Available online at www.sciencedirect.com
SCIENCE DIRECT®

C. R. Physique 4 (2003) 115–126

COMPTES RENDUS PHYSIQUE

Optical telecommunications/Les télécommunications optiques

Submarine cable networks

Réseaux sous-marins

Olivier Gautheron [a,*], Masuo Suyama [b]

[a] *Alcatel, Submarine Networks Division, 91625 Nozay, France*
[b] *Fujitsu Limited, 4-1-1 Kamikodanaka, Nakahara-ku, Kawasaki 211-8588, Japan*

Received 1 October 2002

Presented by Guy Laval

Abstract

The wavelength division multiplexing technique enabled to increase drastically the transmission capacity per fiber over trans-Atlantic distances: from 1×5 Gbit/s in 1995, the figure increases up to 42×10 Gbit/s in 2001 and today, transmission systems providing up to 160×10 Gbit/s are under development. This evolution results mainly from the optical amplification bandwidth increase and the reduction of the spectral variation of the fiber chromatic dispersion. In un-repeatered submarine system, the distributed Raman amplification has been a key technology enabling a 160×10 Gbit/s transmission over a 380 km single fiber. ***To cite this article: O. Gautheron, M. Suyama, C. R. Physique 4 (2003).***

Résumé

Le multiplexage en longueur d'onde a permis d'accroitre sensiblement la capacité de transmission par fibre à-travers l'océan atlantique : de 1×5 Gbit/s en 1995, le chiffre atteint 42×10 Gbit/s en 2002 et aujourd'hui, des systèmes de transmission proposant jusqu'à 160×10 Gbit/s sont encours de développement. Cette évolution résulte principalement de l'augmentation de la bande d'amplification optique et de la réduction de la variation spectrale de la dispersion chromatique de la fibre. Pour les systèmes sans répéteur, l'amplification Raman distribuée a été un facteur clé pour transmettre 160×10 Gbit/s par fibre sur 380 km. ***Pour citer cet article : O. Gautheron, M. Suyama, C. R. Physique 4 (2003).***

Keywords: Wavelength-division multiplexing (WDM); High bit rate modulation; Erbium doped fiber amplifier; Distributed Raman amplification; Remote amplification; Gain equalization; Optical communication systems; Submarine cable systems

Mots-clés : Multiplexage en longueur d'onde (WDM) ; Dispersion chromatique ; Modulation haut débit ; Amplificateur optique à fibre dopé à l'erbium ; Amplification Raman distribuée ; Amplification déportée ; Égalisation de gain ; Systèmes de communications optiques ; Câbles sous-marins

1. Introduction

Over the past few years, the market for very high capacity submarine networks has been growing very fast due to the development of the *wavelength-division multiplexing* (WDM) enabling the transmission of several wavelength channels on a

* Corresponding author.
E-mail address: olivier.gautheron@alcatel.fr (O. Gautheron).

1631-0705/03/$ – see front matter © 2003 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS. Tous droits réservés.
doi:10.1016/S1631-0705(03)00006-9

single optical fibre. In 1995, the first submarine network using *erbium-doped fibre amplifiers* (EDFA) and linking the United States with Europe offered a total capacity of 10 Gbit/s on two fiber pairs, each with a 5 Gbit/s wavelength channel. Soon after, the WDM technique emerged with the ability to increase transmission capacity while offering wavelength-routing functions via *offshore branching units*: an example of this is the Sea-Me-WE 3 (South-East-Asia/Middle-East/Western-Europe) network designed for a 8×2.5 Gbit/s WDM technology per fiber.

However, the race for capacity took rapidly precedence over underwater wavelength-routing. Having installed the first WDM transoceanic system (Gemini), Alcatel has deployed a network capable of transmitting 42 and 80 wavelengths modulated at 10 Gbit/s per fiber over 6300 km across the Atlantic in 2001 and 2002, respectively. Recent laboratory experiments demonstrated that beginning 2004, system suppliers will be able to propose 6500 km-long systems providing a total capacity near 10 *Terabit-per-second* (Tbit/s), corresponding to 128×10 Gbit/s WDM transmission per fiber in a cable with eight fiber pairs). This represents a 1000-fold capacity increase in just eight years over a transoceanic distance. The main technologies that enabled this capacity increase are: broad-band optical amplification (Section 2), management of fiber chromatic dispersion and associated format modulation (Section 3). Apart from very long transmissions systems, there is also a significant market for short-haul submarine systems characterized by the absence of submerged repeaters, thus leading to drastic cost reduction. The specific technologies used in such *un-repeatered* submarine systems, such as *remote-EDFA* and *distributed Raman amplification* are presented in Section 4 of this paper.

2. Broad-band optical amplifiers

2.1. Extended C-band EDFAs

The intrinsic 3 dB optical bandwidth of an EDFA is around 40 nm (1530–1570 nm, as called *C-band*) and the spectral gain approaching peak gain is approximately Gaussian. It follows that the bandwidth of a link including, for example, 100 cascaded EDFAs is reduced to less than 4 nm. Therefore, it is essential to use optical gain-flattening filters (GFF) in each EDFA to obtain the bandwidth needed for transmitting large number of wavelengths. Different technologies are available to realize GFFs, one of them being *in-fiber Bragg gratings* (IFBG) [1,2] (see I. Riant, in this issue, on IFBGs).

Fig. 1 shows the spectral gain of an EDFA without and with a gain flattening filter. From Fig. 1, it is observed that with GFFs, the gain distortion of the EDFA is reduced to 0.2 dB over a 32 nm spectral range. However, this is not sufficient when 150 EDFAs are cascaded (as in transatlantic systems) since this would result in prohibitive link gain distortion of 30 dB (0.2 dB $\times$ 150). Indeed, the link gain distortion must be kept under 10 dB to achieve high transmission quality. For that purpose, an additional GFF (called *gain equalizer*) is periodically inserted along the link, typically every 10 EDFAs. Fig. 2 shows the optical spectrum at the output of a 150 EDFA chain without and with the gain equalizer, showing the reduction of gain distortion from 30 dB to 5 dB.

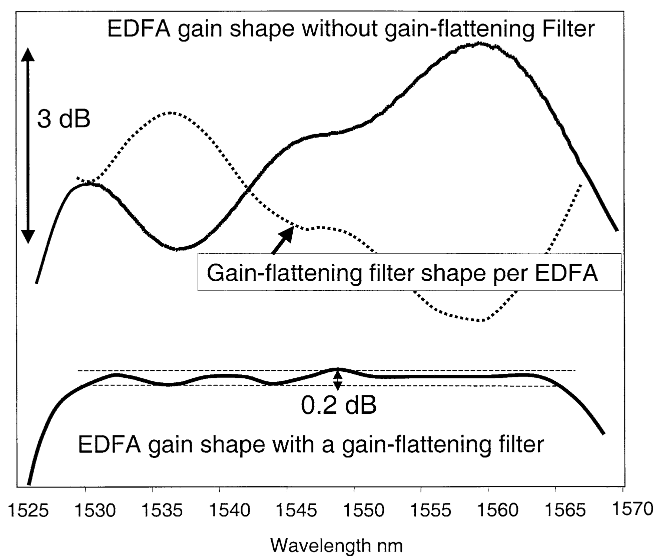

Fig. 1. EDFA gain shape without and with a gain flattening filter.

