Simulation of a Feedback System for Coupled Gyro-Devices at 263 GHz

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M. Thumm and J. Jelonnek

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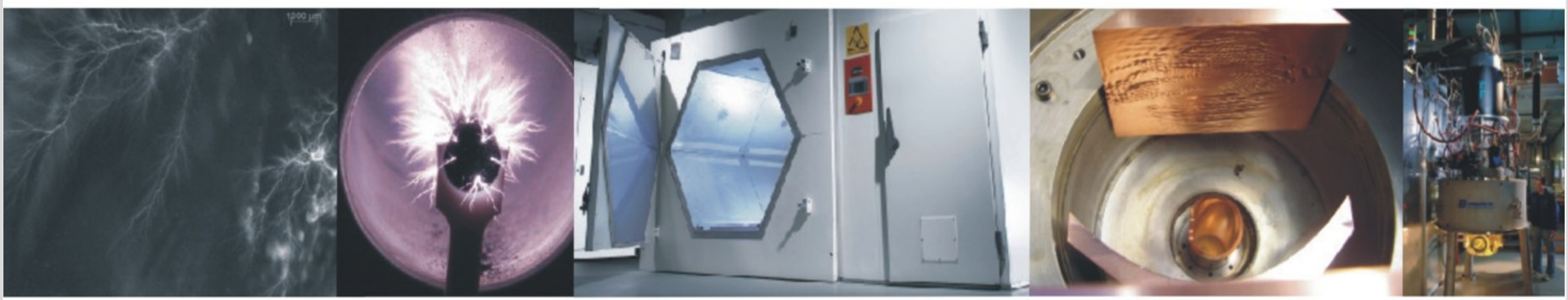
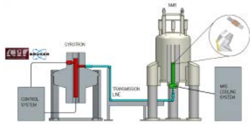
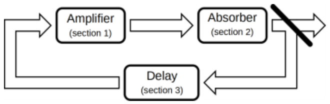


Structure

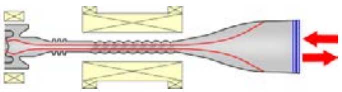
1. Requirement of new sub-THz sources



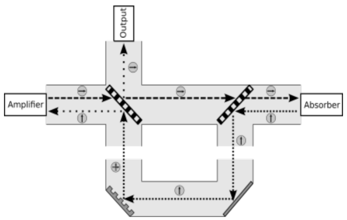
2. Pulse Generation in a Feedback Loop



3. Helical Gyro-TWT as Amplifier and Absorber



4. Feedback System
   - Alternative Designs
   - Design of an Optimized Quasi-Optical System



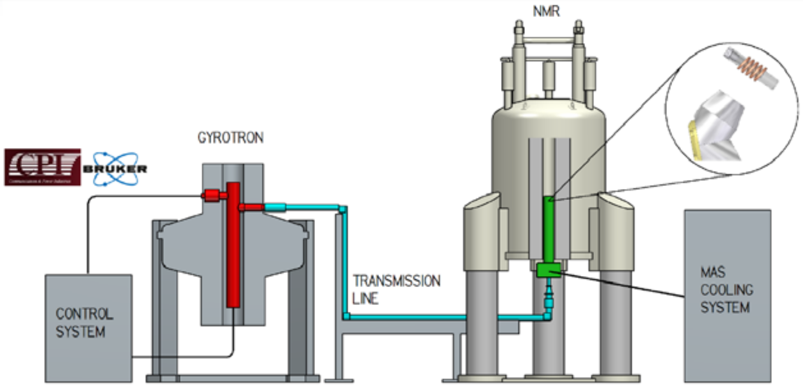
5. Conclusion

Institute for Pulsed Power and Microwave Technology

Motivation

- State of the art: Continuous-wave DNP-NMR (Dynamic nuclear polarization - Nuclear Magnetic Resonance)
  - Transfer of electron spin polarization to nuclear spin systems
  - Via: microwave irradiation at ≈ the electron Larmor frequency
  - Typical frequencies: 263, 395, 527 and 593 GHz
- **Future: pulsed DNP methods**
  - Rapid and efficient polarization transfer
  - Not attenuated at high magnetic fields
  - Powerful, coherent pulses required

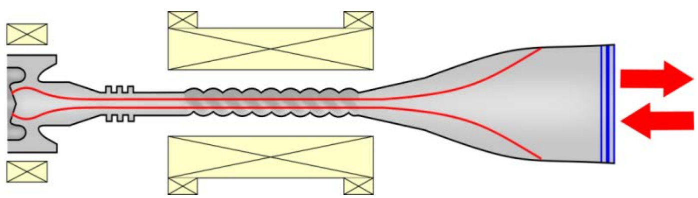
→ New source for coherent high power microwave pulses



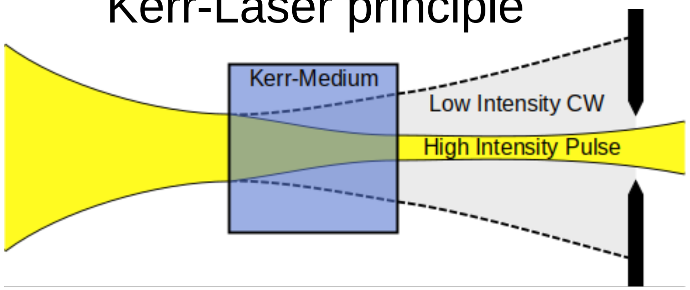
Generation of Ultra-Short Microwave Pulses

Idea [1]: Combine the electron-vacuum-tube technology with ideas from laser physics

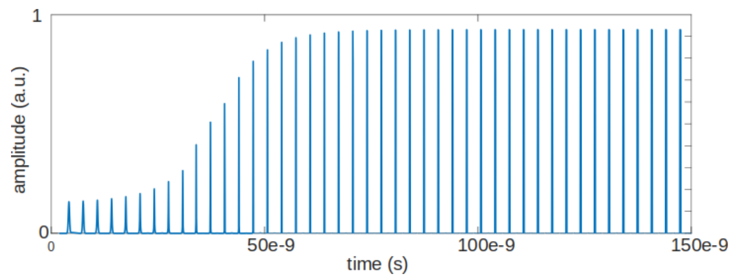
Gyro-TWT technology



Kerr-Laser principle



New pulsed source of coherent µW pulses



[1] Ginzburg et. al. *Technical Physics Letters* 2015

Institute for Pulsed Power and Microwave Technology

Generation of Ultra-Short Microwave Pulses

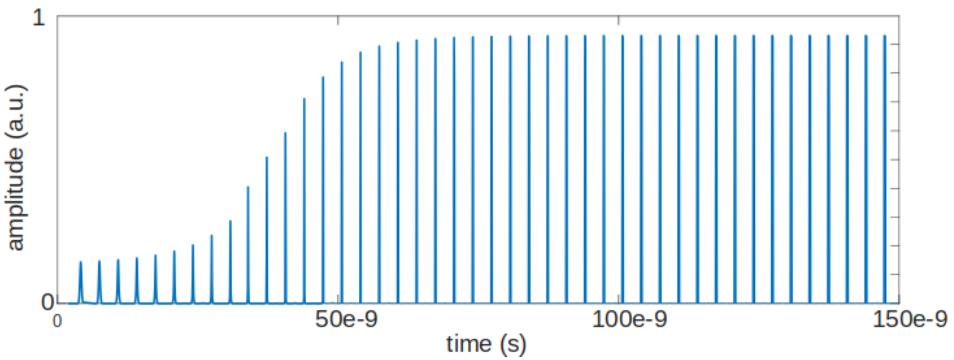
Karlsruhe Institute of Technology

Generation of Ultrashort Pulses in Millimeter and Submillimeter Bands for Spectroscopy and Diagnostic of Various Media Based on Passive Mode-locking in Electronic Devices

