Submission Title: Towards 100-Gbit/s Wireless Using Terahertz Waves
Date Submitted: 9 March, 2010
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Re: IEEE 802.15-15-10-0149-00-0thz

Abstract: Presentation of NTTs work towards 100-Gbit/s Wireless Using Terahertz Waves

Purpose: Information on development of future THz communication systems

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Towards 100-Gbit/s Wireless Communications Using Terahertz Waves

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Acknowledgments

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K. Ajito (NTT), M. Yaita (NTT), N. Kukutsu (NTT),

T. Ishibashi (NTT Electronics), H. Ito (Kitasato U.)

Y. Fujimoto (Osaka U.), K. Miyake (Osaka U.),
K. Takada (Osaka U.), M. Kawamura (Osaka U.)

Fuji Television Network Inc, NHK (Japan Broadcasting Corporation)

Members of Study Group on THz ICT at Kinki Bureau of Telecommunications
in Ministry of Internal Affairs and Communications (MIC)

Part of this work was supported by “The R&D Project for Expansion of Radio
Spectrum Resources” of The Ministry of Information and Communications in
Japan, and by “The Ministry of Education, Science, Sports and Culture, Grant-in-
Aid for Scientific Research (A), 20246062, 2008”.
Outline

- Background & Needs
- 10-G wireless with 120-GHz Bands
- Exploring 300-400 GHz Band
- Summary
Background & Needs

- 10-G wireless with 120-GHz Bands
- Exploring 300-400 GHz Band
- Summary
Trends in Wired Communications

- **GEPON**
- **BPON FastE**
- **GbE**
- **10GbE**
- **100GbE**
- Ethernet

- **PON** (Passive Optical Network)

- ~10 times / 5 years

Speed (Gbit/s) vs. Year (1995 to 2020)
Current Applications of 10-G Wireless

Fixed Wireless Access

- 10GbE
- OC-192

Temporal Wireless Link

- Live relay broadcast of sports events
- Disaster recovery
- Remote medical treatment

High-definition (HD) TVs
Urgent Needs in Broadcast

Multi-Channel Transmission of Uncompressed HDTV Data

Event Site

Broadcast Van (Relay Point)

Relay Point

TV Broadcast Station

Ch1

Ch2

Ch6

HDTV Signals 1.5 Gbit/s/camera

Wireless “Last One-mile”

Optical fiber

1.5 Gbit/s/camera
Gigabit Wireless in Home Networks

Transmission of uncompressed HD (High Definition) data

- Wireless HD: 3.8 Gbit/s with 60 GHz
  Panasonic “VIERA”, Sony “BRAVIA”
- Wireless HD Interface (WHDI): 1.5 Gbit/s with 5 GHz
  Sharp “AQUOS”
- WiGig Alliance: 6 Gbit/s with 60 GHz

>1.5 Gbit/s

No cables, No connectors
Next Generation HDTV “UHD”

Super Hi-Vision (Ultrahigh Definition) TV by NHK, Japan

7680 x 4320 resolution

Uncompressed video signal: ~24 Gbit/s

Super Hi-Vision /Ultra-High Definition Video (7680x4320)
Close Proximity Wireless Transfer

Link Distance: 10 mm to 100 mm

4.48GHz: 560 Mbit/s
Under-70dBm/MHz (average)
Corresponds to low-intensity radio wave regulation

Infrared light data communication with laser diode: 1 Gbit/s

Difficulty in beam positioning
Future Applications (1)

Elimination of bottlenecks in the speed of wired and wireless communications in the core/access networks

Highly-realistic sensation teleconference, telemedicine, remote-education
Increasing needs in instantaneous transfer of high-volume storage data in consumer devices as well as in medical equipments

40-100Gbit/s (5-12.5GB/s)

Proximity link

Cloud Server

Download

Tera Bite → Peta Bite

HD video

SSD memory

SD memory*

*Tera-bite standardized at 2009
Application Scene (THz ICT Study Group, Japan)

Outdoor
- Disaster recovery
- Live Broadcast

Optical Network

THz-wave Access Point

Super-reality Wireless Display

UHDTV camera

Medical sensors

Telemmedicine

THz-wave Access Point

Remote Robot Control

Wireless Cloud PC

3D Teleconference

OS1
ApS1
Data a

ApS2
Data b

ApS3
Data c

ApS4
Data d

Home
- Instantaneous Data Transfer

Business

4K-cinema, UHDTV

Data a

Data b

Data c
Towards 100 Gbit/s Wireless

✓ Multi-value modulation at 60 GHz

✓ Free-space optics (Infrared light) with WDM

✓ Use of “terahertz” carrier frequency with simple modulation format (ASK)

