Recent Japanese Developments on Terahertz Communications

Tadao Nagatsuma

Graduate School of Engineering Science
Osaka University
Outline

Overview of latest challenges and results in THz communications technologies in Japan

1) Photonics-based: 600 GHz, new sources
2) Electronic diode-based: RTD, FMB diode
3) Si-CMOS-based challenges
100 Gbit/s Wireless: Coming Soon!

![Diagram showing data rate evolution from 1990 to 2020. Major milestones include ISDN, ADSL, USB2.0, WiMAX2, 802.11b, 802.11g, 802.11n, 802.11ad, 802.11ac, WiGig, LTE, LTE-A, WiMAX2, Bluetooth, USB3.0, Ethernet, FTTx, FTTH, UWB, and THz Wireless.]}
THz Communications Projects (JPN)

2014

- MIC

2016

- 300 GHz InP-based MMICs (2011-2016)
- 300 GHz Photonics-based (since 2013-2016)

2018

- NTT Fujitsu/NICT
- Kyushu U. +Osaka U.

2020

- MIC: Ministry Internal Affair & Commun.
- Kyushu U. (+NTT, etc.)
- Hiroshima U. Panasonic, NEC/NICT
- Osaka U. Rohm Tokyo Tech.

Horizon 2020, NICT/ThoR
Overview of latest challenges and results in THz communications technologies in Japan

1) Photonics-based: 600 GHz, new sources
2) Electronic diode-based: RTD, FMB diode
3) Si-CMOS-based challenges
Photonics-based Approaches

- Ultra-broadband signal generation and detection
- Ultra-low loss signal distribution by optical fibers and waveguides
- Ease of availability of components from telecom industry
- Use of science & technologies established for light waves
600-GHz band: Next Target for Telecom

100-GHz Atmospheric Windows

- 325 GHz: 1dB/10m
- 275 GHz: 1dB/km
Conventional Structures

CPW: coplanar waveguide
MSL: microstrip line

Top view

Side view
Problems of Coupler at High Frequencies

- **Dielectric loss** → smaller $\varepsilon$

- **Propagation loss** → shorter

- **Connection loss** → eliminate

- **Substrate effect** → thinner (~10 $\mu m$)
Solution: Integrated Coupler

Fabricated UTC-PD Chip

UTC-PD

Coupler

Radiator

100 µm
Fully Packaged Module

DC bias cables

Optical fiber cable

WR-1.5 waveguide

191×381 µm
Evaluated Results

The graph illustrates the evaluated output power (dBm) versus frequency (GHz) for two different currents, $I_{PD} = 6$ mA and $I_{PD} = 9$ mA. The peak output power is $-18.96$ dBm (12.7 µW) at 340 GHz. The frequency range covered by the graph is from 400 to 900 GHz.
600-GHz-band Communications

Optical signal generator → Optical intensity modulator → PD module → Horn antenna

Driver amplifier

Data signal

Optical filter & combiner

Wavelength $\lambda$

$\lambda$

PM: Optical phase modulator

Transmitter

Sub-harmonic mixer

LO signal

Baseband instruments (oscilloscope/bit error rate tester)

Receiver

PM: Optical phase modulator

Laser

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Error-free OOK 10 Gbit/s @670 GHz

T. Nagatsuma et al., IMS 2018, Th1E-1.
Phase Noise Issue: Optical Frequency Comb

Synthesizer \( (f_s) \)

Laser \( (f_0) \)

Optical filter

UTC-PD

Multiplication number

-6 \[\cdots\] 0 \[\cdots\] +6

Phase noise

25 GHz

25 GHz \( \times 12 = 300 \) GHz
Effect of Phase Noise

SSB Phase Noise (dBc/Hz)

Offset frequency (Hz)

Fundamental

$20 \log_{10}(N)$

$N = 12$

21.6 dB

Change in constellation: QPSK
Solution: Brillouin-based Fiber Lasers

UTC-PD: Uni-Traveling Carrier PhotoDiode
SHM: Sub-Harmonic Mixer

For experiment
Towards Terahertz Communications Workshop

Frequency Stability @ 300 GHz

Phase Noise @ 300 GHz

300-GHz QPSK Transmission Experiments

L. Yi et al., EuMC 2019, submitted.
Our Recent Progress with RTD

- New operation regime: injection-locked receiver
  32-Gbit/s error-free at 300 GHz

- Frequency stabilizatin with photonic crystal cavity

- Combination with THz fiber and transmission
Why Resonant Tunneling Diodes?

