Terahertz Waveguides and Interfaces – Current Progress in Standardization

Hans-Ulrich Nickel

SPINNER GmbH, Munich, Germany

Venue: 330. PTB-Seminar – Aktuelle Fortschritte von Kalibrierverfahren im NF- und HF-Bereich 2025

Date: 2025-05-07

Location: Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Outline

- Introduction

- Waveguide Systematics / Examples / Standardization
  - Metallic Waveguides
  - Dielectric Waveguides
  - Quasioptical Beam Waveguides

- Bibliography

Introduction

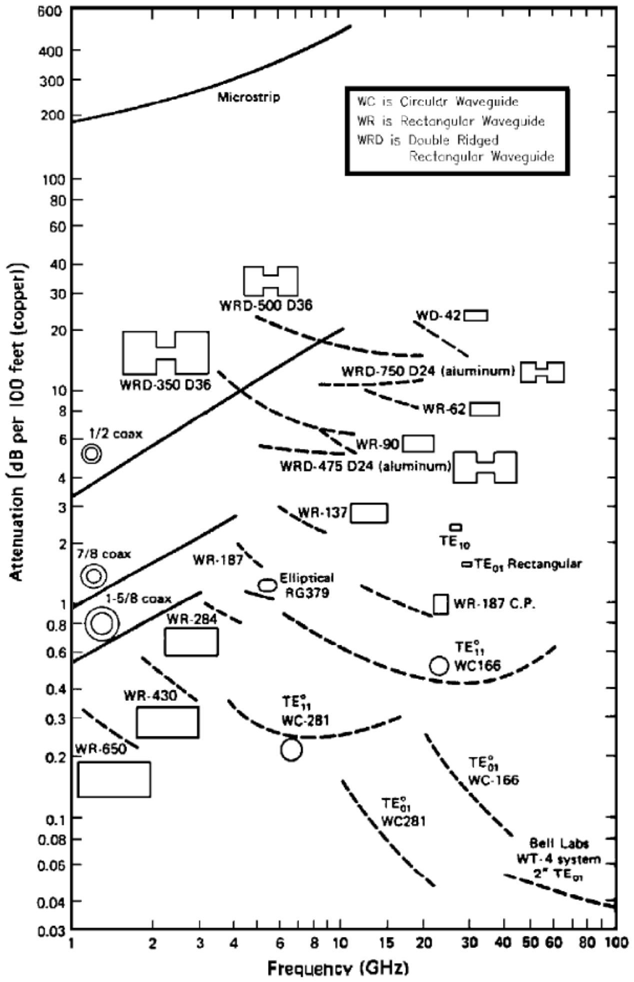
Microwave and Terahertz Frequencies

Typical microwave waveguides

TEM and quasi-TEM lines
- coaxial
- microstrip, coplanar

metallic hollow w/g
- ordinary rectangular (WR)
- circular (WC)
- elliptical
- double-ridge rect. (WRD)

Basic literature: [A], [B], and [C]



Typical terahertz waveguides

TEM and quasi-TEM lines
- coaxial
- coplanar

metallic hollow w/g
- ordinary rectangular
- circular

dielectric w/g

quasioptical beam w/g

Introduction

Standardization Bodies

IEC

International Electrotechnical Commission

Commission électrotechnique internationale

Abbreviation	IEC
Formation	26 June 1906, 118 years old
Type	Standards organization
Legal status	Swiss association[1]
Purpose	Standardization for electrical technology, electronics and related fields.
Headquarters	Geneva, Switzerland
Location	[show] List
Membership	89 countries [show]
Official languages	English, French
President	Jo Cops[2]
General Secretary	Philippe Metzger[2]
Website	www.iec.ch

IEEE

Institute of Electrical and Electronics Engineers

IEEE Advancing Technology for Humanity

Abbreviation	IEEE
Founded	January 1, 1963; 62 years ago
Type	Professional association
Tax ID no.	13-1656633[1]
Legal status	501(c)(3) public charity
Focus	Electrical, electronics, communications, and computer engineering[2]
Location	3 Park Avenue, New York City, U.S.[3]
Origins	Merger of the American Institute of Electrical Engineers and the Institute of Radio Engineers
Method	Industry standards, conferences, publications
Members	460,000+
Key people	Kathleen A. Kramer (President & CEO)[4]
Revenue	US$584 million (2023)[5]
Website	www.ieee.org

EIA

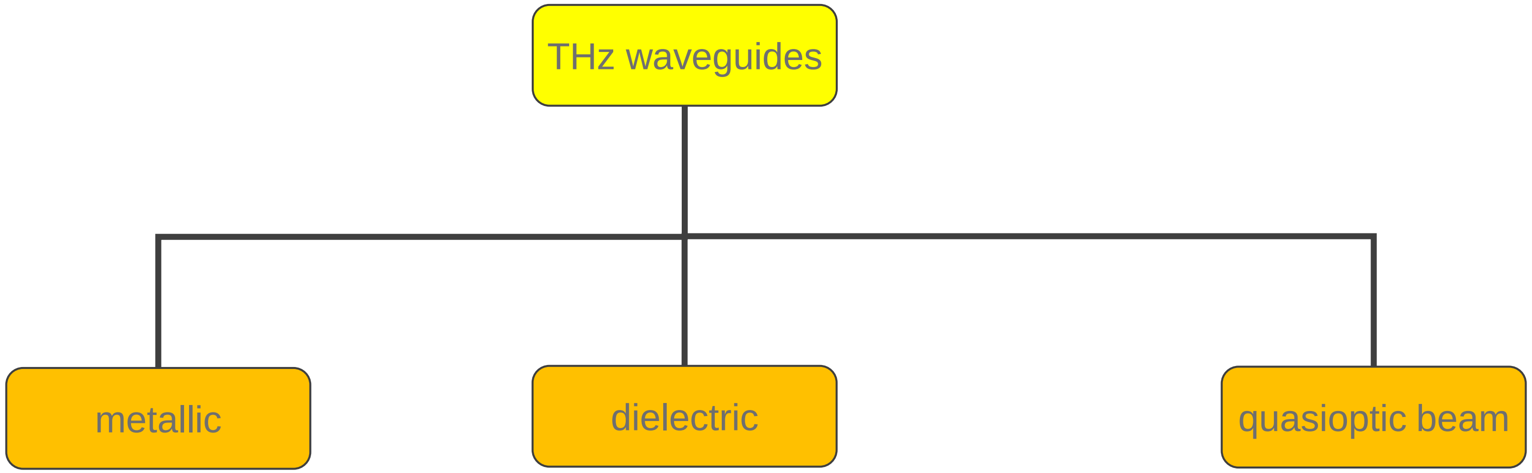
Electronic Components Industry Association, USA

