TeraHertz Photonics for Communications

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Outline

- Bandwidth Requirements
- THz Spectrum
- Predecessor Systems- Wireless Over Fibre
- Architectures
- Heterodyne Signal Generation
- Uni-Travelling Carrier Photo-Detectors as THz Sources
- Heterodyne System Demonstration
- Coherent Signal Generation- Injection Locking, Optical Phase Lock Loop, Optical Injection Phase Lock Loop
- Coherent System Demonstrations
- Conclusion
Bandwidth Requirements

D. Kilper, Alcatel-Lucent (presented at the 2011 OIDA aggregation network workshop)

Path Loss

\[ L_F = (4\pi\lambda/R)^2 \]

where \( \lambda \) : wavelength; \( R \) : range

\[ L_T(dB) = 92.4 + 20 \log_{10}(f) + 20 \log_{10}(R) \]

\[ L_T(dB) = 92.4 + 20 \log_{10}(f) + 20 \log_{10}(R) + k R \]

where \( f \) : frequency (GHz); \( R \) : range (km);
\( k \) : atmospheric attenuation (dB/km)

eg 100m path; 350 GHz; Sea Level 7.5 g/m³ water

\[ L_F = 123 \text{ dB}; L_T = 124 \text{ dB} \]
THz Atmospheric Transmission

- Large available unallocated bandwidth above 300 GHz - 30 times the entire allocated RF spectrum
- For short range systems water absorption penalty is small at the lower THz frequencies

Advantages of THz over Optical Transmission

- For wireless point to point systems fog is a major issue for optical wavelength.
- Rain losses are similar for optics and THz
- At 300 GHz carrier frequency the attenuation from fog drops by 2 orders of magnitude compared to the optical window.

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Wireless Over Fibre Systems

16 Channels Transmit/Receive

CENTRAL SITE  BASE STATION

1.3\,\mu m Laser
PIN Photodiode
PA
Circ.
Antenna

1.3\,\mu m Laser
LNA

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Commercial In-Building Wireless over Fibre

World-wide Distributed Antenna System Market Size: $1.9 Billion in 2012 - Telecomlead

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Wideband Distribution Architecture

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Wireless over PON - Systems Concept

- Wireless overlay on Passive Optical Network (PON)
- Centralised base station functions
- Remote units on buildings, not on hilltops
- Cost-shared backhaul
- Greatly enhanced wireless data rates
- Greener power budget

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Wireless over PON

- 50 m path loss 93 dB
- 100 Mb/s requires base station EIRP of 20 mW for 10dB margin
- The hilltop base station alternative would require an EIRP of 3kW

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THz over Fibre - Systems Concept

- THz wireless provides high bandwidth capacity.
- Limited propagation distance allows well defined microcells and frequency reuse.
- Inexpensive THz equipment is essential.
- Base stations and central station are connected by low-loss optical fibre.
- Possible applications are:
  - High resolution mobile multimedia services
  - Wireless Video Distribution Systems
  - Wireless Local Area Networks (WLANs)
Assumptions:
- Carrier frequency: 350 GHz
- Transmitted power: -10 dBm
- Absorption loss: negligible for short range
- Antenna gain: 40 dBi (Tx and Rx)
- Down-conversion loss: 20 dB
- LNA noise figure: 3 dB
- Data rate: 10 Gb/s (20 GHz IF b/w)
- SNR required: 10 dB

Transmission distance, \( R = 17 \) m
- Free-space path loss = \( (4\pi R f / c)^2 = 108 \) dB

Short-range links possible with high antenna gain or with increased transmitter power

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Current THz Technology

- Currently most THz systems use femtosecond pulses from mode-locked lasers and photoconductive switches for signal generation
- Good solution for time and depth resolved imaging over wide frequency spans
- Power consumption is in the kW range
- Spectral purity of the THz signal is limited by laser jitter
- The cost and size of most short pulse systems is also a limitation
- Communications and related applications require the use of single frequency sources, often with high spectral purity
- Recent progress in photonics for optical communications can enable compact, power efficient, coherent THz systems

Heterodyne THz Generation

- Semiconductor diode lasers- power efficient
- Working at 1550nm- advantages due to well developed telecomms. technologies
- Laser linewidths sum in the photomixer
- This results in a tuneable source with MHz linewidth (typical semiconductor laser linewidth 2 MHz)
Heterodyne THz Link

www.iphos-project.eu

G. Carpintero, UC3M

Optical mmW Signal Source

Carrier Generation → Data Modulation

Δν (f_c)