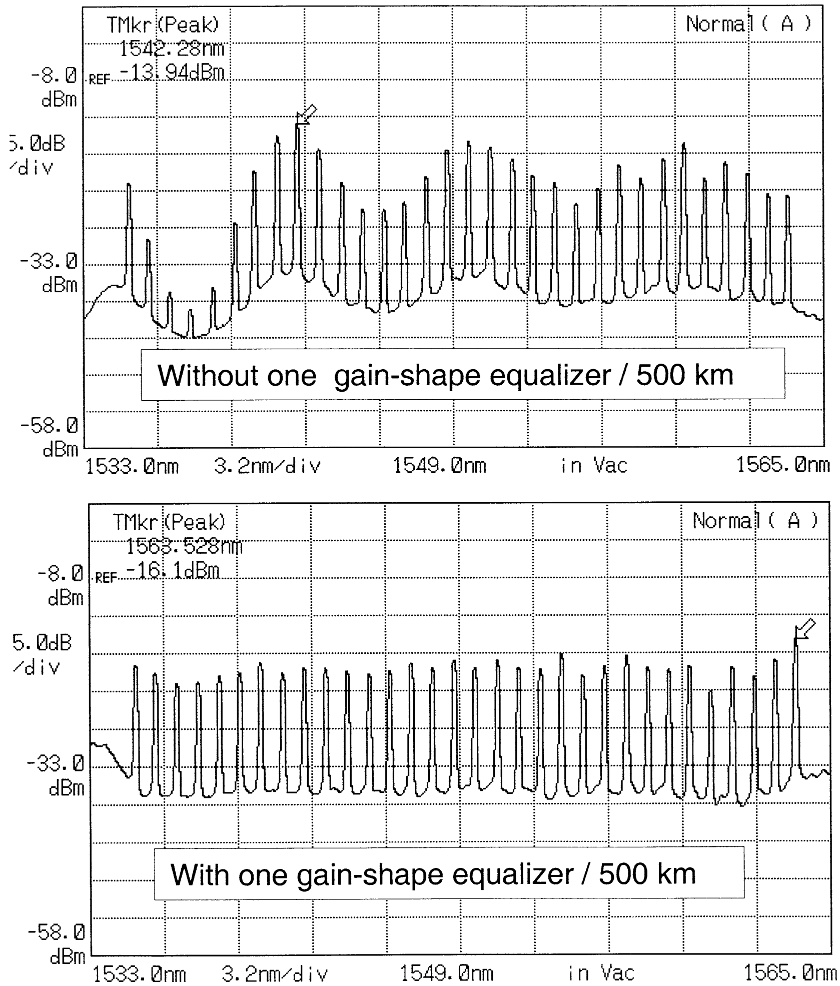

Fig. 2. Optical spectrum at the output of a 150 amplifier chain without and with a gain equalizer every 10 amplifiers.

In addition to two-stage gain equalization, submarine tsystems also include a third type of gain equalizer which compensates distortion occurring during the lifetime of the system (see next subsection).

2.2. Active Gain Equalization for EDFA-based systems

During the system lifetime, fiber ageing and cable repairs lead to an average span loss increase of 0.5 B, typically. In turn, this induces an EDFA mean gain increase of 0.5 dB which leads to a 0.35 dB EDFA gain tilt because the EDFA gain increases more rapidly at the shorter wavelengths. More accurately, when the EDFA mean gain is increased, the induced gain distortion features a spectral linear variation (in dB/nm) (Fig. 3). As a result, for a 150 EDFAs chain, the total gain tilt would be 52 dB (150×0.35 dB) over 32 nm at the system end-of-life. Therefore, a few optical filters featuring a linear (in dB/nm) spectral transmission response which can be changed during system life must be inserted in link. These filters, called *tunable gain equalizers* (TGEQ) are remotely controlled by terminal stations. These TGEQs, based on field-proven isolator technology, are already installed in submarine systems [3,2]. An experiment was carried out to confirm the effectiveness of TGEQs in a 32 wavelengths, 5000 km transmission [4]: one TGEQ is inserted in a recirculating loop and 3 dB losses in 3 spans were introduced every 630 km (in actual submarine links, cable repairs require to add an extra cable length equal to three times the water depth, thus leading to a 3 dB extra loss for repairs made for 5000 m water depths). The total extra loss in the experiment corresponded to an average value of 0.7 dB per span. Without TGEQ adjustment, the signal-to-noise-ratio (SNR) was degraded by 2.4 dB. Then, the TGEQ was tuned, the SNR degradation reduced to 0.7 dB. As Fig. 3 shows, there exists a gain deviation from the linearity at the wavelengths shorter than 1535 nm. Therefore, the compensation for higher-order gain profile in the EDFA is important for further increasing the EDFA bandwidth. For the compensation, a *higher-order variable gain equalizer* was proposed [5].

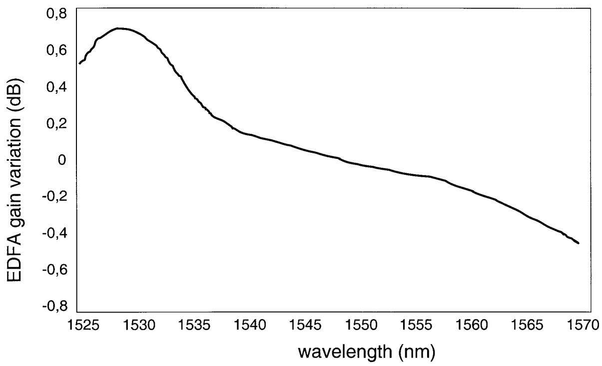

Fig. 3. EDFA gain tilt due to an average gain increase of 1 dB.