- **Joined RSF-DFG Project (IAP-RAS and KIT-IHM):**
- Generation of periodic ultra-short pulses with **vacuum-electron-tubes**
- Target frequency: **263 GHz** → 400 MHz DNP-NMR
- First prove of concept: **34 GHz** → Experiment under preparation at IAP

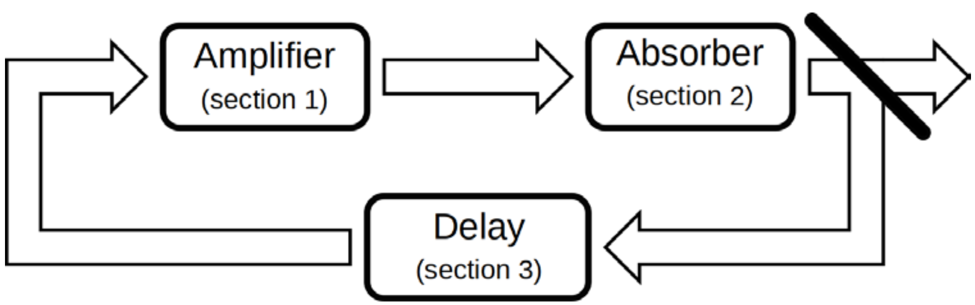
- For 34 GHz:
  - Pulse-width: 0.25 ns
  - Pulse-distance: 5.0 ns
  - Peak-Power: 300 kW

Train of ultra-short coherent pulses



[1] Ginzburg et. al. *Technical Physics Letters* 2015
[2] Ginzburg et. al. *Phys. Plasmas 24* 2017

PULSE GENERATION IN A FEEDBACK LOOP



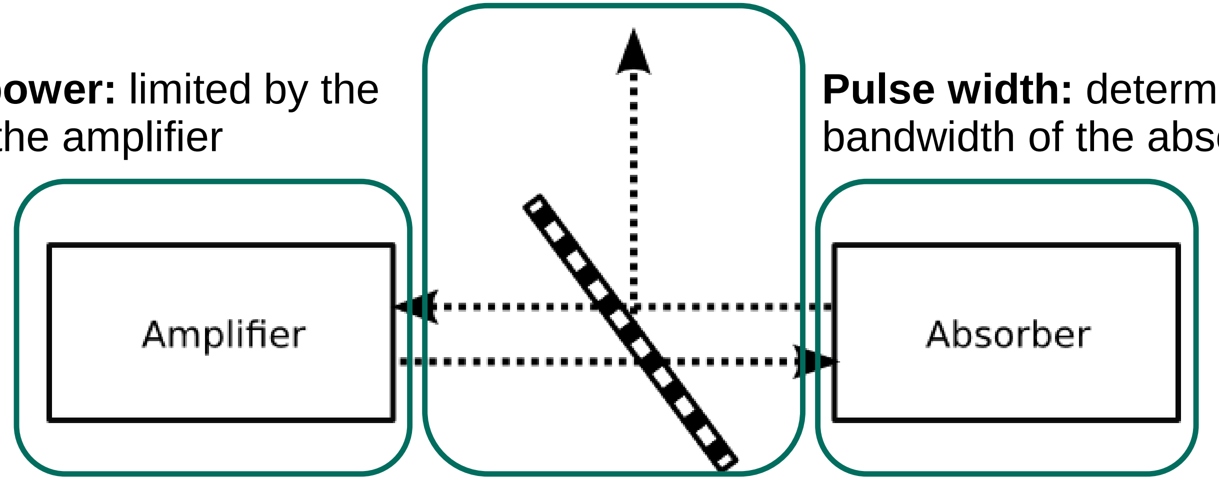
Pulse Generation in a Feedback Loop

- Method of **passive mode locking** (as in laser physics)
- Feedback loop of **amplifier** and **saturable absorber**
  - Amplifier: high amplification of ultra short pulses
  - Saturable absorber: absorption of low power signals, transmission of high power signals

Pulse distance: determined by the time for passing through the feedback loop

Pulse power: limited by the gain of the amplifier

Pulse width: determined by the bandwidth of the absorber



Institute for Pulsed Power and Microwave Technology

Pulse Generation in a Feedback Loop

- Method of **passive mode locking** (as in laser physics)
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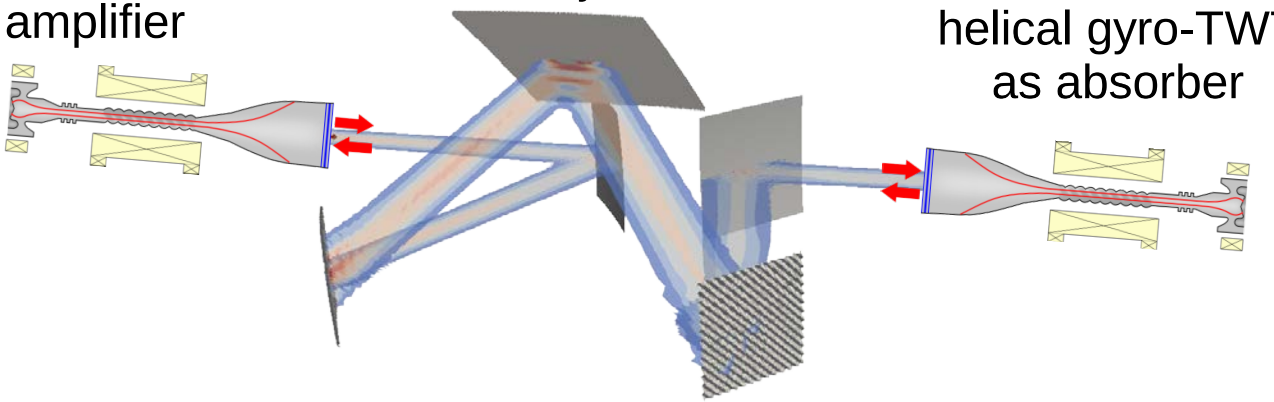
How to realize this “µW laser”?

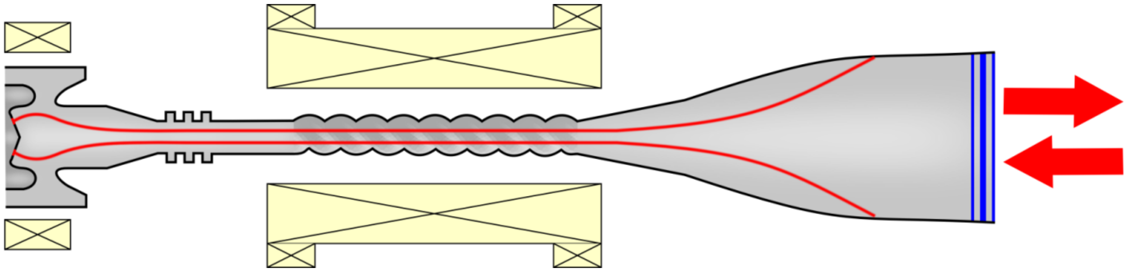
coupled with a
quasi-optical transmission
system

