Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Development of a Waveguide Microcalorimeter as RF Power Standard for Frequencies above 170 GHz

PTB Seminar

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Working Group 2.22, High-Frequency Base Quantities

15 May 2024

Outline

- Background
- Measurement Traceability of RF Power
- RF Power Sensor
- Working Principle of Microcalorimeter
- Transmission Line of R 1.8k Microcalorimeter
- Conclusion and Outlook

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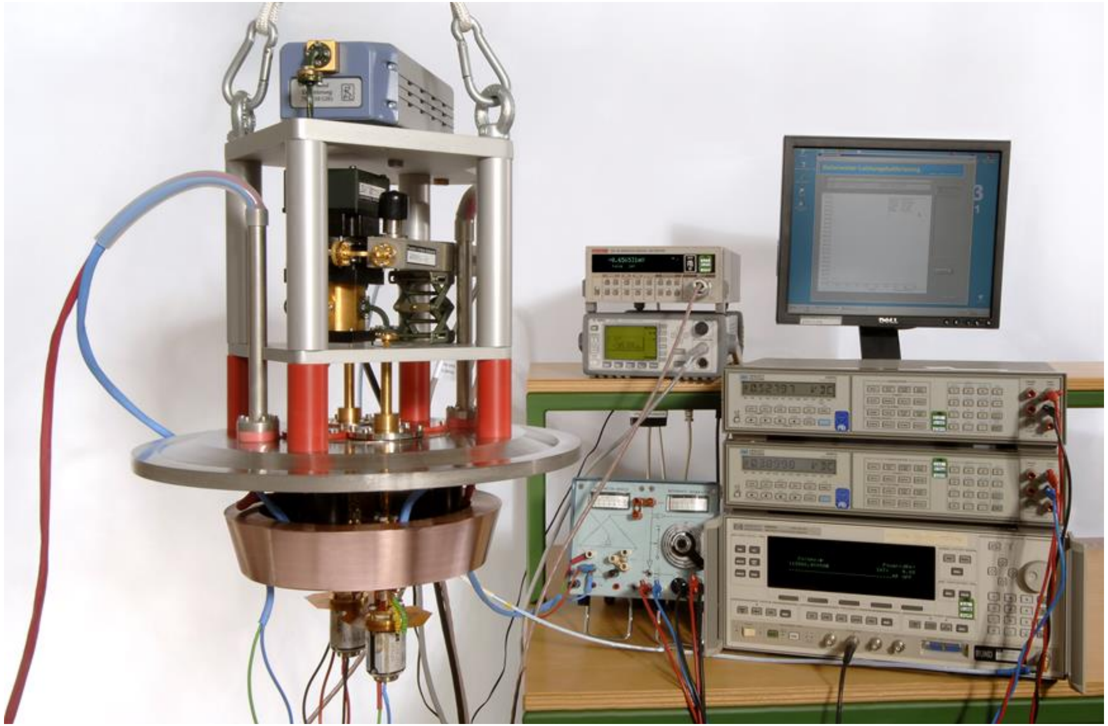
Background

- Microcalorimeter as primary standard of RF power available up to 170 GHz



R 900 microcalorimeter

Background

- Measurement traceability requirement of RF power above 170 GHz → telecommunication devices



- Development of waveguide microcalorimeter as RF power standard for 140 - 220 GHz

Sources: https://en.wikipedia.org/wiki/Telecommunications, https://www.topfreebooks.org/free-telecommunication-engineering-books/, https://www.keysight.com/6g-technology.html.

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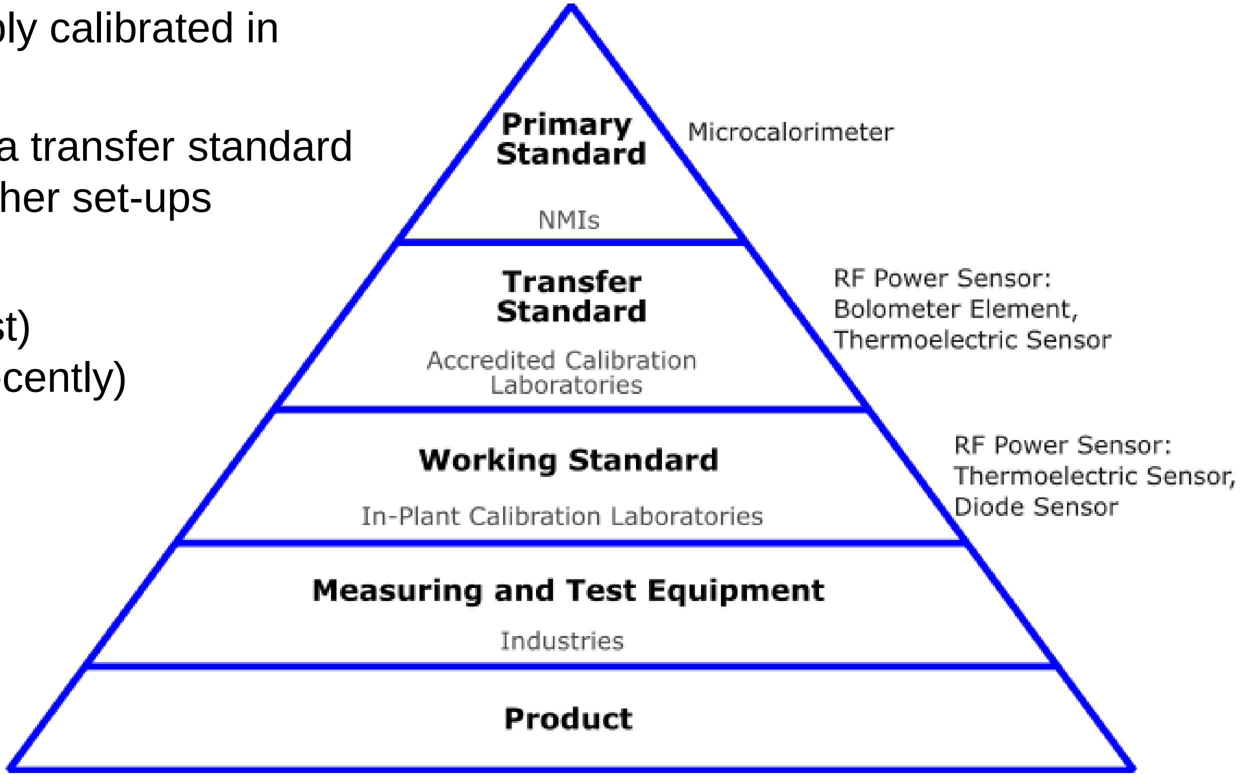
Measurement Traceability of RF Power

- RF power sensor are traceably calibrated in microcalorimeter
- RF power sensor is used as a transfer standard to transport the quantity to other set-ups
- Transfer standard:
  - ✓ Bolometer element (at first)
  - ✓ Thermoelectric sensor (recently)



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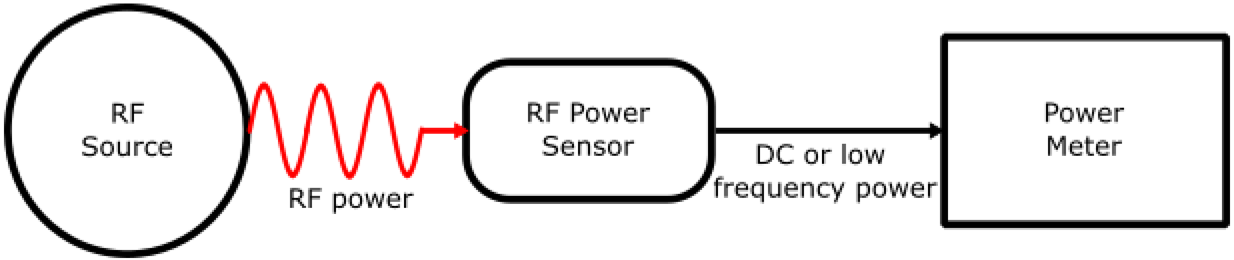
Basic Technique of RF Power Measurement

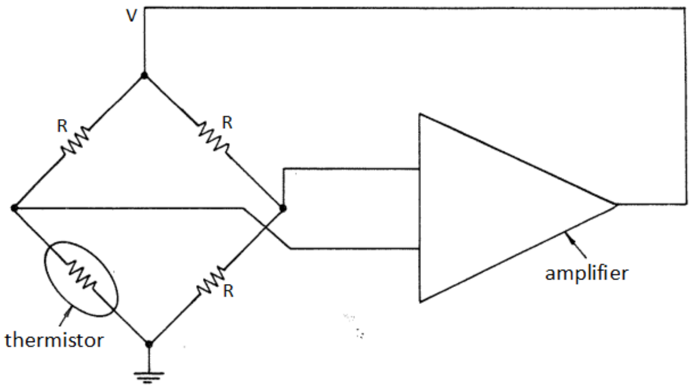
- RF power sensor detects RF power and converts it into DC or lower frequency that can be measured by power meter



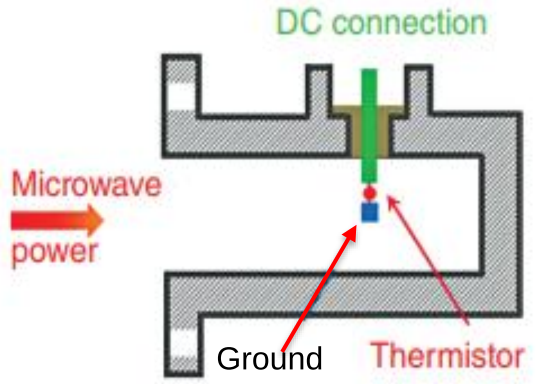
Source: Keysight, Fundamental of RF and microwave power, Application NoteAN1449-1/2/3/4, Keysight Technologies, Tech. Rep., 2017.

