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FOR 2863 Meteracom
Metrology for THz Communications

The 50th International Conference on Infrared, Millimeter, and Terahertz Waves
17-22 August, 2025

METERACOM

THz characterization of building materials

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DFG FOR2863 Meteracom Final Workshop @ IRmmW-THz 2025, 20 August 2025

Outline

- Motivation
- Early work
- Characterization of building materials within METERACOM

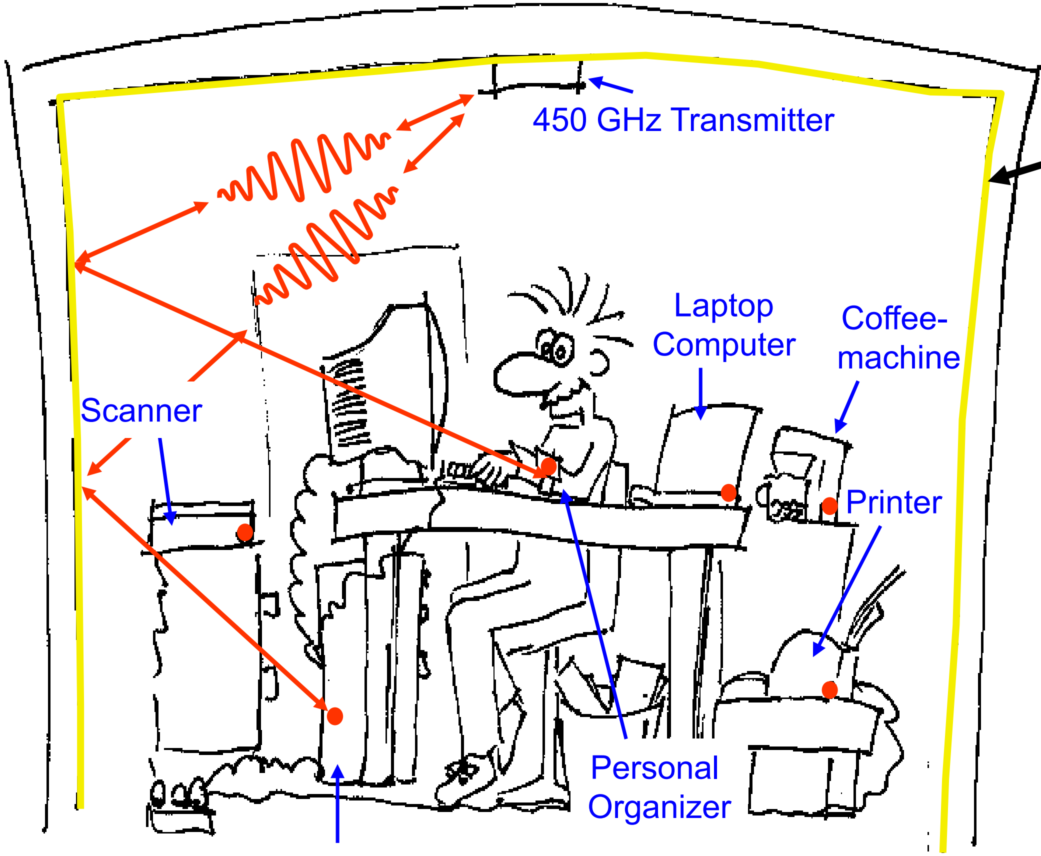
Motivation

Technische Universität Braunschweig

Friis formula

$$P_{\text{rec}} = P_{\text{emitt}} \cdot g_{\text{emitt}} \cdot g_{\text{rec}} \left(\frac{\lambda}{4\pi r} \right)^2$$