helical gyro-TWT as
amplifier

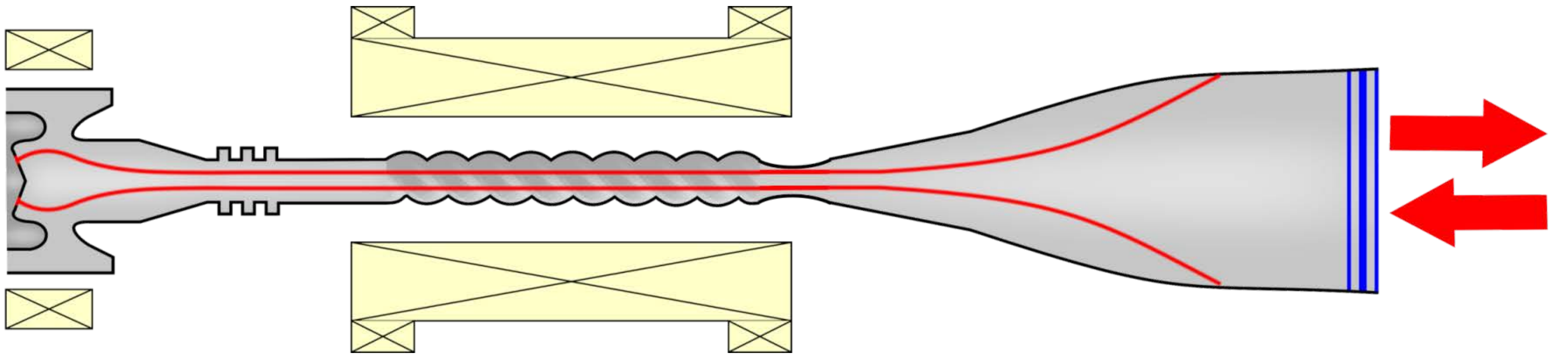
helical gyro-TWT
as absorber



HELICAL GYRO-TWT



Gyro-TWT with helically corrugations



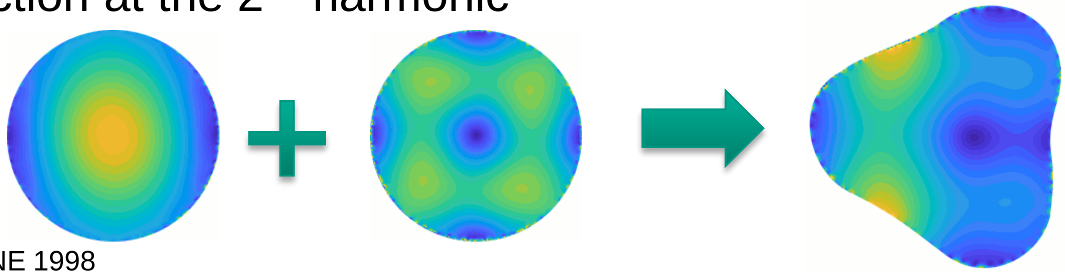
- Gyro-TWT with helical corrugated interaction region [1]

$$r = r_0 + h_0 \cos(m_B\varphi - 2\pi z/d)$$

- Corrugation couples modes which fulfill:

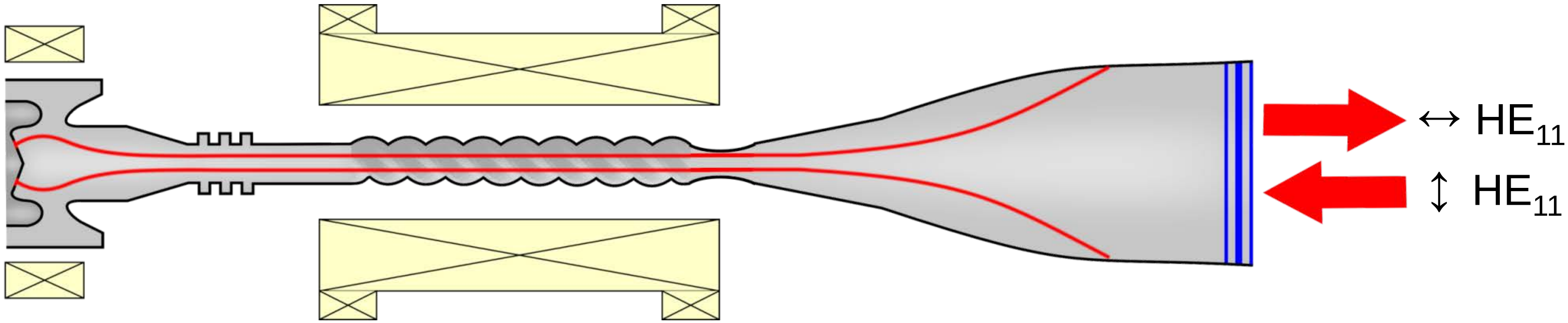
$$m_1 - m_2 = m_B \quad \text{and} \quad h_1 - h_2 = 2\pi/d$$

- $m_B = 3 \rightarrow$ coupling of $TE_{2,1}$ and counter-rotating $TE_{-1,1}$ mode to $TE_{2,1}$ like eigenmode
- Gyro-interaction at the 2nd harmonic

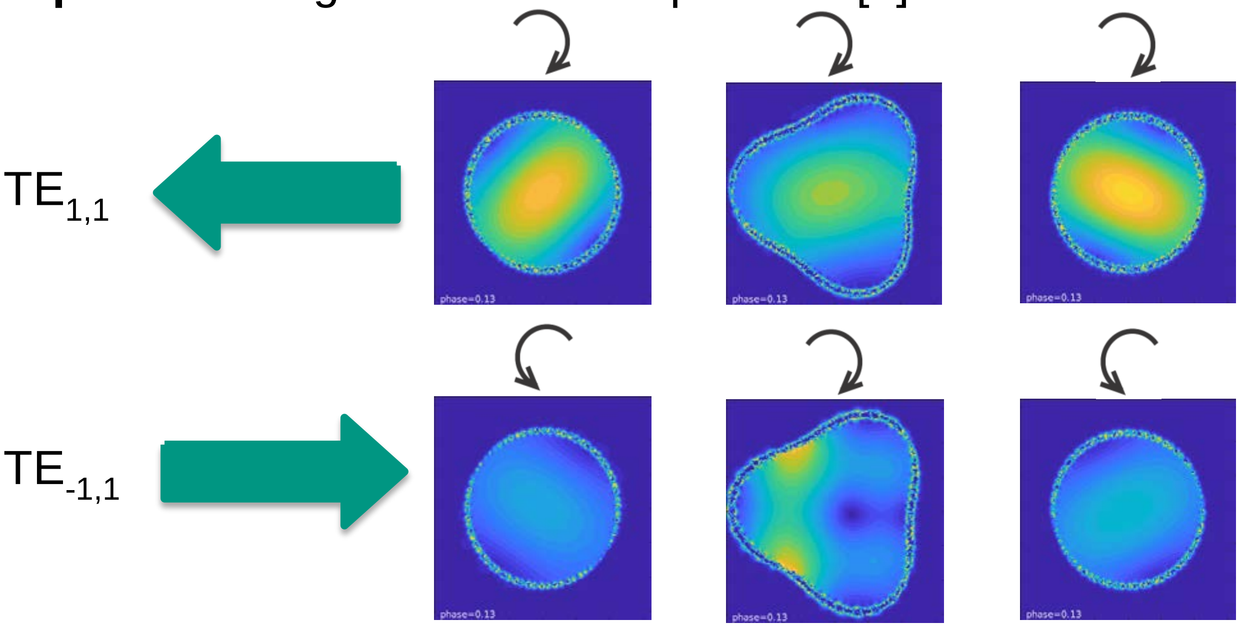


[1] G. DENISOV et al. IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 26, NO. 3, JUNE 1998