Transfer Standard

- Transfer standard → thermistor mount or thermoelectric sensor
- Thermistor mount consist of a temperature-sensitive resistor;
  The resistance changes based on a change in the temperature resulted from absorption of RF power by thermistor element → Detected by a bridge circuit



Thermistor with self-balancing Wheatstone bridge

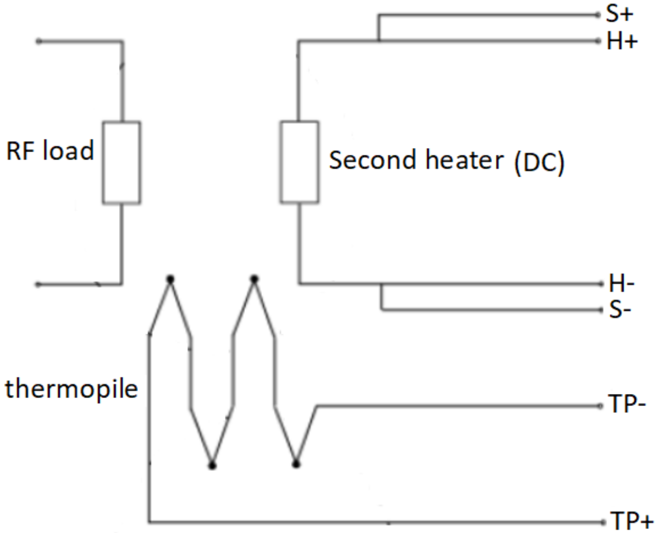


Simplified schematic of waveguide thermistor mount

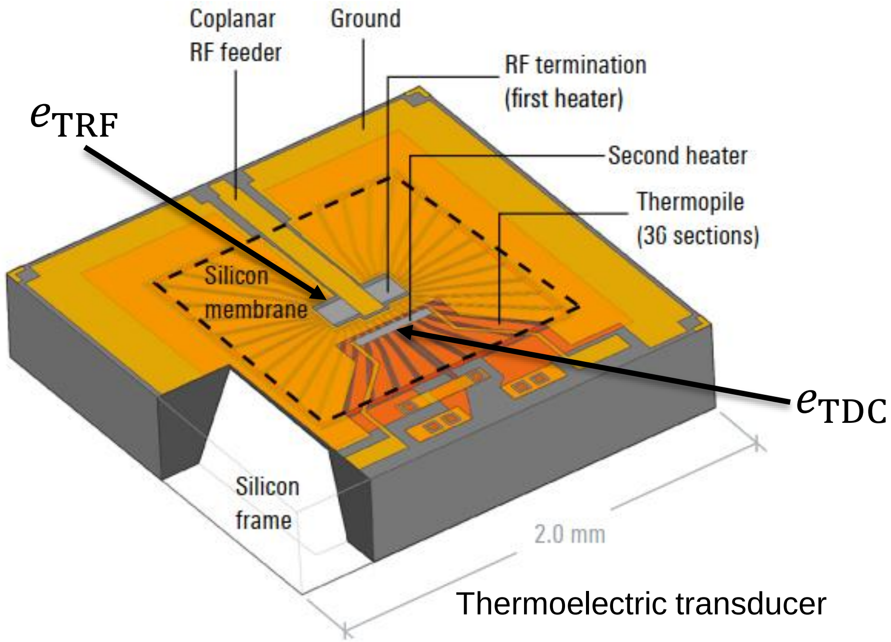
Sources: A. Fantom, Radio Frequency and Microwave Power Measurement, London: Peter Peregrinus Ltd, 1990.; www.intechopen.com/books/new-trends-anddevelopments-in-metrology.

Transfer Standard

- Thermoelectric sensor converts RF power to heat and sense temperature difference by thermopile
- There two loads at thermoelectric sensor: RF termination and second heater (DC)



Simplified schematic of thermoelectric sensor



Thermoelectric transducer

Source: www.rohde-schwarz.com.

Transfer Standard

Thermistor mount

Thermoelectric sensor

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Working Principle of Microcalorimeter

- Microcalorimeter is a heat measuring instrument → Measure RF power in terms of heat generated and detected in a load of a suitable power sensor
- Based on the RF-DC substitution technique → DC power substitutes RF power delivered in a transfer standard to cause equivalent thermal effects
- Substituted DC power (P_{DC}) is proportional to applied RF power

$$P_{DC} = \frac{{V_1}^2 - {V_2}^2}{R}$$

- V_1 and V_2 are DC voltage across transfer standard without RF power and with applied RF power
- R is operating resistance of transfer standard

- Ideal measurement:
  - ✓ RF power is totally absorbed by transfer standard
  - ✓ Transfer standard has the same thermal reaction for DC power and RF power

Source: A. Fantom, Radio Frequency and Microwave Power Measurement, London: Peter Peregrinus Ltd, 1990.

Working Principle of Microcalorimeter

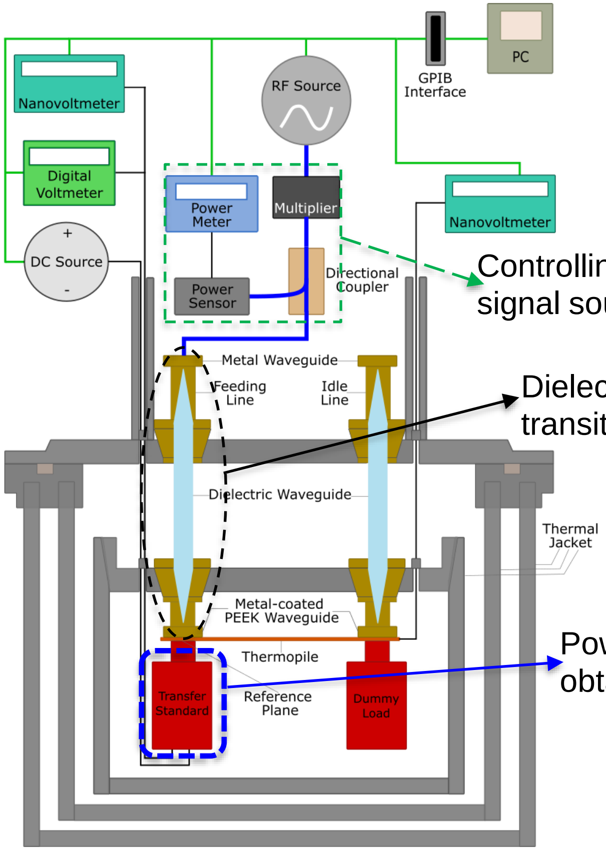
- Practically:
  - ✓ There are power losses in transmission line, wall of transfer standard, input connector, and others → mount efficiency
  - ✓ Elements of transfer standard are not heated identically by equal amounts of DC power and RF power (different thermal reaction) → RF-DC substitution error
- Microcalorimeter is used to measure a correction for transfer standard called the effective efficiency → combination of mount efficiency and RF-DC substitution error
- Effective efficiency (η_e) is defined as the ratio of the substituted DC power (P_{DC}) to the absorbed RF power P_{RFabs} within transfer standard

$$\eta_e = \frac{P_{DC}}{P_{RFabs}}$$

- RF power absorbed at transfer standard can be calculated by dividing substituted DC power with effective efficiency

Source: A. Fantom, Radio Frequency and Microwave Power Measurement, London: Peter Peregrinus Ltd, 1990.

