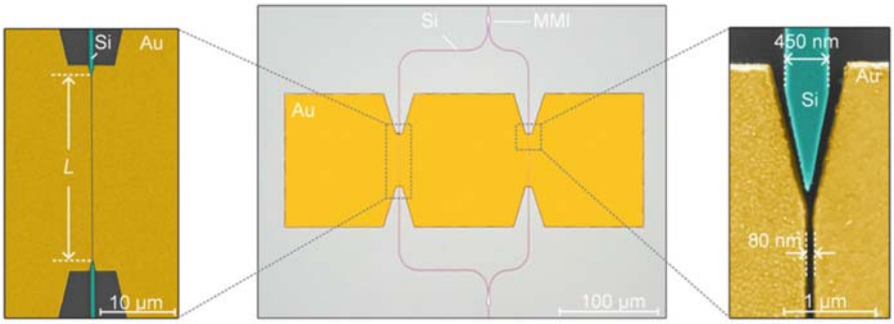
Transparent Optical-THz-Optical Link



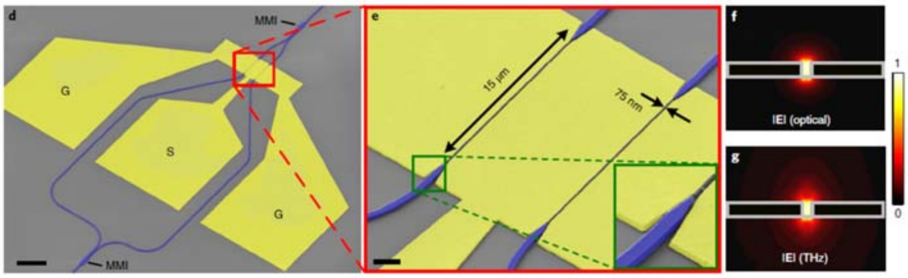
T. Nagatsuma et al., Nature Photonics, vol. 10, 371(2016).

THz Optical Modulators for Reception

W. Heni et al., J. Lightwave Tech., 34, 2, pp. 393-400 (2016).
M. Burla et al., APL Photon., 4, 056106 (2019).



S. Ummethala et al., Nature Photon., 13, pp. 519-524 (2019).



Resent Results for Opt.-THz-Opt. Link

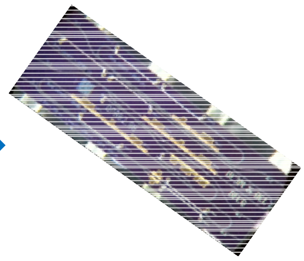
Authors	Frequency	Results	Remarks
S. Ummethala et al. (KIT, 2019)	288.5 GHz	36 Gbit/s (7%FEC) QPSK 16 m	THz preamplifier was used
Y. Horst et al. (ETH, 2021)	230 GHz (79 GHz BW)	190 Gbit/s (**10 ch** FDM) QPSK & 16QAM 115 m	THz preamplifier was used 20% FEC assumed
P. T. Dat et al. (NICT, 2021)	101 GHz (14 GHz BW)	71 Gbit/s 64QAM 5~20 m	LN modulator was developed 20% FEC assumed

Integration of Photonic Systems

Past ***Present*** ***Future***

In Labs

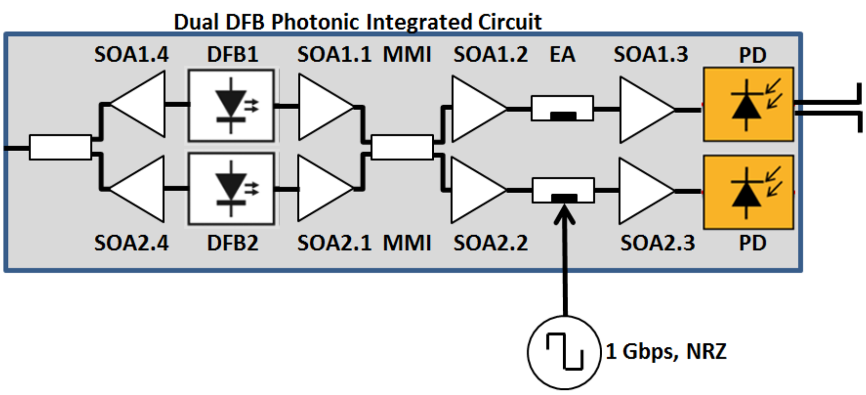
Outside Labs

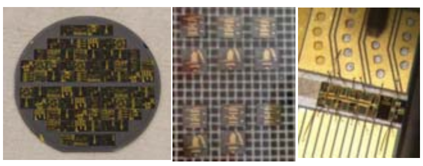


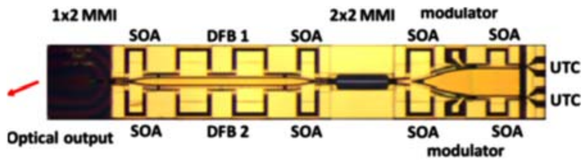
Inside Phones?

