



IEEE Recommended Practice for Precision Coaxial Connectors at RF, Microwave, and Millimeter-Wave Frequencies—Part 3: Connector Effects, Uncertainty Specifications, and Recommendations for Performance

IEEE Instrumentation and Measurement Society
of the
High Frequency Measurement Committee

IEEE Microwave Theory and Techniques Society
of the
Standards Coordinating Committee

IEEE Std 287.3™-2021

IEEE Recommended Practice for Precision Coaxial Connectors at RF, Microwave, and Millimeter-wave Frequencies-Part 3: Connector Effects, Uncertainty Specifications, and Recommendations for Performance

Developed by the

High Frequency Measurement Committee
of the
IEEE Instrumentation and Measurement Society

and the

Standards Coordinating Committee
of the
IEEE Microwave Theory and Techniques Society

Approved 8 December 2021

IEEE SA Standards Board

Abstract: The P287 series of documents presents the combined efforts of IEEE P287 Working Group that reflect the knowledge and experience of leading specialists in the development and measurement of precision coaxial connectors for RF, microwave, and millimeter-wave frequencies. It presents minimum performance requirements to standardize both hermaphroditic and pin-and-socket-type connectors (IEEE Std 287.1™). It provides a recommended practice for electrical and mechanical test procedures for Instrument Grade and Metrology Grade precision connectors (IEEE Std 287.2™, this document). Recommended reference procedures including connector effects, connector care and cleaning, connector repeatability and reproducibility test procedures, and a color code for connectors are detailed in the third part of the standard (IEEE Std 287.3™). The bibliography provides a list of pertinent references for measurement techniques used in determining electrical, mechanical, and dimensional parameters for coaxial connectors.

Keywords: IEEE 287.2™, instrument grade precision connector (IGC), metrology grade precision connector (MGC), minimum performance requirement, pin and socket connector, precision coaxial connector

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2022 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 16 September 2022. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-8277-6 STD25161
Print: ISBN 978-1-5044-8278-3 STDPD25161

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE SA) Standards Board. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA, and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning this standard, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE is the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter's views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and Standards Coordinating Committees are not able to provide an instant response to comments, or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not constitute compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

¹ Available at: <https://development.standards.ieee.org/myproject-web/public/view.html#landing>.

² Available at: <https://standards.ieee.org/content/ieee-standards/en/about/contact/index.html>.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

³ Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴ Available at: <https://standards.ieee.org/standard/index.html>.

Patents

IEEE Standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

IMPORTANT NOTICE

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. IEEE Standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

⁵ Available at: <https://standards.ieee.org/about/sasb/patcom/materials.html>.

Participants

At the time this IEEE recommended practice was completed, the Precision Coaxial Connectors Working Group had the following membership:

Ronald Ginley, *Chair*
Jon Martens, Nick Ridler, *Vice Chairs*

David Blackham
Richard Coppola
Rudy Fuks
Martin Grassl
Rolf Judaschke
Bob Hawkins
Alejandro Martín Henze

Johannes Hoffmann
Masahiro Horibe
Jeong Hwan Kim
Karsten Kuhlmann
Brian Lee
Jihan Mohammed
John Morelli

Rusty Myers
Hans-Ulrich Nickel
Sathya Padmanabhan
Juerg Ruefenacht
Mohamed Sayed
David Shaff
Ken Wong

The following members of the individual Standards Association balloting group voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

Gary Brown
Pin Chang
Euclides Chuma
Ronald Ginley
Alejandro Martín Henze

Werner Hoelzl
Martin Hudlicka
William Kefauver
Yeou Song Lee
Ting Li

Jon Martens
Bansi Patel
Shiva Rai
Nick Ridler
Walter Struppler

When the IEEE SA Standards Board approved this recommended practice on 8 December 2021, it had the following membership:

Gary Hoffman, *Chair*
Jon Walter Rosdahl, *Vice Chair*
John D. Kulick, *Past Chair*
Konstantinos Karachalios, *Secretary*

Edward A. Addy
Doug Edwards
Ramy Ahmed Fathy
J. Travis Griffith
Thomas Koshy
Joseph L. Koepfinger*
David J. Law

Howard Li
Daozhuang Lin
Kevin Lu
Daleep C. Mohla
Chenhui Niu
Damir Novosel
Annette Reilly
Dorothy Stanley

Mehmet Ulema
Lei Wang
F. Keith Waters
Karl Weber
Sha Wei
Howard Wolfman
Daidi Zhong

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 287.3-2021, IEEE Recommended Practice for Precision Coaxial Connectors at RF, Microwave, and Millimeter-wave Frequencies-Part 3: Connector Effects, Uncertainty Specifications, and Recommendations for Performance.