Microcalorimeter Measurement System



Controlling signal source

Dielectric waveguide and transition to metal waveguide

Power sensor, difficult to obtain commercially

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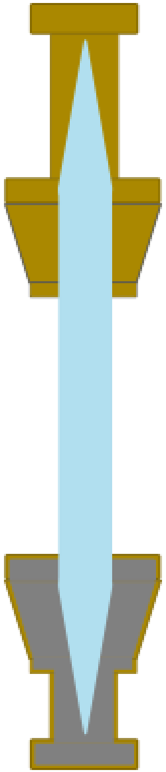
Transmission Line of Microcalorimeter

- Transmission line consists of dielectric waveguide and the transitions to the rectangular metal waveguide interface type R 1.8k (140 GHz – 220 GHz)

- Two different material of the transition section:
  - ✓ Transition at top of transmission line → metal waveguide
  - ✓ Transition at bottom of transmission line → Polyetheretherketone (PEEK), and coated with a thin metal layer

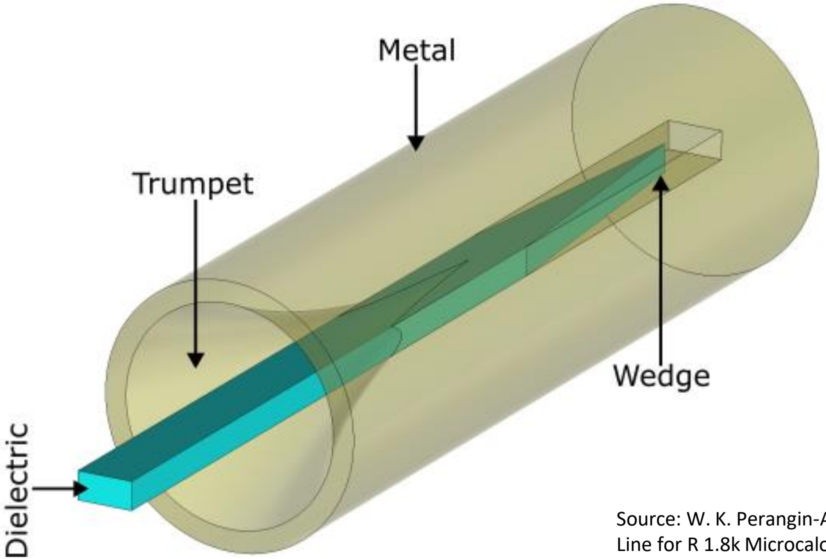
- PEEK is used to extend the thermal insulation to the microcalorimeter reference plane



Source: W. K. Perangin-Angin, K. Kuhlmann, and J. Rühaak, Dielectric Waveguide as Transmission Line for R 1.8k Microcalorimeter, manuscript accepted for publication at CPEM 2024.

Transmission Line of Microcalorimeter

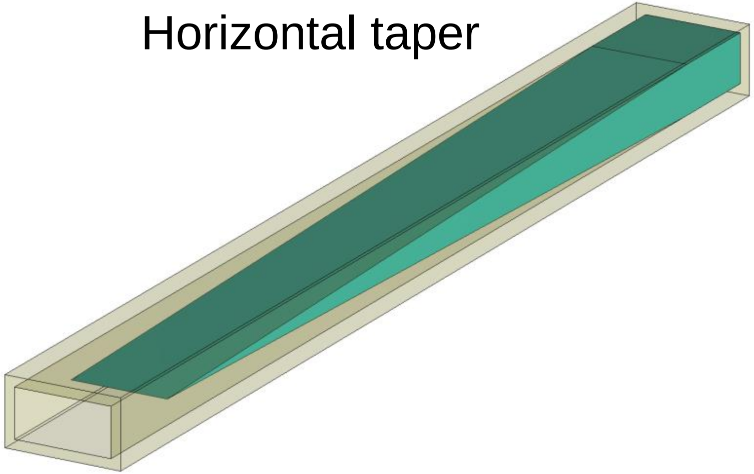
- The transition between the dielectric waveguide and the metal waveguide is optimized by using two matching sections:
  - ✓ The dielectric ends are machined into a wedge shape (tapering) → to improve the transition performance
  - ✓ Trumpet structure is used in the metal waveguide → resulting in a good match



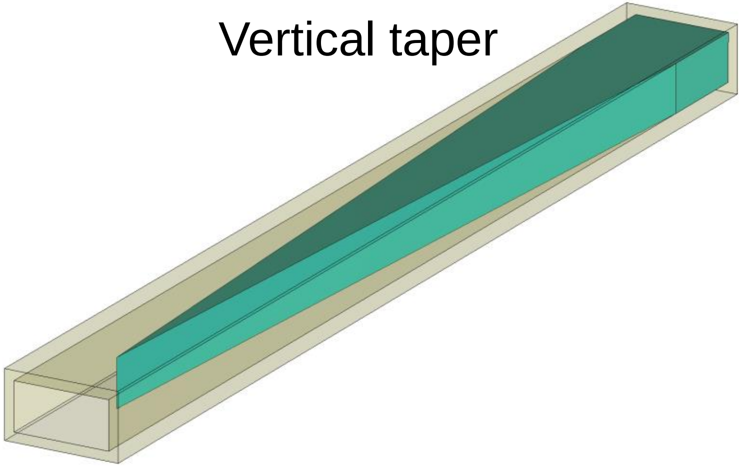
Source: W. K. Perangin-Angin, K. Kuhlmann, and J. Rühaak, Dielectric Waveguide as Transmission Line for R 1.8k Microcalorimeter, manuscript accepted for publication at CPEM 2024.

Simulation of Dielectric Tip (Tapering)

