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Long-Haul Lightwave Transmission Systems Using Optical Amplifier Technique

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SUMMARY

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1. INTRODUCTION

Optical amplifier (OA) technology based on Er-doped fiber amplifiers (EDFA) is now widely used in the telecommunication society, and especially it has brought about a big impact to long-haul undersea cable systems. TPC-5 cable network (CN) and TAT-12 &13, both of which operate at 5 Gbps and will start their commercial service in 1995-1996.

Fig. 1 shows a route map of major optical fiber submarine cables in Asia-Pacific region. TPC-5CN and other cables indicated by bold curves are to use optical amplifier technology. Growth of transmission capacity of the trans-Pacific cables is also depicted in Fig. 2. The average growth rate of 22%/year reflects a worldwide spread of telephone and/or fax service. When we anticipate a global muti-media era in near future, we may have to count the number of channels by a capacity different from 64 kbps. In that scenario more and more bit rates are required and new sophisticated transmission schemes should be developed.

While the OA systems with non-return-to zero (NRZ) signal format at 5 Gbps, or even at 10 Gbps, have been under development, incessant efforts to seek for the next generation transmission technology for more bit rates have been made and long-haul multi-ten Gbps transmission experiments have already been demonstrated both with wavelength division multiplexed (WDM)-NRZ and RZ (Soliton) signal formats.

This paper describes OA technology at present (5 Gbps) and in future (multi-10 Gbps) with the emphasis on long-haul systems, specifically undersea systems and on engineering point of view, i.e., how to achieve the required performance and how to maintain the performance for the design life.

2. SINGLE CHANNEL NRZ SYSTEMS

A schematic illustration of an typical long-haul OA system is given in Fig. 3. An optical replica of a source electrical signal is made by an optical modulator and is launched into a transmission path consisting of dispersion shifted fibers (DSF) and in-line OAs. In this section single channel NRZ systems, which is matured and ready for implementation, are reviewed with the **Supplement [1]** being a reference. Some important aspects are as follows.

<How to Achieve the Required Performance>

- Design Parameters
- Signal-to-Noise Ratio (SNR)
- Statistical Nature of the Transmission Characteristics

<How to Maintain the Required Performance>

- Reliability
- Maintenance

A record transmission with this technique is shown in Fig. 4, in which 10 Gbps NRZ signal was successfully transmitted through 9000km with 276 in-line OAs. Fig. 5 gives an insight of the difficulty in the NRZ transmission at higher bit rate. Severe waveform distortion appears especially when the data "1" is consecutive, which seems to be one of the major limiting factors.

3. WDM SYSTEMS

3.1 IMDD-NRZ Systems

It is straight forward to adopt multi-channel operation using the well developed IMDD-NRZ transmission. Fig. 6 is a simple illustration of WDM transmission, where the four wavelengths are bundled together without any temporal synchronization between channels. At the receiver we usually use a narrow band optical filter to pick up a specific wavelength. Although the technique is based on the matured IMDD scheme, we are encountered to some difficulties to be solved before going into actual implementation.

- Limited gain bandwidth of EDF
- Non-linear interaction between channels
- Higher repeater output power requires higher pump power
- Robustness (or vulnerability) against design offset and degradation

In spite of such difficulties, it is also true that many successful transmission experiments have been reported. Fig. 7 and 8 show an example. An actual undersea cable system with the length of 1000 km as shown in Fig. 7 was used. 5 wavelengths as indicated in Fig. 8, each of which was modulated at 10 Gbps, were multiplexed, transmitted and de-multiplexed. We could confirm BER as low as 10^{-11} for all 5 WDM signals.

In this section we also refer to the attached papers **Supplement [2] & Supplement [3].**

3.2 Coherent Detection Scheme

The advantage of coherent transmission lies in that it occupies much narrower bandwidth compared to IMDD scheme, which usually requires 1 - 1.5 nm per channel. Therefore the difficulty "Limited gain bandwidth of EDF" is considered to be alleviated. However, the coherent transmission suffers from phase noise which is converted from ASE-induced amplitude fluctuation.

In this section we refer to the attached papers **Supplement [4]**.

4. SOLITON SYSTEMS

Unique nature of soliton transmission enables us to balance the non-linear characteristic and dispersive characteristic of the dispersion-shifted fiber. We expect that the waveform distortion observed in NRZ transmission as seen in Fig. 5 could be avoided. Moreover the utilization of a narrow pulse makes it possible to adopt optical time division multiplexing (OTDM). Fig. 9 illustrates the OTDM scheme. Published data on the transmission capacity vs. transmission distance is summarized in Fig. 10. Timing jitters and soliton interaction should be solved by optical filter (fixed or sliding), by in-line modulation or by any other unique technique.

In this section we refer to the attached paper **Supplement [5]** and the effect of alternating-amplitude and filter bandwidth on transmission characteristics is discussed.

5. WHERE TO BE APPLIED

A scope of the transmission distance and the bit rate for the various techniques may be in variety. Fig. 11 is an expected perspective of various transmission techniques for higher bit rates beyond 10 Gbps with respect to the transmission distance.

