Photonics approaches for THz coms

Second Towards TeraHertz Communications Workshop
Brussels, 7 March 2019
Guillaume Ducournau, Prof. University of Lille, France
guillaume.ducournau@univ-lille.fr
Context
Photomixers, Tx/Rx
Some systems
Project Exemples
Conclusions/challenges
Context

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

• 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)

Main focus/challenge

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

Guillaume Ducournau | Photonic approaches for THz communications | Brussels, 7 March 2019| 3/29
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

Optical fibers (1.55 µm)

1 THz 1 ps 300 µm 4,1 meV 49 K

- 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, …)

Optical signals (modulated)

Laser 1, $F_1$

Laser 2, $F_2$

ASE

Optical Noise

$1,55 \mu m$

$P$

$F$

$f_B = F_2 - F_1$

THz noise

$P_{opt} = I/s$

$P$

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

Challenges: max optical power on the device, efficiency

Guillaume Ducournau | Photonic approaches for THz communications | Brussels, 7 March 2019 | 5/29

ThorProject.eu
The photonics emitter… the so called “photomixer”

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

**Uni-travelling carrier PD**
UTC-PD, $\lambda = 1.5 \, \mu m$
$p$ absorbing layer (not PIN)

**Most simple**
Low-temperature grown GaAs PC
LTG-GaAs PC, $\lambda = 0.8 \, \mu m$ / Short-carrier lifetime
Photomixing: results examples… photodiodes

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

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

TW-UTC: 110 µW @ 300 GHz

RCE-UTC-PD: 0.8 mW @ 300 GHz


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

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

[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

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$f$ (GHz)</th>
<th>$P_{RF}$ (mW)</th>
<th>$R$ (A/W)</th>
<th>$I_{dc}$ (mA)</th>
<th>$r_{eff}$ (Ω)</th>
<th>$M$ (W$^{-1}$)</th>
<th>PD Type</th>
<th>PD Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>[29]</td>
<td>350</td>
<td>0.54</td>
<td>0.22</td>
<td>20</td>
<td>1.35</td>
<td>0.065</td>
<td>UTC Packaged</td>
<td></td>
</tr>
<tr>
<td>[18]</td>
<td>306</td>
<td>0.11</td>
<td>0.31</td>
<td>12</td>
<td>0.76</td>
<td>0.073</td>
<td>TWUTC Planar antenna</td>
<td></td>
</tr>
<tr>
<td>[20]</td>
<td>260</td>
<td>0.67</td>
<td>0.08</td>
<td>13</td>
<td>3.96</td>
<td>0.025</td>
<td>NBUTC Flip-chip, wafer-level</td>
<td></td>
</tr>
<tr>
<td>This work</td>
<td>300</td>
<td>0.75</td>
<td>0.12</td>
<td>9.8</td>
<td>7.8</td>
<td>0.109</td>
<td>RCE-UTC Wafer-level</td>
<td></td>
</tr>
</tbody>
</table>


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)...

  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

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

**“Photonics (O/E)” based Tx**
- Optical RF signal generator
- >1 THz
- >100 Gbit/s
- 4.5 THz BW (C-band)
- THz wave
- The ‘famous’ Mach-Zehnder modulator
- 1535-1565 nm
- 1 mW @ 300 G (UTC-PD)
- Good power, High signal integrity*

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

---

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

---

Guillaume Ducournau | Photonic approaches for THz communications | Brussels, 7 March 2019 | 10/29
Using photonics, efficient optical modulations

OOK = amplitude modulation

\[ \frac{P}{P_0} \]  

Modulated laser

MACH ZEHNDER MODULATOR (MZM)

Discrete or integrated (SiPho PIC, ...)

\[ \text{Spectral efficiency} = \frac{\text{Data-rate}}{\text{BW}} \]

The spectrum

Spectral efficiency = Data-rate/BW
Combining I/Q at optical level then to THz

Optical domain

THz domain

Fiber optics technologies

Access network P2P back-haul

Optical QPSK

Optical domain

THz-QPSK

UTC-PD

UTC

Baseband

PIN-PD

pin

MZW

Laser

Precoded data

Optical fiber core networks

Access network, P2P back-haul

Multi-λ, 2-pol

Carrier freq (GHz)

Mobile Rx

THz-QPSK

O/E converter

THz-THz

2X Gbit/s

X Gbit/s

X Gbit/s

Optical QPSK

Optical QPSK

Fiber optics technologies

THz-QPSK

UTC-PD

Baseband

PIN-PD

pin

MZW

Laser

Precoded data

Optical fiber core networks

Access network, P2P back-haul

Multi-λ, 2-pol

Carrier freq (GHz)

Mobile Rx

THz-QPSK

O/E converter

THz-THz

2X Gbit/s

X Gbit/s

X Gbit/s

Optical QPSK

Optical QPSK
In a nutshell... what optics can do for wide-band THz...

