PD IEC/TR 62343-6-1:2011

BSI Standards Publication

Dynamic modules

Part 6-1: Dynamic channel equalizers

National foreword

This Published Document is the UK implementation of IEC/TR 62343-6-1:2011.

The UK participation in its preparation was entrusted by Technical Committee GEL/86, Fibre optics, to Subcommittee GEL/86/3, Fibre optic systems and active devices.

A list of organizations represented on this committee can be obtained on request to its secretary.

ISBN 978 0 580 68475 3

ICS 33.180.30

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 March 2011.

Amendments issued since publication

Amd. No.	Date	Text affected

IEC/TR 62343-6-1

Edition 1.0 2011-02

TECHNICAL REPORT

colour
inside

Dynamic modules –
Part 6-1: Dynamic channel equalizers

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE M

ICS 33.180

ISBN 978-2-88912-365-0

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

DYNAMIC MODULES –

Part 6-1: Dynamic channel equalizers

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.

8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 62343-6-1, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/969/DTR	86C/994/RVC

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

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

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

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

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

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

DYNAMIC MODULES –

Part 6-1: Dynamic channel equalizers

1 Scope

This part of IEC 62343 is a technical report and deals with dynamic channel equalizers (DCE). The report includes a description of the dynamic channel equalization and its benefits in a wavelength division multiplexed (WDM) transmission system and also covers different DCE component technologies that are being used.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
channel non-uniformity
difference (in dB) between the powers of the channel with the most power (in dBm) and the channel with the least power (in dBm). This applies to a multichannel signal across the operating wavelength range

2.2
in-band extinction ratio
within the operating wavelength range, the difference (in dB) between the minimum power of the non-extinguished channels (in dBm) and the maximum power of the extinguished channels (in dBm)

2.3
out-of-band attenuation
attenuation (in dB) of channels that fall outside of the operating wavelength range

2.4
operating wavelength range
specified range of wavelengths from λ_{imin} to λ_{imax} about a nominal operating wavelength λ_{I}, within which a dynamic optical module is designed to operate with a specified performance

2.5
channel frequency range
frequency range within which a device is expected to operate with a specified performance

NOTE For a particular nominal channel central frequency, f_{nomi}, this frequency range is from $f_{\text{imin}} = (f_{\text{nomi}} - \Delta f_{\text{max}})$ to $fi_{\text{max}} = (f_{\text{nomi}} + \Delta f_{\text{max}})$, where Δf_{max} is the maximum channel central frequency deviation.

2.6
ripple
peak to peak difference in insertion loss within a channel frequency (or wavelength) range

2.7
channel spacing
centre-to-centre difference in frequency (or wavelength) between adjacent channels in a device

2.8
channel response time
elapsed time it takes a device to transform a channel from a specified initial power level to a specified final power level desired state, when the resulting output channel non-uniformity tolerance is met, measured from the time the actuation energy is applied or removed

3 Background

The capacity of dense wavelength division multiplexed (DWDM) networks has grown exponentially since 2000 to meet the bandwidth demand created by the Internet. The highest demonstrated transmission capacity over a single fibre now exceeds 10 Tb/s. There is also a push to reduce the overall capital expenditure of building networks and lower the cost of transmitting data.

In order to reduce capital expenditure, the networks are evolving such that high-capacity transmission can be carried out over ultra-long distances of several thousand kilometres without optical-electronic-optical (OEO) regeneration. One of the challenges in ultra-long-haul transmission systems is to equalize the power of WDM channels in order to provide an acceptable optical signal-to-noise ratio (OSNR) and deliver a high quality of service for all optical channels. It is currently difficult to equalize the power of the various wavelengths present in a system because of wavelength dependence in the gain/loss of different elements forming the WDM transmission system.

The key elements that contribute to the wavelength dependent gain/loss include erbium-doped fibre amplifiers (EDFAs), transmission fibre, dispersion compensators and passive optical elements in a fibre optic transmission system. The problem of wavelength-dependent gain/loss becomes more critical in ultra-long-haul networks where signals will have to pass through up to 50 EDFAs and fibre spans without OEO regeneration. Next-generation networks will require some method of dynamic channel equalization to provide uniform OSNR for all the channels in the WDM system and thereby improve the system margin which can be used to lower the cost of ultra-long haul-systems.