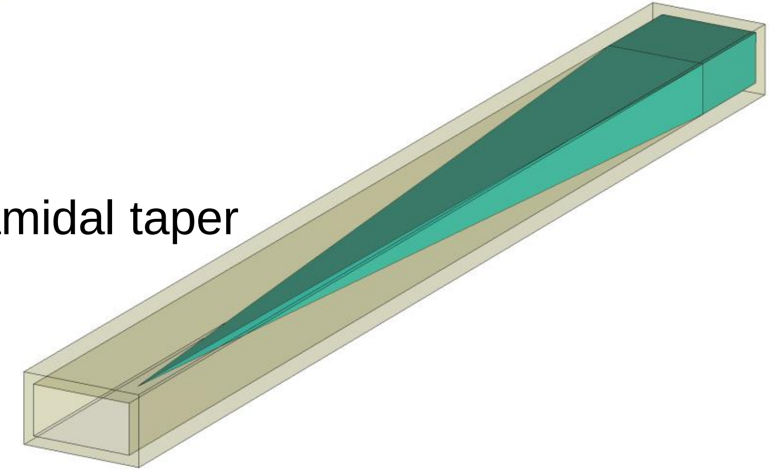
Horizontal taper



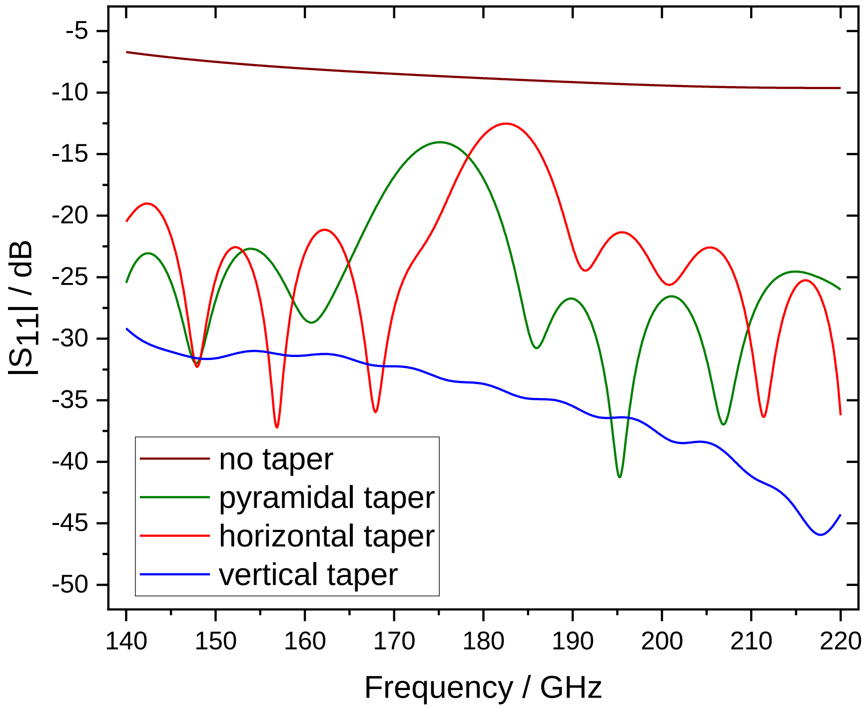
Vertical taper

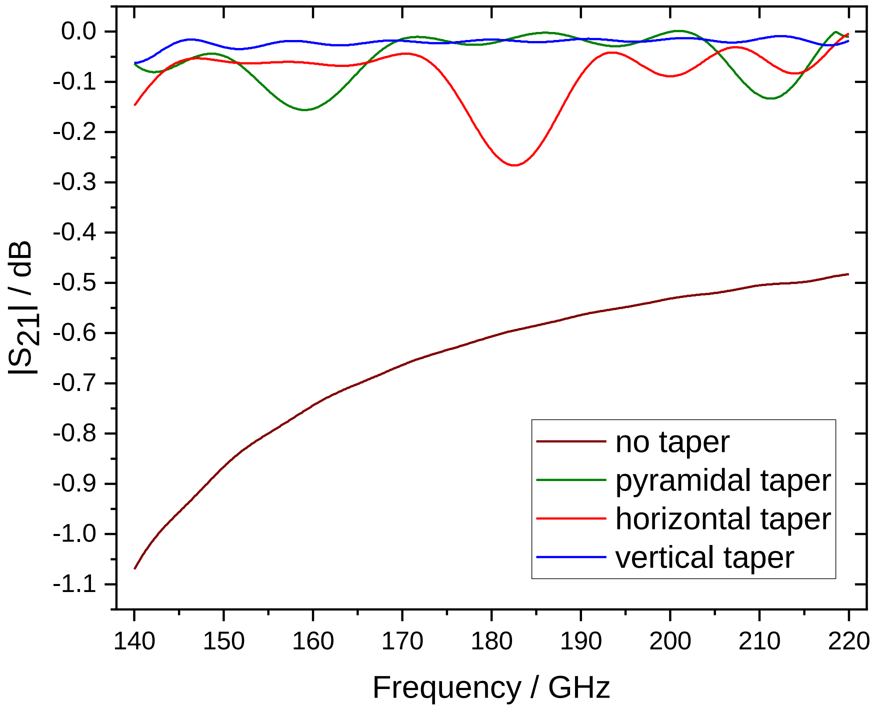


Pyramidal taper

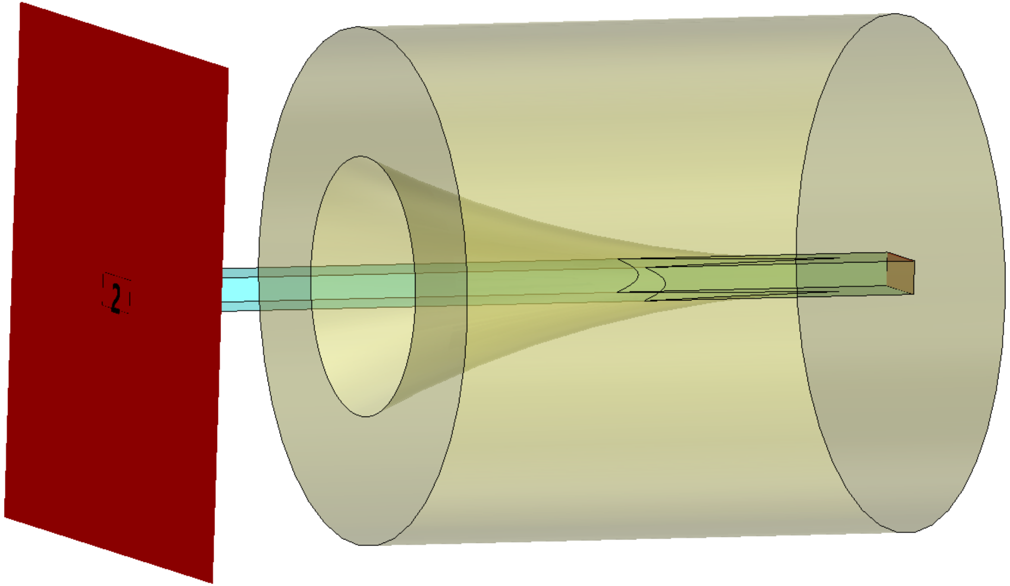


Simulation of Dielectric Tip (Tapering)

