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Edition 1.0 2017-05

INTERNATIONAL STANDARD

colour inside

Optical circuit boards – Basic test and measurement procedures –
Part 2: General guidance for definition of measurement conditions for optical characteristics of optical circuit boards

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CONTENTS

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OPTICAL CIRCUIT BOARDS –
BASIC TEST AND MEASUREMENT PROCEDURES –

Part 2: General guidance for definition of measurement conditions for optical characteristics of optical circuit boards

FOREWORD

International Standard IEC 62496-2 has been prepared by IEC technical committee 86: Fibre optics.

The text of this document is based on the following documents:

CDV	Report on voting
86/509/CDV	86/515/RVC

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62496 series, published under the general title *Optical circuit boards – Basic test and measurement procedures*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

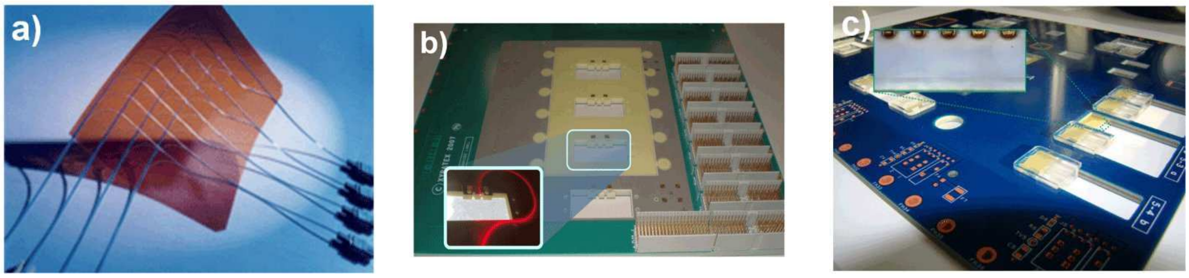
IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Bandwidth densities in modern data communication systems are driven by interconnect speeds and scalable input/output (I/O) and will continue to increase over the coming years, thereby severely impacting cost and performance in future data communication systems, bringing increased demands in terms of signal integrity and power consumption.

The projected increase in capacity, processing power and bandwidth density in future information communication systems will need to be addressed by the migration of embedded optical interconnects into system enclosures. In particular, this would necessitate the deployment of optical circuit board technologies on some or all key system cards, such as the backplane, motherboard and peripheral circuit boards.

Many varieties of optical circuit board technology exist today, which differ strongly from each other in terms of their intrinsic waveguide technology. As shown in Figure 1, these varieties include, but are not limited to: a) fibre-optic laminate, b) polymer waveguides and c) planar glass waveguides. Annex A provides a detailed overview of the state of the art of such optical interconnect technologies.



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a) Fibre-optic laminate **b) Polymer waveguides** **c) Planar glass waveguides**

Figure 1 – Optical circuit board varieties

One important prerequisite to the commercial adoption of optical circuit boards is a reliable test and measurement definition system that is agnostic to the type of waveguide system under test and, therefore, can be applied to different optical circuit board technologies as well as being adaptable to future variants. A serious and common problem with the measurement of optical waveguide systems has been lack of proper definition of the measurement conditions for a given test regime, and consequently strong inconsistencies ensue in the results of measurements by different parties on the same test sample. To date, no methodology has been established to ensure that test and measurement conditions for such optical waveguide systems are properly identified.

This document specifies a method of capturing sufficient information about the measurement conditions for a given optical circuit board to ensure consistency of measurement results within an acceptable margin.

Given the substantial variety in properties and requirements for different optical circuit board types, some test environments and conditions are more appropriate than others for a given optical circuit board. It is, therefore, crucial that this measurement identification standard encompass a comprehensive range of test and measurement scenarios for all known types of optical circuit boards and their waveguide systems, while also being sufficiently adaptable and extendable to accommodate future waveguide technologies. In addition, a degree of customisation is possible to account for arbitrary test parameters.

OPTICAL CIRCUIT BOARDS – BASIC TEST AND MEASUREMENT PROCEDURES –

Part 2: General guidance for definition of measurement conditions for optical characteristics of optical circuit boards

1 Scope

This part of IEC 62496 specifies a method of defining the conditions for measurements of optical characteristics of optical circuit boards. The method comprises the use of code reference look-up tables to identify different critical aspects of the measurement environment. The values extracted from the tables are used to construct a measurement identification code, which, in itself, captures sufficient information about the measurement conditions, so as to ensure consistency of independently measured results within an acceptable margin. Recommended measurement conditions are specified to minimise further variation in independently measured results.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61300-1, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 1: General and guidance*

IEC 61300-3-53, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-53: Examinations and measurements – Encircled angular flux (EAF) measurement method based on two-dimensional far field data from step index multimode waveguide (including fibre)*

IEC 62614, *Fibre optics – Launch condition requirements for measuring multimode attenuation*

IEC 62496-2-1:2011, *Optical circuit boards – Part 2-1: Measurements – Optical attenuation and isolation*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62496-2-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
optical channel measurement identification code
MIC
numerical code used to capture sufficient information about the measurement conditions on a waveguide under test in an optical circuit board, such as to ensure independent repeatability of the measurement and consistency of measured results on an identical sample

3.2
optical channel under test
optical circuit board channel subjected to test and measurement regime

3.3
parabolic profile parameter
parameter which describes the refractive index profile of waveguide according to the following equation

$$n(r) = \begin{cases} n_1\sqrt{1-2\Delta\left(\dfrac{r}{a}\right)^g} & r < a \\ n_1\sqrt{1-2\Delta} & r > a \end{cases}$$

where

g is the parabolic profile parameter;

a is the core radius;

r is the radial distance from core centre;

n_1 is the refractive index at r = 0;

Δ is given by the relation $\Delta = \left(n_1^2 - n_2^2\right)/2n_1^2$, where n_1 again is the refractive index at r = 0, i.e. at the axis, and n_2 is the refractive index at the outer edge of the core, i.e. at r = a

3.4
launch conduit
structure or mechanism which guides light from the measurement test source to the input facet of the optical channel under test

Note 1 to entry: Examples include optical fibres, optical waveguides or optical trains.

3.5
capturing conduit
structure or mechanism which guides light from the output facet of the optical channel under test to a measurement device

3.6
top input axis of channel under test
axis defined by the tester within the plane of the input facet used as a reference, against which the polarisation axis of the launch conduit can be defined

3.7
top output axis of channel under test
axis defined by the tester within the plane of the output facet used as a reference, against which the polarisation axis of the capturing conduit can be defined

3.8
polarisation maintaining optical fibre
single-mode optical fibre in which linearly polarized light, if properly launched into the fibre, maintains a linear polarisation during propagation, exiting the fibre in a specific linear

polarisation state with little or no cross-coupling of optical power between the two polarisation modes

Note 1 to entry: Such fibre is used in special applications where preserving polarisation is essential and is characterised by a fast axis and a slow axis.

3.9
refractive index matching material
compliant or fixed material with a refractive index equal to the refractive index of the core of the channel under test at the measurement wavelength and measurement conditions, which, unless otherwise stated, is the standard atmospheric conditions as according to IEC 61300-1

3.10
refractive index damping material
compliant or fixed material with a refractive index within 0,05 of the refractive index of the core of the channel under test at the measurement wavelength and measurement conditions, which, unless otherwise stated, is the standard atmospheric conditions as according to IEC 61300-1

4 Measurement definition system for optical circuit boards

4.1 General

A reliable test and measurement definition system for optical interconnect is a crucial prerequisite for future commercial adoption of optical circuit board technology.

Independent repeatability of waveguide measurements is still very difficult to achieve due to the lack of clarity on how measurement conditions are specified.

Therefore, such a definition system shall capture sufficient information about the measurement conditions to ensure that the results of measurement on an identical test sample by independent parties will be consistent within an acceptable margin of error.

Given the large number of measurement parameter permutations possible, the amount of information required to describe sufficiently the measurement conditions is prohibitive. It would be impractical for testers to provide a full textual description for each type of measurement, especially in situations where optical circuit boards are subjected to a variety of different measurement regimes, for instance, as part of a comprehensive quality assurance regime in a commercial optical circuit board foundry.