Recently, point-to-point systems have evolved towards ring and mesh networks. Reconfigurable optical add-drop multiplexer (ROADM)-based architectures have emerged to provide flexible and reconfigurable networks.

An example of the ROADM node architecture is shown in Figure 1a. A multichannel DWDM fibre enters the node and the optical power is immediately split to provide paths for wavelengths that transit through the node and dropped wavelengths that get routed to a demultiplexer. The through traffic enters a 1 × 1 WSS (i.e. it has just one input and one output port so there is no switching) that under remote control either passes through, equalizes, or blocks (extinguishes) any or all wavelengths. New wavelengths are added by passive combination after the WSS. The WSS blocks any wavelengths identical to the added wavelengths so that there are no duplicate wavelengths carrying traffic in the same channel. Discrete variable optical attenuators (VOAs) are used to equalize the optical power of the added wavelengths and an optical power monitor (OPM) provides feedback for the optical power equalization controls of the WSS and VOAs. Figure 1b shows a variation on this architecture where the locally added wavelengths are still combined at a multiplexer but are now directed to the Add port of a 2 × 1 WSS. The WSS selects specific wavelengths from either the In or Add port and routes these to the Out port for transmission to the next network node. The WSS in this architecture also equalizes the optical power of the added wavelengths, eliminating the need for discrete VOAs.

Both architectures of Figures 1a and 1b are termed fixed add/drop because the dropped and added wavelengths are associated with specific or fixed ports on the multiplexers. While these wavelengths are still connected manually to specific service line cards (e.g. 10 Gb Ethernet or SAN protocol), one school of thought holds that this is of no major concern because it is usually done in conjunction with the manual provisioning of the service line cards themselves. The main advantage of these ROADM architectures is that the multiple wavelengths passing through the node are routed and equalized in an automated fashion. Figures 1c and 1d show two-degree ROADM configurations that eliminate the fixed physical associations for the dropped and added wavelengths with the demux and mux ports. The industry calls this feature colourless because any colour (frequency) or wavelength can be directed to any Drop port and from any Add port.

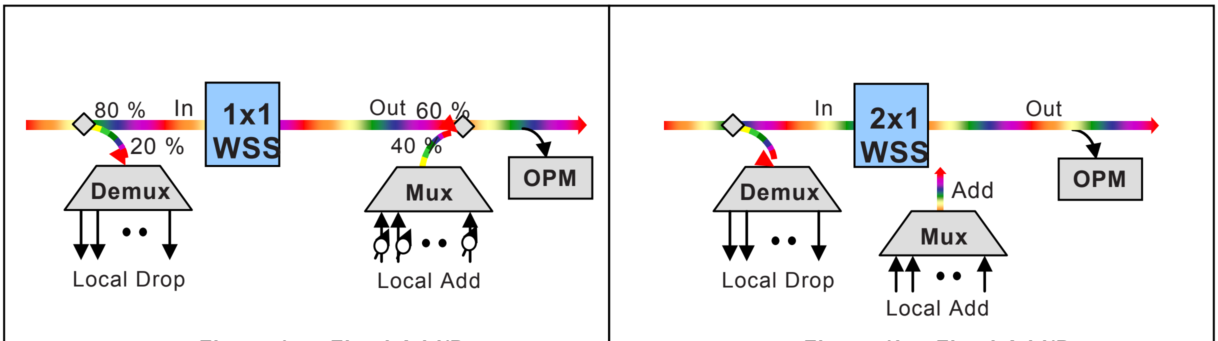
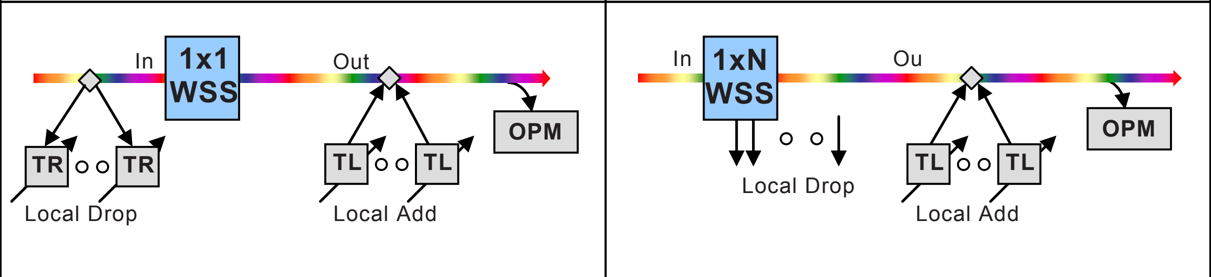