Fully Integrated THz Photonics System

Integrated transmitter for communication (90-100GHz)





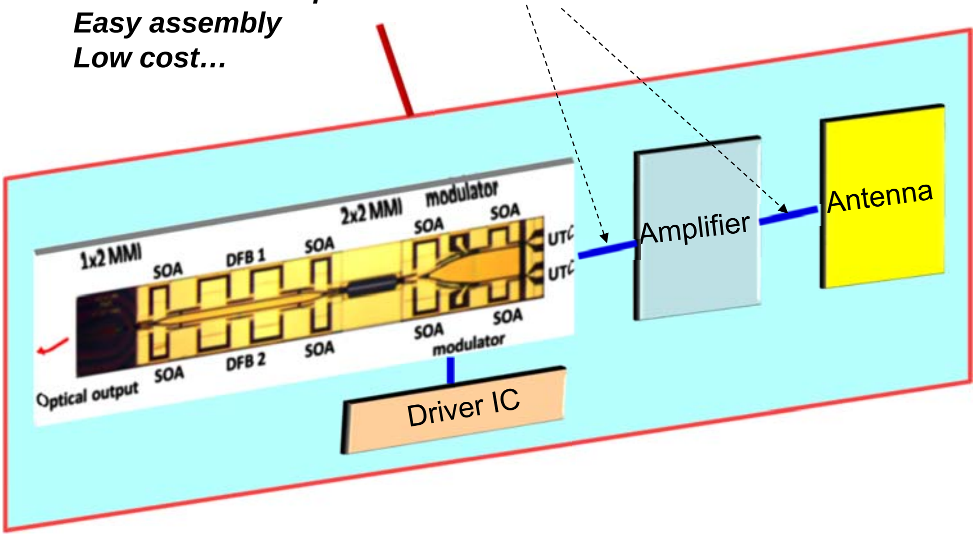


G. Carpintero et al., IEEE Journal of Lightwave Tech., vol. 32, 3495 (2014).

Still Needs Integration/Packaging

Integration platform

Wide bandwidth interconnect
Low loss/Low dispersion interconnect
Easy assembly
Low cost…



What is the Best THz Transmission Media?

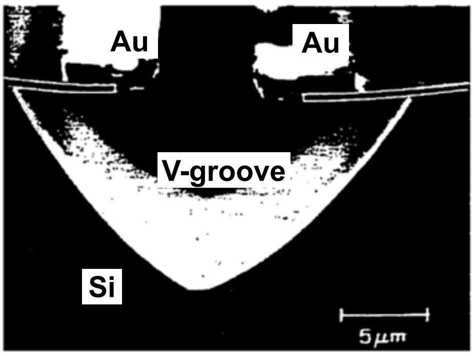
From electronics:

metallic transmission line
metallic hollow waveguide

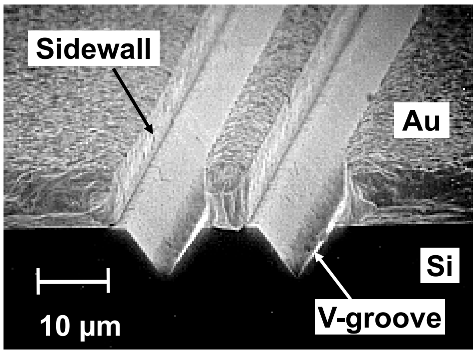
From photonics:

dielectric waveguide

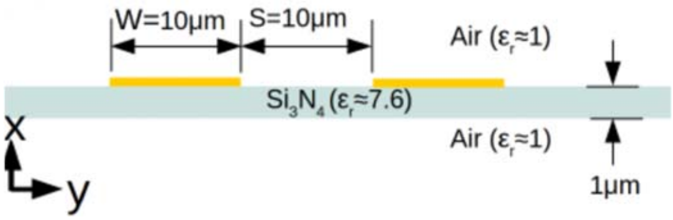
Metallic Lines with Reduced Dielectric Layer



D. R. Dykaar et al., APL, 1990.

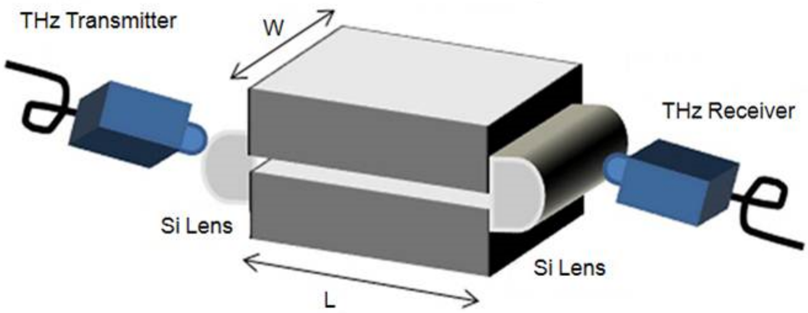


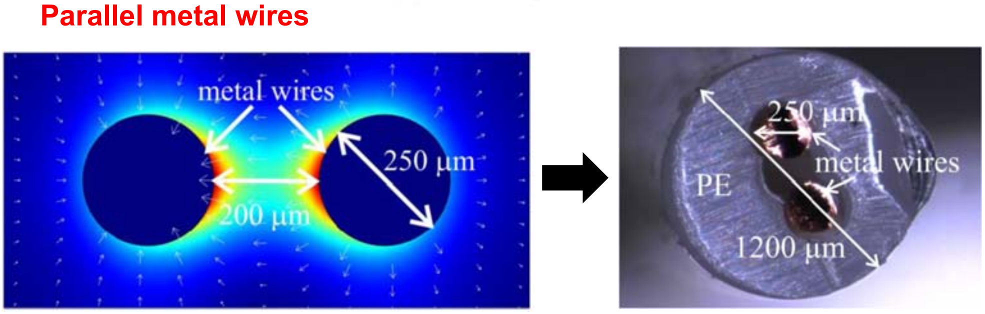
T. Nagatsuma et al., IEEE MTT, 2001.