IEC 62496-2-1 provides details on various types of measurements that can be carried out on optical circuit boards.

4.2 Measurement definition system requirements

4.2.1 Accuracy

The measurement definition system shall capture sufficient information to ensure variability in independently measured results within an acceptable margin.

4.2.2 Accountability

The measurement definition system shall force testers to be accountable to provide sufficient information about the measurement conditions. The system shall therefore comprise a formalised framework to capture the required amount of information about the measurement conditions.

4.2.3 Efficiency

The measurement definition system shall allow the entirety of the measurement condition information to be abbreviated into an optical channel measurement identification code (MIC) such that it can be contained within no more than one line of text.

4.2.4 Convenience

The measurement identification code should be easy to construct and deconstruct using the references look-up tables in this document.

4.2.5 Independent

The measurement definition system shall be independent of the type of optical circuit board under test in order to accommodate different varieties of optical interconnect. To this end, the type of optical channel under test will not be included in the information to be specified; it will be treated as a "black box" bounded by the input facet and output facet of the optical channel under test.

4.2.6 Scalable

The measurement definition system shall be scalable to accommodate new measurement conditions appropriate to existing or as yet unknown optical interconnect types. To this end, the system will have placeholders to allow easy addition of new information in future.

4.2.7 Customised requirements

Where the parameters of a measurement condition are not explicitly provided in the corresponding look-up tables, the MIC shall be extendable to accommodate user-defined parameters.

4.2.8 Prioritised structure

The measurement definition system shall give preference to measurement configurations that are

- accessible, favouring the use of available and affordable equipment,
- viable, favouring measurements which can be easily carried out by most organisations without the requirement for specialised or restricted equipment or expertise, and
- useful, favouring measurement of optical channel characteristics, which are most common and relevant to its deployment and operation, for example insertion loss.

4.3 Measurement definition criteria

4.3.1 General

The measurement definition system shall provide information on the following five critical aspects of the measurement environment:

- source characteristics (4.3.2);
- launch conditions (4.3.3);
- input coupling conditions (4.3.4);
- output coupling conditions (4.3.5);
- capturing conditions (4.3.6).

4.3.2 Source characteristics

4.3.2.1 General

Typical sources for common measurements on optical circuit board channels include LEDs, laser diodes and white light sources, while less common sources include amplified spontaneous emission devices. In order to accommodate a comprehensive range of available source types and characteristics, the measurement identification system will define most sources in terms of permutations of key properties including wavelength and spectral width. Source optical power or modal profile need not be specified as only the optical power, and modal profile at the launch facet need be specified as part of the launch conditions. Table 1 in IEC 62496-2-1:2011 provides a list of recommended source characteristics.

4.3.2.2 Modulated sources

According to this document, the source amplitude and phase is considered un-modulated. Optical modulation is a large and complex area with many possible permutations of modulation type, duty cycle and data characteristics. Modulation schemes include standard on-off keying (OOK) and multi-level modulation schemes such as phase amplitude modulation (PAM), in-phase and quaternary (IQ) modulation schemes such as quadrature phase shift keying (QPSK), multi-level quadrature amplitude modulation (nQAM), multi-pulse modulation schemes, and discrete multi-tone (DMT). Data characteristics would include pseudo random binary sequence (PRBS) data with various correlation lengths, as well as test data associated with real data transmission protocols. Modulation will not be included in the measurement definition system described in this document. In the event of a modulated source, the modulation characteristics shall be stated explicitly.

4.3.2.3 Wavelength division multiplexed sources

According to this document, the source is considered to be centred on a single wavelength with varying spectral widths, or white, which is consistent with the use of common commercial sources including laser diodes, LEDs or amplified spontaneous emission devices. It may be desirable to characterise the performance of the channel under test with wavelength division multiplexed (WDM) light in which multiple wavelengths are superposed onto the launch conduit in accordance with various WDM schemes. For example, the coarse wavelength division multiplexing (CWDM) scheme allows on the order of ten signals to be encoded onto separate wavelengths. The dense wavelength division multiplexing (DWDM) scheme allows on the order of hundreds of signals to be encoded onto separate, more closely spaced, wavelengths.

WDM sources are not included in this document, as the possible permutations would be prohibitively complex. In the event of a wavelength division multiplexed source, the wavelength division multiplexing characteristics shall be explicitly stated. Preferably, if convenient, each wavelength-encoded channel can be uniquely specified using the measurement identification system outlined in this document.

4.3.3 Launch conditions

4.3.3.1 General

Launch conditions have the greatest effect on variability of measurement results on optical circuit board channels. It is, therefore, crucial that these be sufficiently defined.

Launch conditions shall include the following information that determines how light propagates through the optical channel under test and, therefore, determines the independent reproducibility of the measurement:

a) launch facet size and shape, which is typically defined by the core of the launch conduit – for a standard fibre, it would be sufficient to specify the fibre type;

b) total optical power amplitude at the launch facet;

c) spatial (near-field) and angular (far-field) optical power distribution of light at the launch facet. The launch conditions for multimode fibres should preferably comply with encircled flux (EF) requirements defined in IEC 61300-1 or encircled angular flux (EAF) requirements defined in IEC 61300-3-53. Such launch conditions can be reliably achieved by deploying appropriate mode filtering equipment around or in-line with the launch conduit. The launch conditions for single-mode fibres should comply with IEC 61300-1.

4.3.3.2 Recommended launch conditions

Table 1 defines key recommended launch profiles, including underfilled profiles, various mode filtered multimode profiles and overfilled profiles, as well as recommendations on how to reproduce some of these modal profiles.

Table 1 – Recommended modal launch profiles

Designation	Modal distribution at launch facet	Recommended measurement setup to achieve modal distribution
Single-mode launch		
L1	***UF*** Underfilled launch complies with single-mode launch requirements in IEC 61300-1.	Preferably, optical isolator between source and OS1 launch fibre 2 m long OS1 single-mode fibre (SMF) provides a single-mode launch profile.
Multimode launch		
L2 [a)]	***EF/EMD*** Complies with EF requirements in IEC 61300-1.	The source is passed into a 5 m graded index multimode fibre (GI-MMF), which is wrapped 20 times around a 38 mm diameter mandrel. The output of the mandrel is then passed through a mode controller/filter producing a mode filtered optical intensity profile, which complies with EF requirement of IEC 61280-4-1. This is then used as the input to a 5 m GI-MMF, which is wrapped 20 times around a 38 mm diameter mandrel to produce a mode-stripped optical intensity profile at the GI-MMF launch facet.
L3 [a)]	***EF*** Complies with EF requirements in IEC 61300-1.	5 m graded index multimode fibre (GI-MMF) is passed through a mode controller/filter producing a mode filtered optical intensity profile at the GI-MMF launch facet, which complies with EF requirement of IEC 61280-4-1.
L4 [a)]	***EMD*** Equilibrium modal distribution	5 m 50 µm graded index OM3 multimode fibre (GI-MMF) is wrapped 20 times around a 38 mm diameter mandrel to produce a mode-stripped optical intensity profile at the GI-MMF launch facet.
L5 [a)]	***OF*** Overfilled distribution – uniform near-field optical intensity distribution	5 m 105 µm step index multimode fibre (SI-MMF) is wrapped 20 times around a 38 mm diameter mandrel to create a mode-scrambled, overfilled optical intensity profile at the SI-MMF launch facet.
L6 [a]	***VOF/EAF*** Very overfilled distribution Complies with EAF requirements in IEC 61300-3-53.	5 m 200µm core step-index fibre (SI-MMF) is passed through a mode controller producing a mode filtered optical intensity profile at the launch facet, which complies with the EAF requirement of IEC 61300-3-53.
[a)] Bend insensitive fibre is not recommended for MM or SM test leads.		