Gyro-TWT with helically corrugations



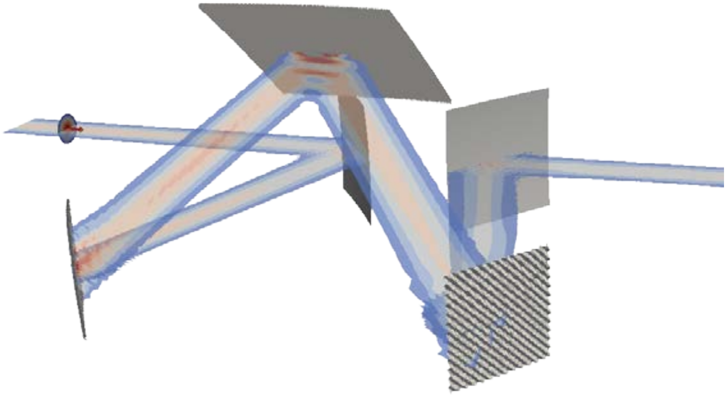
Important: Single I/O-window operation [1]:



Advantage:
Suitable for high-power input signals

[1] G. DENISOV et al. IEEE ELECTRON DEVICE LETTERS, VOL. 35, NO. 7, JULY 2014

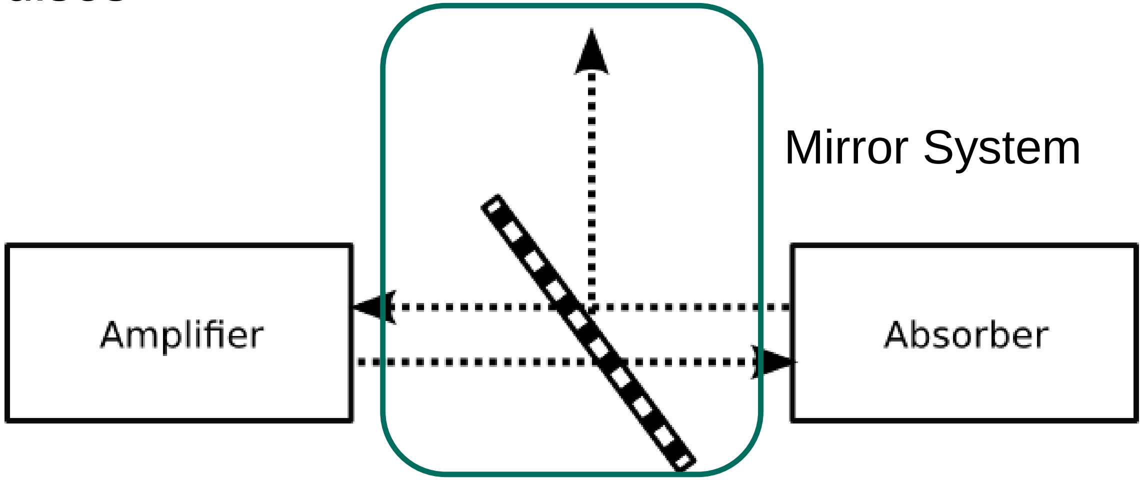
QUASI-OPTICAL MIRROR SYSTEM DESIGNS



Mirror System: Requirements

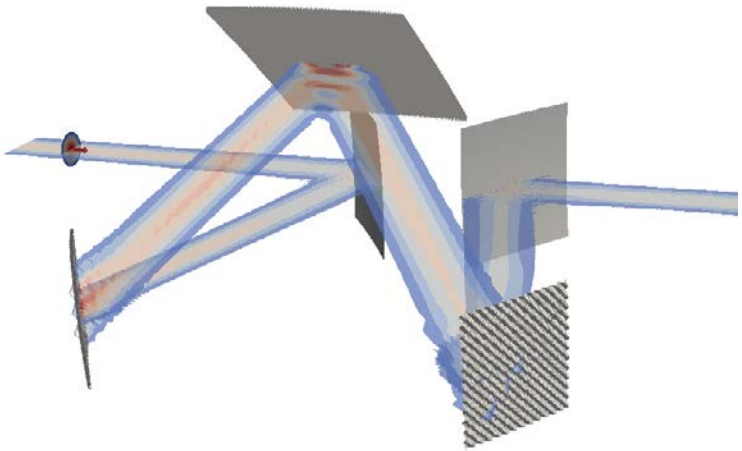
Requirements

- Decoupling of the output signal only on the path absorber-to-amplifier
  → separation of signal paths
- Tunable signal decoupling
  → output power and stability
- Tunable delay time
  → pulse distance and stability
- High Bandwidth ≥10 GHz
  → short pulses

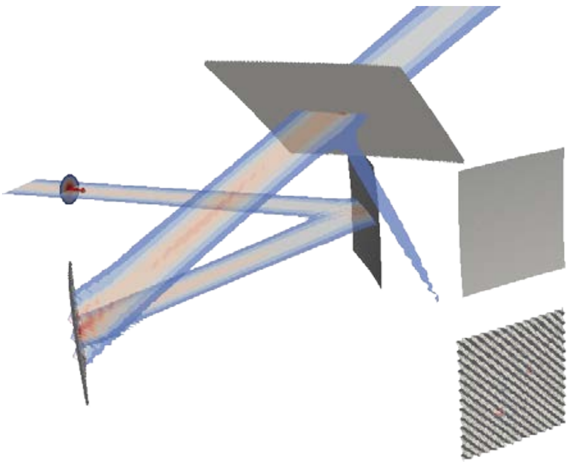


Mirror System:
First Design – 2018 [1]

Reflection



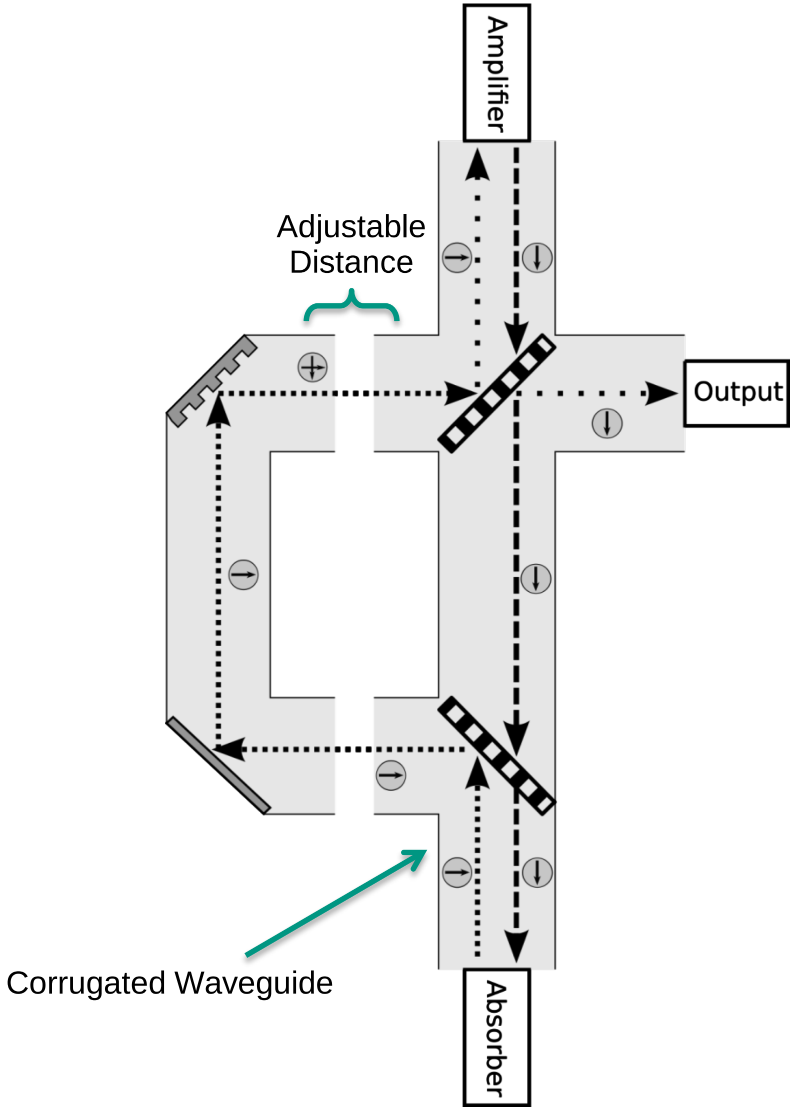
Transmission



- Operating principle:
  - Separation of the cross-polarized signal paths by mirrors with sinusoidal grading
  - Transmission through a grid of stacked metal plates
- Features:
  - ✔ Decoupling only on the path absorber-to-amplifier
  - ✔ Tunable decoupling coefficient
  - ✖ Tunable delay time
- Advantage:
  - High bandwidth of sinusoidal mirrors
- Disadvantages:
  - Complicated mirror-positions
  - Impractical direction of output-signal