Not yet allocated for specific use at >275 GHz !!!
Wireless Data Rate vs. Carrier Frequency

Data Rate (Gbit/s)

Carrier frequency (GHz)

WiMAX
FPU
Wireless LAN
Mobile phones
3.5G
3G

Fixed wireless (p-p)
Atmospheric Attenuation

Appropriate for 100 m~1 km transmission

1 dB/10 m

Future use
## Progress in Transistors and ICs

<table>
<thead>
<tr>
<th>Transistor Technology</th>
<th>ft (GHz)</th>
<th>f&lt;sub&gt;max&lt;/sub&gt; (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15nm InAlAs/InGaAs MHEMT</td>
<td>610</td>
<td>305</td>
</tr>
<tr>
<td>45nm SOI CMOS</td>
<td>485(NFET)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>345(PFET)</td>
<td></td>
</tr>
<tr>
<td>GaAsSb/InP DHBT</td>
<td>670(480)</td>
<td>350(420)</td>
</tr>
<tr>
<td>50nm InP HEMT#</td>
<td>385</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>35nm InP HEMT##</td>
<td>480</td>
<td>1200</td>
</tr>
</tbody>
</table>

# Amplifier: 12 dB Gain @335 GHz

## Amplifier: 13-15 dB Gain @300-345 GHz
Progress in Electronic Oscillators

- SiGe HBT
- InP HBT
- InP HEMT
- CMOS
- RTD

Output Power (dBm) vs Frequency (GHz)

- CMOS (20nW)
- 10 µW
Small Antennas

For TV

120GHz Yagi-Uda Antenna

120GHz Patch Antenna

For GPS

300GHz Horn Antenna

Laser Pointer

USB

300-500 GHz

+ MEMS & Metamaterials

Like “IrDA” Module!
- Background & Needs
- **10-G wireless with 120-GHz Bands**
- Exploring 300-400 GHz Band
- Summary
Choice of Radio-Waves: 120-GHz Band

Millimeter-Wave Region
(30GHz - 300 GHz)

Frequency (GHz)

Attenuation Constant (dB/km)

H2O
H2
O2
H2O
O2

Dry Air

Usual Rain
(a few mm/hr)

Fog
0.1g/m³

120-160G
220-320G
350-430G
75-100G
Approaches: Electronics vs. Photonics

◆ “Electronics” based Tx

- Electrical RF signal generator
- Electrical modulator
- Amplifier
- Coax/Waveguide
- THz wave

◆ “Photonics (O/E)” based Tx

- Optical RF signal generator
- Optical modulator
- Amplifier
- O/E converter
- THz wave

**Comparison:**
- Electronics:
  - < 500 GHz
  - < 40 Gbit/s
  - < 300 GHz

- Photonics (O/E):
  - > 1 THz
  - > 100 Gbit/s
  - > 300 GHz
Hardware Evolution in 10 years

Photonics-based Transmitter

- 2000-2002
- Transmitter
- Receiver
- Transmitter Core
- Photonic MMW Generator
- Data Modulator
- Output power: 10 mW, ~2 km
- Power consumption: 600W

Electronics-based Transmitter

- 2007/1
- Transmitter
- Volume: 1/6
- Weight: 1/2
- Battery operation
- Output power: 10 mW, 2.2 km
- Power consumption: 60 W

Easy set-up system
120-GHz-band System with Photonic Tx

Optical MMW/THz Carrier Generators (1)

Heterodyning two lasers
~10 THz

Actively mode-locked laser
~300 GHz

Passively mode-locked laser
~1 THz
Optical MMW/THz Carrier Generators (2)

Optical frequency comb generator (OFCG) “multi-wavelength source”

Continuously tunable and stable

Example of OFCG

High-Power O-E Converter “UTC-PD”

Layer Structure

- n-ohmic Contact
- Diffusion Block Layer
- Light Absorption Layer \((p-InGaAs)\)
- Carrier Collection Layer \((n-InP)\)
- InP
- AR Coating
- Back Illumination

Band Diagram

- p-ohmic Contact
- Hole
- Electron
- V.B.
- C.B.