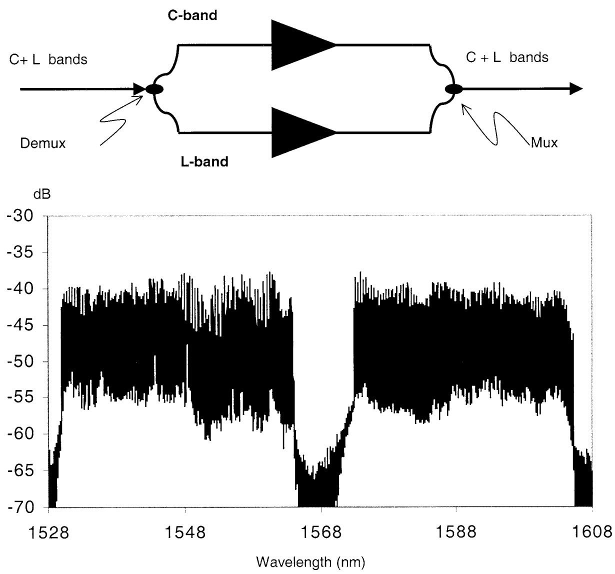

Fig. 4. Optical spectrum at the output of a 365 × 10 Gb/s transmission in C + L band over 6850 km.

2.3. C + L band EDFA

By modifying some EDFA parameters, the amplification band can be shifted towards long wavelengths (1575–1610 nm, called L-band). It is then possible to design a C + L *band* amplifier through the parallel coupling of a C-band EDFA with a L-band EDFA [6]. Hence, the C + L band amplifier is composed at the input of an optical demultiplexer which separates the C-band from the L-band and which feeds each spectral band into the appropriate EDFA (see Fig. 4). Then, after passing through the appropriate EDFA, the two multiplex are recombined by an optical multiplexer and launched into the line fiber. In order to avoid crosstalk between the C and L bands during demultiplexing/multiplexing, a mid-point *guard band* of a few nanometers is required. The absence of wavelengths between the C and L bands is clearly seen in Fig. 4. Using this technique, a 3.65 Tbit/s transmission over 6890 km could be demonstrated [7]. The total bandwidth was 65 nm, and the optical spectrum at the link output is shown in Fig. 4.

2.4. C + L band using distributed Raman amplifiers

The principle of *distributed Raman amplification* (DRA) is to launch into the line fiber an optical pump signal that generates, a at longer wavelength, distributed Raman gain along the fiber. Typically, if the wavelength of the pump is 1450 nm, the Raman gain is maximum at 1550 nm. Therefore, it is possible to broaden and flatten the Raman amplification gain by *wavelength-multiplexing* a selection of pump sources. A 240 ×10 Gbit/s transmission experiment over 7400 km was carried out with a full in-line Raman amplification using four contra-directionally pumping wavelengths [8]. In the experiment, the total optical

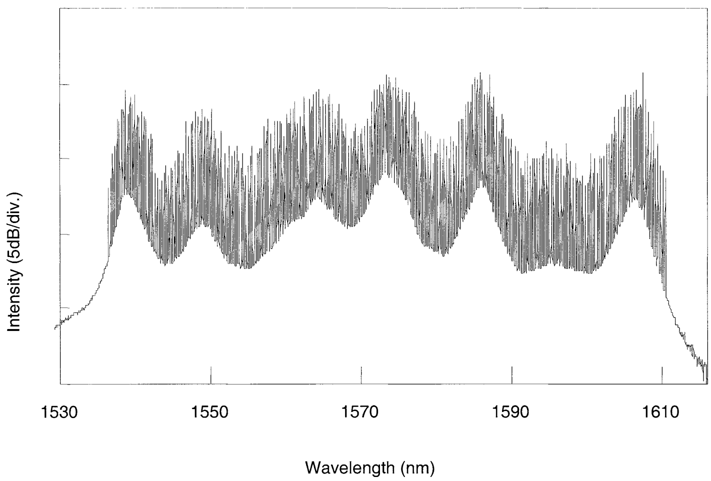

Fig. 5. Optical spectrum at the output of a 240 × 10 Gb/s transmission in C + L band using full Raman amplification over 7400 km.

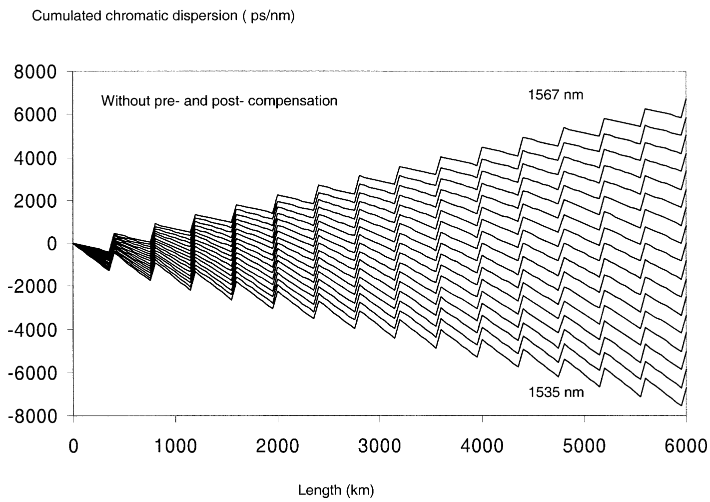

Fig. 6. Line cumulated CD as a function of distance with NZDSF map.

bandwidth ranged from 1537 nm to 1611 nm, thus providing a 74 nm seamless amplification band. Fig. 5 shows the optical spectrum of the 240 channels at 7400 km.

The advantage of DRA is the possibility to increase the span length compared to EDFA-based systems without significant degradation of the SNR. A 210 × 10 Gbit/s transmission experiment over 7221 km with a 80 km span length has been reported using an *hybrid amplification* technique. Each hybrid amplifier is includes a C + L band EDFA and a contra-directionally pumped DRA [4]. This result advantageously compares to the 45 km typical repeater spacing of EDFA-based systems. In another example of hybrid amplification, the EDFA provides C-band gain and the DRA the L-band gain, resulting in 80 nm seamless amplification bandwidth for 256 × 10 Gb/s transmission over 11 000 km [9].

3. Fiber chromatic-dispersion management and modulation formats

The previous section focused on broadband optical amplification for transmitting of large numbers of wavelength channels. This section describes the main parameters, i.e., *fiber chromatic dispersion* (CD) and *modulation format* which with fiber non-linearities impact upon pulse distortion and therefore transmission quality for the wavelength multiplex. Our description considers two main line-fiber types, referred to as NZDSF and DSCF, respectively.

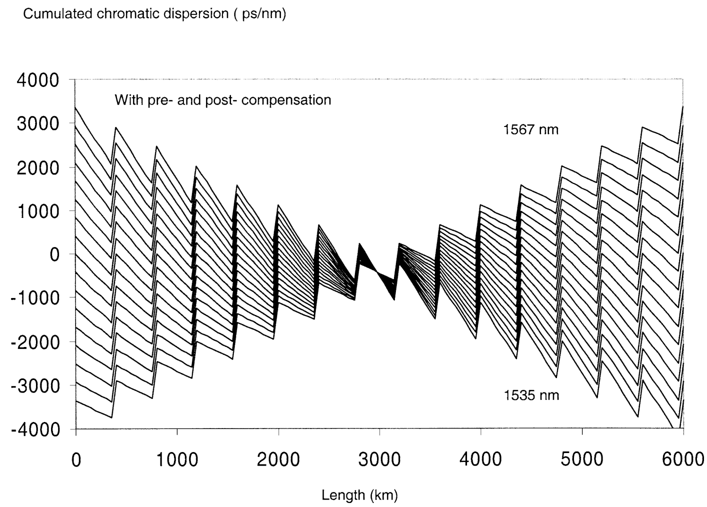

Fig. 7. Cumulated CD as a function of distance with NZDSF map with pre and post-CD compensation.