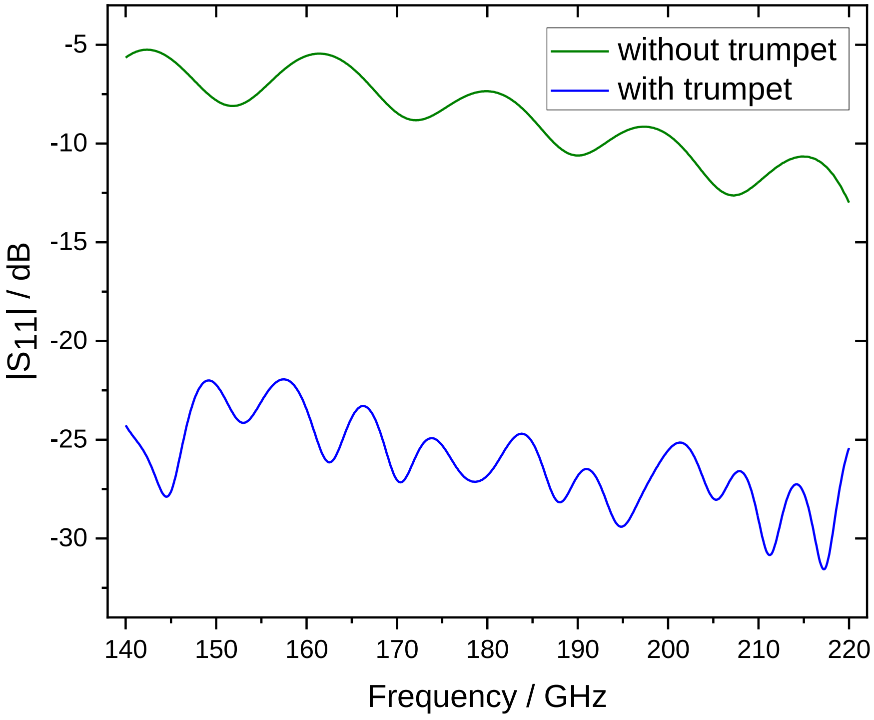


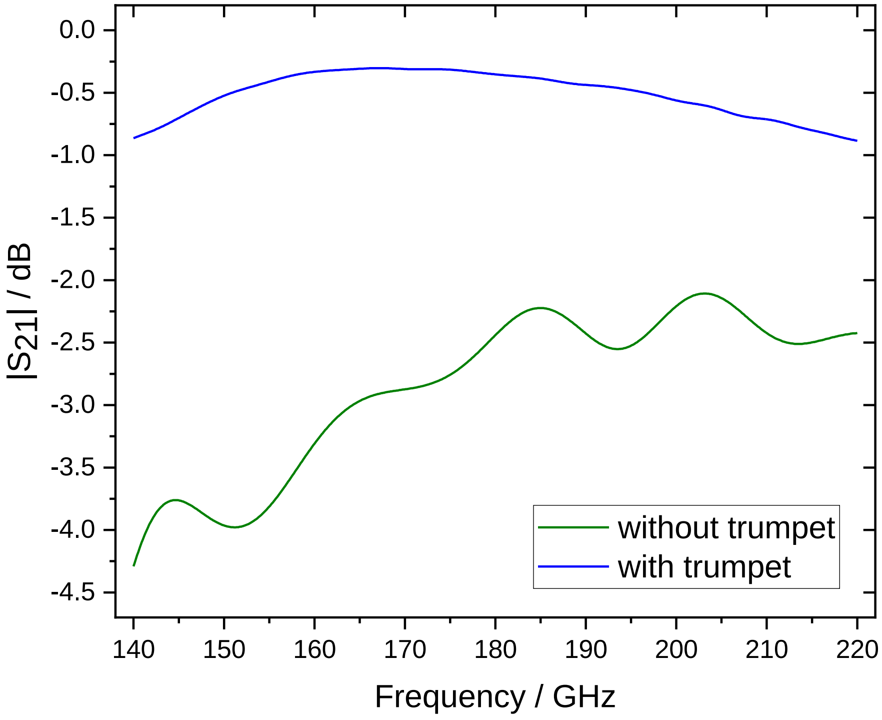


Simulation of Trumpet Structure

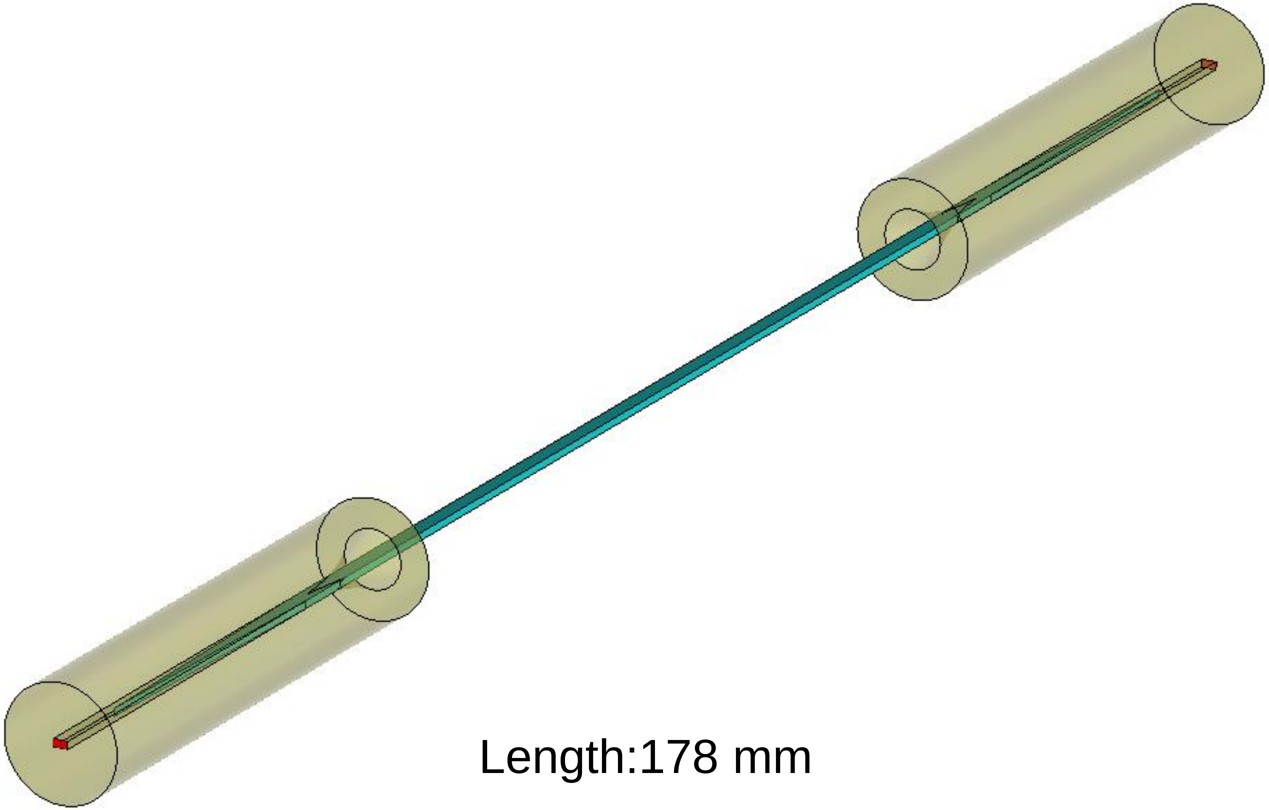


Simulation of Trumpet Structure



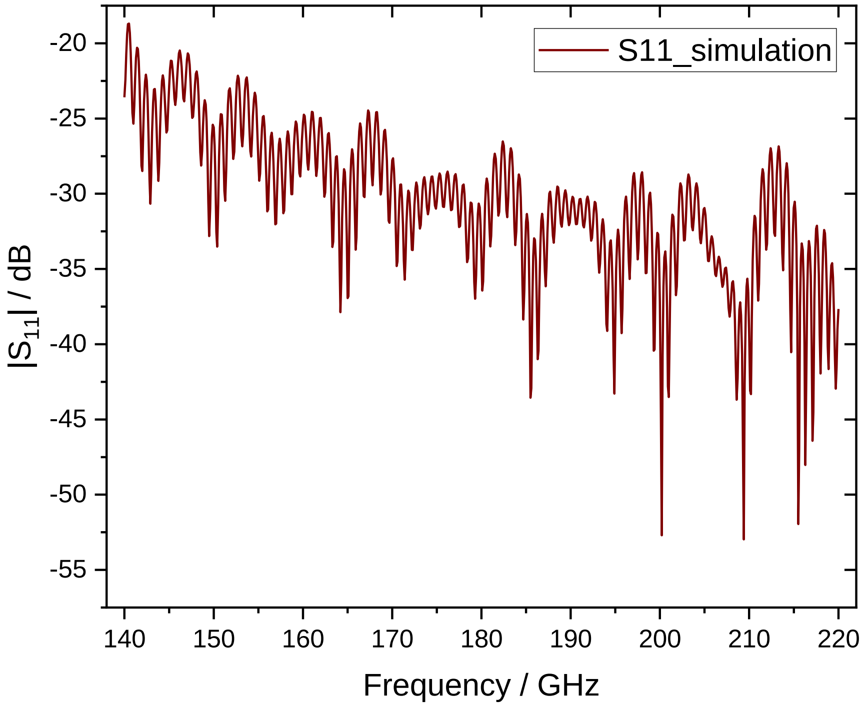


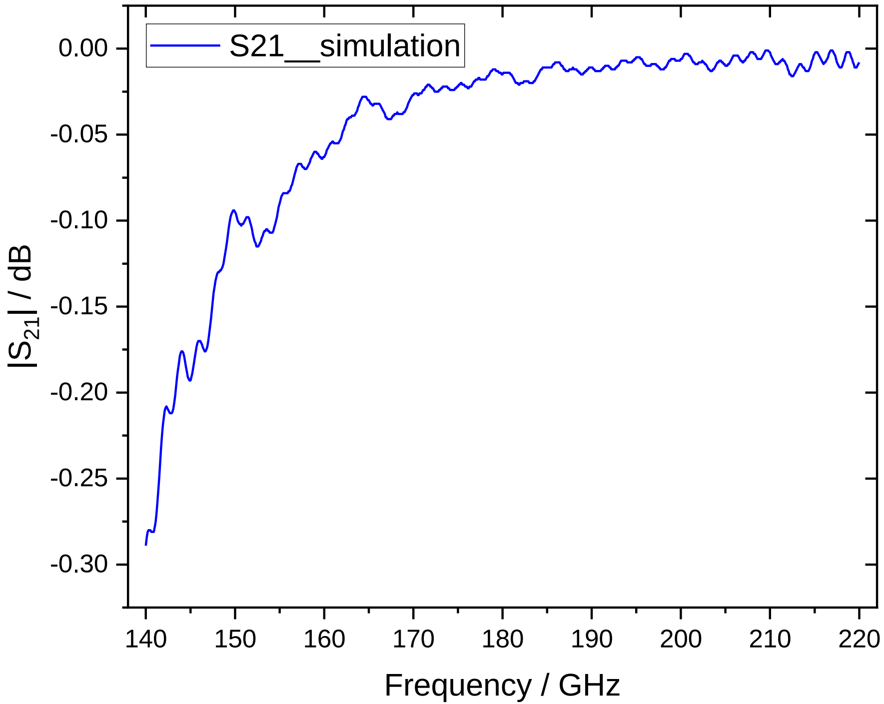
Simulation of Transmission Line



Length:178 mm

Simulation of Transmission Line (lossless)





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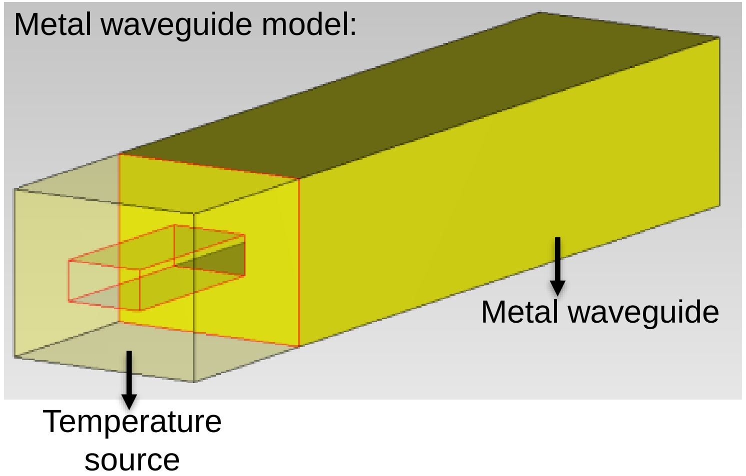
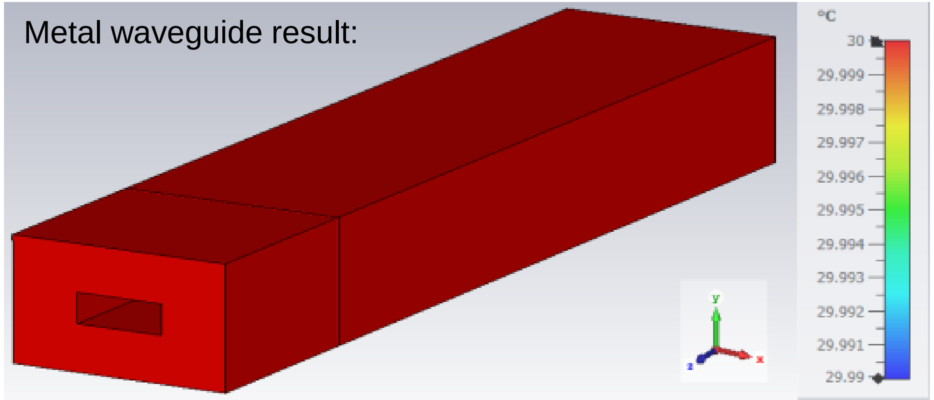
Thermal Simulation of Transmission Line

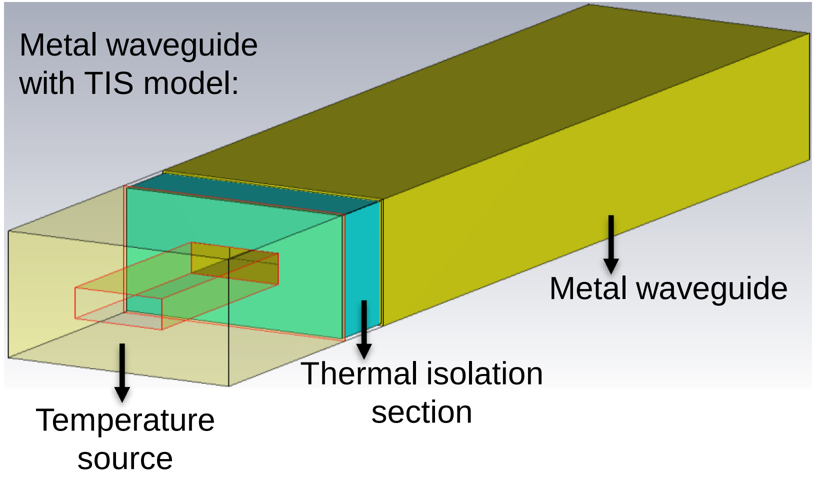


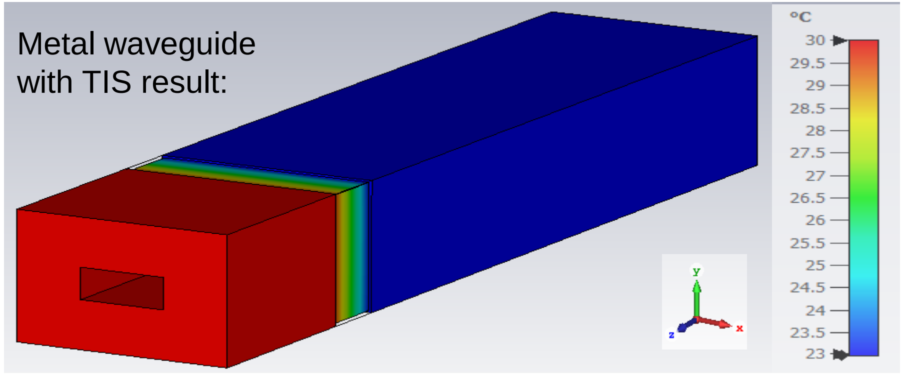


- Thermal boundary condition: 23 ˚C
- Temperature source is added at the input port of the waveguide line: 30 ˚C
- The temperature of the waveguide line is increased to 30 ˚C over the complete waveguide up to the output port