<Transoceanic or Long Distance>

As long as a transoceanic distance is concerned, it may be difficult to use the NRZ transmission and extensive feasibility study on soliton systems is expected. It is considered that certain soliton control techniques are definitely required beyond 20-30 Gbps. All optical reshaping and/or retiming function is attractive for that purpose.

<Middle to Short Distance>

WDM systems based on IMDD-NRZ transmission could play important role up to several thousand kilometers, which are the distance in most of the systems both of terrestrial and undersea applications. As is expected from the above-mentioned experiment, it may not be so difficult to carry 100 Gbps in an 1000 km undersea cable if the number of fiber pairs is increased. Future interests are how the WDM techniques are improved for longer distances beyond several thousand kilometers and for higher bit rates beyond 100 Gbps. Combination of

WDM and OTDM techniques with an RZ signal format may help expand the scope of application.

6. CONCLUSION

Present and future of long-haul optical amplifier transmission systems have been briefly looked over. EDF-OA technology based on single channel NRZ-IMDD at the bit rate of 5 -10 Gbps is almost ready for practical use in long haul systems. The WDM transmission will be in practical use soon for new projects and for upgrade of the existing systems. We expect that soliton transmission may also find an application in future transoceanic undersea cable systems.

SUPPLEMENTS

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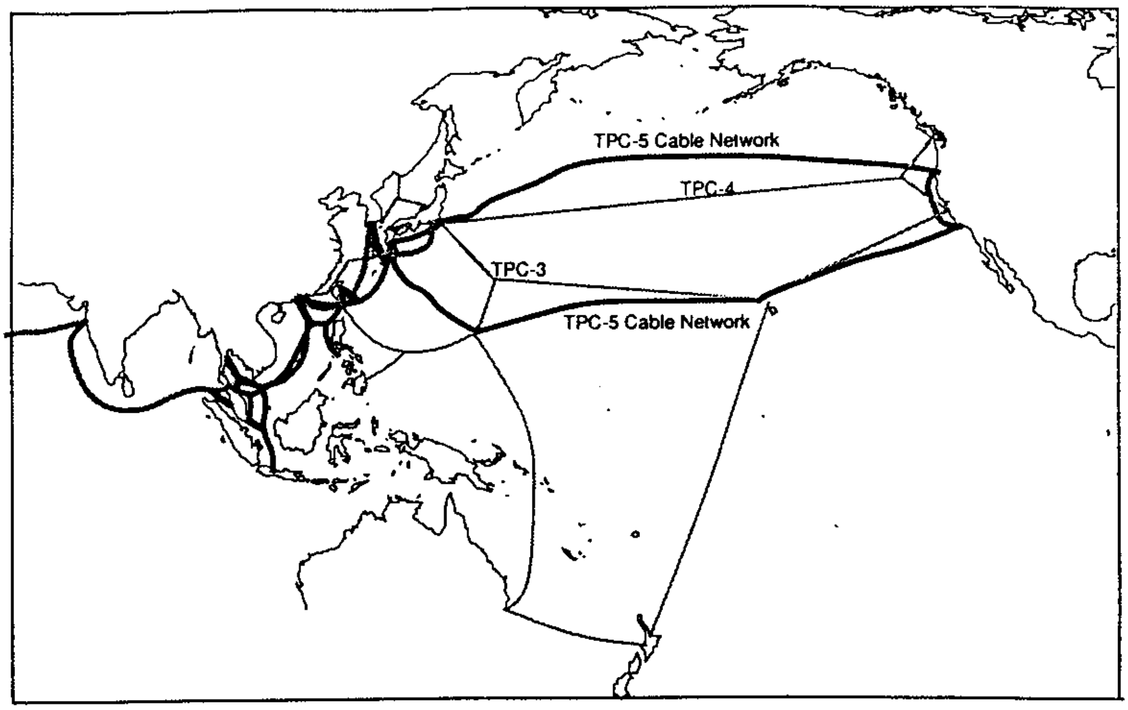

Fig. 1 Schematic route map of optical undersea cables in Asia-Pacific region. Bold lines indicate 5 Gbps OA systems under construction and under planning.

