

ITU-T Technical Report

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GSTR-SDM

**Optical fibre, cable, and components for space
division multiplexing transmission**



Technical Report ITU-T GSTR-SDM

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Summary

Technical Report ITU-T GSTR-SDM on optical fibre and cable for space division multiplexing (SDM) transmission is established for analysing the current state of the SDM technical maturity, clarifying the technical and commercial aspects of this technology, and highlighting the characteristics of related technologies and network configuration / installation / operations. The goal is to develop a cost-effective network and ecosystem utilizing the SDM optical fibre and cable technologies. The classification and definition of existing SDM optical fibre and cable technologies are described from the viewpoint of the geometrical, mechanical and optical properties of various SDM optical fibres. Potential application areas are investigated to examine the relationship between various SDM optical fibre and cable technologies. Furthermore, aspects of how to use SDM optical fibres in anticipated applications are addressed, including considerations on connectorisation, splicing, breakout technologies and how to embed this technology in current optical systems. The purpose of this Technical Report is to establish a clear and agreed roadmap for SDM optical fibre and cable technologies including related technologies such as test methods, connectivity, maintenance and restoration.

Keywords

Components, cable, optical fibre, space division multiplexing, test methods.

Note

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1 Introduction

Data communication is a mandatory social infrastructure of our daily life. The worldwide spread of communications and the rapid progress toward and beyond 5G and 6G have led to unique new services and innovations for our lifestyles. This rapid progress in data communication has also led to strong demands for more optical fibre and cable-based large-capacity backbones and distributed networks. Against this backdrop, the transmission capacity in the latest optical submarine systems is close to the Shannon limit. Thus, massive parallelism and/or innovative optical fibre and cable technology are required to continuously support the increasing capacity demands sustainably.

This Technical Report is established to clarify the current technical level of optical fibre and cable for space division multiplexing (SDM) transmission. The remaining challenges that need to be resolved for achieving SDM-based optical fibre and cable networks of the future are also investigated to provide a roadmap for future deployment and standardisation of SDM optical fibre and cable technology.

2 Scope

This Technical Report describes the technical aspects of the optical fibre and cable that can be used for space division multiplexing (SDM) transmission. An SDM optical fibre cable is defined as one that can improve the spatial density of an optical fibre in a unit cross-section and/or increase the number of spatial transmission channels in a common cladding.

The classification and definition of various SDM optical fibres, including (but not limited to) reduced coating / cladding diameter fibre, a multicore fibre (MCF) and few-mode fibre (FMF), are described in this Technical Report and their geometrical, mechanical, and optical properties are analysed. The examination of potential application areas and network configurations / installations / operations are investigated with respect to various SDM optical fibre and cable technologies. This Report addresses the relationship between SDM and traditional optical fibre and cable manufacturing methods. Furthermore, aspects of how to use SDM optical fibres in anticipated applications are addressed, including considerations on connectorisation, splicing and breakout technologies, and how to imbed these technologies in current optical systems. This Technical Report provides a clear and agreed roadmap for SDM optical fibre and cable technologies that will ideally assist in achieving future SDM optical fibre, cable deployment and standardisation.

3 Abbreviations and definitions

3.1 Abbreviations and acronyms

This Technical Report uses the following abbreviations and acronyms:

ADC	Analogue to Digital Converter
ASIC	Application-Specific Integrated Circuit
CFP	C Form-factor Pluggable
CO	Central Office
CPO	Co-Packaged Optics
DAC	Digital to Analogue Converter

DC	Data Centre
DCI	Data Centre Interconnects
DGD	Differential Group Delay
DMA	Differential Modal Attenuation
DMD	Differential Modal Delay
DMG	Differential Modal Gain
DMGD	Differential Modal Group Delay
DSP	Digital Signal Processing
DWDM	Dense WDM
EDFA	Erbium-Doped Fibre Amplifier
FAU	Fibre Array Unit
FIFO	Fan-in/Fan-out
FMF	Few-Mode Fibre
FM-MCF	Few Mode Multicore Fibre
FTTx	Fibre To The x
IL	Insertion Loss
LD	Laser Diode
LP mode	Linearly Polarised mode
MC-EDF	Multicore Erbium-Doped Fibre
MCF	Multicore Fibre
MDL	Mode-Dependent Loss
MDM	Mode Division Multiplexing
MFD	Mode Field Diameter
MFH	Mobile Front Haul
MIMO	Multiple-Input Multiple-Output
MSC	Mode Selective Coupler
OCT	Outer Cladding Thickness
O/E	Optical signal to Electrical signal converter
OSFP	Octal Small Form-factor Pluggable
OSNR	Optical Signal-to-Noise Ratio
PDL	Polarization Dependent Loss
PLC	Planar Lightwave Circuit
PMD	Polarization Mode Dispersion
QSFP	Quad Small Form-factor Pluggable
RCF	Reduced Cladding Fibre
RCDF	Reduced Coating Diameter Fibre
RC-MCF	Randomly Coupled Multicore Fibre

ROADM	Reconfigurable Optical Add/Drop Multiplexer
SCF	Single-Core Fibre
SC-MDM	Single-Core Mode Division Multiplexing
SDM	Space Division Multiplexing
SFP	Small Form-factor Pluggable
SMD	Spatial Mode Dispersion
SMF	Single-Mode Fibre
SNR	Signal-to-Noise Ratio
TDM	Time Division Multiplexing
TIA	Trans Impedance Amplifier
ToF	Time of Flight
UHC	Ultra-High fibre count Cable
WC-FMF	Weakly Coupled Few-Mode Fibre
WC-MCF	Weakly Coupled Multicore Fibre
WDM	Wavelength Division Multiplexing
XT	Crosstalk

3.2 Definitions

This Technical Report defines the following terms:

3.2.1 crosstalk (XT): The ratio of transmitted optical power between an excited spatial channel and the other spatial channels. An XT between cores is called an inter-core XT. An XT between modes is called an inter-modal XT.

3.2.2 differential modal attenuation (DMA): The difference between the attenuation coefficients among transmission modes in an optical fibre for multi-mode transmission.

3.2.3 differential modal delay (DMD): A differential group delay (DGD) among multiple spatial modes.

3.2.4 differential modal gain (DMG): The optical amplification gain difference among multiple spatial modes in a space division multiplexing (SDM) optical fibre.

3.2.5 differential modal group delay (DMGD): A DGD among multiple spatial mode groups.

3.2.6 mode-dependent loss (MDL): The ratio of the minimum to maximum (peak to peak MDL) or root mean square (RMS-MDL) of the power of singular values of the channel transfer matrix for multi-mode transmission systems. The MDL in an optical fibre contains the DMA and the inter-modal XT contributions. The MDL in an optical link also contains the other optical components factors such as MDL in a fan-in/fan-out (FIFO), DMG in an optical amplifier, and so on.

3.2.7 spatial mode dispersion (SMD): The square root of the second moment of the DGD distribution in an RC-MCF or a mode group. Random coupling results in a Gaussian dispersion spread in the time domain, and SMD is determined as 2σ (σ : standard deviation) of the impulse response distribution.

NOTE 1 – The definition of differential group delay (DGD) between two orthogonal polarizations in an SMF is described in clause 3.1.3 of [b-ITU-T G.650.2]. This Technical Report also considers the DGD among the multiple spatial channels in an SDM optical fibre.

NOTE 2 – The definition of polarization mode dispersion (PMD) is described in clause 3.1.4 of [b-ITU-T G.650.2]. PMD_{AVG} and PMD_{RMS} are defined as the linear average or root mean square of the DGD values over a given optical frequency range.

4 Background of SDM

Ever since [b-ITU-T G.652] was established as the first international standard of single-mode fibre (SMF) in 1984, optical fibres have been continuously developed with optical transmission technologies to support the increasing transmission capacity. During the late 1980s and early 1990s, the development of the erbium-doped fibre amplifier (EDFA) and time division multiplexing (TDM) enabled optically amplified long-haul transmission at 1550 nm. To support these optical transmission systems, [b-ITU-T G.653] and [b-ITU-T G.654] fibres were respectively developed in 1988 and 1993. In the late 1990s, wavelength division multiplexing (WDM) effectively increased the transmission capacity in the C-band (1530 – 1565 nm), which led to the development of [b-ITU-T G.655] fibre in 1996. In the 2000s, remarkable progress in dense WDM (DWDM) technology and the expansion of the transmission window, such as to the L-band (1565-1625 nm) or S-band (1460-1530 nm), required the revision/establishment of [b-ITU-T G.655] and [b-ITU-T G.656] fibres. In the 2010s, coherent technology and digital signal processing further increased the transmission capacity, and these trends have been accelerating the effective use of [b-ITU-T G.652] and [b-ITU-T G.654] fibres in optical networks. The [b-ITU-T G.657] fibre standard was also established in 2006 to provide standardised definitions around macrobend loss protection.

The transmission capacity of the first SMF-based system launched in the 1980s was a few tens of Mb/s. In contrast, the latest terrestrial and submarine systems now support more than 10 Tb/s per SMF with a spectral efficiency of more than 2 b/s/Hz using a multilevel modulation technique as well as the above-mentioned technologies. The capacity growth rate over the past 40 years corresponds to 40% per year. This suggests that optical transmission systems will be able to support more than 100-Tb/s capacity in 2025 and over 1-Pb/s capacity by the early 2030s. However, the existing G.65x fibres have a limited maximum capacity because the maximum input power in an SMF is limited by an optical nonlinear effect, which results in limited improvement in the optical signal-to-noise ratio (OSNR). The total input power of all the DWDM channels is also restricted by a physical limitation, namely the fibre fuse. Thus, the maximum capacity in one SMF is limited to around 110 Tb/s when an optically amplified transmission window and a spectral efficiency are assumed to be a C-L band and 10-b/s/Hz, respectively. Even if the S-L band is available as an optically amplified DWDM transmission bandwidth, the maximum capacity of one SMF will be difficult to increase beyond 200 Tb/s.

In addition to the increase in bandwidth (B) and signal-to-noise ratio (SNR), the industry has been exploring the space option (increase in N) for capacity increase, which is the third and final dimension in Shannon's formula, to achieve a sizeable increase in transmission capacity (Figure 1). In its most conventional sense, SDM could simply mean more fibres in the cable. However, to further increase cable capacity by means of a further increase in spatial paths, the belief within the industry is that more radical solutions will be needed. Such solutions may involve reduced-coating diameter fibres (RCDF), reduced-cladding fibres (RCF), a multicore fibre (MCF), or few-mode fibre (FMF).

$$C = \underbrace{2 \times B \times N}_{\text{Linear capacity gain}} \times \underbrace{\log_2(1 + \text{SNR})}_{\text{Logarithmic capacity gain}}$$

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Figure 1 – Shannon formula showing cable capacity (C) as a function of fibre bandwidth (B), number of spatial paths (N), and signal-to-noise ratio (SNR)

5 Potential application areas that can benefit from SDM

The use of SDM optical fibre and cable has been considered in various optical communication areas they are:

- i) long-haul submarine and terrestrial backbone networks,
- ii) inter-central office (CO) / data centre (CO to CO / DC to DC) and metro networks,
- iii) access network and mobile front haul (MFH),
- iv) data centre (DC) interconnect (DCI), and
- i) long-haul submarine and terrestrial backbone networks.

As data traffic demands continue to increase worldwide [b-Winzer], achieving greater transmission capacity in long-haul submarine / terrestrial optical cables has become a key area of focus. Recently, SDM concepts have been implemented to further increase cable capacity via more channels in the cable. To manage electrical capacity constraints, more channels are used, but at lower launch powers such that each fibre operates in a more linear range compared to legacy non-SDM systems. As of today, SDM is the de-facto technique used to design optically amplified long-haul submarine / terrestrial systems, although it must be noted that the term "SDM" is used in a very specific way and does not yet imply the use of innovative optical fibre options, such as RCDF, RCF, MCF or FMF.

One factor motivating the interest in using MCF in optically amplified submarine systems is the space limitation in cable designs. The cross-sectional area of the cable's central tube typically limits the number of regular, single-core fibres (SCFs) that can be accommodated in the cable before microbend losses become significant. An increase in tube size is also not desirable since this increases the cable cost and weight. MCF could potentially overcome these cable design limitations, thus allowing for more spatial paths in a cable.

