Terahertz communications using photonics based emitters for 300 GHz band

From mmWave to terahertz communications for beyond 5G

G. Ducournau, IEMN
IEMN is a French CNRS/University institute
Located north of France, close to (5 km!) Belgium

1h10 min by fast train from CDG
30 min from Brussels midi
Outline

THz communications: context
Photomixing for optical to radio conversion, towards high-level schemes
Links using photonics
Conclusion / Challenges
A little bit of Terahertz

- **Sources**
  - Electronic sources:
    - Multiplication chains, RTD, transistors, diodes ...
    (compact, room temp., but bandwidth limited / efficiency)
  - Opto-electronics:
    - Photodiodes, photoconductors
      (tunable, room temp., but power limited, efficiency)
  - Direct generation
    - QCL, non-linear optics, molecular lasers
      (power = ok, but efficiency, bulky, sometime cryogenic, ...)

1 THz $\leftrightarrow$ 1 ps $\leftrightarrow$ 300 µm $\leftrightarrow$ 4,1 meV $\leftrightarrow$ 49 K

Optical fibers (1.55 µm)
1. Context

Exponential Growth on IP traffic / Fastest growth on wireless channel

- Context: Possible interest for THz?

Adapté de [P.J. Winzer; IEEE Proceedings]

Future P2P links
Future mobile wireless links

"We will use THz carrier frequencies by 2020", after T. S. Bird, Keynote talk at Asia-Pacific Microwave Conference, Melbourne, Australia, December 2011.
**Context**

**P2P applications: first enabler of THz coms?**

From Shannon theorem: $B$ bandwidth, $S/N =$ signal to noise ratio, $C =$ channel capacity

**RADIO:** Small $B$, thus high $S/N$ required/complex modulations

**THz:** Huge $B$, thus more margin on $S/N$ (in theory)...
However THz power is often limited
=>$\textbf{Importance}$ of amplifiers, as SSPA, Tube, LNAs...

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

**Alternatives**

« FSO »
(Free Space optics, 0.4 / 0.78 µm)
(ex: Intellimax) ~ Gbit/s

Backhaul Q & E-band
ELVA: 10 Gbps / 10 km (clear sky)
**Context**

Inter-city

In the city [THOR Project, thorproject.eu]

2018-2021

Outdoor demo of THz links combining photonic-based LO, Solid-state active devices + TWT @ 300 GHz
Which frequencies?

Major interest in ‘300 GHz-band’:

- Technologies start to be available
- Link budget is ok for km-range links
- Frequencies not allocated > 275 GHz

T. Nagatsuma, G. Ducournau, C.C. Renaud

doi:10.1038/nphoton.2016.65
Photomixer: from optical to THz

UTC-PD / Photoconductor

Optical signals (modulated)

Laser 1, $F_1$

1.55 µm

THz

Laser 2, $F_2$

ASE

Optical Noise

$I = s \cdot P_{opt}$

THz noise

THz power $\propto I^2 / \alpha (\text{Optical power})^2$
**Photomixer: from optical to THz**

**UTC-PD**: en cavité résonnante

![Graph showing power vs. photocurrent](image)

- **Power at UTC-PD level**
- **Output power after GSG probe**

**F = 300 GHz**

**RCE-UTC**: resonant cavity enhanced UTC-PD

**Illumination**

- InP - collection
- InGaAs - absorption

- Au mirror
- Si substrate

(c)
**Tx architecture comparison (electronic/photonic)**

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

**“Electronics” based Tx**
- Oscillators: 20-40 GHz
- > 10 mW @ 300 G (PA)
- Good phase noise
  - + 20.log(N) degradation from reference
- I/Q Mixer, SHM
- THz wave

**“Photonics (O/E)” based Tx**
- Optical RF signal generator: >1 THz
- >100 Gbit/s (C-band)
- 4.5 THz BW
  - + O/E converter
  - > Up to THz
  - + Amp
- Optical signal
  - > Electrical signal
- 1535-1565 nm
- The ‘famous’ Mach-Zehnder modulator
- THz wave

**Next steps**
- Amp. And photodiodes -> SiPho?
- Good power, High signal integrity*
  - Amp. BW
- High power, Less signal integrity
  - BW of the TWT?

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*Note: *High signal integrity* refers to the quality of the signal after amplification, ensuring minimal distortion and noise.
Dual structure in I/Q at optical level enable QPSK

G. Ducournau – Journée CEA PTC Instrum & Detection – Oct 11th, 2019
At the end… what optics can do for THz spectra…

**Optical domain**

- Optical fiber core networks
- Multi $\lambda$, 2-Pol
- WDM channels 10-40 Gbit/s (25 GHz spacing)
- $F_{opt} \approx 193$ THz

**THz domain**

- $\lambda$, $\lambda$ pilot
- 1-Pol
- $\lambda$ pilot
- $\lambda$ pilot
- UTC-PD
- Access network, P2P back-haul
- THz-QPSK

### Advantages:
- Frequency agility
- Re-use of the spectrum
- Dynamic allocation

G. Ducournau – Journée CEA PTC Instrum & Detection – Oct 11th, 2019
We have to consider this towards future system developments

Carriers: from 252 to 321 GHz

BW: 2.16 GHz to 69.12 GHz

Formats: ASK, PSK... up to 64-QAM

Photonics is an enabler of multi-frequency THz com systems
Usually, initial THz links have been enabled by photonics-based transmitters, coupled to waveguide-based systems.

Now, integrated Rx are also used in combination to Photonic-Tx.

