Metrology for performance analysis of THz devices and systems – Impact of lack of standards

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The UK’s National Measurement Institute (NMI)

- Founded in 1900
- 400+ Scientists
- State-of-the-art facilities
- **Focus on metrology**
- Fundamental research
- Applied science
- Support for industry
## THz measurement needs:

<table>
<thead>
<tr>
<th>Device</th>
<th>Measurement</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitters</td>
<td>Center frequency and linewidth</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>Broadband spectral profile</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>Limited</td>
</tr>
<tr>
<td></td>
<td>Beam profile</td>
<td>NO</td>
</tr>
<tr>
<td>Detectors</td>
<td>Spectral responsivity</td>
<td>Limited</td>
</tr>
<tr>
<td></td>
<td>Spectral NEP</td>
<td>NO</td>
</tr>
<tr>
<td>Systems:</td>
<td>System specifications</td>
<td>NO</td>
</tr>
<tr>
<td>THz TDS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
THz frequency measurement

**Need:**

- **Centre frequency & linewidth**
  - Carrier frequency
  - Frequency stability/jitter
  - High resolution spectroscopy

**Need:**

- **Broadband spectral profile**
  - THz Spectroscopy
  - Broad features in narrow-line sources
THz frequency measurement

THz frequency is the only parameter in THz measurements where traceable calibration and standards exist and are widely used.
Frequency measurement of electronic THz emitters: heterodyne

**Heterodyne:**
- The most common technique
- The most accurate
- The most precise
- Can be traceable

Note: The LO must be frequency-calibrated!
THz spectrum analyser: state of the art (example)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum frequency</td>
<td>50 GHz</td>
</tr>
<tr>
<td>with mixers</td>
<td>up to 1.1 THz</td>
</tr>
<tr>
<td>Sweep bandwidth</td>
<td>1 GHz</td>
</tr>
<tr>
<td>Amplitude accuracy</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>Frequency accuracy</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>e.g.:</td>
<td>$\pm 50$ kHz @ 500 GHz</td>
</tr>
</tbody>
</table>

**Limitations:**
- Limited top frequency
- Waveguide coupling / multiple waveguides needed

Excellent for measuring central frequency & linewidth for narrow-line cw sources up to ~1 THz.
THz frequency measurement at frequencies > 1 THz

Frequency calibration using absorption lines in gases

Frequencies of gas lines are known with high accuracy: http://hitran.org/
THz frequency measurement at frequencies > 1 THz

Frequency combs

THz spectral profile measurement: broadband & free-space

Lamellar interferometer

- **Advantages:**
  - Large bandwidth: \( f_{\text{max}}/f_{\text{min}} = N_{\text{fingers}} \)
  - With suitable detector, bandwidth up to 10 THz.
  - Detects higher harmonics.
  - Measures spectral emission profile.
  - Is suitable for free-space sources.
  - With a known source can measure spectral responsivity of detectors.

- **Disadvantages:**
  - Requires frequency & linearity calibration.
  - Low frequency resolution (>1 GHz).

The lamellar mirror acts as both beam-splitter and moveable mirror.
THz power measurement

Need:

- **Power**
  - Emitter performance
  - Link power budget
  - Health & safety
- **Antenna characterization**
- **Broadband spectral profile**
- **Polarization**
- **Beam profile**
## THz power measurement

### Main types of THz power meters

<table>
<thead>
<tr>
<th>Detector</th>
<th>Traceability</th>
<th>Commercial availability</th>
<th>Ease of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiometer</td>
<td>Traceable to a black body</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Calorimeter</strong></td>
<td>Traceable to a black body</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td><strong>Pyroelectric detector</strong></td>
<td>Calibrated against traceable detector</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Thermopile</td>
<td>Calibrated against traceable detector</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td><strong>Acousto-optic (Golay cell)</strong></td>
<td>Drifts, nonlinear response</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>Cryogenic bolometer</td>
<td>Not calibrated</td>
<td>V</td>
<td>X</td>
</tr>
</tbody>
</table>
THz calorimeter – de facto industry standard

Waveguide-coupled
- Frequency range: 75 GHz to >3 THz
- Input power range: 1 µW – 0.2 W
- Calibrated

<table>
<thead>
<tr>
<th>Typical PM5 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>200 mW</td>
</tr>
<tr>
<td>20 mW</td>
</tr>
<tr>
<td>2 mW</td>
</tr>
<tr>
<td>200 µW</td>
</tr>
</tbody>
</table>

*Response time is given as the time from the application of an input to a response at the analog output of 90% of the final reading.