4.3.3.3 Recommended single-mode fibre launch measurement setup

The recommended measurement setup for single-mode fibre launch conditions is shown in Figure 2. A single-mode optical source should be connected with a single-mode optical fibre, first through a single-mode optical isolator to shield the source from unwanted back-reflections occurring at different interfaces further on down the test link, especially the interface between the launch facet and the input facet of the channel under test. The output from the optical isolator should then be connected through a variable single-mode optical attenuator. This will allow the tester to adjust the optical power at the launch facet to match the required optical power as defined in the measurement identification code. This can alternatively be achieved by using a power tuneable source.

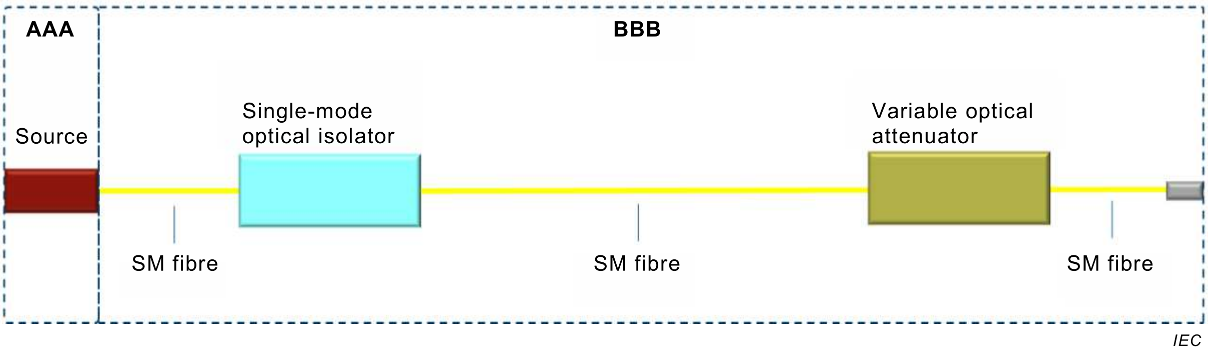


Figure 2 – Recommended test setup for single-mode fibre launch conditions

4.3.3.4 Recommended multimode fibre launch measurement setup

A single-mode or multimode optical source should be connected with a single-mode or multimode optical fibre, first through a single-mode or multimode optical isolator to shield the source from unwanted back-reflections occurring at different interfaces further on in the test link, especially the interface between the launch facet and the input facet of the channel under test. If the source is a coherent source, it will be important to use a speckle filter to average out the effects of speckle at the launch facet. One device can be an electromechanical shaker applied after the source but before the variable optical attenuator. If using such a device, it is important that the fibre be completely mechanically decoupled from the launch facet, so the device should be applied between the source and the variable optical attenuator. The photodetector used to measure the received light would need to be configured to record average values over an appropriate time period, rather than immediate values. The output from the optical isolator should then be connected with single-mode or multimode fibre to the input of a variable single-mode or multimode optical attenuator. This will allow the tester to adjust the optical power at the launch facet to match the required optical power as defined in the measurement identification code. Alternatively, this can be achieved by using a power tuneable source. Then the output of the variable optical attenuator will be connected with multimode fibre to the input of a modal conditioning or filtering system, the output of which will be connected with multimode fibre to the launch facet. The purpose of the modal conditioning or filtering system is to ensure that the modal profile of the launch facet is defined according to L2, L3, L4, L5 or L6 in Table 1. Figure 3 shows the recommended test setup.

L2 is the preferred launch condition, in which a modal profile is generated, which complies with the restricted launch EF requirements of IEC 61300-1, and this in turn is injected into a GI-MMF fibre mandrel to produce a normalised output.

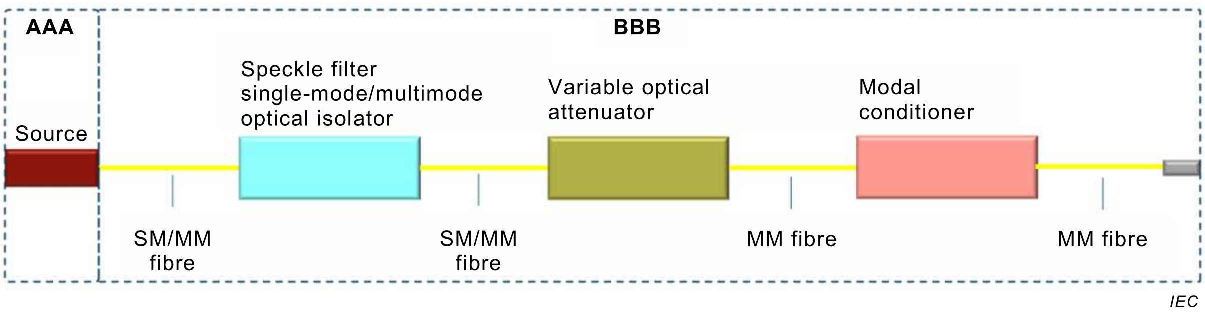


Figure 3 – Recommended test setup for multimode fibre launch conditions

4.3.4 Input coupling conditions

4.3.4.1 General

Input coupling conditions provide information on how the launch conduit is connected to the input facet of the optical channel under test, for example through butt-coupling or imaging through a lens system, and whether or not the input facet is treated with refractive index matching or damping materials to mitigate scattering losses.

4.3.4.2 Compliant and fixed refractive index matching material or refractive index damping material

It is common practice to apply a refractive index matching or damping material to the input and/or output facet of the channel under test in order to mitigate Fresnel reflection and scattering effects caused by the roughness of the input and/or output facet surface. The refractive index material can be in the form of a liquid or gel, which will provide a compliant buffer, and is best suited to measurement whereby the launch facet is butt-coupled in direct contact or within a few microns of the input facet, such that the liquid or gel completely fills the gap between the launch facet and the input facet of the channel under test. The use of liquid or gel would not be suitable in the case of a free space projection of light onto the input facet of the channel under test (such as imaging of the output of a fibre facet onto the input facet of the channel under test using a lens assembly), as the surface tension of the compliant material would cause it to form a boundary of unpredictable geometry around the input facet of the channel under test. The alternative to using a compliant refractive index matching material or refractive index damping material is to use a fixed refractive index matching or damping material with a defined flat surface, such as a thin film. This is useful when the input facet of the channel under test has high roughness, but a free space launch is used.

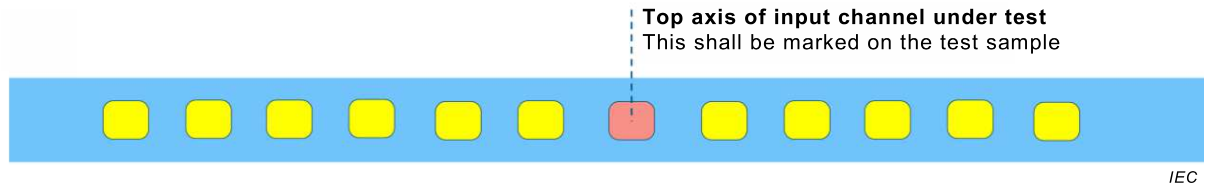
4.3.4.3 Polarisation dependent input coupling conditions

One important possible measurement parameter for single-mode launch conditions is the fast or slow polarisation axis of the launch facet relative to the channel under test. For example, this would be required to characterise the polarisation dependent loss or the birefringence of the channel under test. For this purpose, a top axis of the input channel under test shall be defined by the first tester or test sample creator and clearly marked on the sample containing the one or more channels under test or otherwise described in accompanying literature.

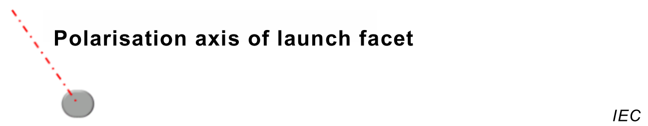
In measurements requiring a defined polarisation, the single-mode fibre could be a polarisation maintaining optical fibre as defined in IEC TR 62349. The optical power exiting a polarisation maintaining optical fibre will be divided between the fast axis and the orthogonal slow axis. The ratio of optical power contained in the fast axis to the optical power contained in the slow axis depends on a number of conditions, including how the power was launched into fibre.