Source: W. K. Perangin-Angin, K. Kuhlmann and J. Ruhaak, "Thermal Isolation in Microcalorimeter Measurements," 2024 15th German Microwave Conference (GeMiC), Duisburg, Germany, 2024, pp. 159-162.

Thermal Simulation of Transmission Line

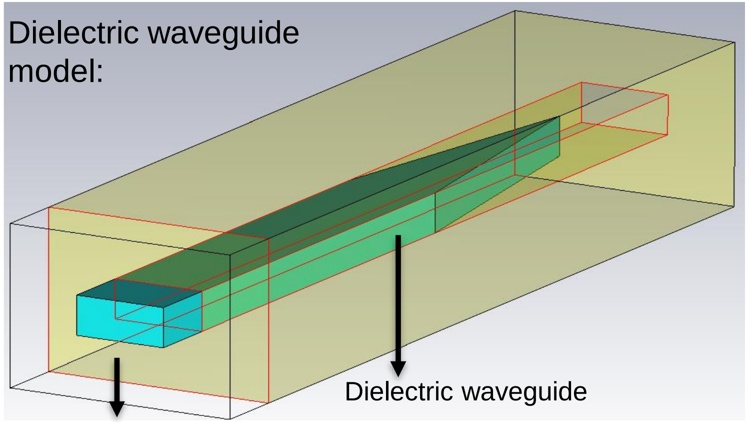


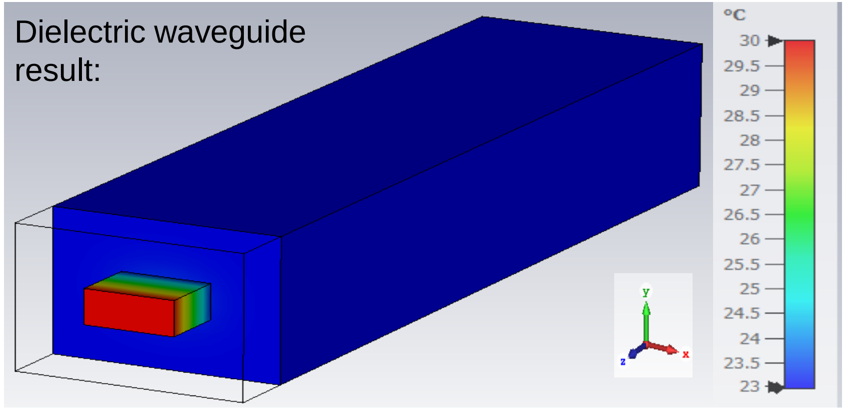


- Thermal boundary condition: 23 ˚C
- Temperature source is added at the input port of the waveguide line: 30 ˚C
- The temperature of the waveguide line behind the thermal isolation section remains stable at 23 ˚C

Source: W. K. Perangin-Angin, K. Kuhlmann and J. Ruhaak, "Thermal Isolation in Microcalorimeter Measurements," 2024 15th German Microwave Conference (GeMiC), Duisburg, Germany, 2024, pp. 159-162.

Thermal Simulation of Transmission Line

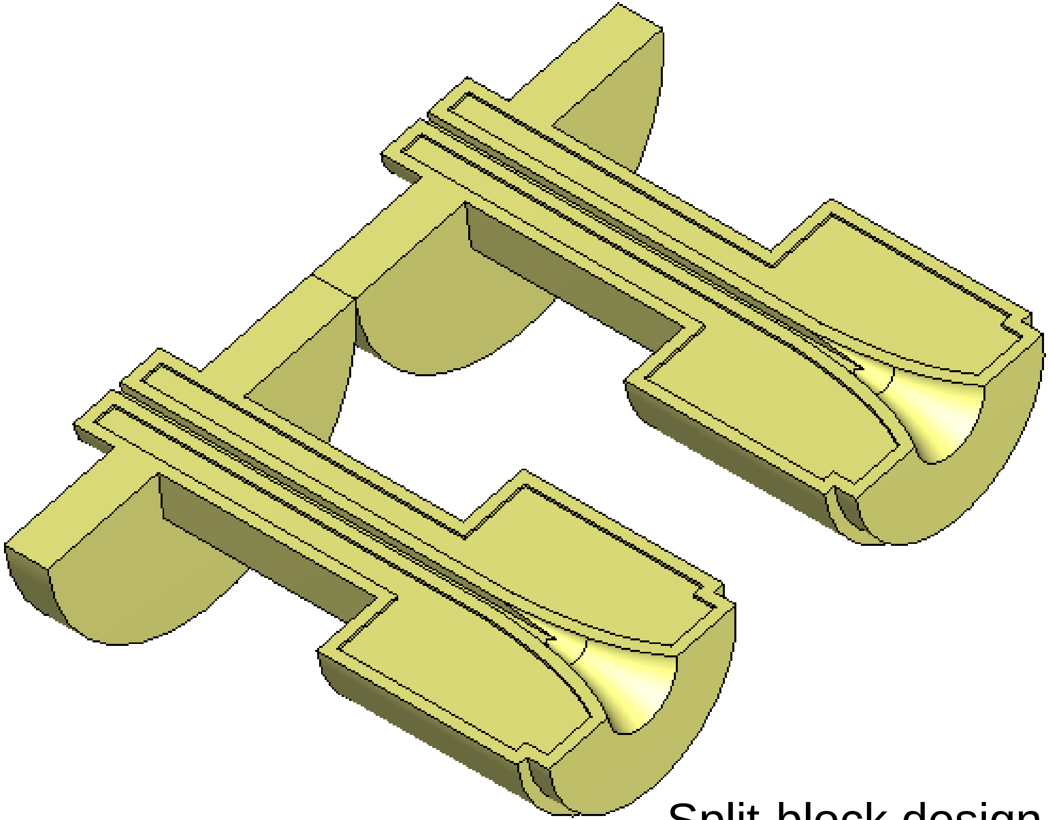




- Thermal boundary condition: 23 ˚C
- Temperature source is added at the input port of the waveguide line: 30 ˚C
- The dielectric waveguide simulation result is similar to the result of the metallic waveguide using the TIS (23 ˚C)
- The dielectric waveguide has advantage as transmission line for microcalorimeters without requiring the additional TIS as in the metallic waveguide

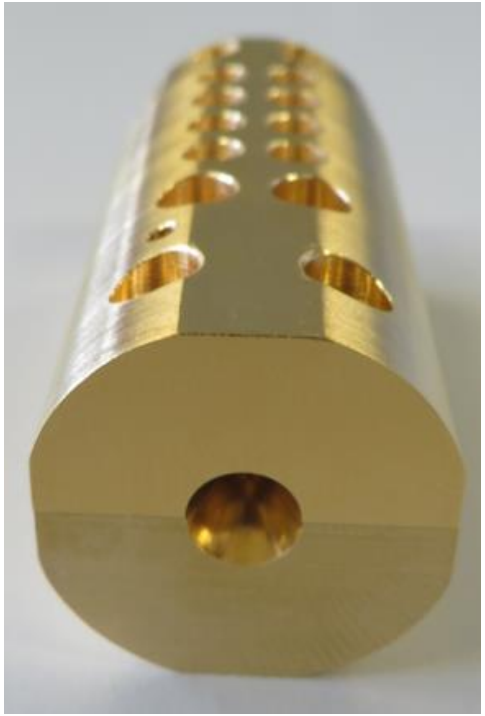
Source: W. K. Perangin-Angin, K. Kuhlmann and J. Ruhaak, "Thermal Isolation in Microcalorimeter Measurements," 2024 15th German Microwave Conference (GeMiC), Duisburg, Germany, 2024, pp. 159-162.