λ

Wireless Transmitter

High Speed Photodiode → PA

Δν (f_c)

λ

Wireless Receiver

SBD

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Carrier Generation

www.iphos-project.eu

F. Van-Dijk, III-V Lab.; E. Bente, TuE

Optical mmW Signal Source

Carrier Generation → Data Modulation

Δν (f_c)

λ

Dual DFB based

Arrayed Waveguide Grating based

MMIRs

Output SOA

Arrayed Waveguide Grating based

SOAs

Phase shifters

Photonic Integrated Circuit-based dual wavelength sources based on two different approaches:

• Monolithic integration of a dual DFB PIC
• Arrayed Waveguide Grating Laser

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Dual Laser Integrated Heterodyne Source

www.iphos-project.eu

Microscopic photo of the device

Dual DFB approach advantages are:
- Wide continuous tuning range
- Fabrication process compatible with Photodiodes

F. Van Dijk et al,
III-V Lab

AWG Dual-\(\lambda\) Source

www.iphos-project.eu

Dual AWG approach has the following advantages:
- Stable beat note (Optical Linewidth \(<\ 130\ kHz\ and\ Electrical\ beat\ linewidth\ \(<\ 250\ kHz\))
- Fixed wavelength spacing by AWG channel separation (100 GHz)
- AWG channel spacing spread due to fabrication tolerances

Packaged Dual Laser Integrated Source

These Photonic Integrated Circuits can be packaged to form compact dual-κ sources:

- TEC controlled
- DC bias inputs in one connection
- RF modulation on SMA access
- Fiber output for the modulated dual wavelength signal
- Submounts to tilt the PIC for optimum coupling from angled waveguides to reduce reflections at facets

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- **Uni-Travelling Carrier Photo-Detectors as THz Sources**
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Uni-Travelling Carrier Photodiode

- The structure was designed with a depletion layer thickness such that the carrier transit limited 3 dB bandwidth was about 340 GHz.

- The diffusion barrier was sufficiently doped to be used as a contact layer.

- The device was designed such that its capacitance and series resistance will allow it to be used in a travelling wave design.

300-GHz Band Modified UTC-PD

T. Nagatsuma, NTT/Osaka Univ.

Band diagram

- Refracting facet structure: edge illumination

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Wide Bandwidth & High Power

T. Nagatsuma, NTT/Osaka Univ.

Maximum power: > 500 µW @ 20 mA
3-dB bandwidth

Faster transport – Hot electrons in the depletion region, no hole transport.

Travelling Wave UTC Photodiode

The device is a combination of:

Uni – Travelling Carrier Photodiode

Travelling Wave Photodiode

Travelling Wave Effects can achieve better response at high frequencies.
Transmission Line Model

- “Slow-wave” propagation.
- Photocurrent is modelled as a distributed current source.
- Circuit elements are distributed over the length of the device.

Electrical Design Parameters

- Characteristic impedance approaches 50 Ω for narrow ridge devices (<2 µm).
- Attenuation becomes limiting factor only at very high frequencies.
- Velocity matching is achieved only at high frequencies.
Optimisation of the TW-UTC-PD

- Transmission Line Model combined with carrier transport was used to predict the frequency response of a 4×15 µm² TW-UTC-PD.

- The device is compared to a vertically illuminated UTC-PD and a p-i-n TW-PD with the same active area dimensions and intrinsic layer thickness.

Millimetre-wave Generation

- The output power from CPW-integrated devices was measured in the G-Band (140 – 220 GHz) using the same optical heterodyne generation system.

- The experimental arrangement included a G-Band probe, a 20 dBi gain horn antenna and the Thomas Keating power meter.