MIL

Department of Defense, USA

Systematics [1]

THz Waveguides



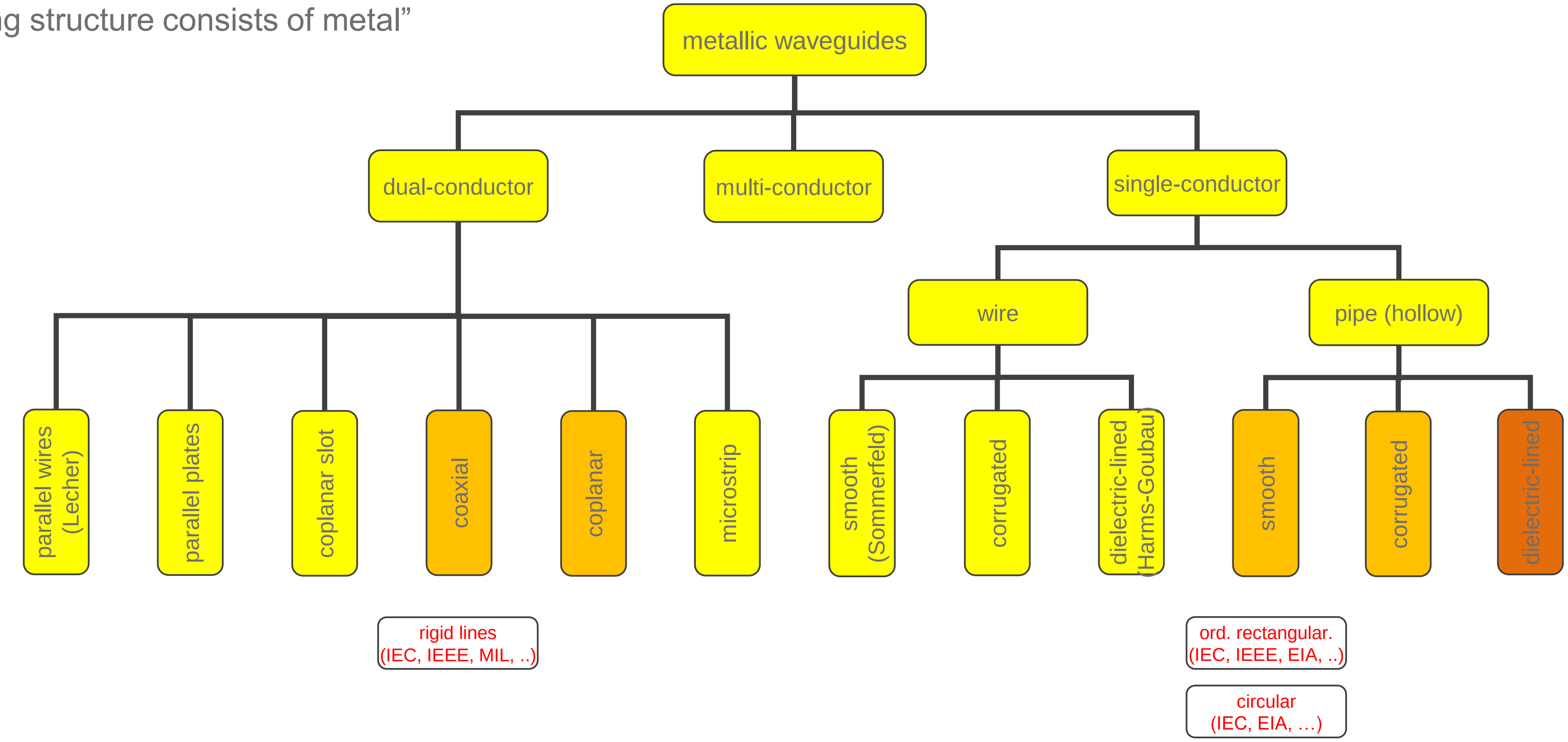
Definitions:

- metallic: “Basic guiding structure consists of metal”
- dielectric: “Basic guiding structure consists of dielectric”
- quasioptic beam: “Gaussian free space beam without guiding structure”

Systematics [1]

THz Metallic Waveguides

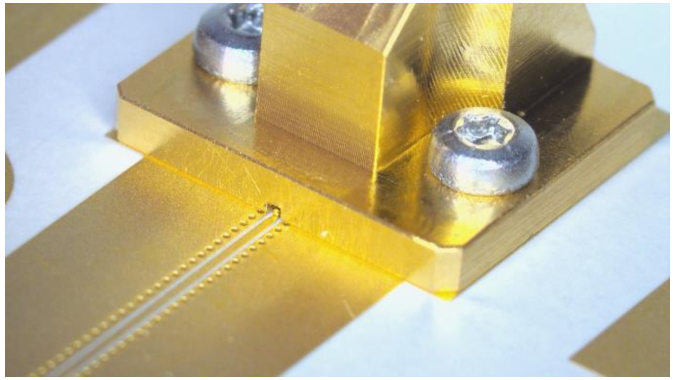
“Basic guiding structure consists of metal”

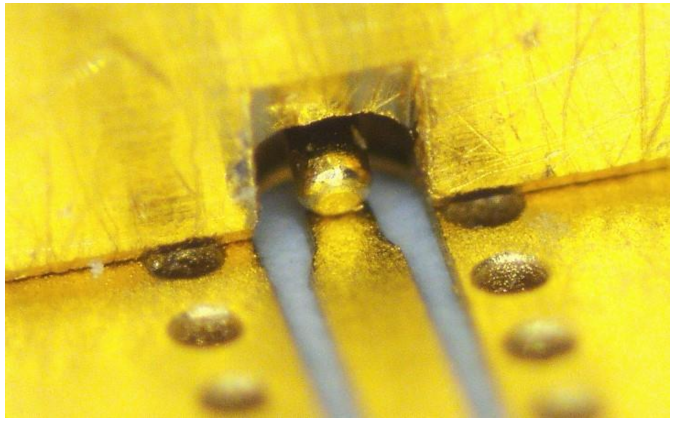


Examples

THz Coaxial and Coplanar Lines and Connectors

0.8 mm coaxial connector and coplanar connector on a PCB adapter for DC to 167 GHz (SPINNER GmbH, Munich, Germany).