3.1. Systems based upon Non-Zero-Dispersion-Shifted Fibers (NZDSF)

The line fiber affects transmission quality through the combined effects of chromatic dispersion (CD) and Kerr-like non-linearities such as *four-wave-mixing* (FWM), *self-phase modulation* (SPM) and *cross-phase modulation* (XPM) [27]. To reduce power fluctuations generated by FWM, what is needed is to make the three mixing channels propagate without *phase matching*, as obtained when the fiber dispersion is non-zero. In the case of SPM or XPM, however, pulse distortion is avoided by reducing the cumulative dispersion along the link.

This explains why today's submarine links, as developed for 2.5 Gbit/s and 10 Gbit/s WDM transmission, use two types of fiber: the *non-zero-dispersion-shifted fiber* (NZDSF) has a chromatic dispersion of -2 ps/nm·km, and the *non-dispersion shifted fiber* (NDSF) has a dispersion of $+18$ ps/nm·km. Over ten fiber sections, typically nine sections consists in NZDSF and one section is NDSF, thus leading to a cumulated CD brought back to zero every 10 sections, although local CD is non-zero [28]. However, the drawback of such a 'fiber map' is that within a map period the CD linearly varies with wavelength, typically $+0.08$ ps/(nm^2·km), as referred to as *CD slope*. Due to this non-zero slope, the cumulated CD cannot be brought back to zero for all wavelengths at once, see Fig. 6.

The large amount of uncompensated CD for the outermost comb wavelengths induces transmission-quality degradation, as discussed in a later section. Therefore, to reduce cumulated CD one technique consists in inserting a piece of dispersive fiber in the transmitter and receiver terminals to provide pre-CD and post-CD compensation, respectively [10]. The amount of pre- and post-CD compensation is different for each channel, resulting in a X-shape trace of cumulated CD along the link, as illustrated in Fig. 7.

Although pre/post CD compensation enables one to divide by two the maximum cumulated CD, it is not sufficient to avoid significant quality degradation when considering for very-long distance, high-capacity systems. To overcome this problem, a new type of fiber called DSCF was developed [11], as seen in the next subsection.

3.2. Systems based upon Dispersion-Slope Compensating fibers (DSCF)

An alternative is to concatenate, in each repeater section, a length of NDSF with a length of *reverse-dispersion fiber* (RDF). Since the RDF-CD and CD slope are both opposite to that of the NDSF (Fig. 8), the cumulated CD along the link is almost the same for all wavelength channels. The RDF-CD is equal to -40 ps/nm km and the slope is equal to -0.16 ps/nm^2·km. Therefore, 2/3 of each fiber span consists in NDSF and 1/3 in RDF [6]. The combination of the NDSF and RDF is called *dispersion-slope compensating fiber* (DSCF). In practice, the DSCF-CD slope is not exactly zero and is typically equal to 0.005 ps/nm^2·km (Fig. 8). In order to optimize transmission quality, the CD must be carefully managed. In particular, the best transmission quality is achieved when the span-averaged CD is not exactly zero but typically equal to + or -2 ps/nm·km. Then, as with the NZDSF map, about every 10 spans, the cumulated CD is compensated by a span of NDSF to bring back the cumulated CD to zero.

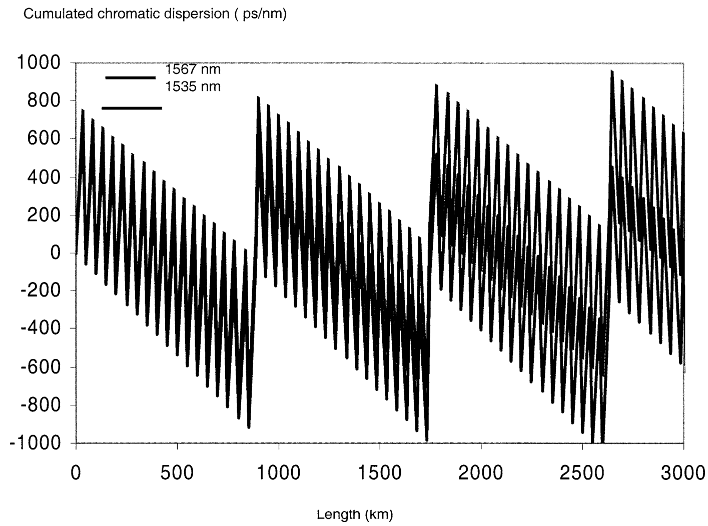

Fig. 8. Cumulated CD as a function of distance with DSCF map.

Some dispersion management techniques can reduce waveform distorsion induced not only by SPM but also XPM. In dense-WDM (DWDM) transmission systems, XPM is a dominant transmission impairment factor. To suppress XPM distortion, a dispersion map with a delay time of a half timeslot between adjacent signals per fiber span has been proposed [11].

3.3. Modulation format with NZDSF-based systems

In 2.5 Gbit/s WDM systems, *the non-return-to-zero* (NRZ) modulation format and NZDSF were used, leading to high transmission qualities for 8 and 16 × 2.5 Gb/s over 8000 km [28]. Upon increasing the channel bit-rate to 10 Gbit/s, the NRZ format was inadequate for this transmission quality. In a first generation of 10 Gbit/s WDM systems, a specific modulation format called *chirped return-to-zero* (CRZ) gave the best results for NZDSF-based links. The CRZ format is obtained by cascading *return-to-zero* (RZ) amplitude modulation stage with a bit-synchronous 10 GHz phase modulation (PM) [12]. The goal of the phase modulation is to counterbalance pulse distortion induced by the interplay between non-linearities and cumulated CD. Since all channels do not experience the same cumulated CD because of the non-zero NZDSF-CD slope, the amount of PM is not the same for all wavelengths and increases with the cumulated CD experienced by each channel. This bit-synchronous PM has however the drawback to broaden the spectral width, thus requiring larger wavelength spacings, leading to reduced capacities when increasing the transmission distance. In a 64 × 10 Gbit/s 8700 km transmission experiment [13] for instance, the wavelength spacing was 0.35 nm for the center wavelengths and 0.6 nm for the other wavelengths to enable the larger PM required for the comb's outermost wavelengths. For comparison, a shorter-distance, 105 ×10 Gbit/s 6700 km transmission experiment has been carried out also with CRZ but with an *equal* channel spacing of 0.32 nm [13]. Fig. 9 shows the optical spectrum of five adjacent wavelengths without and with 300° PM: the spectral broadening due to the phase modulation is clearly observed.