To achieve such an increase in spatial paths, MCF must also have an ultra-low level of typical attenuation (no more than ~ 0.01 dB/km typical attenuation increase versus a typical SCF). Another key performance metric in submarine systems is the cost/bit, including the required power per bit contribution, will have to move lower down the cost curve for the MCF to be considered for these systems.

- ii) Inter-CO / DC and metro networks

The data capacity between COs has been increasing exponentially, and the growth rate has tended to be higher than that of the data capacity between a long-haul submarine and terrestrial backbone networks. Several COs are expected to function as data centres (DCs) in addition to their legacy role. These trends will result in a much higher increase in the transmission capacity and require many more SMFs in the inter-CO and metro networks. Although the transmission distances in inter-CO and metro networks are shorter than those in terrestrial backbone networks, SDM optical fibres and cables potentially support sustainable parallelisation with only minimal impact on the existing physical infrastructure. Massive and simultaneous connection technology for SDM optical fibres and cables can enhance the usefulness of SDM optical fibres and cables in the inter-CO and metro networks.

A preference for point-to-point connectivity over WDM has resulted in the proliferation of ever-increasing high fibre count cables in these networks. In some cases, these DC/CO buildings are physically distributed across a metropolitan area where duct space is very limited. In the face of this duct space challenge, cables with SDM optical fibre types offer the potential to significantly achieve higher levels of cabled optical fibre density.

- iii) Access network and MFH

Future access networks will require further harmonisation and convergence with advanced mobile technology. Moreover, future data-centric communication and computing with lower latency will require flexible and numerous connections between various antennas / devices / edges and centre clouds.

Yesterday's separate networks will likely evolve into tomorrow's converged services networks (Figure 2). Individual services will be carried over the same fibre using technologies such as WDM to achieve service separation. Under this common platform, emerging services such as 4k video, 5G services, and IoT management software may reach a new development stage through technology-agnostic access points.

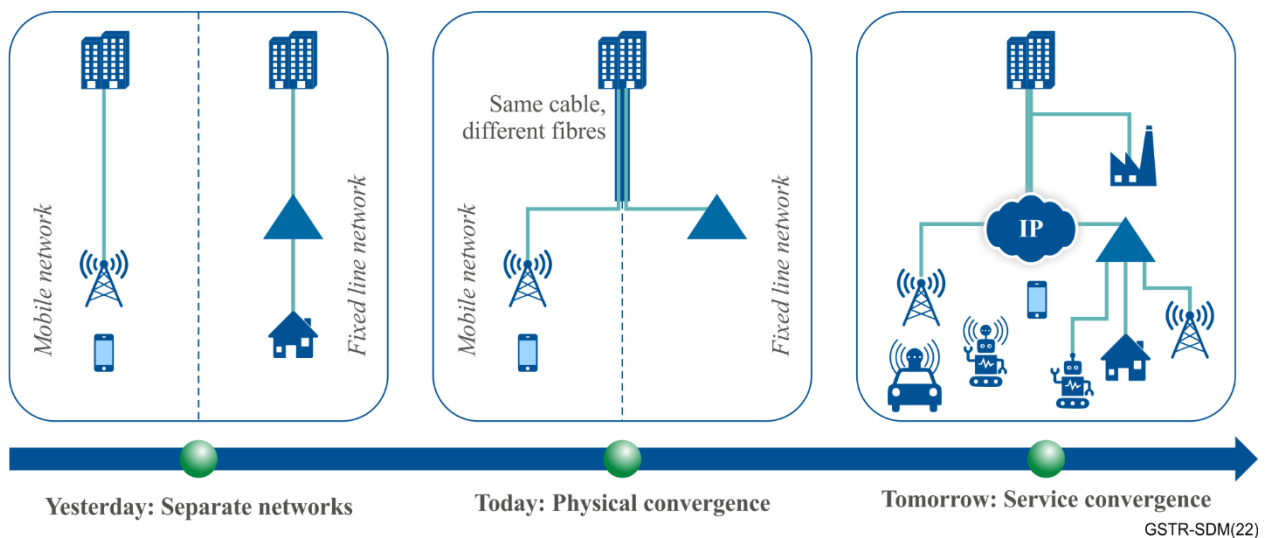


Figure 2 – Access networks are evolving from separate networks into service convergence of the future

Even with service convergence, feeder cable capacity and the associated optical fibre count will remain high due to the ever-increasing data volume in the network, the continued proliferation of diverse endpoint connections, the practicalities of distribution, and the diverse locations of network equipment. However, the implementation of a high-capacity cable infrastructure is very capital intensive hence, it is always preferable for network operators to find ways to utilize existing duct pipes for the routing of new optical cabling. SDM solutions are well positioned to provide increased pathway density over this converged network.

iv) Data centre interconnect (DCI)

Worldwide penetration of Fibre to the x (FTTx) and data-centric communication will significantly increase the number of SMFs in a high-speed DCI, and DCs will require massive and effective optical connections/wiring. Parallelised optical transmission has already been deployed in the current DCI network to increase data transmission speed cost-effectively. Moreover, further optical integration requires an optical fibre suitable for optical wiring in an extremely limited space.

Co-packaged optics (CPO) promise to greatly reduce power by moving the optical transceiver function closer to the switch application-specific integrated circuit (ASIC), permitting a new optical switching platform to support the faster and larger radix switches.

Major optical interface challenges exist as hundreds (or even thousands) of optical fibres need to converge onto a miniaturized onboard optical module. Therefore, an advanced optical fibre solution becomes a prerequisite to address the chip edge density challenge. With high-density optical fibre solutions such as RCF or MCF, the intrinsic nature of the high-density core arrangement will greatly alleviate the space limitation challenge at the optical interface. Figure 3 shows the optical interface density that various optical solutions can offer. Here the optical units based on 400G-DR4 building blocks are assumed as the latest example technology around 2022. Specifically, considering a two-sided 25.6-Tb/s co-packaged optics arrangement and remote light source technique, 288 optical lanes (including 32 polarization maintaining fibres) are needed for the optical interface. Such a density will be challenging to achieve with conventional optical fibre attachment approaches based on legacy

SMF with 125/250- μm cladding / coating size. An RCF solution, e.g., 80/160- μm and/or 100/160- μm cladding / coating size, can improve the optical interface density, but an MCF solution, e.g., 125/250- μm cladding / coating size with four cores, offers the highest density among all three fibre solutions (based upon geometrical considerations only), with the capability of delivering higher density compared to regular 125/250- μm cladding / coating SMF.



Figure 3 – Optical interface density achieved with regular single-mode fibre, RCF and MCF

In addition, an advanced packaged high-density MCF or RCF array may help achieve a fast and cost-effective optical alignment solution. For example, with an MCF-based fibre array unit (FAU), one single optical fibre alignment step would automatically bring all the cores into alignment, which could potentially simplify the alignment process and thus significantly improve the optical fibre alignment cost structure.

Figure 4 summarises the prospective application areas of an SDM optical fibre and cable technology, and their expected effectiveness.

Application area	Schematic configuration	Remarks
Long-haul submarine terrestrial backbone		<ul style="list-style-type: none"> Potentially overcoming spatial channel density limitation in a cable Low loss and cost/bit characteristics should be maintained
Inter-CO / DC metro		<ul style="list-style-type: none"> Provide significant pathways in a limited infrastructure
Access MFH		<ul style="list-style-type: none"> Provide significant pathways in a limited infrastructure to support service-converged network Lowering delay differences among the paths may

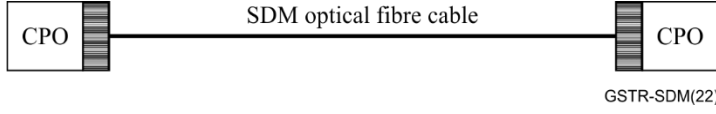
		benefit advanced mobile technology
DCI		<ul style="list-style-type: none"> • Provide the highest density and potentially achieve cost-effective fibre alignment

Figure 4 – Prospective application areas of an SDM technology

6 Space division multiplexing (SDM) technologies

6.1 SDM optical fibre technologies and properties

Figure 5 summarises the SDM optical fibre classification that is used in this Technical Report. These classifications can be considered as a combination of single-core design, multicore design and multi-mode design. The simplest SDM optical fibre can be obtained by considering RCDF or RCF. RCDF has already been deployed in an advanced optical fibre cable. Single-core design can evolve into a multi-mode design. A single-core FMF can support multiple transmission modes (M) in one core. MCF involves multiple cores (N) in a common cladding. MCF can be classified into two types according to the coupling strength between the neighbouring cores. A weakly coupled MCF (WC-MCF) has negligible crosstalk (XT) between the cores and can thus provide N individual spatial paths. A randomly coupled MCF (RC-MCF) supports N spatial modes based on the random coupling between N cores. Finally, a few mode multicore fibre (FM-MCF) can potentially provide $M \times N$ spatial channels by mixing the mode and core multiplexing design.

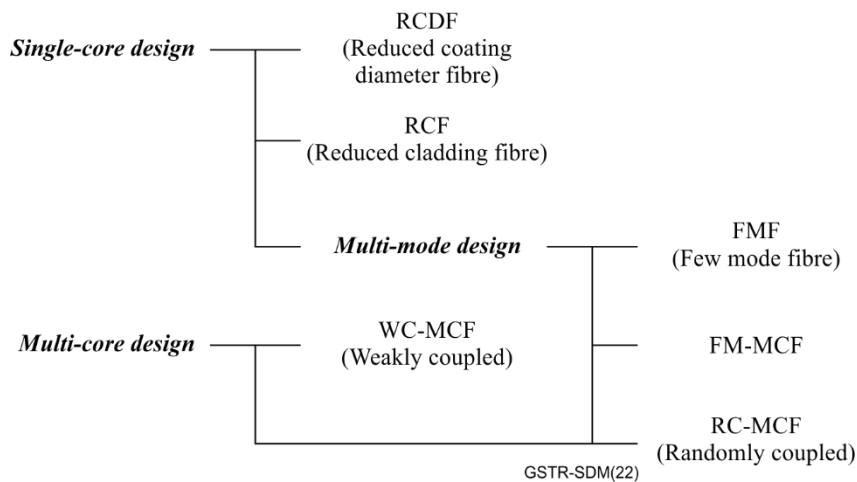


Figure 5 – Classification of SDM optical fibres

Table 1 summarises the general features of each SDM optical fibre. The following clauses 6.1.1 and 6.1.2 provide more detailed explanations of each core design.

Table 1 – General features of SDM optical fibres

Type		General features
Single-core design	RCDF	The coating diameter is reduced compared to that of the standard optical fibres while maintaining a cladding diameter of 125 μm . <ul style="list-style-type: none"> – Higher count optical fibre cable is achieved – Microbending sensitivity may be elevated – Puncture and abrasion resistance may be reduced
	RCF	The cladding diameter is reduced compared to that of the standard optical fibres. <ul style="list-style-type: none"> – Higher count optical fibre cable and/or higher density connection is achieved – Microbending sensitivity may be elevated – Puncture and abrasion resistance may be reduced – Tensile strength may be reduced
	FMF	A core is designed to support multiple-mode propagation. <ul style="list-style-type: none"> – Higher spatial multiplicity is achieved with a standard cladding diameter – Multiple-input and multiple-output digital signal processing (MIMO-DSP) is required due to strong mode coupling
Multicore design	Weakly coupled MCF	Multiple cores are allocated within a cladding so that each core supports an individual spatial path. <ul style="list-style-type: none"> – Each core design can be compatible with the conventional SMFs – The number of cores in the standard cladding diameter is limited by inter-core XT and loss
	Randomly coupled MCF	Multiple cores are allocated within a cladding so that sufficient signal coupling among the cores is achieved. <ul style="list-style-type: none"> – Higher core multiplicity is achieved than with a weakly coupled MCF – MIMO-DSP is mandatory
	FM-MCF	Multiple few-mode cores are allocated within one cladding so that each core has sufficiently low XT. <ul style="list-style-type: none"> – Higher spatial channels are achieved thanks to the multiplication of core and mode numbers – MIMO-DSP is required due to strong mode coupling

6.1.1 Single-core fibre

6.1.1.1 Reduced coating diameter fibre (RCDF)

6.1.1.1.1 Description

One approach to increase fibre density is to reduce the coated fibre diameter. Conventional optical fibres have a cladding diameter of 125 μm and a coating diameter of 250 μm . In RCDF, the cladding diameter is kept the same (125 μm) to maintain compatibility with conventional fibres while reducing the coating diameter [b-Li]. Figure 6 shows the fibre density in a cable as a function of fibre coating diameter based on the fibre cross-sectional area. If the coating diameter is reduced to 175 μm , 145 μm , or lower, the fibre density is increased by a factor of 2, 3, or theoretically up to 4, respectively (relative to the standard fibre coating diameter of 250 μm).

