60 GHz Wireless Data Transfer for Tracker Readout Systems - First Studies and Results

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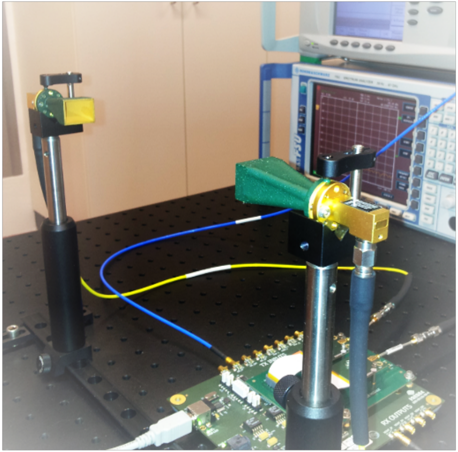
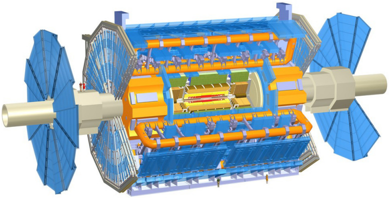
Outline

1. Introduction
2. Quality of data transmission
3. Crosstalk in detectors
4. Conclusion



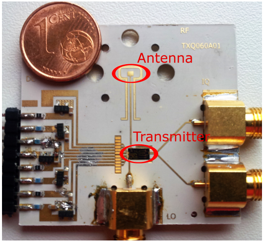
Data readout of particle detectors

- Huge data rates of HEP detectors at frontend, e.g. upgraded ATLAS tracker $\sim$ 100 Tb/s
- Fast readout system with $\sim$ 20 000 links at $\sim$ 5 Gb/s ?
- Approach: wireless data transmission at 60 GHz



Why to use this frequency band?

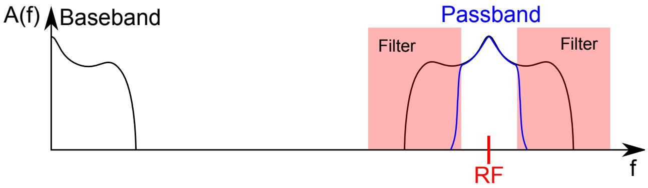
- License-free band 57 - 66 GHz (Europe)
- Large bandwidth $\rightarrow$ data rates of 10's Gb/s
- Wavelength $\lambda \approx 5$ mm $\rightarrow$ small form factor



Gotmic TXQ060A01 development board

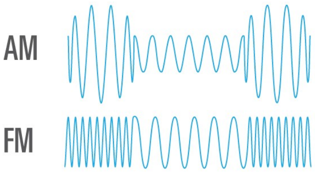
Signal transmission

- **Wired** Baseband data
- **Optical** Modulation of light
- **Wireless** Modulation onto a carrier (60 GHz)
  Filtered frequency range around the carrier: passband



Modulation

- Spectral efficiency (bit/s/Hz) depends on modulation scheme

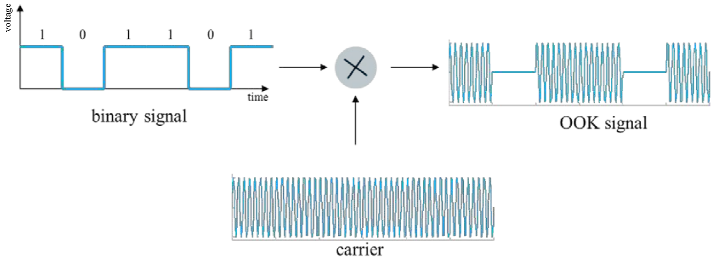


General modulation schemes: analog and digital

AM	Amplitude modulation
FM	Frequency modulation
PM	Phase modulation
ASK	Amplitude shift keying
FSK	Frequency shift keying
PSK	Phase shift keying
QAM	Quadrature amplitude modulation

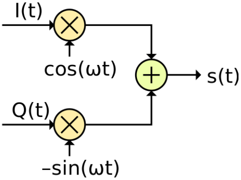
Modulation schemes: On-Off-Keying

- Simple implementation
- Non-coherent demodulation: no Tx phase information required at Rx
- No large baseband circuitry required, little power consumption
- Spectral efficiency $\leq 0.5\,\text{bit/s/Hz}$



Modulation schemes: IQ Modulation

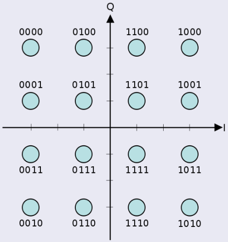
- In-phase and Quadrature components



- Requirements:
  - Higher signal to noise
  - Coherent demodulation
  - ADC baseband circuitry

Example for IQ-modulation

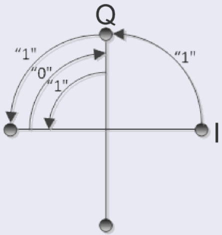
16-Quadrature amplitude modulation (16-QAM, 4 bit/s/Hz)



Modulation schemes: Minimum Shift Keying

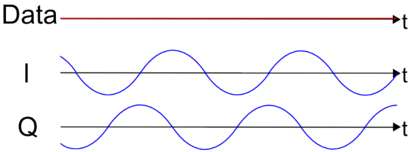
Constellation Diagram: MSK

Continuous Phase Frequency Shift Keying (CPFSK, 1 bit/s/Hz)



