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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media and optical systems characteristics – Characteristics of optical components and subsystems

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Application-related aspects of optical amplifier devices and subsystems

Amendment 1

Recommendation ITU-T G.663 (2011) – Amendment 1

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Recommendation ITU-T G.663

Application-related aspects of optical amplifier devices and subsystems

Amendment 1

Summary

Recommendation ITU-T G.663 covers application-related aspects of optical amplifier (OA) devices and subsystems, primarily those used in digital systems. Applications include both single-channel and multi-channel systems used in point-to-point and point-to-multipoint configurations for use in long-distance networks and optical access networks. The purpose of this Recommendation is to identify which aspects should be considered for each application and to specify appropriate parameter values and ranges for each type of OA device. In this version of this Recommendation, information about non-linear optical effects in Appendix II is updated.

Amendment 1 adds a new clause II.3.4 to Appendix II for cross-polarization modulation and updates the list of abbreviations in clause 4.

History

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FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

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Recommendation ITU-T G.663

Application-related aspects of optical amplifier devices and subsystems

Editorial note: This is a complete-text publication. Modifications introduced by this amendment are shown in revision marks relative to Recommendation ITU-T G.663 (2011).

1 Scope

This Recommendation covers application-related aspects of optical amplifier (OA) devices and subsystems, primarily those used in digital systems. Optical amplifiers operating in the 1550 nm region, or 1310 nm region, or other wavelength regions are included. Generic characteristics of OA devices and subsystems are described in [ITU-T G.662]. Applications include both single-channel and multi-channel systems used in point-to-point and point-to-multipoint configurations for use in long-distance networks and optical access networks.

The purpose of this Recommendation is to identify which aspects should be considered for each application and to specify common parameter values and ranges for each type of OA device (booster amplifier, pre-amplifier, and line amplifier). This Recommendation pertains to the development of new equipment including OA devices and includes guidelines to apply OA devices and OA subsystems to existing equipment. As an objective, for systems specified as transversely compatible, the degree of compatibility should not be changed by the use of OA devices.

Important topics contained in this Recommendation include transmission aspects, maintenance aspects, and optical safety.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.652] Recommendation ITU-T G.652 (2009), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.653] Recommendation ITU-T G.653 (2010), *Characteristics of a dispersion-shifted, single-mode optical fibre and cable*.

[ITU-T G.654] Recommendation ITU-T G.654 (2010), *Characteristics of a cut-off shifted, single-mode optical fibre and cable*.

[ITU-T G.655] Recommendation ITU-T G.655 (2009), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*.

[ITU-T G.661] Recommendation ITU-T G.661 (2007), *Definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems*.

[ITU-T G.662] Recommendation ITU-T G.662 (2005), *Generic characteristics of optical amplifier devices and subsystems*.

[ITU-T G.664] Recommendation ITU-T G.664 (2006), *Optical safety procedures and requirements for optical transport systems*.

[ITU-T G.671] Recommendation ITU-T G.671 (2009), *Transmission characteristics of optical components and subsystems*.

[ITU-T G.691] Recommendation ITU-T G.691 (2006), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers*.

[ITU-T G.692] Recommendation ITU-T G.692 (1998), *Optical interfaces for multichannel systems with optical amplifiers*.

[ITU-T G.783] Recommendation ITU-T G.783 (2006), *Characteristics of synchronous digital hierarchy (SDH) equipment functional blocks*.

[ITU-T G.955] Recommendation ITU-T G.955 (1996), *Digital line systems based on the 1544 kbit/s and the 2048 kbit/s hierarchy on optical fibre cables*.

[ITU-T G.957] Recommendation ITU-T G.957 (2006), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*.

[IEC 60721-3-0] IEC 60721-3-0 (1997), *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities. Introduction*.

[IEC 60721-3-1] IEC 60721-3-1 (1997), *Classification of environmental conditions – Part 3 Classification of groups of environmental parameters and their severities – Section 1: Storage*.

[IEC 60721-3-2] IEC 60721-3-2 (1997), *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: Transportation*.

[IEC 60721-3-3] IEC 60721-3-3 (1994), *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 3: Stationary use at weatherprotected locations*.

[IEC 60721-3-4] IEC 60721-3-4 (1995), *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 4: Stationary use at non-weatherprotected locations*.

[IEC 60825-1] IEC 60825-1 (2007), *Safety of laser products – Part 1: Equipment classification and requirements*.

[IEC 60825-2] IEC 60825-2 (2010), *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*.

[IEC/TR 61282-3] IEC/TR 61282-3 (2006), *Fibre optic communication system design guides – Part 3: Calculation of link polarization mode dispersion*.

3 Definitions

For the purpose of this Recommendation, the definitions given in [ITU-T G.661] and [ITU-T G.662] apply.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

AM Amplitude Modulation

APR Automatic Power Reduction

ASE Amplified Spontaneous Emission

ASK	Amplitude Shift Keying
BA	Booster (power) Amplifier
BER	Bit Error Ratio
CD	Chromatic Dispersion
CMC	Coherent Multichannel
CW	Continuous Wave
DA	Dispersion Accommodation
DP	Dual Polarization
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
EDFA	Erbium-Doped Fibre Amplifier
FDM	Frequency-Division Multiplexing
FWHM	Full Width at Half Maximum
FWM	Four-Wave Mixing
IFWM	Intra-channel Four-Wave Mixing
IXPM	Intra-channel Cross-Phase Modulation
LA	Line Amplifier
LOS	Loss of Signal
MI	Modulation Instability
NPN	Non-linear Phase Noise
NRZ	Non-Return to Zero
OA	Optical Amplifier
OAM	Operation, Administration and Maintenance
OAN	Optically Amplified Network
OAR	Optically Amplified Receiver
OAT	Optically Amplified Transmitter
OFA	Optical Fibre Amplifier
OFDM	Optical Frequency Domain Multiplexing
PA	Pre-Amplifier
PDH	Plesiochronous Digital Hierarchy
PDL	Polarization Dependent Loss
PHB	Polarization Hole Burning
PM	Phase Modulation
PMD	Polarization Mode Dispersion
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
RZ	Return to Zero

SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SMF	Single-Mode Fibre
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SOP	State of Polarization
SP	Single Polarization
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
TRE	Terminal Receiver Equipment
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase Modulation
XPolM	Cross-Polarization Modulation

5 Applications

Application of OAs in optical transmission systems offers a number of advantages. Chief among these advantages is the ability to realize very significant unrepeated system lengths as well as very long unregenerated system lengths. Deployment of OAs is likely to permit the retirement of many existing conventional regenerator sites and, in the case of new routes, to render unnecessary the construction of many new sites. OAs also enable serious consideration of new optical system architectures for application in terrestrial and submarine long haul, and access networks. Two examples of this are wavelength division multiplexing and point-to-multipoint applications, approaches heretofore generally considered prohibitively complex and expensive. OAs also offer potential advantages with respect to network upgrade options due to their independence from modulation format and bit rate.

However, the application of OAs also brings to light some new and potentially serious system impairments, which result from the high power levels produced by the OAs and the long distances between regeneration. These transmission effects include optical fibre non-linearities, polarization effects and effects due to the amplification characteristics of the OA itself. Chromatic dispersion also becomes increasingly significant for the long unregenerated systems enabled by the OA. In addition to determining chromatic dispersion limitations, the dispersion characteristics of the fibre influence the severity of the impairment produced by several of the dominant non-linear effects. As a result, dispersion management has been considered in system design. In the following clauses, the OA applications are described and important considerations for each application are identified.

If the characteristics are longitudinally compatible, the OA devices specified in this Recommendation can also be used to increase the distance in ITU-T G.955 plesiochronous digital hierarchy (PDH) optical line systems (which are not transversely compatible). To ensure transverse compatibility between OA devices and synchronous digital hierarchy (SDH) equipments and to satisfy the requirements of the ITU-T G.690-series Recommendations, either ITU-T G.957 equipment in accordance with clauses 6.1 and 6.2.2 of [ITU-T G.957] or a transponder(s) may be used.

5.1 Booster (power) amplifier

The booster (power) amplifier (BA) is a high saturation-power OA device to be used directly after the optical transmitter to increase its signal power level. The BA does not need stringent requirements for noise and optical filtering. The operation, administration and maintenance (OAM) functions for the BA may or may not be shared with the optical transmitter.

The application of BAs (often in conjunction with pre-amplifiers) is very attractive, especially in those cases where intermediate locations with active equipment are either undesirable or inaccessible, as in submarine systems. In any case, fewer intermediate locations imply easier maintenance for the network operator. The most direct and simple means to increase the available power budget is to use either a BA directly after the regular transmitter or an optically amplified transmitter (see clause 5.4).

Because of the relatively high level of input power, the undesirable amplified spontaneous emission (ASE) noise, inherently present due to the statistical process of photon generation inside the OA, is usually negligible. However, application of BAs may result in fibre non-linearity induced system penalties due to the high optical power levels produced by BAs and the long interactive lengths provided by the optical path.

5.2 Pre-amplifier

The pre-amplifier (PA) is a very low noise OA device to be used directly before an optical receiver to improve its sensitivity. The requisite low level of ASE noise may be achieved through the use of narrow-band optical filters. In this case, automatic tuning of the centre wavelength of the pre-amplifier filter to the transmitter wavelength would be advantageous, since it would permit the relaxation of requirements on both the initial transmitter wavelength tolerance and its long-term stability. As noted previously, the use of PAs (usually in conjunction with BAs) is a straightforward means to realize significant increases in available power budget. The OAM function for PAs may or may not be shared with the optical receiver. In STM-64 or higher level systems, the use of a PA-only configuration can be useful (e.g., to avoid potential problems due to fibre non-linearities).

5.3 Line amplifier

The line amplifier (LA) is a low-noise OA device to be used between passive fibre sections to increase the regeneration lengths or in correspondence with a multipoint connection to compensate for branching losses in the optical access network. As noted previously, line amplifiers might replace some or all conventional regenerators in long-haul fibre sections. It can be envisioned that more than one conventional regenerator can be replaced by a single LA, with the evident advantage of reduced equipment in transmission links. Furthermore, a situation can be envisaged where both line amplifiers for compensation of signal attenuation, and conventional regenerators for compensation of signal distortion, appear in long-distance networks.

A separate communication channel must exist in systems using LAs, which would allow alarming, supervision and control of the installed remote LAs. It is preferable for such a supervisory channel not to place restrictions on the selection of pump laser wavelength or operating window. Because each LA must be able to insert its own status and alarm information, the supervisory channel must be recovered, regenerated (with new information inserted) and retransmitted at each LA.

Theoretically, ultra-long (thousands of kilometres) transmission distances can be realized by periodically inserting line amplifiers in the optical path. However, in the case where many OAs are cascaded, deteriorated system performance can occur due to noise accumulation, spectral dependency of total gain, effects of polarization and chromatic dispersion and non-linear effects. Laboratory tests have shown that the overall system behaviour in the case of many cascaded line amplifiers is much more complex than that for the case of a few cascaded line amplifiers. In particular, the total gain of a chain of line amplifiers in series is generally peaked around a specific wavelength, depending on the specific amplifier configuration, giving considerable reduction of the usable OA operating wavelength range. Therefore, design of this type of system will be very much different from the situation with only a few cascaded line amplifiers.

5.4 Optically amplified transmitter

The optically amplified transmitter (OAT) is an OA subsystem in which a power amplifier is integrated with the laser transmitter, resulting in a high-power transmitter. The connection between the transmitter and the OA is proprietary and shall not be specified. The application considerations of OATs are generally the same as those for BAs (see clause 5.1).

5.5 Optically amplified receiver

The optically amplified receiver (OAR) is an OA subsystem in which a pre-amplifier is integrated with the optical receiver, resulting in a high sensitivity receiver. The connection between the receiver and the OA is proprietary and shall not be specified. The application considerations of OARs are generally the same as those for PAs (see clause 5.2).

5.6 Single-channel applications

BAs, PAs, LAs, OATs and OARs all find application in single-channel systems. In the case of single-channel transmission, noise accumulation can be reduced by using low noise OAs in combination with adequate band pass optical filtering. The dispersion limitations can be normally minimized by operating close to the fibre zero dispersion wavelength or by using suitable dispersion accommodation (DA) techniques. Furthermore, care must be taken to keep non-linear effects, like stimulated Brillouin scattering (see clause II.3.76) and self-phase modulation (see clause II.3.1), under control.

The main optical path interface parameter values for point-to-point, single-channel, long-haul synchronous digital hierarchy (SDH) systems utilizing OAs are described in the ITU-T G.690-series Recommendations. The reference configurations and functional characteristics of these systems are described in [ITU-T G.783].

5.7 Multi-channel applications

OAs also find application in multi-channel systems. In addition to the transmission impairments found in single-channel systems, multi-channel systems may also suffer degraded performance due to certain non-linear effects. These include four-wave mixing (FWM), cross-phase modulation (XPM) and potentially stimulated Raman scattering (SRS). As a result, special precautions must be taken when designing multi-channel systems to avoid or alleviate these impairments. In multi-channel systems using a series of LAs to provide long unregenerated lengths, the effects of cascaded amplifiers, especially the reduction of the usable gain spectrum, must also be considered.

The optical interface parameter values for point-to-point, multi-channel, long-haul SDH systems utilizing OAs are described in [ITU-T G.692]. The reference configurations and functional characteristics of these systems are described in [ITU-T G.783].

5.8 Point-to-point applications

Schemes of insertion of OA devices and subsystems in point-to-point applications are indicated in [ITU-T G.662] (see in particular, Figures 1, 2 and 3 of [ITU-T G.662]).