The above 64 × 10 Gbit/s and 105 × 10 Gbit/s transmission experiments over 8700 and 6700 km, are the highest capacity reported to date over NZDSF transpacific and transatlantic distances, respectively. Higher capacities or longer transmission distances would require the use of DSCF to reduce cumulated CD for the outermost multiple wavelengths. With such a fiber map, new modulation formats can be considered, as seen next.

3.4. Modulation formats with DSCF-based systems

With the introduction of DSCF maps, PM is no longer required since cumulated CD over the multiplex is drastically reduced. Hence, other formats, such as RZ, NRZ, *carrier-suppressed RZ* (CS-RZ) or *vestigial side-band* (VSB-RZ) have been considered to *narrow wavelength or channel spacings* and hence increase transmission capacity. The VSB-RZ format is achieved in practice by inserting an optical filter at the RZ modulator output in such a way that only half of the signal spectrum passes though the filter's passband. The CS-RZ format is obtained by applying PM at twice the rate frequency in such a way that adjacent bits feature a 180° phase shift. The optical spectra obtained with these four possible modulation formats are shown in Fig. 10.

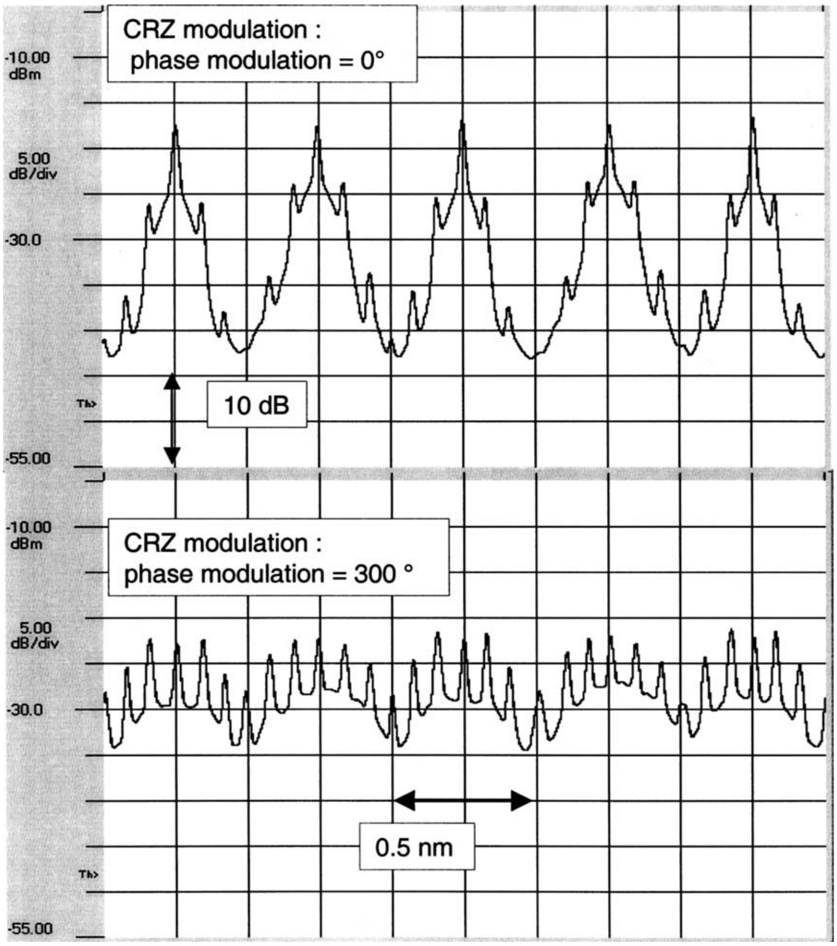

Fig. 9. Optical spectrum of five adjacent wavelengths without and with 300° phase modulation.

Using any of these formats with DSCF maps, very narrow wavelength spacings can be obtained, resulting in higher capacity transmission over longer distances. With RZ the minimum channel spacing is typically 0.27 nm for avoiding channel crosstalk: a 101 × 10 Gbit/s transmission experiment over 9000 km with a 0.28 nm channel spacing high transmission quality has been reported [18]. The CS-RZ format was tested in a 640 Gbit/s WDM, 6200 km transmission [29] where the channel spacing was 0.5 nm for a 20 Gbit/s bit-rate per wavelength.

Using VSB-RZ, a 200 × 10 Gbit/s transmission with a 0.16 nm wavelength spacing over 9000 km has been reported [15]. However, this laboratory experiment did not exhibit sufficient margin to demonstrate industrial system feasibility. Finally, the basic NRZ format enables very narrow channel spacings while still ensuring sufficient margins for industrial implementation, as demonstrated in a 180 × 10 Gbit/s transmission over 6500 km with 0.2 nm channel spacing [26].

3.5. Transmission experiments: a summary

Recently installed long-haul submarine systems use C-band EDFAs and NZDSF for maximum capacities of 80 ×10 Gbit/s per fiber over 6400 km (e.g., Apollo cable linking Europe to the US coast). In the next system generation, since longer distances and higher capacities are targeted, the NZDSF will be replaced by the DSCF but it is likely that C-band amplification will be sufficient for a maximum of 160 wavelengths-per-fiber modulated at 10 Gbit/s. In the longer term, C + L band transmission over DSCF could be implemented, enabling over 2 Tbit/s transmission capacity per fiber, either by using EDFAs or DRAs, or both. To increase capacity, another approach consists in increasing the bit-rate per wavelength. Recent laboratory experiments have been carried out over 6000 km to 9000 km at 40 Gbit/s channel rate [21,22], but the transmission quality as well as the total transmitted capacity is lower than that obtained in 10 Gbit/s WDM transmission. Fig. 11 shows the state-of-the-art for 10 Gbit/s WDM laboratory transmission experiments as based upon C-band over NZDSF and C-band over DSCF, both

