KATHOLIEKE UNIVERSITEIT LEUVEN

Conceptual *Metamaterials*

Prof. Guy A. E. Vandenbosch

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ESAT

TELEMIC

Outline

- Introduction
- Definition
- Structure
- Types
- Maxwell and material characteristics
- Wave propagation
- Applications
- Limitations
- Conclusions

The Irresistible Fantasy of the Invisible Man, and Machine

Humans have always dreamed of invisibility. Perseus, in Greek mythology, had a cap to make him disappear. Leprechauns and other magical creatures did it on their own.

In more recent times, invisibility has been a theme in fiction from H. G. Wells to Harry Potter. In "The Invisible Man," Wells had a scientist change the refractive index of his own body. In Harry Potter, a cloak does the trick. In "The Lord of the Rings," it is, of course, a ring that makes the wearer vanish, with some rather unpleasant side effects.

Both Wonder Woman and the Romulans of "Star Trek" managed to make their flying craft invisible, and in the movie "Predator" an alien hunter used high technology to cloak itself, while Arnold Schwarzenegger, prey for once, went low-tech. He used cold mud to mask his body heat, making himself invisible to the alien in the infrared spectrum.

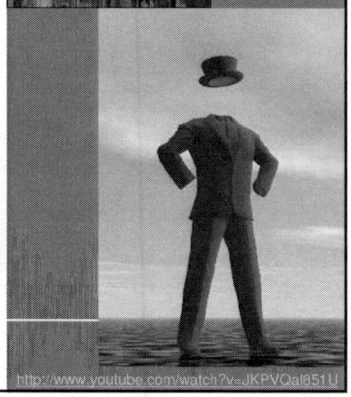







CAN'T SEE ME Clockwise from top left, Claude Rains in "The Invisible Man" (1933), the Klingon Bird of Prey (first seen in the 1984 "Star Trek III: The Search for Spock"), Daniel Radcliffe in "Harry Potter and the Goblet of Fire" (2005), Elijah Wood in the first "Lord of the Rings" (2001), Kevin Peter Hall as the title character in "Predator" (1987) and Wonder Woman in a 1977 animation.

Clockwise from top left, Universal Pictures/Photofest; Christie's, via Associated Press; Murray Close/Warner Brothers Pictures; New Line Cinema; 20th Century Fox/Photofest; Hanna-Barbera Productions/Photofest

http://www.youtube.com/watch?v=JKPVQal851U

Definition

- meta: from Greek word μετα "after/beyond"
  - Example: metaphysics ("beyond nature"): *a branch of philosophy concerned with giving a general and fundamental account of the way the world is.* (Wikipedia)
- metamaterial: material that gains its (electromagnetic) properties from its structure rather than inheriting them directly from the materials it is composed of

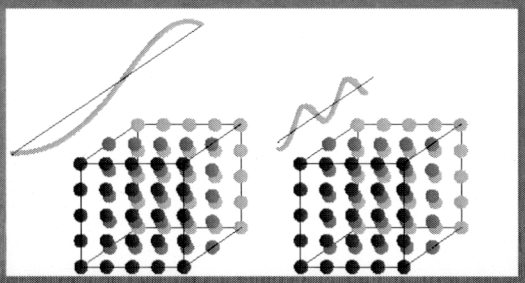
Periodic structure, like in a crystal.

Structure

Material properties are determined by the properties of the sub-units plus their spatial distribution.

For a $<< \lambda$ → effective medium theory

For a $\sim \lambda$ → photonic effects



What about meso-scale materials: bigger than atom but smaller than the wavelength?

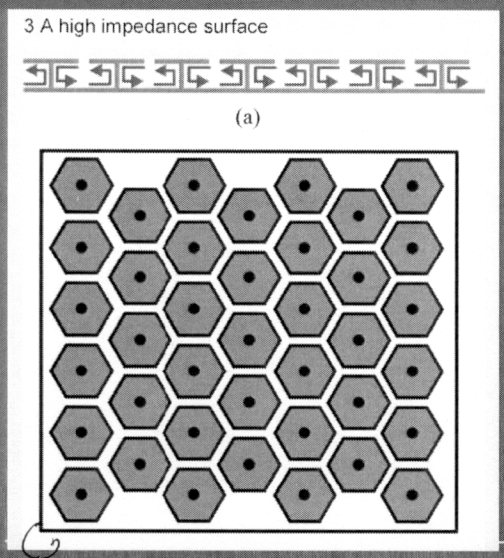
Types

- **Photonic Bandgap (PBG) / Electromagnetic Bandgap (EBG), Frequency Selective Surfaces**
  - 3-D periodic objects that prevent the propagation of the electromagnetic waves in a specified band of frequency for specified angles of arrival and for specified polarization states of EM waves
- **Negative Refraction Index metamaterials**
  - with both negative permittivity and permeability

cross view →

top view →

Example 1: Perfect Magnetic Conductor



Can one make a "perfect magnetic conductor"?

Yes!

Shown is the "High Impedance" (Z=E/H) surface that suppresses magnetic field

Application: low-lying patch antennas that would not work on a conducting substrate.

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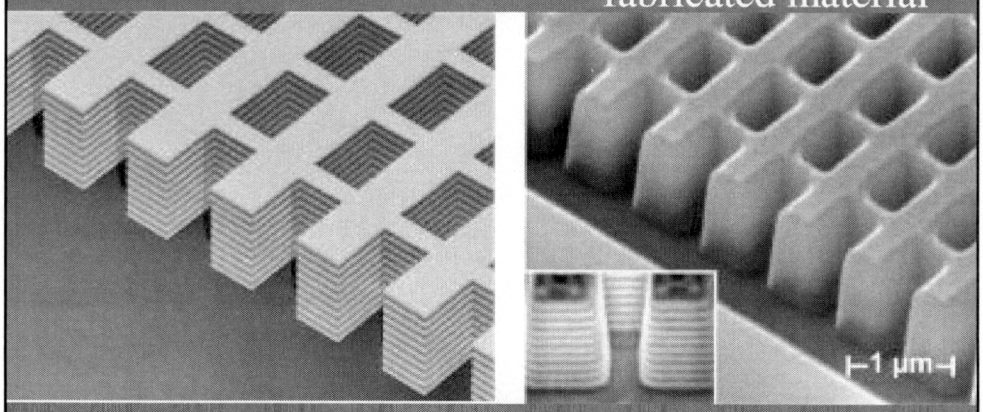
this mimics a magnetic conductor.

you can make this very small → nano technology

Example 2: NRI metamaterial

Model

Image of a nano-fabricated material



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Maxwell's laws

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H}$$

$$\nabla \times \mathbf{H} = j\omega\varepsilon\mathbf{E} + \sigma\mathbf{E} + \mathbf{J}^{f} = j\omega\varepsilon_0(\varepsilon_r + \frac{\sigma}{j\omega\varepsilon_0})\mathbf{E} + \mathbf{J}^{f}$$