UTC-PD: Uni-Traveling-Carrier-Photodiode
Output Power from UTC-PDs

- Maximum detected power ($\mu$W) vs. Frequency (THz)
- Log-log scale
- Various types of UTC-PDs:
  - NTT UTC-PD (wideband)
  - NTT UTC-PD (resonant)
  - UCL UTC-PD (resonant)
  - LT-GaAs

- Pin PD

- Frequency ($f$) - $f^{-4}$ relationship

- 20 dB shift

- Diagrams of UTC-PD structures

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120-GHz Emitter

Microwave Photonics 2000

Slot Antenna
(774 x 95 mm²)

PD Chip

Optical Fiber

Optical Signal

Antenna

Si-Lens

Si Platform

MMW Signal

1 mm
120-GHz Receiver for 10-Gbit/s

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Antennas for Long Distance Link

Lens Antenna

- Feed Horn
- Dielectric Lens
- Sub-THz

Cassegrain Antenna

- Feed Horn
- Parabolic Reflector
- Hyperbolic Subreflector
120-GHz Emitter for Long Link

Hybrid integration with butt-joint structure

120-GHz Receiver for Long Link

Monolithic IC Receiver

MMIC

Input

Pre-Amplifiers

Demodulator (Schottky Barrier Diode)

Output

Packaged Module

From Antenna (125 GHz)

Data Output (10 Gbit/s)
Electronic Devices: InP HEMT

- 0.1-μm-gate InAlAs/InGaAs HEMT
- $g_m = 1.2$ S/mm, $f_t = 170$ GHz, $f_{max} = 350$ GHz
- MIM capacitor, double-layer interconnection process with BCB

Fully matured production level technology (NTT Electronics)
120-GHz Band Transmitter

Setup for Field Test

Transmission Characteristics

Receiver power

Bit error rate (BER)

<table>
<thead>
<tr>
<th></th>
<th>Total number of bit errors</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st day</td>
<td>3</td>
<td>1X10^{-14}</td>
</tr>
<tr>
<td>2nd day</td>
<td>5</td>
<td>2X10^{-14}</td>
</tr>
<tr>
<td>3rd day</td>
<td>13</td>
<td>5X10^{-14}</td>
</tr>
</tbody>
</table>

- Fluctuations in received power: < 1 dB for 6 hours
- BER of wireless link: < 1X10^{-13}

→ Meets OC-192 and 10GbE standards

Multiplexed HDTV Wireless Transmission System

- “i-Visto gateway” converts two HDTV video streams into IP packets and then multiplexes the packets using the 10 Gigabit Ethernet protocol.
- Packets from three i-Visto are multiplexed by a 10GbE switch.
- Six channels of HDTV signals are transmitted as 10GbE signals over the 120-GHz-band wireless link.

Multi-band System with Optical WDM

Transmitter

Amp. PD

WDM Filter

Control Unit (Optical Signal Source)

λ1: 125 GHz (10Gb/s)

λ2: 90 GHz (5Gb/s)

λ3: 30 GHz (1Gb/s)

Amplification Const. (dB/km)

10 100 1000

Frequency (GHz)

H2O H2O

110-150 GHz

30-40 GHz

75-100 GHz

O2 O2

Attenuation Const. (dB/km)

100

10

1

0.1

0.01

0.001

10 20 40 100 200 400 1000

Frequency (GHz)
120-GHz-band Transmitter with Electronics

Transmitter module

LO signal IN
LO: 62.5 GHz

Multiplier (x4)
MMIC

Transmitter
MMIC

120 GHz with WR-8 waveguide (1 mW)

Power amp. module

Power amp. MMIC

120 GHz with WR-8 waveguide (10 mW)

to antenna

Battery operated

XFP module (O/E)

Optical data (10-Gbit/s)

DATA IN

DATA IN

LO: 15.625 GHz

Advanced All-Electronics System

Controller

Tx Frontend

Controller Tx Frontend

Advanced All-Electronics System

Typical Performance

Data rate: 10.3125 Gbit/s

Bit Error Rate vs. Received Power (dBm)

Minimum received power: -38 dBm
Trials at Olympics: Configuration

International Broadcast Center

RF Tower

120 GHz-band link (distance 1 km)

Fuji TV booth

Water Cube

Beijing Olympic Park

Bird’s Nest

Specially built live-broadcast studio (Beijing Media Center)