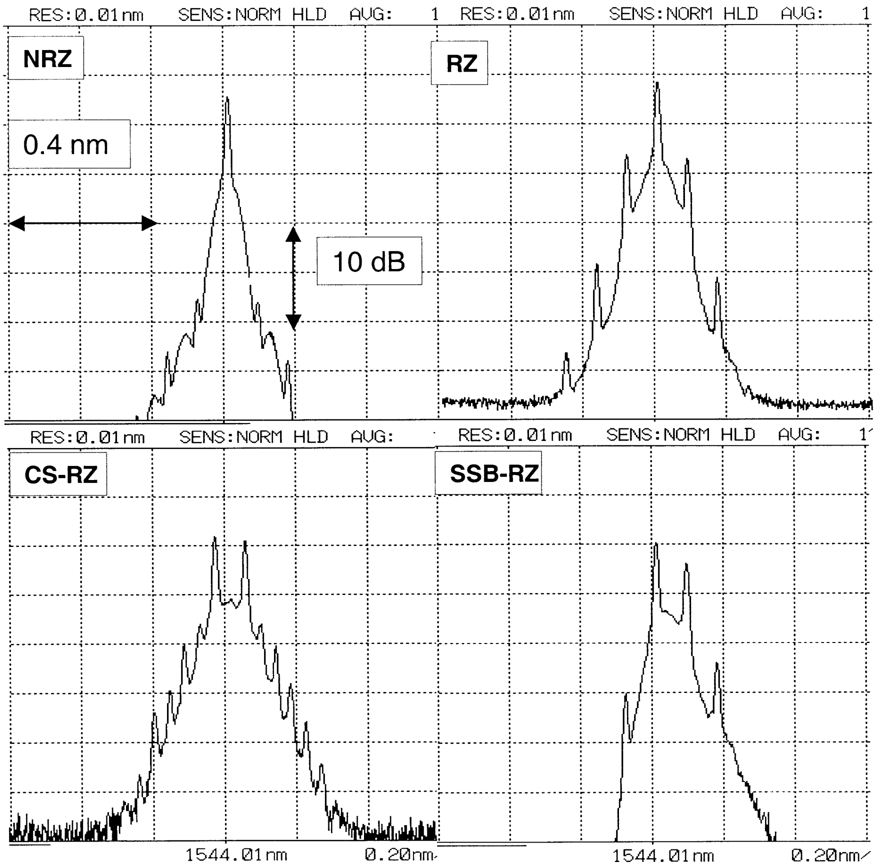

Fig. 10. Optical spectrum of one wavelength modulated at 10 Gbit/s with NRZ, RZ, CS-RZ or VSB-RZ (SSB-RZ).

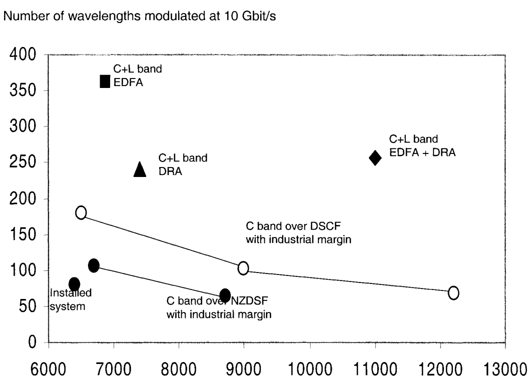

Fig. 11. Main10 Gbit/s WDM transmission experiments (full circles: C-band over NZDSF, open circles = C-band over DSCF, square = C + L band of EDFA, triangle = C + L band with DRA, diamond = C + L band of EDFA with DRA, DRA = distributed Raman amplication).

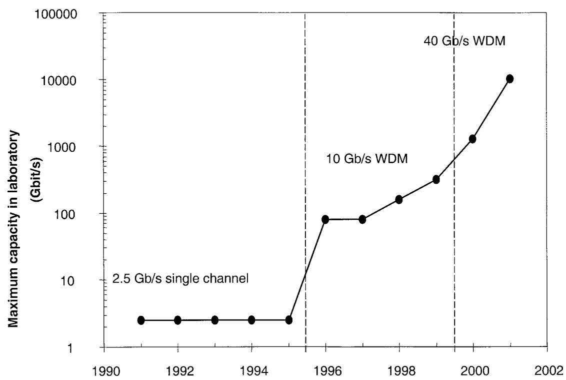

Fig. 12. Transmission capacity increase in laboratory experiments in the 1991–2001 decade.

having transmission quality compliant with industrialization. The other transmission-record data concern full EDFA C + L amplification [7], or full DRA amplification [8], or a mix of the two [9] but none of the results offer sufficient margins for industrial feasibility.

4. Unrepeatered systems

4.1. *Typical capacity*

By definition, *un-repeatered* or *repeaterless* submarine systems do not involve in-line repeaters, therefore they do not require electrical power feeding of the cable, nor electrically-active submerged components. Typical distances covered are of a few hundred kilometers and may significantly vary according to the capacity to be transmitted. In addition to applications such as linking islands to a mainland or a group of islands together, repeaterless systems are very popular for *coastal festoons*.

The phenomenal growth of transmission capacity obtained in laboratory demonstrations over the 1991–2001 decade is summarized in Fig. 12. Over this period, three bit-rate generations combined with the introduction of WDM allowed us to progress from 2.5 Gbit/s toward 10 Tbit/s per fiber. The network capacity is also directly proportional to the fiber count. In the early 1990s, unrepeatered cables were designed to support 12 fibers at maximum, typically, and the capacity was mainly achieved by the extensive use of high bit-rate terminal equipment. With increasing capacity demand, the need for more fibers gradually appeared. Thus, 48 fiber submarine cables were deployed all around the world by the mid 1990s. Recently, cables incorporating 192 fibers (96 pairs) have been developed and deployed [23].

4.2. *Key technologies*

For several years, teams investigated how to increase the repeaterless distances using the three key technologies:

4.2.1. *Remote Optically Pumped Amplifiers (ROPA)*

'Remote' pre-amplification consists in pumping from one end of the link a strand of erbium doped fiber spliced into the line fiber at a few tens of kilometers from the receiver side. Pumping can be done through the line fiber itself or through a separate/dedicated fiber within the same cable. Despite the presence of optical in-line amplifiers, systems using this scheme are considered 'unrepeatered', since there are no submerged electrical/active components. Early ROPA demonstration in the laboratory (1989) led to a record experiment at 1.8 Gbit/s [24] while the first submarine installation at 2.5 Gbit/s occurred in 1995 (RIOJA system).

4.2.2. *Distributed Raman pre-amplification (DRA)*

While the Raman effect has been studied since the early 1960s, the first laboratory experiments for long unrepeatered transmissions have been reported in 1996 [30,31]. The first industrial implementation of unrepeatered-DRA took place in the Hydro-Quebec cable system in early 2000. The Raman pre-amplification principle applies to broadband WDM systems, through the multiplexing of several pump sources at different wavelengths. In [32], a mean Raman gain of 25 dB has been demonstrated over a seamless total bandwidth of 104 nm (1492–1596 nm) with four pump sources, at 1390 nm, 1425 nm, 1455 nm and 1485 nm, respectively.