- The device generated record levels of power from a photomixer in the mm-wave range with 1 mW at 200 GHz.
Integration with Antennas

- TW-UTC devices integrated with antennas
- Antennas made of 800 nm thick sputtered gold
- Three types of antenna were used:
  - A resonant antenna (dipole) with narrow peak response around 450 GHz and 900 GHz
  - A bow tie broadband antenna with a peak response around 800 GHz (picture)
  - A log-periodic broadband antenna (picture)

Generation of Tuneable THz Signal

- Measured power generated over the frequency range of 140GHz to 300GHz using a PD with a partially doped absorber layer with an integrated bow-tie antenna
- Optical power at the PD was 15dBm and photocurrent was 3mA
- Power was measured using a calibrated large area Thomas Keating power meter
Broadband emission up to 1.5 THz using bow-tie and log-periodic antennas mounted on a hyper-hemispherical High Resistivity Si lens.
Continuous Wave THz Generation

- The devices achieved the highest output power ever recorded from a continuous wave photomixing source in this frequency range.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>frequency (GHz)</th>
<th>Power (µW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log-periodic</td>
<td>700</td>
<td>39</td>
</tr>
<tr>
<td>Bow-Tie</td>
<td>408</td>
<td>75</td>
</tr>
<tr>
<td>Resonant</td>
<td>457, 914</td>
<td>148, 24</td>
</tr>
</tbody>
</table>

THz Emission

- Broadband antenna-integrated devices showed high output power up to 1.5 THz.
- Packaged devices were successfully developed without any degradation in the frequency response.
Performance Summary

 Responsivity (A/W) vs. 3 dB response frequency (GHz)

UCL TW-UTC-PD  
NTT UTC-PD  
III-V MUTC  
Virginia MUTC  
Duisburg partially doped  
Commercial p-i-n

Performance Summary

 RF extracted power (dBm) vs. Frequency (GHz)

UCL TW-UTC-PD  
NTT UTC-PD  
III-V MUTC  
Virginia MUTC  
Duisburg partially doped  
Commercial p-i-n

Copyright © 2014 UCL
- Record levels of Terahertz figure of merit were achieved up to 1.5 THz.

Vitaly Rymanov, Andreas Stöhr, Sebastian Dülme, and Tolga Tekin, "Triple transit region photodiodes (TTR-PDs) providing high millimeter wave output power", submitted to Optica Express in December 2013
Enhancing Output Power by Power Combining

Chip Structure

1 mW @ 300 GHz @ 18 mA per PD

H. J. Song et al., 2012 Asia-Pacific Microwave Photonics Conference.
K. Arakawa et al., ibid.

T. Nagatsuma, Osaka Univ.

Commercially Available Devices from NEL

Antenna-integrated 1550 nm 6 mA

W-band F-band D-band

T. Nagatsuma, Osaka Univ.
Packaged THz Photodiode

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Heterodyne System Demonstration

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Monolithic Transmitter

Optical mmW Signal Source On-a-Chip

- Carrier Generation
- Data Modulation
- High Speed Photodiode

To achieve low propagation loss in the passive sections.

To design high-speed PDs despite increased series resistance.

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Monolithic Transmitter

DFB lasers | Dual wavelength generation
SOAs | Data modulation
MMI | Wavelength combiner
PD | O/E conversion

Transmission System Demonstration

35Lab Y-coupled DFB laser

UCL packaged UTC PD source

Schottky Barrier Diode sub-harmonic mixer

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Transmission Result

D = 27 mm; 1 Gb/s OOK; 2^7-1 PRBS; 1000 bits; IF = 2.5 GHz; UTC: 2.0 mA, 2.0 V, 17°C
Envelope detection with 0.7 GHz Bessel5 baseband filter (offline processing)

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Extreme-bandwidth 300-GHz Wireless Link

T. Nagatsuma, Osaka Univ.
SISO Transmission at 300 GHz

40 Gbit/s

Bit Error Rate

Photocurrent (mA)

1E-12
1E-4
1E-6
1E-8
1E-10
1E-12

5.0
6.0
7.0
8.0

Polarization MUX Transmission at 300 GHz

T. Nagatsuma, Osaka Univ.
THz Wire-grid Polarizer

Extinction Ratio: >20 dB

Transmittance & Reflectance [dB]

Angle [°]

Transmitter Power (µW)

Bit Error Rate

24 Gbit/s x 2

48 Gbit/s Transmission

Ch.1: 24 Gbit/

Ch.2: 24 Gbit/

Receiver BW: 19/15 GHz @Ch.1/2

Transmitter Power (µW)
Data Rate vs. Carrier Frequency


Use of Higher Carrier Frequencies: 600-GHz Band

Usable BW: 270 GHz → 160 Gbit/s, >105 Ch. HDTV
Coherent THz Synthesis

- The first part of the system is the reference source which is an Optical Frequency Comb Generator (OFCG) offering a set of optical frequencies over a span of >2 THz.
- The OFCG output is then sent to two Optical Phase Lock Loop (OPLL) active filters to extract two comb lines while retaining their phase relation.
- These two lines are then combined to generate an highly pure heterodyne signal through a high speed photodetector and the resulting THz signal is emitted through an antenna.
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For low THz frequencies source a modest span suffices.