6 equations in 6 scalar unknowns

ε = permittivity
σ = conductivity
μ = permeability

} describe *macroscopic* material characteristics

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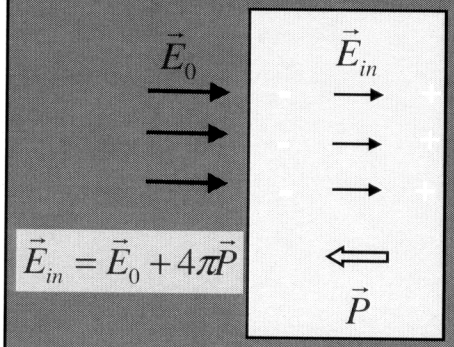
What is permittivity ?



$$\vec{E}_{in} = \vec{E}_0 + 4\pi\vec{P}$$

Incident field polarizes dielectric
→ field inside smaller than outside
→ ratio is permittivity ε

$$\varepsilon = \frac{E_0}{E_{in}}$$

- In most materials ε > 1 (e.g., ε = 12 for Si, ε = 2.25 for glass)
- Permittivity ***depends on frequency***
- Not without exceptions: ε < 0 in metals (visible, IR,…)

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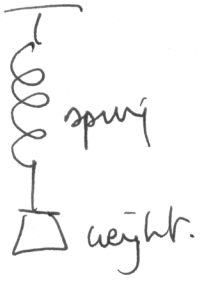
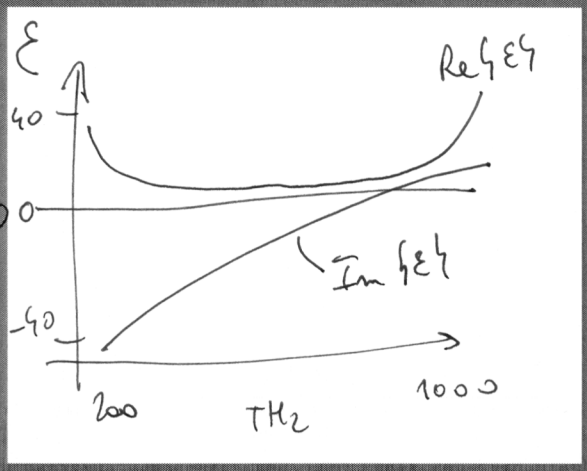
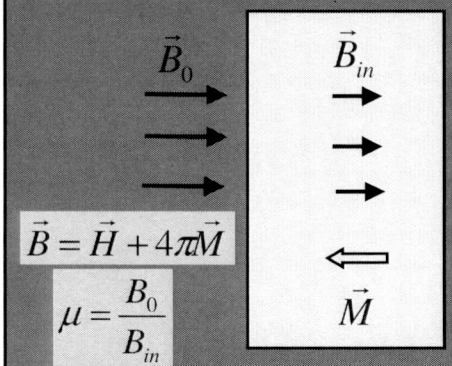


Material properties: Ag



- measured by experimental ellipsometry

What is permeability ?



$$\vec{B} = \vec{H} + 4\pi\vec{M}$$

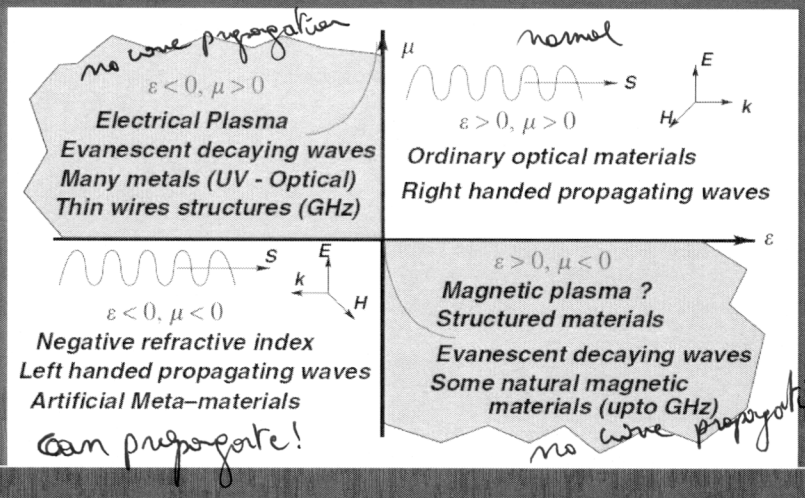
$$\mu = \frac{B_0}{B_{in}}$$

- **Incident field magnetizes material**
- **Complex mechanisms: electron/ nuclear spins**
- **Field inside can be smaller, larger, much larger**

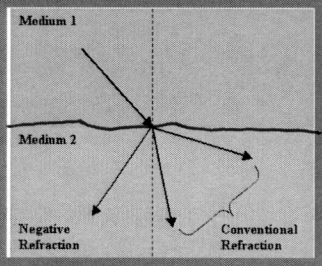
- In most materials $\mu > 0$
- There are exceptions (ferrites), but only at microwave frequencies

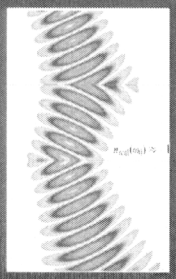
How waves propagate

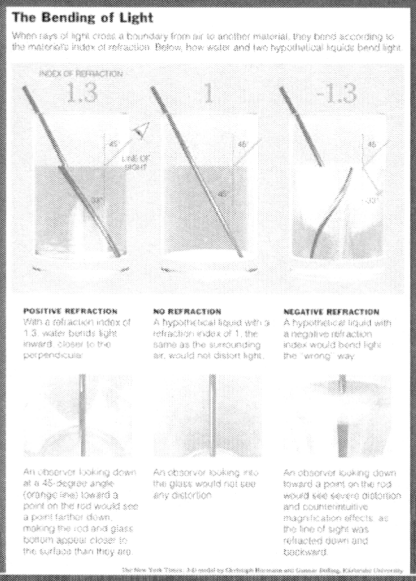
$$\nabla^2\mathbf{E}+k^2\mathbf{E}=0 \qquad k\equiv\omega\sqrt{\varepsilon\mu}=\omega\frac{n}{c}$$



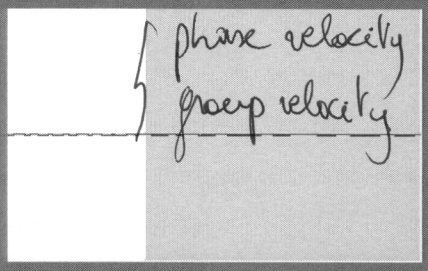
Negative refraction







Positive / negative index interface



Positive Index Medium

Negative Index Medium

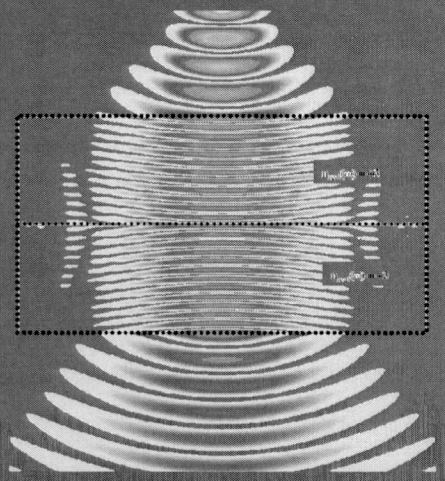
Fundaments

- **This new way of propagation is fundamentally new. It is the basis that opened a lot of speculation about great new mechanisms and devices.**

V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Sov. Phys. Uspekhi*, vol. 10, no. 4, pp. 509–514, 1968. [*Usp. Fiz. Nauk*, vol. 92, pp. 517–526, 1967.]