5.9 Point-to-multipoint applications

OAs can be used in optically amplified networks (OANs) to increase the optical power budget or to allow for higher splitting ratios in point-to-multipoint networks. Therefore, generally speaking, both power and line amplifiers will be used in these types of networks. The use of OAs in ring networks just before branching devices, in order to compensate for splitting/branching losses, is an example of a potential application.

NOTE – One of the first applications of the OAs may be for the distribution of video signals. In the case of analogue video systems, additional requirements compared to the ones of the OAs for digital applications are necessary in order to maintain adequate carrier-to-noise ratio and avoid signal distortion. If AM modulated lasers are used, for instance, the OA gain must be very flat, in order to avoid frequency to intensity modulation conversions, leading to increased signal distortions. This effect can be minimized when using continuous wave (CW) operated lasers in combination with external modulators. In this way, polarization effects could be minimized too. Also, special care must be taken to keep OAs output power at acceptable levels in order to reduce non-linear effects like SBS.

6 Operation, administration and maintenance aspects

Certain considerations on operation, administration and maintenance (OAM) aspects of OAs are given in Appendix IV.

7 Parameter values and ranges for OFA devices

In this clause, parameter values of optical power amplifier (OFA) devices (BA, PA, LA) are provided, according to the lists given in clauses 7, 8 and 9 of [ITU-T G.662], with the aim of ensuring, as far as possible, optical transverse compatibility amongst OFA subsystems and OFA devices in point-to-point system configurations.

7.1 Booster (power) amplifier

7.1.1 Point-to-point

The output parameters for power amplifiers are system specific and are specified in the relevant system Recommendations (ITU-T G.690-series). Some example, input parameter values for power amplifiers can be found in Appendix I. The output parameters for power amplifiers, as described by the interfaces in the relevant system Recommendations, are assumed to be applicable for PDH systems as well.

7.1.1.1 Single-channel systems

Some example input parameter values for power amplifiers can be found in Appendix I. Output parameter values are specified in the ITU-T G.690-series Recommendations.

7.1.1.2 Multi-channel systems

Parameter values for power amplifiers to be used in digital multi-channel systems are for further study.

7.1.2 Point-to-multipoint

Because applications in point-to-multipoint architectures requiring power amplifiers are more likely to be analogue in nature, the associated parameter values are for further study.

7.2 Pre-amplifier

7.2.1 Point-to-point

The input parameters for pre-amplifiers are system specific and are specified in the relevant system ITU-T G.690-series Recommendations. Some example output parameter values for pre-amplifiers can be found in Appendix I. The input parameters for pre-amplifiers, as described by the interfaces in the relevant system Recommendations, are assumed to be applicable for PDH systems as well.

7.2.1.1 Single-channel systems

Some example output parameter values for pre-amplifiers can be found in Appendix I. Input parameter values are specified in the ITU-T G.690-series Recommendations.

7.2.1.2 Multi-channel systems

Parameter values for pre-amplifiers to be used in digital multi-channel systems are for further study.

7.3 Line amplifier

7.3.1 Point-to-point

7.3.1.1 Single-channel systems

Specific parameter values for line amplifiers in point-to-point single-channel systems are specified in the ITU-T G.690-series Recommendations.

7.3.1.2 Multi-channel systems

Specific parameter values for line amplifiers in point-to-point multi-channel systems are for further study.

7.3.2 Point-to-multipoint

Because applications in point-to-multipoint architectures requiring line amplifiers are more likely to be analogue in nature, the associated parameter values are for further study.

8 Parameter values and ranges for OFA-related aspects of OFA subsystems

8.1 Optically amplified transmitter

Parameter values for optically amplified transmitters for single-channel systems are specified in the ITU-T G.690-series Recommendations.

8.2 Optically amplified receiver

Parameter values for optically amplified receivers for single-channel systems are specified in the ITU-T G.690-series Recommendations.

9 Environmental conditions

Various classes of environmental conditions are specified in [IEC 60721-3-0]. Further details can be found in [IEC 60721-3-1] for storage, [IEC 60721-3-2] for transportation, [IEC 60721-3-3] for stationary use at weatherprotected locations, and [IEC 60721-3-4] for stationary use at non-weatherprotected locations.

10 Optical safety aspects

Under certain conditions (fibre break, open connectors), the optical output power of an OA may become accessible and may be hazardous to the human eye. Special precautions and requirements for installation and use of optical systems (including amplifiers) and a description of viewing aids are given in [IEC 60825-2].

Due to the high level of optical power involved, mainly in booster amplifiers and OATs, optical safety and optical surge generation issues (i.e., protection of personnel and equipment) are of primary relevance in line systems using OA devices and subsystems.

An appropriate procedure for automatic power reduction (APR), restart and safe operation of OAs is given in [ITU-T G.664].

Appendix I

Parameter values and ranges for OFA devices in single-channel point-to-point systems

(This appendix does not form an integral part of this Recommendation.)

In this appendix, example parameter values for OFA devices (BA and PA) are shown for single-channel point-to-point systems. These parameter values are according to the lists given in clauses 7 and 8 of [ITU-T G.662] and were developed to ensure, as far as possible, compatibility with parameter values specified in [ITU-T G.957].

As indicated in clause 7, optical interface specifications for the main optical path are provided by the ITU-T G.690-series Recommendations.

I.1 Booster (power) amplifier

The parameter values given in Table I.1 are examples of a minimum list of relevant input parameters (as given in [ITU-T G.662]) for power amplifiers in point-to-point single-channel systems. Only the input parameters have been included in the table, since the output parameters are system specific and are specified in the ITU-T G.690-series Recommendations.

Table I.1 – Input parameters for power amplifiers in single-channel systems

Parameter	Unit	Value
Input power range	dBm	–6/+3
Reverse ASE power level	dBm	≤−20
Input reflectance	dB	≤−27
Pump leakage	dBm	≤−15 (Note)
Maximum reflectance tolerable at input	dB	−27
Power wavelength band	nm	1530-1565
NOTE – The measured value of –15 dBm (max) takes into account all of the contributions coming from the power distribution around the peak value down to 30 dB below the peak value itself.		

I.2 Pre-amplifier

The parameter values given in Table I.2 are examples of a minimum list of relevant output parameters (as given in [ITU-T G.662]) for pre-amplifiers in point-to-point single-channel systems. Only the output parameters have been included in the table, since the input parameters are system specific and are specified in the ITU-T G.690-series Recommendations.

Table I.2 – Output parameters for pre-amplifier in single-channel systems

Parameter	Unit	Value
Output power range	dBm	–16/–9
Small signal gain	dB	≥20
Signal-spontaneous noise figure	dB	under study
Maximum reflectance tolerable at output	dB	–27
Maximum total output power (Note)	dBm	–9
(Small-signal gain) wavelength band	nm	1530-1565
NOTE – This parameter is evaluated in the available signal wavelength band, when an optical filter is used inside the OFA.		

Appendix II

Transmission-related aspects

(This appendix does not form an integral part of this Recommendation.)

II.1 Purpose

OAs permit the consideration of new optical transmission system architectures by providing very high optical power levels and allowing much longer distances between regenerators. When combined with wavelength division multiplexing, OAs also simplify the transport of multiple channels of information by reducing the need for dedicated equipment for each channel. This makes it more economical to achieve greater amounts of bandwidth. As a result of the use of OAs, new transmission effects and limitations have emerged which must now be considered. These include optical non-linearities such as stimulated Brillouin scattering, four-wave mixing and self-phase modulation. These new effects add or combine with fibre chromatic dispersion and polarization mode dispersion. In addition, characteristics of the OA can also contribute to system impairments. Many approaches for solving transmission-related problems have been investigated. However, the technologies differ in their performance and application.

In order to design economical and reliable OA-supported systems following ITU-T Recommendations on optical interface parameters, it is important that both operators and equipment vendors share a common understanding regarding OA-related problems and their remedy. To that end, this clause seeks to do the following:

– Describe the transmission effects induced by optical non-linearities, polarization and chromatic dispersion properties, and other OA-related properties in OA-supported transmission systems.

– Identify the limitations due to the mentioned effects in the various types of relevant transmission systems (e.g., digital/analogue, coherent, wavelength division multiplexing, etc.).

– Indicate possible remedies for these impairments, together with the corresponding field of effectiveness.

II.2 Factors influencing OA transmission applications

The factors influencing OA transmission applications can be divided into four general categories: optical non-linearities, polarization properties, dispersion properties, and other OA-related properties. The factors dealt with in each category are given below and their effects are described in the following clauses:

a) *Fibre optical non-linearities*

1) self-phase modulation;

2) soliton formation;

3) cross-phase modulation;

4) cross-polarization modulation;

~~4~~5) modulation instability;

~~5~~6) four-wave mixing;

~~6~~7) stimulated Brillouin scattering;

~~7~~8) stimulated Raman scattering.

b) *Polarization properties*

1) polarization mode dispersion;

2) polarization dependent loss;

3) polarization hole burning.

c) *Fibre dispersion properties*

– chromatic dispersion.

d) *Other OA-related properties*

1) noise accumulation;

2) self-filtering effect;

3) optical surge generation;

4) induced non-linearity in SOAs.

II.3 Fibre optical non-linearities

Non-linear interactions between the signal and the silica fibre transmission medium begin to appear as optical signal powers are increased to achieve longer span lengths at high bit rates. Consequently, non-linear fibre behaviour has emerged as an important consideration both in high capacity systems and in long unregenerated routes. These non-linearities can be generally categorized as either scattering effects (stimulated Brillouin scattering and stimulated Raman scattering) or effects related to the fibre's intensity dependent index of refraction (self-phase modulation, cross-phase modulation, modulation instability, soliton formation and four-wave mixing). A variety of parameters influence the severity of these non-linear effects, including line code (modulation format), transmission rate, fibre dispersion characteristics, the effective area and non-linear refractive index of the fibre, the number and spacing of channels in multiple channel systems, overall unregenerated system length, as well as signal intensity and source line-width. Since the implementation of transmission systems with higher bit rates than 10 Gbit/s and alternative line codes (modulation formats) than NRZ-ASK or RZ-ASK, described in [b-ITU-T G-Sup.39], non-linear fibre effects previously not considered can have a significant influence, e.g., intra-channel cross-phase modulation (IXPM), intra-channel four-wave mixing (IFWM) and non-linear phase noise (NPN).

II.3.1 Self-phase modulation

II.3.1.1 Description of effects

Because a fibre's refractive index depends on the optical intensity of the signal, the temporal variation of the optical intensity of the signal induces a modulation of its own phase. This effect is called self-phase modulation (SPM). The fibre refractive index may be written [b-Marcuse] as:

$$n = n_0 + \frac{n_2}{A_{eff}} P$$

hence:

$$\frac{\partial n}{\partial t} = \frac{n_2}{A_{eff}} \frac{\partial P}{\partial t}$$

where n_2 is the fibre non-linear refractive index in m^2/W, A_{eff} is the fibre effective area, and P is the launched power.

In single wavelength systems, self-phase modulation will gradually broaden the signal spectrum when changes in optical intensity result in changes in phase (see Figure II.3-1). Once spectral broadening is introduced by SPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre, due to the effects of chromatic dispersion, in the normal dispersion region of the fibre (i.e., below the zero-dispersion wavelength). Conversely, in the anomalous dispersion region, the chromatic dispersion and SPM can compensate each other, giving less temporal broadening. The soliton propagation is based on this phenomenon (see clause II.3.2).

The interaction of a signal with the ASE noise of optical amplifiers results in amplitude to phase-noise conversion by the Gordon-Mollenauer effect. The generated NPN has also been called Gordon-Mollenauer phase noise or phase jitter [b-Gordon].

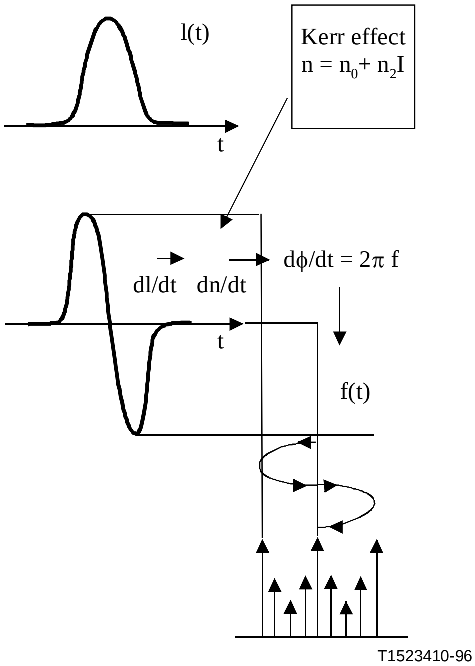

Figure II.3-1 – Spectral broadening mechanism due to self-phase modulation

II.3.1.2 Induced transmission limitations

Generally, the effects of SPM are significant only in systems with high cumulative dispersion or in very long systems. Systems operating in the normal dispersion regime which are dispersion-limited may not tolerate the additional effects due to SPM. In multiple-channel systems with very closely spaced channels, the spectral broadening induced by SPM may also create interference between adjacent channels. The effect of SPM may also induce degradation when combined with narrow-band optical filtering. Since SPM is essentially a single channel effect, it is not influenced by the greater channel counts. The distortion penalty of SPM is increased by larger launched channel powers. It is also increased by a higher channel bit rate, since signals with higher bit rates have higher rising/falling bit slopes.

SPM on low-chirp intensity-modulated signals leads to pulse compression on ITU-T G.652 fibres and on ITU-T G.655 fibres with anomalous dispersion as a function of transmitter power. The pulse compression counteracts the chromatic dispersion and offers some dispersion accommodation. However, limits of maximum dispersion and related transmission length exist.

For transmission over multiple fibre spans, the SPM-introduced phase shift accumulates in each successive fibre span. The maximum tolerable channel launch power into each span becomes respectively smaller as more fibre spans are applied. This phase shift accumulation has been described by the "integrated power product" behaviour [b-Faerbert].