In the event that a polarisation maintaining optical fibre or other speciality fibre is used in which the optical power contained in the two orthogonal polarisation axes of the launch facet is a required measurement parameter, the measurement will be defined using two instances of the measurement identification system outlined in this document. In this way, a single measurement will be treated as two separate measurements, each defining one of the polarisations on its own.

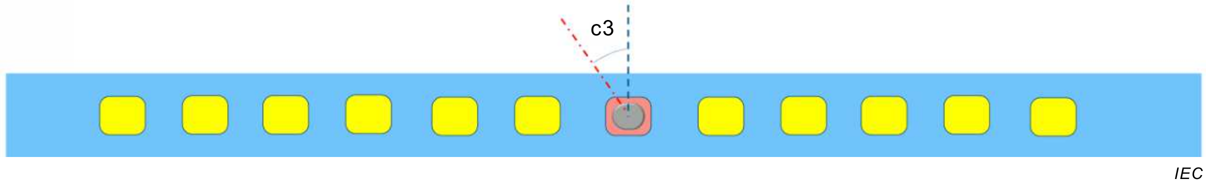
Figure 4 shows that the top axis of the channel under test and the chosen polarisation axis of the launch facet of a polarisation maintaining optical fibre will form a relative angle c3 in units of degrees. This angle will be defined as part of the measurement identification system outlined in this document.



4 a) Cross-sectional front view of the input facet of the channel under test



4 b) Cross-sectional back view of launch conduit



4 c) Cross-sectional front view of channel under test with launch facet aligned over it

NOTE 1 In Figure 4 a), the top input axis is shown.

NOTE 2 In Figure 4 b), the chosen polarisation axis of the launch facet is included.

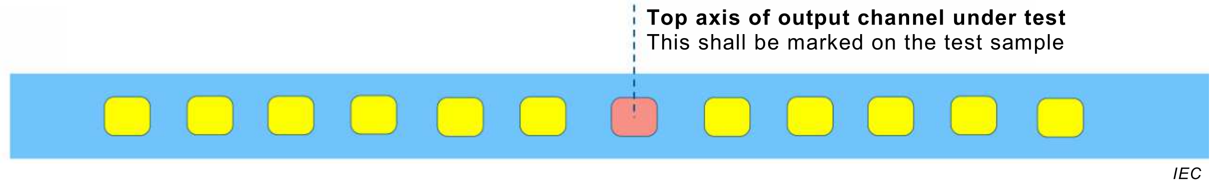
NOTE 3 In Figure 4 c), the top axis of the channel under test forms an angle c3 in degrees with the chosen polarisation axis of the launch facet.

Figure 4 – Cross-sectional views of channel under test at input

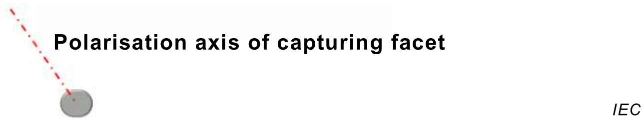
4.3.5 Output coupling conditions

Output coupling conditions provide information on how the light is coupled out of the output facet of the optical channel under test to the capturing conduit, for example through butt-coupling or imaging through a lens system, and whether or not the output facet is treated with refractive index matching or damping materials to mitigate scattering losses.

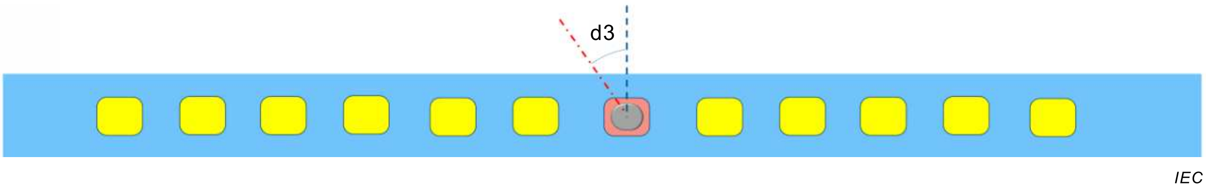
One important possible measurement parameter for single-mode capturing conditions is the polarisation axis of the capturing facet relative to the top axis of the output facet of the channel under test. For this purpose, a top axis of the output channel under test shall be defined by the first tester or test sample creator and clearly marked on the sample containing the one or more channels under test or otherwise described in accompanying literature. In measurements requiring a defined polarisation, the single-mode fibre should be a polarisation maintaining optical fibre as defined in IEC TR 62349. Figure 5 shows that the top axis of the output facet of the channel under test and the chosen polarisation axis of the capturing facet of a polarisation maintaining optical fibre will form a relative angle d3 in units of degrees. This angle will be defined as part of the measurement identification system outlined in this document. As viewed facing the output facet of the channel under test, moving anticlockwise from the top axis, the angle increases positively for the entire revolution.



5 a) Cross-sectional front view of the output facet of the channel under test



5 b) Cross-sectional back view of the capturing conduit



5 c) Cross-sectional front view of the output facet of channel under test
with the capturing facet aligned over it

NOTE 1 In Figure 5 a), the top output axis of channel under test is shown.

NOTE 2 In Figure 5 b), the chosen polarisation axis of the capturing facet is included.

NOTE 3 In Figure 5 c), the top axis of the output channel under test forms an angle d3 in degrees with the chosen polarisation axis of the capturing facet.

Figure 5 – Cross-sectional views of the channel under test at output

4.3.6 Capturing conditions

The capturing conditions include information on the capturing conduit used to extract the optical signal from the optical channel under test and basic information on the measuring element, such as a photodetector or CCD camera. However, it shall be noted that, all other conditions being equal, the response of the measurement equipment itself will vary from device to device, so it is a requirement of this document that the measurement equipment be specified explicitly as well.

4.4 Launch and capturing position

The position of the launch facet relative to the input facet of the channel under test and the position of the capturing facet relative to the output facet of the channel under test are critical parameters. In waveguide measurements, the standard procedure is to adjust the launch and capturing axes around the input and output facets of a channel under test respectively to achieve the maximum transmittance or minimum insertion loss. The respective positions of launch and capturing axes relative to the input and output facets of the channel under test required to achieve maximum transmittance depend strongly on the geometry of the channel under test and rarely coincide with the exact centre of the input and output facets. Indeed, it would be prohibitively difficult for testers to identify the exact centre of the input and output facets and align the centres of their launch and capturing facets to them.

The most viable and repeatable measurement is, therefore, the maximum transmittance achievable on a given channel under test. This assumes competences of the testers to adjust properly their launch and capturing devices to identify this, but this is the most reproducible approach. This will be referred to as the fundamental measurement.

4.5 Launch and capture direction

The input facet of the optical channel under test is defined as the area through which the light needs to be injected in order to be best conveyed into the optical channel under test. The output facet of the optical channel under test is defined as the area through which light exits the optical channel under test.

In most optical waveguide channels, the input and output facets of the channel under test are orthogonal to the axis of the channel under test, as shown in Figure 6. If the input facet of the channel under test is orthogonal to the axis of the channel under test, the axis of the launch conduit shall be collinear with the axis of the channel under test when carrying out the fundamental measurement. If the output facet of the channel under test is orthogonal to the axis of the channel under test, then the axis of the capturing conduit shall be collinear with the axis of the channel under test when carrying out the fundamental measurement.

Figure 6 – Measurement setup with collinear launch and capture direction

In some optical waveguide channels, a deflection element or structure that deflects the light propagating along the main waveguide axis by 90° can be incorporated. In such cases, the input and/or output facets of the channel under test can be parallel to the axis of the channel under test, as shown in Figure 7.

If the input facet of the channel under test is parallel to the axis of the channel under test, the axis of the launch conduit shall be orthogonal to the axis of the channel under test when carrying out the fundamental measurement of minimum insertion loss. If the output facet of the channel under test is orthogonal to the axis of the channel under test, the axis of the capturing conduit shall be orthogonal to the axis of the channel under test when carrying out the fundamental measurement of minimum insertion loss.