The IEEE 287 series of documents presents minimum performance requirements for precision coaxial connectors developed by the IEEE Subcommittee P287. The documents build on the previous version of the IEEE 287 standard. The main purpose of this rewrite is to modernize the standard to include drawings, mechanical and electrical tests, and include several new connector sizes that were not available when the standard was rewritten in 2007. The IEEE 287 series of documents has three parts. The first part, IEEE Std 287.1TM-2021 contains the specifications for all of the included coaxial connector types. IEEE Std 287.2TM-2021 is a recommended practice for all of the mechanical and electrical tests that are needed to verify the specifications of the connectors. The third part, IEEE Std 287.3TM-2021 (this document), is a recommended practice guide that contains a set of guidelines, practices, and information that should be useful to users of coaxial connectors.

The work in Clause 3 of this document, “Connector effects,” was funded through the European Metrology Research Programme (EMRP) Project SIB62 “Metrology for New Electrical Measurement Quantities in High-Frequency circuits.” The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

There are many different guides about the care and use of microwave connectors. The authors of Clause 4 of this document, “Connector care and handling guide,” would especially like to acknowledge the guides from Keysight Technologies [B25] and The Rohde & Schwarz Co. [B37].

Contents

1. Overview	10
1.1 Scope	10
1.2 Purpose	10
1.3 Word usage	10
2. Normative references	11
3. Connector effect	12
3.1 Introduction	12
3.2 Connector parametrization	13
3.3 Reflection and transmission coefficients	20
3.4 Sensitivity coefficients	23
3.5 Pin depth specifications and minimal pin gap	38
4. Connector care and handling guide	41
4.1 Introduction	41
4.2 Quick guide	41
4.3 Detailed guide for inspection and cleaning	42
4.4 Detailed guide for connection/disconnection	52
4.5 Handling and storage	56
5. Connector measurement repeatability and reproducibility	57
5.1 General	57
5.2 Data analysis	59
5.3 Level-1 <i>LM</i> repeatability standard deviations	59
5.4 Level-2 <i>LM</i> repeatability standard deviations	61
5.5 Level-3 repeatability of multiple connector artifacts over multiple test ports	61
5.6 Level-3 reproducibility of connector repeatability over multiple test ports	62
5.7 Connector repeatability and reproducibility algorithm pseudo code at a single frequency	62
6. Color coding guide	65
Annex A (informative) Bibliography	66

IEEE Recommended Practice for Precision Coaxial Connectors at RF, Microwave, and Millimeter-wave Frequencies-Part 3: Connector Effects, Uncertainty Specifications, and Recommendations for Performance

1. Overview

1.1 Scope

This recommended practice provides supplementary information that enhances the user's knowledge and promotes the proper use of precision coaxial connectors.

1.2 Purpose

The purpose of this recommended practice is to present information and tools that will inform coaxial connector users and will enhance users' use of coaxial connectors at RF, microwave, and millimeter-wave frequencies. Included is the latest research on the effects seen when connecting coaxial connectors together, a scheme for color coding different sizes of coaxial connectors, guidance for the care and handling of coaxial connectors, and details of how software can be used for looking at the effects and uncertainties encountered when connecting different tolerance connectors together.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{1,2}

¹ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

² The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

There are no normative references in this recommended practice.