4.2.3. *Post-amplification*

This is the simplest application of optical amplifiers in repeaterless systems. Using 1.48 μm semiconductor diodes to pump the erbium doped fiber, it is possible to reach more than 20 dBm output power (100 mW). Taking advantage from 1.48 μm high-power laser sources, Raman post-amplifiers can reach output power of several Watts. The same power level can be obtained

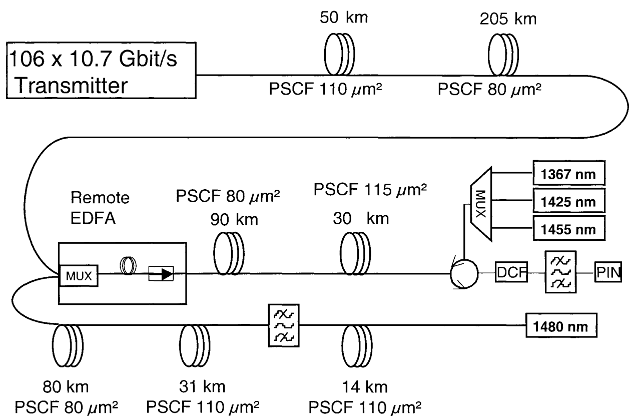

Fig. 13. Experimental set-up of a 160 × 10 Gb/s, 380 km unrepeatered transmission.

from erbium-doped fibers with *ytterbium* as co-dopant, as pumped with 0.975 µm semi-conductor diodes [33]. EDFAs can also deliver powers of several Watts when based on *double-clad* structure. In this approach, the pump power of *multi-mode* diodes is launched into a multi-mode waveguide around the erbium-doped core guide where single-mode signals are guided. This allows us to reach high power levels but also high reliability when redundant semiconductor pumps are included.

An unrepeatered 380 km distance transmission of 160 channels, each carrying 10 Gbit/s capacity, is described in [34]. This experiment used most advanced technologies: *forward error correction* (FEC) encoding/decoding (see O. Ait-Sab, H. Bissessur in this issue), use of high-power boosters, implementation of a remote amplifier, and *second-Stokes-order-pumped* Raman amplification. Fig. 13 shows the experimental set-up of this world-record experiment. A detailed description of unrepeatered systems is made in [25].

5. Conclusion

Increasing transmission capacity can be achieved by simultaneously increasing the bit-rate per wavelength and the number of wavelengths. Over the past few years, the bit-rate was increased from 2.5 Gbit/s to 10 Gbit/s and the optical amplifier bandwidth from a few nanometers to 30 nm. Further bit-rate increase, such as 40 Gbit/s, is under research but preliminary results do not reveal any benefit compared to 10 Gbit/s WDM transmission. Therefore, the current technologies developed for high-capacity long-haul systems aim mainly at increasing the number of transmitted wavelengths. For this purpose, the optical amplifiers bandwidth was increased by insertion of gain-flattening filters. With this technique, bandwidths between 30 nm and 40 nm could be obtained in the C-band, enabling the transmission of about 160 wavelengths. In a second step, C + L band transmission has been achieved either through the parallel combination of two EDFAs or through multi-wavelength-pumped distributed Raman amplifiers (DRA), or alternatively through the mix of EDFA and DRAs, leading to bandwidths between 60 nm and 80 nm.

Another possible approach is reducing the channel/wavelength spacing: appropriate modulation formats such as SS-RZ or simply NRZ were used to achieve a spacings smaller than 0.18 nm. However, these efficient formats can been employed only with the appropriate line-fiber type, NZDSF or DSCF. The first generation of WDM submarine systems, such as 2.5 Gbit/s WDM systems or trans-atlantic C-band 10 Gbit/s WDM systems used NZDSF. For higher capacities and longer distances, the DSCF is required to compensate dispersion over broad spectral ranges. This new fiber type will be used in the next generation of 10 Gbit/s WDM submarine systems, enabling dense WDM. Introduction of C + L band amplification, and 40 Gbit/s wavelength bit-rate belong is more remote.

Concerning unrepeatered systems, thanks to the multi-wavelength DRA combined with the remote-EDFA amplification, transmission lengths up to 380 km for a 160×10 Gb/s capacities were achieved. The related technologies are now implementedin real systems for shorter link distances and smaller capacities. Since up to 96 fiber pairs can be inserted in an unrepeatered cable, a 15 Tbit/s system spanning 300 km distances could be installed in the near future.

References

[1] O. Gautheron, P. Sansonetti, G. Bassier, I. Riant, in: Proc. European Conference on Optical Communications, ECOC '97, Vol. 3, Edinburgh, UK, 1997, pp. 131–134.
[2] T. Kogure, K. Motoshima, K. Kasahara, in: Proc. Conference SubOptic 2001, Kyoto, Japan, 2001, paper P4.3.4.
[3] T. Naito, T. Terahara, N. Fukushima, N. Shimojoh, T. Toshiki, M. Suyama, in: Proc. Topical Meeting on Optical Amplifiers and Applications, OAA '99, Optical Society of America, Washington, DC, 1999, pp. 36–39, paper WC5.
[4] I. Yokota, M. Suyama, T. Naito, Line design of more than 1 Tbit/s ($>100 \times 10$ Gbit/s) submarine D-WDM system, in: Proc. Conference SubOptic 2001, Kyoto, Japan, 2001, paper T. 3.3.1.
[5] N. Shimojoh, T. Naito, N. Fukushima, H. Nakamoto, T. Tanaka, M. Suyama, Compensation of L-band gain-wavelength characteristics using liner and second-order variable gain equalizer, in: Proc. Topical Meeting on Optical Amplifiers and Applications, OAA '00, Optical Society of America, Washington, DC, 2000, pp. 170–172, paper OWA3.
[6] T. Naito, N. Shimojoh, T. Tanaka, H. Nakamoto, M. Doi, T. Ueki, M. Suyama, 1 Tbit/s WDM transmission over 10000 km, in: Proc. European Conference on Optical Communications, ECOC '99, Nice, 1999, post-deadline paper PD2-1.
[7] G. Vareille, B. Julien, F. Pitel, J.F. Marcerou, in: Proc. European Conference on Optical Communications, ECOC '01, Amsterdam, Netherlands, 2001, post-deadline paper PD. M1.7.
[8] N. Shimojoh, T. Naito, T. Tanaka, H. Nakamoto, T. Ueki, A. Sugiyama, K. Torii, M. Suyama, in: Proc. European Conference on Optical Communications, ECOC '01, Amsterdam, Netherlands, 2001, post-deadline paper PD. M1.4.
[9] D.G. Foursa, C.R. Davidson, M. Nissov, M.A. Mills, L. Xu, J.X. Cai, A.N. Pilipetskii, Y. Cai, C. Breverman, R.R. Cordell, T.J. Carvelli, P.C. Corbett, H.D. Kidorf, N.S. Bergano, in: Proc. Conference on Optical Fiber Communications, OFC '02, Anaheim, CA, Optical Society of America, Washington, DC, 2002, post-deadline paper FC3-1.