Non-coherent demodulation

Data information in phase rotation of baseband I/Q sinusoids



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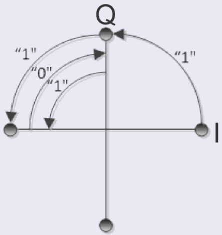

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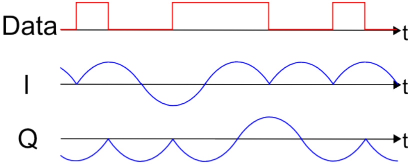


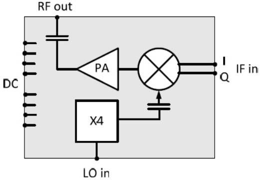
Current 60 GHz transceivers

- Two examples with separate Tx and Rx

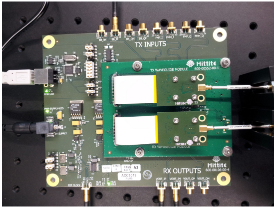
  Gotmic TX/RXQ060A01
  - 8 GHz IF bandwidth
  - IQ-modulator

  Hittite HMC6000/6001
  - 1.8 GHz IF bandwidth
  - IQ-modulator with MSK
  - AM-, FM-detector

- Commercial chips are not designed for harsh detector environment
- Using full bandwidth, we could use a simple modulation scheme



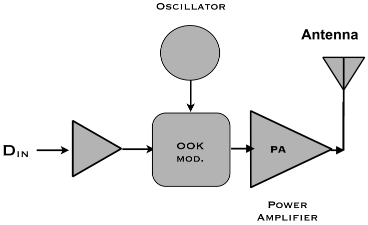
Schematic of Gotmic TXQ060A01



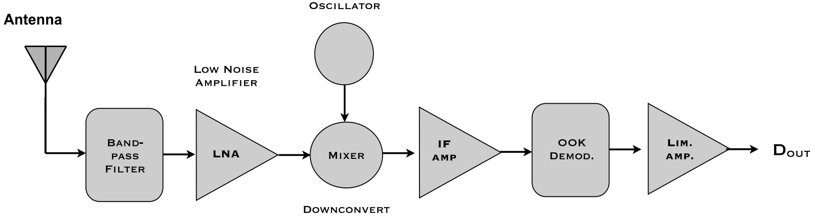
Hittite Transceiver Evaluation Kit

Heidelberg 60 GHz transceiver

- Under development by Hans Kristian Soltveit
- Radiation hard transceiver
- 130 nm SiGe BiCMOS 8HP technology
- Aims at 4.5 Gb/s using 9 GHz bandwidth with OOK
- Power consumption ≈ 0.25 – 0.5 W

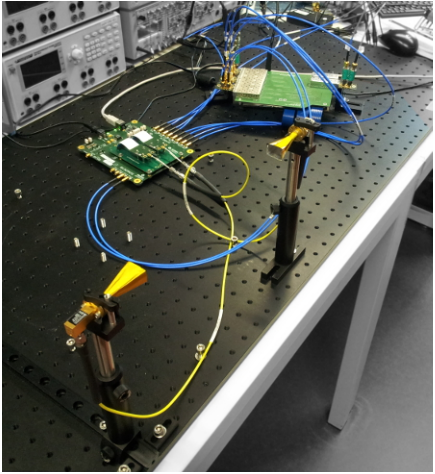


H K Soltveit et al 2012 JINST 7 C12016
doi:10.1088/1748-0221/7/12/C12016
Multi-gigabit wireless data transfer at 60 GHz



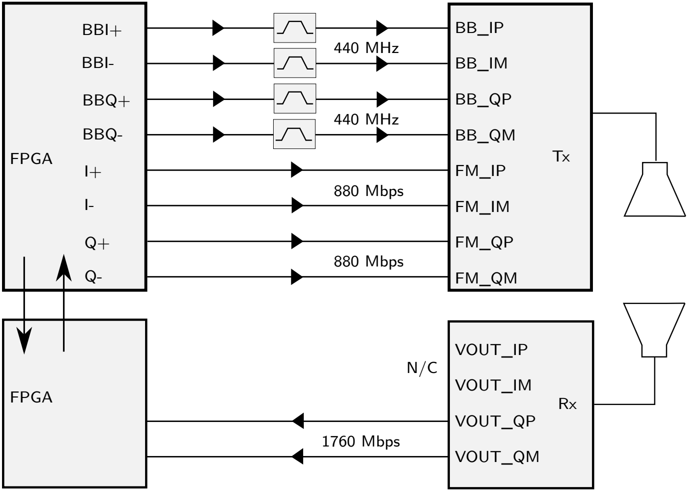
Test bench: bit error rate test using MSK

- For efficient testing: operating setup required
- Test bench built using commercial transceiver by Hittite
- Tx: MSK-modulation
- Rx: internal FM-demodulator
- Implemented with Stratix V GS FPGA

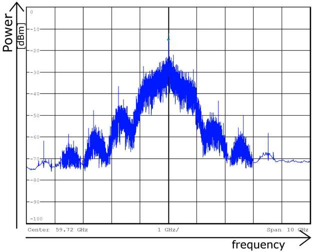


Radio link with Kapton/aluminium horn antennas over a distance of 22 cm

Setup of wireless data transmission



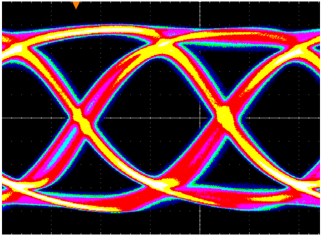
Results with Hittite transceiver

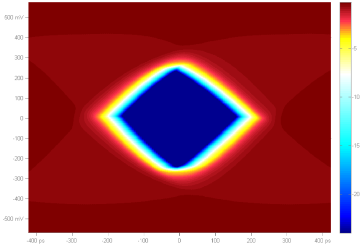


Measured bit error rate

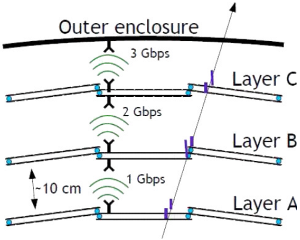
at 1.76 Gbps: $BER < 4.0 \times 10^{-15}$