R. Smith et al., Opt. Express, 2019.

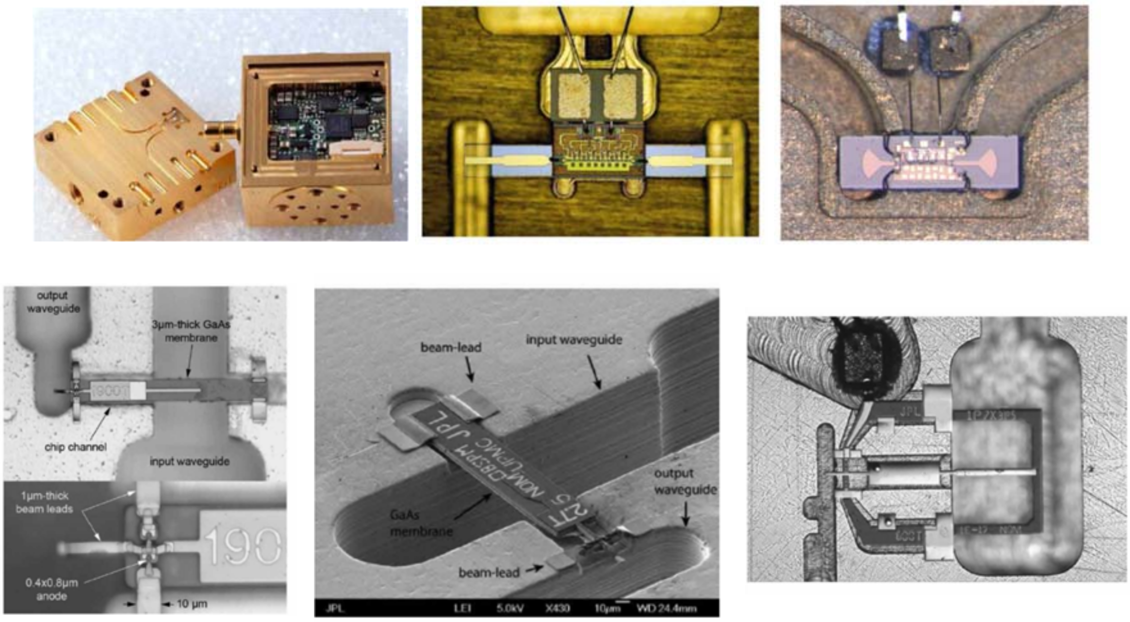
Metallic-Line Only is the Best?





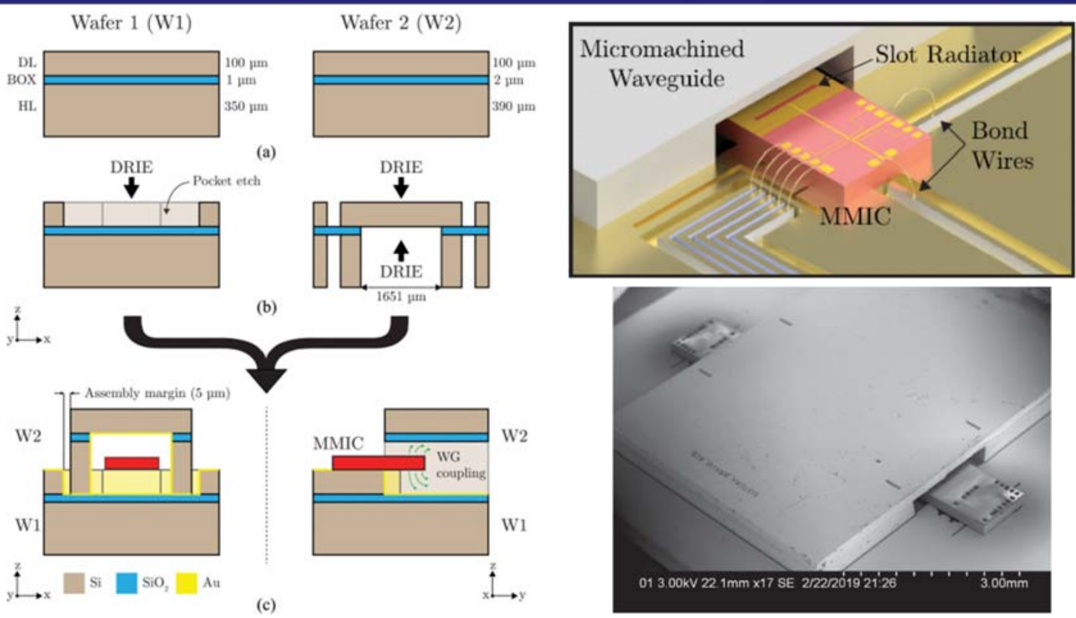
A. Markov et al., J. Opt. Soc. Am., no. 11, Nov.2014.