Figure 1a – Fixed Add/Drop IEC 297/11

Figure 1b – Fixed Add/Drop IEC 298/11



Figur 1c – Colourless Add/Drop IEC 299/11

Figure 1d – Colourless Add/Drop IEC 300/11

Figure 1 – ROADM architecture

This technical report explains how the wavelength dependent gain in EDFAs can impair the system performance of a long haul system and how the use of dynamic channel equalization devices such as dynamic gain equalization filters (GEFs) can improve the end of system OSNR to extend their reach to ultra long distances.

4 Gain equalized EDFAs

Manufacturers of wideband EDFAs insert static gain equalization filters (GEFs) between the stages of an EDFA to flatten the gain spectrum. The most commonly used GEFs, based on thin film technology, consist of translucent multi-layer structures of materials with different indices of refraction that create interference effects.

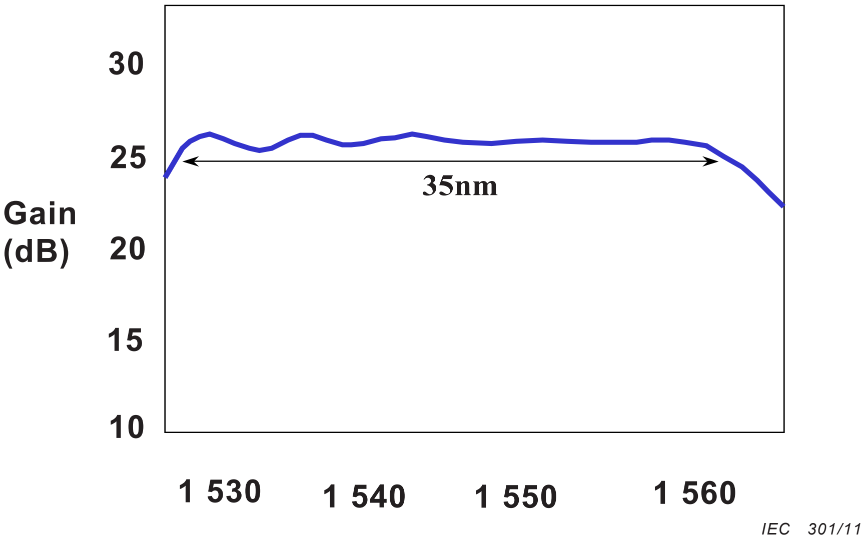


Figure 2 – Gain spectrum of an EDFA with GEF

The ideal GEF would have a transmission spectrum that resembles the inverse of the EDFAs gain spectrum. Despite the sophisticated thin film technology of the GEFs, they do not compensate for the spectral gain variation perfectly and therefore leave the power of the various channels somewhat unequal. In other words, the gain spectrum of the integrated EDFA and GEF subsystem still has peaks and valleys. The "ripple", i.e. the difference between the highest peak and the lowest valley, is still typically about 1 dB. Gain spectrum of a typical EDFA with GEF is shown in Figure 2. The amplifier has a 35 nm bandwidth covering 1 527 nm to 1 563 nm with gain ripple <1 dB.

A ripple of 1 dB may be tolerable at the end of a transmission system, but the ripple increases as the signals propagate through a cascade of EDFAs and GEFs because different GEFs manufactured in the same batch tend to generate peaks and valleys at the same wavelengths. The systematic error introduced at each transmission span compounds throughout the network. Another problem is that GEFs have to be custom designed for each EDFA design, which contributes greatly to development time and cost.