Tx-Rx fully based on photonics is generally a little bit more difficult due to conversion losses of optically-pumped mixers.
THz passive hot-spot: from fiber to radio THz: almost 10 years ago

• Simple ASK
• 200 G carrier / Passive hot-spot (just fed by a fiber, no bias)


IET Premium award 2011

• BER « Error-free » $10^{-11}$
10 Gbit/s (Real-time) using UTC-PD (Tx) + Schottky mixer (Rx)

G. Ducournau / T. Nagatsuma, 2014

Use an optical comb, phase-locked on a microwave reference + electronic receiver =>
- Bandwidth: ✓
- Sensitivity: ✓

10 Gbps @ -28 dBm in Rx

UTC-PD

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Link examples using photonics Tx – 25m 32 Gbit/s


Antenna + lenses: 38 dBi

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lab demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path loss</td>
<td>110 dB</td>
</tr>
<tr>
<td>Tx ant. Gain (dBi)</td>
<td>38</td>
</tr>
<tr>
<td>Rx ant. Gain (dBi)</td>
<td>38</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>10</td>
</tr>
<tr>
<td>Format</td>
<td>QAM-16</td>
</tr>
<tr>
<td>SNR, dB</td>
<td>20</td>
</tr>
<tr>
<td>NF receiver, dB</td>
<td>10</td>
</tr>
<tr>
<td>Margin, dB</td>
<td>-</td>
</tr>
<tr>
<td>Data rate (Gbit/s)</td>
<td>32</td>
</tr>
</tbody>
</table>

Tx output ~ 50-100 µW

Parameter Lab demo

Path loss 110 dB
Tx ant. Gain (dBi) 38
Rx ant. Gain (dBi) 38
Bandwidth (GHz) 10
Format QAM-16
SNR, dB 20
NF receiver, dB 10
Margin, dB -
Data rate (Gbit/s) 32
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

G. Ducournau 2018
Going out of the lab

Testing « real-life » scenario for THz transmissions...

In the-lab...

Exemple of HD-TV link

Going out-of-the-lab... link with 750 m
Real-time HD-TV

300 GHz Tx

750 m

300 GHz Rx

Live Demo, THz days, Dunkerque, June 2017
In a nutshell

**Photonics is pushing the data-rate**

More distance
More data-rate

More compact systems for future...

So far, the compactness is not scaling for decrease of wavelength...

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: photonic-based Tx usually**

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Running projects

**Increase the range of THz links:** combination of photonic approaches and TWTA (Collab with Lancaster, Prof. Paoloni)

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
</tr>
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<tbody>
<tr>
<td><strong>220-260 GHz</strong></td>
<td></td>
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| THz source       | up to 1 mW / packaged |

<table>
<thead>
<tr>
<th>TWT power amplifier</th>
<th>Gain &gt; 30 dB</th>
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<tbody>
<tr>
<td></td>
<td>Power: 3-4 W</td>
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<table>
<thead>
<tr>
<th>Antenna</th>
<th>50 dBi (high gain)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>&gt; 20 dBi, beam-steering capable (indoor)</td>
</tr>
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<table>
<thead>
<tr>
<th>Receiver (direct)</th>
<th>Zero bias detector</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Schottky ~ 1 kV/W</td>
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| Rx bandwidth (GHz) | 40 GHz, including baseband amplifier |

<table>
<thead>
<tr>
<th>Modulation</th>
<th>ASK (real-time)</th>
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<tbody>
<tr>
<td></td>
<td>40 Gbit/s</td>
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<table>
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<tr>
<th>Link budget (outdoor)</th>
<th>140 dB (1 km)</th>
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<tbody>
<tr>
<td></td>
<td>40 dB with 50 dBi antennas</td>
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</table>

**Photonics**

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

*TERASONIC: Beyond 100 Gbit/s using combined technologies*

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

**TERASONIC** Project

Datas: QPSK or QAM-16

Optical fiber

300 GHz link

Point-to-point (Back-haul targeted)

THz receiver

Solid-state Transistor based

Optical feed

Modulator

LNA, Mixer, I/Q outputs

Antenna

UTC-PD (B)

+ Signal processing

TERASONIC: Beyond 100 Gbit/s using combined technologies

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Couple of challenges

Advances in terahertz communications accelerated by photonics
Tadao Nagatsuma, Guillaume Ducournau & Cyril C. Renaud

<table>
<thead>
<tr>
<th>Item</th>
<th>Target</th>
<th>Technology options</th>
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</thead>
</table>
| Data rate             | 100 Gbit/s ~ 1 Tbit/s | Multi-band (multi-carrier) system  
Ultra-wideband optical modulators |
| Link distance         | 1 km ~ 5 km     | Integrated photodiode arrays  
Use of amplifiers and integration |
| Efficiency            | -               | Photonic integration  
(III-V photonics/Si photonics) |
| Key component         | -               | Low-loss waveguide/interconnect  
Wide-band antenna  
Wide-band passive devices  
(filter/coupler/diplexer)  
New materials & devices  
(metamaterial, graphene, plasma-wave, etc.) |
| Miscellaneous         | -               | Propagation model  
Standardization  
Spectrum regulation |

Robust system, in ‘real-life’ case, using III-V or Silicon photonic devices (for integration level)

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‘system-level’
Active devices
Circuits
Antennas
(fix or reconfigurable)
Radio channel
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…
Thanks to...

- 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, ...
- Technology: M. Zaknoune
- T. Nagatsuma from OSAKA Univ (10 Gbit/s coherent link)
- Telecom platform: R. Kassi
- PhLAM laboratory P. Szriftgiser, M. Douay, ...
- ST-IEMN common lab: D. Gloria, F. GIANESELLO, C. Luxey

CPER PHOTONICS FOR SOCIETY (2016-2020)
Thank you.