Packaging in Hollow Waveguides



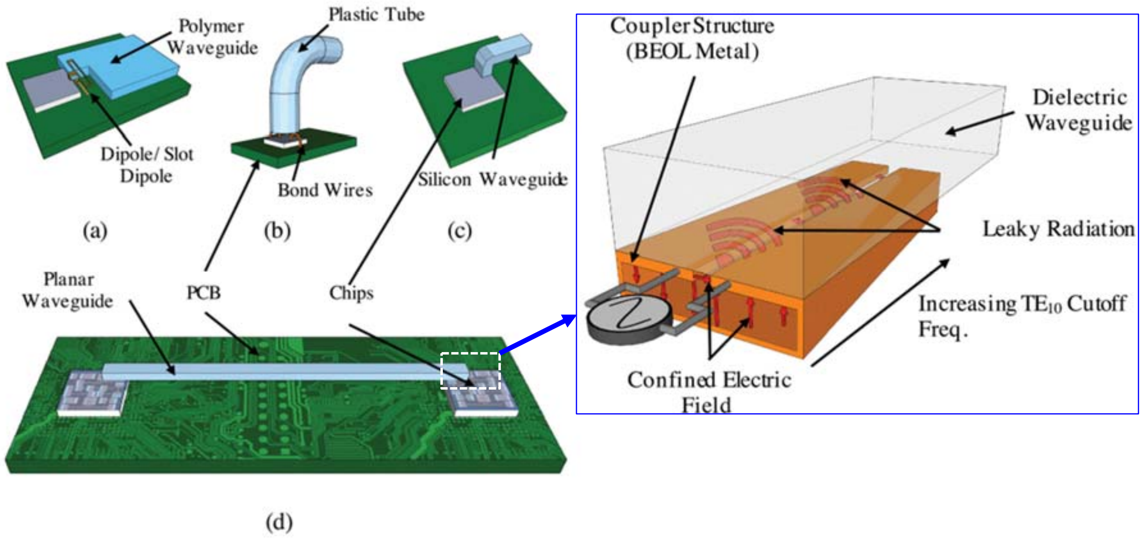
Ho-Jin Song, "Packages for terahertz electronics," Proc. IEEE, 105, 6, 2017.

MEMS-based Hollow-Waveguide Platform



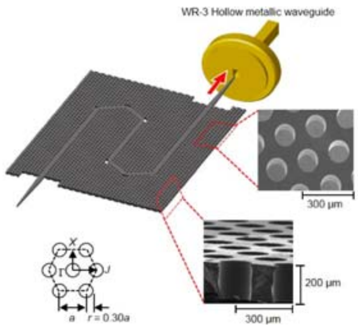
James Campion et al., "Toward industrial exploitation of THz frequencies: integration of SiGe MMICs in **silicon-micromachined waveguide systems**," IEEE Trans. THz Science and Tech., vol. 9, p. 624, (2019): KTH.

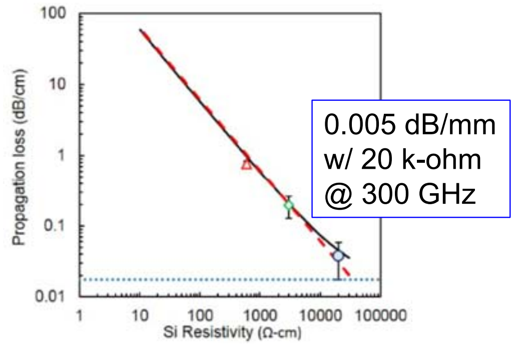
Dielectric Waveguide Inspired by Photonics



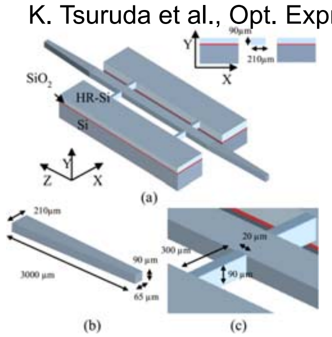
J. W. Holloway et al., "A fully integrated broadband sub-mmWave **chip-to-chip interconnect**," IEEE Trans. Microw. Theory Techn., vol. 65, no. 7, pp. 2373-2386, (2017): MIT.