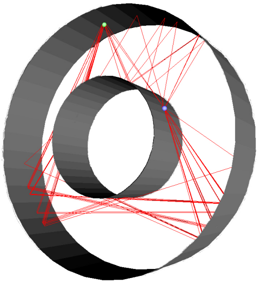
fast and stable data transmission





Crosstalk problem in detectors





Bachelor thesis by Thomas Hugle, Heidelberg 2013

- Possible radial readout direction
- What are the challenges?

Simulations with ray tracer

- Assumption: signal cannot penetrate tracker layer
- Reflections introduce crosstalk
- Absorbing reflections would be a solution

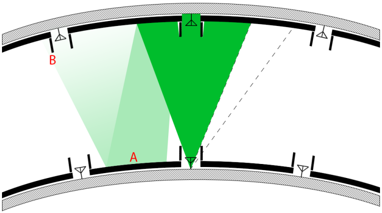
Bachelor thesis by Thomas Hugle, Heidelberg 2013

Approaches to reduce crosstalk

Two types of crosstalk: direct and induced by reflections

How to control crosstalk

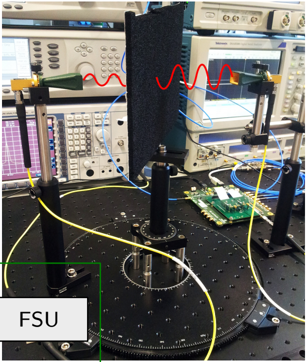
Antennas	with high directivity
Polarisation	of antennas
Channelling	of frequency band
Absorbing	material to reduce reflections

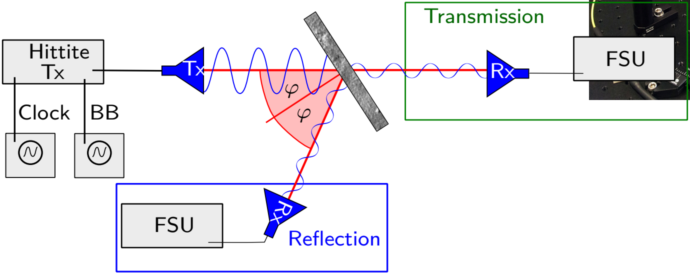


- Low density materials required (multiple scattering)
- Aluminized Kapton foil for antennas
- Graphite foam as absorber (density: $\rho \approx 50 - 74\,\mathrm{kg/m^3}$)

Material studies: setup

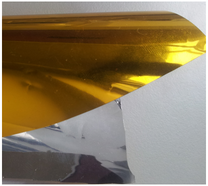
- Characterize reflection and transmission of
  - Common detector materials to estimate crosstalk signal power
  - Graphite foam as a candidate to be used as absorber



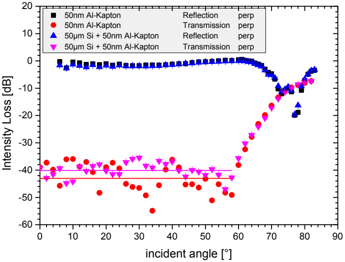


FSU = spectrum analyzer by R&S

Material properties at 60 GHz

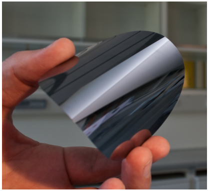


25 μm Kapton foil with 50 nm aluminum

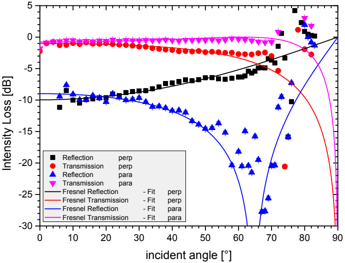


50 nm Al

perfect reflector



50 μm silicon



50 μm Si (unprocessed)

almost transparent

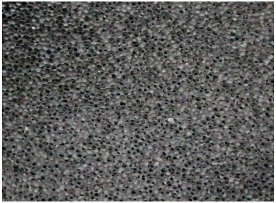
transmitted intensity

reduced by $\approx$ 1 dB

at small angles

Properties of graphite foam

- Under test: four different samples of foam
- Measure reflectivity R and transmittance T
  $\rightarrow$ absorbance $A = 1 - T - R$
- Pores of foam $\ll \lambda \approx 5\,\text{mm}$
  $\rightarrow$ assumption: flat surfaces