THz pico cell



THz-Mirror as wall paper

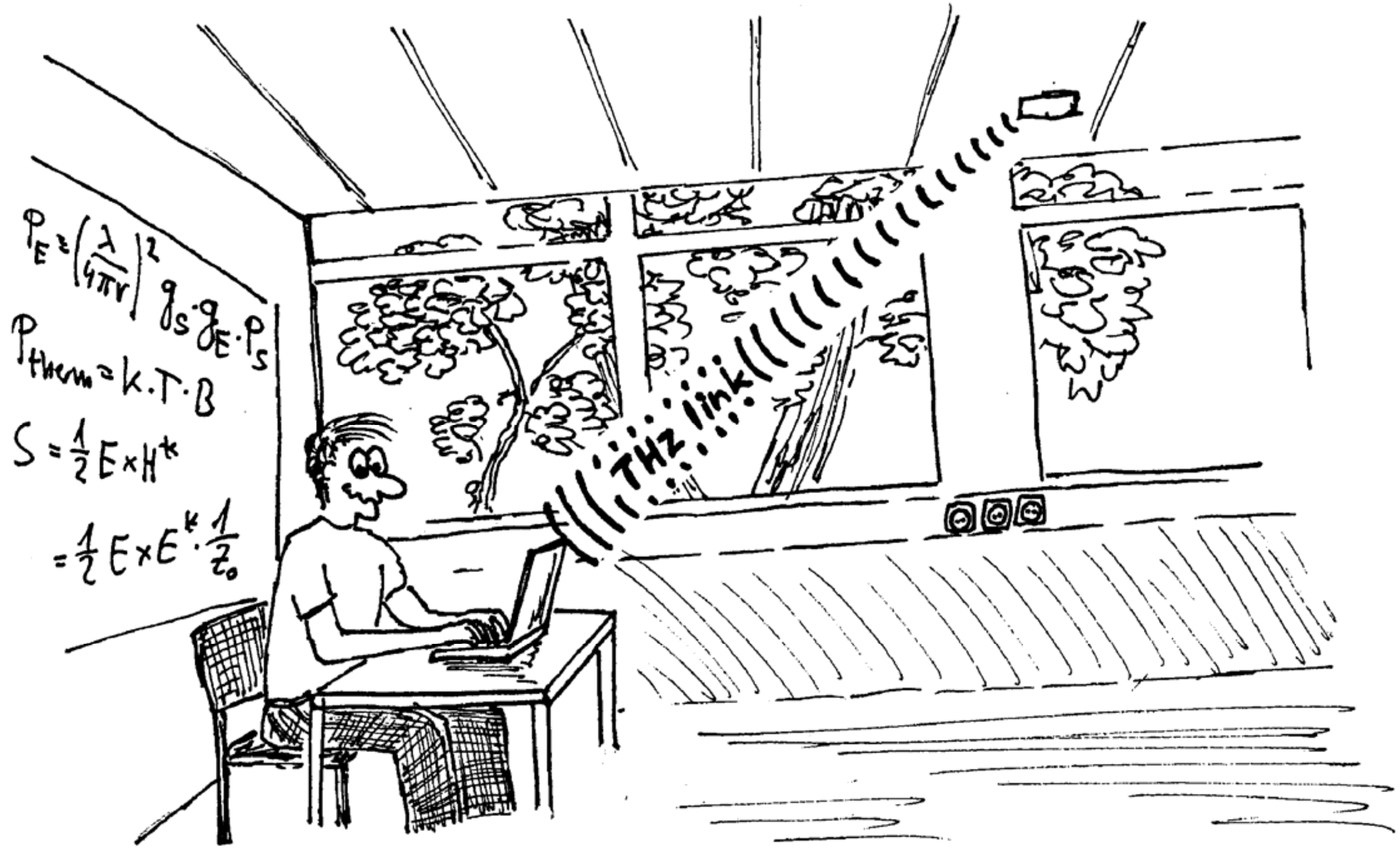
⇩

Better coverage in the cell, NLOS propagation with reflections

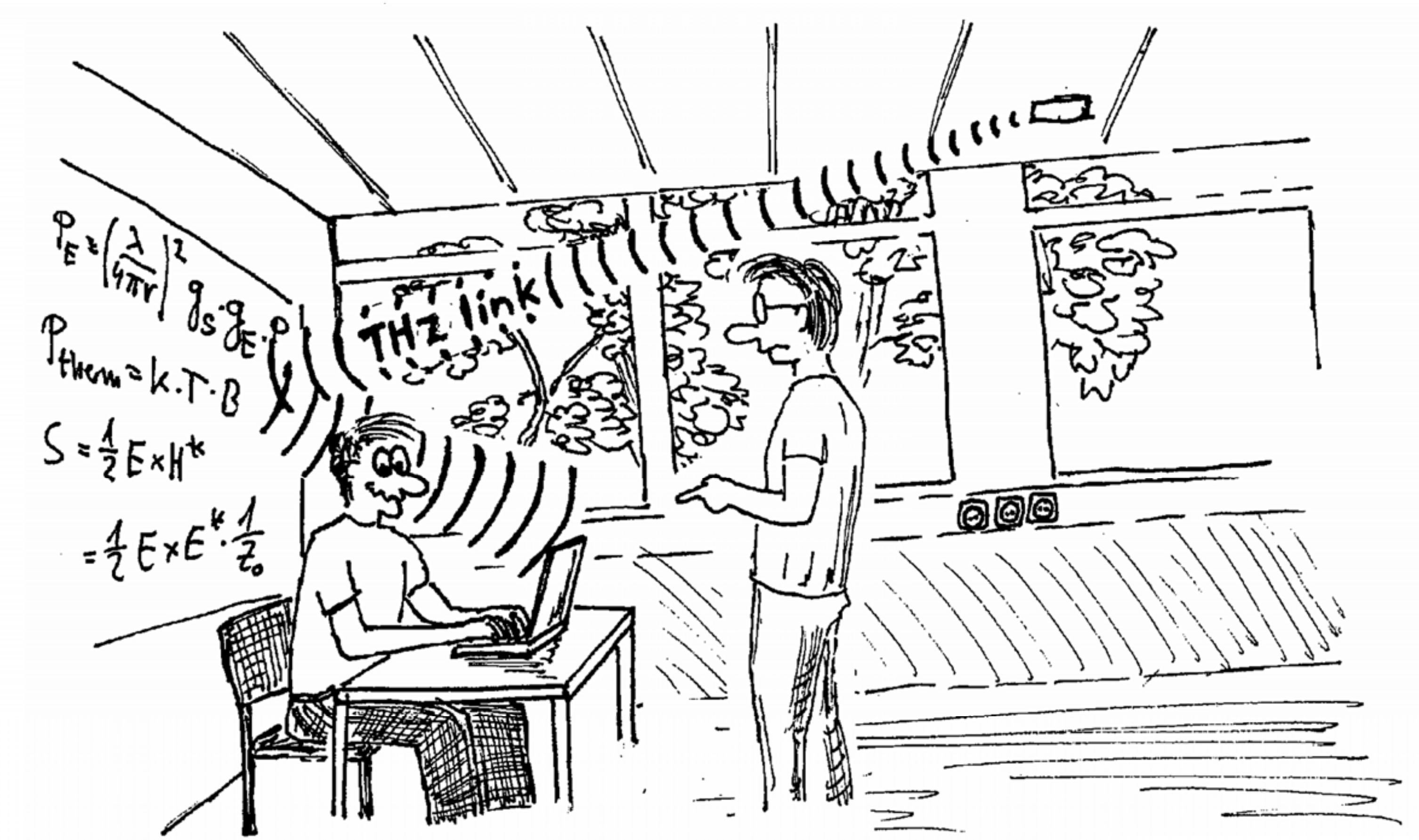
&

Frequency selective separation of the cells

drawn in 2000



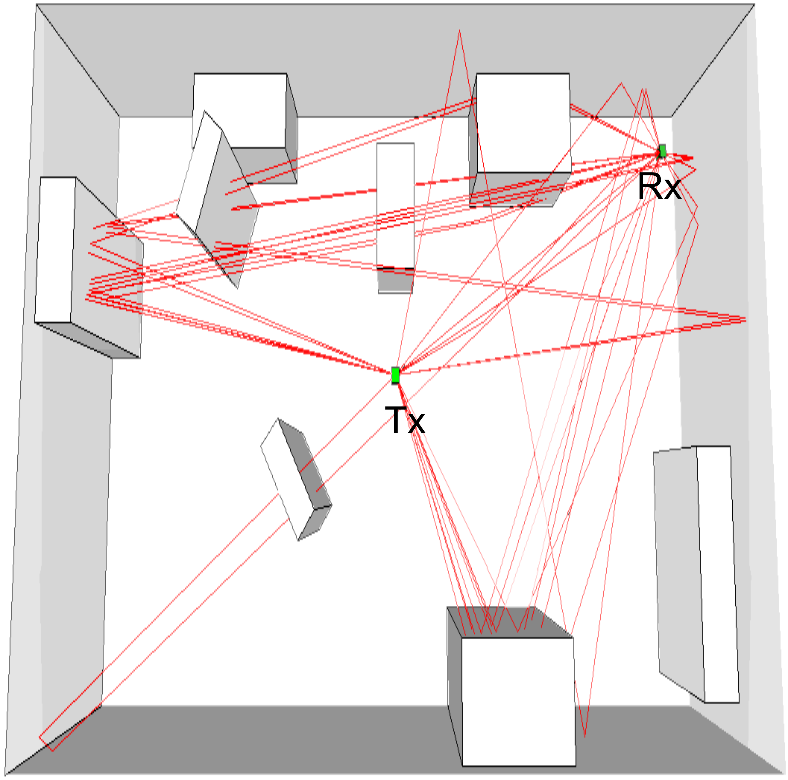
$P_E = \left(\frac{\lambda}{4\pi r}\right)^2 g_S \cdot g_E \cdot P_S$
$P_{therm} = k \cdot T \cdot B$
$S = \frac{1}{2} E \times H^*$
$= \frac{1}{2} E \times E^* \cdot \frac{1}{Z_0}$
THz link


$P_E = \left(\frac{\lambda}{4\pi r}\right)^2 g_S \cdot g_E \cdot P$
$P_{therm} = k \cdot T \cdot B$
$S = \frac{1}{2} E \times H^*$
$= \frac{1}{2} E \times E^* \cdot \frac{1}{Z_0}$
THz link

The problem with LOS communication

- Link is broken if somebody steps into the beam.
- Solution: use indirect non-line of sight paths as back up links.
- This involves the reflections off the walls (billard)
- One would also need smart antennas.

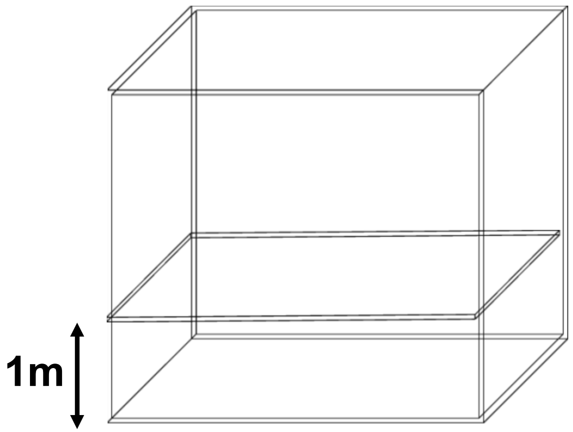
Ray-Tracing simulations



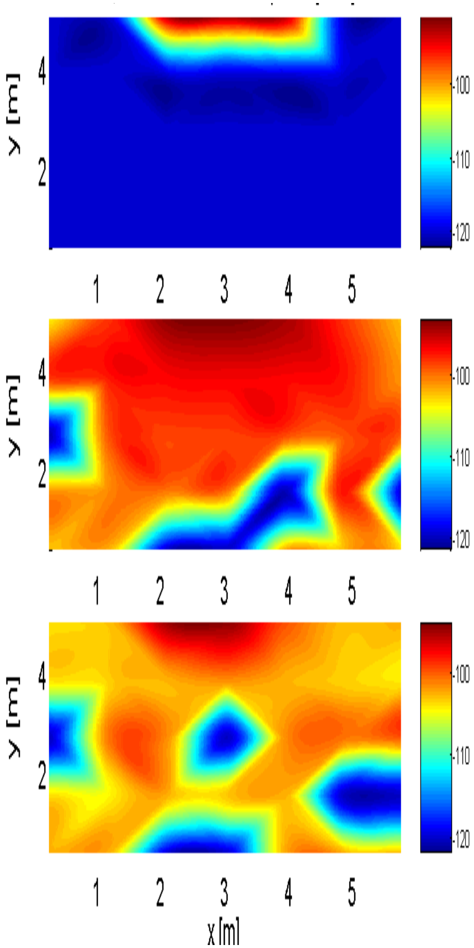
- Randomly placed objects
- Random-walk algorithm
- Monte Carlo simulations