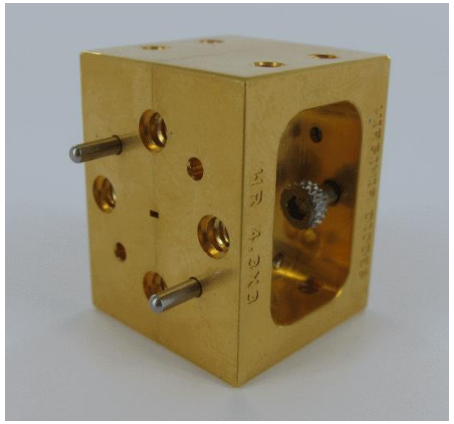




Examples

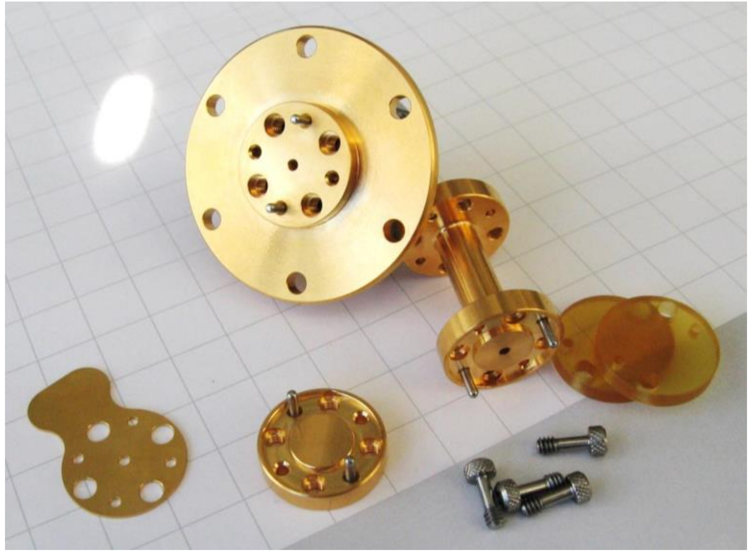
THz Hollow Metallic Waveguides and Interfaces

R 900 (WR 10) for 75 to 110 GHz: PCB adaptor, brazed w/g section, milled w/g section, λ/4-shim (SPINNER GmbH, Munich, Germany)



R 2.2k (WR 4.3) on a frequency tripler for 170 to 260 GHz (Virginia Diodes Inc., Charlottesville, VA, USA)

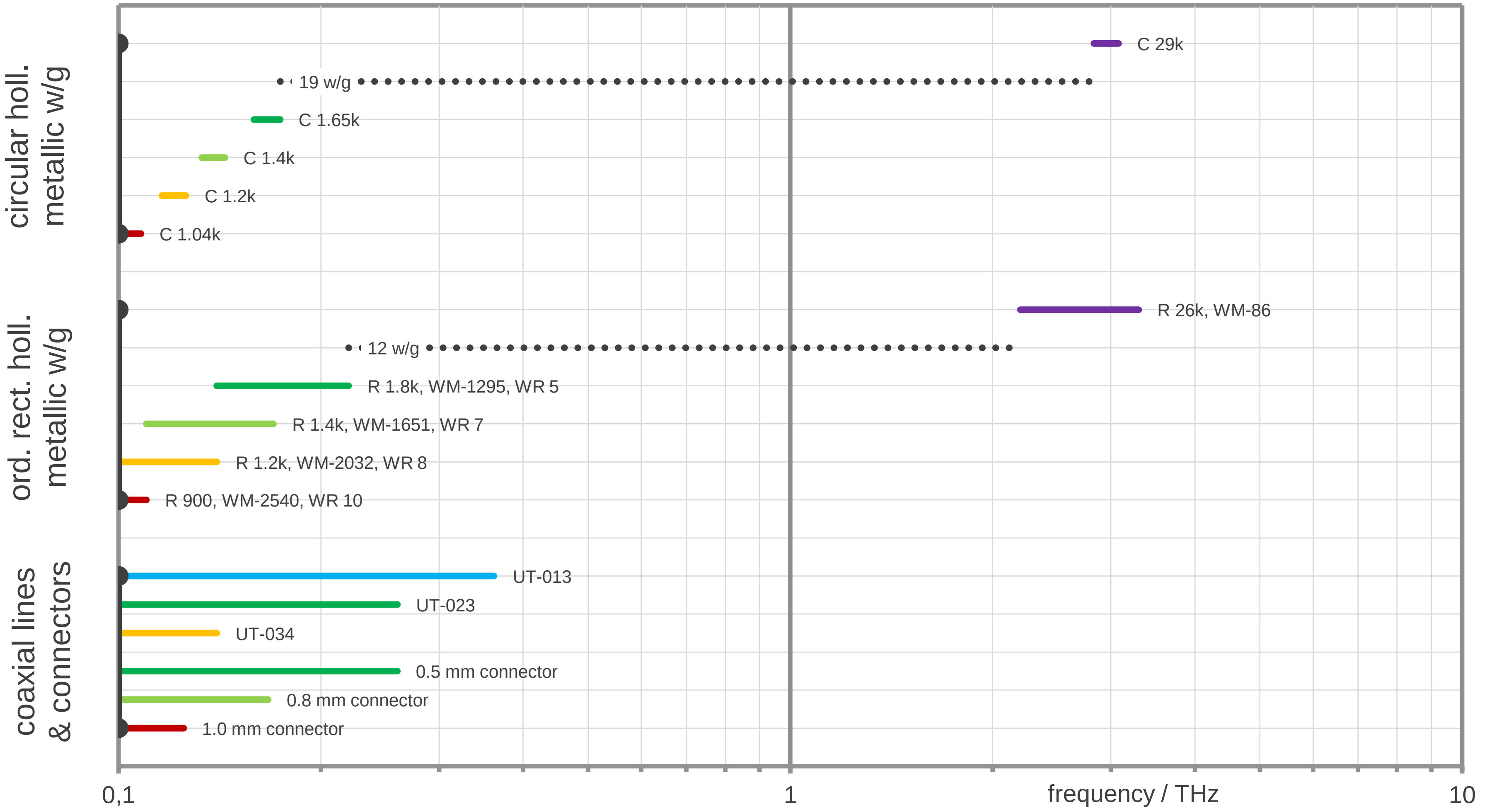
R 5k (WR 1.9) on a frequency doubler for 400 to 600 GHz (Virginia Diodes Inc., Charlottesville, VA, USA)