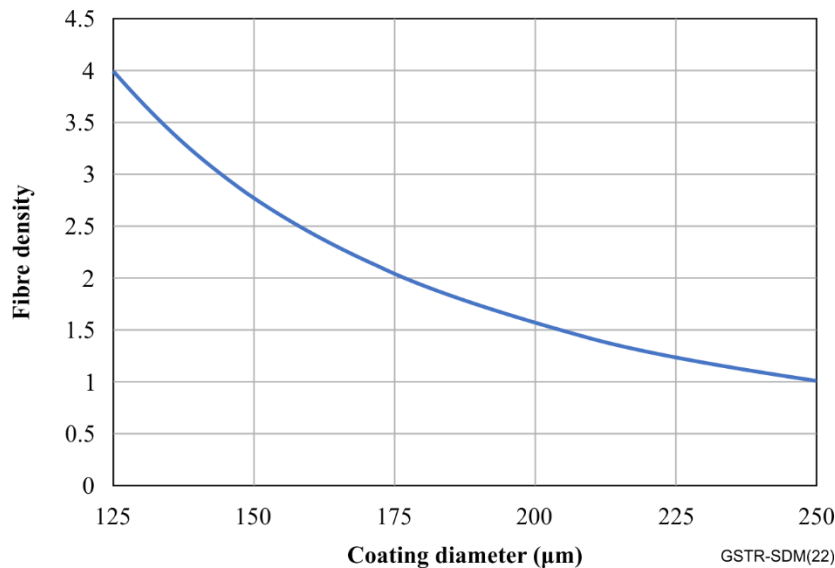


Figure 6 – Fibre density as a function of the coating diameter

6.1.1.1.2 Relevant attributes (geometric, environmental, transmission)

Reduced coating diameter fibre (RCDF) should meet the fibre attributes defined for conventional 125/250-µm cladding / coating diameter fibre standards. The influence of the reduced dimensions on microbending and mechanical reliability will require further study.

6.1.1.1.3 Advantages / disadvantages

The advantages of the RCDF are as follows.

- Increased fibre density in a cable
- Compatible with the standard 125 µm cladding diameter fibre
- Does not need SDM components such as fan-in/fan-out (FIFO) or mode mux / demux
- Compatible with conventional fibre transmission systems

The disadvantages of RCDF are as follows.

- May require better cable design to reduce microbending due to external perturbations
- May require better handling to avoid mechanical damage to thin coatings
- SDM improvement factor (increase in fibre density in a cable with constant diameter) is limited to less than 4.

6.1.1.2 Reduced cladding fibre (RCF)

6.1.1.2.1 Description

RCF offers the potential of higher connectivity density, overcoming the fibre density constraint by providing smaller-diameter fibres compared to conventional 125/250 µm cladding / coating diameter fibres. To put the size reduction into perspective, Figure 7 compares the cross-sectional geometry of a conventional SMF with an example of an RCF that has cladding and coating diameters of 80 and 165 µm, respectively.

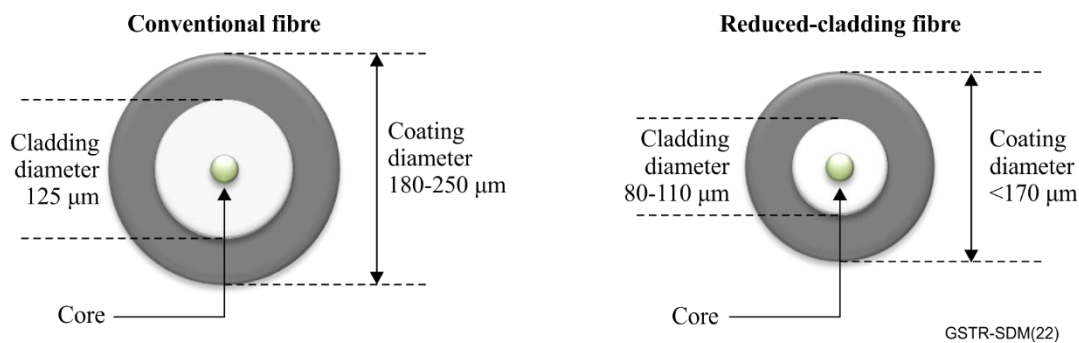


Figure 7 – RCF enables higher density compared to conventional 250 µm fibre

The biggest trade-off when it comes to reducing the fibre cladding diameter is a significant increase in microbending sensitivity when the cladding diameter is less than 100 µm, which is one reason the RCFs used as photonic coupling fibres, have smaller mode-field diameters and/or larger numerical apertures than conventional single-mode fibre. If not mitigated, this microbending sensitivity can lead to an increase in the overall fibre attenuation and make the fibre overly sensitive to deployment conditions.

To address this challenge, bend-insensitive RCF designs with a trench in the cladding have been introduced. The trench helps isolate the LP₀₁ mode guided by the core from the perturbations in the outer cladding that induces microbending, and dimensions can be optimized to permit the LP₁₁ mode to attenuate rapidly enough to ensure that the fibre cut-off wavelength is less than 1 260 nm for short-reach deployments [b-Bickham].

6.1.1.2.2 Relevant attributes (geometric, environmental, transmission)

RCF should meet the fibre attributes defined for conventional 125 µm and 250 µm fibre standards, except for fibre geometry. The influence of the reduced dimensions on the microbending and mechanical reliability of the protective coatings will require further study.

6.1.1.2.3 Advantages / disadvantages

The advantages of RCF are as follows.

- Increased fibre density in a limited space
- Does not need SDM components such as FIFO or mode mux / demux
- Compatible with conventional fibre transmission systems

The disadvantages of RCF are as follows.

- Requires adaptation to connect with standard 125 µm cladding diameter fibre
- May require better cable design to reduce microbending due to external perturbations
- May require better cable design to reduce tensile strain
- May require better handling to avoid mechanical damage to the glass if the thinner protective coatings are damaged.

6.1.1.3 Few-mode fibre (FMF)

6.1.1.3.1 Description

Few-mode fibres (FMFs) use individual modes as transmission channels to increase fibre capacity. Figure 8 shows examples of different linearly polarised (LP) modes. Because a single core can support a large number of modes, the transmission capacity of FMFs can be much larger than an MCF with a 125 µm cladding diameter [b-Sillard]. Figure 9 shows a schematic of the cross-sectional structure of FMF. The fibre has a cladding diameter of 125 µm and a coating diameter of 250 µm. To improve the bending loss properties, a low index trench can be applied in the cladding. FMFs can be classified

into two categories: strongly coupled and weakly coupled. In strongly coupled FMFs, multiple-input multiple-output digital signal processing (MIMO-DSP) is required to separate different modes. The computation load of the MIMO-DSP for receivers in strongly coupled single-core mode division multiplexing (SC-MDM) systems will grow dramatically as the number of modes increases. To enable effective MIMO-DSP, fibre designs that minimize the differential modal delay (DMD) between modes are required. When the degenerate modes are not distinguished, DMD can be considered as a differential modal group delay (DMGD). For low DMD/DMGD, a graded index profile can be utilized by choosing the optimal α parameter (shape of the parabolic refractive index profile of the core). The actual DMD/DMGD of the strongly coupled FMF (SC-FMF) will be different from the simulation value due to the partial perturbation, longitudinal non-uniformity, and/or fabrication tolerance. For weakly coupled FMFs (WC-FMFs), inter-modal XT is minimized so that each mode is separately detected without using MIMO-DSP. Step index and ring-core-index profile designs can be used to suppress inter-modal XT. XT can also be suppressed by utilizing the elliptical core designs. The 150-km MIMO-free WDM-MDM transmission was demonstrated using a ring-core-index WC-FMF [b-Shen]. This indicates that the WC-FMF can be used for both short distances (e.g., DCs) and middle distances (e.g., metro networks). Moreover, since there is no need for rotated alignment, the splicing of the FMF is much easier than that of the MCF.

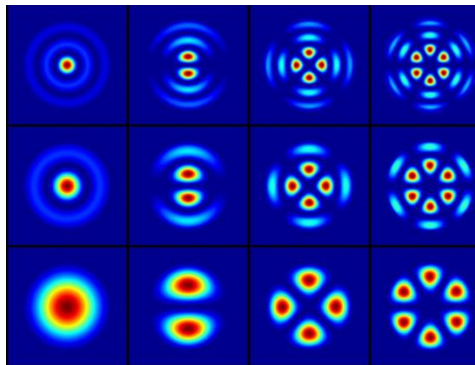


Figure 8 – Electrical field intensity distribution of different LP modes in FMF [b-Sillard]

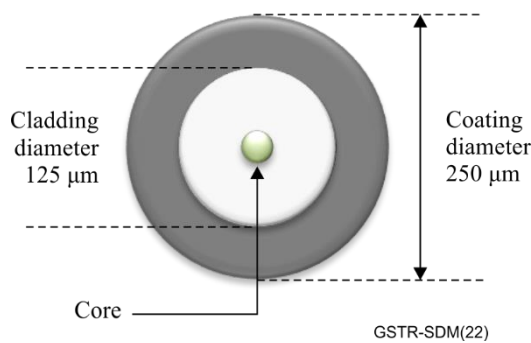


Figure 9 – Cross-sectional structure of FMF

6.1.1.3.2 Relevant attributes (geometric, environmental, transmission)

Unlike with the standard SMF, the transmission properties of each propagation mode must be considered with the FMF. Inter-modal XT must be designed adequately. A reduced coating diameter (e.g., 200 μm) can possibly be applied, but further research into the microbending properties and mechanical reliability is required.

6.1.1.3.3 Advantages / disadvantages

The advantages of FMF are as follows.

- Number of SDM channels in a limited cladding diameter can be much larger than in MCF

- Compatible with standard 125 μm cladding diameter
- Easier splicing and connectorisation than the MCF

The disadvantages of FMF are as follows.

- Requires mode mux / demux
- Limitation in transmission distance for WC-FMFs
- Requires low DMD/DMGD for SC-FMFs
- May require better cable design to reduce microbending
- May require better handling to avoid mechanical damage to thin coatings
- Differential modal attenuation (DMA) may erode the overall performance
- Differential modal gain (DMG) in the amplification system may erode the transmission performance.

6.1.2 Multicore fibre (MCF)

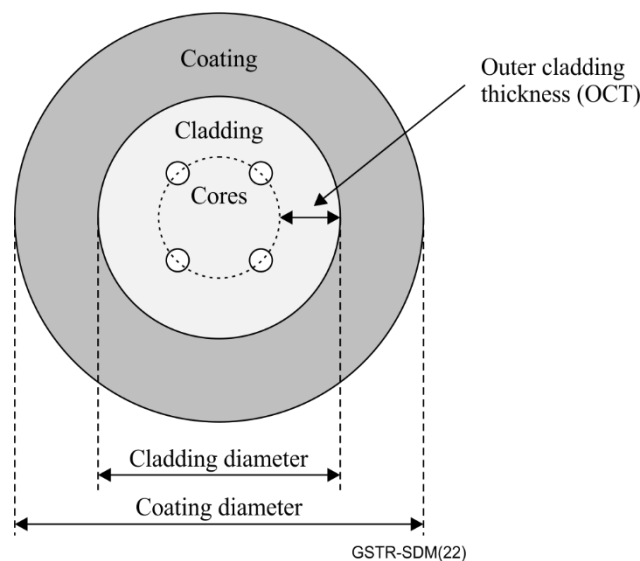


Figure 10 – MCF with various design parameters

An MCF is an optical fibre that includes multiple cores in one common cladding. The purpose of utilizing multiple cores is to aggregate more physical transmission paths within one fibre than which are found with standard optical fibres, that only have a single core located in the centre. This can provide greater signal bandwidth density than which is possible with the SCFs.