VDI – Erickson PM5


Isothermal calorimeter: has two identical radiation inputs; radiation is coupled into one, while the other is electrically heated to equal temperature. The electrical power is then equal to the absorbed radiation power.

Unsuitable for free-space measurements
THz pyroelectric detector

Thin-film pyroelectric THz detector developed by Physikalisch-Technische Bundesanstalt (PTB) and Sensor und Lasertechnik (SLT), Germany.

Pyroelectric material: 10 µm thick PVDF polymer foil.
Absorber: Thin metallic layer on both sides of the foil.

Pyroelectric sensor: pyroelectric material absorbs radiation, raising its temperature, which changes its permanent electric dipole moment. This can be monitored as current or voltage.

Maximum optical responsivity (amplified): $10^4$ V/W
Golay cell: a type of acousto-optic sensor. Radiation is absorbed by a thin metal layer, which heats the gas in a cell and raises its pressure. The cell has a flexible mirror wall whose deformation is optically detected as signal.

Has the highest sensitivity of all room-temperature THz detectors.

A Golay detector made by Tydex
http://www.tydexoptics.com/products/thz_devices/golay_cell/

Optical responsivity: $10^5$ V/W
Maximum incident power: 10 µW
NEP @ 15 Hz: $10^{-10}$ W/Hz$^{1/2}$
Other THz power detectors

**Radiometer:** measures absorbed radiation power in comparison with a traceably calibrated optical source (black body or laser).

**Thermopile:** a series array of thermocouples using the thermoelectric (Peltier) effect to convert a thermal gradient created by absorbed radiation into an electrical signal.

**Cryogenic bolometers:** use free-carrier absorption by electrons in a doped semiconductor. Come in many different designs and materials. *Have by far the highest sensitivity of all THz detectors.*

For all THz detectors:
the frequency range and spectral flatness of responsivity depend on the absorption properties of the radiation absorber.
THz power standards?

Agreed standards do not exist:
- THz power source standards
- THz power measurement standards

PTB provides a limited-availability traceable calibration service for THz power meters.

e.g.
There are no facilities or instruments for calibrated measurements of THz beam profile. (Nothing similar to antenna ranges for RF.)

**Need:**
- Beam spread
- Lobes and/or other features
- Collimation & focusing optics
- Fraction of power in the central spot
- Phase variations
THz cameras

TeraSense Tera-256
• 256 pixels (16 x 16 array)
• 1.5 mm pixel pitch
• NEP = 1 nW/√Hz
• 10 cm x 10 cm x 5.5 cm device size
http://terasense.com/products/sub-thz-imaging-cameras/

INO-IRXCAM-384THZ TERAHERTZ CAMERA
• 384 x 288 pixels uncooledmicrobolometerFPA
• 35 μm pixel pitch
• 4.25–0.094THz
• 61 mm (H) x61 mm (W)x 65mm (L)

Issues:
• Responsivity calibration uncertain
• Frequency dependent responsivity
• Requires input optics
THz systems

THz time domain spectrometer – the most widely used THz system

System specification requirements:
• Operating bandwidth
• Dynamic range
• Noise floor
• Frequency resolution

No agreed definitions exist
THz THz specifications

Typical THz TDS spectrum

Amplitude (arb.) vs Frequency (THz)

Dynamic range?

Bandwidth?

Noise floor?

Frequency resolution = data point spacing?
Conclusion

There is an urgent need for industry standards:

- THz power measurement
- Device and system specification
- Beam imaging

Industry standards – especially for THz communications – are necessary for widespread adoption of THz technologies.
Thank you