3. Connector effect

3.1 Introduction

Comprehensive work on the SI traceability of S-parameter measurements (see Hoffman et al. [B34]) in the coaxial line system has led to the realization that the mechanical discontinuities introduced by the coaxial connector have a non-negligible influence on electrical properties. Therefore, it is necessary to include the connector in the characterization of vector network analyzer (VNA) calibration standards (see Hoffman et al. [B16]). Typical changes in S-parameters, which result from this consideration are, as an example, $|\Delta S_{11}| = 0.01 \dots 0.02$ for female device under tests (DUTs) in the 2.4 mm line system. Neglecting the connectors of the standards has different impact for male and female DUTs. Male DUTs are less influenced because the reflection of the male part of the connector is lower than that of the female part. In general, it can be stated that the assumption of ideal connectors for calibration standards leads to inconsistent definitions of measurement reference planes and thus to degraded accuracy in measurements. It has further been found that the pin gap, inherent to sexed coaxial connectors, shows unpredictable behavior due to resonant effects when it has become too small (see Hoffman, Leuchtmann, and Vahldieck [B17]). This is in contradiction to the previously established belief that a connection should be as flush as possible. It is therefore expected that in future revisions of this recommended practice the acceptable range of pin depth will be changed in such a way that too small pin gaps are no longer acceptable. See 3.5 for an explanation.

As an example: The air-dielectric line, which is considered as a golden standard among coaxial VNA calibration standards, has a center conductor that is not kept at a fixed position by a supporting bead in order to make the line section calculable from the diameter profiles. The center conductor has thus a variability in the longitudinal position, resulting in arbitrary pin gaps at the connections on both sides. Air-dielectric lines have been used to establish S-parameter traceability and to calculate uncertainties associated with S-parameters (with the so-called Ripple Method, see EURAMET [B8]) and the assumption was usually that the connectors are ideal. From today's point of view, air-dielectric lines without a support bead are unstable (see Wong and Hoffman [B26]) and are only suitable as standards when additional measures (see Hoffman et al. [B15]) are taken to control the position of the center conductor. And even then, it is necessary to include the connector in the characterization of the standard.

Coaxial connectors of primary measurement standards, i.e., calculable standards, which are used to establish traceability to SI units, can be taken into account by mechanically parametrizing them and performing electromagnetic field simulations on them. In 3.2 through 3.5, the mechanical parametrization for a subset of the coaxial connectors covered by IEEE Std 287.1™-2021 [B21] are given. Results of calculations of reflection and transmission coefficients of connector pairs based on typical values for the geometry parameters are shown. Furthermore, sensitivity coefficients of reflection and transmission coefficients with respect to the geometry parameters are displayed, and, finally, minimal pin gap requirements are discussed.

Please refer to Annex A references Zeier et al. [B34]; Hoffman et al. [B16]; Hoffman, Leuchtmann, and Vahldieck [B17]; Wong and Hoffman [B26]; EURAMET [B8]; and Hoffmann et al. [B15] for the references that are specific to Clause 3.

3.2 Connector parametrization

Mechanical models of slotless and slotted connectors are shown in Figure 1 through Figure 7.

3.2.1 Model of the slotless connector

Geometries of the male and female part of a slotless coaxial connector are shown in Figure 1 and Figure 2, respectively. The assembled slotless connector pair is shown in Figure 3.

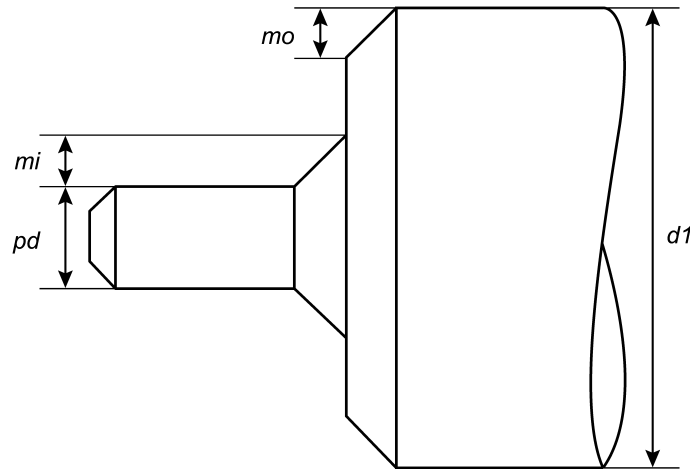


Figure 1—Male part of the connector

The various chamfers are unavoidable machining artifacts. As given in Figure 1 the following dimensions are used to characterize the male connector:

- **d1**: Diameter of male center conductor
- **mo**: Male outer chamfer
- **mi**: Male inner chamfer
- **pd**: Pin diameter

The female slotless connector, Figure 2, can be characterized by the following dimensions:

- **fo**: Female outer chamfer
- **fi**: Female inner chamfer
- **dh**: Hole diameter
- **hl**: Hole length
- **d2**: Female center conductor diameter

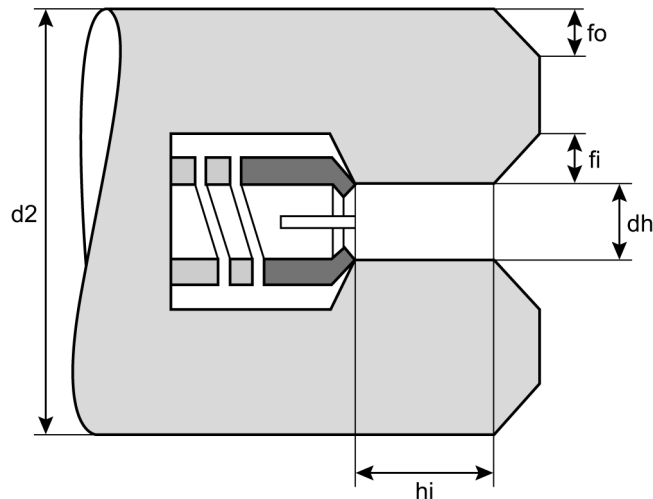


Figure 2—Cross-section of the female slotless connector

A slotless connector, which is assembled, is depicted in Figure 3.

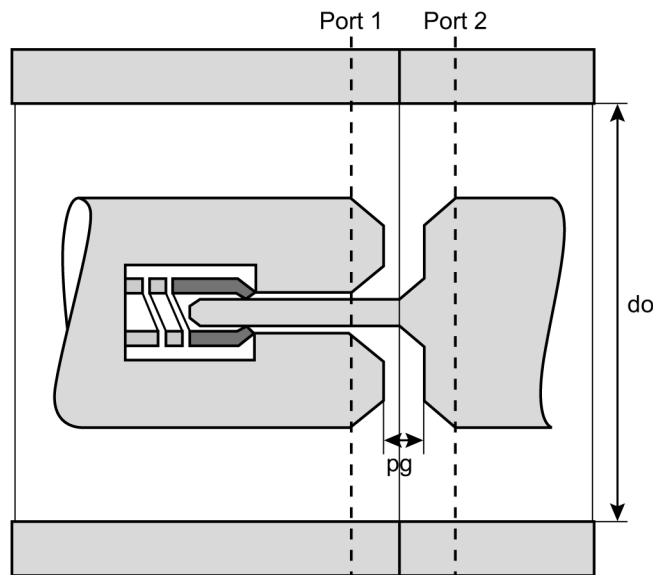


Figure 3—Cross-section of the assembled slotless connector

The assembly of a male and female slotless connector (Figure 3) yields two additional geometry variables as follows:

- **pg**: Pin gap
- **do**: Diameter of outer conductor

3.2.2 Model of the slotted connector

The male slotted connector is identical to the slotless version (Figure 1) with the same dimensions.

The geometry of a slotted female connector is more complicated. A very intuitive way to define the dimensions of such a connector is to specify the production process. The first step for the production of the female slotted contact is to lathe a profile on the center conductor. Then the hole for the male pin is drilled and the inner and outer chamfers are made (see Figure 4).