Various MCF designs have been created for a variety of potential applications. As shown in Figure 10, an MCF has a certain amount of design flexibility when it comes to the core count, core pitch, core layout, and outer cladding thickness (OCT), which is defined as the distance between the cladding edge and the centre of the outermost core and cladding / coating diameters. For example, the number of cores in an MCF can vary from two up to very large numbers with counts of four, seven, eight, or even 19. These cores can be single-mode or few-mode and can maintain polarization with many different designs. The arrangement of cores is often described as linear, hexagonal, square, rectangular or circular. There is a similar diversity in cladding dimensions and forms, with circular, D-shaped, square, and rectangular forms all represented in the literature. Most MCFs have a circular cladding with diameters ranging from 125 to 250 μm . These parameters must be optimized to achieve the desired optical / mechanical performance in the designated application space.

MCFs can be divided into two types, weakly coupled and randomly coupled, based on the inter-core XT.

6.1.2.1 Weakly coupled multicore fibre (WC-MCF)

6.1.2.1.1 Description

In WC-MCFs, which are arguably the most representative type of MCF, coupling between the cores (inter-core XT) is suppressed and each core is used as an individual spatial optical channel. Considering the design of a refractive index profile of the core, the same method as SCFs can be applied. This means that compatibility with a G.65x fibre is supported. Generally, the FM-MCF has the potential to increase the number of spatial channels due to the multiplication of core and mode numbers [b-Saitoh]. However, the connection from the SCF to the FM-MCF requires a higher alignment accuracy and more complex mode muxing and demuxing.

For WC-MCF, it is essential to maintain a relatively large core pitch to ensure an isolated mode transmission with less XT [b-Koshihira]. The crosstalk (XT) is reduced by introducing a complex refractive index profile such as an index trench. In addition to the XT, the cut-off wavelength is also affected by the core pitch. When each core is surrounded by an index trench layer and the core pitch is too small, the cut-off wavelength of a core that is surrounded by the other cores may be increased. The XT is expected to decrease when it is used for bi-directional communication, which means the adjacent cores are used in opposite directions.

On the other hand, as the number of cores increases within the cladding, the OCT decreases. The smaller OCT affects the attenuation property due to the light coupling from the outer cores to the coating. Even though a larger cladding diameter can relax the XT, cut-off wavelength, and OCT limitations, an MCF with a standard 125 μm cladding diameter is expected to minimize the negative impact on the fabrication process and will support the effective use of existing fibre and/or cable manufacturing processes and materials (such as using a ferrule as a connector [b-Matsui]).

In data transmission with WC-MCF, the system may need to optically interface with the SCFs. To enable that, transition elements known as FIFOs are required to spread out the tightly packed optical signals in the MCF to an array of SCFs.

6.1.2.1.2 Relevant attributes (geometric, environmental, transmission)

WC-MCF can be designed to satisfy the optical properties that are comparable to the existing standard SMF. Unlike the standard SCFs, XT must be taken into consideration. A reduced coating diameter, e.g., 200 μm , can be applied [b-Sasaki], but further studies on multicore geometry and the microbending loss properties are required.

6.1.2.1.3 Advantages / disadvantages

The advantages of WC-MCF are as follows.

- Increased core density in a limited cross-section
- Can be designed to support compatibility with G.65x fibre

The disadvantages of WC-MCF are as follows.

- Standard 125 μm cladding diameter limits the number of multiplexing cores to four or five due to managing the balance of XT and excess loss
- Requires core alignment to facilitate splicing and connectorisation, and a marker may be required when the number of cores is managed
- Needs SDM components such as FIFO
- May require better cable design to reduce microbending loss due to external perturbations
- May require better handling to avoid mechanical damage to thin coatings
- Differential gain among the cores in the amplification system may erode transmission performance
- DMA may erode the overall performance in the few mode multicore fibre (FM-MCF)

- DMG in the amplification system may erode the transmission performance in the FM-MCF.

6.1.2.2 Randomly coupled multicore fibre (RC-MCF)

6.1.2.2.1 Description

RC-MCF consists of cores that are packed closely together to encourage optical coupling among them. With a tighter core pitch, one of the obvious benefits is a higher spatial/core density [b-Sakamoto1].

For RC-MCF, the closer core pitch induces random mode coupling, but a core pitch that is too close causes strong mode coupling and results in the re-enlargement of the effective refractive index between spatial modes. When the neighbouring cores exhibit strong mode coupling, a time of flight (ToF) difference between the modes can be observed at the end of the fibre, similar to the DMD/DMGD in an FMF. DMD/DMGD is caused by the effective refractive index difference between the modes/mode groups, and it accumulates along the transmission distance linearly. On the other hand, the impulse response between modes changes to a Gaussian-like response in the time domain when the random coupling is implemented. In this case, a spatial mode dispersion (SMD) coefficient can be considered as a modal dispersion spread in the time domain instead of the DMD/DMGD. In the random coupling regime, SMD increases in proportion to the square root of the transmission distance, so the RC-MCF is expected to reduce the accumulated modal dispersion to less than that in the FMF. Moreover, random coupling can result in a lower mode-dependent loss (MDL) / differential modal attenuation (DMA) and lower nonlinearity, which in turn simplifies the calculation complexity in the MIMO-DSP. Therefore, RC-MCF is a possible candidate for overcoming the XT limitation in a WC-MCF and the DMD/DMGD limitation in an FMF. RC-MCF is also beneficial for achieving low loss properties. Because the RC-MCF can be composed of simple step-index pure silica cores it does not require engineered graded index cores and/or additional trench structures. In addition, random mode coupling does not require a marker for core number management.

6.1.2.2.2 Relevant attributes (geometric, environmental, transmission)

In contrast to the standard SCFs, XT must be well designed to achieve random coupling. A reduced coating diameter, e.g., 200 μm , can be applied but further studies on multicore geometry and the microbending loss properties are required.

6.1.2.2.3 Advantages / disadvantages

The advantages of RC-MCF are as follows.

- Increased spatial channel density and the potential to provide more than ten spatial channels in a 125 μm cladding diameter
- Simplified MIMO-DSP compared to the conventional few-mode transmission [b-Hayashi1]
- Ultra-low attenuation potential
- No marker for the management of core numbers is required

The disadvantages of RC-MCF are as follows.

- Not compatible with the existing SMF
- Requires a core alignment to facilitate splicing and connectorisation
- MIMO-DSP is required for inter-modal XT compensation
- Needs SDM components such as FIFO
- May require better cable design to reduce the microbending loss due to external perturbations
- May require better handling to avoid mechanical damage to thin coatings.

6.2 SDM cable technologies and properties

An optical fibre cable for a telecom network can be categorised as a loose or tight structure. The accommodated optical fibres are free or not free in a loose or tight structure cable, respectively [b-IEC/TR 61931].

A loose structure cable is more suitable for achieving an optical link with low loss and low polarization mode dispersion (PMD) since the loose structure enables the reduction of excessive stress on the cabled optical fibres. Most optical submarine cables use the loose structure for ensuring long-haul and large-capacity transmission performance. Increasing the number of implemented optical fibres is the most basic approach to using an SDM in an optical fibre cable, which contributes to increasing the spatial utilization efficiency per cable. For unrepeated applications, a 2016-fibre cable appeared in 2019, and an ultra-high fibre count cable, e.g., beyond several thousand, has been investigated using a reduced coating diameter. Meanwhile, for optically amplified systems, the number of fibre pairs implemented in transpacific optical submarine systems has reached 12 (i.e., 24 SMFs) in 2020 to support the growing capacity demands. Also, 24-fibre pairs are expected to be achieved in the 2020s by using an RCDF with a 200 μm coating.

The power feeding limit is a unique objective in a submarine system. Since the electrical power for a submarine repeater is fed from land terminals located at both ends of the link, the available electrical power for each repeater is limited. Therefore, it is important to increase not only the fibre capacity (i.e., the number of fibre pairs) but also the power efficiency in an optical submarine link. Note that the design principle of a power-efficient cable utilizing the SDM comes from the Shannon's theorem (shown in Figure 1). The number of spaces contributes to increasing the capacity proportionally, while the signal-to-noise ratio (SNR) gives an almost logarithmic increment. This means that sharing the finite total signal power between multiple fibres provides a higher cable capacity even if the SNR at each fibre is decreased. The theory is also applicable for the multicore fibre (MCF) regarding the number of cores as the number of spaces.

Tight structure cables are mainly used in a part of a terrestrial link. A typical tight structure cable contains laminated fibre ribbons that enable the cable to be effectively installed by fusion-splicing all the arrayed optical fibres simultaneously. Ribbon structures are typically designated as edge-bonded, encapsulated or partially bonded. Traditional fibre ribbons (edge-bonded or encapsulated) cannot be easily deformed in the cross-sectional direction since the arrayed optical fibres are completely fixed with a UV curable resin along their length [b-ITU-T L.100]. Partially bonded ribbons have been developed and deployed in some terrestrial cables. Since the arrayed optical fibres in this type of ribbon are partially bonded along their length, the fibre ribbon can be deformed in its cross-sectional direction. Thus, the partially bonded ribbon can be packed densely while maintaining the ribbon-based fusion-splicing features. For example, 200 optical fibres were implemented in a cable with an 11 mm diameter by using a partially bonded ribbon [b-Hogari]. A partially bonded ribbon-based tight structure cable enables the development of an ultra-high fibre count cable (UHC). For example, UHCs with more than several thousand optical fibres have been reported [b-Sato, b-Kaneko], and these cables are expected to be particularly useful for inter-DC networks.

Optimistically speaking, the SDM optical fibres described in clause 6.1 can be used in both loose and tight structure cables, where they can ensure sufficient optical properties such as low loss and/or PMD insensitivity under macro/micro-bending. RCDF and RCF have better applicability to current optical cable technology than MCF or the FMF. At least three aspects should be considered when an SDM optical fibre-based cable is deployed.

i) Connectivity of MCF / FMF

Multicore structures intrinsically require rotational alignment as well as a conventional axial offset alignment. A fusion splicer with an angle alignment mechanism connects single MCFs located opposite to each other, but ideally the development of a fusion splicer that can connect all MCF-based

ribbon fibres at the same time is needed. Thus, both the installation and operability must carefully be considered when an MCF-based cable is deployed.

FMF splicing and connectorisation is easier than that of MCFs. However, the influence of splicing and connectorisation, especially on inter-modal XT needs to be considered carefully when installing an FMF-based cable.

ii) XT under cabled and installed conditions

Both inter-core and inter-modal XTs vary with bending and twisting conditions. Inter-core XT has a unique bending radius R_{pk} at which the XT degrades to the maximum [b-Koshiha]. An R_{pk} value in an MCF should therefore be carefully designed while considering the possible bending radius during usage. Inter-core XT in a fabricated cable should be examined considering the bending radius dependence. Random bending and twisting can also affect the inter-modal XT, and this random modal coupling results in DMD/DMGD and the SMD variation in the time/frequency domain. [b-Yamada] reported that an SMD coefficient in a densely packed partially bonded ribbon can be potentially controlled by means of the design parameters of the cable. However, the relationship between the conditions of the implemented SDM optical fibres and the inter-modal XT is still being studied.

iii) Mechanical reliability

The mechanical reliability of SDM optical fibre-based cables when the fibres are used with modified geometrical dimensions (e.g., a thinner or thicker cladding diameter) must be considered. If an SDM optical fibre with a thinner or thicker cladding diameter is implemented in a cable, its mechanical reliability under bending or tension needs to be examined carefully.

6.3 SDM component technologies and properties

Figure 11 shows an example of an SDM optical fibre cable link and its key components. RCDF and RCF can basically utilize the existing component technologies. Although the connectorisation and fusion-splicing of the RCDF/RCF may need additional consideration, RCDF/RCF does not require additional components for building a link. In contrast, MCF and the FMF may require FIFO or mode mux / demux in addition to an existing SCF-based link. The connectors and fusion-splicing of the MCF/FMF require additional care to ensure capable connectivity in all spatial channels, and the MCFs intrinsically require precise angle alignment for their connection point. An optical amplifier in an SDM link will also be required to construct an optically amplified long-haul link. The connection between an FIFO (or mux / demux) and the connector(s) at a terminal apparatus can be conventional SCF and/or SDM fibres, as described later (see clauses 6.3.2 and 8.4).