Simulations performed 20 years ago
in the group of Prof. Kürner
Institute for Communication Technology,
TU Braunschweig

Signal level: worst case scenario



Signal level in dB
1m above the ground



Direct path

Once reflected

Twice reflected

THz channel characterization for future wireless gigabit indoor communication systems.
R. Piesiewicz, J. Jemai, M. Koch,* and *T. Kürner
Proc. SPIE Int. Soc. Opt. Eng. 5727, 166 (2005)

→ Link is much more reliable if NLOS paths are available

Reflective properties of walls or furniture in the THz range?

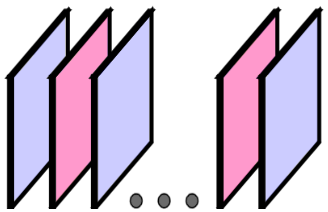
One need to study the reflective properties of typical building materials (plaster, glass,…)

R. Piesiewicz et al., Electron. Lett. 41, 1002 (2005).

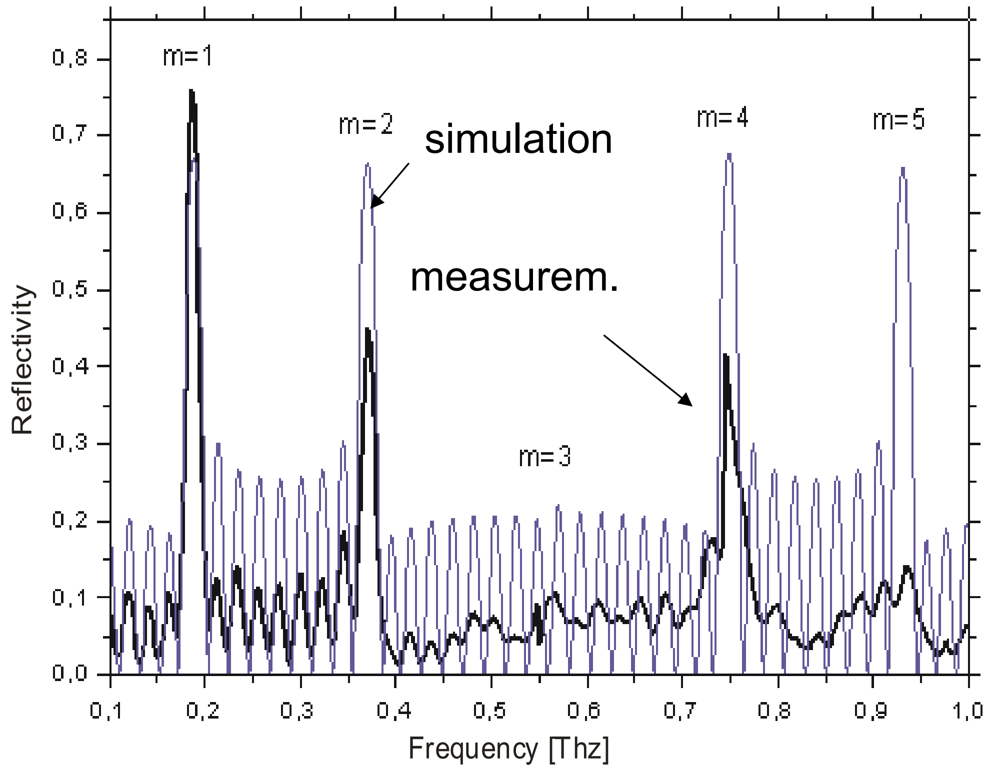
→ Most building materials are not very reflecting.

What can be done to enhance the reflectivity of the walls?

Flexible all-plastic THz mirrors



8.5 alternating pairs:
205 µm PE (n=1,77)
310µm Styrolux (n=1,59)