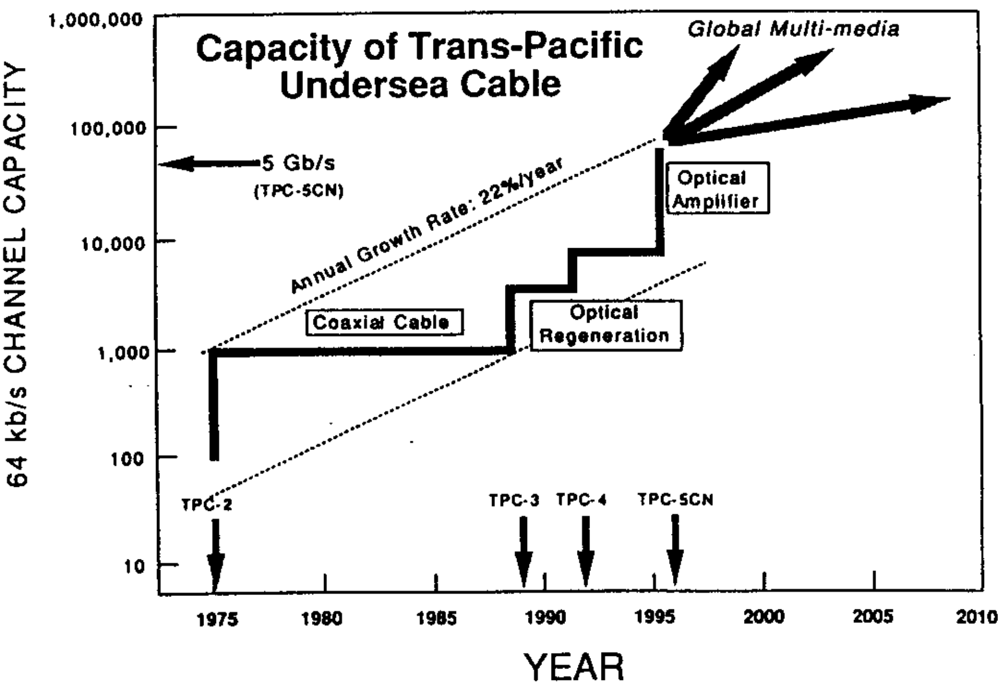

Fig. 2 Growth of transmission capacity of trans-Pacific cables toward global multi-media services.

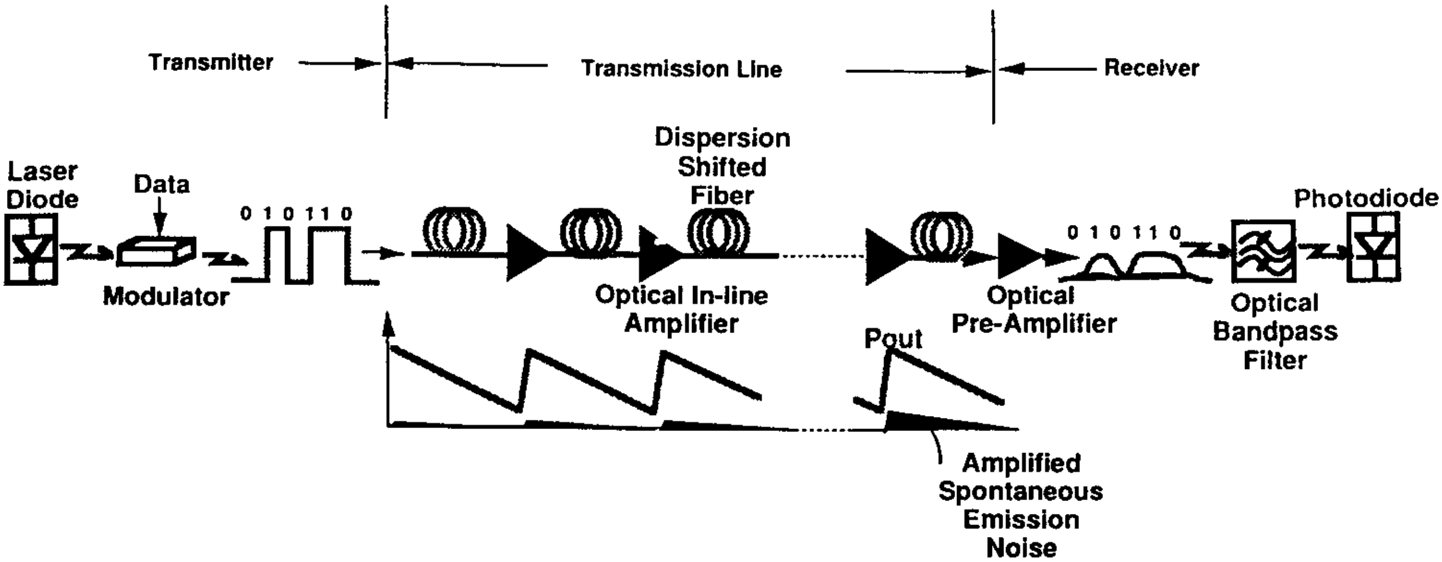

Fig. 3 Model of OA systems with dispersion shifted fibers and OA repeaters.

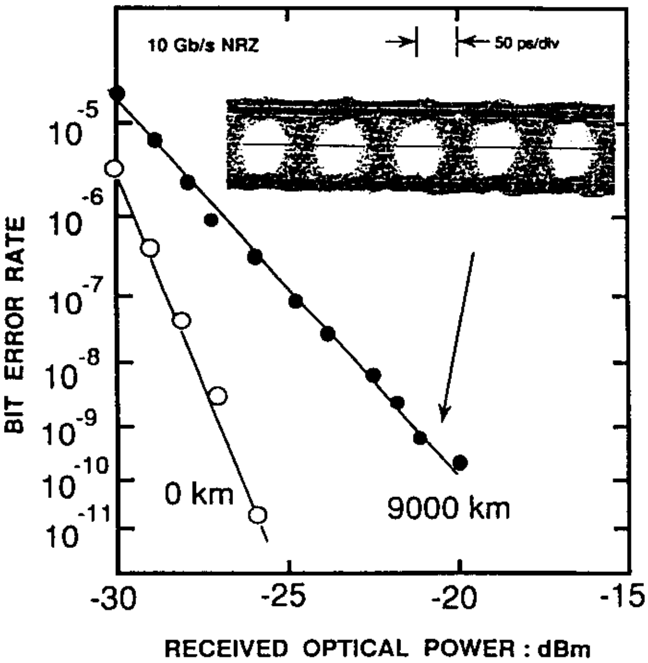

Fig. 4
Bit error rate performance of 9000 km transmission at 10 Gbps. 276 OA repeaters were cascaded with 33 km span.