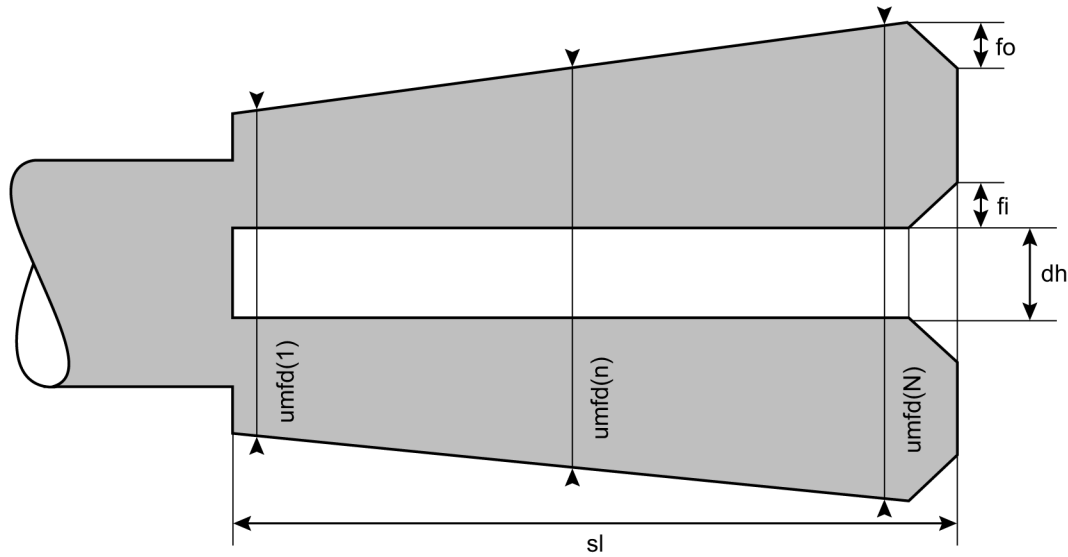


Figure 4—Cross-section of the slotted contact before slotting

In Figure 4 the following variables are defined:

- **sl**: Slot length
- **fo**: Female outer chamfer
- **fi**: Female inner chamfer
- **dh**: Hole diameter
- **umfd(n)**: Uncompressed mid finger diameter

Note that an arbitrary number of uncompressed mid finger diameters can be used to describe the lathed profile. The distance between the length locations of the diameters is constant. As a next step the slots are cut. This introduces a new geometry variable as follows (see Figure 5):

- **sw** : Slot width

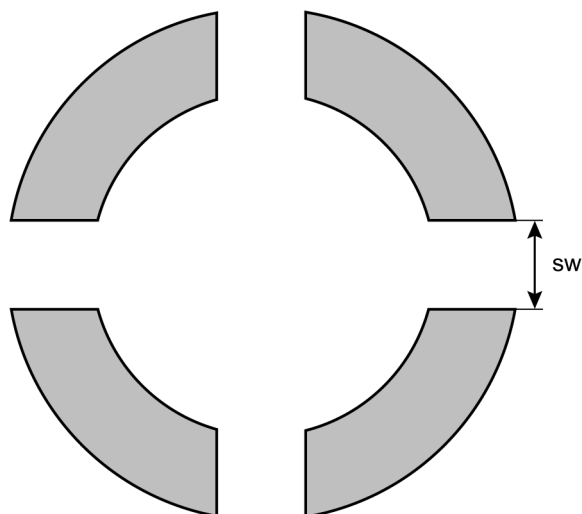


Figure 5—Front view of contact fingers after drilling and slotting

Then the fingers are bent towards the center. In Figure 6 a lateral cut through the slotted section with an inserted male pin is shown.

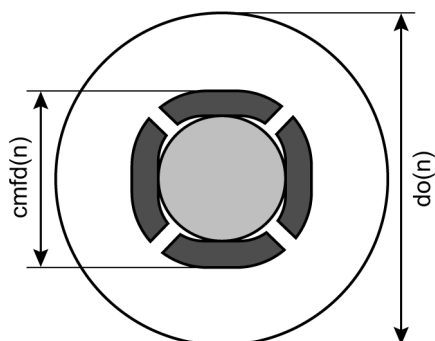


Figure 6—Lateral cut through the slotted section

The bending process can be characterized by two variables as follows:

- **cmfd(n)**: Compressed mid finger diameter
- **do(n)**: Outer diameter

Note that all geometry variables, which are indexed with (n), are meant as a list of values describing the longitudinal geometry profile. Depending on the size of the connector, a step width of 100 μm or smaller is chosen for these parameters, i.e., a slotted section with a length of 1 mm would be described by diameter profiles, each consisting of 11 or more values.