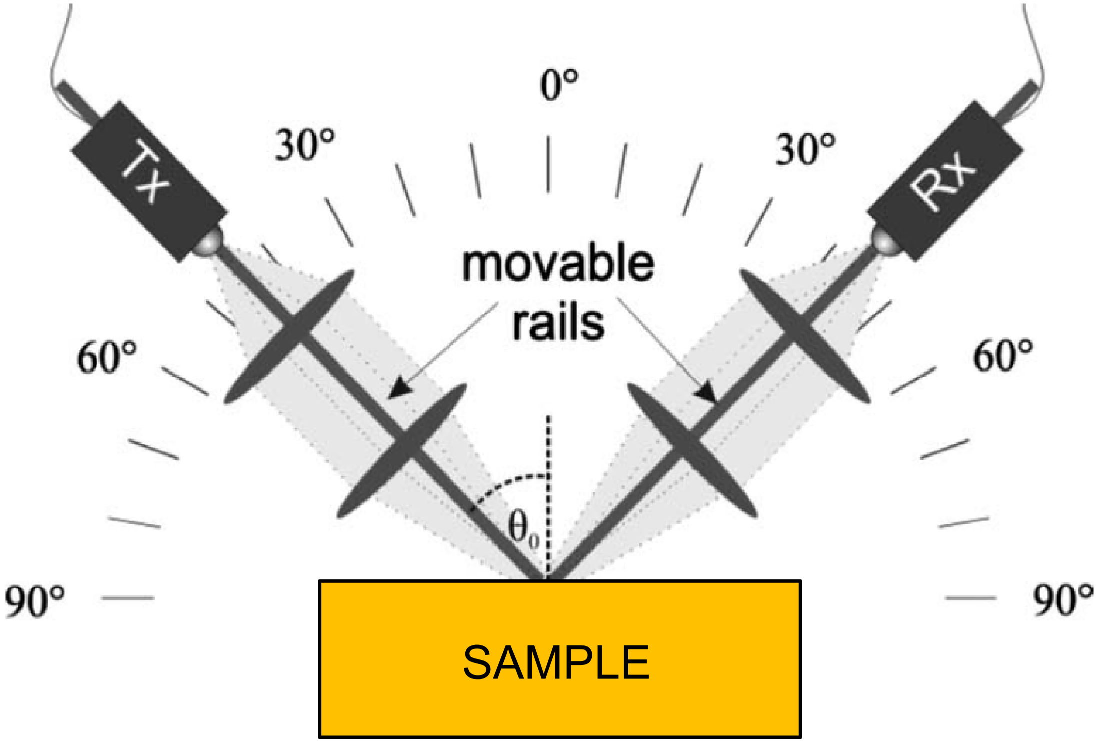


THZ mirrors as
ıll paper to support
NLOS channels
ın THz pico cells

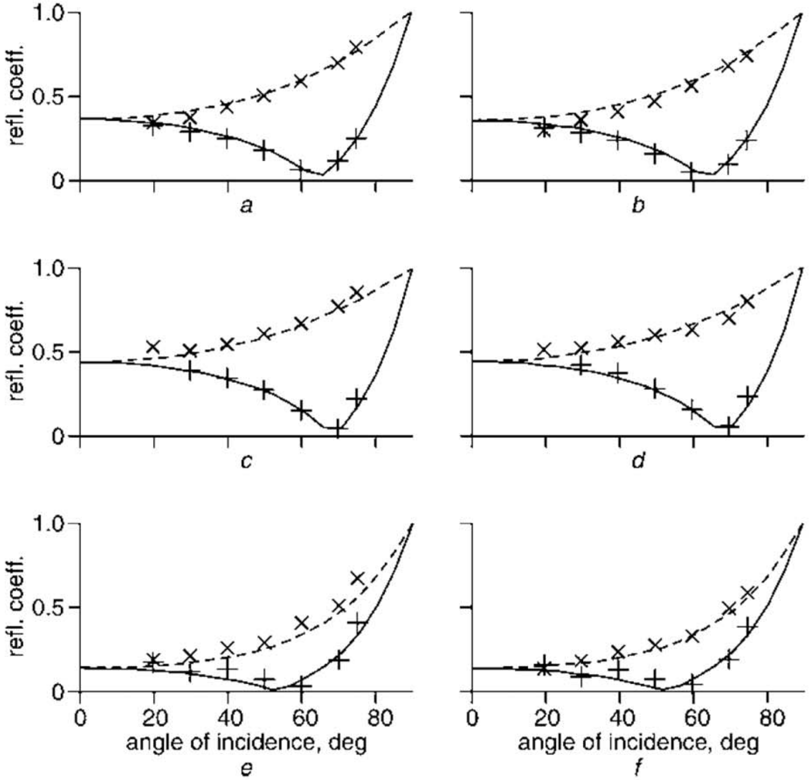
D.Turchinovich, Appl. Phys. Lett. A, 74 (2002) and US patent No.: US 6.954.309 B2

Early work

Fibe-coupled THz spectrometer combined with a goniometer



Fresnel formula are valid in the THz range…



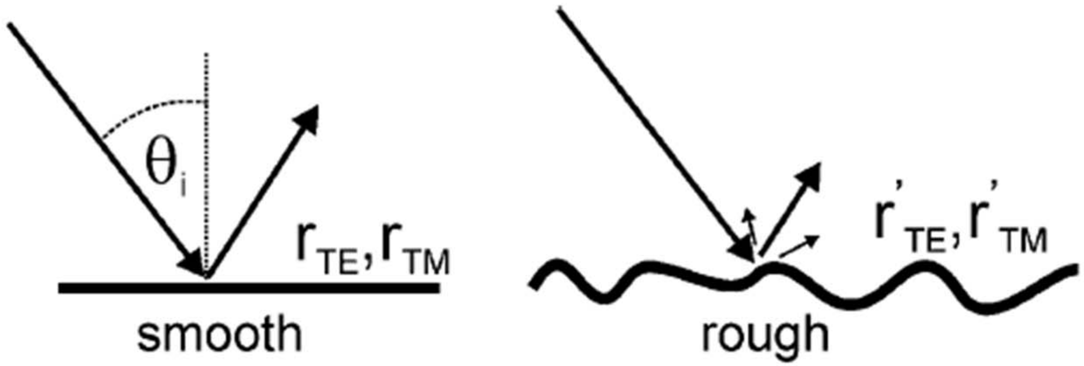
…for smooth materials

a Plaster at 150 GHz *b* Plaster at 300 GHz
c Glass at 150 GHz *d* Glass at 300 GHz
e Wood at 150 GHz *f* Wood at 300 GHz

------ TE simulated × TE measured
—— TM simulated + TM measured

R. Piesiewicz et al., Electron. Lett. 41, 1002 (2005)

Scattering significantly reduces the signal level of the reflected beam

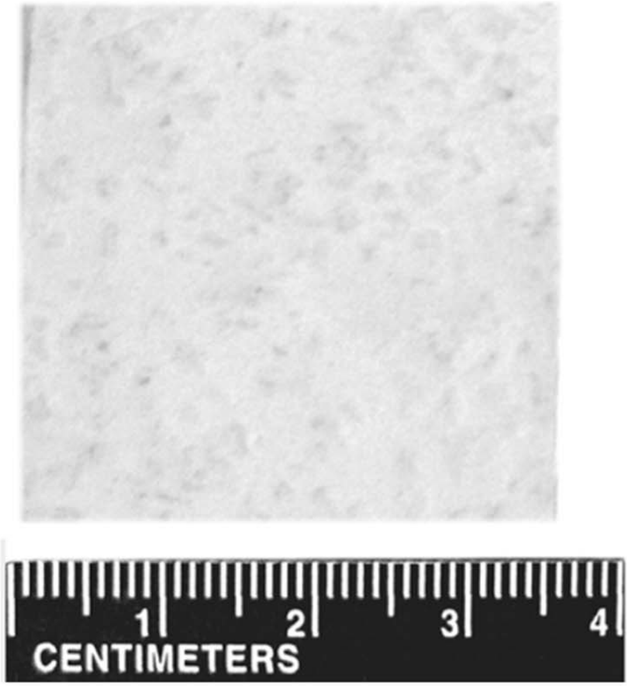


R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007).

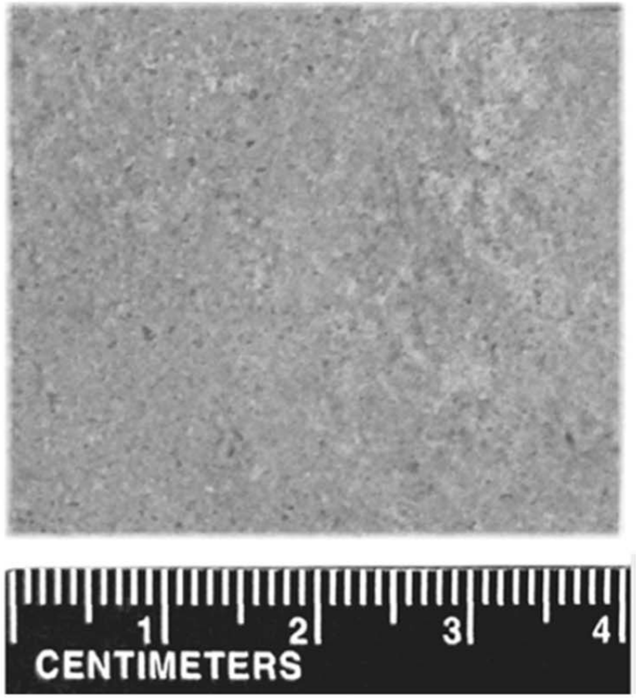
Scattering significantly reduces the signal level of the reflected beam

Investigated materials:

R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007).



ingrain wallpaper



concrete plaster

Fresnel reflection coefficients (for smooth surfaces)

$$r_{\mathrm{TE}} = \frac{Z \cos \Theta_i - Z_0 \cos \Theta_t}{Z \cos \Theta_i + Z_0 \cos \Theta_t}$$

$$r_{\mathrm{TM}} = \frac{Z \cos \Theta_t - Z_0 \cos \Theta_i}{Z \cos \Theta_t + Z_0 \cos \Theta_i}.$$

Rayleigh roughness factor

$$r'_{\mathrm{TE}} = \rho \cdot r_{\mathrm{TE}}$$

$$r'_{\mathrm{TM}} = \rho \cdot \mathrm{r}_{\mathrm{TM}}$$

$$\rho = e^{-\frac{g}{2}}$$

$$\mathrm{g} = \left(\frac{4\pi \cdot \sigma \cdot \cos \Theta_{\mathrm{i}}}{\lambda} \right)^2$$

σ = *standard deviation of the surface roughness*

P. Beckmann and A. Spizzichino, The Scattering of Electromagnetic Waves from Rough Surfaces. Norwood, MA: Artech House, 1987, pp. 80–98.