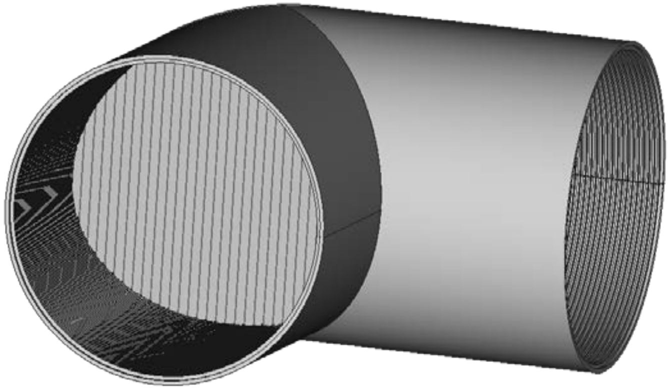
[1] A.Marek, 3rd International Conference on Terahertz and Microwave Radiation: Generation, Detection and Applications (TERA-2018)

Mirror System:
For 263 GHz Generator – Design 2020

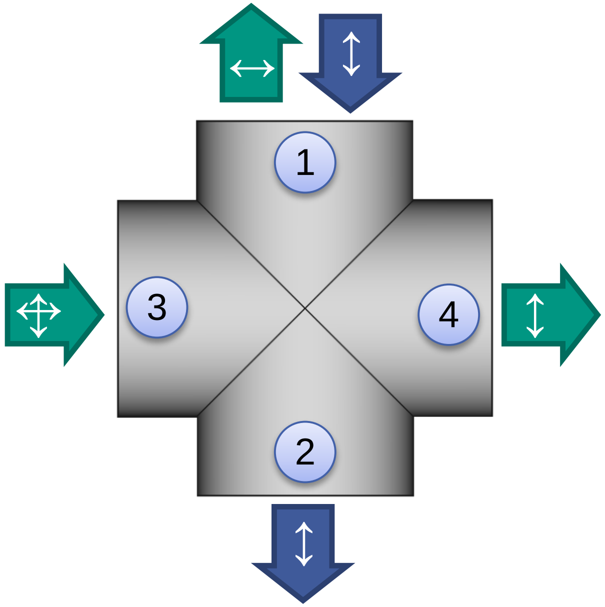


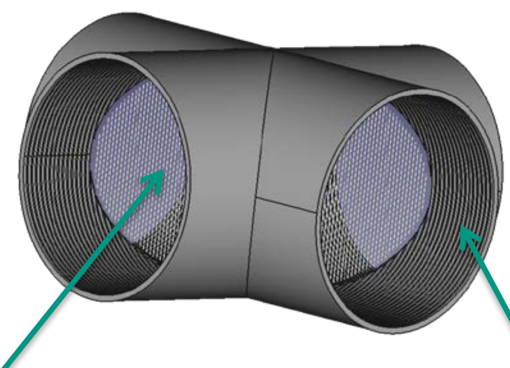
- Operating principle:
  - Separation of the cross-polarized signal paths through a grid of wires
  - Rectilinear grating as polarizer
- Features:
  - ✔ Decoupling only on the path absorber-to-amplifier
  - ✔ Tunable decoupling coefficient
  - ✔ Tunable delay time
- Advantages:
  - Simple positioning of all components and ports
  - Can be realized as transmission-line with overmoded corrugated waveguides

DESIGN OF COMPONENTS



Mirror System for 263 GHz: Beam Splitter– Requirements

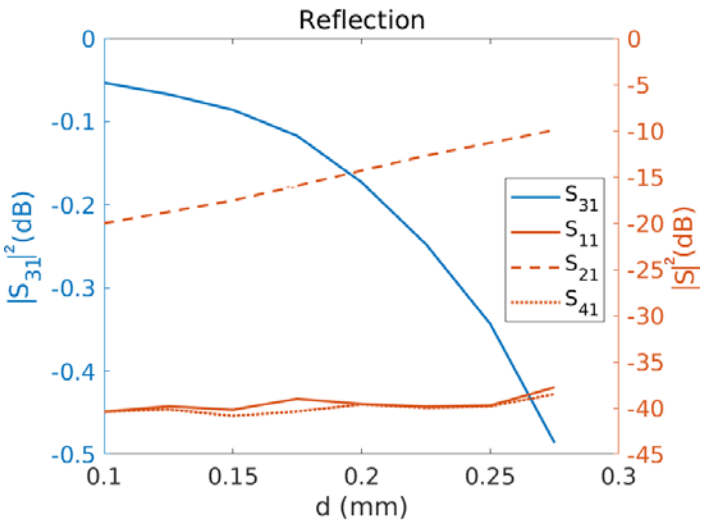


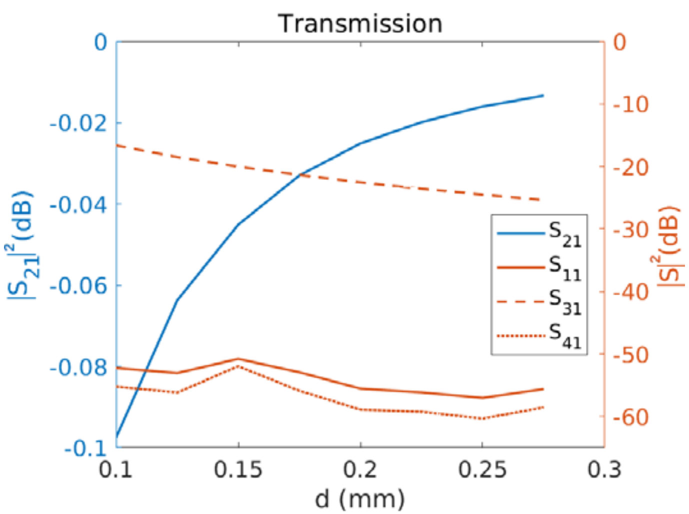


Semitransparent Grid   Corrugated Waveguide

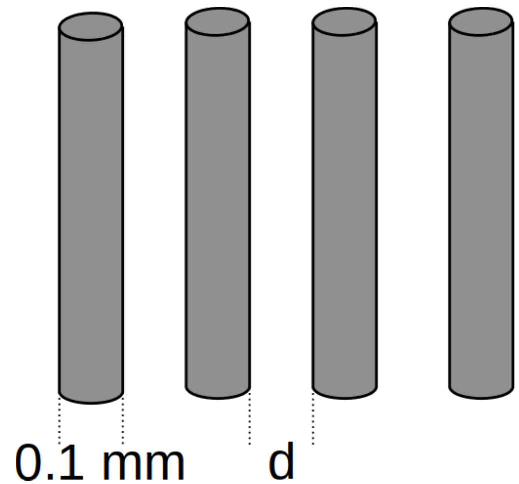
- **Idea:** Separation of the cross-polarized HE_{11} modes by a grid thin metal wires
- Required properties:
  - Low back reflections
    → $S_{11} < -30$ dB
  - High transmission
    → $S_{21} > -0.05$ dB
    → $S_{31} < -20$ dB
  - Good reflection
    → $S_{13} > -0.1$ dB
    → $S_{43} < -16$ dB
  - Bandwidth ≥ 10 GHz