Assembling the slotted connector yields two additional variables as follows (see Figure 7):

- **pg**: Pin gap
- **do**: Diameter of outer conductor

Note that $do(n)$ refers to the diameter of the outer conductor at the longitudinal location n in the slotted section, whereas do refers to the diameter of the outer conductors between the outer edge of the outer female chamfer and the outer edge of the outer male chamfer.

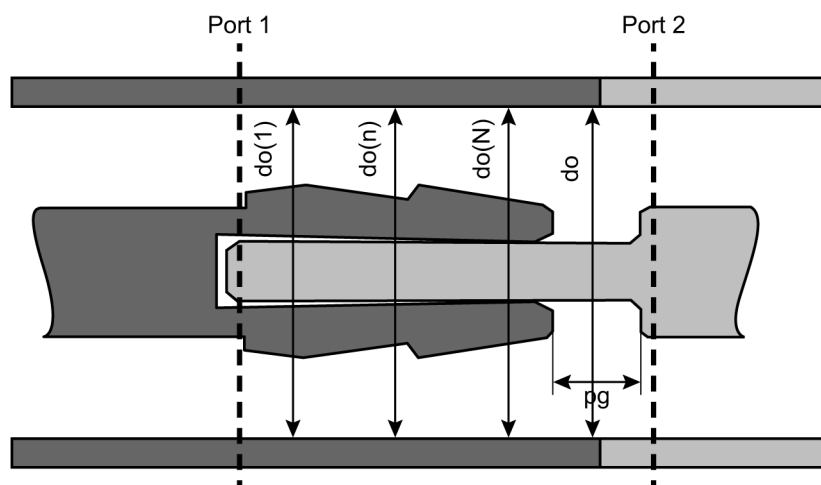


Figure 7—Cross section of the slotted connector

3.2.3 Typical parameters and uncertainties of slotless connectors

In Table 1 through Table 6 typical values and associated measurement uncertainties (with a coverage factor of $k = 2$) of the mechanical parametrization of the slotless connectors Type-N 50 Ω , 3.5 mm, and 2.4 mm are listed. Electromagnetic simulations were carried out using a frequency grid of 100 MHz, e.g., a connector with recommended upper operating frequency 18 GHz will have 180 points. The conductivity of metal is assumed as infinite and the dielectric is assumed to be vacuum. Hermaphroditic and some pin and socket connectors are not listed here. The hermaphroditic connectors are mostly used for low frequencies; thus modelling is not very crucial, and secondly they are difficult to model because of the hermaphroditic contact. The data given for pin and socket connectors is meant as a reference for characterizing connectors by electromagnetic simulation. Thus, the dimensions shown in Table 1 through Table 3 and S-parameters can be used to test electromagnetic simulation programs. The listed S-parameters are a result of the given set of geometry parameters, other parameters would yield other results. For that reason, examples are given only for the most often used connectors. Once an electromagnetic simulation technique is validated with the examples given here, it can be applied to other pin and socket connectors with good confidence.

3.2.3.1 Type-N 50 Ω connector

The recommended upper operating frequency of the Type-N 50 Ω connector is 18 GHz.

Table 1— Typical parameter values for the Type-N 50 Ω connector

Parameter	Value	Uncertainty
pg	15 μm	3 μm
mi	15 μm	5 μm
mo	15 μm	5 μm
fi	50 μm	5 μm
fo	15 μm	5 μm
hl	150 μm	10 μm
dh	1.69 mm	1 μm
pd	1.651 mm	1 μm
$d1$	3.04 mm	1 μm
do	7 mm	1 μm
$d2$	3.04 mm	1 μm

3.2.3.2 3.5 mm connector

The recommended upper operating frequency of the 3.5 mm connector is 33 GHz.

Table 2— Typical parameter values for the 3.5 mm connector

Parameter	Value	Uncertainty
pg	15 μm	3 μm
mi	15 μm	5 μm
mo	15 μm	5 μm
fi	50 μm	5 μm
fo	15 μm	5 μm
hl	150 μm	10 μm
dh	950 μm	1 μm
pd	930 μm	1 μm
$d1$	1.52 mm	1 μm
do	3.5 mm	1 μm
$d2$	1.52 mm	1 μm

3.2.3.3 2.4 mm connector

The recommended upper operating frequency of the 2.4 mm connector is 50 GHz.