Rayleigh roughness factor

$$\rho = e^{-\frac{g}{2}}$$

$$g = \left(\frac{4\pi \cdot \sigma \cdot \cos \Theta_i}{\lambda} \right)^2$$

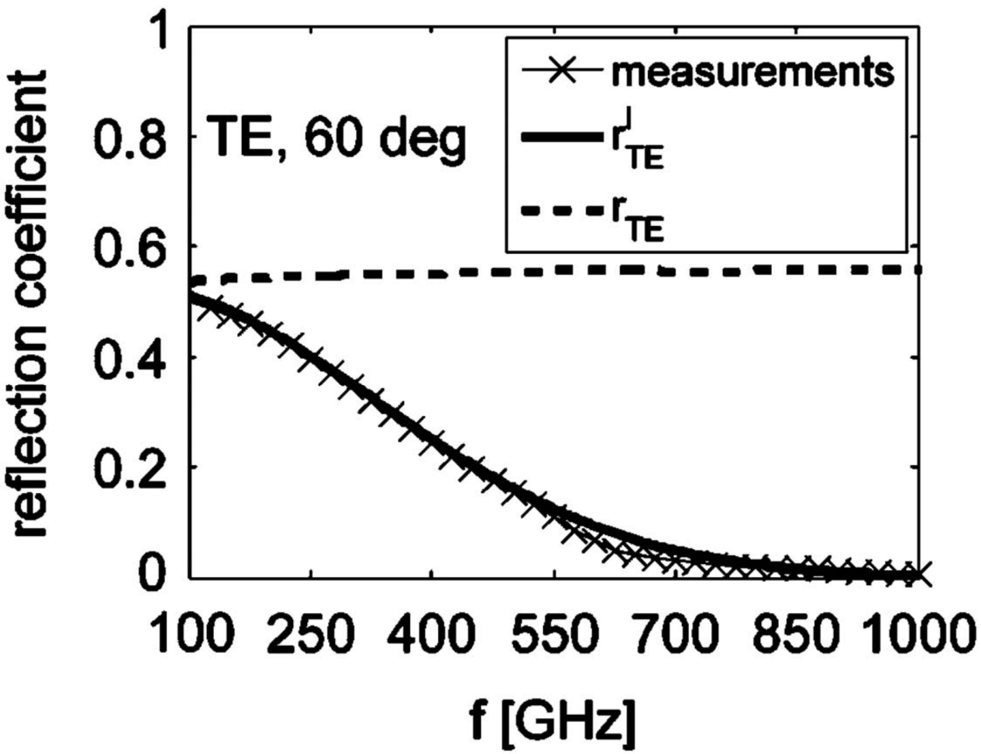
Rayleigh roughness factor depends on the ratio between surface roughness and the wavelength.

The smaller the wavelength, the larger is g and the samller is ρ.

Higher frequencies will experience more scattering.

R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007)

Scattering significantly reduces the signal level of the reflected beam



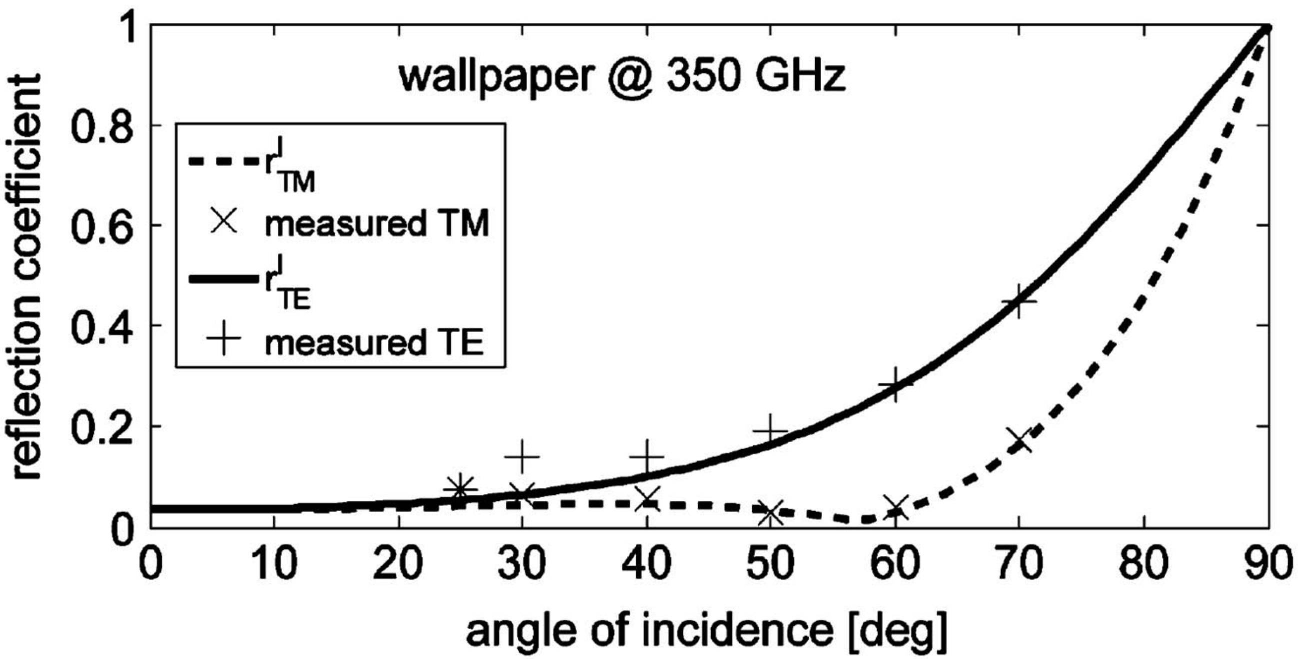
Measurements on a plaster sample

Higher frequencies experience more scattering.

→ The reflected beam experiences a stronger reduction.

R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007)

Overall reduction of the reflectivity



R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007).

R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007)

→ Scattering significantly reduces the signal level of the reflected beam

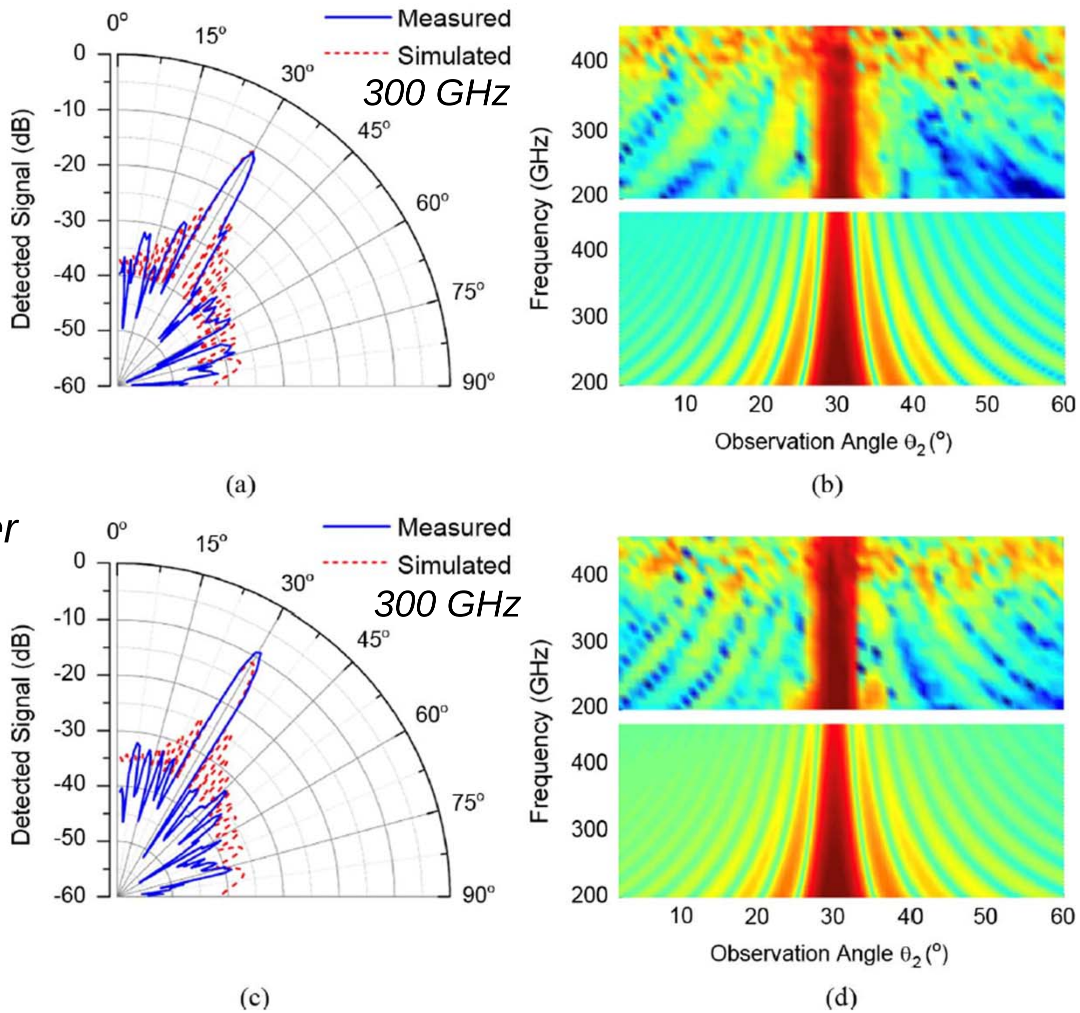
How much is scattered in the other directions?