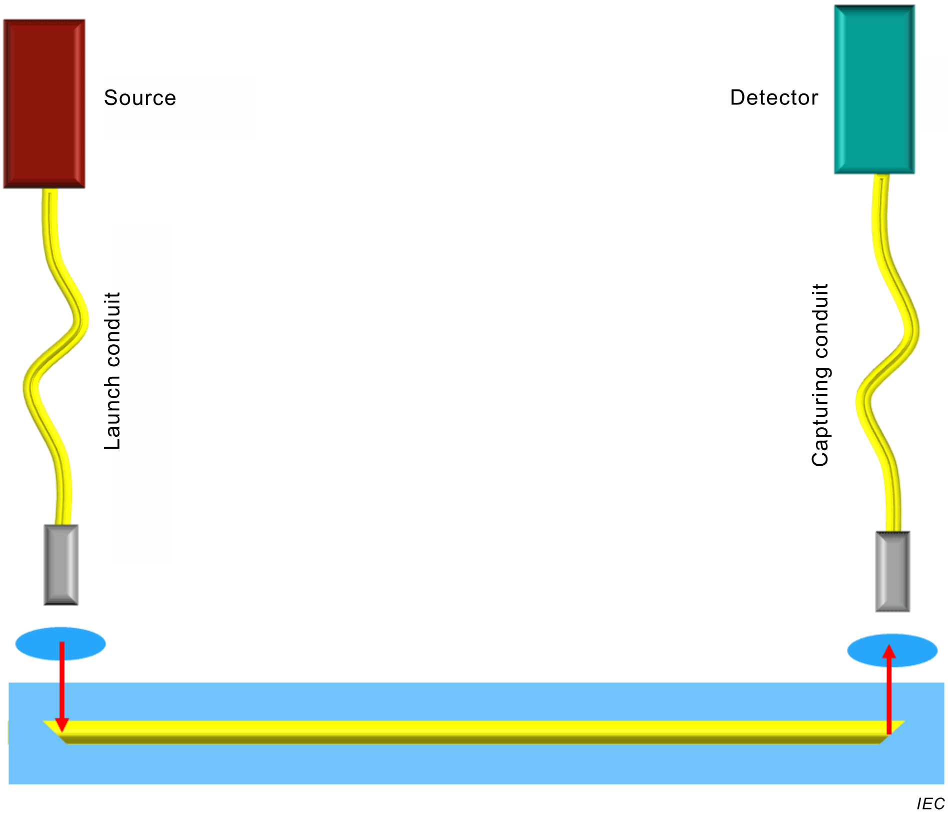


Figure 7 – Measurement setup with orthogonal launch and capture direction

There may be other cases in which the axis of the launch conduit and the capturing conduit are not normal to the input and output facet. For example, Figure 8 shows a waveguide with a surface grating coupling structure optimised to deflect light out of the waveguide at an oblique angle, although the input facet and output facet are parallel to the waveguide axis.

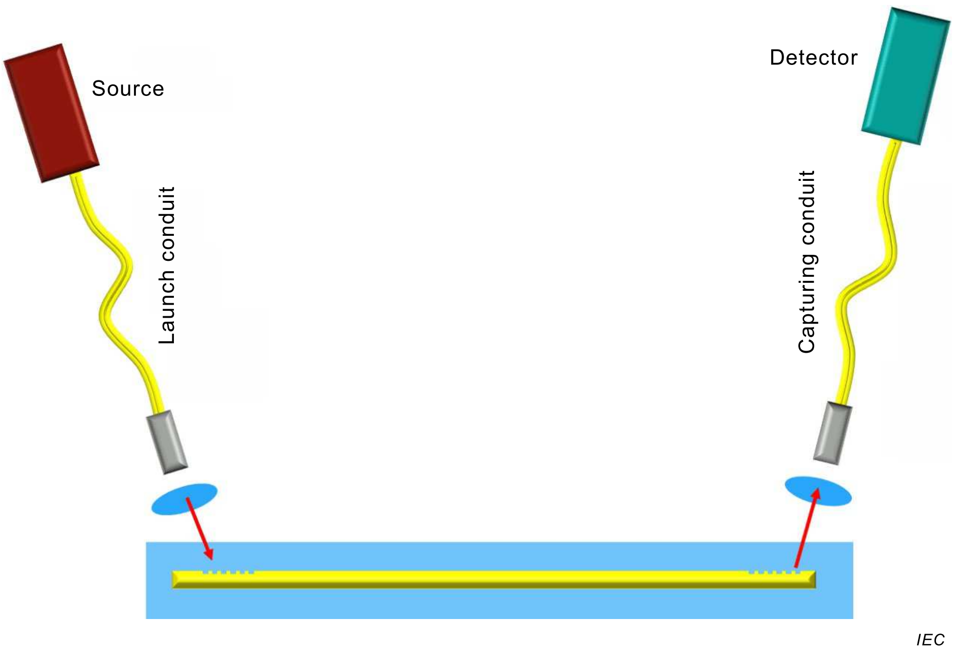


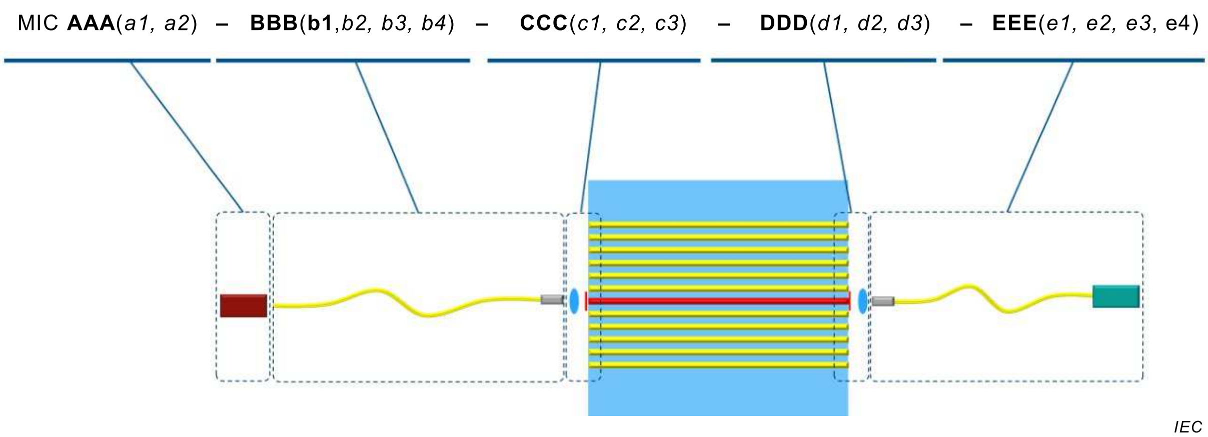
Figure 8 – Measurement setup with oblique launch and capture direction

It is understood in this document that the launch conduit and capturing conduit will be oriented as required relative to the input and output facets of the optical channel under test to allow the fundamental measurement. Therefore, there is no restriction on the direction of the launch and capturing conduit relative to the input facet and output facet of the channel under test.

5 Measurement identification code

5.1 General

The measurement definition system requires the use a measurement identification code (MIC) to specify sufficiently the measurement conditions for the optical channel under test (Figure 9).



NOTE 1 Mandatory parameters are in bold text.

NOTE 2 Customisation parameters are in italics.

Figure 9 – Measurement identification code construction

5.2 Measurement identification code construction

5.2.1 General

The MIC is comprised of five three-digit numerical coordinates that represent the five critical areas of the measurement environment, as described above. Each coordinate is also followed by a set of customisation parameters in parentheses relating to that coordinate.

5.2.2 AAA – Source characteristics

Coordinate AAA contains the information about the source used to stimulate the optical channel. The coordinate value is obtained from the first reference look-up table (Table 2).

5.2.3 BBB(b1) – Launch conditions

Coordinate BBB contains information about the conduit used between the light from the source and the input point of the optical channel under test. The coordinate value is obtained from the second reference look-up table (Table 3). The BBB coordinate shall be followed by the value of the total average optical power as measured at the launch facet expressed in units of microwatts. This is mandatory.