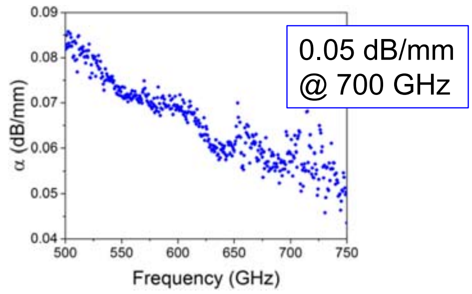
Dielectric Waveguide Based on Si-MEMS





K. Tsuruda et al., Opt. Express, 23, 25, pp. 31977-31990 (2015): Osaka U.

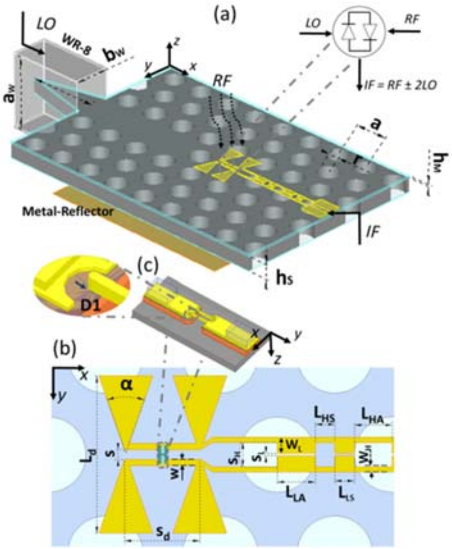




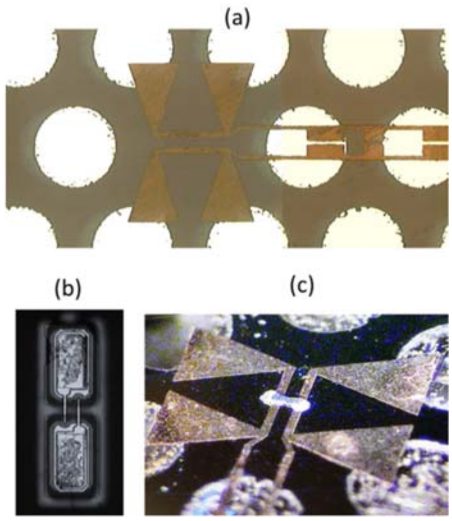
E. Akiki et al., IEEE THz, 11, 1, pp. 42-53 (2021): IEMN.

Example of Integration with Active Devices

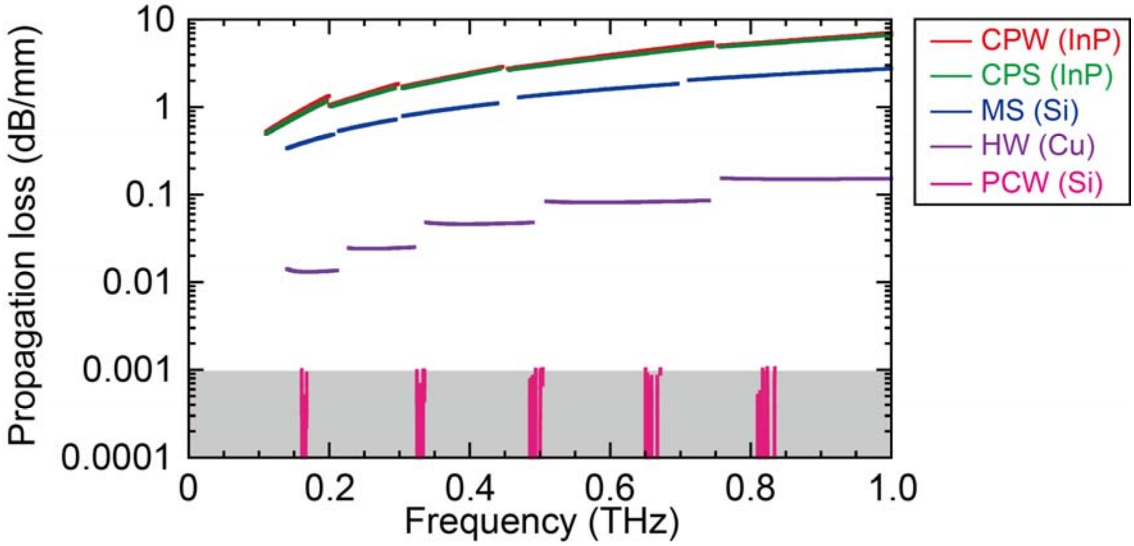
A. E. Torres-García et al., "Silicon integrated subharmonic mixer on a **photonic-crystal platform**," IEEE THz,11, 1(2021): UPNA.