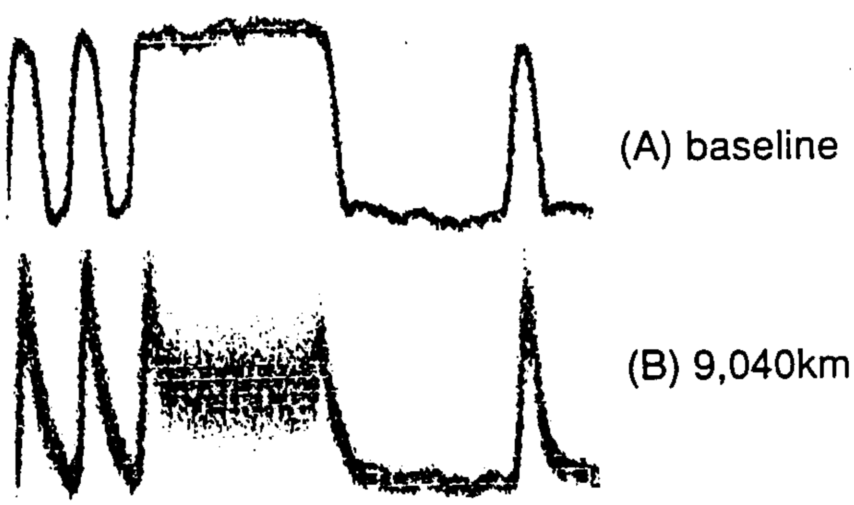

Fig. 5
Waveform in the experiment in Fig. 4. Serious waveform distortion is seen after 9000 km, especially when the signal 1 is consecutive.

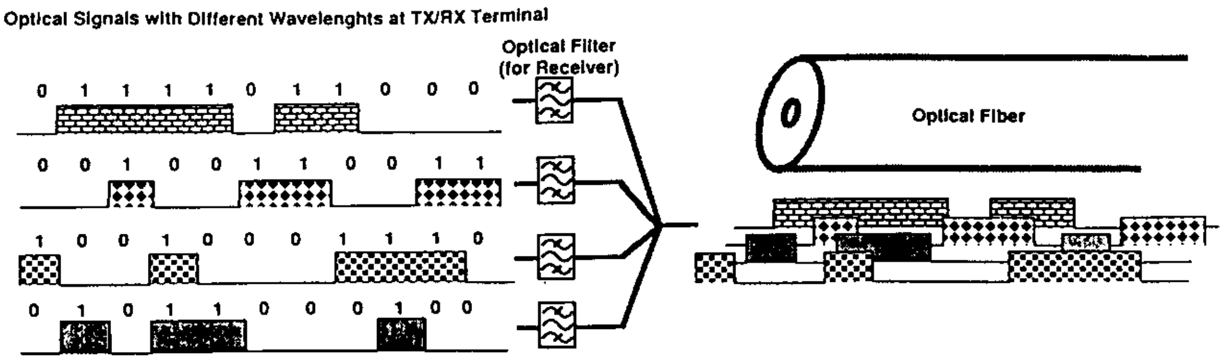

Fig. 6 Schematic illustration of WDM transmission. Optical bandpass filter is not necessary at the transmitter side.