5.2.4 CCC – Input coupling conditions

Coordinate CCC contains information about how light is coupled from the launch conduit to the input point of the optical channel under test. The coordinate value is obtained from the third reference look-up table (Table 4).

5.2.5 DDD – Output coupling conditions

Coordinate DDD contains information about how light is coupled out of the output facet of the optical channel under test to the capturing conduit or element. The coordinate value is obtained from the fourth reference look-up table (Table 5).

5.2.6 EEE – Capturing conditions

Coordinate EEE contains information about the capturing conduit (if any) between the output facet and the optical measurement device. The coordinate value is obtained from the fifth reference look-up table (Table 6).

The numerical value of each coordinate will be extracted from the corresponding coordinate reference tables in the following subclauses.

5.3 Extended measurement identification code with customisation parameters

5.3.1 General

The MIC can be extended, if necessary, to accommodate specific customisation parameters for user definable measurement characteristics.

In this case, the customisation parameters are included in brackets immediately after the 3-digit coordinate value to which it applies. The customisation parameters are defined for each coordinate reference table.

The full MIC with all customisation parameters is defined as follows:

MIC AAA(a1, a2) – BBB(b1, b2, b3, b4) – CCC(c1, c2, c3) – DDD(d1, d2, d3) – EEE(e1, e2, e3, e4)

For certain coordinate values, customisation parameters shall be specified.

Customisation adds complexity to the measurement definition system, potentially increases measurement uncertainty, and should be avoided.

The BBB customisation parameter b1, however, shall always be specified.

Preferably, the measurement conditions chosen in most cases will be from a small set of common test setups and will not require customisation.

5.3.2 Customisation parameters with placeholders

In most cases, for a given coordinate value (e.g. CCC), only some of all possible customisation parameters will be required, with others not applicable. If any customisation parameters are specified for a given coordinate value, inapplicable customisation parameters should have an "X" value in the corresponding position to serve as a placeholder. The only exception is b1, which is a mandatory parameter, so if there are no values required for b2, b3 or b4, only the b1 parameter need be shown after the BBB coordinate value.

For example: MIC AAA(X, a2) – BBB(b1) – CCC(c1, c2, X) – DDD(d1,d2,d3) – EEE(e1, X, e3)

5.4 Reference measurements

Reference measurements (or back-to-back measurements) are measurements taken with the DUT removed to provide a comparative reference required for various quantities such as insertion loss.

In order for a reference measurement to be valid, the same MIC shall be applied to the reference measurement as is applied to the corresponding measurement on the DUT (see Figure 10), with one exception: for reference measurements, the input and output facet treatment associated with the CCC and DDD coordinates respectively will be ignored.

MIC **AAA**(*a1, a2*) – **BBB**(**b1**,*b2, b3, b4*) – **CCC**(*c1, c2, c3*) – **DDD**(*d1, d2, d3*) – **EEE**(*e1, e2, e3*, e4)

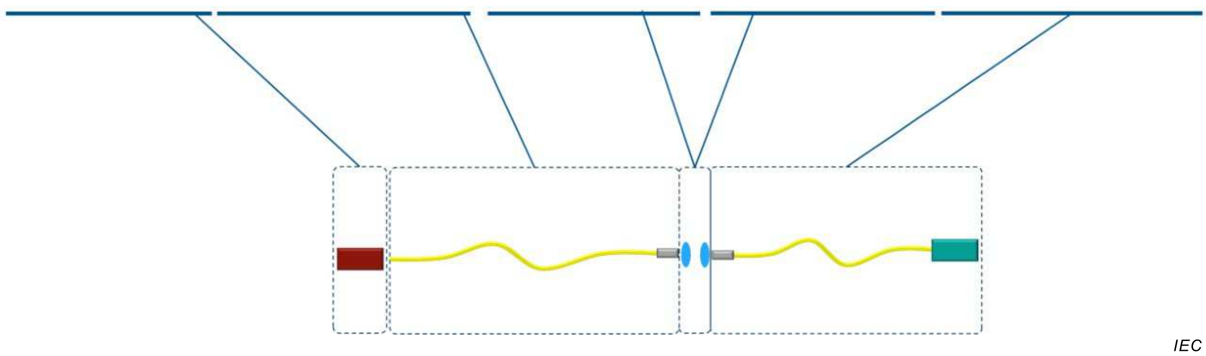


Figure 10 – Reference measurements with the same MIC

5.5 Coordinate table AAA – Source characteristics

5.5.1 Mandatory parameters

There are no mandatory parameters.

5.5.2 Customisation parameters

The following customisation parameters are defined for Table 2:

- a1 – centre wavelength (λ) of source in units of nanometres
- a2 – full width half maximum of source spectral width ($\delta\lambda$) in units of nanometres

Table 2 – AAA coordinate reference for source characteristics

Source →	Single-mode [a]	Multimode – narrow spectral [b]	Multimode – medium spectral [c]	Multimode – broad spectral [d]	Multimode – very broad spectral [e]	Custom [f]	Reserved			
Centre wavelength (λ) ↓										
Custom λ (a1) nm	001	002	003	004	005	006	007	008	009	010
532 nm	011	012	013	014	015	016	017	018	019	020
660nm	021	022	023	024	025	026	027	028	029	030
780nm	031	032	033	034	035	036	037	038	039	040
850 nm	041	042	043	044	045	046	047	048	049	050
935 nm	051	052	053	054	055	056	057	058	059	060
980 nm	061	062	063	064	065	066	067	068	069	070
1 000 nm	071	072	073	074	075	076	077	078	079	080
1 060 nm	081	082	083	084	085	086	087	088	089	090
1 300 nm	091	092	093	094	095	096	097	098	099	100
1 310 nm	101	102	103	104	105	106	107	108	109	110
1 470 nm	111	112	113	114	115	116	117	118	119	120
1 490 nm	121	122	123	124	125	126	127	128	129	130
1 510 nm	131	132	133	134	135	136	137	138	139	140
1 530 nm	141	142	143	144	145	146	147	148	149	150
1 550 nm	151	152	153	154	155	156	157	158	159	160
1 570 nm	161	162	163	164	165	166	167	168	169	170
1 590 nm	171	172	173	174	175	176	177	178	179	180
1 610 nm	181	182	183	184	185	186	187	188	189	190
1 625 nm	191	192	193	194	195	196	197	198	199	200
White	201	202	203	204	205	206	207	208	209	210

Source →	**Single-mode** [a)]	**Multimode – narrow spectral** [b)]	**Multimode – medium spectral** [c)]	**Multimode – broad spectral** [d)]	**Multimode – very broad spectral** [e)]	**Custom** [f)]	**Reserved**			
Centre wavelength (λ) ↓										
Reserved	211	212	213	214	215	216	217	218	219	220
Reserved	221	222	223	224	225	226	227	228	229	230

a) Spectral width ≤ 10 nm (e.g. laser diode)

b) 2 nm ≤ spectral width < 10 nm (e.g. VCSEL, edge-emitting semiconductor laser)

c) 10 nm ≤ spectral width < 30 nm (e.g. laser diode or LED)

d) 30 nm ≤ spectral width < 150 nm (LED, amplified spontaneous emission)

e) 150 nm ≤ spectral width (LED, amplified spontaneous emission)

f) FWHM spectral width (a2) nm

5.6 Coordinate table BBB – Launch conditions

5.6.1 Mandatory parameter

The following mandatory parameter shall always be included after the BBB coordinate:

- (b1) – optical power as measured at launch facet in units of microwatts

For example, a coordinate of AAA-BBB(500)–CCC–DDD–EEE would indicate that the optical power measured at the launch facet is 500 µW.