**Optical domain**

- **WDM channels 10-40 Gbit/s (25 GHz spacing)**
- **F_{opt} ~ 193 THz**

**THz domain**

- **\( \lambda_1 \)**
- **\( \lambda_{pilot} \)**

**Advantages:**
- Frequency agility
- 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!**

- Use of **UTC-PD** as receivers (possible but structure has to be adapted)
- Use of **photoconductors** (possible but devices to be optimized for 1.55 µm)
- 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. Schmidt1, S. Nellen1, L. Hahn1, W. Freude1, C. Koos*1,2*
Examples. LT-GaAs & plasmonic-based

- Use photoconductive switches

\[ f_{IF} = |f_r \pm f_B| \]

\[ f_B = v_2 - v_1 \]

Current

Voltage

\[ \text{homodyne} (f_H=0) \text{ if } f_r = f_B \]

Optical injection

\[ \text{THz} \]

O/T conversion using silicon

-55 dBm @ 300 GHz (Tx)

66 dB conv losses at Rx.

Silicon based


28 dB @ 300 GHz

Wideband, scalable beyond 1THz

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

Guillaume Ducournau | Photonic approaches for THz communications
Photonics: where could (should) it also be useful??

- Beam steering, forming, switching? Arrays of

**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...

Indoor THz beam control, alignment of P2P links...

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 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**
Example 1/3

240 GHz band / 100 Gbit/s using several carriers


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

Optical comb, driven by reference $F_0 \Rightarrow 12.F_0$

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

Source = UTC-PD

+ Need to correct relative phase fluctuations

Same LO than Tx
Example 3/3

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

**Linear photomixer (UTC photodiode)**

![Graph showing the photodiode output vs current](image)

- Photodiode output (dBm) vs Photodiode current (mA)
- THz Bias
- 100 Gbit/s Bias point
- F = 280 GHz

**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 length (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

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

(TWTA: Prof. C. Paoloni)

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

30 GHz of BW combining power and efficient modulation (thanks to optically driven sources)
Example of on-going projects

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

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

- Datas: QPSK or QAM-16
- Optical fiber
- Modulator
- Optical feed

**Point-to-point (Back-haul targeted)**

- 300 GHz link
- LNA, Mixer, I/Q outputs
- THz receiver
- Solid-state Transistor based

**TERASONIC**

- TERASONIC: Beyond 100 Gbit/s using combined technologies
- Increase the range of THz links: combination of photonic approaches and electronic based

**Contributors**

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

**Projects**

- TERASONIC
- PsLAM
- iemn
- IL
- Institut für Robuste Leistungshalbleitersysteme

**Acknowledgments**

Guillaume Ducournau | Photonic approaches for THz communications | Brussels, 7 March 2019 | 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

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

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

16QAM / 56 Gbps data-rate transmission.

**DEMO 2 and 3: increase the range using TWT**

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

- 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, V. Chinni
- PhLAM laboratory P. Szriftgiser, M. Douay, ...

CPER PHOTONICS FOR SOCIETY (2016-2020)

« WITH » project: CNRS and IMEP-LAHC RIKEN, Tohokhu Univ, OSAKA Univ 2010-2013
T. Nagatsuma & S. Histake, T. Otsuji UM2, LAHC.

« WITH », « OSMOTUS », « COM’TONIQ »

Guillaume Ducournau | Photonic approaches for THz communications | Brussels, 7 March 2019| 27/29

ThorProject.eu
Thank you for your attention!
ご清聴ありがとうございました

This project has received funding from Horizon 2020, the European Union’s Framework Programme for Research and Innovation, under grant agreement No. 814523. ThoR has also received funding from the National Institute of Information and Communications Technology in Japan (NICT).