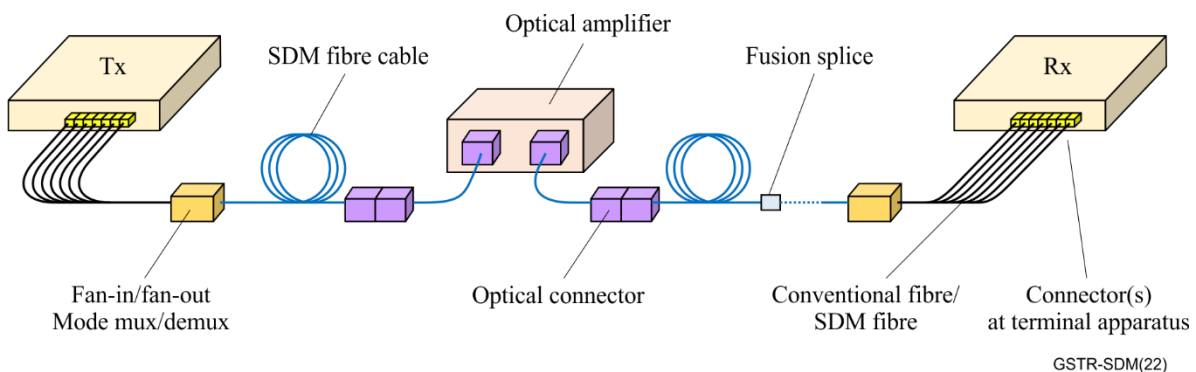


Figure 11 – SDM optical fibre cable link and key components

Table 2 summarises the SDM component technologies with the latest scenarios, which are classified into the following three categories.

a) Existing technology and standards can be used.

- b) Technology and standards exist, but modification / refinement is needed.
- c) New technology and standards are needed.

Examples of technologies for a), b) and c) are described in clauses 6.3.1 to 6.3.3.

Table 2 – Summary of the SDM component technologies.

Component	RCDF	RCF	FMF	WC-MCF	RC-MCF	FM-MCF
FIFO	–	–	–	c)	–	c)
Mode mux / demux	–	–	c)	–	c)	c)
Connector	b)	b)	b)	c)	c)	c)
Splicing	a)	b)	b)	c)	c)	c)
Optical amplifier	a)	a)	c)	c)	c)	c)

6.3.1 FIFO and mode-mux / demux

RCF/RCDF does not require these additional components. A FIFO device is required when a link contains an interface between a conventional single-core SMF and an MCF. To date, five types of FIFO have been proposed: free space coupling, fused taper, 3D waveguide, fibre bundle and laminated planar lightwave circuit (PLC) types. Table 3 shows a summary of the candidate FIFO technologies for the MCF. The free space coupling type is easy to couple but difficult to integrate [b-Takahata]. The fused tapered type is easy to fabricate but its encapsulation length tends to be long [b-Kopp], [b-Uemura]. The 3D waveguide type is capable of high integration and is applicable to the arbitrary core arrangement but has low manufacturing efficiency [b-Thomson]. The fibre bundle type has low insertion loss (IL) and polarization dependent loss (PDL) but severe alignment challenges [b-Watanabe1]. The PLC type can easily achieve a parallel waveguide structure and is suitable for mass production, but it needs a laminated structure to support a two-dimensional core arrangement, and it also requires strict positioning and alignment [b-Nakajima]. For practical use of the FIFO, the following features are required: low insertion loss, low XT, small size and high manufacturability. To standardise the FIFO devices, it is important to clarify the requirements of the characteristics, components, and transmission system using the MCFs.

Table 3 – Summary of FIFO for the MCF

Type	General remarks	Pros	Cons
Free space coupling	Light from the SMF deforms the parallel light using the collimating lens at the edge of the MCF, so each light couples one core of the MCF.	– Low insertion loss and low XT by precisely adjusting the lens	– Relatively large size due to being composed of many optical parts (e.g., lenses, collimators) and having to offer robustness to the vibration
Fused tapered	Each SMF is inserted into the multi-porous glass capillary, and then the glass itself, which is a FIFO device with a cross-sectional structure similar to an MCF, which is annealed, drawn and cut.	– Capability of fusion splice by using the conventional MCF fusion splice equipment	– Mode field diameter (MFD) differences between SMF and the MCF need to be small to enable low splice loss
3D waveguide	A waveguide is formed in the high and low refractive index area by	– Compact	– Relatively large insertion loss originating

Table 3 – Summary of FIFO for the MCF

Type	General remarks	Pros	Cons
	irradiating the femtosecond pulse laser to the dielectric substrate (e.g., SiO ₂).	– Applicable to the arbitrary core arrangement	from the bending loss in the waveguide – Mode field and axis differentiations between the waveguide and optical fibres
Fibre bundle	The thinner cladding diameter of the SMFs is almost equal to the core-to-core pitch of the MCF. The SMFs are bundled with polymer to control the refractive index and are connected with the MCF.	– Low insertion loss – Low polarization-dependent loss (PDL)	– Severe alignment challenges with the thinner cladding SMFs
Laminated PLC	Laminated PLCs guide the optical beam from one particular core of the MCF to the opposite side of the PLCs while expanding the core pitch to achieve a butt joint with a conventional SMF.	– Enables mass production with low loss by applying semiconductor technologies	– Laminated structure requires precise positioning – It is difficult to achieve three layers or more

Both FMF and the few mode multicore fibre (FM-MCF) require a mode mux / demux or an SMF-FMF adaptor to multiplex the modal transmission channels. At present, four main types have been reported, as detailed in Table 4: multiple phase plates, photonic lantern, fibre-based mode selective coupler (MSC), and PLC-based MSC types. Multiple phase plates are based on the unitary phase conversion. An adequate combination of different phase plates enables multiplexing / demultiplexing of the arbitrary spatial modes. Photonic lanterns are made by adiabatically merging several single-mode cores into one few-mode core. They provide low-loss interfaces between single-mode and multi-mode systems. One production approach is to put several SMFs into a capillary tube and then perform tapering. Fibre- and PLC-based MSCs are based on modal coupling between parallel light guides. These types enable a relatively low MDL and offer mass productivity.

For practical use, the following features are required: low insertion loss, low modal XT, low MDL, small size and mass productivity. To standardise the mode mux / demux devices, it is important to clarify the system requirements for MDM transmission systems.

Table 4 – Summary of mode mux / demux and the SMF-FMF adaptors

Type	General remarks	Pros	Cons
Multiple phase plate	Unitary phase conversion is performed using multiple phase plates.	– Capability of multiplexing many modes – High selectivity	– Large size of substrates – Large mode-dependent deviation
Photonic lantern	The diameter of the low refractive index capillary around several SMFs is shrunk just like tapering, resulting in the cladding layer of the SMFs and the capillary transforming the core and cladding layer of the FMF, respectively.	– Low insertion loss and small MFD differences between the SMFs and FMF – Easy fusion-splicing	– Mode extensibility

Table 4 – Summary of mode mux / demux and the SMF-FMF adaptors

Type	General remarks	Pros	Cons
Fibre-based MSC	SMFs that have almost the same effective refractive index as the FMF are placed spatially close to the FMF and the mode transitions between the SMFs and the FMF so that mode multiplexing is achieved.	– Low MDL	– Precise positioning is required – Precise design of the effective refractive index of higher-order modes is required – Large wavelength dependences
PLC-based MSC	A waveguide is fabricated on the substrate and the effective refractive index is adjusted by changing the waveguide width / refractive index. The mode transitions near the proximal section of the waveguide and then multiplexing of the modes is achieved.	– Easy to establish mass productivity	– Rotation mechanism is required for the degenerate modes (e.g., LP _{11a} and LP _{11b}) – Relatively large attenuation – Mode extensibility

6.3.2 Connectorisation and splicing

Table 5 summarises the connector and splicing technologies for SDM optical fibres with the latest scenarios, which are classified into the following three categories.

- Existing technology and standards can be used.
- Technology and standards exist, but modification / refinement is needed.
- New technology and standards are needed.

Table 5 – Summary of the connector and splicing technologies for SDM optical fibres

		RCDF	RCF	FMF	WC / RC / FM-MCF
Connector	Single and duplex types	a)	b)	b)	c)
	Multiple-fibre type	b)	c)	b)	c)
Splice	Passive alignment	b)	b)	b)	c)
	Active alignment	a)	a)	b)	b)

Conventional connectors can be classified into several types (SC, FC, LC, ST, MPO, etc.). Splicing equipment can be basically classified into active and passive alignment versus single fibres and ribbons [b-ITU-T G.671], [b-ITU-T L.400]. While the RCDF/RCF can use these technologies, certain refinement and/or modification will be needed if the RCDF/RCF has a different cladding / coating diameter than an existing SMF. SC/LC/FC connectors with 80 µm diameters have been commercialized for the RCF and has a 12 fibre count 80 µm diameter MT ferrule. The advantage here is the compatibility with current connectors and the disadvantage is the need to develop precise manufacturing equipment.

Active alignment type fusion splicers for the 80 µm cladding/200 µm coated diameter and a passive alignment type fusion splicer for the 125 µm cladding/200 µm coated diameter have both been commercialized. Active alignment type fusion splicers support both single fibres and ribbons, while

the passive alignment type fusion splicer does not fully support ribbons. Some vendors have recently launched products for supporting 125 μm cladding/200 μm coated diameter RCDFs.

For practical use, single fibres or ribbons are required. At the moment, single fibres with up to 80 μm cladding/100 μm coated diameters are being utilized, so clause 7.5.1.4 in [b-ITU-T L.400] should be discussed regarding the diameter values from 250 μm (nominal) to the other values to correspond with the RCDF and the RCF.

FMF can intrinsically utilize the existing connector and fusion splice technologies, which can be considered as an important advantage. However, FMF requires more precise alignment compared to that for an SMF, as even a slight misalignment leads to non-negligible property differences among the spatial modes as well as to the modal XT.

MCF can also use existing connectors and fusion splice technologies, but the proper alignment of an MCF must be considered not only its vertical / horizontal positions but also the rotational positions of the cores. Regarding the optical connectors, Oldham's coupling is used to realize sufficient angle alignment while keeping a floating structure [b-Sakaime]. The LC adaptor with an MU ferrule instead of an LC ferrule [b-Morishima] and the MT ferrule with multiple MCFs [b-Watanabe2] have been proposed to improve productivity and to achieve multiple MCF connections respectively. Since an MCF contains cores that are not allocated in the centre of the cladding, connector endface geometries such as the curvature radius of the ferrule endface, fibre undercut / protrusion and the apex offset may need different specifications compared with that of a conventional single core connector.

Concerning an MCF fusion splice, various types of rotational angle alignment methods have been reported, such as side-view-based angle alignment techniques [b-Saito] and end-view functions [b-Yoshida]. In addition, a mass fusion-splicing of (4-core) MCFs has been widely studied. Unfortunately, it will likely take some time to achieve a balance between the technology and the economic feasibility, particularly as compared to the (four) SCF-based ribbons.

Various methods of connectorisation and splicing have been proposed. The suitable connector type and splicing method can be determined after the design and structure of MCFs are specified. Indeed, the core geometry affects the optimization of physical pressuring forces and the curvature radius of the ferrule in the connectors. The rotation alignment of the cores also affects the criteria of the fusion splice loss.

As shown in Figure 11, the connection from the SMF to the transmitter (Tx)/receiver (Rx) (terminal apparatus) could be used as the receptacle for an optical interface of a pluggable receiver depending on the progress of the integration technology (see also clause 8).

6.3.3 Optical amplifier

International standards on optical amplifiers have been established in [b-ITU-T G.661], [b-ITU-T G.662], [b-ITU-T G.663], and [b-IEC 61291-1]. The RCDF/RCF-, MCF-, and the FMF-based optical amplifiers could basically comply with these documents, but further discussion regarding the IEC standards is needed to clarify and specify additional requirements, particularly for spatial channels. In addition, regarding IEC technical reports, [b-IEC TR 61292-1], [b-IEC TR 61292-2], [b-IEC TR 61292-3], [b-IEC TR 61292-8], [b-IEC TR 62572-2], and [b-IEC TR 62572-4], should be examined in order to make further progress on an optical amplifier for SDM optical fibres. Table 6 summarises the applicability of existing single-core single-mode EDFA to SDM optical fibres, which is classified into the following three categories.

- a) Existing technology and standards can be used.
- b) Technology and standards exist but modification / refinement is needed.
- c) New technology and standards are needed.

Table 6 – Applicability of single-core and single-mode EDFA to SDM fibres

	RCF	RCDF	FMF	WC-MCF	RC-MCF	FM-MCF
Applicability of existing EDFA	a)	a)	b)	a)	b)	b)

Conventional single-core and single-mode EDFAs can basically be used for all types of SDM optical fibres. RCF and RCDF do not need additional components and/or specifications, but the differences in geometrical dimensions should be considered for each connection / splicing point.