- Compact (~mm²)
- Low power consumption (~10 mW)
- High-frequency oscillation at room temperature (1.98 THz*)
- Operating as both a transmitter and receiver

**NDR** : Negative differential resistance

![Diagram of Resonant Tunneling Diodes](image)

*R. Izumi et al. IRMMW-THz (2017)
Packaged RTD Transmitter and Receiver

Top view
Baseband circuit

Side view
RTD chip
Si lens
Connector

Schematic diagram of RTD chip

Shunt resistor
RTD
MIM

Signal line

Bowtie antenna
CPS
50 μm

Signal line

RTD
MIM
Shunt resistor
Principle of Coherent Homodyne Receiver

- **Data signal**
- **Received signal**
- **Injection locking phenomenon**
  - **RTD oscillation**
  - **Signal line**
- **Self-oscillating mixer**
- **RTD**
- **Bias within the NDR region**
- **I-V characteristic**
Experimental Setup with Photonics Transmitter

Record Data Rate with RTD Receiver

N. Nishigami et al., APMC 2018.

Error-free transmission (BER < $10^{-11}$) was achieved at 32 Gbit/s. FEC-limited data rate reached ~50 Gbit/s.
Record performance among all electronic semiconductor devices including InP, GaAs, SiGe, Si-CMOS.

“Error-free” >26 Gbit/s (BER < 10^{-12})


It is best to make things simple!!
THz Photonic Crystal Waveguide

- Ultra-low propagating loss (< 0.1 dB/cm@300 GHz)

THz Photonic Crystal Cavity

Q > 10000@ 300 GHz

Efficient Coupling Structure

Photonic crystal waveguide

Si
Air hole

240 μm

200 μm Coupling structure

2.7 mm

InP

320 μm
100 μm
The measured coupling efficiency between RTD and PC waveguide is ~80%.

The measured Q value and oscillation frequency of the PC cavity is ~500 and 335.4 GHz, respectively.

The RTD oscillation frequency is locked strongly by PC cavity.
The locked frequency is the same as the resonant frequency of PC cavity.
The linewidth of RTD oscillator is decreased significantly from 8 MHz to 8 kHz.

X. Yu et al., APMC 2018.

**Condition**
- RBW(kHz): 10 kHz
- VBW(kHz): 10 kHz
- Average: 5
## RTD with THz Fiber

<table>
<thead>
<tr>
<th>Waveguide type</th>
<th>Propagation loss</th>
<th>Flexibility</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic transmission line</td>
<td>×</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Metallic hollow waveguide</td>
<td>○</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>Photonic-crystal waveguide</td>
<td>○</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>Hollow fiber</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

Our recent result: loss ~2 dB/m @ 300 GHz

Porous PTFE (R1 = 0.25 mm, R2 = 0.14 mm)
Dielectric Waveguide as an Interface

RTD-RTD Transmission via THz Fiber

DC power → Bias Tee → TX (1 m) → Bias Tee → DC power

Arbitrary waveform generator

or

4K player

Pre-amplifier → Limiting amplifier → Oscilloscope → Bit error detector → 4K monitor

or

4K monitor

MIM

RTD

2 cm

700 μm
Fermi-level Management Barrier Diode

FMB Diode: Fermi-level Management Barrier Diode

- Low barrier height: 70 meV → lower differential resistance → high frequency operation, lower required LO as mixers
Packaged FMB Diode Module