A simple approach is to use a phase modulated laser.

This can be combined with a resonator to extend the span over 4 THz in a monolithic package.
Monolithic Mode Locked Comb Source

- Quantum dash monolithic laser
- Locked to a 24.6 GHz source
- Span of 1.6 THz
- Resulting beat linewidth <1kHz

F. Van Dijk et al, III-V Lab

Phase-Locked Mode-Locked Lasers

- >2 THz MLL envelope demonstrated for MLL with integrated gain flattening filter (GFF)
- Linear and ring actively locked MLLs fabricated with integrated OPLLs for comb-line stabilization


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Phase-locked Synthesiser

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Optical Injection Locking

- A simple locking technique is to inject coherent photons within a laser cavity.
- Above a certain threshold the slave source will be fully locked to the master through the stimulated emission process.
- The master frequency needs to be close to the resonance of the slave cavity.

Advantages:
- Quasi instantaneous locking
- Exact frequency locking
- Simplicity (optical only)

Disadvantages:
- Narrow locking range
- Critical temperature control
Optical Phase Lock Loop (OPLL)

- To obtain long term tracking a phase lock loop is a better solution
- The slave laser frequency is locked by feeding back the phase error signal (after it has been suitably processed)
- Since frequency is the derivative of phase, the phase of the slave depends on the integral of the control signal

\[ u(t) = K_1 \sin[m(t) - s(t)] \]
\[ = K_1 [m(t) - s(t)] \]
\[ = K_1 e(t) \]

\[ u_2(t) = f'(t) \]
\[ u_1(t) = \int f'(t) \, dt = K_3 . u_2(t) \]

OPLL Requirements

- Maximum summed linewidth of master and slave lasers is inversely proportional to the loop propagation delay
- For second-order loop with damping factor = 1/√2 and optimised loop gain, the summed linewidth should be less than 2 MHz
  - Assuming
    - 1 ns loop delay
    - 0.03 rad² phase variance

\[ \text{Linewidths of master and slave lasers should both be } < 1 \text{ MHz} \]
Hybrid THz Generator System

The various elements of the THz generator are mounted on daughterboards, which are then combined on a common silicon chip, the motherboard.

- Two EAMs used as photodetectors (for detuning beat signal)
- The optical path, facet to facet, is 8.1 mm.
- The various elements of the THz generator include:
  - Laser 1 contacts
  - Laser 2 contacts
  - Slot for fibre array
  - DBR phase
  - 13 mm Matching cct

Hybrid OPLL with Active Loop Filter

- Hybrid OPLL integrated with low delay loop filter and control circuit fabricated on multi-layer board
- Total delay < 1.4 ns
- Special electronics design and fabrication by L. Pavlovic and M. Vidmar, University of Ljubljana
Demonstration of Offset Phase Locking

- Master laser is a tuneable ECL with a FWHM linewidth of 100kHz
- Slave laser (SL) operated with 150mA into each of gain and SOA sections
- Master laser set at 7dBm output power to provide ~28dBm of RF power for the loop electronics
  (Minimum power required by the loop electronics: -40dBm to -25dBm)
- Linewidth of
  Unlocked Signals: 70MHz
  Locked Signal <1kHz
  (limited by decorrelated ECL noise)

Phase Noise Measurements

- Phase noise was < -80dBc/Hz at an offset of 10kHz for a locking range of 3 – 5GHz
- With an increased SOA current of 300mA, locking was achieved over the entire locking range of 2 – 7GHz.
- Optimum performance was at an offset frequency of 4GHz due to the frequency response of the loop electronics, giving phase noise of <-90dBc/Hz
Generation of mm-Wave Signal

- Master laser is a phase modulated external cavity laser covering a frequency range of 300GHz (linewidth of each line is 100kHz)
- As only one OPLL is operational in this 1st device, THz generation is demonstrated by injection locking a DBR laser to another comb line to provide the 2nd input to the fast PD
- Spectral purity of the synthesised signal was assessed using a UTC PD (3dB b.w 110GHz; responsivity 0.5A/W), coplanar probe, external mixer and an RF spectrum analyser
- Linewidth < 1kHz (limited by decorrelated ECL noise)