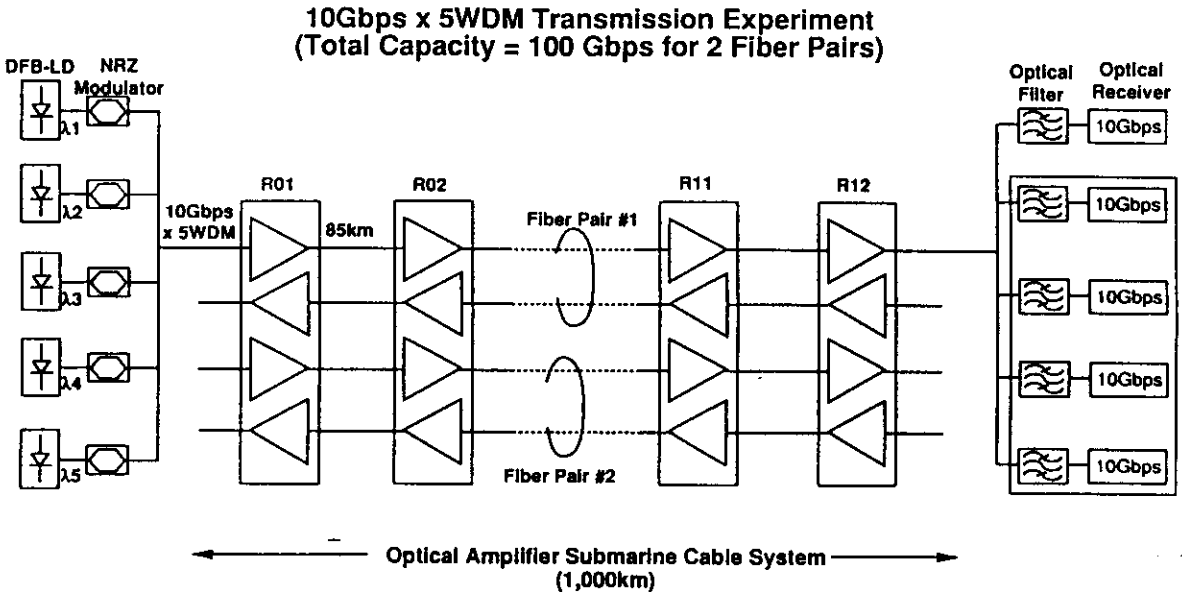

Fig. 7 10 Gbps x 5 WDM transmission experiments in an OA undersea cable system with 2 fiber pairs, which results in the total capacity of 100 Gbps.

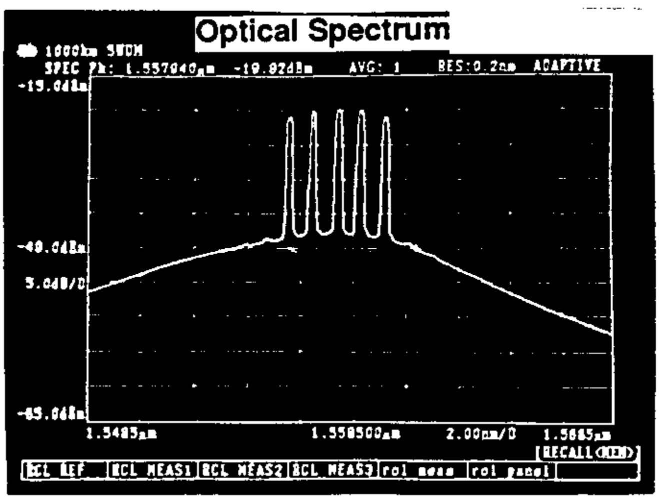

Fig. 8 Spectrum of 5 WDM signals in the experiment in Fig. 7.

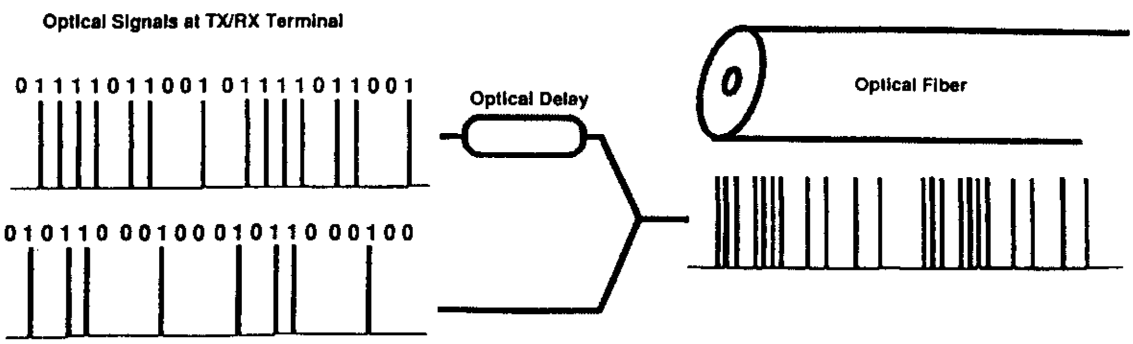

Fig. 9 Schematic illustration of optical TDM transmission.