Trials at Olympics: Configuration

TV programs with 120-GHz system
Trials at Olympics: Live-broadcasting

Fluctuations in received power
(August 8, opening day of Olympics)

Received power (dBm)

Time (hr)

< 2dB

- Background & Needs
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Carrier Frequency vs. Data Rate

- **UWB @ 3-5 GHz:** 15 Gbit/s, 1m
- **CMOS @ 60 GHz:**
- **NTT-NHK @ 120 GHz:**
- **Max. Data rate with ASK in 10%-BW**
- **Target - 300-400 GHz**
Objective of 300-GHz Band Wireless

- Examine “giga-bit” wireless link using full 300-400 GHz band
- Photonics-based transmitter as technology demonstrator
- Discuss possibility of >20-40 Gbit/s wireless

T. Nagatsuma et al., Tech. Dig. 2009 International Topical Meeting on Microwave Photonics, 15 October, Session Th.2.
Possible Utilization of 300-400 GHz

(a) Ultra-broadband channel

Carrier

>40 GHz (24 Gbit/s)

UHD

>70 GHz (43 Gbit/s)

OC-768

(b) Multiple giga-bit channels

Carrier

2.5 GHz (1.5 Gbit/s)

HDTV

Frequency
Experimental Wireless Link

Transmitter

UTC-PD

Horn Antenna

Optical Amplifier

Optical Modulator

Pulse-Pattern Generator

Wavelength-Tunable Laser

Wavelength-Tunable Laser

Receiver

Terahertz Wave

SBD

Pre-Amplifier

Limiting Amplifier

SBC

Oscilloscope

Bit Error Detector

Radio frequency

IF frequency

IF frequency

1 0 1 1 0 0 1

Radio frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency

Optical frequency
Modified UTC-PD (Composite Structure)

Modified UTC-PD (Composite Structure) diagram showing layers such as diffusion block layer, p-doped absorption layer, un-doped collection layer, and n-contact layer. A graph showing output power (dBm) versus frequency (GHz) with a peak of 500 μW at 20 mA.

A. Wakatsuki et al., IRMMW-THz 2008.
Menu of “Hamburgers”

(a) Dual depletion pin
(b) Conventional pin
(c) UTC
(d) Partially doped absorber
(e) Modified UTC (composite)
Output Power at 300-400 GHz

- Frequency (GHz): 270-410 GHz
- Detected Power (μW)
  - 6 mA
  - 10 mA
- Output Power at 300-400 GHz
  - 270-410 GHz
Photo of Transmitter

Dielectric Lens

Optical Fiber

Horn Antenna

PD Module
Receiver Bandwidth

WR2.8ZBD, Virginia Diode Inc.

Frequency (MHz)

Relative Response (dB)

300 MHz @-3dB

800 MHz @-10dB
Transmission Characteristics (1)

2 Gbit/s
Distance: 50-100 cm

→ >20 Gbit/s with >100 μW

Graph:
- X-axis: Photocurrent (mA)
- Y-axis: BER
- Major ticks: 1E-12, 1E-10, 1E-8, 1E-6, 1E-4, 0.01
- Tx Power: 10 μW
- Distance: 50-100 cm

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Transmission Characteristics (2)

(a) 280 GHz  
(b) 300 GHz  
(c) 320 GHz  
(d) 340 GHz  
(e) 360 GHz  
(f) 380 GHz

(g) 400 GHz  
← 500 ps

→ 40 ch. x 1 Gbit/s with 200 μW

1 Gbit/s
Increasing Bit Rate (1)

250-GHz Wireless Link with Integrated Receiver

Slot-ring Antenna
IF (low-pass) filter
Diode
Hemispherical Silicon Lens
Receiver Chip (1.5 x 2 mm²)
Module
Increasing Bit Rate (2)

250 GHz

IF Bandwidth: ~4.5 GHz

Integrated Detector

Commercial Detector

IF Frequency (GHz)

Relative Response (dB)

8 Gbit/s

Photocurrent (mA)

Tx Power

10 µW

(100ps/div)
Summary

- Established 120-GHz band system with 10-Gbit/s
- First demonstration of giga-bit wireless at 300-400 GHz band using photonics-based transmitter
- Error-free transmission at 1-Gbit/s from 280 to 400 GHz
- Max rate (2 Gbit/s) was limited mainly by bandwidth of receiver
- >20 Gbit/s is feasible by increasing a receiver IF bandwidth with the same photonics-based transmitter