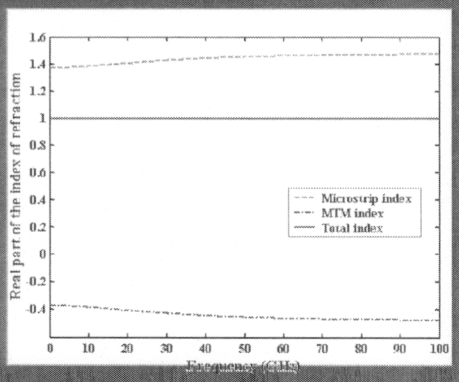
time delay but zero phase delay

Phase Compensation



- Phase difference
  $|n_1|k_0 d_1 - |n_2|k_0 d_2$
- Zero phase difference
  $d_1/d_2 = |n_2|/|n_1|$
- Time-delayed WG with zero phase delay

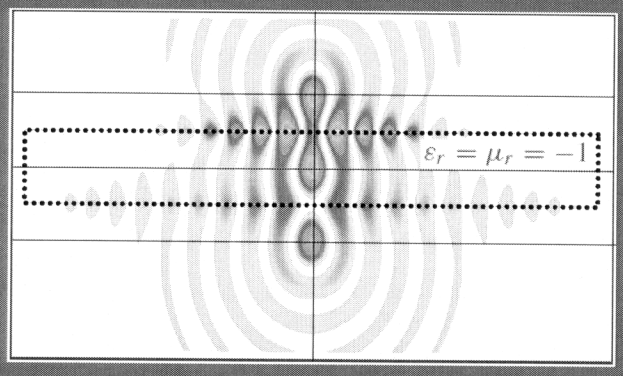
Dispersion Compensation



- Dispersion causes variance of group speed (= signal speed)
- By correcting for the frequency dependence of the effective permittivity

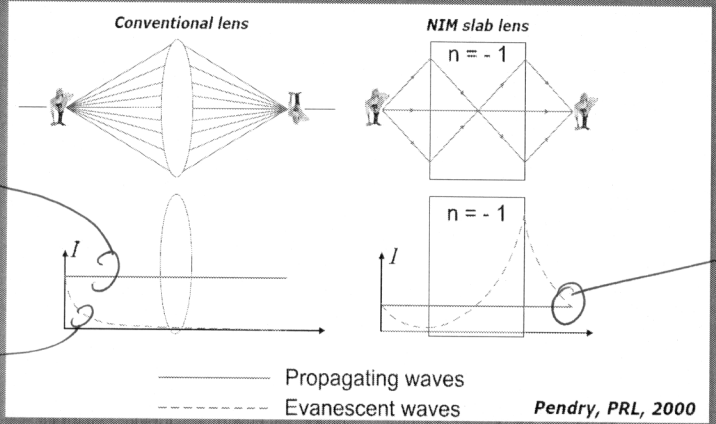


Subwavelength Focusing



- Slab of NRI metamaterial causes two focal points
- Due to exponentially increasing fields in the slab

Theoretical applications … the perfect lens



prop. waves

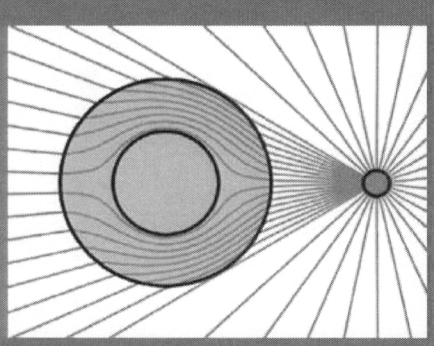
decaying waves are gone!

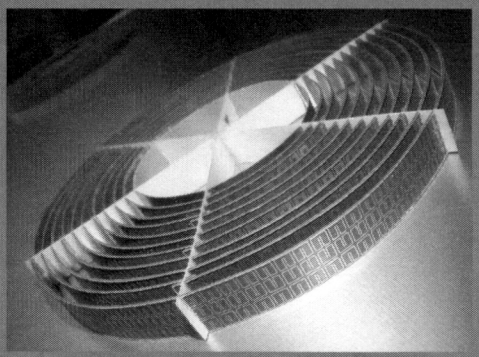
both prop. waves decaying waves are there!

Zero index of refraction

- covering of subwavelength tiny aperture
  - A. Alu et all, "How metamaterials may significantly affect the wave transmission through a sub-wavelength hole in as flat perfectly conducting screen", Workshop on Metamaterials, London, Nov, 24, 2003.

Theoretical applications … cloaking





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- ***Limitations***
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limitation 1: ALWAYS DISPERSIVE

- **NRI Metamaterial ALWAYS dispersive**
  - **Energy density in medium** $W = \frac{\partial(\varepsilon\omega)}{\partial\omega}E^2 + \frac{\partial(\mu\omega)}{\partial\omega}H^2$
  - **thus** $\frac{\partial(\varepsilon\omega)}{\partial\omega} > 0\,;\, \frac{\partial(\mu\omega)}{\partial\omega} > 0$

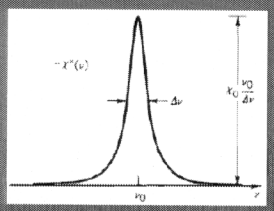
limitation 2: ALWAYS DISSIPATIVE

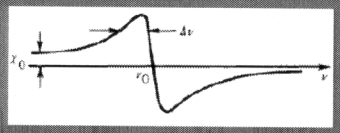
- nr (refractive index) and K (absorption) are interdepedent !

$$n_r(\omega) = 1 + \frac{2\omega}{c\pi} \cdot CPV \cdot \int_0^{+\infty} \frac{K(\omega')}{\omega' - \omega} d\omega'$$

CPV: Cauchy principle value

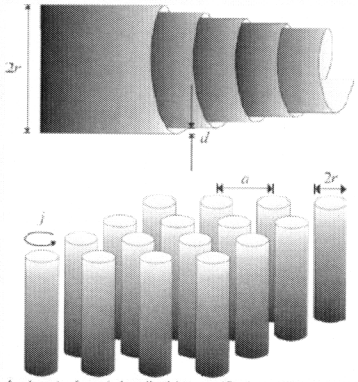
Absorption peak ⟷ Variation of refractive index