[10] T. Tanaka, T. Shimojoh, T. Naito, H. Nakamoto, I. Yokota, T. Ueki, A. Suguyama, M. Suyama, 2.1 Tbit/s WDM transmission over 7221 km with 80 km repeater spacing, in: Proc. European Conference on Optical Communications, ECOC '2000, Munich, 2000, post-deadline paper PD1.8.
[11] T. Tanaka, T. Naito, N. Shimojoh, H. Nakamoto, T. Ueki, M. Suyama, in: Proc. OptoElectronics and Communications Conference, OECC '00, Makuhari, Japan, 2000, pp. 16–17, paper 11A1-5.
[12] T. Naito, T. Terahara, T. Chikama, M. Suyama, in: Proc. Conference on Optical Fiber Communications, OFC '96, San Jose, CA, Optical Society of America, Washington, DC, 1996, pp. 182–183, paper WM3.
[13] M. Murakami, T. Matsuda, T. Imai, in: Proc. European Conference on Optical Communications, ECOC '98, Madrid, Spain, 1998, pp. 79–81.
[14] T. Tanaka, T. Naito, N. Shimojoh, H. Nakamoto, T. Ueki, M. Suyama, in: Proc. Conference on Optical Fiber Communications, OFC '02, Anaheim, CA, Optical Society of America, Washington, DC, 2002, pp. 359–361, paper WX1.
[15] O. Gautheron, G. Bassier, V. Letellier, G. Grandpierre, P. Bollaert, Electron. Lett. 32 (11) (1996) 1019–1020.
[16] N.S. Bergano, C.R. Davidson, M.A. Mills, P.C. Corbett, S.G. Evangelides, B. Pedersen, R. Menges, J.L. Zyskind, J.W. Sulhoff, A.K. Srivastava, C. Wolf, J. Judkins, in: Proc. Conference on Optical Fiber Communications, OFC '97, Dallas, TX, Optical Society of America, Washington, DC, 1997, paper PD16.
[17] J.B. Leroy, P. Marmier, C. Le Flao, V. Letellier, A. Fagon, P. Plantady, C. De Barros, O. Sachot, Long haul high capacity transmissions over Non Zero Dispersion Shifted Fiber, in: Proc. OptoElectronics and Communications Conference, OECC '2001, 2001, paper TUM4.
[18] B. Bakshi, M.F. Arend, M. Vaa, E.A. Golovshenko, D. Duff, H. Li, S. Jiang, W.W. Patterson, R.L. Maybach, D. Kovsh, in: Proc. Conference on Optical Fiber Communications, OFC '2001, Anaheim, Optical Society of America, Washington, DC, 2001, post-deadline paper PD21.
[19] Y.S. Yamada, Nakagawa, T. Kawazawa, H. Taga, K. Goto, in: Proc. Conference SubOptic 2001, Kyoto, Japan, 2001, post-deadline paper PDP-1.
[20] G. Vareille, J.F. Marcerou, in: Proc. European Conference on Optical Communications, ECOC '2002, Vol. 4, 2002, paper 9.1.3.
[21] J.K. Cai, M. Nissov, C.R. Davidson, Y. Cai, N. Pilipetskii, H. Li, M.A. Mills, R.M. Mu, U. Feiste, L. Xu, D.G. Foursa, N.S. Bergano, in: Proc. Conference on Optical Communications, OFC '02, Anaheim, CA, Optical Society of America, Washington, DC, 2002, post-deadline paper FC4-1.
[22] H. Sugahara, K. Fukuchi, A. Tanaka, Y. Inada, T. Ono, in: Proc. Conference on Optical Communications, OFC '02, Anaheim, CA, Optical Society of America, Washington, DC, 2002, post-deadline paper FC6-1.
[23] I. Vintermyr, R. Vogt, J.S. Andreassen, in: Proc. International Wires & Cables Symposium, Atlantic City, IWSC '99, USA, 1999.
[24] K. Aida, S. Nishi, Y. Sato, K. Hagimoto, K. Nakagawa, in: Proc. European Conference on Optical Communications, ECOC '89, Göthenburg, Sweden, 1989, post-deadline paper PDA-7.
[25] J. Chesnoy (Ed.), Undersea Fiber Communication Systems, Academic Press, 2002.
[26] G. Vareille, in: Proc. European Conference on Optical Communications, ECOC '02, Vol. 4, Copenhagen, Denmark, 2002, paper 10.1.2.
[27] G.P. Agrawal, Nonlinear Fiber Optics, Academic Press, Boston, 1995.
[28] N.S. Bergano, C.R. Davidson, B.M. Nyman, S.G. Evangelides, J.M. Darcie, J.D. Evankow, P.C. Corbette, M.A. Mills, G.A. Ferguson, J.A. Nagel, J.L. Zyskind, J.W. Sulhoff, A.J. Lucero, A.A. Klein, in: Proc. Conference on Optical Fiber Communications, OFC '95, San Diego, CA, Optical Society of America, Washington, DC, 1995, post-deadline paper PD19.
[29] M. Nissov, J.X. Cai, M.I. Hayee, A. Pilipetskii, S.G. Evangelides Jr., B. Pedersen, N. Ramanujam, C.R. Davidson, C.J. Chen, M.A. Mills, R. Menges, P.C. Corbett, C. Rivers, N.S. Bergano, in: Proc. Conference on Optical Fiber Communications, OFC '2000, Baltimore, Optical Society of America, Washington, DC, 2000, paper PD 30.
[30] P.B. Hansen, L. Eskilden, S.G. Grubb, A.M. Vengsarkar, S.K. Korotky, T.A. Strasser, J.E.J. Alphonsus, J.J. Veselka, D.J. DiGiovanni, D.W. Peckham, D. Truxal, W.Y. Cheung, S.G. Kosinski, P.F. Wysocki, IEEE Photonics Technol. Lett. 8 (8) (1996).
[31] K.M. Guild, S.M. Webb, S.S. Sian, Electron. Lett. 32 (22) (1996).
[32] F. Boubal, E. Brandon, L. Buet, S. Chernikov, V. Havard, C. Heerdt, A. Hugbart, W. Idler, L. Labrunie, P. Le Roux, S.A.E. Lewis, A. Pham, L. Piriou, R. Uhel, J.-P. Blondel, in: Proc. European Conference on Optical Communications, ECOC '2001, Vol. 1, Amsterdam, Netherlands, 2001, p. 58, paper Mo F3.4.
[33] P.C. Becker, N.A. Olsson, J.R. Simpson, Erbium-Doped Fiber Amplifiers, Fundamentals and Technology, Academic Press, 1999.
[34] P. Le Roux, F. Boubal, E. Brandon, L. Buet, N. Darbois, V. Havard, L. Labrunie, L. Piriou, A. Tran, J.-P. Blondel, in: Proc. European Conference on Optical Communications, ECOC '01, Vol. 56, 2001, p. 10, post-deadline.