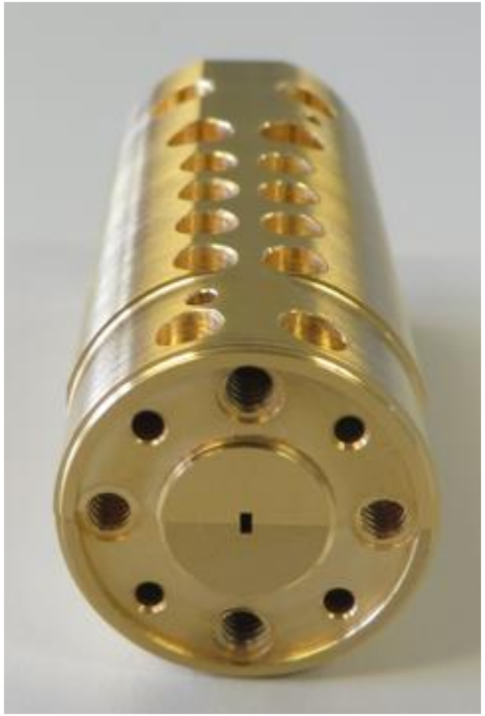
Construction of the transition



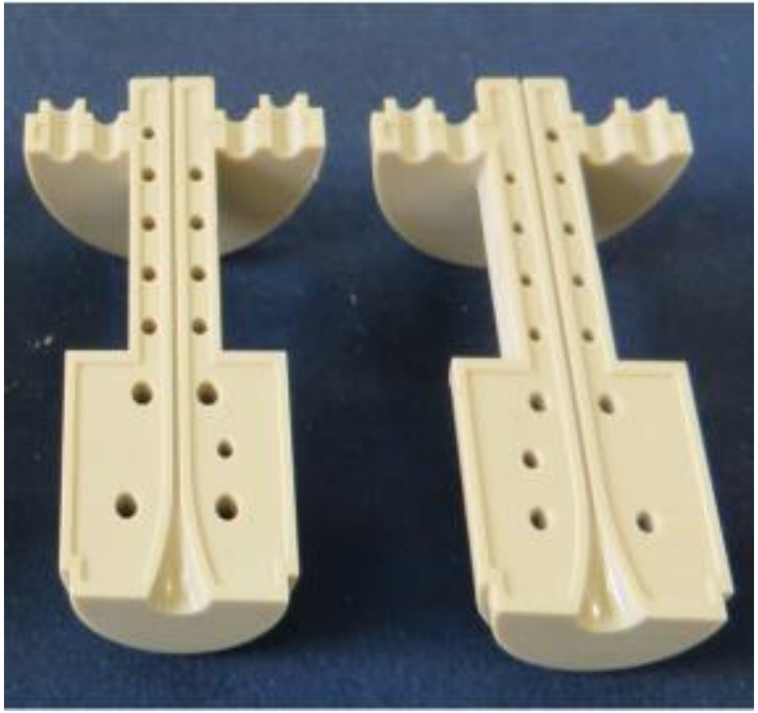
Split-block design R 1.8k

Fabricated brass waveguide (Au plated)





Fabricated PEEK Waveguide



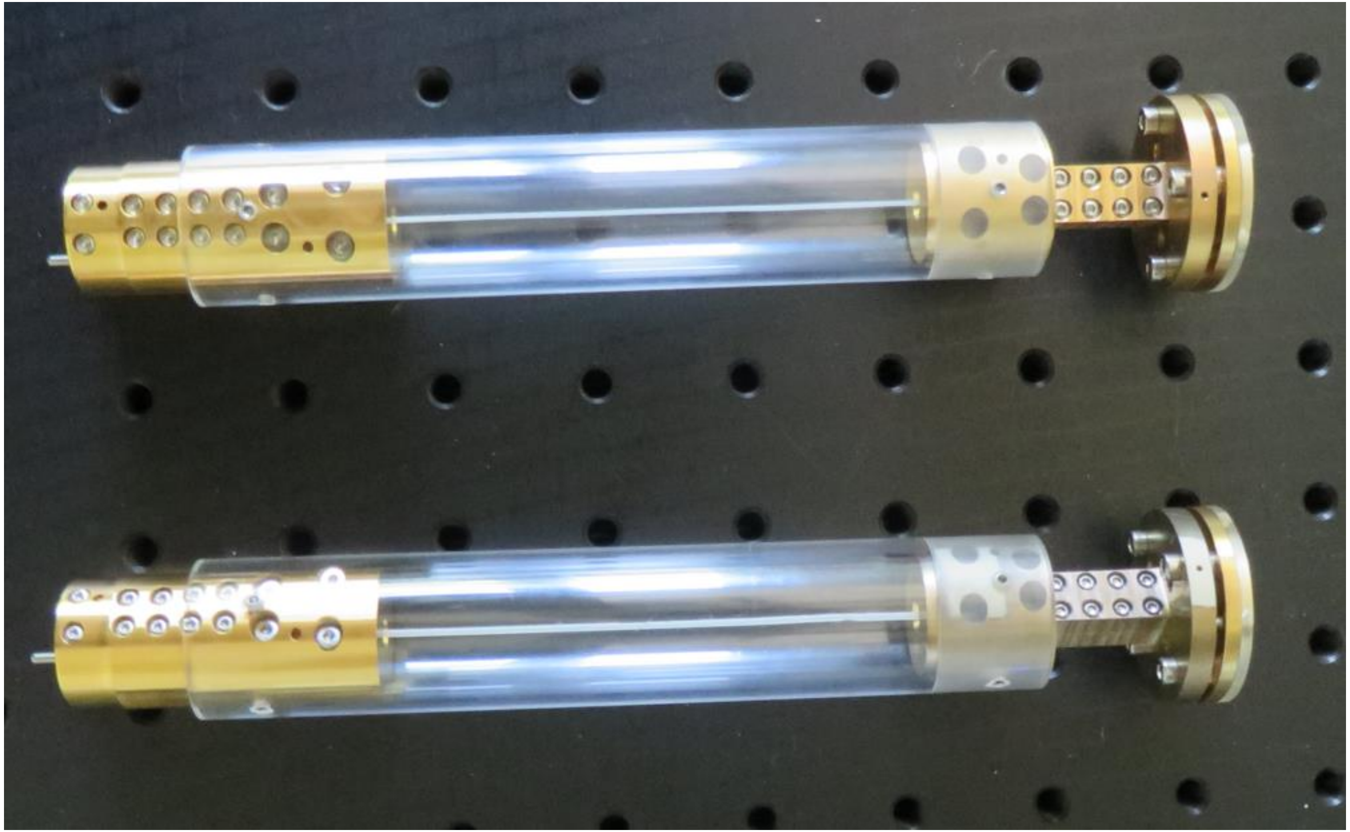
Fabricated Dielectric Wavegudie

Dielectric waveguide works also as thermal isolation

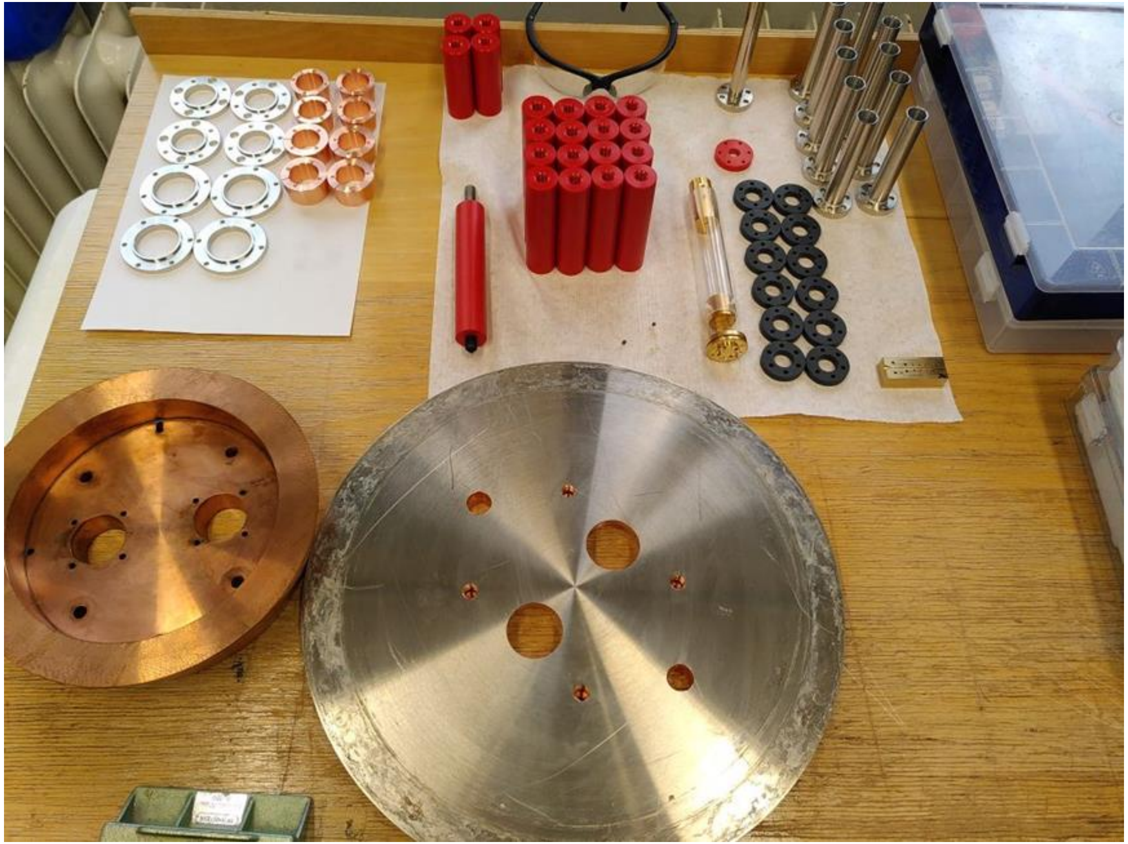
High-density polyethylene (HDPE) with dielectric constant (ϵ_r) : 2.3