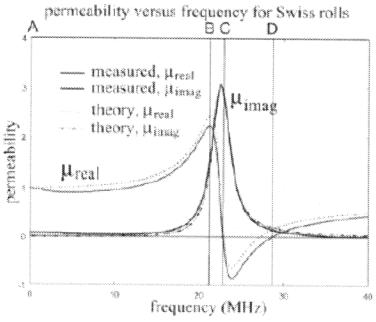




permeability in terms of frequency

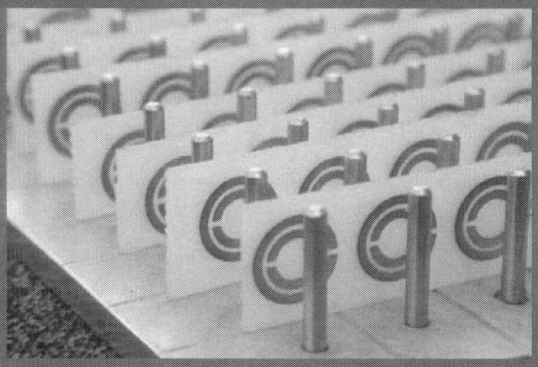
2 Swiss rolls and magnetic materials





A sheet of metal coiled into a 'Swiss roll' responds to a magnetic field with a current. An array of Swiss rolls produces a material which has negative magnetic permeability over a range of frequencies. Improving the dielectrics used can considerably reduce the imaginary part of μ and increase the resonant response.

limitation 3: ALWAYS APPROXIMATIVE



and …

- most results have been obtained *theoretically* only, using analytical and computational tools that start from a continuous material with negative permittivity and permeability
- Ben A. Munk, "Metamaterials: Critique and Alternatives", Wiley, 2009.
  - He is an authority on periodic structures and does NOT believe in NRI metamaterials …

Conclusions

- Metamaterials are here to stay, FSS and EBG materials have proven to work !
- NRI materials have been theoretically investigated a lot. At this moment only few structures have been built really showing a theoretical prediction realized in practice to a sufficient extent

Engineers, Physicists, and Mathematicians

- If an engineer walks into a room and sees a fire in the middle and a bucket of water in the corner, he takes the bucket of water and pours it on the fire and puts it out.
- If a physicist walks into a room and sees a fire in the middle and a bucket of water in the corner, he takes the bucket of water and pours it eloquently around the fire and lets the fire put itself out.
- If a mathematician walks into a room and sees a fire in the middle and a bucket of water in the corner, he convinces himself there is a solution and leaves.

Technische Universität Braunschweig

Philipps Universität Marburg

Concept of THz Technologies

- Seeing the world through T-Ray-Eyes

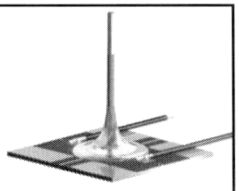


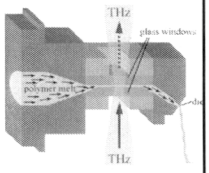
Dipl.-Ing. Christian Jansen, 2010-06-15
Terahertz Systems Group (AG Martin Koch)

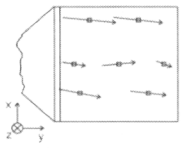
contact: christian.jansen@staff.uni-marburg.de

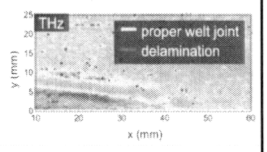
Outline

- THz Systems and Data Extraction
- Seeing the World through T-Ray Eyes
  - Inline Monitoring
  - Plastic Component Testing
    - Revealing Fiber Orientation
    - Determining Water Content
    - Weld Joint Inspection
  - Quality Inspection of Food Products
  - Hydration Monitoring of Plants
- Conclusion









Outline

- **THz Systems and Data Extraction**
  - Seeing the World through T-Ray Eyes
    - Inline Monitoring
    - Plastic Component Testing
      - Revealing Fiber Orientation
      - Determining Water Content
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    - Quality Inspection of Food Products
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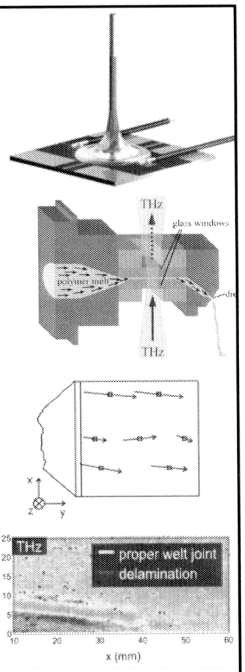
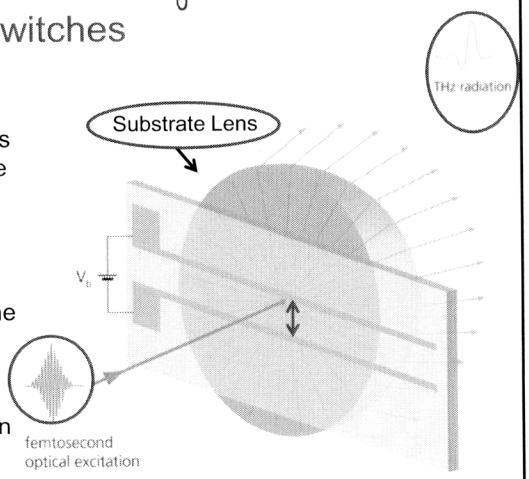


Generation of THz Pulses with Photoconductive Switches

generation

- A femtosecond laser pulse generates carriers in a semiconducting substrate
- The carriers are diverted in an externally applied bias field
- This carrier acceleration results in the emission of a terahertz pulse
- A HR-Si substrate lens suppresses substrate modes due to total reflection and pre-collimates the beam



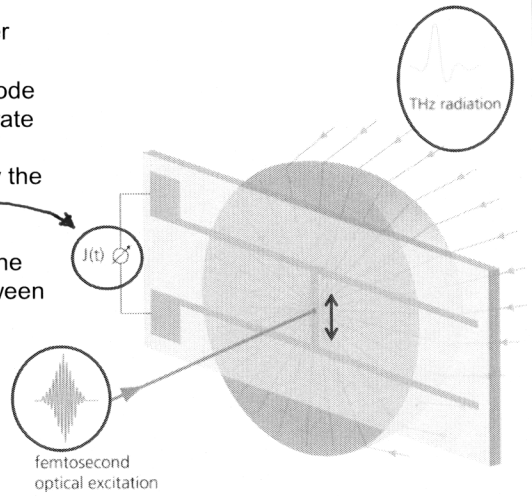
Terahertz Detection with Photoconductive Dipole Antennas

- „Inverse“ principle of the THz emitter

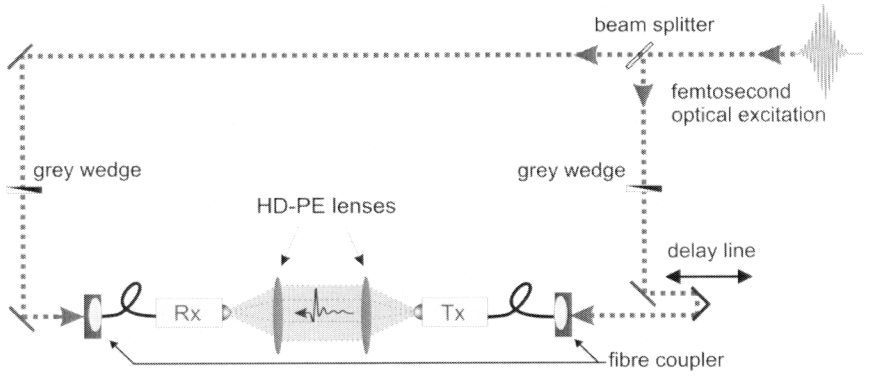
- A fs-Pulse gates a dipole-like electrode structure on a semiconducting substrate