Mirror System for 263 GHz: Beam Splitter– Optimization





- *1. Step*: Guess initial parameter
- *2. Step*: Optimize the separator by parameter-sweeps for different *d*

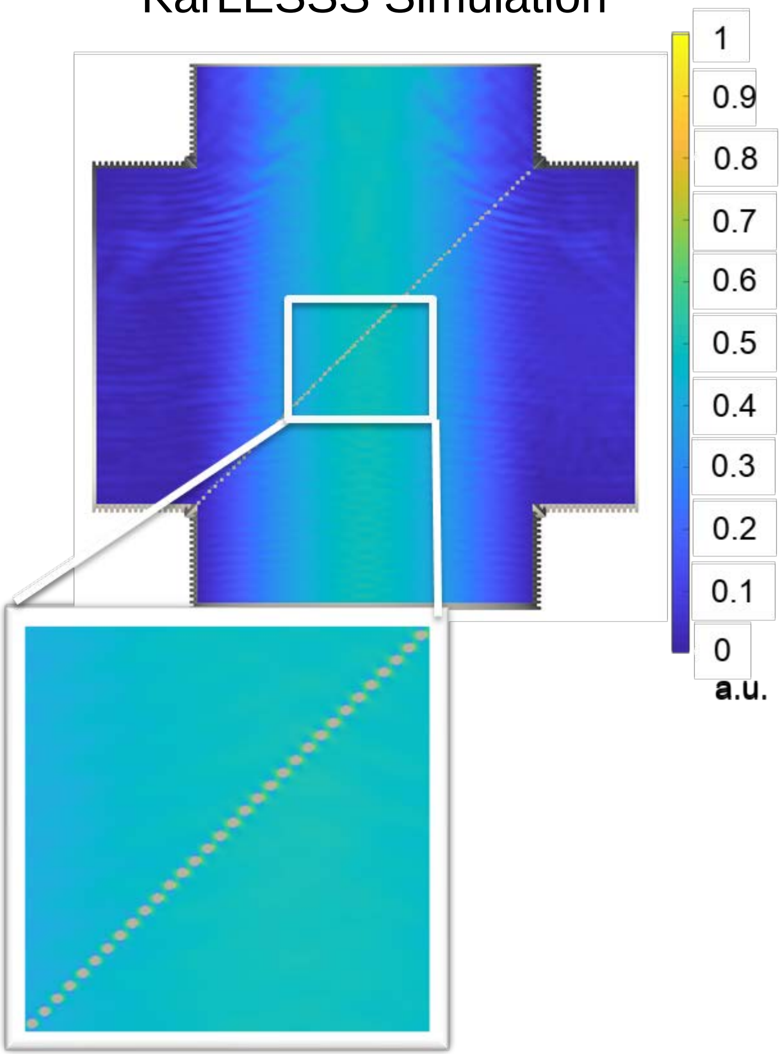


Optimal Parameter:

$d = 0.15$ mm

Mirror System for 263 GHz: Beam Splitter– Optimization

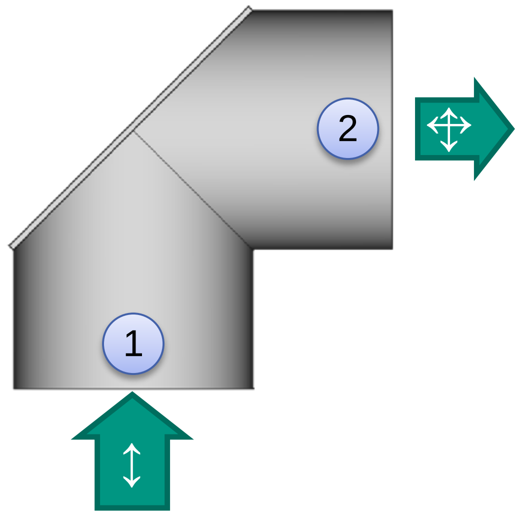
KarLESSS Simulation

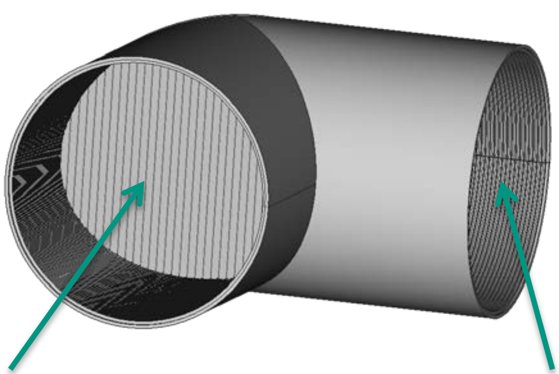


- *3. Step*: Check of the Frequency dependence
- *4. Step*: Check of max. field-strength
  - ➡ Max. electric field:
    - 1 W → 0.225 kV/m
    - 2 kW → 7.2 kV/m
- *5. Step*: Check of ohmic losses and mode conversion
  - ➡ On-going

Mirror System for 263 GHz: Polarization Rotator – Requirements

Miter Bend with polarizing grid





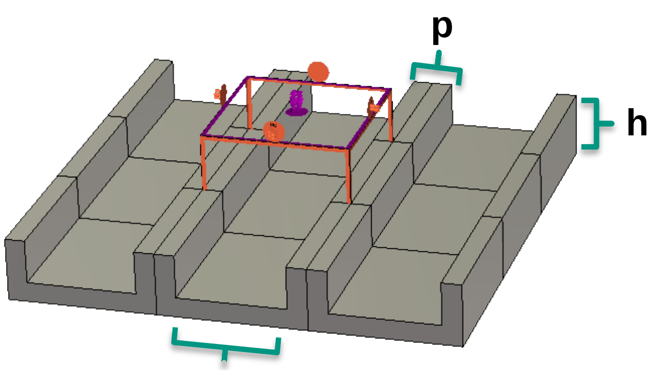
Polarizing Grid

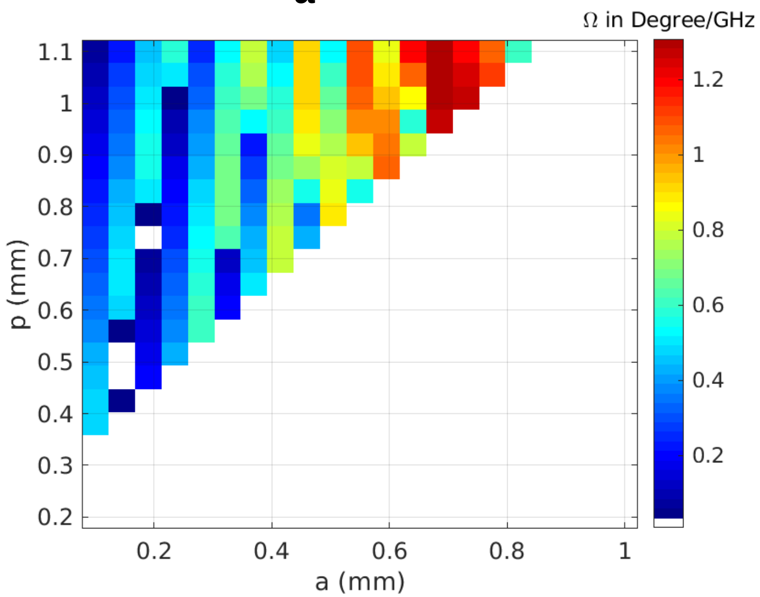
Corrugated Waveguide

- **Idea:** Reflective rectilinear grating as polarizer
  - Rotate the polarization of a HE_{11} mode
  - A part of the signal can be coupled-out by the polarization separator
  - Tunable out-coupling by rotating the polarizer
- Required properties:
  - Tunable polarization: $0 - 70\%$
  - $S_{11} < -30$ dB
  - Bandwidth of 10 GHz