WC 6.7 (approx. C 1.27k) on a rotary joint for 110 GHz to 210 GHz, a w/g straight, and a λ/4-shim (SPINNER GmbH, Munich, Germany)

Standardization

THz Metallic Waveguides and Interfaces



Standardization

THz Coaxial Lines and Connectors

topic	std, available	std project	note
semi-rigid cables	factory stds only	no IEEE or IEC projects	modified MIL-DTL-17 type cables, mostly with low-density PTFE dielectrics
1.0 mm connector	IEC 61169-31:1999 [2]	-	almost up to date
	IEEE 287.1-2021 Annex L [4]	-	up to date
0.8 mm connector	IEC 61169-64:2019 (ED1) [3]	P-IEC 61169-64 ED2	→ CC; publ. 2026
	IEEE 287.1-2021 Annex M [4]	-	up to date
0.5 mm connector	factory std only	no IEEE or IEC project	std not foreseeable

Standardization

THz Hollow Metallic Waveguides and Interfaces

topic	std, available	std project	note
w/g, ordinary rectangular, family	IEC 60153-2:2016 (ED3) [5]	P-IEC 60153-2 ED4	→ FDIS; publ. 2026
	IEEE 1785.1-2012 [6]	IEEE P1785.1	→ balloting; publ. ?
w/g, circular, family	IEC 60153-4:2022 (ED4) [7]	-	up to date
i/f for ordinary rectangular w/g	IEC 60154-2:2016 (ED4) [8]	-	to be revised
	IEEE 1785.2-2016 [9]	IEEE P1785.2	just started
universal i/f for w/g *	-	IEEE P3136	requirements compl.; project halted for alignment with P1785.2

* New interface family shall

- accept hollow metallic w/g of any cross-section (size, shape)
- accept dielectric w/g with metallic shielding
- small cross section
- truly suitable for frequencies above 1 THz

IEEE P3136
rface Requirement

Examples

THz Hollow Metallic Waveguides with Corrugated Walls

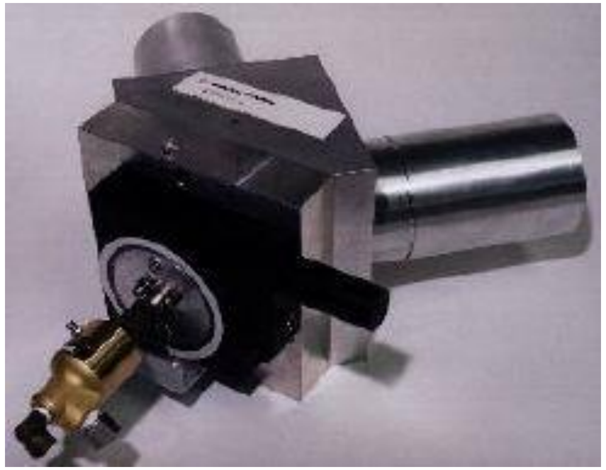
Propagation: fundamental **HE_{11} mode** in a multi-mode regime

Features: weak dispersion, medium-banded ($f_o/f_u \approx 2$), low-loss, tightly confined

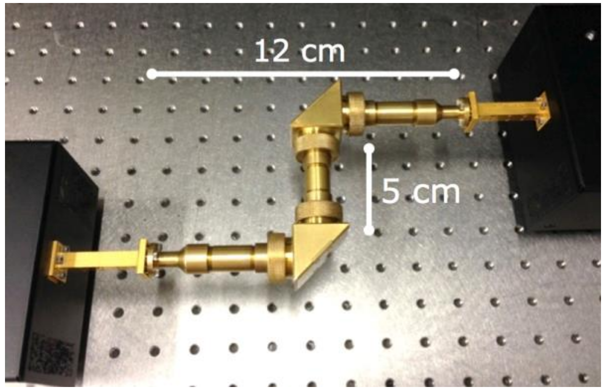
Standards: none

Highly over-moded w/g for high-power transmission at various mm-wave frequencies (General Atomics, San Diego, CA, USA)

Moderately over-moded w/g adapter for 500 to 750 GHz (SWISSto12 SA, Lausanne, Switzerland)



Highly over-moded w/g (88.9 mm) for 110 GHz on a high-power vacuum miter bend with water-cooled remote-controlled polarizer (General Atomics, San Diego, CA, USA)



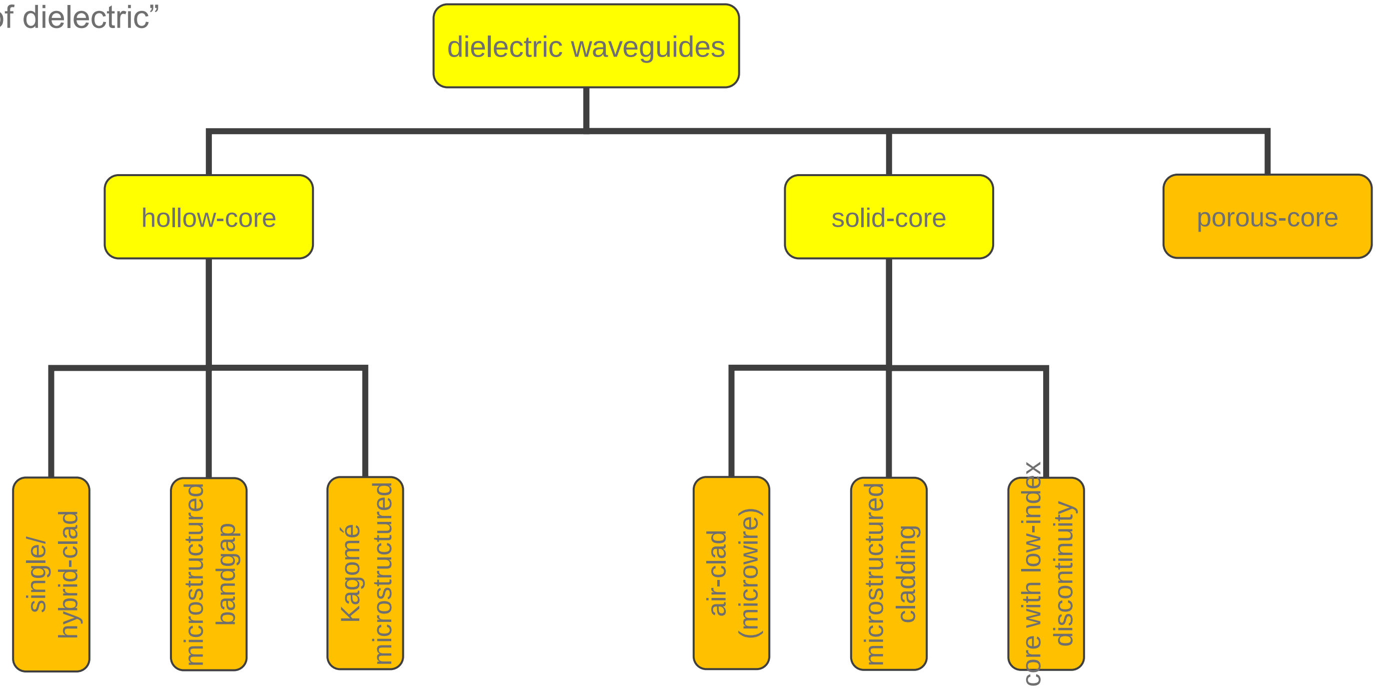
Moderately over-moded w/g line run for 500 to 750 GHz (SWISSto12 SA, Lausanne, Switzerland)