100 µm

Baseband Signal Output

DC Bias

Transimpedance Amplifier (11 GHz)
300-GHz Transmission Experiments

**Transmitter**

```
Wavelength-Tunable Laser → EDFA → EOAM → UTC-PD
<table>
<thead>
<tr>
<th></th>
<th>EDFA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PPG</td>
</tr>
</tbody>
</table>

**Receiver**

```
FMB Diode Module → Limiting Amplifier → ED
<table>
<thead>
<tr>
<th></th>
<th>Oscilloscope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-amplifier</td>
</tr>
</tbody>
</table>

To be presented at IEEE IMS2019.
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300-GHz CMOS IC Transmitter

ISSCC 2016, Hiroshima U., Panasonic and NICT

40-nm CMOS ($f_{\text{max}}=280$ GHz)

17.5 Gb/s x 6CH (105 Gb/s) 5 GHz/ch

32QAM (5 bit/time frame)

<table>
<thead>
<tr>
<th>Channel</th>
<th>CH1</th>
<th>CH2</th>
<th>CH3</th>
<th>CH4</th>
<th>CH5</th>
<th>CH6</th>
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</thead>
<tbody>
<tr>
<td>Constellation (Equalized)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVM (rms)</td>
<td>8.9%</td>
<td>4.8%</td>
<td>7.0%</td>
<td>7.1%</td>
<td>6.4%</td>
<td>5.9%</td>
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<tr>
<td>Data-rate (Gb/s)</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
</tr>
</tbody>
</table>
300-GHz CMOS IC Transmitter

ISSCC 2017, Hiroshima U., Panasonic and NICT

Single channel

<table>
<thead>
<tr>
<th>Modulation</th>
<th>32QAM</th>
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</thead>
<tbody>
<tr>
<td>Constellation (Equalized)</td>
<td></td>
</tr>
<tr>
<td>EVM</td>
<td>8.9%</td>
</tr>
<tr>
<td>Data rate</td>
<td>105Gbit/s</td>
</tr>
</tbody>
</table>

Technology: 40nm CMOS

<table>
<thead>
<tr>
<th>Technology</th>
<th>[1]</th>
<th>[2]</th>
<th>[3]</th>
<th>[4]</th>
<th>[5]</th>
<th>This work</th>
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</thead>
<tbody>
<tr>
<td>Technology</td>
<td>250nm InP</td>
<td>35nm GaAs</td>
<td>35nm GaAs</td>
<td>0.13µm SiGe</td>
<td>40nm CMOS</td>
<td>40nm CMOS</td>
</tr>
<tr>
<td>Freq. (GHz)</td>
<td>300</td>
<td>240</td>
<td>300</td>
<td>240</td>
<td>300</td>
<td>302</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
<td>8PSK</td>
<td>QPSK</td>
<td>64QAM</td>
<td>16QAM</td>
<td>32QAM</td>
</tr>
<tr>
<td>Pout (dBm)</td>
<td>–</td>
<td>–3.5</td>
<td>–4</td>
<td>7</td>
<td>–14.5</td>
<td>–5.5</td>
</tr>
<tr>
<td>Pdc (W)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.54</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Data rate (Gbit/s)</td>
<td>50</td>
<td>96</td>
<td>64</td>
<td>1.02</td>
<td>28</td>
<td>105</td>
</tr>
</tbody>
</table>

IEEE Std 802.15.3d: Channels

252~325 GHz
300-GHz CMOS IC Transceiver

ISSCC 2019, Hiroshima U., Panasonic and NICT

80 Gbit/s with 16QAM by 40-nm CMOS
Summary

- Steady progress towards 100Gbit/s wireless
  - GaAs/InP/Photonics/RTD/Si-CMOS/SiGe HBT
    Interconnection is a key: hollow vs. dielectric

- Meeting network trend in fiber-wireless convergence
  - RF photonics integration is a key
    RF Si-photonics or hybrid integration

- Towards real success in market places
  - Let potential customers use THz comms by bringing THz outside our labs!
  - International collaboration is a key