Mirror System for 263 GHz: Polarization Rotator – Optimization

CST-Setup

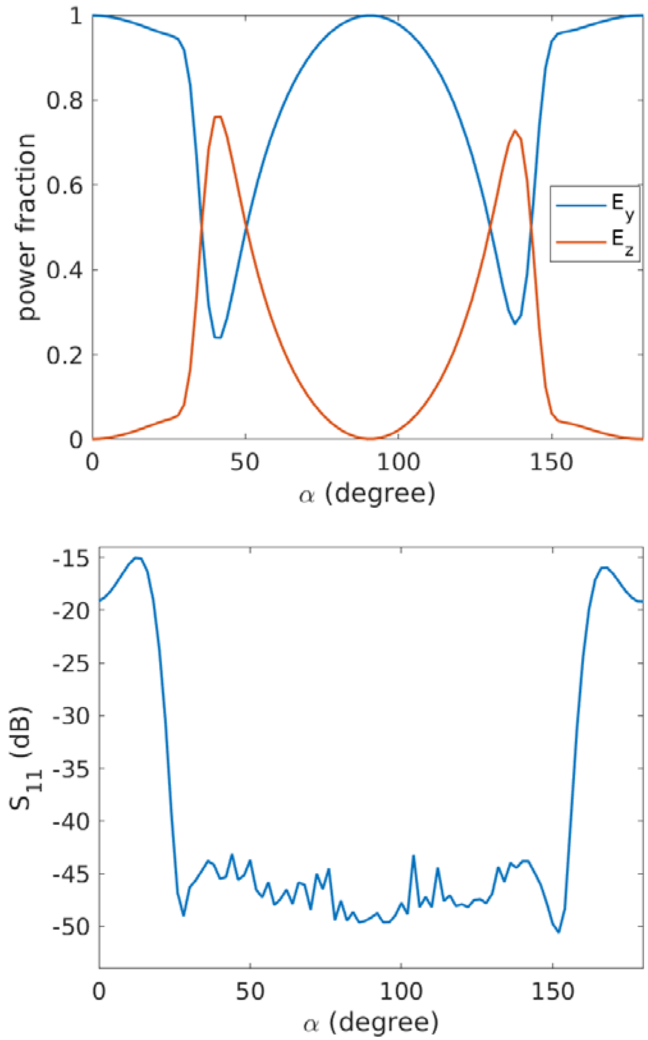




- *Step 1*: Optimization of the geometrical parameter for a high bandwidth
  - Simulations via CST
  - Incident plane wave
  - Sweep over frequency
- Merit function: $\Omega = |\frac{\partial \phi}{\partial f}|$

Optimal Parameter:
- $p = 0.75$ mm
- $a = 0.2$ mm
- $h = 0.218$ mm

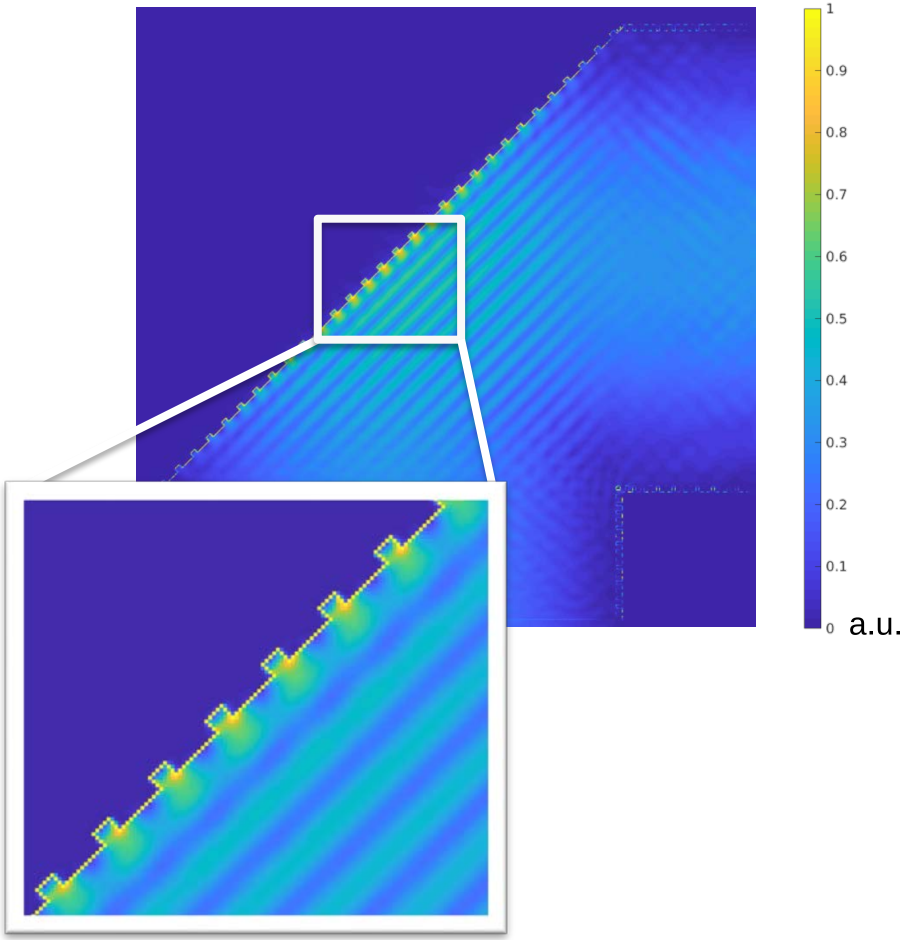
Mirror System for 263 GHz: Polarization Rotator – Results



- *Step 2:* Full-wave simulation to check efficiency and S_{11} parameter for incident HE_{11} mode
  - Operating region: $\mathbf{45° - 135°}$
  - Wide tunable decoupling $\mathbf{0 - 70\ \%}$
  - Low back–reflections $\boldsymbol{S_{11} < -40}$ **dB**
- *Step 3:* Check the bandwidth

Mirror System for 263 GHz: Polarization Rotator – Results

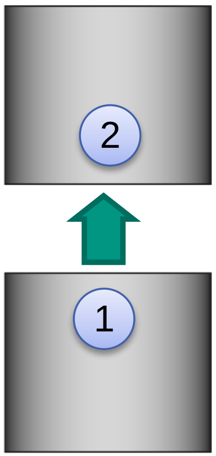
KarLESSS Simulation



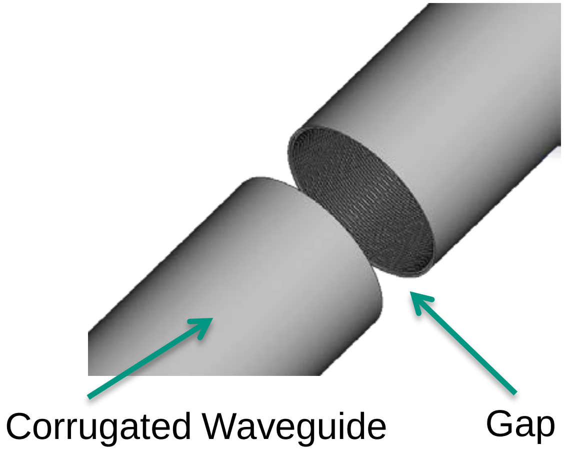
- *4. Step:* Check of max. field-strength
  - Highest fields for decoupling of 50%
  - Max. electric field:
    - 1 W → 2 kV/m
    - 2 kW → 90 kV/m
- *5. Step*: Check of ohmic losses and mode conversion