Systematics [1]

THz Dielectric Waveguides

“Basic guiding structure consists of dielectric”

Basic literature: [D] and [E]



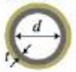
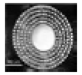
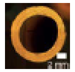
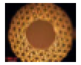
Guiding mechanism:

total external reflection
metal: reflection
dielectric: antiresonance
metamaterial: bandgap antiresonance

total internal reflection since average refractive index of core exceeds that of cladding

Examples

THz Hollow-Core Waveguides

Waveguide	Dimensions	Material	α_{eff} [cm^{-1}]	Remarks
Single clad 	$d = 8$ mm, $t = 0$ 12 mm, $l = 30$ cm	PVDF	0 015 (ave) ($1 < f < 2$ THz)	Loss 3 times lower than Ni–Cu pipe
	$d = 9$ mm, $t = 0$ 5 mm, $l = 3$ m	Teflon	<0 02 (0 34 $< f <$0 53 THz) ≈8 × 10^{-4} $f = 0$ 4 THz	Mode: HE$_{11}$ 200–300 GHz bandwidth
Hybrid clad 	$t = 10$ μm, $d = 2$ 2 cm, $l = 30$ 90 cm	Ag/PS coated	<0 002 $f = 2$ 5 THz	Mode: TE$_{01}$ or TE$_{11}$; thickness of the coating determines the lowest loss mode
	$t = 26$ μm, $d = 3$ mm, $l = 30$ & 100 cm	Ag/PE coated	<4 × 10^{-3} (1 2 $< f <$ 2 THz) ≈3 2 × 10^{-3} $f = 1$ 5 THz	3 dB lower than Ag pipe
Microstructured band-gap 	$\Lambda = 900$ μm, $d = 882$ μm, $t = 9$ μm, $R_c = 2$ 7 mm	Teflon HDPE	<0 01 (0 895 $< f <$1 145 THz) ≈0 005 $f = 1$ THz < 0 01 (0 82 $< f <$ 1 02 THz) ≈0 0035 $f = 1$ THz	Only theoretical results reported Mode: HE$_{11}$ (multimode) Dispersion: <2 ps/nm/km Confinement loss: 0 1 dB/m narrow transmission bandwidth
Bragg 	$D_{core} = 1$ mm, $l = 1$ m 31 layers of PVD/PC t of each layer ≈50 μm	PVDF & PC	<0 02 ($1 < \omega < 3$ THz)	Only theoretical results reported Mode: HE$_{11}$ (TEM) Different guiding mechanisms
	$D_{core} = 16$, 20 & 30 mm, $d_{air} = 0$ 5, 0 7 & 2 25 mm, $d_{material} = 25$, 70 & 150 μm, $l = 28$ cm	HDPE	<2 × 10^{-5} (0 3 $< f <$4 3 THz) ≈2 × 10^{-6} $f = 3$ 34 THz	Only theoretical results reported Mode: TE$_{01}$ The frequency range is covered by three different waveguides
	$D_{core} = 670$ μm, $l < 1$ 5 cm $D_{fiber} = 6$ 3 & 5 6 mm	PMMA	1 3 (ave) (0 8 $< f <$ 1 4 THz) ≈0 4 $f = 1$ THz 1 1 (ave) ($1 < f <$1 6 THz) ≈0 2 $f = 1$ 3 THz	Mode: HE$_{11}$ (TEM) Ave: average loss values THz radiation propagates both in the core and in the cladding
	$D_{core} = 6$ 73 mm, $l = 21$ 4 cm 10 layers of $d_{air} = 150$ μm, $d_{material} = 254$ μm	PTFE	<0 3 (0 1 $< f <$ 2 THz) ≈0 028 $f = 0$ 82 THz	Lower mode (HE$_{11}$) losses compared to doped PE Bragg Multimode propagation
	$D_{core} = 6$ 33 mm, $l = 22$ 5 cm 12 layers of $d_{mat1} = 100$ μm, $d_{mat2} = 135$ μm	PE & TiO_2 doped PE	<0 3 (0 1 $< f <$ 2 THz) ≈0 042 $f = 0$ 69 THz	Less clear transmission window compared to air-PE Bragg Multimode propagation
Kagomé 	$D_{core} = 5$ 5 mm, $l = 20$ cm, tubes In/out diameters: 1 68/2 08 mm	Teflon tubes	< 0 01 ($f = 0$ 77 THz)	Mode: HE$_{11}$ (multimode) $d \propto$ minimum loss $t \propto$ bandwidth
	$D_{core} = 6$ 33 mm, $l = 15$ 45 mm 12 layers of $d_{core} = 1$ 6 & 2 2 mm, $d_{fiber} = 5$ & 6 8 mm	PMMA	0 6 (ave) (0 65 $< f <$ 1 THz)	Mode loss ≈20 times less than clad-PMMA loss Ave: average loss values

taken from [D]

Propagation: **low-order mode** in a moderately over-moded regime

Features: weak dispersion, narrow-banded, low-loss, tightly or moderately confined

Standards: none

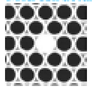
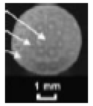
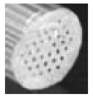
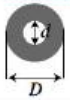
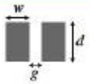
Examples