- The free carriers are accelerated by the incoming THz field

- The resulting photocurrent follows the THz amplitude and is measured between the two electrodes



Terahertz Time Domain Spectroscopy Setup



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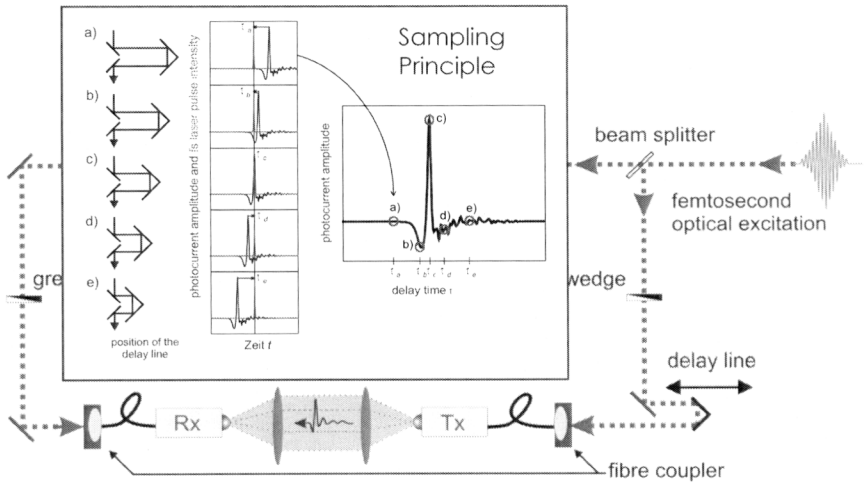
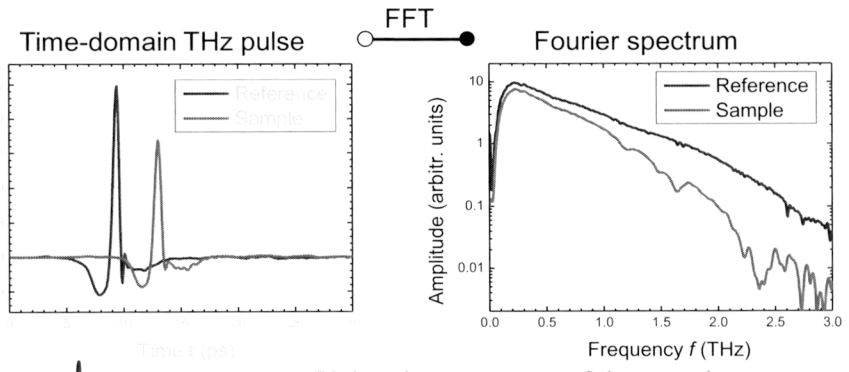
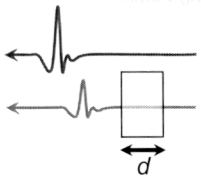


THz Time-domain Spectroscopy





Dielectric parameters of the sample:

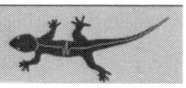
$$\underline{n} = n - i\kappa \qquad \kappa = \alpha \cdot c_0 / 4\pi\lambda$$

Phase ↔ **refractive index *n*(*f*)**

Amplitude ratio ↔ **absorption coefficient *α*(*f*)**

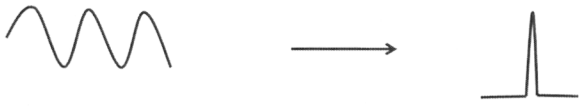
Tera Lyzer www.lytera.com

Taking T-Ray data analysis to the next level!



- a theoretic transfer function is derived: $H_{theory}(f, n, \alpha, d)$
- comparison with the measured transfer function

→ FFT($n(f, \boldsymbol{d})$, $\alpha(f, \boldsymbol{d})$) quasi space



→ minimizing the peak

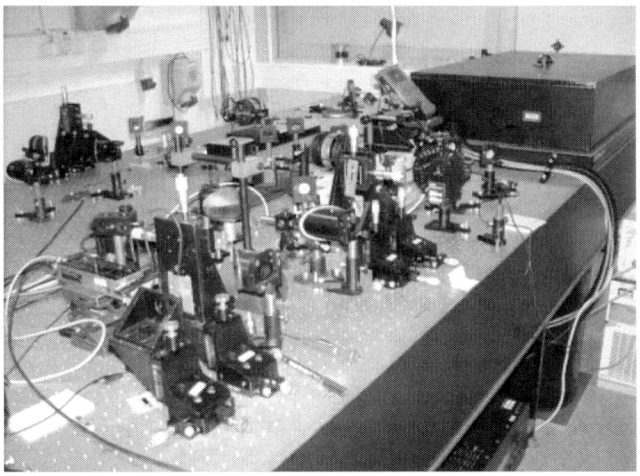


$d_{correct}$, $n(f)$, $\alpha(f)$

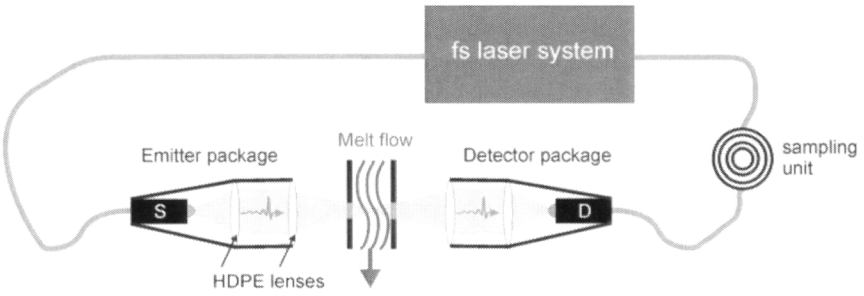
→ analysis of sub-100 µm samples possible