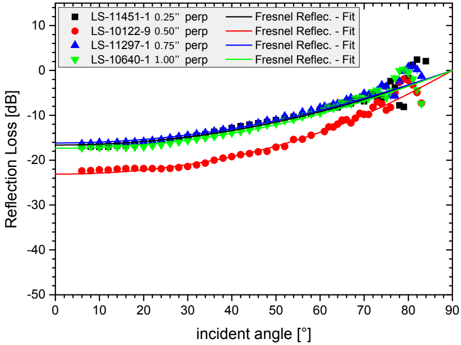


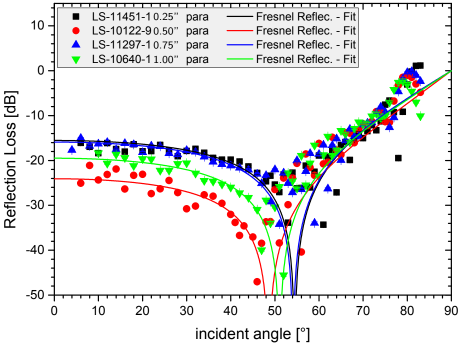
graphite foam sample

Foam	Thickness [mm]	ρ [mg/cm^3]	X_0 [m]	$1\,\text{cm}/X_0$[%]
LS-11451-1	6.35	73.8 ± 0.7	6.06 ± 0.06	0.165 ± 0.002
LS-10122-9	12.70	54.0 ± 1.0	8.29 ± 0.15	0.121 ± 0.002
LS-11297-1	19.05	58.8 ± 0.5	7.61 ± 0.06	0.138 ± 0.001
LS-10640-1	25.40	50.7 ± 0.5	8.83 ± 0.08	0.113 ± 0.001

Reflectivity of graphite foam

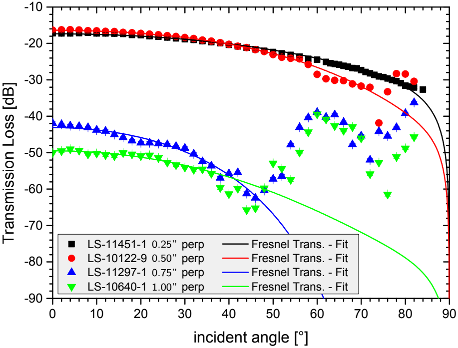
- Reflections are reduced by more than 10 dB up to large incident angles
- These are single reflection measurements
- Crosstalk by multiple reflections can be highly suppressed

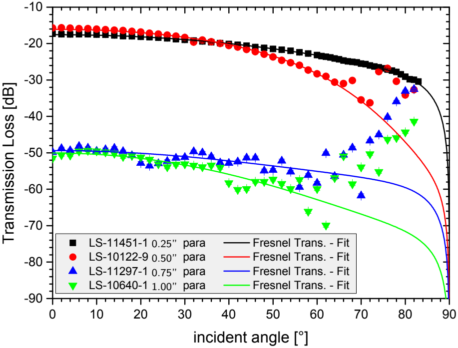




Transmittance of graphite foam

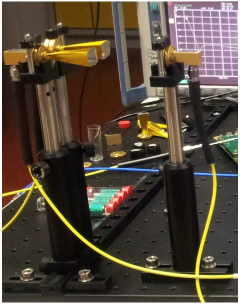
- Insertion loss strongly dependent on thickness
- Samples show large differences
- High absorbance: $A \approx 13 - 27\,\mathrm{dB/cm}$

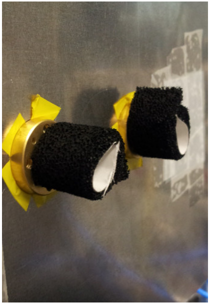


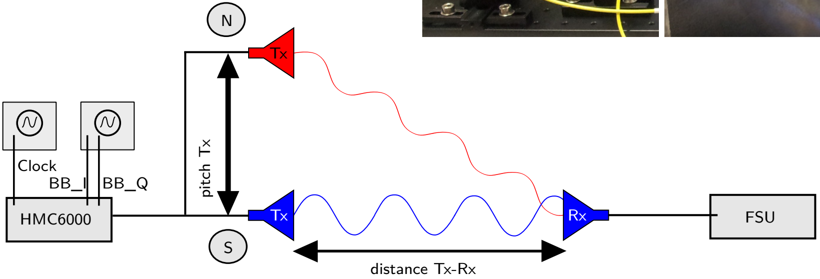


Quantify direct crosstalk - without reflections

- Compare direct transmission to displaced transmitter
- Under test
  - Kapton horn antennas
  - Graphite foam cylinders
- Distance 10 cm

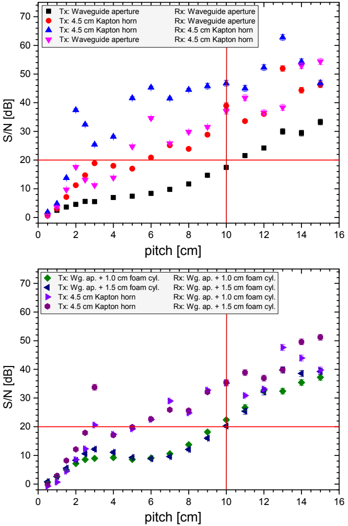






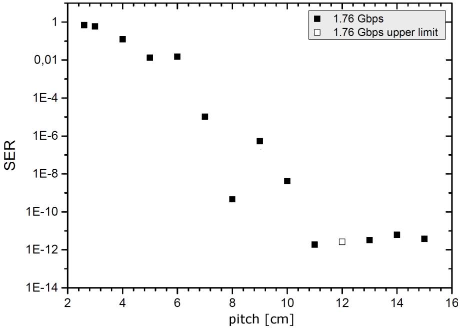
Direct crosstalk suppression

- Requirement: S/N > 20 dB
- Even with low directivity sufficient S/N possible at a pitch of 10 cm
- At larger pitches directive antennas are more efficient
- Graphite foam "antennas" reduce direct crosstalk if links are close