THz Solid-Core Waveguides

Propagation: **low-order mode** in a moderately over-moded regime

Features: moderately dispersive, medium-banded, lossy, weakly confined

Standards: none

Waveguide	Dimensions	Material	α_{eff} [cm^{-1}]	Dispersion	Remarks
	$D = 150, 250, \& 325$ µm, $l = 7 3, 7 8 \& 8 3$ mm	Sapphire	<6 (f<2 5 THz)	0 6 ps → 10–13 ps	Mode: HE_{11}
	$D = 200$ µm, $l = 6, 13, 17 5$ cm	PE	<0 01 (0 35 < f < 0 35 THz)	No value reported	Different regimes of guidance in the transmission band
	$b = 150 \& 120$ µm, $a = 2$ cm, $l = 10 \& 20$ mm	HDPE	<1 (0 1 < f < 3 5 THz)	1 ps → 20, 40 ps	Mode: TM_0
Microstructured 	$D_{core} = 500$ µm, tubes in/out diameters: 0 5/0 55 mm, $l = 2$ cm	HDPE	<0 5 (0 1 < f < 3 THz) ≈0 2 (f = 1 THz)	0 8 ps → 5 ps ≈14 (f = 0 25 THz) ≈2 (f = 0 4 THz) ≈0 (f = 0 5 THz) ≈ −0 3 (f > 0 6 THz)	Mode:HE_{11} Dispersions are in ps/THz/cm
	$D_{core} = 1$ mm, tubes in/out diameters: 0 25/0 75 mm, $l = 5, 10, \& 15$ cm	Teflon	<0 12 (0 1 < f < 1 3 THz)	No value reported	Mode:HE_{11} Knife-edge measurements to test the confinement of THz radiation
	$D_{hole} = 250$ µm, $\Lambda = 560$ µm, $l = 29$ mm	COC	<0 1 (0 35 < f <0 65 THz) ≈0 02 (f = 0 6 THz)	<1 (0 4 < f <1 4 THz) ≈0 (0 5 < f <0 6 THz)	Mode:HE_{11} Dispersion parameters β_2 are in ps/THz/cm
	$D_{core} = 400$ 600 µm, $D_{fiber} = 3$ 4 mm, $l = 20$ 70 mm	COC	<0 3 (0 2 < f < 1 THz)	<1 (0 4 < f < 1 2 THz) ≈0 (0 7 THz)	Mode loss (HE_{11}) equal to material loss dispersion parameter β_2 is in ps/THz/cm
Low index discontinuity 	$D = 181 5$ µm, $d = 27$ µm, $l = 30 \& 40$ mm	Silica	<0 7 (0 4 < f < 0 6 THz)	$2 < \varepsilon_{eff} < 4$ (0 3 < f < 0 7 THz)	Mode: HE_{11}
	$g = 15$ µm, $w = 45$ µm, $h = 75$ µm	High-resistivity silicon	<0 01 (0 5 < f < 0 9 THz)	$1 < \varepsilon_{eff} < 2$ (0 5 < f < 0 9 THz)	Mode: quasi TE (analogous to TM mode in slab waveguides) Only theoretical results reported

taken from [D]

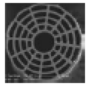
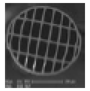
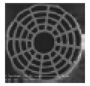
Examples

THz Porous-Core Waveguides

Propagation: **low-order mode** in a moderately over-moded regime

Features: weak dispersion, medium-banded, moderately lossy, weakly confined

Standards: none

Waveguide	Dimensions	Material	α_{eff} [cm^{-1}]	n_{eff}	Remarks
	$D = 200$ 300 µm, $l = 15$ 25 mm, Porosity = 57%	PMMA	——	$n_{eff} < 1$ (0 35 < f < 0 8)	Extrusion technique Uncertainty in the loss measurement due to cleaving
	$D = 350$ µm, $l = 30$ 39 mm, Porosity = 64%	PMMA	——	$n_{eff} < 1$ 05 (0 35 < f < 0 8)	Birefringence 0 012 at 0 65 THz
	$D = 350$ µm, $l = 6$ 13 cm, Porosity = 40%	PE	0 001 at $f = 0$ 3 THz	——	Directional coupler technique Detector: bolometer Only loss reported
	$D = 775$ µm, $l = 23$ 38 cm, Porosity = 86%	PE	<0 05 (0 18 < f < 0 3 THz)	——	Deformation of structure during draw Only loss reported
	$D = 600$ µm, $l = 75$ 95 mm, Porosity = 64%	COC	<0 08 (0 2 < f < 0 35 THz)	$n_{eff} < 1$ 05 (0 2 < f < 0 35 THz)	Detector: near-field probe-tip Both waveguide parameters reported

taken from [D]

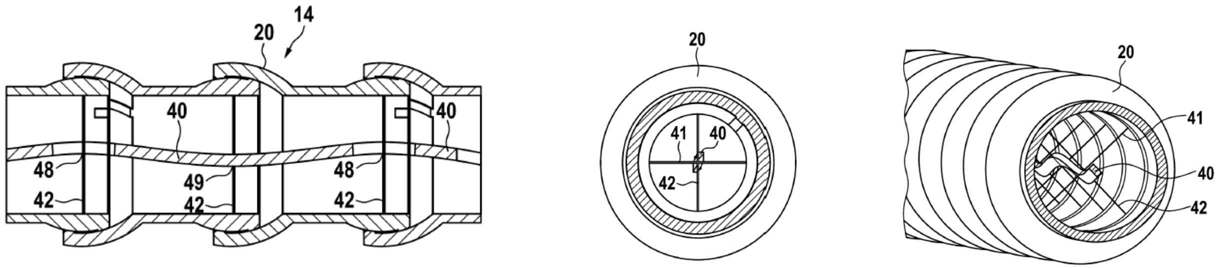
Examples

THz Solid-Core Waveguide with Air Cladding

Propagation: fundamental **HE_{11} mode** in a moderately over-moded regime

Features: weak dispersion, medium-banded ($f_o/f_u \approx 2$), low-loss, weakly confined

Standards: none



Rectangular HDPE ribbon (40) centered within a segmented protective polymer tube (20) by thin polymer strings (41, 42) (SPINNER GmbH, Munich, Germany, [10])