5 OSNR in WDM systems

In an optically amplified system, the signal reaching the receiver at the end of the link is optically degraded by accumulated amplified spontaneous emission (ASE) noise from the optical amplifiers in the chain. At the front end of receiver, ASE noise is converted to electrical noise, primarily through signal-ASE beating, leading to bit-error-rate (BER) flooring. OSNR is the most important design parameter for an optically amplified system. Other optical system design parameters include channel power divergence, which is generated primarily due to the spectral gain non-uniformity in EDFAs (described in Clause 6) and maximum channel power relative to the threshold levels of optical non linearities such as self-phase modulation, cross-phase modulation and four-photon mixing.

Although optical amplifiers are conventionally classified into power, in-line and pre-amplifiers, state-of-the-art WDM systems require all three types of amplifiers to have low noise figure, high output power and uniform gain spectrum. These three types of amplifiers will not be distinguished in the discussion presented in this clause. The nominal OSNR for a 1,55 μm WDM system with N optical transmission spans can be given by the following formula:

$$OSNR_{\mathrm{nom}} = 58 + P_{\mathrm{out}} - 10\log_{10}(N_{\mathrm{ch}}) - L_{\mathrm{sp}} - NF - 10\ \log_{10}(N) \qquad (1)$$

where

$OSNR$ is normalized to 0,1 nm bandwidth;

P_{out} is the optical amplifier output power in dBm;

N_{ch} is the number of WDM channels;

L_{sp} is the fibre span loss in dB;

NF is the amplifier noise figure in dB.

For simplicity, it has been assumed here that both optical gain and noise figure are uniform for all channels.

6 System impact of amplifier gain flatness

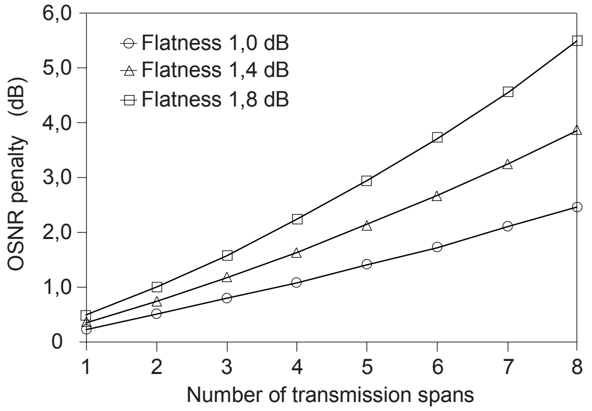
Amplifier gain flatness is a critical parameter for WDM system design. As the WDM channels traverse multiple EDFAs in an optical network, the spectral gain non-uniformity adds up to create a divergence in channel powers. The worst WDM channel, the channel that consistently experiences the lowest amplifier gain, will have an OSNR value lower than the nominal value given in Equation (1). The power deficit, which can be viewed as a form of penalty given rise by amplifier gain non-uniformity, is a complicated function of individual amplifier gain shape and correlation of the shapes of the amplifiers in the chain. The gain flatness is a parameter that can have significant impact on the end of system OSNR. The penalty is especially severe for a long amplifier chain, as in the case of long-haul and ultra-long-haul applications.

Amplifiers with flat gain wide bandwidth can enable high capacity systems having large number of channels with flexible routing capability. The gain flatness affects system performance in multiple ways, flat-gain amplifiers are essential to getting the system OSNR margin for routed channels and minimizing power divergence to allow practical implementation of networking on the optical layer. Amplifier gain flatness, as discussed earlier, is critical to maintaining system performance under varied channel loading conditions caused by either network reconfiguration or partial failure.

Figure 3 shows how the OSNR penalty increases as a non linear function of the number of transmission spans for the three cases: amplifier ripple (flatness) of 1,0 dB, 1,4 dB and 1,8 dB. After a number of amplifiers in the transmission line, the accumulated variation in signal strengths due to amplifier ripple and other wavelength dependent losses may exceed the system margin. This could degrade the OSNR and cause an increase in the BER for the lower power channels, particularly if the OSNR penalty exceeds 5 dB. From Figure 2, OSNR degradation of 5 dB is observed after 8 transmission spans for the case of amplifier gain spectrum flatness of 1,8 dB. The use of DCE to improve the amplifier gain flatness will reduce the channel power divergence and thereby reduce the OSNR penalty. This OSNR penalty limits the reach of the WDM line system and requires signal regenerators at intervals of approximately 500 km. These expensive devices convert the signals from the optical domain to the electrical domain, typically reshaping, retiming and re-amplifying the signal before triggering lasers to convert the signal back from the electrical domain to the optical domain. In ultra-long-haul networks, carriers would like to increase the spacing between regenerators to several thousand kilometres – in which case the signal would have to pass through up to 50 amplifiers without electrical regeneration. These networks require EDFAs with excellent gain uniformity, which could be achieved by a dynamic channel equalization filter.