for 200-220 GHz

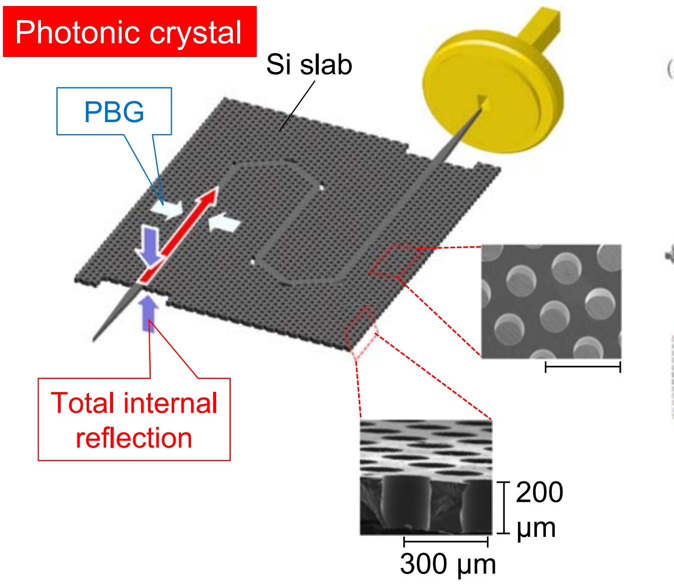


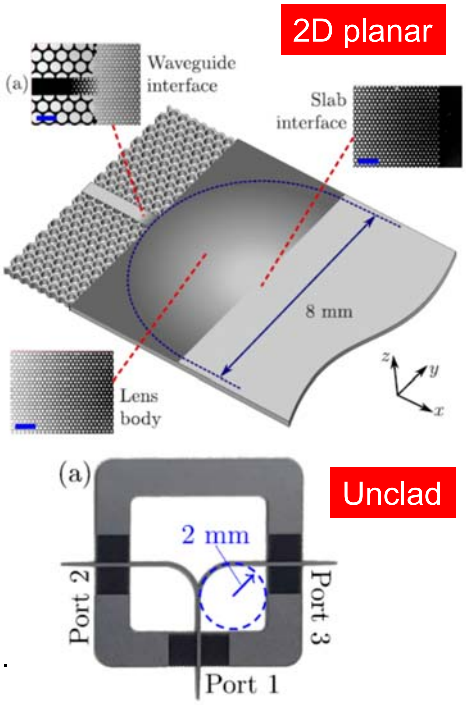
General Comparison



X. Yu., PhD Thesis, Osaka University, 2020.

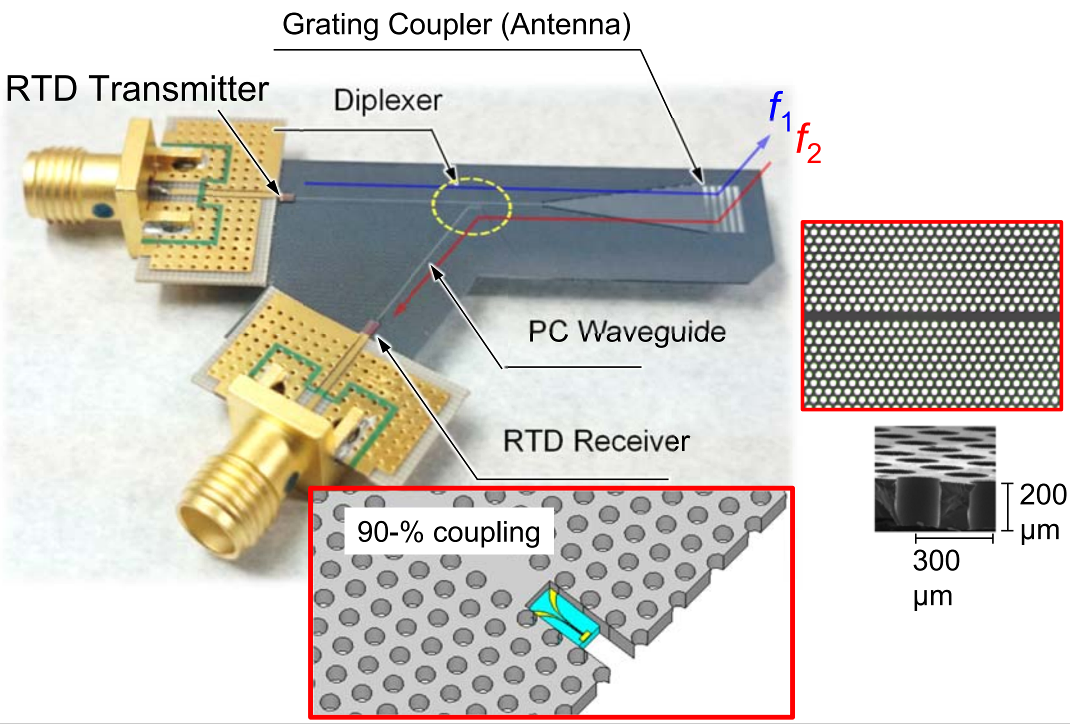
Dielectric Waveguide Families at Osaka U.





D. Headland et al., "Unclad Microphotonics for Terahertz Waveguides and Systems, IEEE/OSA J. Lightwave Tech., 2020.

Example of THz System using PhC Waveguide



Phased Array Problem in THz Integrated Circuits

2D phased array has not been realized at 300 GHz.

	Antenna pitch ($\lambda/2$)		Chip size
28 GHz (5G)	5~6 mm	>	1 mm
300 GHz (6G)	0.5 mm	<	1 mm