5.6.2 Customisation parameters

The following customisation parameters are defined for Table 3:

- (b2) – diameter of fibre core in units of micrometres
- (b3) – numerical aperture of fibre
- (b4) – parabolic profile parameter of the fibre core

Table 3 – BBB coordinate reference for launch conditions

Mode filtered output →	No mode filtering	L1 (UF) [a)]	L2 (EF / EMD) [b)]	L3 (EF) [c)]	L4 (EMD) [d)]	L5 (OF)	L6 (VOF/EAF) [e)]	Reserved		
Launch conduit ↓										
Direct source coupling	001	002	003	004	005	006	007	008	009	010
Glass fibre SI										
Ø9/125 µm SMF (OS1)	011	012	013	014	015	016	017	018	019	020
Ø9/125 µm BI SMF	021	022	023	024	025	026	027	028	029	030
Ø50/125 µm	031	032	033	034	035	036	037	038	039	040
Ø62,5/125 µm	041	042	043	044	045	046	047	048	049	050
Ø105 µm	051	052	053	054	055	056	057	058	059	060
Ø200 µm	061	062	063	064	065	066	067	068	069	070
Glass fibre GI										
Ø50/125 µm OM5 MMF (non-bend insensitive)	071	072	073	074	075	076	077	078	079	080
Ø50/125 µm OM5 BIMMF (bend insensitive)	081	082	083	084	085	086	087	088	089	090
Ø50/125 µm OM4 MMF (non-bend insensitive)	091	092	093	094	095	096	097	098	099	100
Ø50/125 µm OM4 BIMMF (bend insensitive)	101	102	103	104	105	106	107	108	109	110
Ø50/125 µm OM3 MMF (non-bend insensitive)	111	112	113	114	115	116	117	118	119	120
Ø50/125 µm OM3 BIMMF (bend insensitive)	121	122	123	124	125	126	127	128	129	130
Ø50/125 µm (OM2)	131	132	133	134	135	136	137	138	139	140
Ø62,5/125 µm (OM1)	141	142	143	144	145	146	147	148	149	150

Mode filtered output →	**No mode filtering**	**L1 (UF) [a)]**	**L2 (EF / EMD) [b)]**	**L3 (EF) [c)]**	**L4 (EMD) [d)]**	**L5 (OF)**	**L6 (VOF/EAF) [e)]**	**Reserved**		
Launch conduit ↓										
Ø105 µm, NA 0,22	151	152	153	154	155	156	157	158	159	160
Ø200 µm, NA 0,39	161	162	163	164	165	166	167	168	169	170
Hard polymer cladding fibre (HPCF)[f)]										
Ø200/230 µm A3	171	172	173	174	175	176	177	178	179	180
Plastic optical fibre SI										
Ø980/1 000 µm (A4)	181	182	183	184	185	186	187	188	189	190
Plastic optical fibre GI										
Ø50/125 µm	191	192	193	194	195	196	197	198	199	200
Ø62,5/125 µm	201	202	203	204	205	206	207	208	209	210
Ø980/1 000 µm (A4)	211	212	213	214	215	216	217	218	219	220
Custom										
Ø (b2) µm, NA (b3), profile parameter (b4)	221	222	223	224	225	226	227	228	229	230
Specialist Glass fibre GI										
Ø25 µm, NA 0.1	231	232	233	234	235	236	237	238	239	240

a) Underfilled launch complies with single-mode launch requirements in IEC 61300-1.

b) Complies with EF requirements in IEC 61280-4-1 and EAF requirements in IEC 61300-3-53.

c) Complies with EF requirements in IEC 61280-4-1.

d) Complies with EAF requirements in IEC 61300-3-53.

e) Overfilled distribution with uniform near-field optical intensity distribution.

f) Complies with IEC 60793-2.

5.7 Coordinate table CCC – Input coupling conditions

5.7.1 Mandatory parameters

There are no mandatory parameters.

5.7.2 Customisation parameters

The following customisation parameters are defined for Table 4:

- (c1) – refractive index of index matching material (gel, oil or film) applied to input facet
- (c2) – axial distance between launch conduit output facet and input facet
- (c3) – angle between polarisation plane and top input axis of channel under test

Table 4 – CCC coordinate reference for input coupling conditions

Input facet treatment →	**Untreated**	**Refractive index interface material applied where $n_{\text{interface}}$ = c1**	**Refractive index interface film applied where n_{film} = c1**							
Coupling arrangement ↓										
Butt coupling										
Axial displacement = 0 µm	001	002	003	004	005	006	007	008	009	010
Axial displacement = 5 µm	011	012	013	014	015	016	017	018	019	020
Axial displacement = 50 µm	021	022	023	024	025	026	027	028	029	030
Axial displacement = 100 µm	031	032	033	034	035	036	037	038	039	040
Axial displacement = (c2) µm	041	042	043	044	045	046	047	048	049	050
Lens coupling arrangement										
Imaging Source/launch conduit onto input facet	051	052	053	054	055	056	057	058	059	060

5.8 Coordinate table DDD – Output coupling conditions

5.8.1 Mandatory parameters

There are no mandatory parameters.

5.8.2 Customisation parameters

The following customisation parameters are defined for Table 5:

- (d1) – refractive index of index matching material (gel, oil or film) applied to output facet
- (d2) – axial distance between output facet and capturing conduit input facet
- (d3) – angle between polarisation plane and top input axis of channel under test

Table 5 – DDD coordinate reference for output coupling conditions

Output facet treatment →	**Untreated**	**Refractive index interface material applied where $n_{interface}$ = d1**	**Refractive index interface film applied where n_{film} = d1**							
Coupling arrangement ↓										
Butt coupling										
Axial displacement = 0 µm	001	002	003	004	005	006	007	008	009	010
Axial displacement = 5 µm	011	012	013	014	015	016	017	018	019	020
Axial displacement = 50 µm	021	022	023	024	025	026	027	028	029	030
Axial displacement = 100 µm	031	032	033	034	035	036	037	038	039	040
Axial displacement = (d2) µm	041	042	043	044	045	046	047	048	049	050
Lens coupling arrangement										
Imaging Source/launch conduit onto input facet	051	052	053	054	055	056	057	058	059	060

5.9 Coordinate table EEE – Capturing conditions

5.9.1 Mandatory parameters

There are no mandatory parameters.

5.9.2 Customisation parameters

The following customisation parameters are defined for Table 6:

- (e1) – diameter of fibre core in units of micrometres
- (e2) – numerical aperture of fibre
- (e3) – parabolic profile parameter of the fibre core
- (e4) – diameter of spatial filter

Table 6 – EEE coordinate reference for capturing conditions

Capturing device →	Photodetector detector coupled to capturing conduit	Integrating sphere detector coupled to capturing conduit	Large area photodetector without spatial filter	Large area photodetector with circular spatial filter Ø75 µm	Large area photodetector with circular spatial filter Ø(e4) µm					
Capturing conduit ↓										
Direct coupling without intermediary conduit	001	002	003	004	005	006	007	008	009	010
Glass fibre SI										
Ø9/125 µm SMF (OS1)	011	012	013	014	015	016	017	018	019	020
Ø9/125 µm BI SMF	021	022	023	024	025	026	027	028	029	030
Ø50/125 µm	031	032	033	034	035	036	037	038	039	040
Ø62,5/125 µm	041	042	043	044	045	046	047	048	049	050
Ø105 µm	051	052	053	054	055	056	057	058	059	060
Ø200 µm	061	062	063	064	065	066	067	068	069	070
Glass fibre GI										
Ø50/125 µm OM5 MMF (non-bend insensitive)	071	072	073	074	075	076	077	078	079	080
Ø50/125 µm OM5 BIMMF (bend insensitive)	081	082	083	084	085	086	087	088	089	090
Ø50/125 µm OM4 MMF (non-bend insensitive)	091	092	093	094	095	096	097	098	099	100
Ø50/125 µm OM4 BIMMF (bend insensitive)	101	102	103	104	105	106	107	108	109	110
Ø50/125 µm OM3 MMF (non-bend insensitive)	111	112	113	114	115	116	117	118	119	120
Ø50/125 µm OM3 BIMMF (bend insensitive)	121	122	123	124	125	126	127	128	129	130