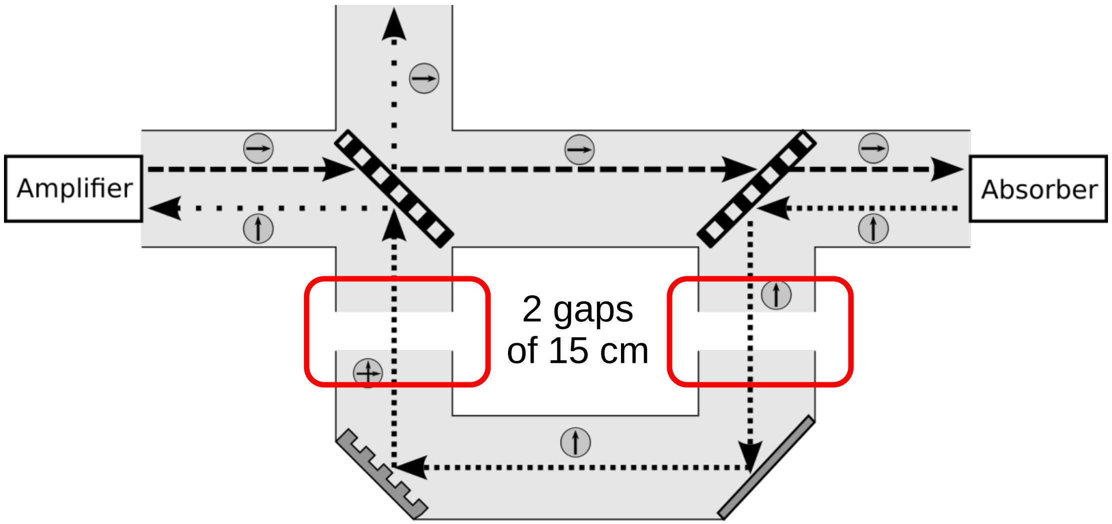
➡ On-going

Mirror System for 263 GHz: Adjustable Delay-Time

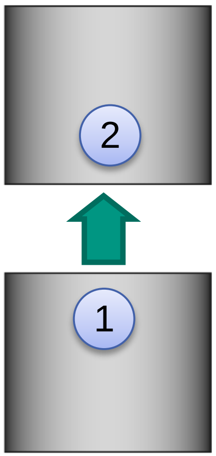


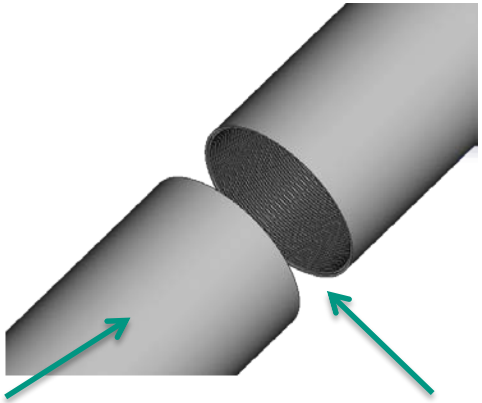
- **Idea**: Adjustment of the delay-time due to an increase of the transmission way
- Simplest solution: Gaps in the waveguides for the signal path Absorber → Amplifier
  ➡ Losses are less critical
- Goal: Increase of the delay-time by **1 ns**
  ➡ Increase of the transmission way of **30 cm**





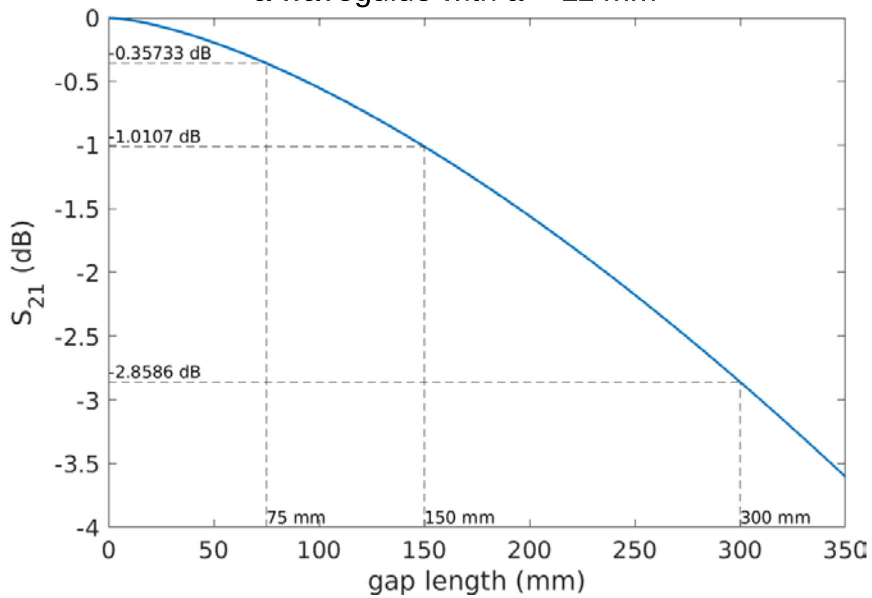
Mirror System for 263 GHz: Adjustable Delay-Time





- Transmission of a HE_{11} mode over a gap can be calculated by the following formula [1]:

$$S_{21} \approx 1.7 \left(\frac{L\,\lambda}{2\,a^2}\right)^{\frac{3}{2}} \text{ dB}$$



Only very short gaps are possible

[1] J. L. DOANE & C. P. MOELLER (1994), INTERNATIONAL JOURNAL OF ELECTRONICS, 77:4, 489-509

Conclusion & Outlook

Conclusion

- A user-friendly quasi-optical feedback-system for a 263 GHz pulsed generator is possible
  - High bandwidth
  - Low losses
- With KarLESSS an in-house tool for the simulation and design of a complete quasi-optical feedback-system is available

Outlook

- Better solution for a tunable delay-time is required
- Design and PIC Simulations of the 263 GHz gyro-devices

We are looking forward to the upcoming experiments at IAP

Acknowledgements

Founded by the Deutsche Forschungsgemeinschaft (DFG) and the Russian Science Foundation (RSF) within the joint RSF-DFG project (DFG: Je 711/1-1, RSF: No. 19-79-30071) “Generation of Ultrashort Pulses in Millimeter and Submillimeter Bands for Spectroscopy and Diagnostic of Various Media Based on Passive Mode-locking in Electronic Devices with Nonlinear Cyclotron Absorber in the Feedback Loop”.

APPENDIX

Simulation of Quasi-Optical Components

Karlsruhe Institute of Technology

- The quasi-optical components are simulated and designed with own tool KarLESSS
- Originally developed for the simulation of the quasi-optical mode-converter in Gyrotrons
- KarLESSS main features:
  - Full-wave analysis of arbitrary shaped perfect conductors based on the EFIE
  - Acceleration via several algorithms: ACA, ACA-SVD, S-ACA
  - FGMRES solver with zero-cost preconditioner
  - High order surfaces and high order basis functions
  - Highly parallelized on shared and distributed memory systems
  - Modular code basis
- Upcoming features:
  - Waveguide-Ports
    → Coupling of full-wave simulations with scattering-matrix methods
  - Support of dielectric and lossy materials

KarLESSS
Karlsruhe Large Electric System Simulation Suite