While ASK modulation formats suffer less from SPM generated non-linear phase noise (phase jitter) than PSK modulation formats i.e., (D)PSK and (D)QPSK, it can become one of the major transmission limitation factors. The more bits per symbol that are transmitted (the lower the symbol rate (baud)), the higher are the NPN impairments.

II.3.1.3 Minimization of induced limitations

The use of ITU-T G.653 fibre and the placement of the signal channel near the dispersion zero will reduce the impact of SPM. For systems less than approximately 1000 km, SPM may be controlled through the implementation of dispersion compensation at appropriate intervals along the length of an ITU-T G.652 fibre system. The effects of SPM may be mitigated by operating at wavelengths above the zero-dispersion wavelength of ITU-T G.655 fibre. Fibres with attributes of increased fibre effective area, or decreased non-linear refractive index, also reduce the SPM penalty. For all fibre designs, SPM effects may be reduced by decreasing the launched channel powers, though system design trends call for larger powers to allow longer span distances.

II.3.2 Soliton formation

II.3.2.1 Description of effects

In the anomalous dispersion region of the fibre (i.e., above the zero-dispersion wavelength), the interplay between the non-linear refractive index and chromatic dispersion may give origin to particular propagation regimes, called soliton pulses, which propagate for long distances periodically reproducing their time shape and frequency spectrum. Other kinds of signals can spontaneously evolve into solitons. Although the fundamental soliton is very robust and can be used to achieve long-distance transmission, the higher order solitons undergo very complex evolution, involving pulse reshaping, spectral modifications, and also pulse breaking. These effects may be detrimental to system operation.

II.3.2.2 Induced transmission limitations

Effects due to soliton formation may be relevant in ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibre systems. While fundamental soliton formation can be useful, other solitons generally give rise to a strong degradation of the transmitted signal. Thus, higher order soliton formation sets a limit to the maximum power that can be launched into the fibre.

II.3.2.3 Methods to minimize induced limitations

Soliton formation can be avoided by operating at wavelengths below the zero-dispersion wavelength of the link. However, in this regime, soliton transmission is not supported and both dispersion and non-linearity contribute to pulse broadening. Signal degradation can be minimized by proper management of the dispersion along the link.

II.3.3 Cross-phase modulation

II.3.3.1 Description of effects

In multi-channel systems, cross-phase modulation (XPM) will gradually broaden the signal spectrum when changes in optical intensity result in changes in phase due to interactions between adjacent channels. The amount of spectral broadening introduced by XPM is related to the rate of the transmission signal, channel separation and fibre chromatic dispersion, since the dispersion-induced differential group velocities will cause the interacting pulses to separate as they propagate down the fibre. Once spectral broadening is introduced by XPM, the signal experiences a greater temporal broadening as it propagates along the length of the fibre due to the effects of chromatic dispersion. With the introduction of systems with higher bit rates than 10 Gbit/s and broader signal spectra, the cross-phase modulation within the channel becomes a dominating factor. This is denoted by the term intra-channel cross-phase modulation (IXPM). The term XPM usually describes the interaction between adjacent channels, also denoted as inter-channel cross-phase modulation.

As in the case of SPM, the interaction of IXPM (XPM) with ASE noise of optical amplifiers also results in NPN or phase jitter.

Besides the bit rate (symbol rate), IXPM as well as XPM impairments are modulation format dependent.

II.3.3.2 Induced transmission limitations

The systems penalty from XPM is increased by smaller channel spacings and larger channel counts (though this saturates depending on distance). As noted for SPM, the change in signal phase is related to the change in fibre refractive index, which in turn is related to the channel power. Larger average launched powers lead to larger phase shifts, which when combined with dispersion effects lead to a larger system penalty.

While the XPM penalty decreases for higher channel bit rates, since lower bit rate signals experience longer bit interactions or "walk-through", IXPM penalty actually increases for higher channel bit rates, especially for ASK modulation format channels, as the higher bit rate signal pulses experience much stronger temporal broadening due to chromatic dispersion (factor of 16 between 10 Gbit/s and 40 Gbit/s) which results in bit interactions or "walk-through" of consecutive bits.

While PSK modulated channels are only slightly affected by IXPM and XPM due to their constant amplitude modulation, they are impaired by non-linear phase noise.

XPM induced non-linear phase noise impairments can also become significant for mixed transmission systems with ASK and PSK line coding, depending on the channel spacing, the rates of the signals and the related bit (symbol) "walk-through". The ASK modulated channels penalize the PSK modulated channels.

The impairments from XPM are more significant in ITU-T G.652 fibre systems, relative to ITU-T G.653 and ITU-T G.655 fibre systems. The broadening due to XPM may result in interference between adjacent channels in multiple-channel systems.

II.3.3.3 Minimization of induced limitations

XPM can be controlled through the appropriate selection of channel spacing. Studies have shown that only adjacent channels contribute significantly to XPM-induced signal distortion in multiple-channel systems. The signal-to-noise ratio (SNR) of the centre channel of a three-channel system will approach that of a single-channel system as channel separation is increased. As a result, the effect of XPM can be rendered negligible with adequate spacing between the signal channels. Channel separations of 100 GHz were shown to be sufficient for 10 Gbit/s ASK systems to reduce XPM effects in a simulation of a system with 5 mW of power/channel [b-Koch]. Dispersion penalties due to XPM may also be controlled by the implementation of dispersion compensation at appropriate intervals along the length of the system. Fibres with attributes of increased fibre effective area, or decreased non-linear refractive index, also reduce the XPM penalty. XPM effects are also reduced by lower fibre attenuation, which ensures that XPM phase distortion between two pulses more nearly equalizes as the pulses "walk through" one another.

For all fibre designs, XPM effects may be reduced by decreasing the launched channel powers, though system design trends call for larger powers to allow longer span distances.

II.3.4 Cross-polarization modulation

II.3.4.1 Description of effects

In multi-channel systems, dual-polarization (DP) signals are more susceptible than single-polarization (SP) signals to fibre nonlinearities, especially to inter-channel nonlinearities which mainly originate from XPM between neighbouring channels. Apart from inducing timing jitter and nonlinear phase noise, XPM causes cross polarization modulation (XPolM).

XPolM describes the effect of nonlinear variation of the refractive index difference between the polarization components of the optical signal under consideration. In general, except in systems with optical polarization-mode-dispersion (PMD) compensators, XPolM can be neglected in systems using SP signals, but it can have a significant impact on DP signals.

In a WDM system with two signals, a and b, where the two signals have non-overlapping spectra, by neglecting PMD, SPM and the four-wave mixing (FWM) between the two signals, the propagation equation (known also as Manakov equation [b-Manakov]) for signal a can be obtained as follows:

$$\frac{\partial \boldsymbol{E}_a}{\partial z} - \frac{1}{2}\alpha - \frac{i}{2}\beta_2 \frac{\partial^2 \boldsymbol{E}_a}{\partial t^2} + \frac{8}{9}\gamma\left(\frac{3}{2}|\boldsymbol{E}_b|^2 + \frac{1}{2}\vec{\boldsymbol{E}}_b\vec{\boldsymbol{\sigma}}\right)\boldsymbol{E}_a = 0$$

where the Pauli matrix expansion is defined as:

$$\vec{\boldsymbol{E}}_b\vec{\boldsymbol{\sigma}} = \vec{\boldsymbol{E}}_b^{(1)}\vec{\boldsymbol{\sigma}}^{(1)} + \vec{\boldsymbol{E}}_b^{(2)}\vec{\boldsymbol{\sigma}}^{(2)} + \vec{\boldsymbol{E}}_b^{(3)}\vec{\boldsymbol{\sigma}}^{(3)}$$

with the index in bracket referring to the Stokes parameters and the Pauli matrices [b-GordonKogelnik], [b-Mollenauer].

In the parenthesis, the first term is polarization-independent and refers to the mean XPM averaged over all possible relative states of polarization (SOP)s between the signal a and the interfering signal b. The second term describes the polarization-dependent contribution to XPM resulting in XPolM. If the two signals have the same polarization, this second term reduces to a phase modulation common to both components of $\boldsymbol{E}_a$ which increases the total XPM contribution by a factor of 2 compared to SPM. Similarly, if the two signals have orthogonal polarization, the XPM contribution is reduced so that it equals the magnitude of SPM. In the Manakov regime, phase modulation due to XPolM is on average more efficient than SPM by a factor of 3/2.

When signals are present with amplitude, phase or polarization modulation, and fibre CD is present, the amplitude and SOP of each signal generally changes with time, and the XPolM generates time dependent nonlinear polarization scattering, according to the equation above. Nonlinear polarization scattering causes the SOP to change at the symbol rate, which is hard to follow with either optical methods in direct detection receivers or digital signal processing in coherent receivers, and may induce severe impairments in optical communication systems [b-Xie].

II.3.4.2 Induced transmission limitations

The fact that the state of polarization of the signals evolve randomly over the transmission due to CD and PMD makes the XPolM effect pattern-dependant and stochastic. XPolM effect results in fast polarization-modulation of signals and therefore to a depolarization of the transmitted signal, causing fading and channel cross-talk for DP signals.

XPolM induced nonlinear polarization scattering could significantly degrade the performance of DP transmission systems when amplitude modulated signals and dispersion management technique are used together [b-Xie].

II.3.4.3 Minimization of induced limitations

To improve the performance of DP signals in dispersion-managed transmission systems, many techniques to mitigate nonlinear polarization scattering have been proposed and demonstrated, which could significantly reduce XPolM degradations [b-Winter]. Examples are: using temporal symbol-interleaving of the polarization subchannels; using periodic-group-delay through the use of fibre gratings as inline dispersion compensators (in replacement of dispersion compensating fibre); adding some PMD along the transmission links; and leaving some residual dispersion per span. The temporal interleaving reduces the signal peak power, and reduces nonlinear polarization scattering leading to reduced XPolM between signals. This can be generated by adding a pulse carver before the data modulators and setting proper time delay between the two polarizations before the polarization beam combiner in the transmitter.

II.3.54 Modulation instability

II.3.54.1 Description of effects

Modulation instability (MI) breaks a CW signal or a pulse into a modulated structure. It can be induced by SPM in the anomalous dispersion regime (i.e., above the zero-dispersion wavelength), where a quasi-monochromatic signal spontaneously tends to generate two symmetric spectral sidebands, as shown in Figure II.3-2. MI can also be induced by XPM. XPM-induced MI can occur in both the anomalous and normal (i.e., below the zero-dispersion wavelength) regimes.

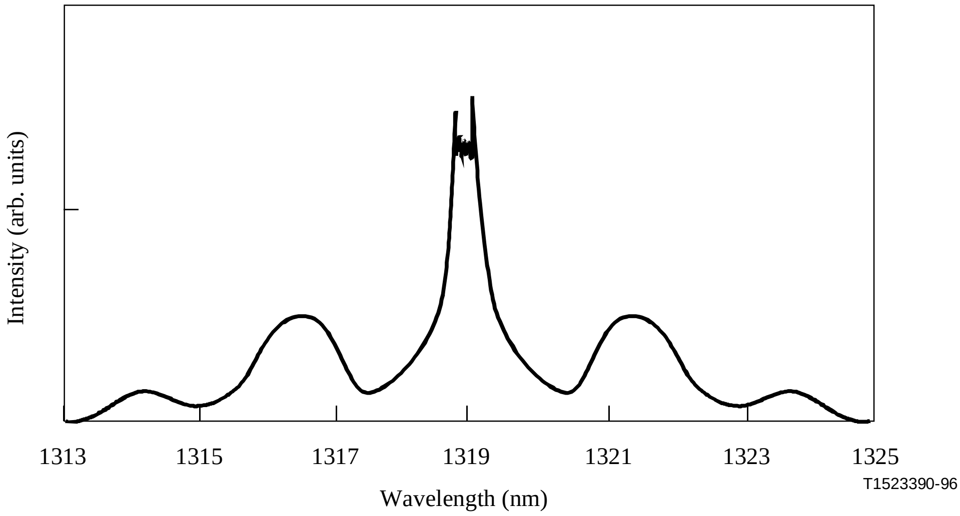

Figure II.3-2 – Power spectrum of a pulse after propagation in 1 km-long fibre (input pulse width: 100 ps, peak power: 7 W). Spectral side lobes appeared due to MI

For SPM-induced MI, frequency separation and gain of the sidebands are determined by the intensity of the wave and by the dispersion and non-linear coefficients of the fibre. The maximum conversion efficiency occurs at a frequency separation given by:

$$\Omega_{\max} = \pm\left[\frac{8\pi^2 c n_2 P_o}{\lambda^3 A_{eff} D(\lambda)}\right]^{1/2}$$

where n_2 is the fibre non-linear refractive index, A_{eff} is the fibre effective area, P_o is the launched power, $D(\lambda)$ is the chromatic dispersion coefficient and λ is the operation wavelength. Sidebands located at $\pm\,\Omega_{\max}$ from the carrier experience a gain per unit length: $g_{\max} = 4\pi P_o/(\lambda A_{eff})$. Fibre loss can be taken into account by slightly modifying the equations above. Dependence of MI gain on the frequency deviation with respect to the signal is given in Figure II.3-3 in the presence of fibre loss and for various values of fibre dispersion.

The MI can be viewed as a particular case of FWM where two photons of the intense incoming signal are converted into two photons at two different frequencies.