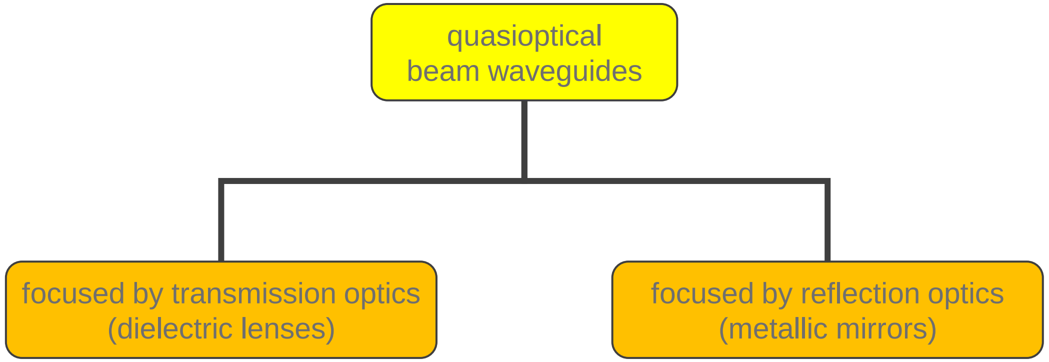
Flexible dielectric w/g with integrated transitions to R 900 (WR 10) metallic w/g (60 cm, 75 to 110 GHz, SPINNER GmbH, Munich, Germany, [10])

Systematics [1]

THZ Quasioptical Beam Waveguides

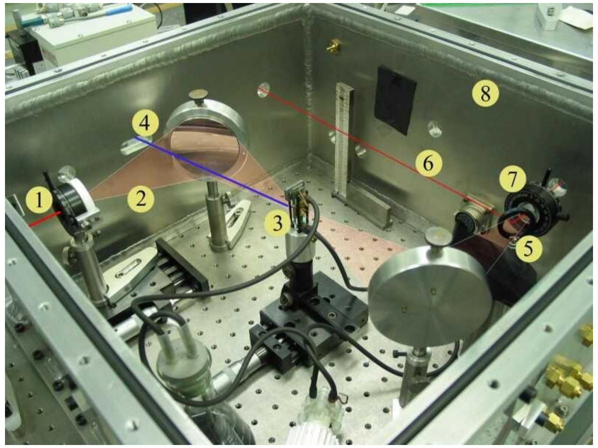
“Gaussian free space beam without guiding structure”

Basic literature: [F]