Individual spatial modes in an FMF can be amplified via a mode mux / demux or an SMF-FMF adaptor. The differences in amplified characteristics between spatial modes should be considered and specified to achieve an optically amplified MDM transmission system.

Individual cores of a WC-MCF can be amplified with a conventional EDFA by using a FIFO. Amplified properties can be specified based on the existing standard taking into account the difference between cores.

An optical signal transmitted in an RC-MCF can also be amplified with the existing EDFA, but FIFO or mode mux / demux is required. As with FMF, the differences of amplified characteristics between spatial modes should be considered.

FM-MCF can also use the conventional EDFA via the FIFO and mode mux / demux, but it requires a complex amplification configuration. Modal dependence among the cores should be considered, the same as with the amplification of the FMF.

When considering an SDM in an optical amplifier itself, another feature of optical amplification in an MCF can be observed. Conventional single-core and single-mode EDFAs utilize single-mode core pumping. When considering a multicore erbium-doped fibre (MC-EDF) as an SDM optical amplification medium, a cladding pump as well as a core pumping can be used. A cladding pump enables the amplification of multiple spatial channels in one EDF by using one multi-mode pump laser diode (LD), thus improving the amplification efficiency. Although further research and optimization for the cladding pump-based amplification technique is needed, this technology can potentially achieve optical amplification with lower power consumption. Another important feature of the SDM in an optical amplifier is the SDM amplifier can be used not only for the SDM optical fibre link but also for the existing SMF link. This feature is described in clause 8.3.

7 SDM characterization

7.1 Optical fibres and cables

ITU-T Recommendations G.65x consider three attributes:

- fibre attributes that are retained throughout cabling and installation,
- cable attributes that are recommended for cables as they are delivered, and
- link attributes that are characteristic of concatenated cables.

This Technical Report examines the SDM optical fibres and cable characteristics with regard to the fibre and cable attributes. Table 7 lists the mandatory parameters for each type of SDM optical fibre, which are classified into the following three categories.

- a) An existing test method can be used.
- b) A test method exists but modification / refinement is needed.
- c) A new test method is needed.

Examples of test methods for b) and c) are described in clauses 7.1.1 to 7.1.15.

For RCF and RCDF, existing test methods can be used for all parameters listed in Table 7, except the proof stress level of the RCF.

Table 7 – Mandatory parameters for SDM optical fibres

Parameter		WC-FMF / SC-FMF	WC-MCF	FM-MCF	RC-MCF
Fibre attribute	MFD	b)	b)	b)	c)
	Cladding diameter	a)	a)	a)	a)
	Core concentricity error	a)	c)	c)	c)
	Cladding non-circularity	a)	a)	a)	a)
	Core pitch	–	c)	c)	c)
	Coating diameter	a)	a)	a)	a)
	Cable cut-off wavelength	a)	b)	b)	b)
	Macrobending loss	b)	b)	b)	b)
	Proof stress	a)	a)	a)	a)
	Chromatic dispersion parameter	b)	b)	b)	b)
Cable attribute	Attenuation	b)	b)	b)	b)
	PMD	b)	b)	b)	b)
	DGD	c)	b)	c)	c)
	DMD/DMGD	c)	–	c)	–
	Inter-core DGD	–	c)	c)	c)
	Inter-core XT	–	c)	c)	c)
	Inter-modal XT	c)	–	c)	–
	SMD	–	–	–	c)

NOTE – Coating diameter is not specified in the ITU-T Recommendations, but it is considered in the IEC documents as well as the corresponding test method.

7.1.1 Mode field diameter (MFD)

For WC-MCF, the existing test method described in clause 6.1 of [b-ITU-T G.650.1] can be used to measure the MFD of each core, but FIFO or an offset launch is required to bring light into each core under test.

For WC-FMF, SC-FMF, and FM-MCF, the existing test method described in clause 6.1.1 of [b-ITU-T G.650.1], far-field scanning, can be used to measure the MFD of each mode, but mode mux is required to selectively excite each mode under test. Both FIFO and mode mux are required for FM-MCF. Here, a requirement for modal XT in a mux should be clarified for ensuring the measurement accuracy of the MFD.

The MFD of the eigenmode (not LP mode but vector mode) in WC-FMF, SC-FMF, and FM-MCF can be derived from a conventional definition of the MFD and can be measured by far-field scanning

[b-Hayashi2]. Further research is required to clarify the relationship between connection loss and the MFD.

For RC-MCF, MFD can be derived from an incoherent far-field distribution measurement. A broadband light source is used to mitigate the intensity profile fluctuations, which are caused by optical interference between cores. The measured far-field distribution will be approximately equal to the average of all the cores [b-Chou]. However, the definitions of MFD for spatial modes considering the relationship with connection loss need to be confirmed.

MFD may vary between cores and/or modes. A requirement for the allowable maximum difference between cores / modes needs to be set.

7.1.2 Cladding diameter

The existing test method described in clause 6.2 of [b-ITU-T G.650.1] can be used to measure the cladding diameter for all types of SDM optical fibres.

7.1.3 Core concentricity error

For WC-FMF and SC-FMF, the existing test method described in clause 6.2 of [b-ITU-T G.650.1] can be used to measure the core concentricity error.

For WC-MCF, FM-MCF, and RC-MCF, new considerations will be needed for lateral offset in a non-centre core.

7.1.4 Cladding non-circularity

The existing test method described in clause 6.2 of [b-ITU-T G.650.1] can be used to measure the cladding non-circularity for all types of SDM optical fibres.

7.1.5 Core pitch

For WC-MCF, FM-MCF, and RC-MCF, the core pitch can be determined from a cross-sectional image of the optical fibre. However, the measurement accuracy and allowable tolerance should be clarified considering the lateral offset of each core described in clause 7.1.3.

7.1.6 Coating diameter

The existing test method described in [b-IEC 60793-1-21] can be used to measure the coating diameter for all types of SDM optical fibres.

7.1.7 Cable cut-off wavelength

For WC-MCF and FM-MCF, the existing test method described in clause 6.3 of [b-ITU-T G.650.1] can be used to measure the cable cut-off wavelength of each core, but FIFO or an offset launch is required to bring light into each core under test. Since the cable cut-off wavelength may vary between cores, the longest cable cut-off wavelength among the cores should be considered. The cut-off wavelength of an MCF can be evaluated by launching a test light to all cores simultaneously [b-Ohashi].

For WC-FMF and SC-FMF, the existing test method described in clause 6.3 of [b-ITU-T G.650.1] can be used to measure the cable cut-off wavelength by considering the corresponding mode.

Coupling between modes in WC-FMF and SC-FMF may affect the measurement accuracy of the cable cut-off wavelength. A requirement for the mode coupling needs to be clarified for ensuring the measurement accuracy of the cable cut-off wavelength, if needed.

For RC-MCF, the existing test method with a multi-mode fibre reference described in clause 6.3 of [b-ITU-T G.650.1] can be used to determine the average cable cut-off wavelength of all the cores [b-Hayashi3], but certain launching conditions must be used to overfill the optical fibre so that all the modes in the fibre under test can be excited. A suitable launch condition could be obtained by using a multi-mode fibre. A detector that can acquire the transmitted power of all modes is required.

7.1.8 Macrobending loss

The test method is the same as that for attenuation in clause 7.1.11.

Macrobending loss may vary between cores and/or modes, so the maximum macrobending loss among cores / modes should be considered. The influence of angle dependence in the MCF and of the modal coupling in the FMF/RC-MCF on the measurement results may require further study.

7.1.9 Proof stress

The existing proof testing method described in clause 6.7 of [b-ITU-T G.650.1] can be applied. Unusual cladding diameters (e.g., not equal to 125 μm) may necessitate a different proof stress level.

7.1.10 Chromatic dispersion parameter

For WC-MCF, the existing test method described in clause 6.5 of [b-ITU-T G.650.1] can be used to measure the chromatic dispersion of each core, but the FIFO or an offset launch is required to bring light into each core under test.

For WC-FMF, SC-FMF, and FM-MCF, the existing test method described in clause 6.5 of [b-ITU-T G.650.1] can be used to measure the chromatic dispersion of each mode, but mode mux / demux is required to selectively excite / detect the corresponding mode under test.

For RC-MCF, the existing test method described in clause 6.5 of [b-ITU-T G.650.1] can be used to measure the average chromatic dispersion parameter of all cores, but 1-core input and 1-core output are required. The average relative group delay of all cores is measured and then the average chromatic dispersion of all the cores is derived from the measured relative group delay.

The chromatic dispersion parameter may vary between cores and/or modes. A requirement for the allowable maximum difference between cores / modes needs to be clarified.

7.1.11 Attenuation

For WC-MCF, the existing test method described in clause 6.4 of [b-ITU-T G.650.1] can be used to measure the attenuation of each core, but the FIFO or an offset launch is required to bring a light into each core under test.

For WC-FMF, SC-FMF, and FM-MCF, the existing test method described in clause 6.4 of [b-ITU-T G.650.1] can be used to measure the attenuation of each mode, but mode mux is required to selectively excite each mode under test.

For RC-MCF, the existing test method described in clause 6.4 of [b-ITU-T G.650.1] can be used to measure the average attenuation of all cores, but 1-core input is required. For a cut-back technique, a detector must detect the transmitted optical power from all cores. Determining the adequate cut-back length may require further study to ensure measurement accuracy, since the coupling condition may be dependent on the transmission length.

7.1.12 Polarization mode dispersion (PMD)

For WC-MCF, the existing test method described in clause 6.1 of [b-ITU-T G.650.2] can be used to measure the DGD between polarization modes and the PMD of each core, but the FIFO or an offset launch is required to bring a light into each core under test. Since DGD and PMD may vary between cores, a requirement for the allowable maximum difference between the cores needs to be clarified.

For WC-FMF, SC-FMF, and FM-MCF, the DGD between the polarization modes can be measured with S^2 imaging [b-Nicholson] or the ToF method [b-Liu] described in clause 7.1.14 by considering two orthogonally polarised input lights.

NOTE – This Technical Report assumes that the definition of DGD and PMD for a higher order mode is the same as that for the fundamental mode. The DGD between fundamental and higher order modes is described in clause 7.1.14.

For RC-MCF, the DGD between the polarization modes can theoretically be measured with the test method described in clause 7.1.15 by considering two orthogonally polarised input lights. However, the DGD between spatial modes tends to be larger than that between the polarization modes, and the random coupling nature of the RC-MCF makes it difficult to accurately extract the polarization-based DGD.

7.1.13 Inter-core / inter-modal crosstalk (XT)

XT can occur between the cores of WC-MCF, FM-MCF, or RC-MCF (inter-core XT), or between the modes in WC-FMF, SC-FMF, or RC-MCF (inter-modal XT). The XT is a statistical value because it can longitudinally change at phase-matching points, and phase offsets between the cores or modes at these points can fluctuate due to perturbations of optical fibre conditions such as bending and twisting. The distribution and mean value of the statistical XT can be measured as the transmitted optical power ratio between cores / modes by sweeping the light wavelength, as the phase offsets vary not only due to the optical fibre conditions but also the wavelength [b-Hayashi4]. A mode mux / demux is needed for evaluating the inter-modal XT.

7.1.14 Differential group delay / Differential modal delay / Differential modal group delay (DGD/DMD/DMGD)

There are four types of DGD for SDM optical fibres and the test methods are described below.

DGD between polarization modes in each core of WC-MCF can be measured by the test method described in clause 7.1.12.

DGD between cores (inter-core DGD) of WC-MCF, FM-MCF, or RC-MCF, which is also referred to as skew can be measured by an impulse response method [b-Sakamoto2]. In this method, an optical impulse signal with a short duration is launched into each core of a fibre under test, and the impulse response is measured. The DGD is obtained as the difference in the time delays between the cores. Although the inter-core DGD of the RC-MCF theoretically exists, further research is needed for measuring it, as the random coupling nature of the RC-MCF makes it difficult to extract the inter-core DGD.