→ C. Jansen, et al, IEEE Trans. on THz Science and Techn. 1, 462 (2011)

Scattering in other directions

plaster

wallpaper



Resonable agreement considering the low SNR in the experiment.

Simulations on the basis of Kirchhoff scattering theory.

For details see:

C. Jansen, et al, IEEE Trans. on THz Science and Techn. 1, 462 (2011)

Characterization of building materials within METERACOM

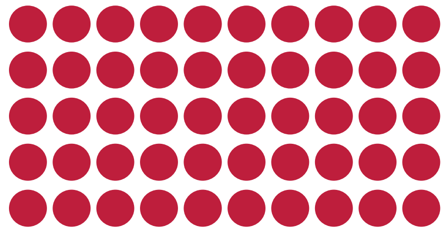
R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007)

C. Jansen, et al, IEEE Trans. on THz Science and Techn. 1, 462 (2011)

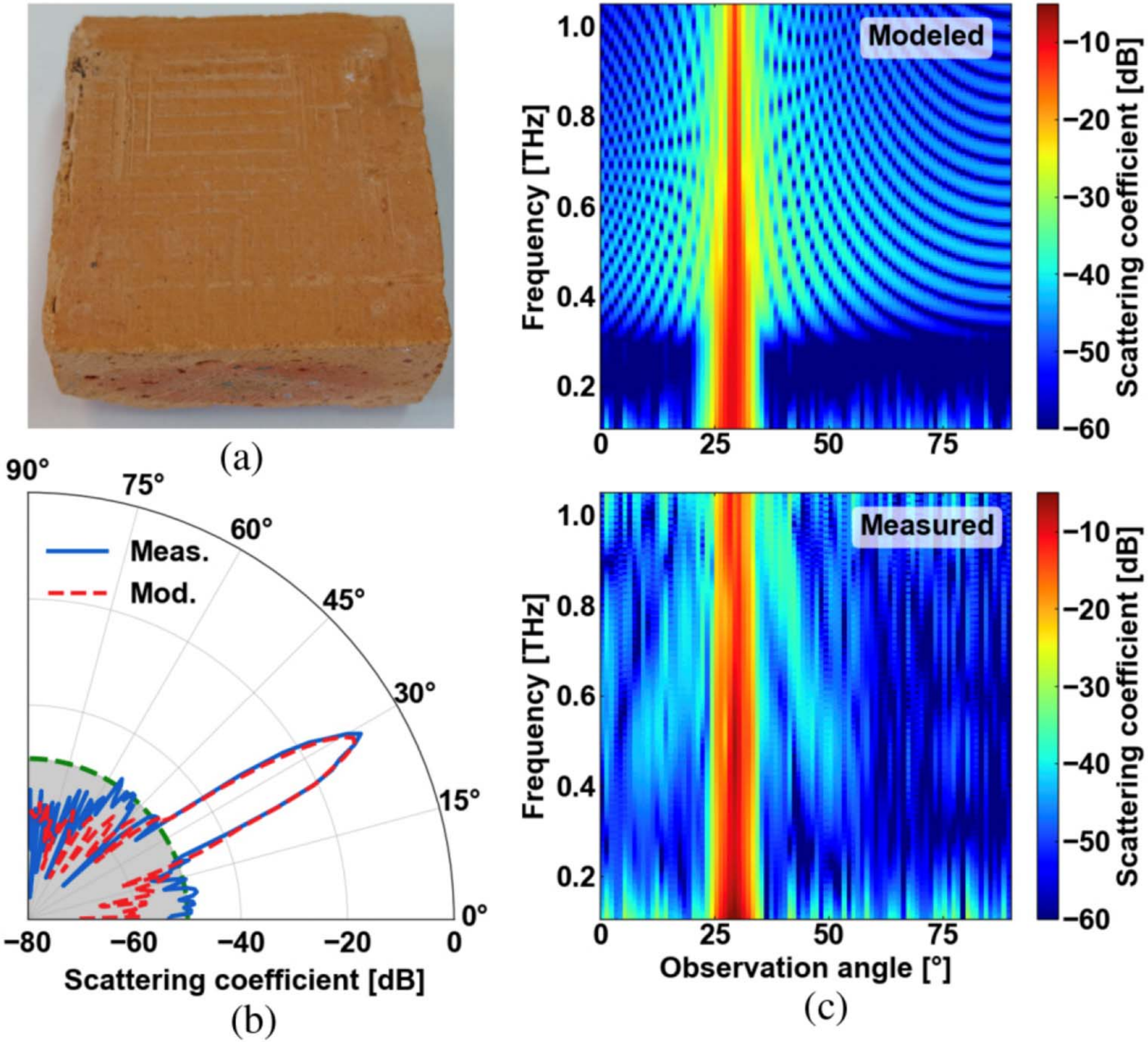
R. Piesiewicz et al., IEEE Transactions on Antennas and Propagation 55, 3002 (2007)

C. Jansen, et al, IEEE Trans. on THz Science and Techn. 1, 462 (2011)

F. Taleb, et al., IEEE Trans. on THz Science and Techn. 13, 421 (2023)



Fire clay brick sample



F. Taleb, et al., IEEE Trans. on THz Science and Techn. 13, 421 (2023)

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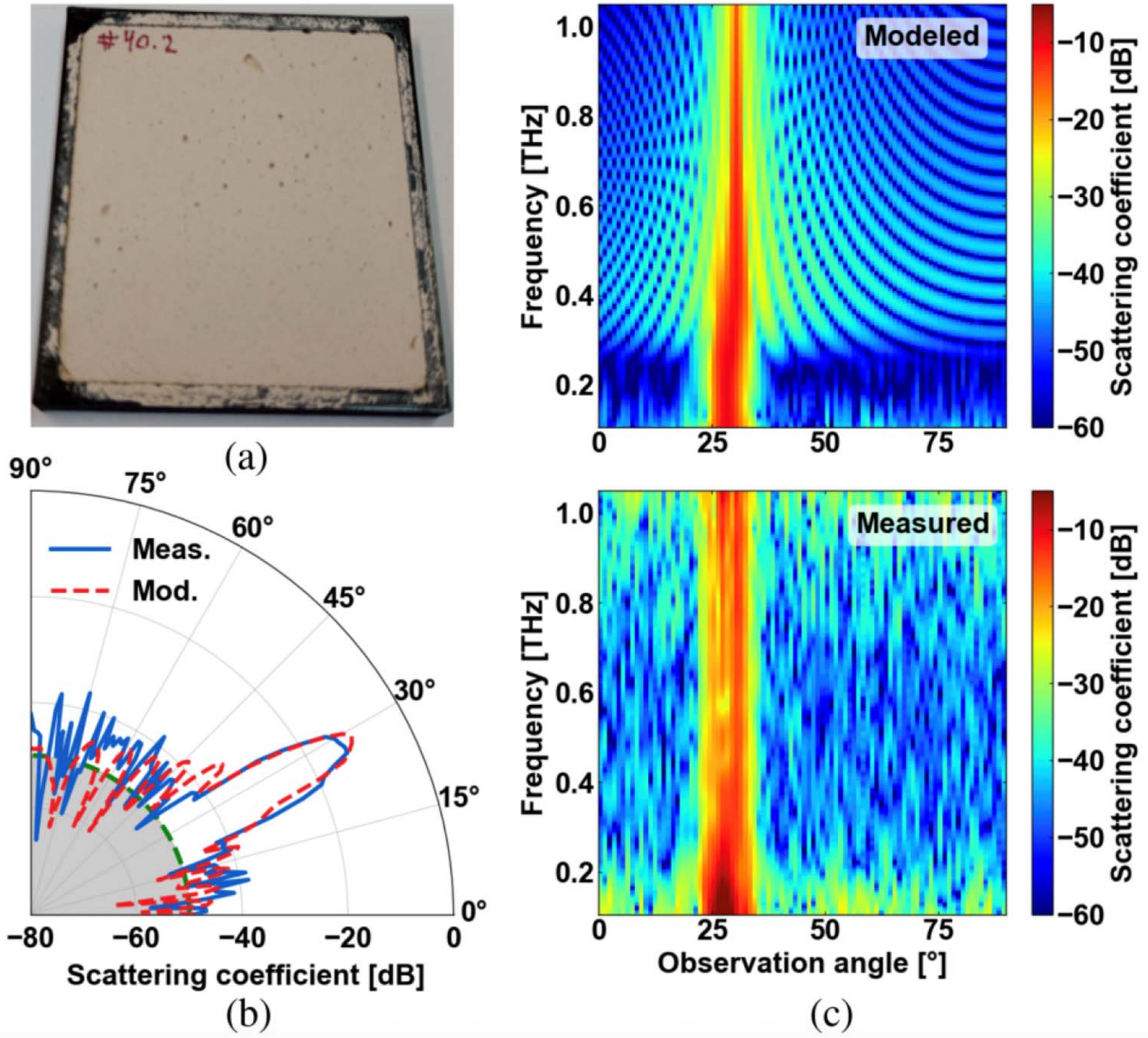
Flexfuge cement sample