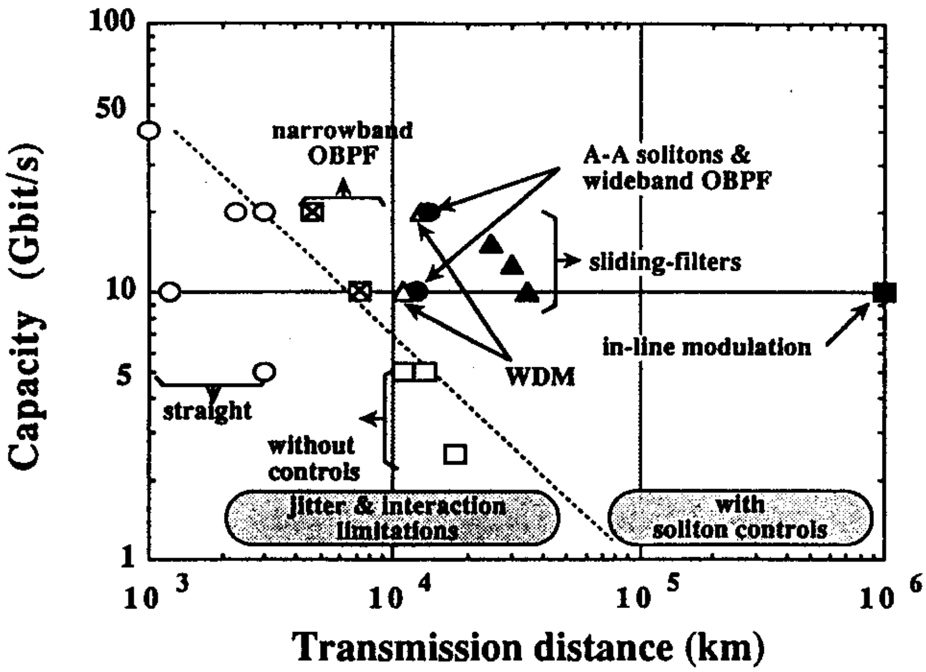

Fig. 10 Transmission capacity vs. transmission distance in recent soliton transmission experiments.

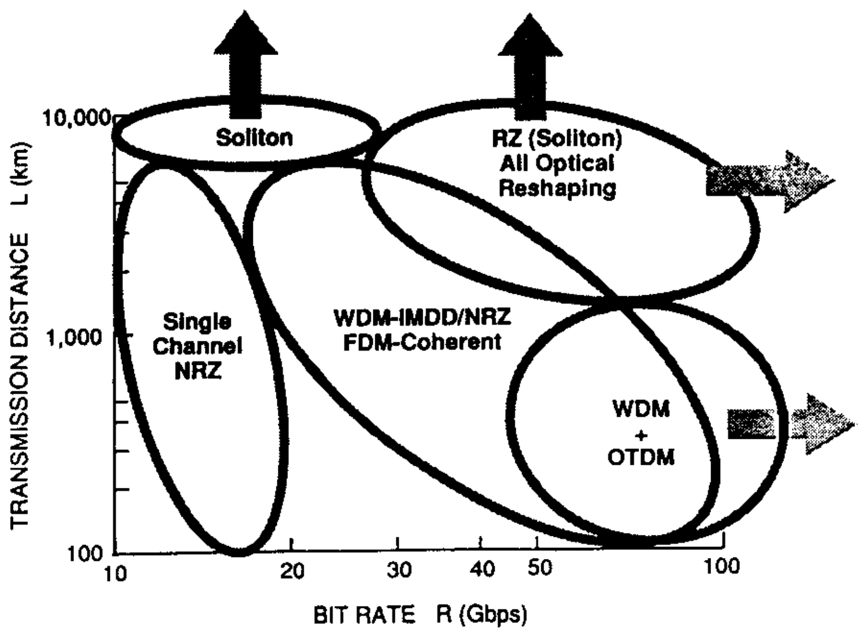

Fig. 11
Various candidate techniques may be used in various application area in terms of distance and bit rate.

Long-Haul Optical Amplifier System Engineering Based on EDFA Technology

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1. INTRODUCTION

Evolution of optical amplifier (OA) technology based on Er-doped fiber amplifiers (EDFA), which has made remarkable progress in recent years, has brought about a big impact to long-haul optical fiber transmission systems.[1]-[3] One of the largest benefits of EDFA technology would be gifted to the area of undersea cable systems highlighted by TPC-5 cable network (CN) and TAT-12 &13, both of which are planned to be completed in 1996.[4][5] From the engineering point of view, how to achieve the required performance and how to maintain the performance for the design life are important. This paper outlines these issues by showing recent development results. [6]

2. DESIGN PARAMETERS

The performance requirements are usually based on the CCITT Recommendations for the envisioned transmission network. The optical fiber transmission has traditionally offered very high quality lines and then the required performance seems to be getting even higher, especially when long-haul and high bit rate systems are concerned.

Table 1 is a typical example of design parameters of transoceanic undersea EDFA systems. For example, TPC-5CN as shown in Fig. 1 has 6 segments with different system lengths and they will have slightly different design parameters such as repeater spacing and launch power.

The system design for the requirements is made through detailed performance examination by computer simulation and loop experiments and is finally verified by straight line test bed. It is also important to take into account the maintenance including monitoring, fault localization and repair, in undersea cable system.

3. SIGNAL-TO-NOISE RATIO (SNR)

An end-to-end optical SNR is simply determined from the input signal power into the EDFA repeater and the total ASE noise generated from all the repeaters.[7] In a recent repeater architecture auto-filtering of EDFA is used to suppress signal gain saturation by accumulated spontaneous emission (ASE).[8] Gain compression property of EDF makes the system robust against loss and gain variation in each span. As increasing the signal launch power into fiber, the effect of fiber nonlinearity becomes a limiting factor, where self-phase modulation (SPM) due to Kerr effect and Brillouin scattering are dominant effects. When the design parameters in Table 1 are assumed, the optical SNR of about 10 dB can be obtained for a 9000km system with a 33 km repeater span. BER is derived from the so-called Q-factor[7][9], which can be measured more quickly and will be used as a convenient parameter for assessment of transmission quality.