DGD between the LP modes in WC-FMF, SC-FMF, or FM-MCF, which is also referred to as DMD/DMGD, can be measured by S^2 imaging [b-Nicholson] or the ToF method [b-Liu]. In the S^2 imaging (also referred to as spatially and spectrally resolved imaging), a light with a swept wavelength is launched into a fibre under test and the interference patterns between LP modes in the fibre are measured at each point of the fibre cross-section. The DGD between the LP modes is derived by means of the Fourier transformation of the interference patterns [b-Nicholson]. In the ToF method, each LP mode is selectively excited at the input of a fibre under test, and the time delay after traveling along a predetermined length of fibre is measured. The DGD is obtained as the difference of time delays between the two LP modes [b-Liu]. If strongly / randomly coupled mode groups exist, the DGD among these groups is referred to as the DMGD.

DMD in the FM-MCF may vary between the cores. A requirement for the allowable maximum difference between cores needs to be clarified.

DGD between spatial modes in RC-MCF or a mode group, of which the root mean square is SMD, can be measured by the test method described in clause 7.1.15.

7.1.15 Spatial mode dispersion (SMD)

SMD of a mode group in WC-FMF, SC-FMF, FM-MCF, or RC-MCF can be measured by a wavelength scanning method similar to the fixed analyser method, which is used for measuring the PMD of the SMF, described in clause 6.1.4 of [b-ITU-T G.650.2]. In this method, an interference pattern between the multiple spatial modes is measured by sweeping the light wavelength. Modal dispersion distribution in the time domain is then calculated by the Fourier transformation of the

measured interference spectrum pattern. SMD under random mode coupling is obtained as the root mean square of the time domain distribution [b-Sakamoto3].

7.2 Components

Table 8 summarises the mandatory component parameters (FIFO, mode mux / demux, connector and optical amplifier) for each type of SDM optical fibre, which are classified into the following three categories.

- a) An existing test method can be used.
- b) A test method exists but modification / refinement is needed.
- c) A new test method is needed.

More details for b) and c) are described in clauses 7.2.1 to 7.2.5.

Table 8 – Mandatory parameters for the SDM components

Parameter	FIFO	Mode mux/ demux	Connector			Optical amplifier	
	For MCF	For FMF	For RCDF and RCF	For MCF	For FMF	For MCF	For FMF
Insertion loss (IL)	b)	b)	a)	b)	b)	b)	b)
Return loss	b)	b)	a)	b)	b)	–	–
XT	c)	c)	–	c)	c)	c)	c)
Dispersion	b)	c)	–	–	–	b)	c)
Optical power and gain	–	–	–	–	–	b)	b)
Noise	–	–	–	–	–	b)	b)
Transient	–	–	–	–	–	b)	b)
Reflectance	–	–	–	–	–	b)	b)
Pump leakage	–	–	–	–	–	b)	b)
Multichannel gain and noise	–	–	–	–	–	b)	b)

NOTE – Both the FIFO and mode mux / demux are required for FM-MCF and their characterizations are the same as the FIFO for WC-MCF and mode mux / demux for the FMF.

7.2.1 Insertion loss (IL)

For each component, IL should be evaluated. The IL of the SDM components such as the FIFO, mode mux / demux and the connector can be measured by utilizing the measurement method for the SMF connector [b-IEC 61300-3-4], and the IL of the optical amplifier can be measured by referring to [b-IEC 61290-7-1]. The IL may be different with each spatial channel, which means that the core-dependent loss and the MDL should be considered for the MCF- and FMF-based components, respectively.

Additionally, PDL should be evaluated for the FIFO, mode mux / demux and the connector. The PDL can be measured using the measurement method for the SMF connector [b-IEC 61300-3-2]. The PDL

may be different with each spatial channel, which means that the core- or mode-dependent PDL should be considered for the MCF- or FMF-based components respectively.

7.2.2 Return loss

For each component except the optical amplifier the return loss should be evaluated. The return loss of the SDM components such as the FIFO, mode mux / demux and the connector can be measured using the measurement method for the SMF connector [b-IEC 61300-3-6]. For the optical amplifier, these parameters are discussed as the reflectance (see clause 7.2.5). Return loss may be different with each spatial channel, which means that the core- and mode-dependent return loss should be considered for the MCF- and FMF-based components respectively.

7.2.3 Crosstalk (XT)

For the MCF- and FMF-based components, inter-core and/or inter-modal XT should be evaluated. XT is caused by the energy coupling between the adjacent spatial channels and can occur in both optical fibres and components. It might also change when the optical fibre is bent or fused. For an MCF or FMF and their components, while XT is one of the most important characteristics there is currently no standardised document that describes the measurement method. It might be possible to refer to the polarization XT measurement for polarization maintaining fibre which is described in [b-IEC 60793-1-61].

7.2.4 Dispersion

For FIFO, mode mux / demux and the optical amplifier, dispersion parameters such as PMD, DGD, DMD/DMGD, and SMD should be evaluated. The PMD and DMD of the FMF components can be measured using the measurement method for the SMF connector [b-IEC 61300-3-32] and the multimode fibre [b-IEC 60793-1-49], respectively. However, there is no standardised document that describes the measurement method of the DGD and DMD of the WC-MCF components or the SMD of the RC-MCF components. For the optical amplifiers used for a link composed of the SDM optical fibres, all related dispersion properties of each spatial channel should be minimised.

7.2.5 Parameters related to an optical amplifier

The optical power and gain, noise, transients, reflectance, pump leakage, and multichannel gain and noise are parameters unique to the optical amplifier. These parameters of an SDM optical amplifier can be measured using the measurement method for a conventional optical amplifier [b-IEC 61290-7-1-x], [b-IEC 61290-3-x], [b-IEC 61290-4-x], [b-IEC 61290-5-x], [b-IEC 61290-6-1], and [b-IEC 61290-10-x], respectively. As these parameters may be different with each spatial channel, the core- and mode-dependent values should be considered for the MCF- and FMF-based components, respectively. Additionally, gain is one of the most important parameters in the optical amplifier. The differences between the maximum and minimum gain in each spatial channel, which are called the differential core gain for the MCF optical amplifier and the differential modal gain (DMG) for the FMF optical amplifier, should be considered.

8 System / deployment considerations of SDM optical fibres, cables and components

8.1 Motivating factors for usage of SDM in each application area

Three aspects can be considered to obtain further scalability in transmission capacity:

- i) higher bit rate and/or wider bandwidth,
- ii) multiple optical fibres / cables,
- iii) spatial channel increase in one fibre.

In an optical submarine network, higher bit rate and wider bandwidth are limited by nonlinear effects and the transparency of an optical fibre. Traditional cable structures also limit the space for multiple optical fibres, and thicker cables significantly degrade the fabrication and installation efficiency.

Thus, SDM optical fibres can be considered as a potential solution for a high-count fibre submarine cable if the SDM-based submarine cable is able to maintain a similar cable diameter. Here, an SDM optical amplifier is another important motivating factor (see also clause 8.3).

The transmission capacity per optical fibre in a terrestrial long-haul network is also restricted by the available bitrate and bandwidth, similar to a submarine network. A terrestrial link has a certain flexibility in the cable diameter limitation compared to the submarine link, but it is not preferable to prepare multiple ducts for increasing the transmission capacity for a network operator from the viewpoint of the capital expenditure (CAPEX). Table 9 summarizes the strategy considerations for installing multiple cables in a common duct. The simplest approach is to increase the number of cables while keeping the original fibre count and cable diameter as shown in Table 9(a). The total capacity per duct increases in proportion to the number of cables N , and this approach enables the cable capacity, installation and workability and the total optical fibre length accommodated in one cable to be kept constant. However, as the duct will be filled with cables, another duct will eventually be required to support the increasing capacity demand. As shown in Table 9(b), it is relatively easy to increase the multiplicity of conventional SMFs in one cable because existing technology can also be used. However, the diameter of a cable increases with the number of accommodated optical fibres, and the total capacity and space utilization efficiency of a duct will be limited by the diameter of cable B. Moreover, the total optical fibre length in cable B increases with the number of SMFs. This inevitably leads to increased installation costs and larger energy consumption to fabricate and deploy one cable. Alternatively, (c) in Table 9 considers maintaining the optical fibre count and cable diameter by introducing the SDM optical fibre. This approach enables the cable capacity to be increased step by step using the degrees of the SDM while keeping the optical fibre count and total length constant, although the SDM may require new technology to maintain sufficient workability. It thus enables the sustainable use of an existing duct, and an operator can replace a legacy lower capacity cable with one that has the latest larger capacity. Moreover, carbon emissions stemming from optical fibre fabrication can be minimized by keeping the total length of an optical fibre in a new cable instead of increasing the number of optical fibres in one cable. Thus, the sustainable use of the existing duct would be a motivating factor to utilize SDM technology in a terrestrial long-haul network.

Table 9 – Strategies for installing multiple cables in a common duct

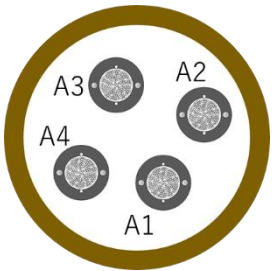
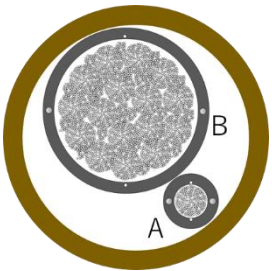
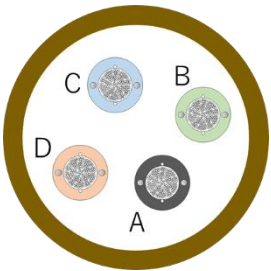
	(a) Multiply the same cables	(b) Increase fibre count and the cable diameter	(c) Implement SDM with constant fibre count and the cable diameter
			
Capacity per cable	Constant $A1 = A2 = A3 = A4$	Increases with cable diameter $A < B$	Increases with degree of the SDM $A < B < C < D$
Capacity per duct	Limited by multiple numbers N $\sim N \times A1$	Limited by the cable diameter $\sim B$	Increases with degree of SDM, enabling legacy to be replaced with the latest
Installation and workability	Constant $A1 = A2 = A3 = A4$	Depends on the fibre count $A < B$	Constant, but SDM requires new technology $A = B = C = D$

Table 9 – Strategies for installing multiple cables in a common duct

Fibre length per cable	Constant A1 = A2 = A3 = A4	Depends on the fibre count A < B	Constant A = B = C = D
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Metro, access, and DC networks have an extremely strong demand for a greater number of optical fibres, and they have much more flexibility than the long-haul network to accommodate multiple optical fibre-based solutions. One of the interesting features of these application spaces is the effective use of wavelength resources. For example, access networks can specify the wavelength allocation in order to achieve bi-directional communication in one fibre effectively. Future service-converged networks may require further wavelength resources. SDM optical fibres can directly increase the wavelength resources in proportion to the number of spatial channels, and the MCF can provide additional wavelength resources while keeping the bi-directional transmission in one fibre. Moreover, the convergence between the co-packaged optics (CPO) and the SDM optical fibre technology can significantly improve the higher density connection in the data centre interconnects (DCI). These advantages obtained by using the SDM technology may be attractive in those application areas.

Table 10 highlights the factors for considering SDM technologies in each application area. The flexibility and/or requirement for i) bitrate and bandwidth, ii) multiplicity in one cable, and iii) multiplicity in one optical fibre differ depending on the application space, as described above. Table 10 considers five factors namely, capacity scalability, power reduction, spatial efficiency, wavelength scalability and fibre count, for considering the usefulness of the SDM optical fibres in each application area. High, medium and low indicate the importance of the key factors in each application area, and remarks in italics describe the major bottleneck.

Table 10 – Relationship between key factors and application areas for considering the usefulness of the SDM optical fibres

	Submarine long-haul terrestrial	Access	DCI
Capacity scalability	High • <i>Nonlinear limitation</i> • <i>Bandwidth limitation</i>	Low	Low
Power reduction	High • <i>Electrical power constraints</i> • <i>Massive EDFAs</i>	Low	Low
Spatial efficiency	High • <i>Cable diameter limitation</i> • <i>Effective use of duct</i>	Medium • <i>Effective use of duct</i>	High • <i>Spatial limitation in the optical interface</i>
Wavelength scalability	Low	High • <i>Application diversity</i> • <i>Bi-directional operation</i>	Low
Fibre count	Low	Medium • <i>Transition to service-converged link</i>	High • <i>Exponential increase in path count demand</i>

8.2 Objectives for SDM fibre cable deployment

RCF/RCDF can be deployed using existing technology except for a slight consideration to the connection point with an optical fibre featuring the standard geometrical dimensions. However, a multicore structure intrinsically requires additional considerations for deployment. For example, the universal design and operation of the MCF are important objectives.