Table 3—Typical parameter values for the 2.4 mm connector

Parameter	Value	Uncertainty
<i>pg</i>	15 μm	3 μm
<i>mi</i>	15 μm	5 μm
<i>mo</i>	15 μm	5 μm
<i>fi</i>	50 μm	5 μm
<i>fo</i>	15 μm	5 μm
<i>hl</i>	150 μm	10 μm
<i>dh</i>	530 μm	1 μm
<i>pd</i>	511 μm	1 μm
<i>d1</i>	1.0423 mm	1 μm
<i>do</i>	2.4 mm	1 μm
<i>d2</i>	1.0423 mm	1 μm

3.2.4 Typical parameters and uncertainties of slotted connectors

Table 4 and Table 5 list values and associated measurement uncertainties ($k=2$) of the mechanical parametrization of the slotted connectors 2.92 mm, 1.85 mm, and 1 mm. It is assumed that the profile between $\mu\text{mfd}(1)$ and $\mu\text{mfd}(N)$ is straight, i.e., a linear decrease or increase of diameter with respect to z -position. Additionally, it is assumed that the profile between $\text{cmfd}(1)$ and $\text{cmfd}(N)$ is straight as well. There are always four slots in the slotted female contact. Electromagnetic simulations were carried out using a frequency grid of 100 MHz (e.g., a connector with maximum operating frequency 40 GHz will have 400 points). The conductivity of metal is assumed as infinite and the dielectric is assumed to be vacuum.

3.2.4.1 2.92 mm connector

The recommended upper operating frequency of the 2.92 mm connector is 40 GHz.

Table 4—Typical parameter values for the 2.92 mm connector

Parameter	Value	Uncertainty
<i>pg</i>	15 μm	3 μm
<i>mi</i>	15 μm	5 μm
<i>mo</i>	15 μm	5 μm
<i>fi</i>	50 μm	5 μm
<i>fo</i>	15 μm	5 μm
<i>sl</i>	2.5 mm	50 μm
<i>sw</i>	100 μm	5 μm
<i>pd</i>	930 μm	1 μm
<i>dh</i>	950 μm	1 μm
<i>d1</i>	1.27 mm	1 μm
<i>do</i>	2.92 mm	1 μm
<i>cmfd(1)</i>	1.27 mm	1 μm
<i>cmfd(N)</i>	1.32 mm	1 μm

The recommended upper operating frequency of the 1.85 mm connector is 65 GHz.

Table 5—Typical parameter values for the 1.85 mm connector

Parameter	Value	Uncertainty
pg	15 μm	3 μm
mi	15 μm	5 μm
mo	15 μm	5 μm
fi	50 μm	5 μm
fo	15 μm	5 μm
sl	1.5 mm	50 μm
sw	100 μm	5 μm
pd	511 μm	1 μm
dh	530 μm	1 μm
dI	803.6 μm	1 μm
do	1.85 mm	1 μm
$cmfd(1)$	803.6 μm	1 μm
$cmfd(N)$	820 μm	1 μm

3.2.4.2 1 mm connector

The recommended upper operating frequency of the 1 mm connector is 110 GHz.

Table 6—Typical parameter values for the 1 mm connector

Parameter	Value	Uncertainty
pg	15 μm	5 μm
mi	15 μm	5 μm
mo	15 μm	5 μm
fi	30 μm	5 μm
fo	15 μm	5 μm
sl	1 mm	50 μm
sw	0.75 mm	10 μm
pd	250 μm	1 μm
dh	270 μm	1 μm
dI	434 μm	1 μm
do	1 mm	1 μm
$cmfd(1)$	434 μm	1 μm
$cmfd(N)$	450 μm	1 μm

3.3 Reflection and transmission coefficients

The calculated reflection and transmission coefficients of the previously defined connectors are plotted in Figure 8 through Figure 13. The respective reference planes are depicted in Figure 3 and Figure 7, labelled as Port 1 and Port 2. The plotted results refer to reflection at the port on the female side and transmission from the port on the female side to the male side. The link between trace and corresponding connector can be made by referring to the recommended upper frequency of the connector.