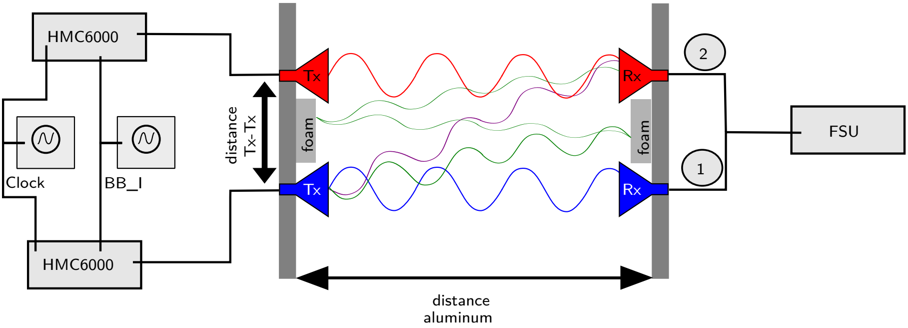
Direct crosstalk suppression: Bit error rates

- 1 cm long hollow graphite foam cylinder shielding
- Links over 10 cm distance
- BER $< 10^{-12}$ for pitch between links > 10 cm



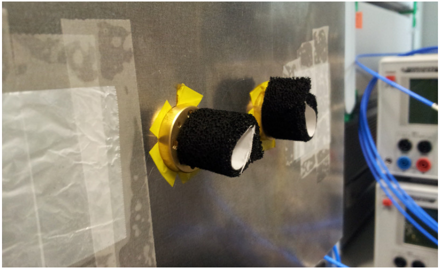
Multi-path crosstalk setup

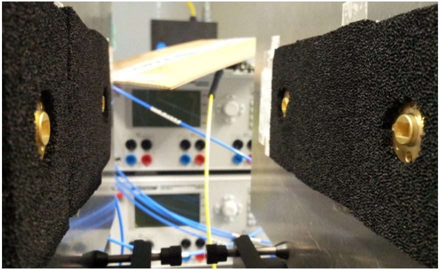
- Study reflections in multi-path setup
- Measured signal to noise in RF
- Different transmitter pitches: 5 cm, 10 cm and 15 cm



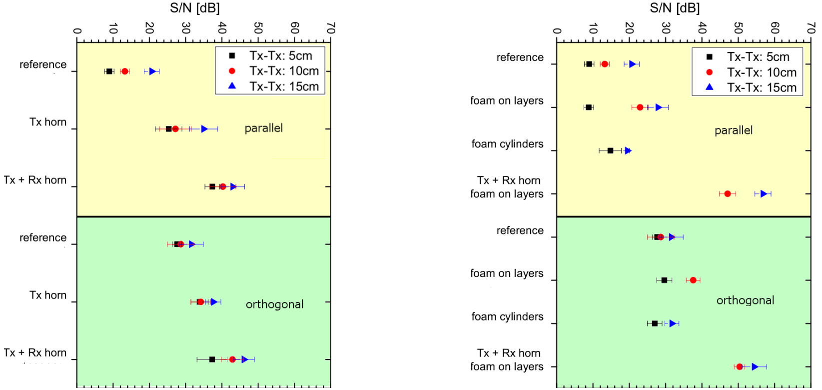
Multi-path crosstalk setup in the lab

- Under test
  - Kapton horn antennas
  - Graphite foam cylinders
  - Graphite foam coating of Al board
- Tested with parallel and orthogonally polarised transmitters





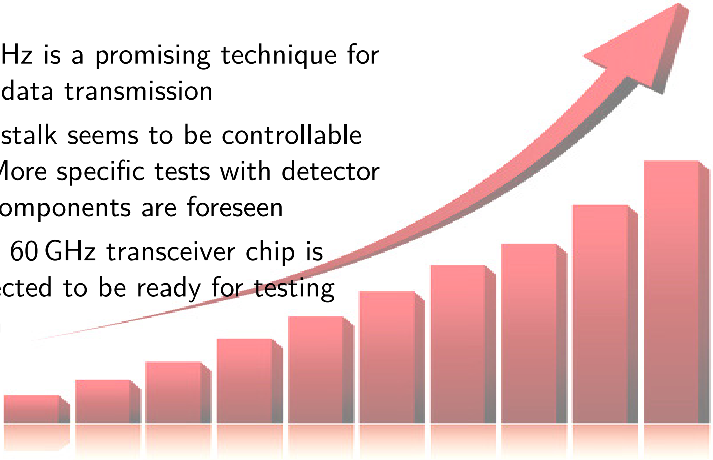
Multi-path signal to noise ratios



- Polarisation has huge effect for close-by links
- High directivity also decreases multi-path crosstalk strongly
- Foam on layers can reduce noise additionally

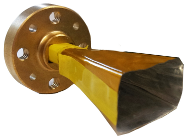
Conclusion

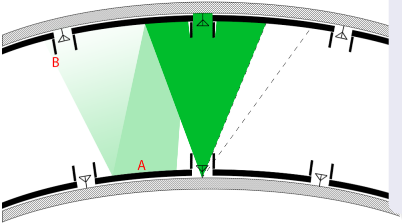
- 60 GHz is a promising technique for fast data transmission
- Crosstalk seems to be controllable
  → More specific tests with detector components are foreseen
- New 60 GHz transceiver chip is expected to be ready for testing soon



Backup

Material budget calculation





Material budget per layer (Tx + Rx)