F. Taleb, et al., IEEE Trans. on THz Science and Techn. 13, 421 (2023)

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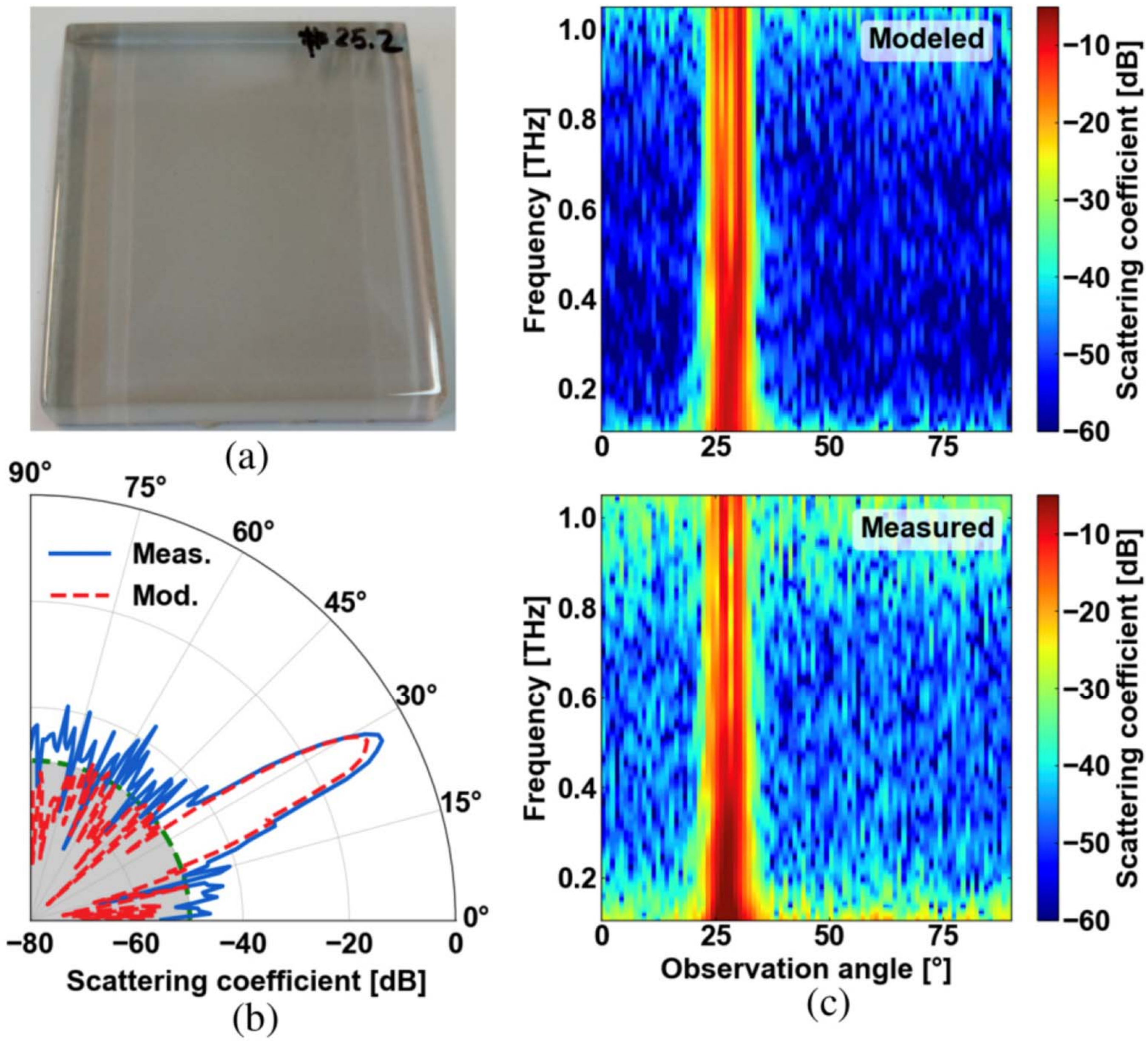
Glass sample



F. Taleb, et al., IEEE Trans. on THz Science and Techn. 13, 421 (2023)

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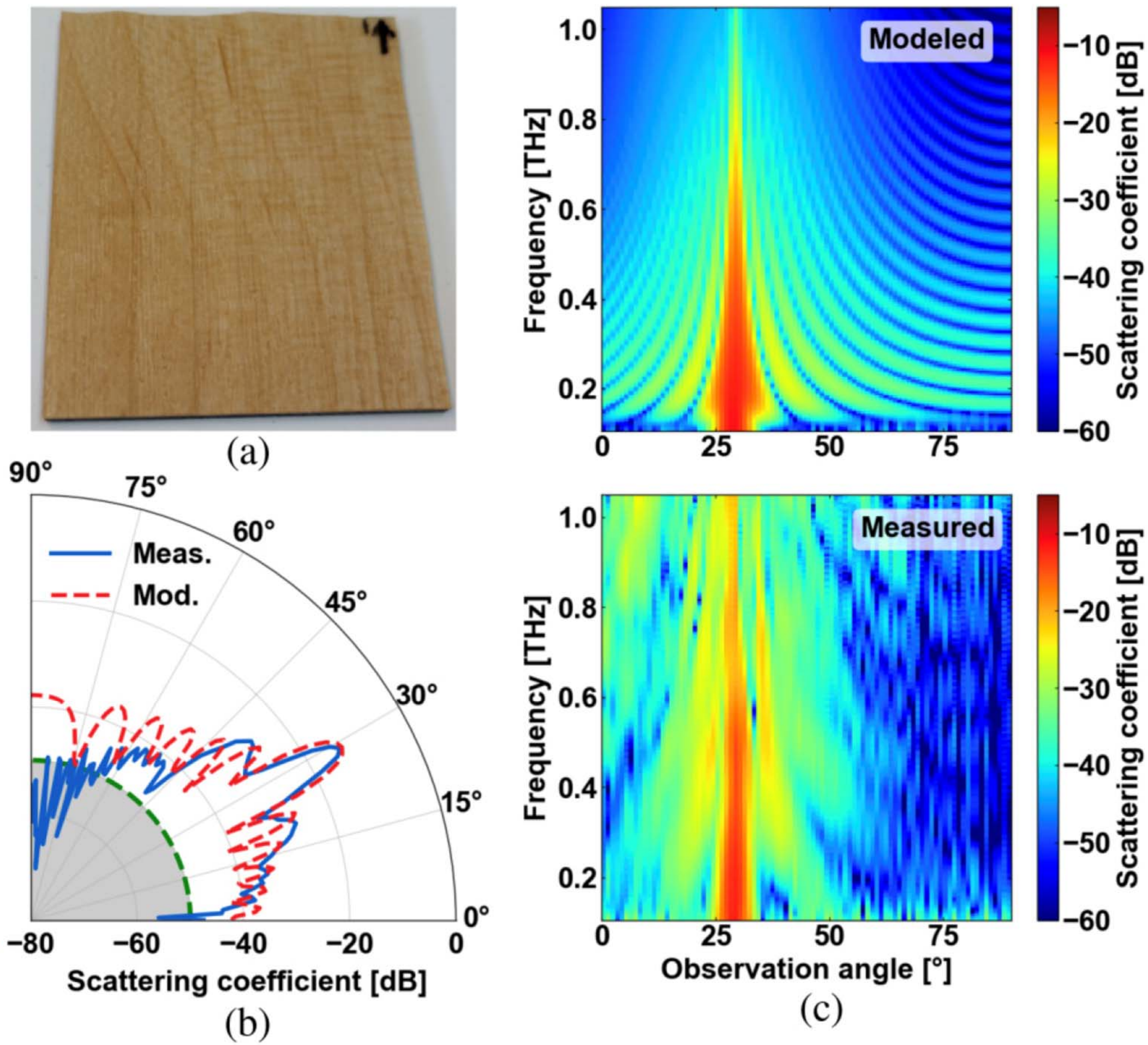
Tile with polyurethane coating