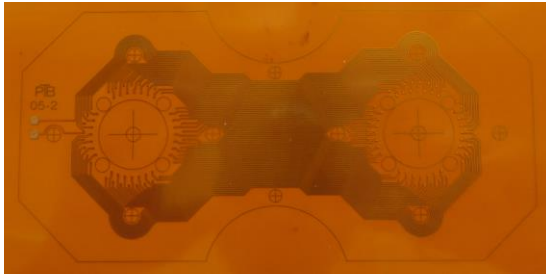
Rectangular dielectric
1.2954 mm x 0.6477 mm

Microcalorimeter Transmission Line

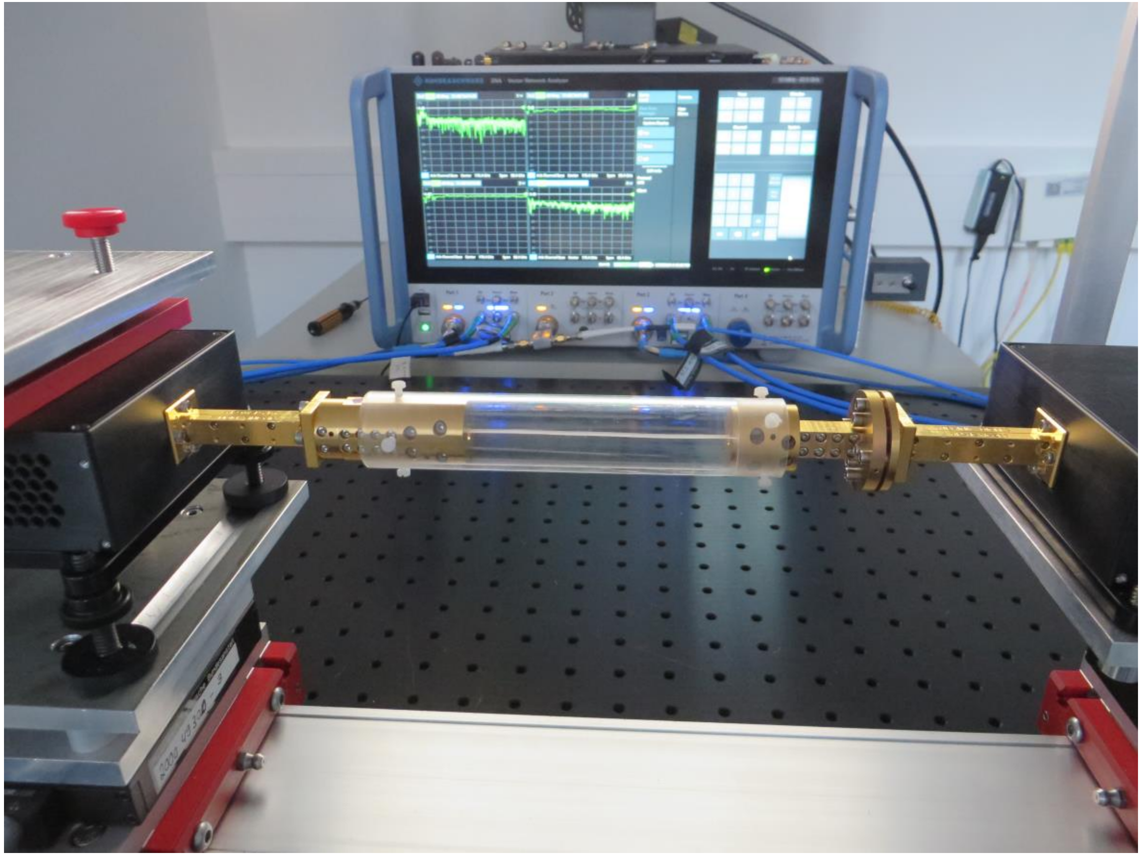


Microcalorimeter Parts

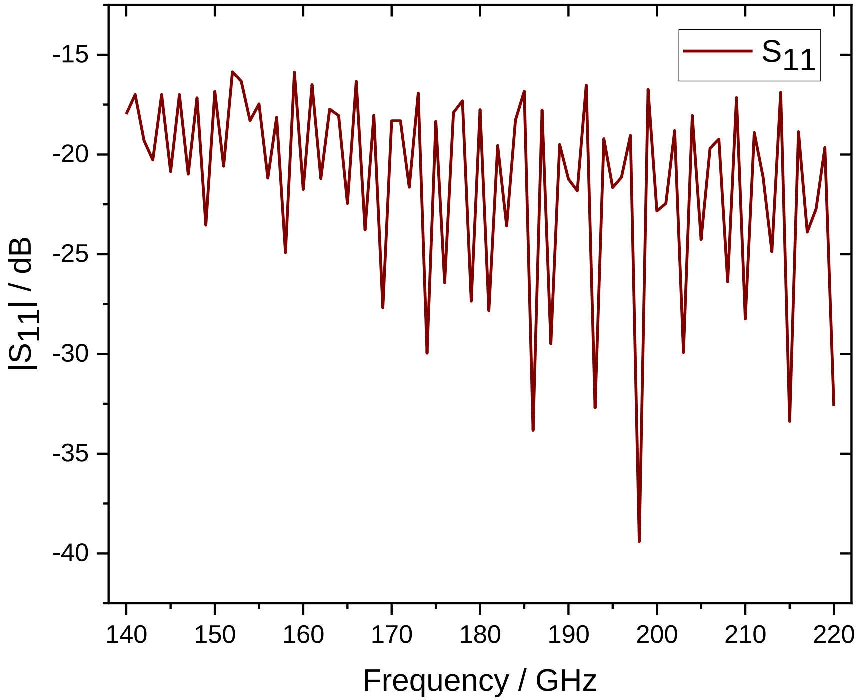


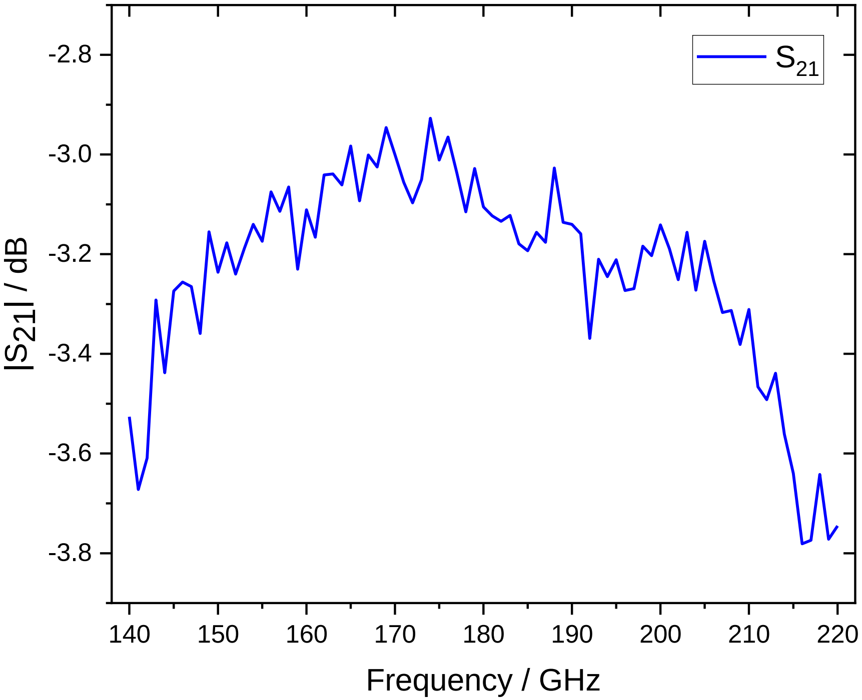


Microcalorimeter Transmission Line



S-parameter Measurement





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Conclusion and Outlook

- Transmission lines for an R 1.8k microcalorimeter have been produced with a good performance
- The transmission line can be applied as the feeding line of the R 1.8k waveguide microcalorimeter
- Ongoing and further work:
  - Integration of microcalorimeter parts
  - Characterization of microcalorimeter and associated transfer standard
  - Comparison of the R 1.8k waveguide microcalorimeter with R 1.4k waveguide microcalorimeter

Acknowledgment

2.2 Thomas Baron (manufacturing), Florian Rausche (measurements)

2.4 Alexander Fernandez Scarioni (gold plating)

5.5 Steffen Weiß (gold plating)

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THANK YOU

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