Assumption: 10 cm between links

- Transceiver (Si):
  $2 \times (5 \times 5)\text{mm}^2 \times 100\,\mu\text{m} \rightarrow 5.35 \times 10^{-4}\,\%\,X_0$
- Foam:
  $2 \times (5 \times 5)\text{cm}^2 \times 1\,\text{cm} \rightarrow 7.15 \times 10^{-2}\,\%\,X_0$
- Kapton:
  $2 \times 15.2\,\text{cm}^2 \times 35\,\mu\text{m} \rightarrow 2.68 \times 10^{-6}\,\%\,X_0$
- Aluminium:
  $2 \times 15.2\,\text{cm}^2 \times 25\,\mu\text{m} \rightarrow 4.44 \times 10^{-6}\,\%\,X_0$

Total: $0.072\,\%\,X_0$ per layer

Wireless signal transmission

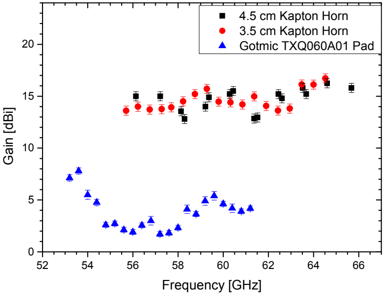
What limits the bandwidth?

- Antennas: gain and efficiency
  - depend on frequency
  - determined by dimensions
- Free space path loss depends on frequency

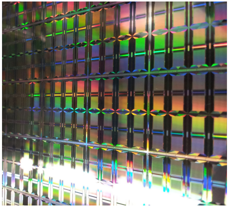
$$FSPL = \left(\frac{4\pi df}{c}\right)^2$$

- Passband defines bandwidth < carrier frequency

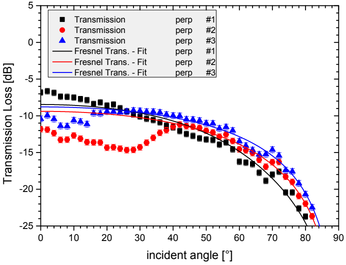
Pad antenna for 60 GHz
size about 1 mm^2

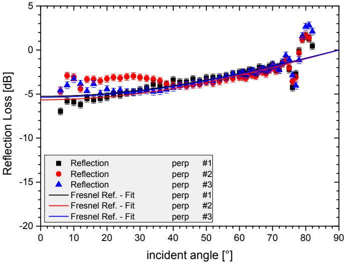


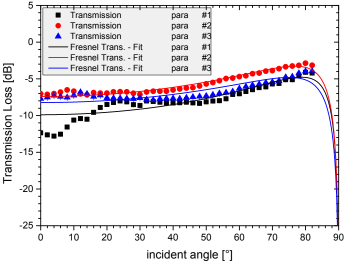
Detector materials' properties at 60 GHz



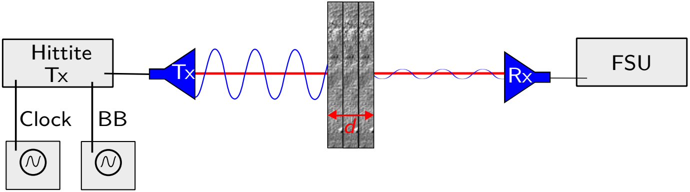
730 µm silicon wafer with test structures





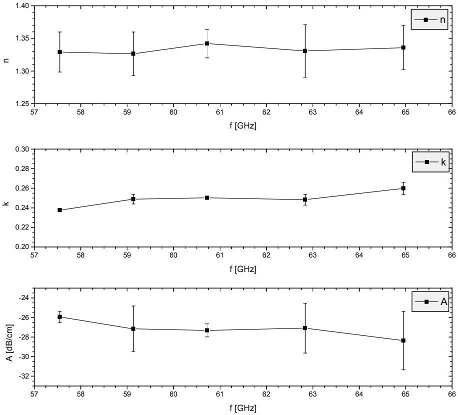


Frequency dependent insertion loss measurement setup

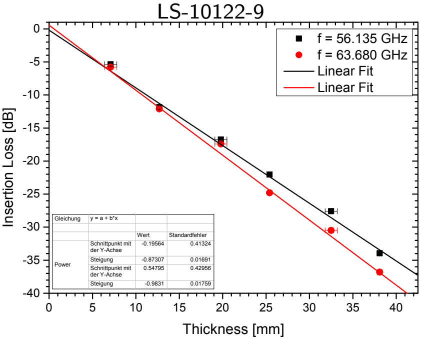


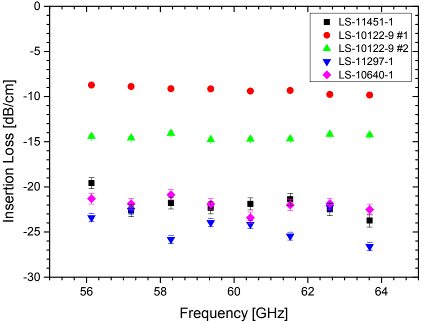
Frequency dependence of graphite foam's properties

- Properties of graphite foam stable in the whole 60 GHz band



Transmission loss of graphite foam at 0 ř incident angle



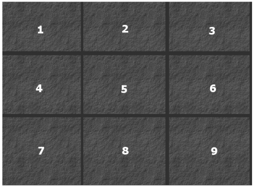


Results

1. Differences between foams
2. Large variations in material LS-10122-9
   $\rightarrow$ in other foams as well?

Inhomogeneity of graphite foam

- $61 \times 61\,\text{cm}^2$ foam pads segmented into 9 pieces
- Compared transmission loss of each piece at $f = 56.134\,\text{GHz}$
- Minimum and maximum peak values