Monolithic Optical Phase Lock Loop (OPLL)

Monolithic chip

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Monolithic OPLL Chip

- The optical delay is reduced to a minimum (16 ps)
- Main source of delay is loop electronics

Integrated Twin DBR Lasers- Thermal Tracking

Frequency change with temperature

Over a 5 °C temperature change
- Each laser emission frequency changes by ~ 60 GHz
- The heterodyne signal frequency changes by < 2.5GHz
Dual OPLL THz Generation

- Heterodyne linewidth less than 1kHz
- Generation of signal up to 1.6 THz with an OFCG
- Compact source using only InP based technology

Monolithic OPLL Assembly

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Monolithically Integrated OPLL Results

- The optical delay is reduced to a minimum (16 ps)
- 1st order loop (1 ns delay) in parallel with slower second order for tracking
- Locking at offsets from 3 to 5 GHz (circuit limited) with -98 dBc/Hz noise at 10 kHz offset

![RF Power and Phase Noise Graphs](image_url)
High Resolution Spectra for Single OPLL

Device C7R32, 80 kHz span, 1kHz RBW

Heterodyne OPLL with SSB Mixer

- Heterodyne OPLL:
  - Precise wavelength offset generation
  - Precise optical heterodyne RF generation
- Close integration:
  - OPLL PIC and custom InP feedback electronics
  - Very short delay → Large bandwidth

L. Johansson et al, UCSB
Heterodyne OPLL with SSB Mixer: Results

- SSB mixer capable of selectively locking to positive or negative offsets
- ~ 400 MHz loop bandwidth
- > 15 GHz hold-in range
- < -100 dBc/Hz above 5 kHz
- < 0.03 rad² phase error variance

For more information - Please see: Mingzhi Lu, et. al, – Tu2H.4, OFC2014

Optical Injection Phase Lock Loop

- For application not requiring fine tuning of the frequency an hybrid solution could be used
- Injection locking gives wideband noise suppression and tracking of slow drift is through a long delay phase lock loop
### OIPLL Results

- High spectral purity
- Temperature tolerant operation

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**First WoF System Demonstration using IQ-Modulation**

- Optical Carrier Generator - DOB modulation & carrier suppression
- Data Modulation - 8-QAM OFDM @ 7 GHz bandwidth
- Wireless Transmitter - using 7GHz EPHOBAC photodetector
- Wireless Receiver - RF to IF down-conversion
- OFDM with 2048 subcarriers, each carrier QAM modulated
- Bandwidth set to 7 GHz
- IF-Q mixer with IF LO of 8.5 GHz (+24 dBm)
- Optical carrier suppression: ~19 dB
- Consumed RF-bandwidth: 57.4 – 64.4 GHz
- Spectral efficiency: 3.86 bits/Hz
- 2.5 m wireless path length
- 23 dB antenna gain
- -1 dBm transmit power


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**Coherent System Towards >100 Gbit/s**

- Phase-stabilized optical signal generator
- EOM
- UTC
- PD
- Harmonic mixer
- LO signal
- LNA
- LIA
- FEC board
- Pulse pattern generator
- Error detector

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T. Nagatsuma, Osaka Univ.
Coherent Transmitter Based on OFCG

Optical frequency comb generator

EOM

EOM (25 GHz)

Laser

Data signal

AWG filter

EOM

Optical cable

To photodiode

Phase fluctuates independently


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T. Nagatsuma, Osaka Univ.
Effect of Phase Fluctuation on Eye

Demodulated Data Signals at Receiver

Without stabilization

With stabilization

Effect of FEC w/ Stabilizer

10.3 Gbit/s
(11.1 Gbit/s w/ FEC)

w/o stabilizer → FEC was NOT possible
Conclusion

- THz wireless systems offer ultra-high bit rate transmission without the fog outages that affect free-space optical systems.

- THz wireless systems are attractive for both in-building and outdoor access applications.

- Photonic THz signal generation and detection techniques enable transfer of signals over optical fibre, enabling integration with fibre access systems.

- Advances in photonic integration techniques are key to cost effective photonically enabled THz system deployment.

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