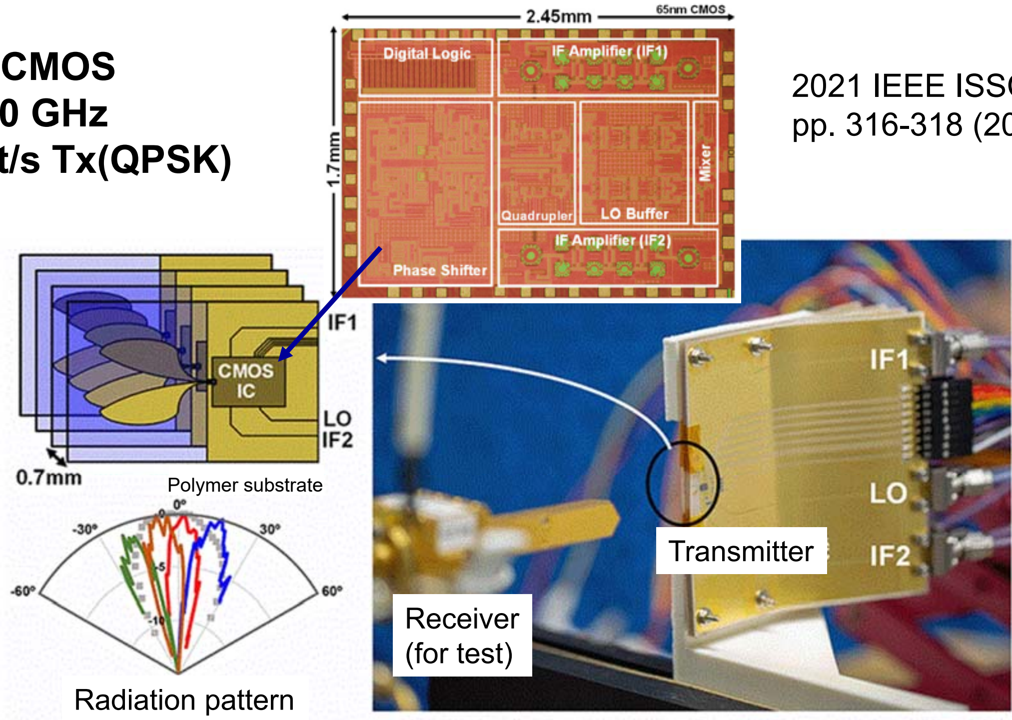
Hybrid integration/packaging

Antenna array **+** **Efficient interconnect (incl. photonics)** **+** **TX/Rx array**

300-GHz-band Si-CMOS Phased Array (Titech)

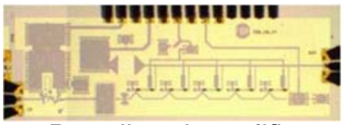
65 nm CMOS
242-280 GHz
52 Gbit/s Tx(QPSK)

2021 IEEE ISSCC, 22.2, pp. 316-318 (2021)

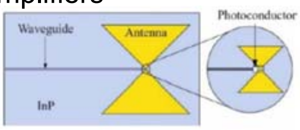


Expectations for TERAWAY

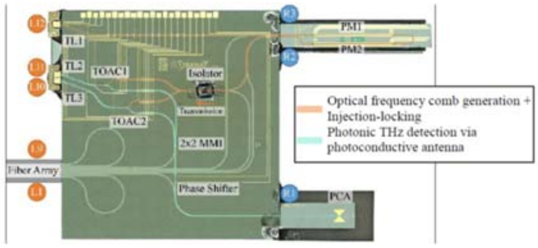
TERAWAY provides key technologies, which all meet future directions!!
~Aggressive integration of electronics and photonics~