$T :=$ Transmission loss

Material	T_{min} [dB/cm]	T_{max} [dB/cm]
LS-11451-1	-19.6 ± 0.6	-29.2 ± 1.0
LS-10122-9	-8.7 ± 0.2	-17.5 ± 1.0
LS-11297-1	-23.4 ± 0.4	-28.7 ± 1.0
LS-10640-1	-20.0 ± 1.0	-24.7 ± 1.0

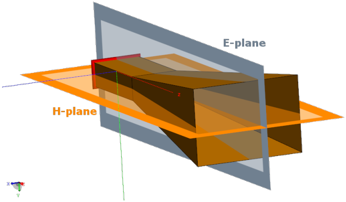
$\Rightarrow$ 5 - 10 dB variations in all foams!

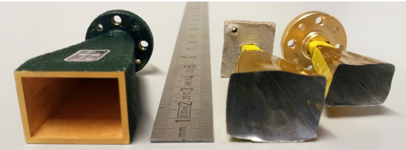
Characterisation of antennas

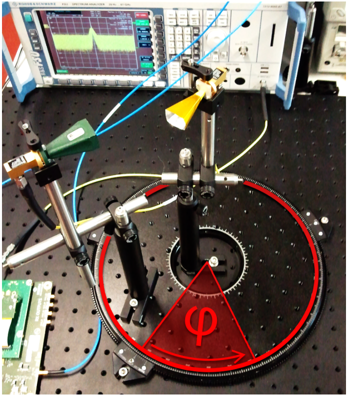
Goal

Reduce crosstalk: high directivity, little material
→ Horn antennas made from aluminized Kapton foil

- Characteristics:
    - Polar pattern
    - Gain [dBi]
    - 3dB-beamwidth [°]
    - Polarisation

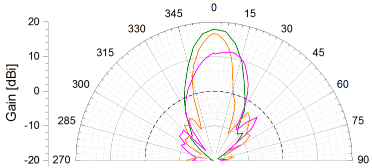






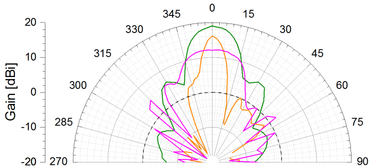
Comparison of directivity

Polar patterns



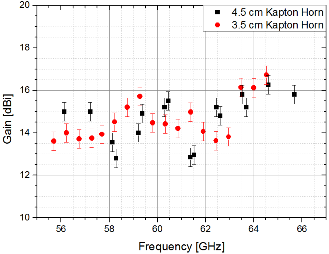
H-plane

Standard Gain Horn	61.00 GHz
4.5cm Kapton Horn	61.37 GHz
3.5cm Kapton Horn	60.85 GHz

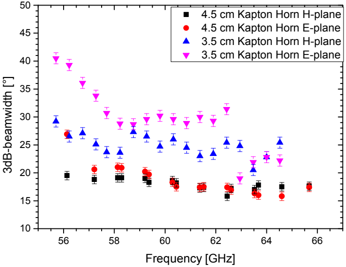


E-plane

Gain



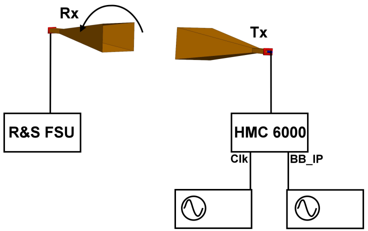
Beamwidth

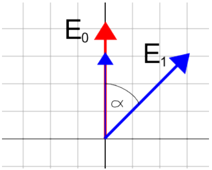


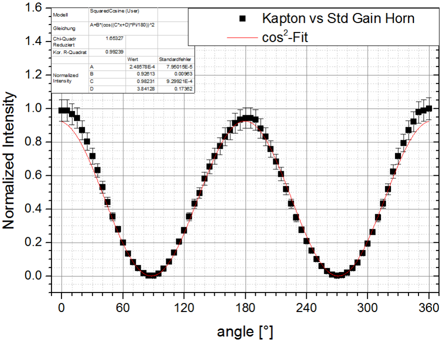
Linear polarised waves: Measurements

Use polarisation to place transceivers in closer proximity to each other

Rotating Rx antenna





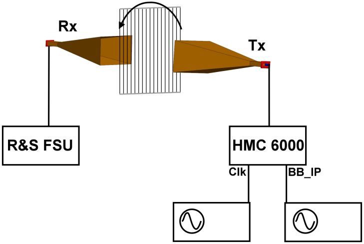


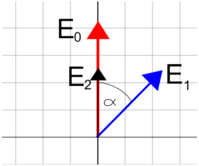
- Suppression of orthogonal polarisation component ≈ 30 dB by rotating Kapton antenna