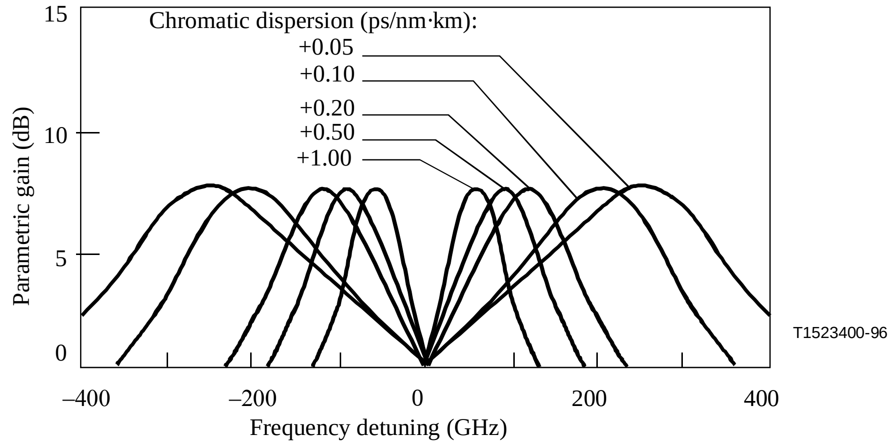

Figure II.3-3 – Calculated MI gain versus frequency detuning, from 30 km-long fibres (0.24 dB/km loss) with five different dispersion coefficient values, for +16 dBm CW signal launched power

II.3.54.2 Induced transmission limitations

Modulation instability may decrease the signal-to-noise ratio (SNR) due to the generation of sidebands either spontaneously or seeded by the amplifier spontaneous emission. As the maximum degradation of the signal is expected for high values of g_{max} and for Ω close to the bandwidth of the signal, MI may be critical when using very powerful boosters in dispersion-shifted fibre links with directly modulated lasers. On long-distance unrepeated systems, MI can be observed at lower power levels and may cause excess amplification of the spontaneous emission noise of the cascaded OAs. The broadening at signal spectral tails can cause signal-carrier depletion and the tails may be attenuated by the narrow-band ASE filters or by the self-filtering effect in very long systems.

II.3.54.3 Methods to minimize induced limitations

The effect of MI can be minimized either by decreasing the power level or by operating at wavelengths below the zero-dispersion wavelength of the link. Dispersion managing may also be useful to reduce MI sidebands formation. Otherwise, the received signal should be electrically filtered in order to lower the level of the spurious amplified noise. External modulation of the lasers, giving narrower spectra, may decrease considerably the impact of MI.

II.3.65 Four-wave mixing

II.3.65.1 Description of effects

Four-wave mixing (FWM), also called four-photon mixing, occurs when the interaction of two or three optical waves at different wavelengths generates new optical waves, called mixing products or sidebands, at other wavelengths. This interaction can occur between signals in multiple-channel systems, between OA ASE noise and a single channel (NPN), as well as between the main mode and side modes of a single channel (IFWM). In the case of two signals, the intensity modulation at their beat frequency modulates the fibre refractive index and produces a phase modulation at a difference frequency. The phase modulation creates two sidebands at frequencies given by this difference. In the case of three signals, more and stronger mixing products are produced (see Figure II.3-4) which will fall directly on adjacent signal channels when the channel spacings are equal in frequency. Two optical waves propagating along a fibre produce FWM with high efficiency if the phase matching condition is achieved between the sidebands and the initial signals.

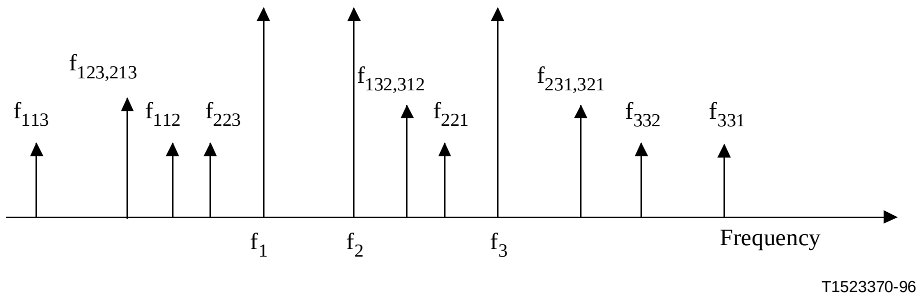

Figure II.3-4 – Mixing products generated due to four-wave mixing of three signals

Assuming that all channels have the same modulation format, input power and equal channel spacing, the FWM efficiency, η, of a fibre can be expressed as the ratio of the FWM power to the per channel output power from the fibre and is proportional to [b-Kaminow]:

$$\eta \propto \left[\frac{n_2 P}{A_{eff} D (\Delta\lambda)^2} \right]^2$$

where n_2 is the fibre non-linear refractive index, P is the channel input power, A_{eff} is the fibre effective area, D is the fibre chromatic dispersion coefficient, and $\Delta\lambda$ is the channel spacing. Note that FWM efficiency is not influenced by an increasing bit rate.

As for IXPM, with the introduction of systems with bit rates higher than 10 Gbit/s and broader signal spectra, the four-wave mixing within the channel becomes a dominating factor. This is denoted by the term intra-channel four-wave mixing (IFWM). The term FWM usually describes the interaction between adjacent channels, also denoted as inter-channel four-wave mixing.

II.3.6~~5~~.2 Induced transmission limitations

The generation of FWM sidebands can result in a significant depletion of the signal power. Furthermore, when the mixing products fall directly on signal channels, they cause a parametric interference which manifests itself as amplitude gain or loss in the signal pulse, depending on the phase interaction of the signal and sideband.

Parametric interference causes closure of the eye pattern at the receiver output, thereby degrading bit error ratio (BER) performance. Multi-channel systems are trending towards greater channel counts, which increases the number of possible mixing products falling on signal channels.

As seen by the equation in clause II.3.6~~5~~.1, increased frequency spacing and chromatic dispersion reduce the efficiency of the FWM process by destroying the phase matching between the interacting waves. However, systems are trending towards decreased frequency spacings, to allow more channels to occupy the same OA passband. Furthermore, as launched channel powers increase, the FWM efficiency (and hence system penalty) also increases.

Multi-channel systems deployed in the 1550 nm operating window over ITU-T G.652 fibre experience much less FWM impairment compared to systems deployed over ITU-T G.653 fibre, because ITU-T G.652 fibre has much more chromatic dispersion, as well as a larger fibre effective area. Conversely, the placement of a signal channel directly at or near the dispersion zero can result in a very significant build-up of the FWM products over a relatively short fibre length (i.e., 10 s of km).

When used in the 1550 nm zero dispersion region of ITU-T G.653 fibres, sometimes referred to as C-Band, four-wave mixing can create a serious system impairment in multi-channel systems on ITU-T G.653 fibre, since the signal channels experience only a small value of chromatic dispersion. The impact of dispersion on achievable system capacity for a four-channel system over three amplifier spans is shown in Figure II.3-5. This illustrates what can happen at high power levels when conditions promote the generation of mixing products. The capacity limitation is based on a worst-case calculation of the mixing products generated by the FWM process with four 8 dBm signal channels centred around the dispersion value shown. This system develops intolerable levels of distortion due to FWM as the dispersion experienced by the signal channels approaches zero.

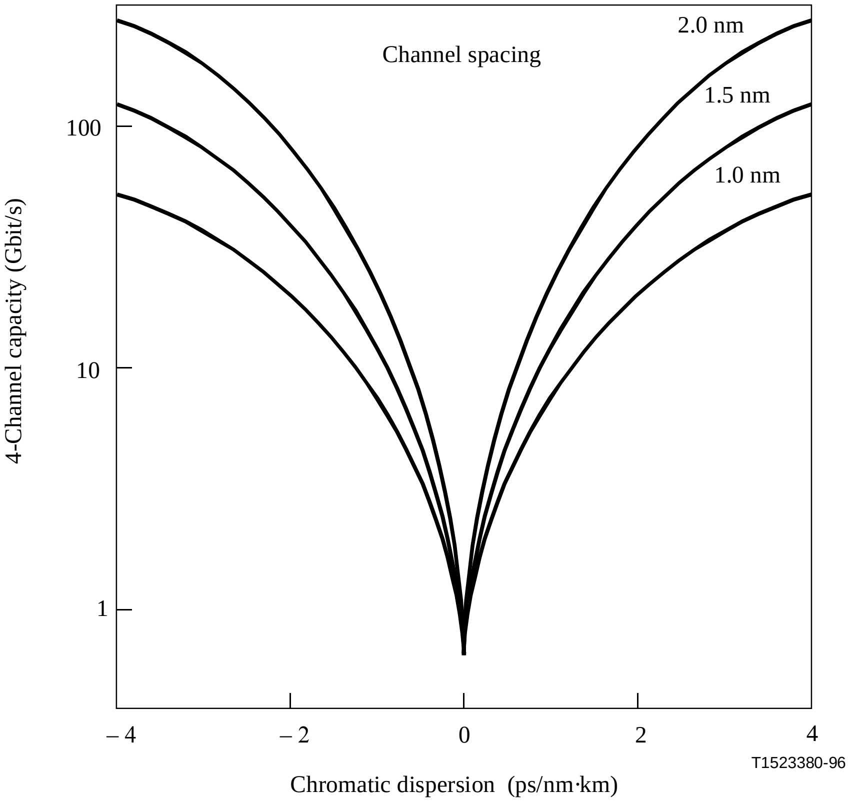

Figure II.3-5 – Impact of dispersion on system capacity in the presence of FWM

The non-zero dispersion shifted fibre [ITU-T G.655] has been developed to eliminate FWM effect in the C-Band. However, four-wave mixing may possibly also impair multi-channel systems even on [ITU-T G.655] fibre, depending on channel spacings of 50 GHz or less, fibre dispersion, and fibre non-linear coefficient (proportional to the non-linear refractive index divided by the effective area).

In single-channel systems, the FWM interaction can occur between OA ASE noise and the transmission channel, as well as between the main mode and the side modes of the optical transmitter. Phase noise is added to the signal carrier due to the accumulated ASE via the non-linear index of refraction effect, thus broadening the signal spectral tails.

II.3.6~~5~~.3 Minimization of induced limitations

As previously noted, chromatic dispersion, such as that in ITU-T G.652 and ITU-T G.655 fibres, may be used to suppress the generation of the FWM sidebands. Fibres with attributes of an increased fibre effective area, or a decreased non-linear refractive index, also reduce the FWM efficiency. Uneven channel spacing may also be incorporated to mitigate the severity of the FWM impairment. Reduction of the input power levels in ITU-T G.653 fibre systems could permit multiple channel operation, but might compromise the economical advantages of optical amplification.

In order to adequately suppress the generation of mixing products, use of a fibre (covered by either existing or new Recommendations under study) with a minimum permitted (i.e., non-zero) dispersion within the region of the OA amplification band has been proposed. Alternating spans of such non-zero dispersion fibre with opposite dispersion characteristics has also been considered as a potential option, since the resultant cable would maintain a net chromatic dispersion of approximately zero. However, this alternative may present difficulties in the areas of installation, operations and maintenance by introducing a second fibre type into the outside plant environment. Similar approaches using long spans of fibre with small finite dispersion and short lengths of opposite and higher dispersion fibre (to provide compensation) have also been demonstrated. In particular, in links with periodical amplification, a short piece of compensating fibre can be located inside the box in which the optical amplifier is located.

Uneven channel spacing and larger channel spacing have been proposed as means to mitigate the effects of non-linearities and allow deployment of dense WDM systems on ITU-T G.653 fibre. Uneven channel spacing ensures that mixing products generated by three or more channels do not fall directly on other channel wavelengths. However, the transfer of power from the signals into the mixing products (i.e., signal depletion) remains unaffected by making the channel spacing uneven and may still cause significant eye closure. Increased channel spacing also reduces the effects of four-wave mixing. Use of these mitigation techniques may be constrained by the effects of gain narrowing due to the concatenation of optical amplifiers, which reduces the width of the usable amplification spectrum. Uneven channel spacing and increased channel spacing unfortunately also require more of the OA passband.

WDM transmission using longer wavelengths (L-band) in addition to the 1550 nm band is proposed. Transmission using the long wavelength band (L-band) is generally useful on all types of fibre since it allows the total number of wavelengths to be increased. L-band transmission on ITU-T G.652 and ITU-T G.654 fibre may require dispersion compensation due to large dispersion values. With ITU-T G.653 fibres, L-band transmission enables simple wavelength design because minimal FWM effect is observed in the L-band. Dispersion of the L-band in ITU-T G.653 fibre may not require dispersion compensation, depending on the transmission bit rate.

NOTE – The definition of the L-band can be found in [b-ITU-T G-Sup.39].

II.3.7~~6~~ Stimulated Brillouin scattering

II.3.7~~6~~.1 Description of effects

In an intensity-modulated system using a source with a narrow line-width, significant optical power is transferred from the forward-propagating signal to a backward-propagating signal when the stimulated Brillouin scattering (SBS) threshold is exceeded. In the SBS, the forward-propagating light is scattered from acoustic phonons. However, only the backward-propagating scattered light is guided by the single-mode fibre. The scattered light is downshifted or Brillouin-shifted by approximately 11 GHz at 1550 nm.

Of the non-linear effects described here, the SBS has the lowest threshold power. While studies have shown that the SBS threshold can vary between fibre types and even among individual fibres, it is typically in the order of 5 to 10 mW for externally modulated, narrow line-width sources, but may be 20 to 30 mW for directly modulated lasers. The SBS threshold for a system deployed on ITU-T G.653 fibre is slightly lower than that for a system using ITU-T G.652 fibre, due to the smaller effective area of ITU-T G.653 fibre. This is generally true for all of the non-linear effects. The SBS threshold is sensitive to the source line-width and power level. It is independent of the number of channels.