4. NONLINEARITY AND CHROMATIC DISPERSION OF FIBER

It is known that if all the constituent fibers have almost zero chromatic dispersion at the signal wavelength, the output spectrum is broadened due to four-wave mixing.[10] A proper distribution of dispersion gives better eye opening and narrower spectrum.[11] More recent trend is adoption of the concept of dispersion equalization, where most of the constituent fibers have slightly negative group delay dispersion and are equalized by short pieces of normal fibers with positive dispersion at 1550nm range. The equalization length can be a repeater span, several repeater spans or the total system span.

5. STATISTICAL NATURE OF THE TRANSMISSION CHARACTERISTICS

One of the outstanding features of a long-haul OA system is temporal variation of transmission characteristics, which seems to be inherent to the long-haul OA systems.[12] State of polarization (SOP) of light propagating through many thousand kilometers changes due to temperature and/or stress applied to fibers. Both OA repeaters and transmission fibers have polarization dependence. Examples are;

(1) Polarization dependent loss (PDL) of repeater [12]
(2) Polarization hole burning (PHB) of EDFA [13]
(3) Polarization mode dispersion (PMD) of fiber

If very low PMD fibers are available, a depolarized light source may be effective since PDL and PHB can be avoided. It has been reported [13] that polarization scrambling is effective to reduce the SNR degradation due to PHB.

The effects of those temporal variations are combined with fiber nonlinearity and chromatic dispersion properties and exhibit complicated phenomena, requiring detailed statistical analyses. In order to achieve an ultra low BER, the design must be extended to detailed statistical study of transmission performance and be analyzed in terms of the distribution function with certain values of average and standard deviation. Statistical data are available from straight line setup, usually called test bed, which experimentally simulates the actual system. Figure 2 shows an example of BER and SNR variations vs. time measured for 5 Gb/s-4500 km straight test bed, in which the input optical power into the receiver was set to a level lower than the error-free level in order to make the observation of fluctuation easier. It is also important to analyze such behaviors by computer simulation.

6. RELIABILITY

6.1 FIT Allocation

Long-haul systems, especially undersea systems, require ultra high reliability as shown Table 1. OA systems for 9000 km length may have more than 200 repeaters and the failure rate allocated to a repeater is about 10 FITs, which should be realized by some redundant architectures and highly reliable components.

6.2 Redundant Pumping Architecture

It is common to most of the undersea systems that a certain kind of redundancy is used for laser diodes. In OA systems high power pumping lasers in 1450-1490 nm range are used. Figure 3 shows possible redundancy configurations. (a) can be used with the two diodes on and provides relatively uniform excitation along the EDF. The output from the two diodes may be combined and split by a 3dB coupler. In (b) either pumping LD may be cold standby or both LDs pump an EDF for high power amplification. Two EDFs are pumped by two common LDs in (c), providing an efficient use of two diodes.

6.3 Repeater and Component Reliability

Although the number of components is smaller compared to regenerative systems, the output power of pumping lasers is about ten times as high as those used in the regenerative repeaters and detailed performance required for an isolator and optical couplers are much more severer. Not only low insertion losses but very low polarization dependence are essential requirements for the passive components and a fraction of FIT should be maintained over many years. Qualification of most of the components and overall repeater for OS-A system developed by KDD for undersea use is in the final stage.[6][14][15]

7. MAINTENANCE

7.1 Line Monitoring

In-service and out-of-service monitoring is necessary for long-haul systems. Various methods have been proposed and demonstrated. Among those, a loopback gain measurement using a simple but sophisticated loopback circuit in a repeater is attractive.[16] A small portion of outgoing signal is looped back through the optical coupler network to the incoming signal path as shown in Fig. 4. Line monitoring signal with a specialized code is superimposed to the main signal and can be detected and decoded at the terminal. Each repeater is identified by the delay between the reference code sequence and looped-back code sequence. Figure 5 shows an example of the measurement result simulating a failure at the repeater #55 located at 1800 km far from the terminal. The failure mode is distinguished from the pattern of the loopback gain vs. repeater number.

7.2 Fault Localization

Precise fault location of a cable failure can also be detected by means of optical time domain reflectometry (OTDR) using the same loopback circuit shown in Fig. 4. Rayleigh backscattering intensity is detected by coherent signal processing as a function of the location.[17] An OTDR trace, similar to a conventional OTDR trace, is shown in Fig. 6. The slope corresponds to the fiber loss and the spike indicates Fresnel reflection at the fiber break.

8. FIELD TRIAL

System evaluation in an actual environment is important not only to verify the design but also to confirm procedure of measurements, system assembly and laying. The first sea trial of an OA system was successfully demonstrated in late 1992.[15] Prototype repeaters and DSF cables were laid in the 2120 m deep sea bed. SNR, BER, polarization characteristics and line monitoring performance mentioned above have been measured using prototype optical transmitter and receiver and power feeding equipment.

9. CONCLUSION

OA technology with EDFA is almost ready for practical use in long haul undersea systems. Detailed transmission penalty and degradation penalty, which critically depend both on the system design and on the hardware implementation, have also to be studied intensively in order to make sure that the designed and implemented systems have a sufficient margin for the design life.