Capturing device →	**Photodetector detector coupled to capturing conduit**	**Integrating sphere detector coupled to capturing conduit**	**Large area photodetector without spatial filter**	**Large area photodetector with circular spatial filter Ø75 µm**	**Large area photodetector with circular spatial filter Ø(e4) µm**					
Capturing conduit ↓										
Ø50/125 µm (OM2)	131	132	133	134	135	136	137	138	139	140
Ø62,5/125 µm (OM1)	141	142	143	144	145	146	147	148	149	150
Ø105 µm, NA 0,22	151	152	153	154	155	156	157	158	159	160
Ø200 µm, NA 0,39	161	162	163	164	165	166	167	168	169	170
Hard polymer cladding fibre (HPCF)										
Ø200/230 µm A3	171	172	173	174	175	176	177	178	179	180
Plastic optical fibre SI										
Ø50/125 µm	181	182	183	184	185	186	187	188	189	190
Ø62,5/125 µm	191	192	193	194	195	196	197	198	199	200
Ø980/1 000 µm (A4)	201	202	203	204	205	206	207	208	209	210
Custom										
Ø (b2) µm, NA (b3), profile parameter (b4)	211	212	213	214	215	216	217	218	219	220
Specialist glass fibre GI										
Ø25 µm, NA 0.1	221	222	223	224	225	226	227	228	229	230

5.10 Examples of deployment

5.10.1 General

The following examples are presented of the use of the MIC to capture a comprehensive amount of information on the test and measurement conditions for an optical circuit board channel.

5.10.2 MIC-042-113(400)-001-001-112 (integrating sphere device details including supplier and model number)

A multimode 850 nm VCSEL test source with a narrow spectral width of 5 nm is connected to a non-bend insensitive OM3 50/125 µm glass fibre. Mode filtering elements are arranged such that the spatial and angular power distribution of output of the fibre into the input facet of the optical channel under test is compliant with the template profiles for EF and EAF defined in IEC 61300-1 and IEC 61300-3-53, respectively, for non-bend insensitive OM3 50/125 µm glass fibres. The total optical power measured at the launch facet is 400 µW.

The output fibre facet is butt-coupled to the input facet of the optical channel under test with an axial distance of 0 µm and is thus touching the input facet. The input facet is untreated.

The output facet of the optical channel under test is untreated and butt-coupled with an axial displacement of 0 µm to a non-bend insensitive OM3 50/125 µm glass fibre.

The capturing fibre is coupled directly to an integrating sphere detector. The supplier name, model number and any other information required to identify the measurement apparatus used is preferably explicitly stated after the MIC code.

This measurement setup would be recommended to evaluate the optical circuit board for applications requiring multimode fibre-to-board connectivity with repeatable mating.

5.10.3 MIC-072-123(205)-053(1.56, X,X)-001-042 (integrating sphere device details including supplier and model number)

A multimode 1 060 nm test source with a narrow spectral width between 2 nm and 10 nm is connected to a bend insensitive OM3 50/125 µm glass fibre. Mode filtering elements are arranged such that the spatial and angular power distribution of output of the fibre into the input facet of the optical channel under test is compliant with the template profiles for EF and EAF requirements defined in IEC 62614 and IEC 61300-3-53, respectively, for bend insensitive OM3 50/125 µm glass fibres. The total optical power measured at the launch facet is 205 µW.

The launch fibre facet is imaged onto the input facet of the optical channel under test with a lens arrangement. The input facet is treated with a thin film with a refractive index of 1,56.

The output facet of the optical channel under test is untreated and butt-coupled with an axial displacement of 0 µm to a step index glass capturing fibre with core diameter 62,5 µm.

The capturing fibre is coupled directly to an integrating sphere detector. The supplier name, model number and any other information required to identify the measurement apparatus used is preferably explicitly stated after the MIC code.

This measurement setup would be suitable to evaluate the optical circuit board for applications requiring free space imaging optics at the interfaces, such as expanded beam connectors.

5.10.4 Fast polarisation axis: MIC-091-072(150)-042(1.53, 25, -30)-051-004; slow polarisation axis: MIC-091-072(75)-042(1.53, 25, -120)-051-004

A single-mode 1 310 nm test source with a spectral width lower than 10 nm is connected to a 9,2/125 µm graded index polarisation maintaining optical fibre. The fibre is arranged such that output power distribution is compliant with the single-mode launch conditions defined in IEC 61300-1. The total optical power measured at the launch facet from the fast polarisation axis is 150 µW. The total optical power measured at the launch facet from the slow polarisation axis is 75 µW.

The launch fibre facet is oriented relative to the input facet of the channel under test such that the fast polarisation axis forms an angle of –30° to the designated top axis of the input channel under test (i.e. 30° moving anti-clockwise from the top axis of the input facet of the channel under test), and the slow polarisation axis forms an angle of –120° to the designated top axis of the input channel under test (i.e. 120° moving anti-clockwise from the top axis of the input facet of the channel under test). The launch fibre facet is butt-coupled on to the input facet of the optical channel under test with an axial displacement of 25 µm. The input facet is treated with a refractive index fluid with a refractive index of 1,53 for a wavelength of 1 310 nm.

The output facet of the optical channel under test is untreated and imaged through an imaging lens assembly to a large area photo-detector with a 75 µm spatial filter.

This measurement setup would be suitable to evaluate the polarization dependent performance of optical circuit boards for applications requiring polarization sensitive connectivity such as adiabatic waveguide coupling to photonic integrated circuits.

Annex A
(informative)

State of the art in optical interconnect technologies

A.1 Diversity of optical interconnect technologies

There are many varieties of system embedded optical interconnect, which have emerged at different stages over the past 20 years and differ strongly from each other in terms of their material composition, waveguide profile, channel and performance characteristics, fabrication process and compliant technologies. These varieties include,

a) fibre-optic circuit laminates [1][1],

b) embedded planar polymer waveguides [2], [3],

c) embedded planar glass waveguides [4], [5], and

d) free space optics [6].

A.2 Fibre-optic circuit laminates

Laminated fibre-optic circuits in which optical fibres are pressed and glued into place on a substrate benefit from the reliability of conventional optical fibre technology. However, these circuits cannot accommodate waveguide crossings in the same layer, i.e. fibres shall cross over each other and cannot cross through each other. Moreover, with each additional fibre layer, backing substrates shall typically be added to hold the fibres in place, thus significantly increasing the thickness of the circuit. This would limit the long-term usefulness of laminated fibre-optic circuits in PCB stack-ups. At best, they can be glued or bolted onto the surface of a conventional circuit board.

A.3 Polymer waveguides

Polymer waveguides would be unsuited to convey certain operational wavelengths (1 310 nm or 1 550 nm) over longer distances due to higher intrinsic absorption losses, though this can be mitigated in some polymer formulations [7]. However, they would be suitable for very short reach, versatile, low cost links such as inter-chip connections on a board. They would also be suitable for applications in which certain properties of the polymer such as thermo-optic, electro-optic or strain-optic coefficients could be used to support advanced devices such as Mach-Zehnder switches or long range plasmonic interconnects.

A.4 Planar glass waveguides

Planar glass waveguide technology could combine some of the performance benefits of optical fibres, such as lower material absorption at longer operational wavelengths and lower modal dispersion with the ability to fabricate dense complex optical circuit layouts on single layers and integrate these into PCB stack-ups. The Fraunhofer Institute of Reliability and Microintegration (Fraunhofer IZM) [2] in Germany are producers of planar glass waveguide based optical circuit boards.

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1 Figures in square brackets refer to the bibliography.

2 This information is given for the convenience of users of this document and does not constitute an endorsement by IEC.

A.5 Free space optics

With the proliferation of expanded optical beam technologies, a free space optical interconnect represents a viable emerging solution for in-system interconnect applications, as the internal misalignment tolerances inherent to such systems can be more easily accommodated by expanded beam technologies. Target applications include server backplane interconnectivity. Even though free space optical systems do not require a physical circuit board substrate, in order to be purely optical waveguide agnostic, the proposed measurement identification system in this document can be equally applied to free space optical channels.

A.6 Target applications

The target application also plays an important role as this defines the trade-off space constraining the selection of waveguide type. For example in data centre applications, cost would be the dominant factor, while in high performance computers or supercomputers, emphasis is placed on performance optimisation.

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