II.3.7~~6~~.2 Induced transmission limitations

SBS effectively limits the amount of light that can be transmitted through a fibre path. Figure II.3-6 [b-Koch] and [b-Mao] shows this effect for a narrow-band source, where all of the signal power falls within the Brillouin bandwidth. The transmitted power becomes saturated and the backscattered power rapidly increases. The input power level to the fibre at which this rapid increase occurs is defined as the SBS threshold. In the general case, the SBS threshold is expressed as:

$$P_{th} = 21 \frac{KA_{eff}}{gL_{eff}} \cdot \frac{\Delta\nu_p + \Delta\nu_B}{\Delta\nu_B}$$

where g denotes the Brillouin gain coefficient (~ 4 × 10^{-9} cm/W), and A_{eff} is the fibre effective area. K is a constant determined by the degree of freedom of the polarization state (in ITU-T G.652 fibres, $K = 2$). $\Delta\nu_B$ and $\Delta\nu_p$ represent the Brillouin bandwidth and a line-width of a pump light, respectively. L_{eff} denotes the effective length defined as:

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha}$$

where α is the fibre attenuation coefficient and L is the fibre length.

The SBS threshold, P_{th}, depends on the line-width of the pump light, $\Delta\nu_p$. When the line-width of the pump light is small compared to the Brillouin bandwidth, the SBS threshold power can be estimated using the following relation:

$$P_{th} = 21 \frac{KA_{eff}}{gL_{eff}}$$

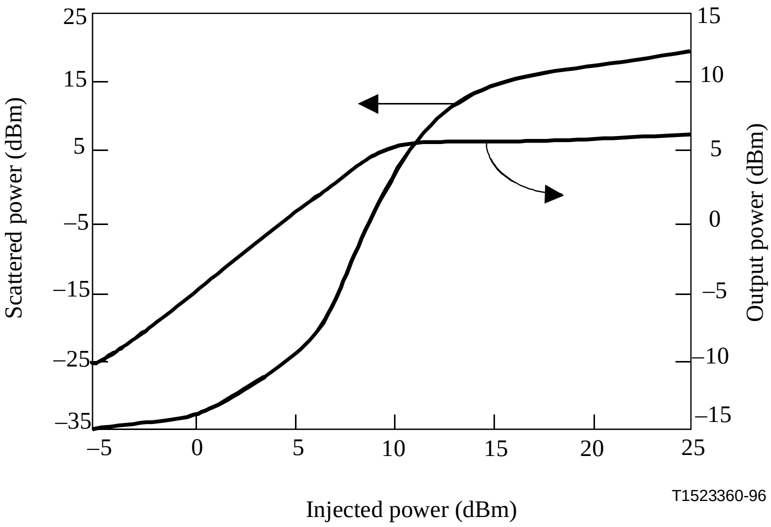

Figure II.3-6 – Stimulated Brillouin scattering effect for narrow-band source

II.3.7~~6~~.3 Minimization of induced limitations

Stimulated Brillouin scattering impairments will not arise in systems where the source line-width significantly exceeds the Brillouin bandwidth or where the signal power is below the threshold power (calculated from expressions in clause II.3.7~~6~~.2).

NOTE – Further information concerning SBS can be found in clause II.5 of [b-ITU-T G.650.2].

II.3.8~~7~~ Stimulated Raman scattering

II.3.8~~7~~.1 Description of effects

Stimulated Raman scattering is a broadband effect which involves the interaction of light and the vibrational modes of silica molecules. SRS causes a signal wavelength to behave as a Raman pump for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light. In any case, the shorter wavelength signal is attenuated by this process, which amplifies the longer wavelength signal.

II.3.8~~7~~.2 Induced transmission limitations

Stimulated Raman scattering (SRS) can occur in both single- and multiple-channel systems. Signal powers in the order of 1W or more are needed to experience impairment from this phenomenon with only a single channel without line amplifiers. However, shorter wavelength signals in multiple-channel systems with channels spanning a wide wavelength range can suffer degraded signal-to-noise performance when a portion of their power is transferred to longer wavelength channels through the SRS. This results in total system capacity limitations based on the total number of channels, channel spacing, average input power and overall system length. In particular, the threshold for the observation of a 1 dB penalty in a multi-channel system due to Raman gain in dispersion-unshifted fibre can be estimated to be [b-Koch] and [b-Chraplyvy]:

$$P_{tot} \cdot \Delta\lambda \cdot L_{eff} < 40\ mW \cdot nm \cdot Mm$$

where P_{tot} is the combined power of all of the channels, $\Delta\lambda$ is the optical spectrum over which the channels are distributed and L_{eff} is the effective length (in units of 10^6 metres (Mm)). The SRS threshold for a system deployed on ITU-T G.653 fibre is slightly lower than that for a system using ITU-T G.652 fibre, due to the smaller effective area of ITU-T G.653 fibre. The SRS does not practically degrade single-channel systems; conversely, it may limit the capability of WDM systems.

II.3.8~~7~~.3 Minimization of induced limitations

In single-channel systems, filters can be used to remove the unwanted spectrum. However, no practical techniques to eliminate the effects of the SRS in multiple-channel systems have been reported. The effects of the SRS may also be mitigated by reducing the input optical power. However, the SRS does not appear to present a practical limitation to the deployment of the currently contemplated WDM systems.

II.3.9~~8~~ Fibre non-linearity summary

A summary of the non-linear effects described in the previous clauses is given in Table II.1.

Table II.1 – Non-linear optical effects in optical fibres

Non-linear optical effect	Cause	Characteristics	Critical light power in SMF	Impact
Self-phase modulation (SPM) and cross-phase modulation (XPM)	Intensity-dependent refractive index	– Phase shift • self-induced (SPM) • adjacent channel (XPM) • spectral frequency broadening • accumulation with each fibre span – Non-linear phase noise • Gordon-Mollenauer effect	P_c > ~10 mW (for single span)	– Spectral broadening increases effect of dispersion – Power/dispersion limited high bit rate transmission – Initial pulse compression (in positive dispersion regime) – Accelerated pulse broadening (in negative dispersion regime) – Pulse propagation (solitons) – Limitations in PSK systems by AM/PM conversion

Table II.1 – Non-linear optical effects in optical fibres

Non-linear optical effect	Cause	Characteristics	Critical light power in SMF	Impact
Four-wave mixing (FWM) or four-photon mixing	Intensity-dependent refractive index	– Mixing products generated fijk = fi + fj – fk (i, j≠k)	P_c > ~10 mW (for ITU-T G.653 fibres) – depends on specific parameters, e.g., channel spacing and closeness to λ_0	– Optical crosstalk in WDM systems – Signal power depletion
Stimulated Brillouin scattering (SBS)	Interaction: photon-acoustic phonons	– Brillouin lines in backward direction f – Δf Δf = ~ 13 GHz (1310 nm) Δf = ~ 11 GHz (1550 nm)	P_c > ~5 mW (for narrow line-width optical source) – P_c increases with signal line-width	– Signal instability – Optical loss in fibre – Optical crosstalk in bidirectional multi-channel systems
Stimulated Raman scattering (SRS)	Interaction of photon-optical phonons	– Raman lines f-n Δf (Stokes) Δf = ~ 12 THz Δλ = ~ 70 nm (1310 nm) Δλ = ~ 102 nm (1550 nm)	P_c > ~1 W (for single channel) P_c > ~1 mW for Raman amplification in a WDM system with critical channel spacing, Δλ	– Optical loss in fibre – Optical crosstalk in a WDM system – Signal power depletion

A second summary is given in Table II.2, comparing long-haul system trends to their effects on non-linear systems penalties.

Table II.2 – Long-haul system trends vs non-linear penalties

Long-haul system trends	SPM penalty	(I)XPM penalty		(I)FWM penalty		NPN penalty (Note)	SBS penalty	SRS penalty
		XPM	I-	FWM	I-			
a) Decreased channel spacing	–	↑	–	↑	–	–	ffs	ffs
b) Increased channel count	–	↑	–	↑	–	–	ffs	↑
c) Increased channel power	↑	↑	↑	↑	↑	↑	↑	↑
d) Increased number of spans	↑	↑	↑	↑	↑	↑	↑	↑
e) Increased channel bit rate (symbol rate)	↑	↓	↑	–	↑	–	↓	ffs
f) PSK versus OOK modulation formats	↓	↓	↓	↓	↓	↑		
↑ Penalty increases ↓ Penalty decreases – Penalty is not significantly affected ffs Penalty is for further study NOTE – NPN can be generated by SMP, (I)XPM or (I)FWM.								

II.4 Polarization properties

II.4.1 Polarization mode dispersion

II.4.1.1 Description of effects

It is well known that the fundamental mode of a circularly symmetric dielectric waveguide is doubly degenerate. In a real optical fibre, this degeneracy is split by birefringence. The birefringence may be introduced deliberately, as in a polarization-maintaining fibre, for example, or it may be an unwanted by-product of fibre manufacture or cable manufacture. In this case, the birefringence is introduced in a random way by, for example, geometrical or stress-induced perturbations.

The propagation constants, β_i (ω), of the two orthogonal modes can be expanded in a Taylor series around the centre frequency, ω_0;

$$\beta_i(\omega_0) = \beta_i(\omega_0) + \left.\frac{\partial \beta_i}{\partial \omega}\right|_{\omega=\omega_0} (\omega - \omega_0) + \frac{1}{2}\left.\frac{\partial^2 \beta_i}{\partial \omega^2}\right|_{\omega=\omega_0} (\omega - \omega_0)^2 + ...$$

where the $\beta_i(\omega_0)$ is the phase velocity v_p, $\frac{\partial \beta_i}{\partial \omega}$ is related to the group velocity v_g, and $\frac{\partial^2 \beta_i}{\partial \omega^2}$ is related to the dispersion of the group velocity (or chromatic dispersion, D), etc.

With the development of dispersion-shifted fibres and the deployment of systems operating near the dispersion-zero wavelength, the contribution to the dispersion from the second order term, or chromatic dispersion, reduces and the first order term can now become significant. For the case of birefringent fibres, this first order term leads to a group delay called polarization dispersion. This polarization dispersion introduces a differential group delay between orthogonal states of polarization. Although the effect of polarization mode dispersion (PMD) is to change randomly the polarization state of a pulse propagating in a fibre, it is possible to define a pair of orthogonal states or "principal states" at the input whose output states are orthogonal and show no dependence on wavelength to the first order. (In some situations, however, this approximation falls apart and the principal states can show a wavelength dependence, leading to a further system degradation through a coupling to chromatic dispersion.)

As alluded to in the first paragraph above, the birefringence introduced to the fibre is caused by local random and asymmetric mechanisms such as stress, bending and twisting. These random birefringence mechanisms redefine the local birefringence axes along the length of the fibre, thus causing random coupling between the polarization modes along the length of the fibre. The cabling process also introduces a certain amount of random birefringence and random mode coupling. The fibre length between such changes is usually referred to as the coupling length, which for a fibre is usually quoted as the ensemble average of all of the local coupling lengths. Furthermore, changes in local environmental conditions, such as temperature for example, cause fluctuations in the local birefringence axes, thus causing random polarization coupling. As a result of the randomly changing polarization coupling, the magnitude of the differential group delay (DGD) becomes a statistically varying function. It can be shown that distribution of the differential group delays is described by a Maxwellian distribution function, defined by:

$$P(\Delta\tau) = \frac{32\Delta\tau^2}{\pi^2\langle\Delta\tau\rangle^3}\exp\left[-\frac{4\Delta\tau^2}{\pi\langle\Delta\tau\rangle^2}\right]$$

where $\Delta\tau$ is the differential group delay between the two principal states, and $\langle\Delta\tau\rangle$ is the mean differential group delay (usually referred to as the PMD value). As a consequence of the statistical nature of polarization mode dispersion, the magnitude of $\langle\Delta\tau\rangle$ increases with the square root of the fibre or cable length, for lengths much longer than the coupling length. Polarization mode dispersion is usually quoted in units of ps or ps/√km. The unit of ps is usually reserved for single optical elements which have a fixed dispersion (e.g., a coupler or isolator) or short fibre sections which do not exhibit mode coupling.

II.4.1.2 Induced transmission limitations

In a digital transmission system, the principal effect of polarization mode dispersion is to cause intersymbol interference. As an approximate rule of thumb, a 1 dB penalty occurs when the total instantaneous differential group delay equals 0.3 T, and both principal states of polarization are excited equally (gamma = 0.5), where T is the bit period. This is a commonly used value for the maximum tolerable system power penalty. The related instantaneous DGD can also be considered, in the same way, as the maximum tolerable system value: $DGD_{max} \leq 0.3$ T. The relationship between DGD_{max} and PMD value is to be determined on the base of the Maxwellian probability distribution, choosing a proper adjustment factor that is related to the desired maximum outage probability. For example, a value of the adjustment factor equal to 3, i.e., $DGD_{max} = 3 \times$ PMD value, corresponds to an outage probability of approximately 4×10^{-5}, see [ITU-T G.691]. Higher bit rate systems have shorter bit periods, so they tolerate less differential group delay. Current studies, e.g., [IEC/TR 61282-3], indicate that optical fibres and cables will be specified according to either the DGD_{max} defined above or to the mean level of differential group delay (PMD value). Using the example value of the adjustment factor of 3, the system design rule for PMD impairments becomes: PMD value ≤ 0.1 T.

In optical transmission systems operating at 10 Gbit/s, a statistical specification of 0.5 ps/sqrt(km) has been proposed for concatenated links of optical fibre cable. From the Maxwell statistics, the probability that the 1 dB penalty at 10 Gbit/s is exceeded for a 400 km span is less than 4×10^{-5} (see [ITU-T G.691]). Here, the contribution of other components to PMD is not taken into account. The PMD impairment can therefore be seen as a system power penalty combined with a probability that this penalty will be exceeded.