Channel power divergence gives rise to other impairments besides OSNR degradation. In particular, the channels with increasing power will experience greater optical nonlinearities, such as self-phase modulation, cross-phase modulation and four-photon mixing. Four-photon-mixing products, like ASE, will degrade the performance of the weakest channels the most. Additionally, large power divergence increases crosstalk at the optical demultiplexer output.

The gain equalization filters are optimized to flatten the gain spectrum of a fully loaded EDFA. However, if a carrier wants to operate the system with fewer channels, for example, to reconfigure it dynamically, then the lower input power can decrease the EDFA's gain uniformity, thereby impairing the effectiveness of the GEF and increasing ripple in the network. Furthermore, spectral hole burning gives rise to channel loading dependent changes in the gain spectrum of the EDFA by creating a dip in the region of the active channels. Spectral hole burning can create a gain spectrum for which the GEF was not optimized, making gain flattening very difficult. For all these reasons, future ultra-long-haul, dynamically re-configurable networks will require EDFAs with dynamic channel equalization. The dynamic channel equalizer can be controlled in a feedback loop in conjunction with an optical channel monitor to provide uniform channel powers or OSNR.



OSNR Optical signal-to-noise ratio

Figure 3 – OSNR penalty caused by optical gain non-uniformity

7 Benefits of dynamic channel equalization

Dynamic channel equalization in optical networks offers the following benefits:

a) increases the average span length and/or the distance between electrical regenerators in ultra-long-haul networks. Similarly, DCEs could facilitate efficient distributed amplification to outweigh high passive losses of modern metropolitan and regional DWDM applications;

b) supports dynamic network reconfiguration by making it possible to load only a few channels without paying a penalty in optical signal-to-noise ratio;

c) makes it possible to use generic rather than custom-designed GEFs, thereby shortening the time to market and reducing development costs;

d) adjusts the linear gain tilt of EDFAs in response to changes in input power, thereby making it possible to eliminate the VOAs which perform this function today;

e) eliminates the need for clean-up filters in ultra-long-haul systems. In submarine DWDM systems, special clean-up filters remove residual ripple from the GEF-filtered EDFA gain spectrum. Ultra-long-haul terrestrial DWDM systems will also require these clean-up filters. Dynamic channel equalization would render them unnecessary in both submarine and terrestrial systems.

8 DCE technologies

DCEs are in the early stages of commercialization and vary widely, both in the optical design architecture and the underlying technology utilized. Ultimately, some approaches will win out over others. However, choosing a particular DCE involves trading off various optical performance metrics as well as operational metrics such as cost, size, power consumption and reliability so that a number of technologies will probably persist to meet the gamut of applications.

Functionally, equalizers can be grouped into two categories – channel equalizers and gain equalizers. Channel equalizers correct arbitrary differences in channel power resulting not only from gain ripple but also from effects such as polarization dependent loss (PDL). These equalizers work by demultiplexing all WDM channels, attenuating each individually and then remultiplexing. Although this approach would seem to offer ideal performance, it actually has a number of drawbacks. First, the equalizer must be designed to a specific channel allocation and spacing, thereby making replacement of the DCE necessary if the system is ever upgraded to a denser channel plan. Second, as equalizers are cascaded, the effective passband for each channel becomes narrower, an effect known as “filter narrowing.” Filter narrowing limits the number of channel equalizers that could practically be used in a single link and forces tighter control of transmitter wavelengths. Third, channel equalizers have a flat spectral response across a channel thus they cannot equalize gain slope within a channel. Residual intra-channel gain slope can produce pulse distortion and inter-symbol interference (ISI). Finally, channel equalizers so far have proven to be bulkier and more costly than gain equalizers. Thus, channel equalizers are likely to be used no more than is necessary to correct the effects of the PDL system.