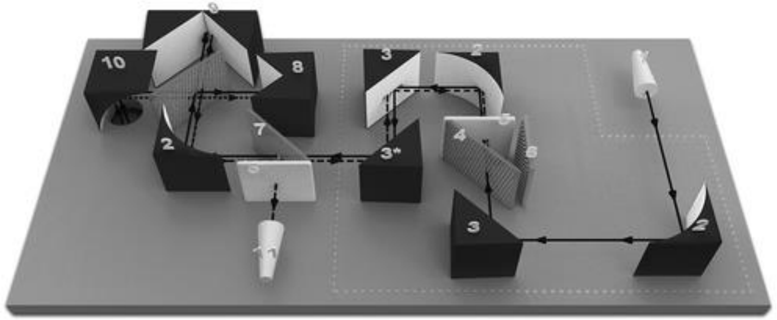


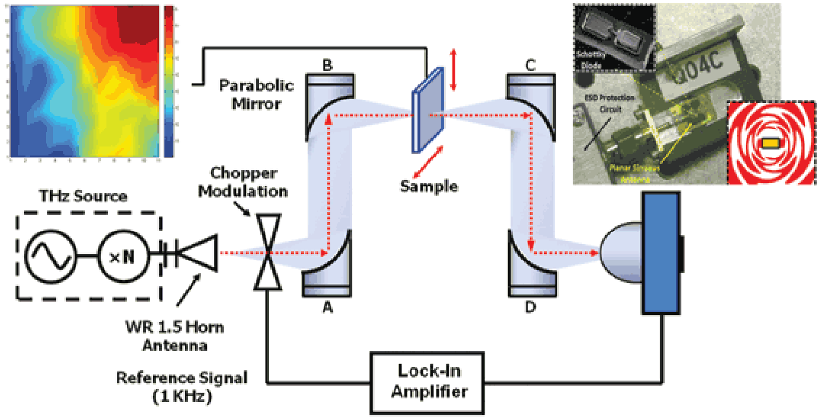
Examples

THz Quasioptical Beam Waveguides for Low Power



Typical quasioptical mirror lines
in low power test set-ups





Propagation: fundamental **Gaussian TEM$_{00}$ mode** in a multi-mode regime

Features: non-dispersive, wide-banded (f_o/f_u > 10 achievable), low-loss

Standards: none

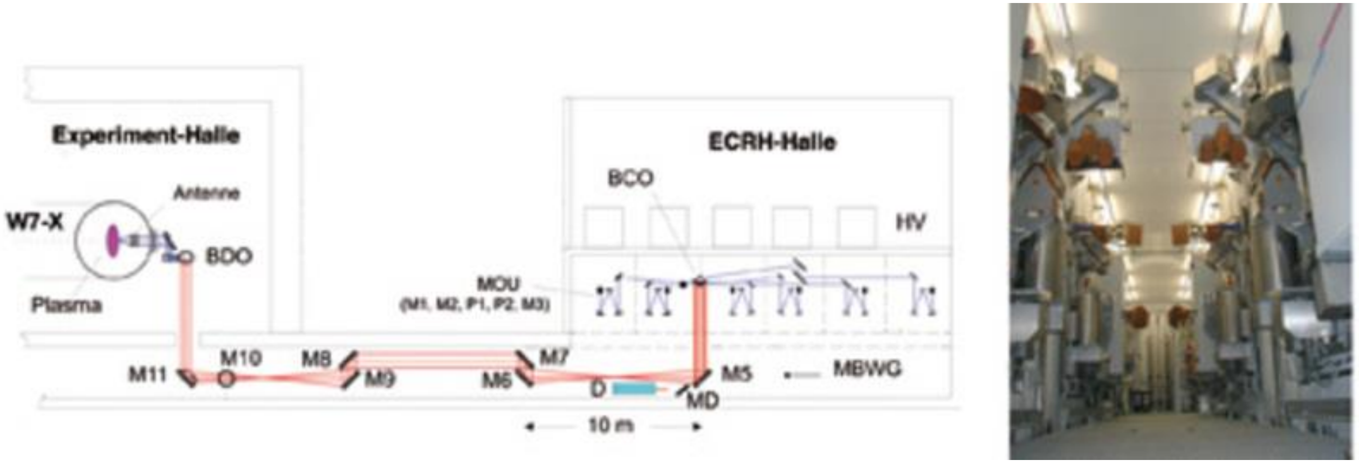
Examples

THz Quasioptical Beam Waveguides for High Power

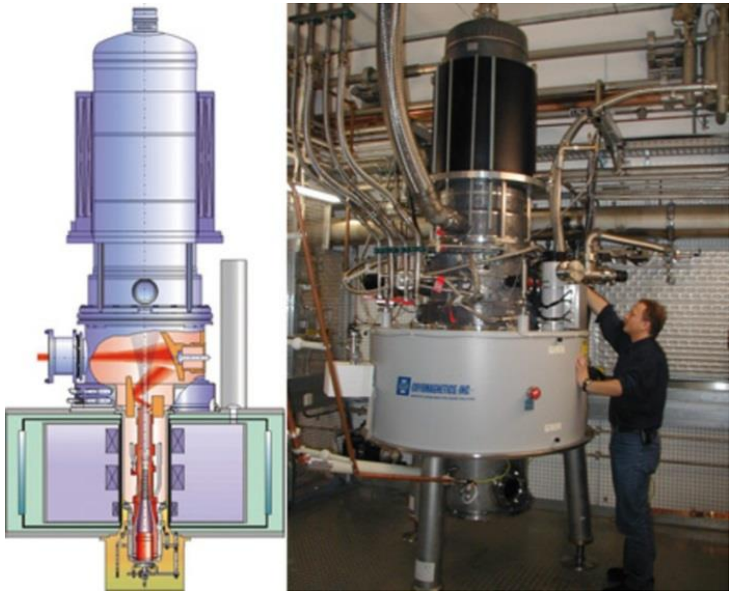
Propagation: fundamental **Gaussian TEM_{00} mode** in a multi-mode regime

Features: non-dispersive, wide-banded (f_o/f_u > 10), low-loss

Standard: none



Quasioptical multi-beam w/g for 140 GHz at a plasma fusion experiment (7 beams per 1 MW, Stellarator W7-X, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany)



Quasioptical beam output on a 1 MW gyrotron oscillator at 140 GHz (Stellarator W7-X, Max-Planck-Institut für Plasmaphysik, Greifswald, Germany)

Bibliography

References

[1] Nickel, H.-U., “Terahertz Waveguides and Interfaces – A Review”, *Meeting of VDE-ITG Fachausschuss 7.2 (Funksysteme)*, May 2016, Darmstadt, Germany.

[2] IEC 61169-31:1999, “Radio-frequency connectors – Part 31: RF coaxial connectors with inner diameter of outer conductor 1,0 mm (0,039 in) with screw coupling – Characteristic impedance 50 ohms (type 1,0)”, *Standard of the International Electrotechnical Commission*, Edition 1, September 1999.

[3] IEC 61169-64:2019, “Radio-frequency connectors – Part 64: Sectional specification – RF coaxial connectors with 0,8 mm inner diameter of outer conductor – Characteristic impedance 50 Ω (type 0,8)”, *Standard of the International Electrotechnical Commission*, Edition 1, September 2019.

[4] IEEE Std 287.1-2021, “Precision Coaxial Connectors at RF, Microwave, and Millimeter-Wave Frequencies – Part 1: General Requirements, Definitions, and Detailed Specifications”, *Standard of the Institute of Electrical and Electronics Engineers*, December 2021.

[5] IEC 60153-2:2016, “Hollow metallic waveguides, Part 2: Relevant specifications for ordinary rectangular waveguides”, *Standard of the International Electrotechnical Commission*, Edition 3, May 2016.

[6] IEEE Std 1785.1-2012, “Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above – Part 1: Frequency Bands and Waveguide Dimensions”, *Standard of the Institute of Electrical and Electronics Engineers*, March 2013.

[7] IEC 60153-4:2022, “Hollow metallic waveguides, Part 4: Relevant specifications for circular waveguides”, *Standard of the International Electrotechnical Commission*, Edition 4, June 2022.

[8] IEC 60154-2:2016, “Flanges for waveguides – Part 2: Relevant specifications for flanges for ordinary rectangular waveguides”, *Standard of the International Electrotechnical Commission*, Edition 3, July 2016.

[9] IEEE Std 1785.2-2016, “Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above – Part 2: Waveguide Interfaces”, *Standard of the Institute of Electrical and Electronics Engineers*, March 2016.

[10] Nickel, H.-U., and Zovo, J., “Novel flexible dielectric waveguide for millimeter and sub-millimeter frequencies – Design and characterization”, *Proc. 84th ARFTG Microwave Measurement Conference*, December 2014, Boulder, Colorado, USA.

Bibliography

Basic Literature

[A] SPINNER GmbH, “HF-Kurs Lektion 5.1: passive HF-Komponenten – technische Leitungen; Verbinder; Übergangsstücke”, in Nickel, H.-U. (Editor), “Grundlagen der Hochfrequenztechnik – HF-Kurs”, *Course Documentation TD-00143*, Issue C, Munich, Germany, 2021.

[B] SPINNER GmbH, “Cross reference for hollow metallic waveguides”, *Technical Information TD-00036*, Issue V, Munich, Germany, 2025, download: https://www.spinner-group.com/images/download/technical_documents/SPINNER_TD00036.pdf

[C] SPINNER GmbH, “Flanges for ordinary rectangular waveguides”, *Technical Information TD-00077*, Issue L, Munich, Germany, 2022, download: https://www.spinner-group.com/images/download/technical_documents/SPINNER_TD00077.pdf

[D] Atakaramians, S., Afshar V., S., Monro, T.M., and Abbott, D., “Terahertz dielectric waveguides”, *Advances in Optics and Photonics*, Vol. 5, pp. 169-215, 2013.

[E] Yeh, C., and Shimabukuro, F., *The Essence of Dielectric Waveguides*, Springer Science+Business Media, New York, NY, USA, 2008.

[F] Goldsmith, P.F., *Quasioptical Systems – Gaussian Beam Quasioptical Propagation and Applications*, IEEE Press, Piscataway, NJ, USA, 1997.

Contact SPINNER

SPINNER GmbH
Headquarters
Erzgiessereistr. 33
80335 Munich
GERMANY

Phone: +49 89 12601-0
info@spinner-group.com

spinner-group.com