For systems operating at 40 Gbit/s, the mean differential group delay equal to one-tenth of a bit period, 0.1 T, corresponds to 2.5 ps. As a general assumption, part of this tolerated value could be allocated to the cable and part to optical repeaters, depending on the link characteristics (PMD quality of used fibres and subsystems). The total PMD of a link encompassing optical fibres and optical subsystems is the quadratic sum (square root of the sum of the squares) of the fibre and subsystems PMD:

$$PMD_{TOT} = \left[PMD_F^2 + \sum_i PMD_{Ci}^2 \right]^{1/2}$$

where:

PMD_{TOT}: TOTAL PMD link (ps)

PMD_F: PMD of concatenated optical fibre cables (ps)

PMD_{Ci}: PMD value of the ith subsystem (ps)

For example, considering a PMD value of the concatenated optical fibre cables of the link of 0.1 ps/sqrt(km), (that can be considered advisable at 40 Gbit/s), 2.0 ps is the PMD cable contribution on 400 km long links. According to the previous formula, this still leaves a 1.5 ps PMD margin for optical subsystems. Assuming the use of 4 optical subsystems with a PMD value of 0.6 ps, the total PMD will be below the 2.5 ps limit stated before for 40 Gbit/s systems.

$$PMD_{TOT} = \sqrt{\left(0.1 \cdot \sqrt{400}\right)^2 + 4 \cdot (0.6)^2} = 2.33 ps < 2.5 ps$$

The second or higher order PMD may give a non-negligible effect on the total PMD penalty. Further study is required.

Furthermore, in long-haul amplifier systems employing polarization scramblers (devices which deliberately modulate the polarization state of a signal laser so that it appears to be unpolarized), the polarization mode dispersion causes an increase in the degree of polarization of the signal. This degrades the system performance through interactions with polarization-dependent loss and polarization hole burning (see the following clauses). In an analogue system, the interaction of polarization mode dispersion with laser chirp leads to a second order distortion proportional to the modulation frequency. A further second order penalty, independent of the modulation frequency, is incurred when additional polarization-dependent loss is present in the system.

It has also been shown, and mentioned briefly above, that a second order effect can cause a coupling between polarization mode dispersion and chromatic dispersion. This is caused by the wavelength dependence of the differential group delay, and more importantly, the wavelength dependence of the principal states of polarization. This leads to a statistical contribution to the chromatic dispersion. This is an area which is not well understood and is under study. The use of chromatic dispersion compensating devices also has an unclear impact on the PMD penalty. The impact of higher launched channel power on non-linear PMD also requires further study.

For amplified 1550 nm systems, PMD is likely to be more of an issue for vintage fibres operating on 10 Gbit/s or higher TDM systems than for newer ITU-T G.652, ITU-T G.653 or ITU-T G.655 fibres.

II.4.1.3 Methods to minimize induced limitations

Given that the problem arises from birefringence, much of the effort in reducing the effects of the polarization mode dispersion have been concerned with minimizing the birefringence introduced by fibre or cable manufacture. Care is taken to optimize fibre production to ensure geometrical and optical circular symmetry, and/or to induce polarization mode coupling. Optical cables are manufactured using materials and processes which minimize the residual strain in the cable structure across the fibre. Elaborate cable structures can also be used which introduce a circular component to the induced birefringence. By careful design, such an effect can counteract linear birefringence to produce a cable with a resultant zero polarization mode dispersion. Typically, the mean polarization mode dispersion of fibres and cables lie in the range:

$$0 < \langle \Delta\tau \rangle < 0.5 \quad ps/\sqrt{km}$$

Furthermore, improved fibre designs show smaller PMD values, e.g., 0.1 ps/sqrt(km), as mentioned earlier.

Additionally, another method to reduce the effect of PMD is dynamic PMD compensation. A PMD compensator can accept at its input a signal affected by PMD and would provide at its output a signal with reduced distortion. It generally consists of a PMD equalizer, a PMD monitor and a feed-back controller. The equalizer and the monitor can be implemented in the optical or in the electrical domain. There is also the possibility for mixed or hybrid solutions. The feed-back controller takes decisions on the basis of the monitored information, according to a predefined algorithm and drives the equalizer according to the decisions. Dynamic PMD compensation is currently performed on a per-wavelength channel basis.

II.4.2 Polarization-dependent loss

II.4.2.1 Description of effects

Polarization-dependent loss (PDL) arises from the dichroism of the passive optical components such as isolators, couplers, etc., in the signal path. When the signal passes through the dichroic element, the component of its electric field parallel to the lossy axis is attenuated. As in the case of polarization mode dispersion, the axes which define the polarization-dependent loss are oriented randomly with respect to each other.

II.4.2.2 Induced transmission limitations

To examine the effect of polarization-dependent loss, let us examine a possible system configuration. In amplified systems, one mode of amplifier control is to operate at constant signal power. Both the signal and noise are affected by polarization-dependent losses. However, because the noise is unpolarized, the signal and noise are affected differently. The noise can be resolved into a component parallel to the signal and a component orthogonal to the signal. It can be shown that the combined effect of PDL and optical amplification is always to increase the component of the noise orthogonal to the signal. Furthermore, the magnitude of the orthogonal noise component changes with time as the signal polarization changes due to polarization mode dispersion. This leads to a reduction in the signal-to-noise ratio and the Q-value at the receiver. Furthermore, the fluctuations time lead to fading of the signal-to-noise and Q-value at the receiver, both of which lead to an impairment in system performance.

In analogue systems, the polarization-dependent loss can interact with laser chirp and polarization mode dispersion to reduce the system performance in terms of composite second order distortion. As expected, this impairment is time varying and leads to fluctuations in the system composite second order with time.

II.4.2.3 Methods to minimize induced limitations

As for the case of polarization mode dispersion, it is important that the polarization-dependent loss of the optical components be minimized. However, it should be noted that the impact of polarization-dependent loss on the system performance increases as the number of amplifiers increases. In long-haul submarine systems, for example, the requirements are extremely tight, because the number of amplifiers can be several hundred. In a short-haul terrestrial system, where only a few amplifiers are concatenated, the impact of polarization-dependent loss on system performance is still under study.

Polarization modulation, or scrambling, has been shown to improve system performance by reducing the fluctuations and improving the average Q. This technique is described more fully in clause II.4.3.3.

II.4.3 Polarization hole burning

II.4.3.1 Description of effects

Polarization hole burning (PHB) results from an anisotropic saturation created by a polarized saturating signal launched into the erbium fibre. This results in a selective depopulation of excited states aligned with the polarized field. Consequently, the available gain in the orthogonal direction is higher. Although the erbium ions are distributed randomly within the glass matrix, on a microscopic level the dipole associated with the erbium ion is anisotropic. The polarization hole burning effect is maximum where the linearly polarized saturating signal is aligned with the major axis of the dipole and is reduced where the polarization state of the saturating signal is elliptical or circular. Both the signal laser and the pump laser contribute to the total effect, the total differential gain being the vector sum of the two contributions. The degree of hole burning is proportional to the degree of the polarization of the saturating signal. For an unpolarized saturating signal, there is no hole burning. In principle, this is similar to the case of a circularly polarized signal.

II.4.3.2 Induced transmission limitations

The polarization hole burning impacts the system performance by causing the noise build-up along the amplifier chain to be greater than that which would be predicted from simple linear theory. That is, the signal-to-noise is reduced by polarization hole burning and, as for the cases of polarization mode dispersion and polarization-dependent loss, the measured Q fluctuates in time. As there are two contributions to polarization hole burning, there are two ways in which the system performance is affected. The total effect is proportional to the gain saturation, increasing with an increased degree of saturation.

First of all, let us consider the effect of the polarized pump laser. It can be considered for the purposes of this discussion that the pump polarization is fixed and invariant. The pump causes a differential gain in the direction orthogonal to its polarization axis. Noise aligned orthogonally to the pump experiences a higher gain than noise aligned with the pump. However, the polarization axes of the pump lasers in each amplifier along a chain are uncorrelated with each other. Therefore, the cumulative effect is similar to a random walk, and the pump-induced polarization hole burning can be considered as a contribution to the polarization-dependent loss of the amplifier. Thus, averaged over a number of amplifiers, the noise build-up should be linear as expected from a simple theory.

The signal laser induced polarization hole burning is slightly different. As the signal laser propagates along the system, the noise polarized along parallel to the signal laser will see the same gain as the signal. However, noise polarized orthogonal to the signal laser will always experience a higher gain because it will always be orthogonal to the signal polarization axis. Therefore, the total noise will increase in a non-linear way along the chain of amplifiers.

The total differential gain due to polarization hole burning varies as the polarization state of the signal changes (due to polarization mode dispersion) along the amplifier chain. It varies because the signal hole burning effect is correlated with the pump effect. As the relative polarization states of the signal and pump lasers change, the magnitude of the differential gain changes. Therefore, although the total noise increases non-linearly along the chain, it does so in such a way that the total noise fluctuates in time. Consequently, as explained above, the signal-to-noise is reduced and fluctuates in time. The system Q is, therefore, reduced and fluctuates in time.

II.4.3.3 Methods to reduce induced transmission limitations

There exist several ways to reduce the effect of polarization hole burning. Operating the amplifiers in the small signal regime is one potential solution, but this is not always possible and, in many cases, not desirable. In practice, the simplest solution is to use a depolarized signal. A depolarized signal can be created in many ways, but is most commonly generated by polarization scrambling. Using a phase modulator, the polarization state is varied between two orthogonal states in time. The signal then appears to be depolarized.

It has been shown that it is optimal to impose the polarization modulation at twice the bit rate. This is because polarization-dependent loss in the amplifier converts the polarization modulation to amplitude modulation. By polarization modulating at twice the bit rate, the amplitude fluctuations are at a rate higher than the detector bandwidth and so are not seen by the receiver. Using such techniques, the performance of very long-haul systems have been improved to the point where the predicted performance is met with a high degree of confidence. Polarization modulation is now a standard implementation in transoceanic amplified systems.

However, in long amplified systems, polarization mode dispersion causes a re-polarization of the signal, thus allowing polarization hole burning to again degrade the system performance. Such an effect illustrates the complex nature of the interaction of the polarization phenomena in amplified links.

II.5 Fibre dispersion properties

II.5.1 Chromatic dispersion

II.5.1.1 Description of effects

Chromatic dispersion is predominantly a transmission capacity limitation which results from the transmission source spectral characteristics and the chromatic dispersion of the optical fibre. Optical amplifiers inherently do not significantly change the chromatic dispersion, unless a form of dispersion compensation function is incorporated into an amplified subsystem.

Optical amplifiers produce light around the signal transmission wavelength, known as amplified spontaneous emission (ASE). Usually, the ASE component is not modulated and so it is not detected synchronously with the signal. In many optical amplifier implementations, the ASE is blocked by a filter within the amplifier, signal path or receiver. Unless the ASE is modulated along with the transmission signal, its presence results in optical noise as described more fully in clause II.6.1. The broader spectrum of the ASE does not alter the interaction of the signal spectral characteristics with the optical fibre chromatic dispersion.

Generally, optical amplifiers do not significantly alter the overall chromatic dispersion by their addition to a system. There is a small amount of chromatic dispersion added by the rare-Earth doped fibre used as the active gain medium in an OFA, but those fibre lengths are in the order of tens of metres to a few hundred metres. The chromatic dispersion of the rare-Earth doped fibres is not significantly different from that found in ITU-T G.652, ITU-T G.653 and ITU-T G.655 fibres. For systems which are tens to hundreds of kilometres in length, this dispersion contribution is considered negligible.

II.5.1.2 Induced transmission limitations

Generally, optical amplifiers do not alter transmission limitations due to chromatic dispersion. Certain non-linear effects may interact with the fibre chromatic dispersion due to the high output amplified power levels. These effects and methods to minimize induced limitations are described more fully in clause II.3.

The presence of an optical amplifier does not affect the chromatic dispersion in a system. However, OAs do enable consideration of long unregenerated systems, where system penalties due to chromatic dispersion may become significant. For example, a zero chirp, single frequency source has an optical power penalty at 1550 nm of up to approximately 1 dB when the following equation is met [b-Kaminow2]:

$$B^2 D L \leq 104'000$$

Where B is bit rate in Gbit/s, D is the chromatic dispersion coefficient in ps/nm-km, and L is the total route length in km.

A relevant detailed discussion can be found in clause 9.2.1.1. of [b-ITU-T G-Sup.39]. The above equation applies to linear systems, but may be incorrect when non-linearities are taken into consideration [b-Chbat]. This is an area requiring further study. Additionally, the interaction of non-linear effects with chromatic dispersion can produce interactions that cannot be undone by dispersion compensation. This has implications on the ideal amount of dispersion that a fibre should have, and on its uniformity with wavelength.

II.5.1.3 Minimization of induced limitations

The presence of an optical amplifier does not affect the chromatic dispersion in a system, and thus no specific methods to minimize these effects are required. In some optically amplified subsystems, a passive dispersion compensation function may be combined with the optical amplifier to result in an amplified subsystem which adds a finite amount of chromatic dispersion to the system, with a sign opposite that of the system fibre. This results in lower overall system chromatic dispersion. This function may be co-located with an OA in order to overcome the losses associated with the passive dispersion compensation function. The changes to the chromatic dispersion in the transmission system are due to the presence of the passive dispersion compensation function (more fully described in the ITU-T G.690-series Recommendations), and not the optical amplifier.

NOTE – Additional techniques to minimize the limitations induced by chromatic dispersion are described in the ITU-T G.690-series Recommendations.

II.6 Other OA-related properties

II.6.1 Noise accumulation

II.6.1.1 Description of effects

In transmission systems with cascaded OAs, the ASE noise generated at an OA repeats a cycle of attenuation and amplification in the same way as the signal light. Since the incoming ASE noise is amplified at each OA and added to the ASE noise generated at that OA, the total ASE noise power increases nearly proportionally with the number of OAs, and the signal power accordingly decreases. The noise power can exceed the signal power.