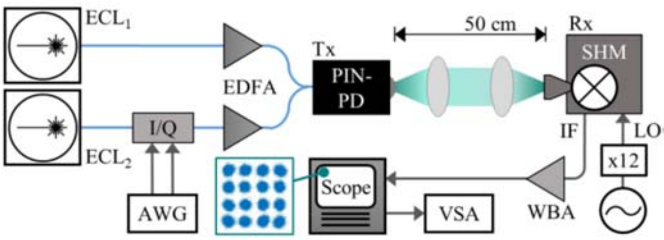
Broadband amplifiers



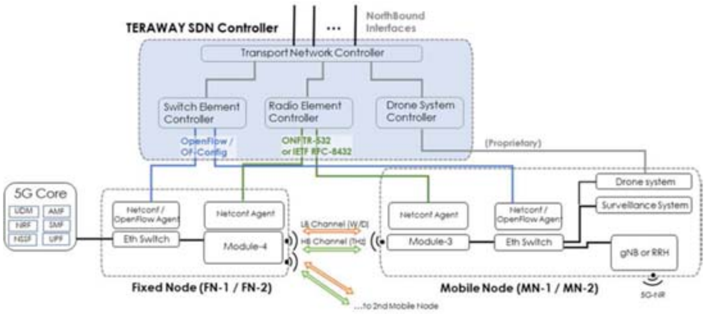
Efficient O/E converters



Integrated photonics-based Rx



THz link using photonics-based Tx

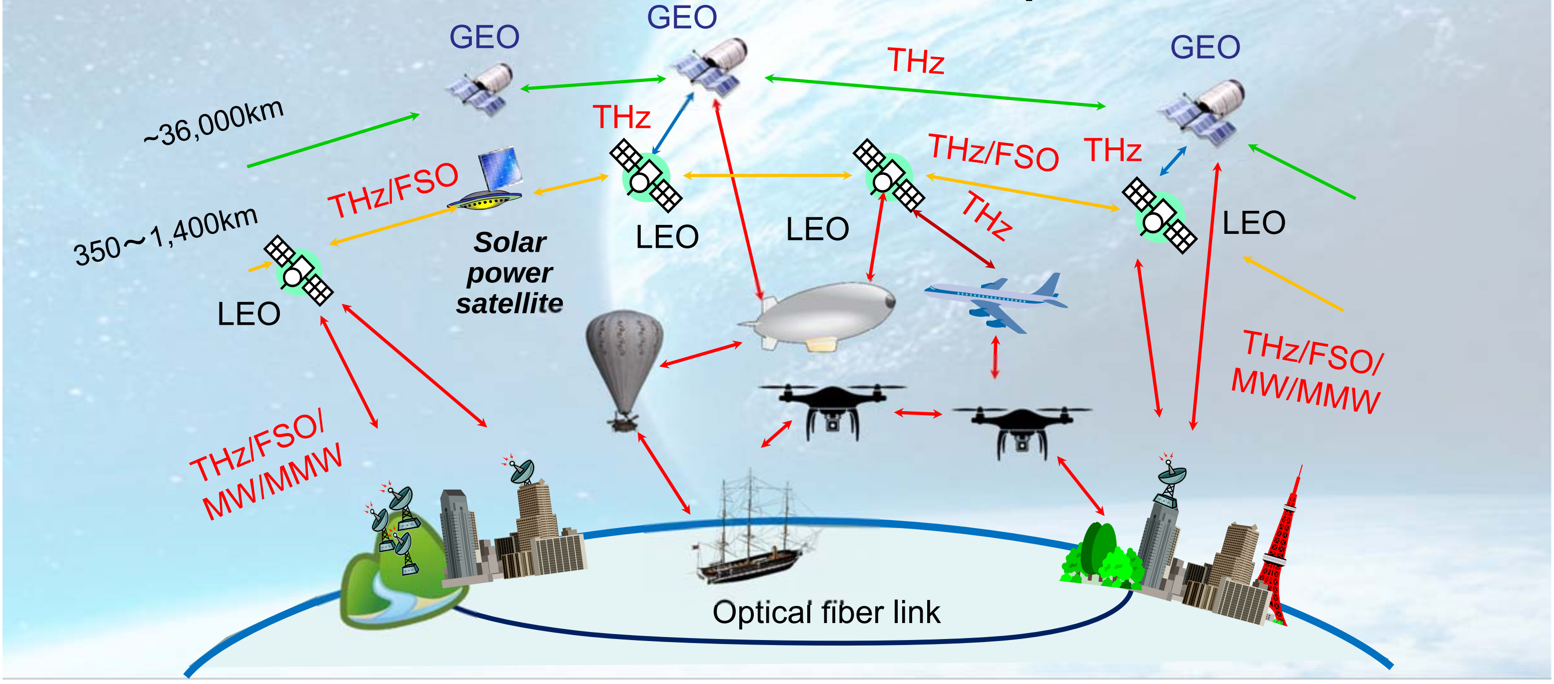


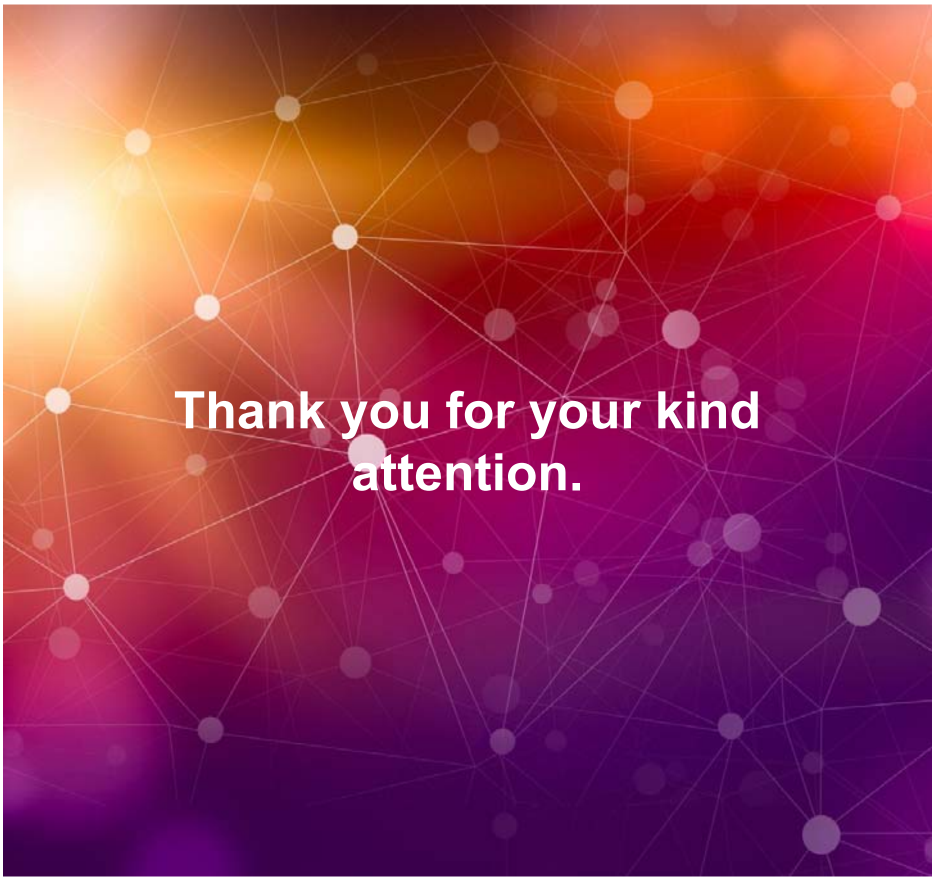
Network architectures

THz x Drone: Students Initiative

6G & Beyond

From 2D NW to Vertical and Space





Acknowledgment

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