MCF needs to specify a core pitch and the crosstalk (XT) to achieve an interoperable MCF-based system. However, it is not easy to establish a universal specification for these parameters because the core pitch and the XT are strongly correlated with each other. When considering the maximum transmission efficiency in a WC-MCF, an XT of -60 dB would be a universal guideline [b-Gené]. However, it may be difficult to obtain -60 dB using a relatively simple refractive index profile while keeping the cladding diameter of $125\ \mu\text{m}$. Optical compatibility with existing G.65x fibres is another viable approach to specify the core pitch. Step, trench, and W-type refractive index profiles have been used commonly in the existing [b-ITU-T G.652], [b-ITU-T G.654], and [b-ITU-T G.657] fibres. When designing a WC-MCF with these refractive index profiles and while keeping the full optical compatibility and a $125\ \mu\text{m}$ cladding diameter, the core pitch can be optimized around $40\ \mu\text{m}$ [b-Matsui]. Moreover, it would be useful to consider a few classes of XT, since the required XT level varies with the transmission length and modulation format.

Regarding the operation of the MCF, three key aspects cannot be neglected: core uniformity, core identification and connectivity. In cases where an individual core has a slight discrepancy from the other cores, that discrepancy will accumulate along the transmission distance and might cause a significant transmission performance difference compared to the other cores. Core identification in a WC-MCF is one of the most important features. In order to establish an optical link in each core, the operator should identify the direction of the installed link as well as determine the marker-based core identification. This is because the core identification changes between the input and the output ports of an MCF [b-Hayashi5]. Bi-directional transmission in one MCF, i.e., neighbouring cores individually used for up/down links, may result in the loss of direction identification at each connection point, but the operator has to distinguish the cores for up/down links after the installation and/or repair. Finally, the connectivity of a WC-MCF is a big issue. Some technical papers have reported the applicability of the WC-MCF to a partially bonded fibre ribbon and an ultra-high fibre count cable. However, there is currently no technology to fusion-splice a WC-MCF-based partially bonded fibre ribbon simultaneously. This represents a serious obstacle in the deployment of a WC-MCF in a terrestrial link.

As for FMF or RC-MCF, these fibres require special considerations to understand the property differences between spatial modes. Moreover, it is important to carefully consider the maturity of the MIMO-DSP technology.

8.3 Features of SDM in an optical amplifier

One of the key features of the space division multiplexing (SDM) in an optical amplifier is that it can be considered independent of the use of the SDM optical fibre cable link. A schematic image of the SDM in an optical amplifier is shown in Figure 12. A conventional single-core and single-mode optical amplifier is composed of a laser diode (LD), an isolator and an erbium-doped fibre (EDF). A traditional system uses individual optical amplifiers for each transmission line, as shown in Figure 12(a). Thus, the increase in optical fibres results in massive parallelism. This is problematic because the massive parallelism linearly increases the power consumption for optical amplification, and it reaches the power feeding limit in an optical submarine network.

The first implementation of the SDM in an optical amplifier can be considered as pump sharing, as shown in Figure 12(b). The latest submarine system has already utilized this scheme. Finally, full SDM in an optical amplifier can be applied by using an MC-EDF, as shown in Figure 12(c). As mentioned above, pump sharing and a full SDM amplifier can be used with both traditional single-core and SDM optical fibres. For this reason, the SDM-based optical amplifier with higher

amplification efficiency is a strong motivating force for optically amplified long-haul networks. However, it is important to note that additional loss caused by the FIFO or mode mux / demux would be a new degradation factor in terms of the power conversion efficiency in an optical amplifier. As described in clause 7.2.4, all optical amplifiers in Figure 12 also have to consider the dispersion and skew property differences among the spatial channels, including the optical fibre link, FIFO, and/or mode mux / demux. Full SDM-EDFA, as shown in Figure 12(c), can potentially minimize dispersion and skew differences by removing the multiple SMF parts.

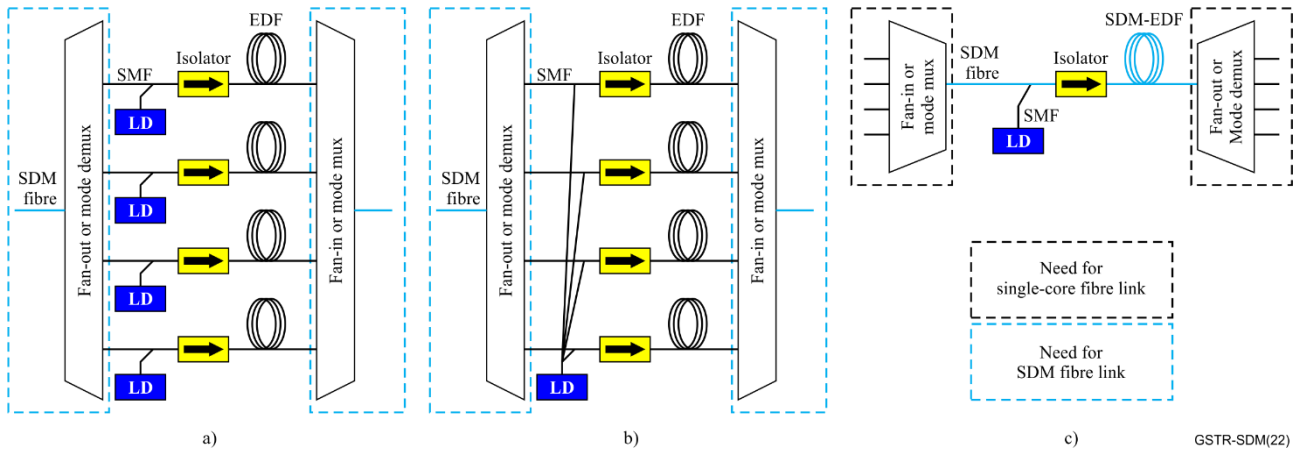


Figure 12 – SDM in an optical amplifier

8.4 Relationship with interconnection and integration

Figure 13 shows the schematic configuration of a transmission module, where DSP, ADC, TIA, O/E, ASIC, DAC, and LD refer to the digital signal processor (DSP), analogue to digital converter (ADC), trans impedance amplifier (TIA), optical signal to electrical signal converter (O/E), application-specific integrated circuit (ASIC), digital to analogue converter (DAC), and the laser diode (LD) respectively. The connection of the SMF to the transmitter (Tx) / receiver (Rx) (terminal apparatus) is achieved with a receptacle similar to the optical interface of a pluggable receiver with conventional connectors. The two different connector types might be considered: single and duplex connectors (SC, LC, etc.) and multiple connectors (MT, MPO, etc.). The receiver is dramatically miniaturized by improving the architecture of the CPO, embedded optics, and pluggable optics such as C form-factor pluggable (CFP), quad small form-factor pluggable (QSFP), octal small form-factor pluggable (OSFP), small form-factor pluggable (SFP), etc. according to the IEEE standards, OIF forum, and other parties [b-IEEE 802.3], [b-OIF]. When the transmission throughput is high, it is generally significant to compensate for the signals. Since this compensation scheme can be used for the RCDF/RCF, MCF, or the FMF, the receivers in the submarine or the DCI network can connect directly by replacing the conventional SMFs in Figure 13 with the SDM optical fibres in the first phase. Many researchers have investigated receivers and connectors for matching the SDM optical fibres [b-Bickham], [b-Gao], [b-Shikama], and [b-Vuong]. It is now possible to apply single and multiple RCDF/RCF, MCF, and FMF to the single and multiple connectors.

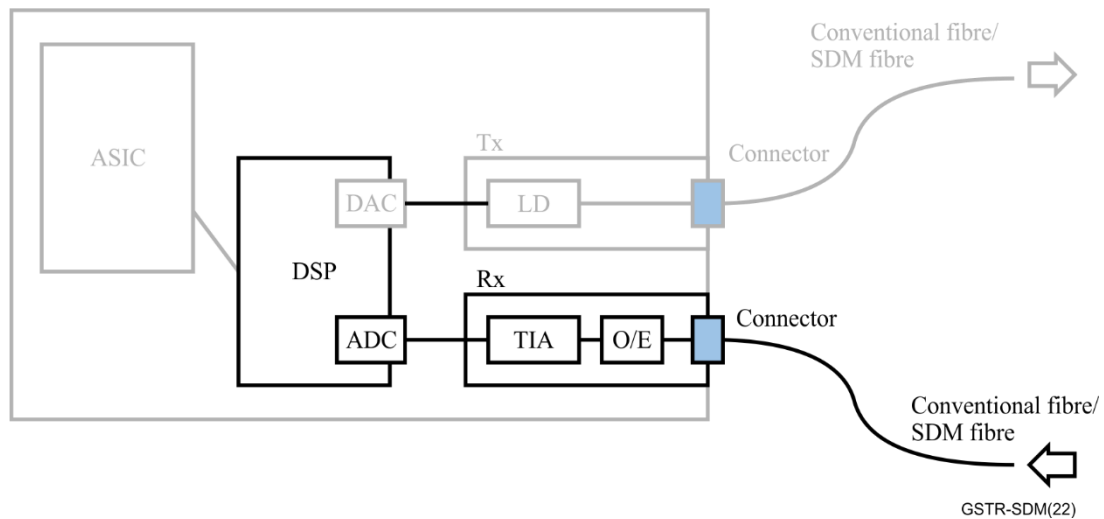


Figure 13 – Configuration of the transmission module

8.5 Example of deployment scenario

A total system cost benefit is a mandatory element for deploying SDM optical fibre cable technology. Three phases can be considered for the future deployment of SDM optical fibres and cable technology.

In phase 1, SDM optical fibres are utilized for the main purpose of overcoming the space limitation in an optical submarine cable or a terrestrial cable for DCI. Both RCDF and WC-MCF are candidate SDM optical fibres in this phase.

In phase 2, a power-efficient SDM amplifier is the key enabler. An SDM-based power-efficient optical submarine link is established in this phase using RCDF or WC-MCF. A terrestrial backbone network with a power-efficient amplifier is an additional application area. A reconfigurable optical add/drop multiplexer (ROADM) with both wavelength and spatial paths is also needed to implement a WC-MCF. CPO with an SDM interface is another key enabler in this phase for overcoming the optical interface density limitation in the DCI. In this application, RCF, WC-FMF, or WC-MCF are candidates for the SDM optical fibre.

In phase 3, it is mandatory that the SDM-based optical components can be used cost-effectively. Based on the technical advances discussed in this work, the SDM terrestrial links may penetrate metro and access areas for achieving service-converged networks. SDM optical fibres for MDM transmission are a candidate solution for overcoming the XT limitation in an optical submarine system. For this purpose, SC-FMF or RC-MCF are candidate SDM optical fibres, along with the corresponding spatial modal devices.

9 Relationship with other standards development organisations

Historically, single-mode optical fibre and cable standards have been developed under harmonisation work between [b-IEC SC 86A] and ITU-T SG15/Q5. ITU-T standards ensure multi-vendor operability, and thus it is important to specify the geometrical, mechanical and optical properties of an optical fibre under the responsibility of ITU-T. IEC specifies the product standard to ensure commercial contracts, so IEC standardises the mandatory parameters for optical fibres and cables based on the optical fibre standard developed in ITU-T. Moreover, the parameters that are used for optical fibre and cable specifications require appropriate authorised test methods. Thus, ITU-T and IEC standardise the test methods for optical fibres and cables respectively. Standardisation of the SDM optical fibre and cable and their test methods should be developed under close collaboration between [b-IEC SC 86A] and ITU-T Q5/SG15.

An optical fibre link intrinsically requires connector technology, and a network node contains various optical components and sub-systems. [b-IEC SC 86B] and [b-IEC SC 86C] specify the product standards and test methods for these network elements. Moreover, ITU-T Q6/SG15 and ITU-T Q2/SG15 have been developing optical interface standards to support multi-vendor operable optical transmission systems and optical access networks, respectively. Therefore, harmonised standardisation with [b-IEC SC 86B], [b-IEC SC 86C], ITU-T Q6/SG15, and ITU-T Q2/SG15 is crucial when it comes to accomplishing a physical layer standard for SDM optical fibre links. It is thus extremely important to consider the relationship between SDM optical fibre and related technologies when the SDM optical fibre standards are established.

10 Bibliography

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