The ASE noise spectral profile also evolves along the system length. When ASE noise from the first OA is input to a second OA, the gain profile of the second OA changes due to the ASE noise power via the gain saturation effect. Similarly, the effective gain profile of the third OA is then modified by the output-power spectrum of the second OA. Such an effect is transmitted all the way down to the last OA. The ASE noise accumulates even if narrow-band filters are used at each OA because the noise exists over frequency ranges that include the signal frequency.

II.6.1.2 Induced transmission limitations

ASE noise accumulation affects the SNR of the system because the degradation in the received-signal SNR is due predominantly to ASE-related beat noise. Such beat noises increase linearly with the number of OAs. Thus, the error rate worsens with the increasing numbers of OAs. In addition, noise accumulates exponentially with the magnitude of the amplifier gain.

As a result of the gain spectrum of the OA, the ASE noise spectrum after many OAs tends to have a peak at a wavelength due to the self-filtering effect, which is described in clause II.6.2. In particular, if a closed all optical ring network architecture is considered, the ASE noise accumulates as if an infinite number of OAs were cascaded. Although the accumulation of ASE noise in filtered systems is considerably reduced by the filters, in-band ASE still increases with the number of cascaded OAs. Thus, the SNR degrades as the number of OAs increases.

II.6.1.3 Minimization of the effect of noise accumulation

The ASE noise accumulation can be reduced by decreasing the OA spacing (while maintaining the total gain equal to the total loss of the transmission path), since ASE noise accumulates exponentially with the magnitude of the amplifier gain. One of the following filtering techniques can further reduce the unwanted effect of ASE noise: use of ASE noise filters, or use of the self-filtering effect (self-filtering method).

The self-filtering method is applicable for systems with several tens of OAs or more. In this method, the signal wavelength is aligned with the self-filtering wavelength so that the ASE noise received at the detector is reduced, just as if a narrow-band filter had been used. This is most effective when used with shortened OA spans and low-gain OAs to reduce the initial ASE noise.

The self-filtering method is not applicable if an all-optical WDM closed ring network is considered. In fact, the resulting peak in the OAs overall gain spectrum may strongly affect the system performance. In this case, the accumulation of the ASE noise can be minimized with the ASE-filter method, which is obtained by filtering the WDM channels not dedicated to the network node before switching them out of the node.

For systems with fewer OAs, the self-filtering method is less effective than the ASE-filter method. The ASE-filter method allows flexibility in the choice of the signal wavelength and provides other advantages (see clause II.6.2). Care must be taken in the selection of the filter characteristics, since the cascaded-filter passband is narrower than the passband of a single filter (unless it has a rectangular spectral passband). Conventional filters with a full width at half maximum (FWHM) in the order of 3 nm could be used in long-distance single-channel systems.

II.6.2 Self-filtering effect

II.6.2.1 Description of effects

As a result of the ASE noise accumulation in non-filtered systems, the characteristic profile of the ASE spectrum (or the overall gain spectrum) tends to have a peak. The peak spectral line-width narrows with increasing numbers of OAs until it finally saturates after some number of OAs. This may result in only 2~3 nm wide spectral line-width after several tens of OAs. This effect is called self-filtering.

The self-filtering effect is determined by the spectral shape of the emission and absorption cross-sections and by the degree of inversion of OAs. The self-filtering wavelength may change with changes in the host glass composition, input optical power, or inter-amplifier loss and their dependence on wavelength, pump wavelength and the length of the doped fibre. The self-filtering effect can generally be considered desirable in single-channel systems (as noted in clause II.6.1.3), but undesirable in multi-channel systems.

II.6.2.2 Induced transmission limitations

For systems with a limited number of OAs, the spectral width of the self-filtering gain peak remains broad and does not reduce ASE noise accumulation, even with the signal wavelength adjusted to the peak wavelength. In systems with many OAs and a well-developed self-filtering gain peak, the SNR can be high but may degrade if the signal wavelength shifts from the self-filtering wavelength. This shift can occur after system reconfiguration or repair because of changes in inter-amplifier loss.

Multi-channel systems with cascaded OAs can suffer from power variation among channels that exponentially increase with the number of OAs (the number of OAs is the exponent). For example, the power spread for a five-channel system of ~3 dB after the first erbium-doped fibre amplifier (EDFA) increases to ~15 dB after the sixth EDFA. For multi-channel systems, changes in the total number of channels result in gain-spectral changes which perturb other channels. Saturation-induced spectrally-dependent gain also generates gain variation among the channels.

Therefore, the loss-budget margin must be carefully designed to accommodate such EDFA-gain spectral changes both in filtered and non-filtered systems. The use of ASE filters eliminates the problem, as described in clause II.6.2.3.

II.6.2.3 Methods to deal with self-filtering effects

This clause discusses the use of both OA self-filtering effects and ASE noise filters to improve system performance.

Using the self-filtering method to improve SNR is most effective when the optimum dispersion wavelength, self-filtering wavelength, and signal wavelength coincide. This method does not require the use of ASE noise filters, which can bring degradation associated with polarization-dependent losses in the filter. This is particularly true in transoceanic submarine systems. On the other hand, reliance on the self-filtering effect complicates system design, reconfiguration and repair because the signal wavelength must always meet the changeable self-filtering wavelength. The spectral characteristics of both OA gains and inter-amplifier losses should be as uniform as possible. Otherwise, the self-filtering gain peak may not become sufficiently narrow, thus degrading the SNR improvement and making it more difficult to prevent ASE noise-induced saturation in long-haul systems.

To avoid such disadvantages, the ASE-filter method can be used to reduce ASE accumulation with the filter passband adjusted to the signal frequency. Narrow-band filters with FWHM < 1 nm are commercially available. The ASE noise accumulation is then minimized and the system can be freed from restrictions such as complexities of system design, reconfiguration and repair, and the requirements of short OA span and uniform performance of each OA.

In multi-channel systems, the inter-channel power spread due to the self-filtering effect can be avoided by amplifying each channel in a physically separated OA. This method, however, demands a costly demultiplexer, separate OAs and a multiplexer. An alternative is to provide optical channel power equalization at each network node, even if this method demands additional control electronics and a more critical power budget through the network. An additional method is to use a less saturated or less strongly inverted OA, because this makes the attenuation less wavelength-dependent, and accordingly reduces inter-channel power spread. In a strongly inverted EDFA cascade, however, the ASE grows with the number of EDFAs at the first gain peak of ~1530 nm and needs to be eliminated with a short-wavelength-eliminating filter. In addition, the pre-emphasis method minimizes SNR differences for all channels by adjusting the transmitter optical powers for each channel based on the received signal information from the end terminal.

II.6.3 Optical surge generation

II.6.3.1 Description of effects

When optical signal input power rapidly increases in sufficiently pumped EDFAs, optical surge occurs because of the slow gain dynamics of EDFAs. The optical surge is likely to occur particularly from output-power-controlled EDFAs. This is because the pump power for such EDFAs increases with the decrease in the optical input power and optical surge tends to occur when the input power suddenly recovers. Figure II.6-1 illustrates optical surge generation.

When reconnecting a conventional connector, an optical-power rise time (10-90%) was ~ 0.3 ms, which is short enough to cause an optical surge. If the EDFA is already optically saturated, however, additional rapid increase in the optical input power may not cause significant optical surges.

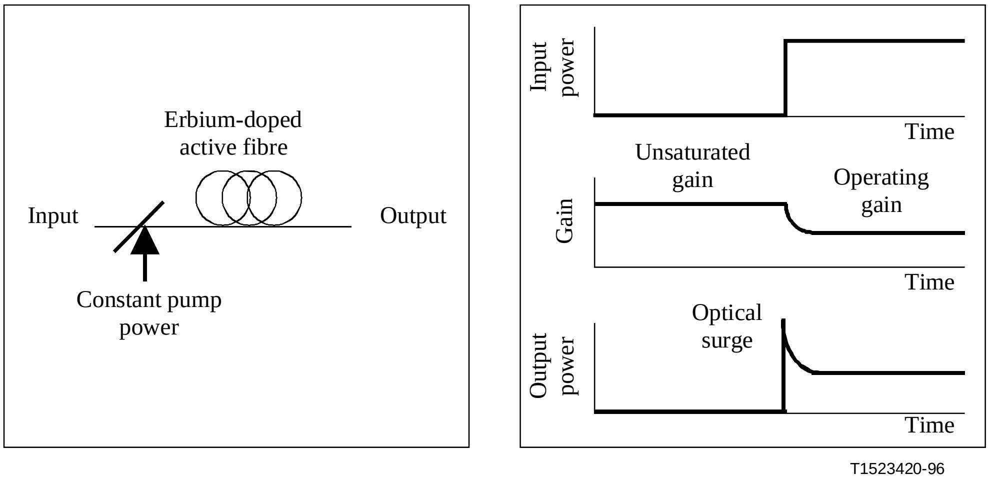

Figure II.6-1 – Example of optical surge generation

II.6.3.2 Induced transmission limitations

In EDFA cascades, under particular conditions, the optical surge peak power can range up to several watts, possibly damaging O/E converters and/or electrical pre-amps and optical components including optical-connector end faces. Optical surge is also harmful to human eyes. The threshold for damage for a contaminated optical-connector end face has been observed to be at optical power levels of about 20 dBm.

II.6.3.3 Minimization of the effect of surge generation

The following functions can be considered for optical surge prevention:

1) to reduce or shut down the pump power to EDFAs when the loss of input signal is detected;
2) to recover the pump power level to EDFAs when the recovery of the input signal is detected. In this respect, the reactivation of the pump laser power level up to its nominal value should happen gradually and a related minimum reactivation time should be defined.

Figure II.6-2 shows an example of configuration that achieves surge prevention, where a loss-of-signal detection unit controls the pump laser on/off status. In case of a loss of signal just for a time sufficiently shorter than the gain dynamics of the EDFA, e.g., < 1 ms, the pump laser power needs to be kept unchanged.

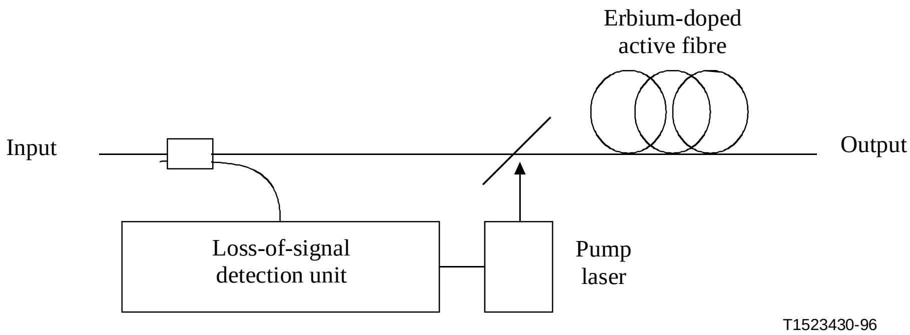

Figure II.6-2 – Example of a surge-prevention system

II.6.4 Saturation-induced non-linearity in SOAs

II.6.4.1 Description of effects

Semiconductor optical amplifiers (SOAs) suffer from a peculiar type of non-linear behaviour, related to the combined action of the fast gain-dynamics of the SOAs and the amplitude-phase coupling typical of semiconductor amplifying media.

This phenomenon, referred to throughout as saturation-induced non-linearity, may affect the performance of telecommunication systems using SOAs due to the fact that the carrier lifetime τ_c (0.2-0.5 ns) of SOA is comparable to the width of the optical pulses used for transmission. In fact, the SOA gain can saturate so fast that the rising edge and the trailing edge of the optical pulse experience different gain. The temporal evolution of saturation depends in general on the temporal profile of the pulse whereas the degree of gain compression depends on the pulse energy, compared to the saturation energy of the SOA ($E_{sat} = P_{sat}\,\tau_c$, where a typical value for the saturation power intrinsic of the SOA is 30 mW – not to be confused with the 3 dB saturation power which is lower, 10-15 mW). This behaviour is ruled by the following equation:

$$\frac{d\Gamma^{(t)}}{dt} = \frac{\Gamma_0 - \Gamma(t)}{\tau_c} - \frac{P_{in}(t)}{E_{sat}}\{\exp(\Gamma(t)) - 1\}$$

where $\Gamma(t)$ is the gain coefficient integrated over the SOA length, Γ_0 is the unsaturated integrated gain of the SOA and $P_{in}(t)$ is the temporal profile of the optical signal. The gain of the SOA is given by $G(t) = exp[\Gamma\,(t)]$.

Therefore, the optical signal exiting the amplifier is distorted by the differential gain, since $P_{out}(t) = G(t)\,P_{in}(t)$. This behaviour can cause pattern effects in the optical data sequence, since the gain experienced by a pulse does change depending on the presence of logical 'marks' or 'spaces' in the preceding bits. It is important to note that this phenomenon can occur in every type of laser amplifier (including EDFAs), but in SOA the gain saturation time scale is comparable to the temporal duration of the optical bit.

The peculiar aspect of SOAs is that the amplified pulse is also chirped and frequency shifted, due to the amplitude-phase coupling typical of semiconductor media. The reason for this is that the optical power of the pulse entering the SOA depletes the carrier population and thus modifies the index of refraction of the semiconductor cavity. As a consequence, the phase of the pulse changes dynamically as follows:

$$\phi_{out}(t) = \phi_{in}(t) - \frac{1}{2}\beta_c\Gamma(t)$$

β_c is the line enhancement factor, the parameter measuring the strength of the amplitude-phase coupling (typically 4-6 for SOAs). The instantaneous frequency shift is obtained by differentiating the equation above with respect to time and taking into account the equation for $\Gamma(t)$. This phenomenon is referred to as *saturation induced self-phase modulation* (SI-SPM), see [b-Agrawal]. SI-SPM can be detrimental when combined with fibre chromatic dispersion.