F. Taleb, et al., IEEE Trans. on THz Science and Techn. 13, 421 (2023)

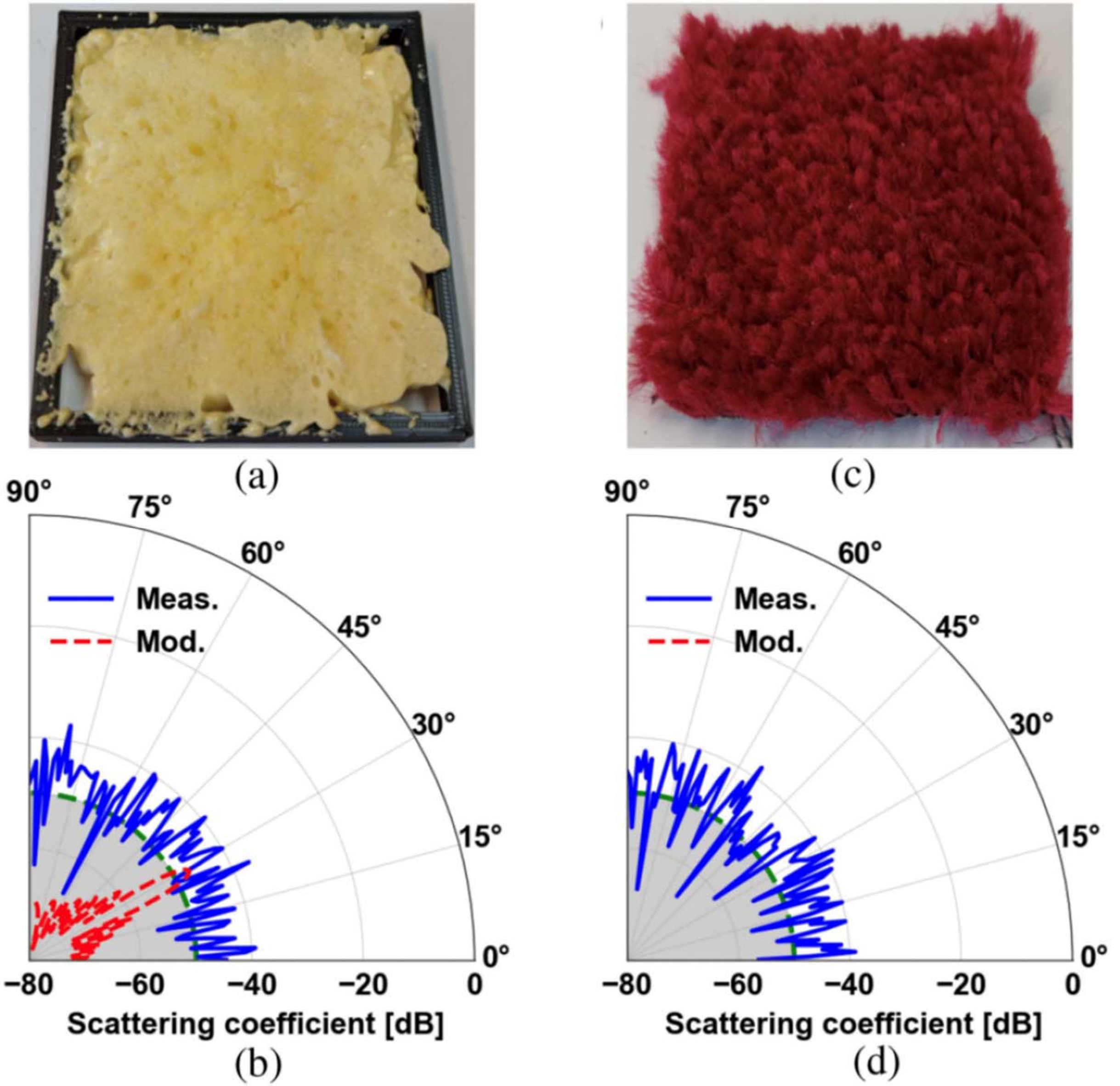
Spray foam (left) and carpet (right)

Spray foam has refractive index close to one.
→ not much is reflected in main direction.

Expected signal level is below or noise floor.

Expected signal level is even lower for the carpet.

→ These measurments should be repeated with the latest generation of fibre-coupled THz systems.



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Fiber-Coupled THz TDS System With mW-Level THz Power and up to 137-dB Dynamic Range

Alexander Dohms, Nico Vieweg, Steffen Breuer, Tina Heßelmann, Robert Herda, Nadja Regner, Shahram Keyvaninia, Marko Gruner, Lars Liebermeister, Martin Schell, and Robert B. Kohlhaas

***Abstract*—Terahertz (THz) time-domain spectroscopy (TDS) offers considerable potential for a wide range of industrial applications, including thickness determination and defect identification through imaging. Fiber-coupled THz TDS systems are particularly promising due to their flexible and robust operation in a variety of environments. However, increasing the THz power of these systems remains a critical challenge for applications that require high dynamic range in very short acquisition times. Here, we present a significant improvement of a commercially available THz TDS system by combining a novel ultrafast Er-doped fiber laser and improved iron-doped InGaAs photoconductive THz emitters. The Er-doped fiber laser offers the combination of high average power up to 70 mW and ultrashort pulse duration down to 45 fs with a fiber delivery of 6.3 m to the THz antennas. The THz emitters are optimized in terms of the photoconductive material and gap**

signal-to-noise ratio within short measurement times. Therefore, the implementation of robust and fast measurement schemes with high THz power is a critical requirement and has emerged as an important area of research.

In recent publications, close to watt-level THz sources have been demonstrated based on optical rectification in nonlinear crystals and two-color plasma filaments [5], [6]. Furthermore, it has been shown that the combination of multi-milliwatt (mW) THz sources with photoconductive receivers based on erbium arsenide (ErAs)-doped InAlGaAs can provide very high dynamic range (DNR) of 115 dB within short measurement times of 120 s [7]. However, the aforementioned THz sources typically suffer

Conclusion

The work carried out in METERACOM lays a foundation for a database. But there is still work to do.

Thank you very much for your Attention

Technische Universität Braunschweig

Universität Stuttgart

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