The transfer function of gain equalizers is smooth and continuous without notches between channels. Thus, the same equalizer can be used for any channel allocation and bit rate and without filter narrowing. Moreover, since these equalizers are less expensive and more compact than channel equalizers, they are likely to be used more frequently. Current thinking allots a DCE to about every fifth amplifier in a link. If the cost of DCEs drops sufficiently, they may eventually be included in every optical amplifier. The insertion loss and optical signal impairments, such as PDL, will also need to be sufficiently low to warrant this level of ubiquity.

Dynamic channel equalizers can be classified as having either series or parallel architectures. The series approach cascades filtering elements in order to achieve the desired composite transfer function. Each filter may attenuate a different band. Alternatively, harmonic equalizers utilize periodic filters with a different free spectral range for each stage. The parallel DCEs disperse the light, often using a grating, onto an array of attenuators before recombining the light using either the same grating or a second grating.

The insertion loss, PDL, size, and cost all tend to scale more rapidly with resolution and bandwidth for the series architecture than the parallel architecture. The required resolution depends on the application. Relatively modest resolution is required to flatten the C-band gain shape of erbium. Thus, series DCE may be the most appropriate for the eventual scenario where the DCE replaces the GEF in every amplifier. However, in the short term, DCEs will only be used in every fifth to tenth amplifier, and they shall correct the accumulated ripple resulting from the imperfect match of the static GEFs in every EDFA to its erbium gain shape. This ripple requires a high resolution DCE to correct. Thus, the parallel architecture may be the best choice for immediate applications.

Whatever basic architecture is chosen, the specific design and resulting performance depend radically on the underlying technology. Many DCEs, both series and parallel, rely on interferometric effects to generate filter shapes. Mach-Zehnder interferometers can be implemented using silica waveguide technology. Other interferometers rely on polarization rotation in liquid crystals or other birefringent media.

Some DCEs use Bragg gratings, induced mechanically, acousto-optically, thermo-optically or electro-optically, to couple light in a particular wavelength band out of a waveguide. If the gratings are induced in optical fibre, then the DCE can have very low insertion loss. MEMs or liquid crystals may be used to create variable attenuators that operate in parallel on light diffracted in free space.

Each technology involves performance trades-offs. A particular design may have low insertion loss but high power consumption, for example. A specification wish list might include the entries in Table 1.

Table 1 – An example of DCE specifications

Test parameter	Unit
Insertion loss	6 dB
Resolution	2 nm
Bandwidth	35 nm
Dynamic range	15 dB
Ripple	± 0,25 dB
PDL	0,3 dB
PMD	0,3 ps
Dispersion slope	1 ps/nm^2
Power consumption	10 W
NOTE For more details see IEC 62343-3-1.	

“Resolution” loosely refers to the minimum achievable wavelength separation between attenuation peaks and valleys, and the “ripple” shall apply to specified spectral shapes.

The system designer cares not only about the static optical performance, but how the DCE will behave dynamically in a system. Much of this depends on the drive electronics and the control algorithm. The DCE transfer function should converge to the target spectrum smoothly and monotonically, using spectral readings from an optical channel monitor (OCM) as feedback. In the absence of feedback, the DCE should be stable over temperature and over time. Moreover, the electronic drive signals should not induce spurious amplitude modulation on the optical signal.

Finally, the DCE shall be highly reliable. This requirement applies not only to the optical performance over time and environmental conditions, but to the robustness of the software and electronic hardware. Moreover, if the DCE should fail, it should default to a relatively transparent state.

Since a DCE requires feedback from an OCM and is typically situated at the midstage of an optical amplifier, it is logical to consider integrating the DCE, OCM, and EDFA into the same subsystem. In fact, this approach yields significant performance advantages as well as reductions in overall footprint and cost. All three modules utilize a common control platform, thereby eliminating the need for the network management software to coordinate their control and communication. The impact of the DCE insertion loss on amplifier noise figure can be minimized if the amplifier is designed appropriately. Since the DCE can perform spectral tilting, the VOA typically included in EDFAs can be eliminated. If a VOA is maintained in order to preserve more of the DCE dynamic range for eliminating ripple in the input spectrum, its operation and that of the DCE can be orchestrated in an intelligent fashion if they are controlled by a common CPU. Finally, adjustments to the DCE will produce changes in the tilt of the EDFA. The optimal convergence of the control algorithm is assured if it is designed for the DCE and EDFA as a whole.