II.6.4.2 Induced transmission limitations

Conventional single-channel point-to-point optical systems using NRZ transmitters are predominantly impaired by pattern effects and, to a lesser extent, by SOA-induced pulse chirp [b-Settembre]. Pattern effects can also affect propagation of RZ pulses; in this case, if the pulse power is sufficiently high, the frequency-shift of the pulse may also play a relevant role. When the fibre dispersion at the wavelength of operation is different from zero, the frequency shift is converted into time jitter that can destroy the original bit sequence, thus setting limitations to the system reach. This effect may be particularly detrimental when non-linear transmission techniques are used, such as optical solitons, because for solitons the pulse energy should be maintained high and the dispersion should be different from zero (anomalous), see [b-Mecozzi].

II.6.4.3 Methods to minimize induced limitations

The saturation-induced non-linearity is inherent to the SOA. It can be avoided by operating the SOA in the linear regime or by implementing gain clamping techniques. In the first case, attention should be paid to ASE accumulation along the optical link; use of an optical filter after each amplifier can be useful to avoid static gain saturation effects due to ASE accumulation. On the other hand, gain clamping reduces the available gain. By keeping the average power low (1-5 mW) and dispersion close to zero, good performance of NRZ and RZ systems has been demonstrated experimentally up to 400 km [b-Reid]. The impairments due to SI-SPM in long-haul soliton systems can be alleviated by using suitable filtering techniques (sliding filters), see [b-Reid].

Appendix III

Pre-amplifier parameters

(This appendix does not form an integral part of this Recommendation.)

This appendix contains the definition of the relevant characteristic parameters of the pre-amplifier which allows, by standard formulae, to obtain the minimum input power which ensures a BER = 10^{-12} at the terminal receiver equipment (TRE).

On the basis of theoretical considerations and experimental tests related to optical amplifier noise, the relevant PA characteristic parameters which allow to obtain the minimum input power which ensures a BER = 10^{-12} at the TRE are:

– max small signal gain "GMax" ([ITU-T G.661]);
– small signal gain "G" ([ITU-T G.661]);
– signal-spontaneous noise figure "$NF_{s\text{-}sp}$" ([ITU-T G.661]);
– noise figure "NF" ([ITU-T G.661]);
– (equivalent) spontaneous-spontaneous beat noise optical bandwidth ($B_{sp\text{-}sp}$) ([ITU-T G.661]).

The optimum amplifier (without internal reflection noise) noise is dominated by two principal components in addition to the contribution of the shot noise of the signal and spontaneous emission noise. These two principal components are the signal-spontaneous beat noise and the spontaneous-spontaneous beat noise.

NOTE – The output noise terms can be subdivided into five categories:

a) shot noise from the amplified input signal;
b) shot noise from the amplified spontaneous emission (ASE);
c) signal-spontaneous beat noise from signal mixing with ASE;
d) spontaneous-spontaneous beat noise from ASE mixing with itself;
e) reflection noise.

Each of the noise contributions can be expressed in the form of a partial noise factor "F", where the total noise figure is the sum of all individual contributions. The total noise factor (in linear, not in logarithmic units) is:

$$F_{total} = F_{shot-sig} + F_{shot-ASE} + F_{sig-sp} + F_{sp-sp} + F_{refl}$$

This equation can be used both for evaluating the noise factor from optical measurements, as well as for estimating the influence of such parameters as gain, reflections, source line-width and baseband frequency. It represents a complete noise factor model of an OFA.

In these conditions it is possible to obtain, by standard formulae, the following expression for total noise factor:

$$F = F_{s-sp}\left(1 + \frac{h\nu n_{sp} B_{sp-sp}}{2P_{in}} \frac{G-1}{G}\right)$$

where:

$$F_{s-sp} = 2n_{sp}\left(\frac{G-1}{G}\right) \text{ and } n_{sp} = \frac{n_2}{n_2 - n_1}$$

$h\nu$ is the signal photon energy, P_{in} is the optical power at PA input, n_2 is the population density of the excited level, n_1 is the population density of the base level and G and $B_{sp\text{-}sp}$ have been defined before. It is clear that F reduces, by reducing the $B_{sp\text{-}sp}$ value, but, for compatibility with existing [ITU-T G.957], it has to be limited at values of the order of 1 nm (ª120 GHz). The SNR at the TRE is given by the following formula:

$$SNR = \frac{m^2 P_{in}}{h\nu \cdot B \cdot F + \frac{N_{R_x}}{P_{in} G^2}}$$

where m is the modulation depth $\left(1 - \frac{1}{ExtRatio}\right)$, B is the receiver electrical bandwidth (proportional to the bit rate) and N_{R_x} is the TRE equivalent noise. From the previous two formulae, it is possible to obtain the minimum input power of the PA for BER = 10^{-12} on the TRE. It is clear that the optimum PA must have a sufficiently high gain in order to make negligible the noise contribution of the TRE compared to the pre-amplifier one. The SNR value for BER better than 10^{-12} must be maintained in all the input power range. The PA will be characterized, from the noise point of view, by defining small signal gain (G), signal-spontaneous emission contribution to the noise factor (F_{s-sp}) and spontaneous-spontaneous beat noise equivalent bandwidth (B_{sp-sp}). It is important to verify the total noise figure of the PA in order to be sure that no contributions from internal reflection noise are affecting the PA.

Example

Calculation of the SNR ratio for a receiver equipped with a PA able to ensure a BER = 10^{-12} at 2.5 Gbit/s SDH-TRE

On the basis of the previous considerations and the previously defined parameters, the SNR at the output of the PA can be calculated from the following formula:

$$SNR_{(PA)} = \frac{m^2 P_{in}}{h\nu \cdot B \cdot F}$$

In the above formula, the shot noise contribution has not been considered because it is negligible compared to the beating noise components, having defined a small signal gain of 20 dB. This formula assumes the worst-case approximation where the noise on the zeros is considered equal to that on the ones (zeros do not present a signal-spontaneous beat noise) and where the output noise is considered Gaussian.

From the above-mentioned formula, it is easy to obtain the sensitivity of the PA.

The overall sensitivity of the composite receiver (PA + TRE) is obtained adding to the divisor of the previous formula the term $\frac{N_{R_x}}{P_{in} G^2}$, in which N_{R_x} is the TRE equivalent noise.

$$SNR_{(PA+TRE)} = \frac{m^2 P_{in}}{h\nu \cdot B \cdot F + \frac{N_{R_x}}{P_{in} G^2}}$$

It is, however, obvious that the term $\frac{N_{R_x}}{P_{in}G^2}$ is negligible for sufficiently high values of the gain *G*.

Taking into account the compatibility in accordance with [ITU-T G.957] for a 2.5 Gbit/s TRE with a minimum sensitivity of −26 dBm for BER = 10^{-12} and the characteristic parameters of the PA previously considered:

– Maximum small signal gain	24 dB
– Small signal gain (*G*)	≥ 20 dB
– Signal-spontaneous noise figure (NF_{s-sp})	≤ 5.5 dB
– Available signal wavelength band (B_{s-sp})	1 nm (0.8 − 1.2)
– Signal-to-noise ratio (SNR) for BER = 10^{-12} on the TRE	3 dB
– Extinction ratio of the optical source	8.2 dB
– TRE pass bandwidth (the electrical bandwidth of the receiver, proportional to the bit rate value) $B = f_{Nyquist}\,(1 + \ell)$; where $f_{Nyquist}$ = (bit rate)/2 = (2.5 Gbit/s)/2 and ℓ is the roll-off coefficient of the Nyquist's channel, variable between 0 and 1	$\begin{cases} \text{min. value} = \frac{2.5}{2}\ \text{GHz} \\ \text{average value} = \frac{2.5}{2}\cdot 1.5\ \text{GHz} \\ \text{maximum value} = 2.5\ \text{GHz} \end{cases}$

It is easy to establish that for values of the receiver signal of −16 dBm, the contribution of the TRE noise can be considered negligible. With the parameter values previously considered, a minimum input power of −36 dBm for BER = 10^{-12} at the TRE is obtained. This value can be considered inclusive of the margin due to the worst-case hypothesis introduced in the calculations. Due to the maximum gain value, the output signal from the PA will be −12 dBm, allowing the sensitivity of the PA to be considered as that of the composite receiver (PA + TRE). With respect to the PA the minimum gain operating conditions (small-signal gain, G = 20 dB), and the average optical power at the output of the PA will be −16 dBm allowing again the sensitivity of the PA to be considered as that of the composite receiver (PA + TRE).

By using the previous values and formulae, it is also possible to compute that a pre-amplifier output SNR ratio better than 13 dB is achievable with a pre-amplifier input power level down to −43 dBm, when a configuration without line amplifiers is used.

Appendix IV

OAM aspects of OAs

(This appendix does not form an integral part of this Recommendation.)

Possible generic OAM aspects for OA subsystems and devices are given below.

IV.1 OA subsystems

Because OATs and OARs from a maintenance perspective are not different from conventional transmitters and receivers, the associated operation, administration and maintenance (OAM) aspects are identical to those of transmitters and receivers specified in [ITU-T G.783].

IV.2 OA devices

The following OAM conditions can be presented as information to the involved management system:

– OA loss of signal (LOS), indicating possible loss of input signal (transmission defect);

– OA failure, indicating that an optical amplifier can no longer perform its basic function of optical amplification (equipment defect);

– OA in shut-down conditions (output status).

This distinction is made to provide the user with information on the equipment and/or cable plant. Furthermore, OAs can be provided with an "enable/disable output" control signal in order to be able to limit optical power levels possibly needed to satisfy optical safety requirements.

NOTE – The use of further sources of equipment failure like "OA degradation" or "loss of optical supervisory channel" (in case of the presence of line amplifiers) is for further study.

Bibliography

[b-ITU-T G.650.2] ITU-T G.650.2 (2007), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.

[b-ITU-T G-Sup.39] ITU-T G-series Recommendations – Supplement 39 (2006), *Optical system design and engineering considerations.*

[b-Agrawal] Agrawal, G.P., Olsson, N.A. (1989), *Self-phase modulation and spectral broadening of optical pulses in semiconductor laser amplifiers*, IEEE Journal of Quantum Electronics, Volume 25, pp. 2297-2306.

[b-Chbat] Chbat, M., Bigo, S. (1998), *Measurement of the impact of fiber non linearities on high data rate, dispersion-managed WDM systems*, Symposium on Optical Fiber Measurements, NIST (USA), September.

[b-Chraplyvy] Chraplyvy, A.R., Tkach, R.W. (1993), *What is the actual capacity of single-mode fibers in amplified lightwave systems?* IEEE Photonics Technology Letters, Volume 5, pp. 666-668.

[b-Faerbert] Faerbert, A., *et al.* (1999), *Optimised dispersion management scheme for long-haul optical communication*, Electronics Letters, Volume 35-21, pp. 1865-1866.

[b-Gordon] Gordon, J.-P., and Mollenauer, L.F. (1990), *Phase noise in photonic communications systems using linear amplifiers*, Optics Letters, Vol. 15, No. 23, pp. 1351-1353, Dec.

[b-GordonKogelnik] J.P. Gordon and H. Kogelnik (2000), *PMD fundamentals: polarization mode dispersion in optical fibers, Proceedings of the National Academy of Sciences of the United States of America*, Volume 97, Number 9, pp. 4541-4550.

[b-Kaminow] Kaminow, I.P., and Koch, T.L. (1997), *Optical Fiber Telecommunications*, Academic Press, Volume IIIA, p. 213.

[b-Kaminow2] Kaminow, I.P., and Koch, T.L., *ibid*. p. 167.

[b-Koch] Koch, T.L., Kaminow, I.P. (1997), *Optical Fiber Telecommunication*, Academic Press, Volume IIIA, Chapter 8.

[b-Mao] Mao, X.P., Tkach, R.W., Chraplyvy, A.R., Jopson, R.M., and Derosier, R.M. (1992), *Stimulated Brillouin Threshold dependence on fiber type and uniformity*, IEEE Photonics Technology Letters, Volume 4, pp. 66.

[b-Marcuse] Marcuse, D., Chraplyvy, A.R., and Tkach, R.W. (1994), *Dependence of cross-phase modulation on channel number in fiber WDM systems*, Journal of Lightwave Technology, Volume 12, Number 5, pp. 885-890, May.

[b-Manakov] S.V. Manakov (1974), *On the theory of two-dimensional stationary self-focusing of electromagnetic waves, Soviet Physics – JETP*, Volume 38, Number 2, pp. 248-253.

[b-Mecozzi] Mecozzi, A. (1995), *Soliton transmission control with semiconductor amplifiers*, Optics Letters, Volume 20, pp. 1616-1618.

[b-Reid] Reid, J.J.E., *et al.*, *An international field trial at 1.3 μm using an 800 km cascade of semiconductor optical amplifiers*, Proc. of ECOC'98 (1998), Volume 1, pp. 567-568, Madrid (Spain).

[b-Settembre] Settembre, M., *et al.* (1997), *Cascaded optical communication systems with in-line semiconductor optical amplifiers*, J. Wavelength Technol., Volume 15, pp. 962-967.

[b-Winter] M. Winter (2009), *A statistical treatment of Cross-Polarization Modulation in DWDM Systems*, *Journal of Lightwave Technology*, Volume 27, Number 17.

[b-Xie] C. Xie (2010), *Nonlinear polarization effects and mitigation in polarization-division-multiplexed coherent transmission systems*, *Chinese Optics Letters*, Volume 8, Number 9.

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