M. Scheller et al., *Optics Commun.* **282**, 1304–1306 (2009).

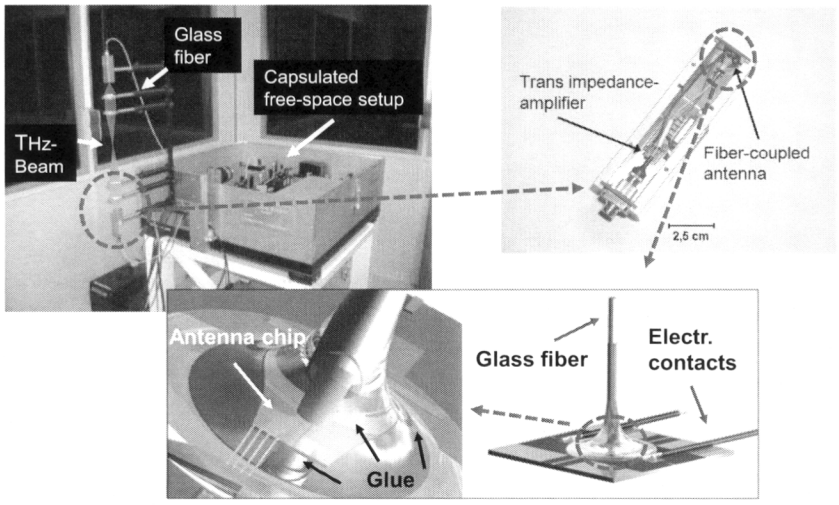
Lab: Free-space THz TDS Setup



Industrial Environment: All-fiber Setup



Industrial Environment: First Fiber-based Setup



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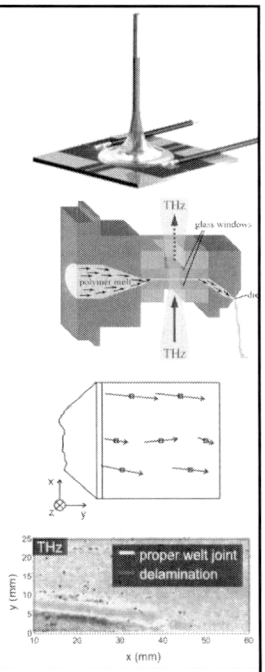
    - Determining Water Content
    - Weld Joint Inspection
  - Quality Inspection of Food Products
  - Hydration Monitoring of Plants
- Conclusion



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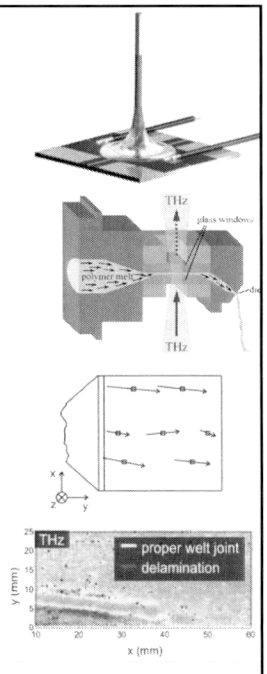
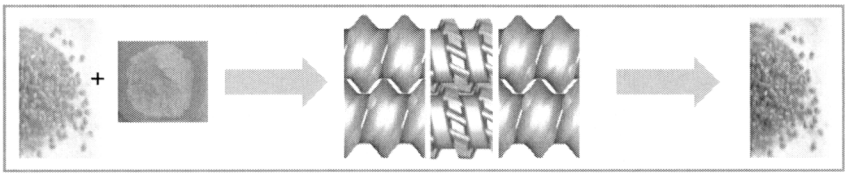


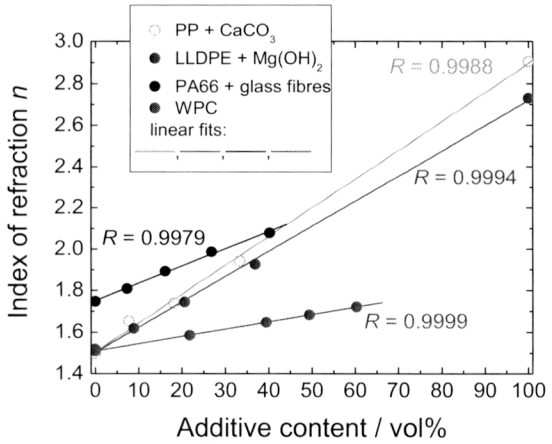
Compounding

polymer + additive(s) = polymeric compound



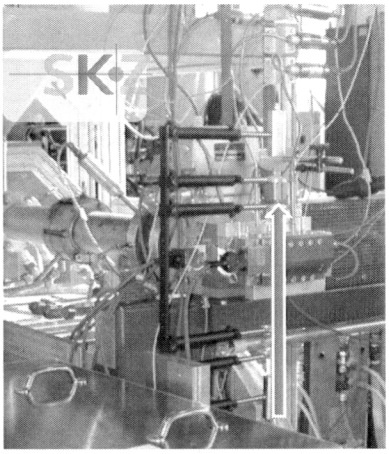
➔ custom-tailored product

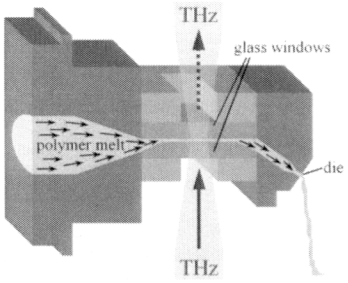
Determination of the Additive Content



M. Scheller et al., *J. Phys. D: Appl. Phys.* **42**, 065415 (2009).

Inline Setup

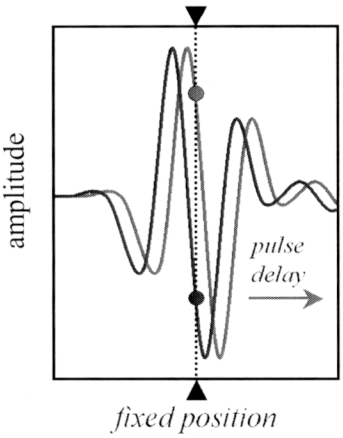


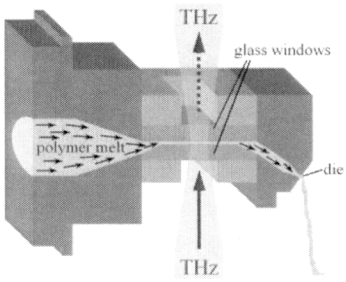


- at the end of the compounding line
- custom-made injector unit

N. Krumbholz et al., *Polymer Testing* **28** (1), 30–35 (2009).

Real-time Inline Measurement





- at the end of the compounding line
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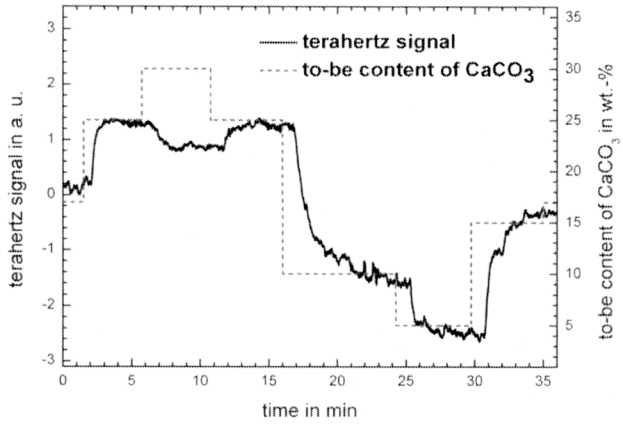
N. Krumbholz et al., *Polymer Testing* **28** (1), 30–35 (2009).