Bibliography

[1] IEC 61300 (all parts), *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures*

[2] IEC 61753-1, *Fibre optic interconnecting devices and passive components performance standard – General operating service environments and definitions – Part 1: General and guidance*

[3] IEC 62343-3-1, *Dynamic modules – Part 3-1: Performance specification templates – Dynamic channel equalizers*

[4] ITU-T Recommendation G.671, *Transmission characteristics of optical components and sub-systems*

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

[6] ITU-T Recommendation G.694.1, *Spectral grids for WDM applications: DWDM frequency grid*

[7] DESURVIRE, Emmanuel, *Erbium-Doped Fiber Amplifiers*, John Wiley & Sons (1994)

[8] BECKER, P.C. OLSSON, N.A. and SIMPSON, J.R. *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*, Academic Press (1999)

[9] DESURVIRE, Emmanuel, BAYART, Dominique DESTHIEUX, Bertrand and BIGO, Sebastien, *Erbium-Doped Fiber Amplifiers, Device and System Developments*, John Wiley & Sons (2002)

[10] FORGIERI, F., TKACH, R.W. and CHRAPLYVY, A.R., *Fiber Nonlinearities and their Impact on Transmission Systems*, Optical Fiber Communications Vol. IIIA, edited by Ivan Kaminow and Thomas Koch, Academic Press, pp.196-264 (1997)

[11] ZYSKIND, J.L., NAGEL, Jonathan A. and KIDORF, Howard D. *Erbium-Doped Fiber Amplifiers for Optical Communications*, Optical Fiber Telecommunications IIIB, edited by Ivan Kaminow and Thomas Koch, Academic Press, pp. 13-68 (1997)

[12] SUN, Y., SRIVASTAVA, A., ZHOU, J. and SULHOFF, J.W., *Optical Fiber Amplifiers for WDM Optical Networks*, Bell Labs. Tech. J., pp.187-205 (Jan-Mar 1999)

[13] SRIVASTAVA, Atul and SUN, Yan, *Advances in Erbium-Doped Fiber Amplifiers*, Chapter 4, Optical Fiber Telecommunications IVA, edited by Ivan Kaminow and Tingye Li, Academic Press, San Diego, pp. 174-212 (2002)

This page deliberately left blank

British Standards Institution (BSI)

BSI is the independent national body responsible for preparing British Standards and other standards-related publications, information and services. It presents the UK view on standards in Europe and at the international level.

It is incorporated by Royal Charter.

Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001

BSI offers Members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

Tel: +44 (0)20 8996 7669 Fax: +44 (0)20 8996 7001
Email: plus@bsigroup.com

Buying standards

You may buy PDF and hard copy versions of standards directly using a credit card from the BSI Shop on the website **www.bsigroup.com/shop.** In addition all orders for BSI, international and foreign standards publications can be addressed to BSI Customer Services.

Tel: +44 (0)20 8996 9001 Fax: +44 (0)20 8996 7001
Email: orders@bsigroup.com

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Knowledge Centre.

Tel: +44 (0)20 8996 7004 Fax: +44 (0)20 8996 7005
Email: knowledgecentre@bsigroup.com

Various BSI electronic information services are also available which give details on all its products and services.

Tel: +44 (0)20 8996 7111 Fax: +44 (0)20 8996 7048
Email: info@bsigroup.com

BSI Subscribing Members are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration.

Tel: +44 (0)20 8996 7002 Fax: +44 (0)20 8996 7001
Email: membership@bsigroup.com

Information regarding online access to British Standards via British Standards Online can be found at **www.bsigroup.com/BSOL**

Further information about BSI is available on the BSI website at **www.bsigroup.com/standards**

Copyright

Tel: +44 (0)20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK

Tel +44 (0)20 8996 9001
Fax +44 (0)20 8996 7001
www.bsigroup.com/standards

raising standards worldwide™