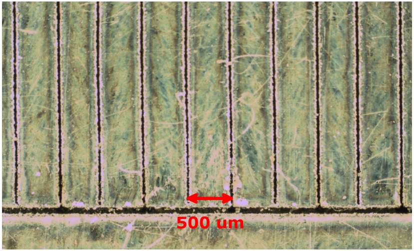
Linear polarised waves: Measurements

Use polarisation to place transceivers in closer proximity to each other

Rotating polarising filter





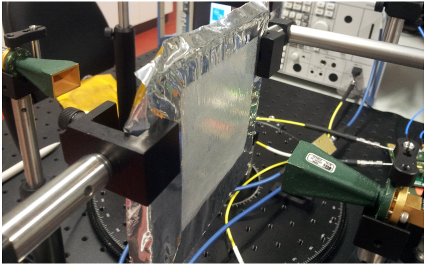


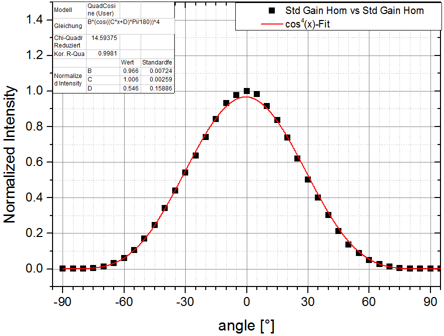
- Wire grid polariser:
  500 μm pitch, 450 μm width
  Al strips on kapton foil
- Stips have been cut out using laser

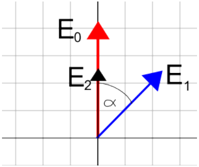
Linear polarised waves: Measurements

Use polarisation to place transceivers in closer proximity to each other

Rotating polarising filter



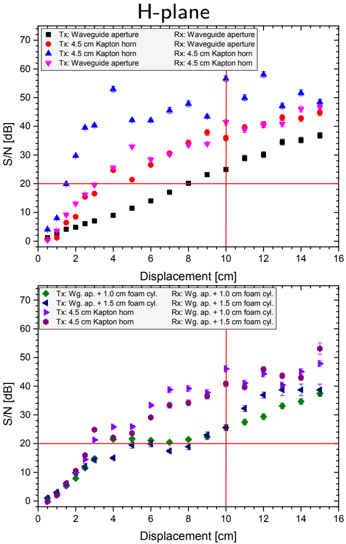




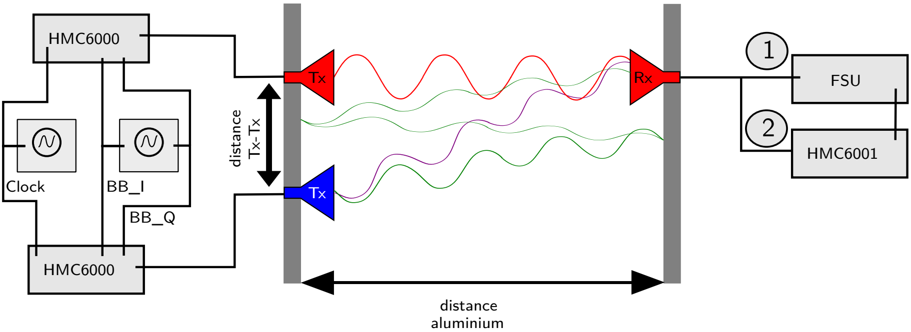
- Wire grid polariser: 500 μm pitch, 450 μm width Al strips on kapton foil
- Stips have been cut out using laser

Direct crosstalk suppression

- Signal is more focused in H-plane
- Even with low directivity we can reach a sufficient signal to noise
- Graphite foam reduces direct crosstalk in close vicinity of the link
- At larger displacement directive antennas are more efficient

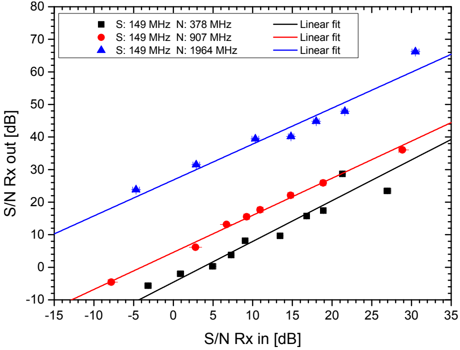


Compare S/N Receiver input and output

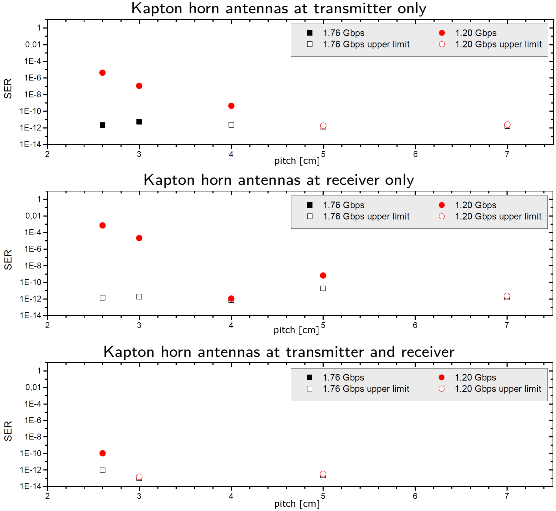


Compare S/N Receiver input and output

- Linear dependence
- Bandwidth affects the offset between S/N output to input

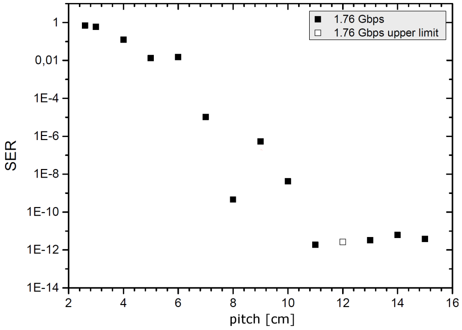


Crosstalk: 2 links with horn antennas



Crosstalk

Cylindrical foam shielding (1 cm)



Channeling : 2 links in immediate vicinity ($pitch < 3$ cm)