Inline Measurement: $CaCO_3$ Content in PP

filler quantity was varied several times:



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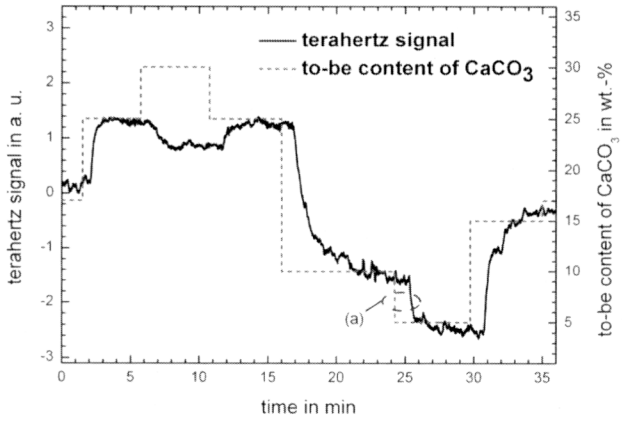

a) Residence time

N. Krumbholz et al., *Polymer Testing* **28** (1), 30–35 (2009).

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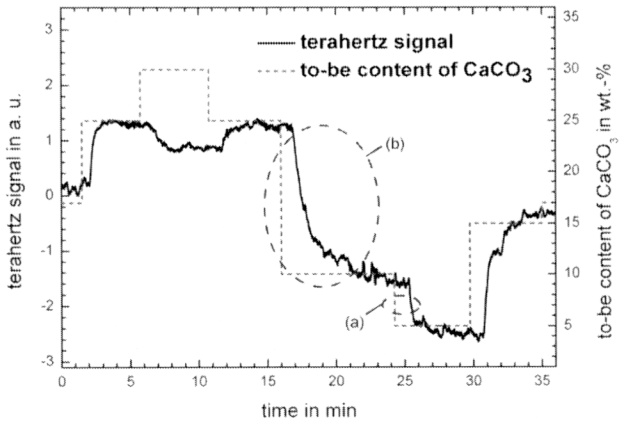
filler quantity was varied several times:



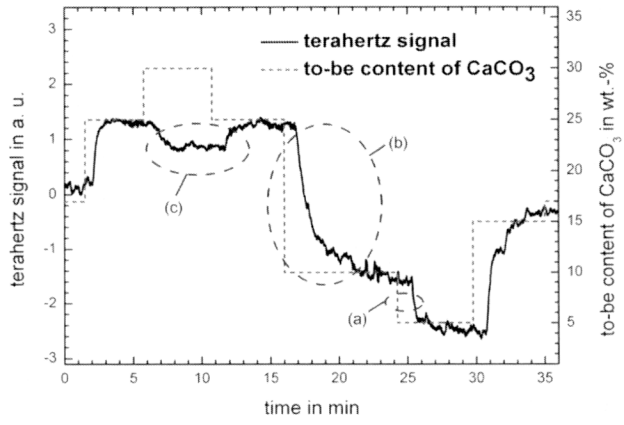
a) Residence time

b) Wash-out time

N. Krumbholz et al., *Polymer Testing* **28** (1), 30–35 (2009).

Inline Measurement: $CaCO_3$ Content in PP

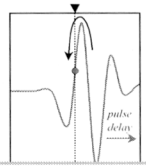
filler quantity was varied several times:



a) Residence time

b) Wash-out time

c) Outside the effective range

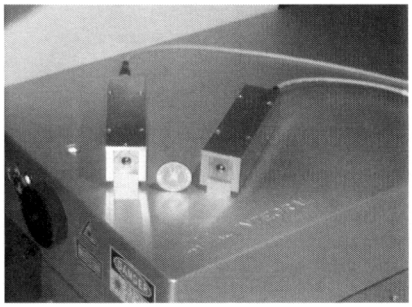


N. Krumbholz et al., *Polymer Testing* **28** (1), 30–35 (2009).

Prizewinning THz System Engineering

AiF Otto von Guericke

Otto von Guericke Award 2009



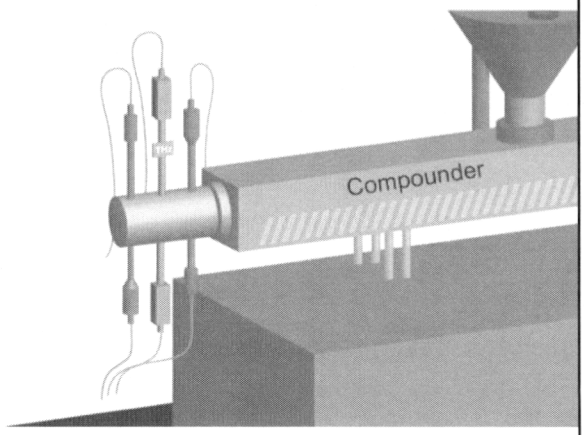


N. Krumbholz

The Vision

The current size of our THz setup is not the lower end of system integration!

➔ all-fiber setup with a THz probe at the end of the extrusion line



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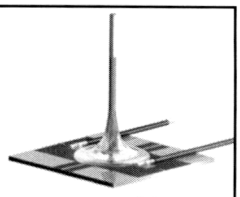

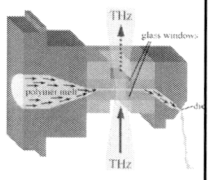

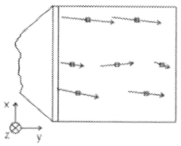

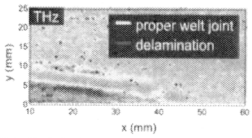

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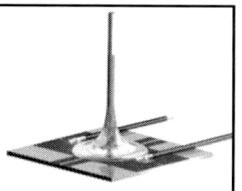
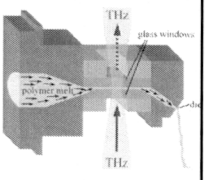
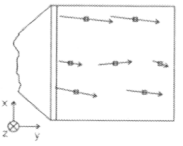
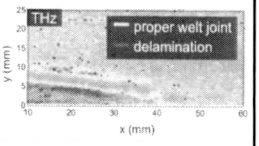
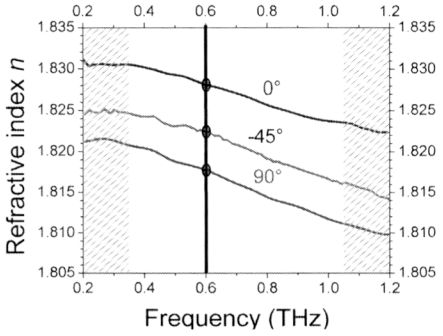


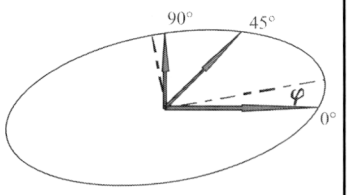


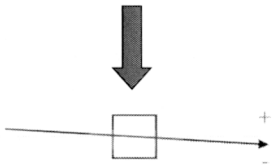




Fiber Orientation Leads to Birefringence





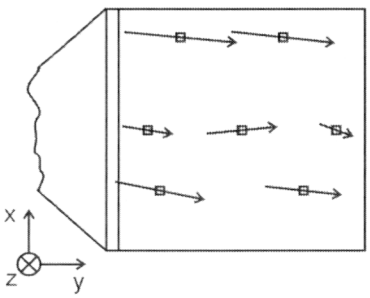


- average fiber orientation (φ)
- degree of orientation (Δn)

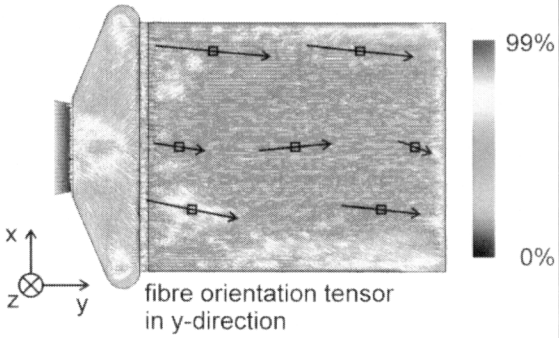
C. Jördens et al., *Compos .Sci. Tech.* **70** (1), 472–477 (2010).

THz TDS Reveals the Fiber Orientation

PA66 (Ultramid A3) reinforced by 30 wt% glass fiber



Moldflow® simulation of the injection moulding process [SKZ]



fibre orientation tensor in y-direction

C. Jördens et al., *Compos .Sci. Tech.* **70** (1), 472–477 (2010).

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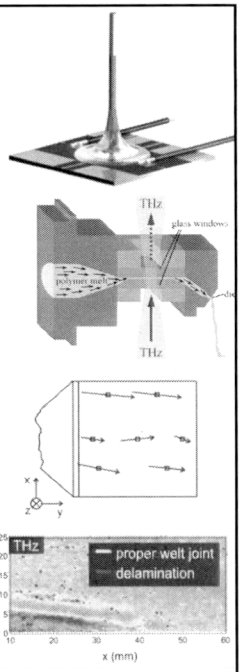
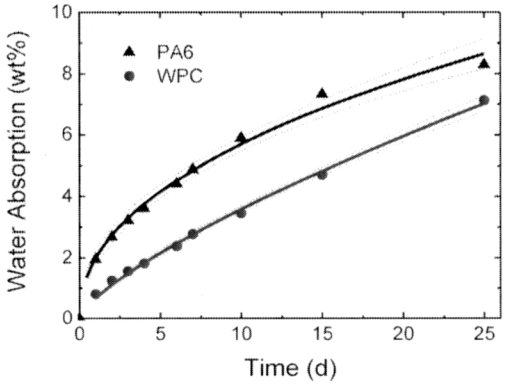


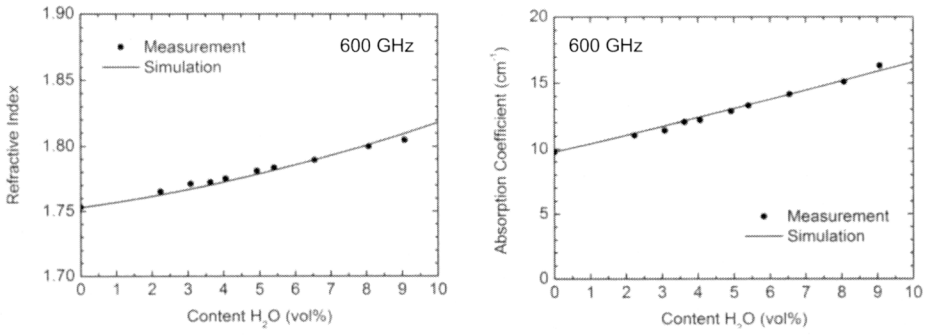
Sample Preparation

PA 6 (Ultramid B3) and a Wood Plastic Composite immersed in destilled water for several days



C. Jördens et al., *Polymer Testing* **29**, 209–215 (2010).

Determining the Water Content in PA6 Sensitively



model: EMT by Landau, Lifshitz, and Looyenga

C. Jördens et al., *Polymer Testing* **29**, 209–215 (2010).

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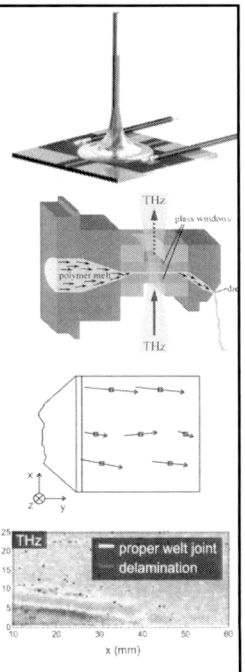
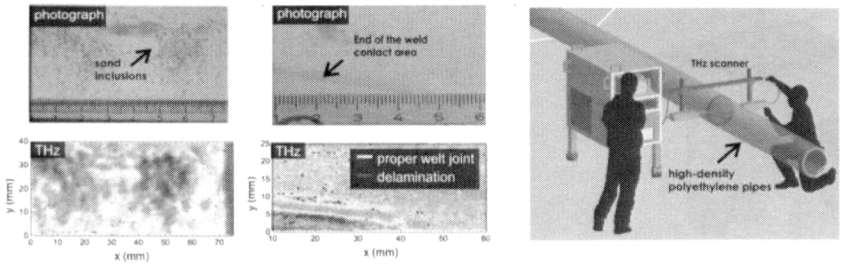
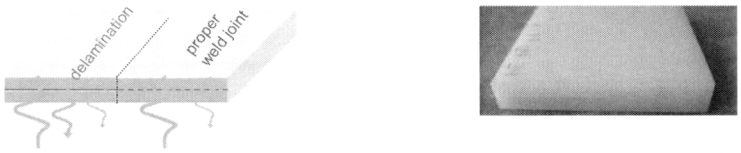


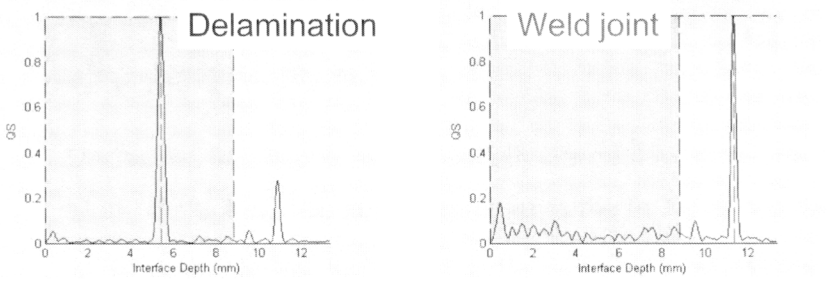
Quality Control of Plastic Weld Joints



- Plastic weld joints are commonly used to permanently connect two polymeric components
- Delamination or inclusion may weaken the joint
- THz-TDS can reliably reveal such defects

Delamination Detection





(Patent Pending DE 10 2010 010 285.7 S. Wietzke, C. Jansen, M. Scheller, M. Koch)