ACKNOWLEDGEMENT

The author is grateful to the people involved in the OS-A system development at KDD for their contribution to the presented results. He would like to acknowledge the joint development effort with AT&T.

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Table 1: Design parameters for long-haul OA system

Specified Item	Design Value
Line bit rate	5 Gb/s nominal
Line code	Binary NRZ
Signal wavelength	1558.5 nominal
Launch power into fiber	1 - 4 dBm
Noise figure	5 - 6 dB
Repeater span	30 - 100 km
<Specific to undersea use: OS-A system>	
Maximum system length	9,000 km
Maximum sea depth	8,000 m
Power feed current	DC 0.92 A nominal
Repeater supervisory	Loopback gain monitoring
Design life	27 years or longer
Ship repair	3 or less in design life

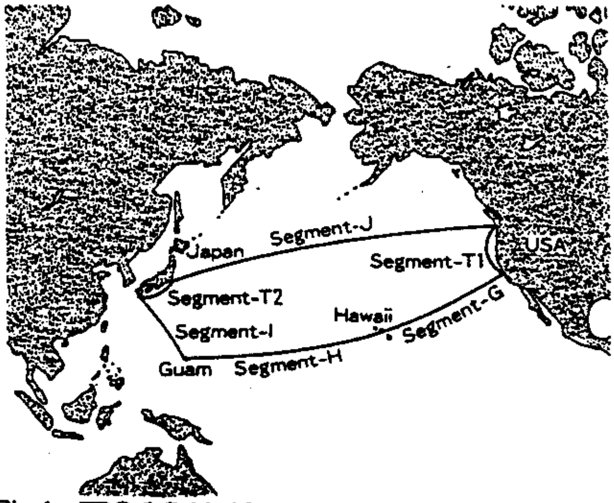

Fig.1: TPC-5 Cable Network using EDFA technology will be supplied by KDD and AT&T and will be completed in 1996.

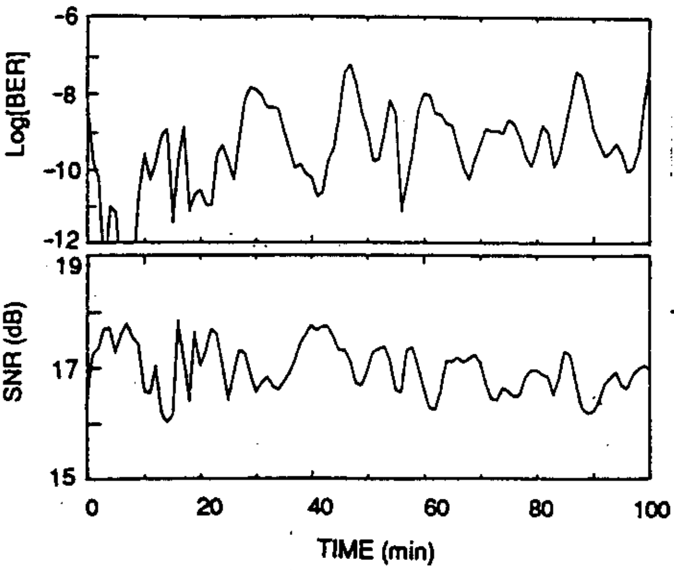

Fig.2: BER fluctuation example in 4500km 5 Gb/s experiment. SNR also varies along with BER fading.

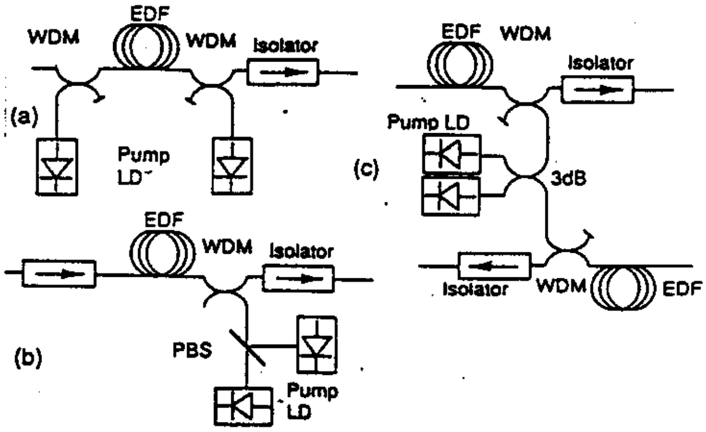

Fig.3: Repeater architectures with redundant pump configuration.

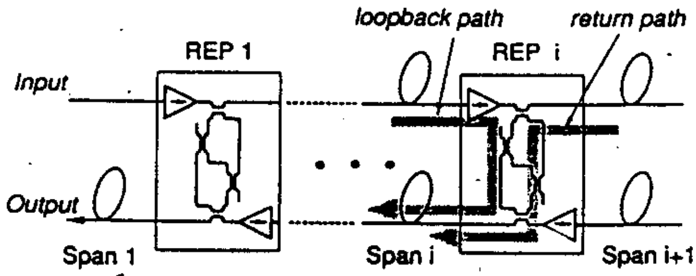

Fig.4: Loopback output circuit provides loopback path for line monitoring and return path for coherent OTDR fault location.

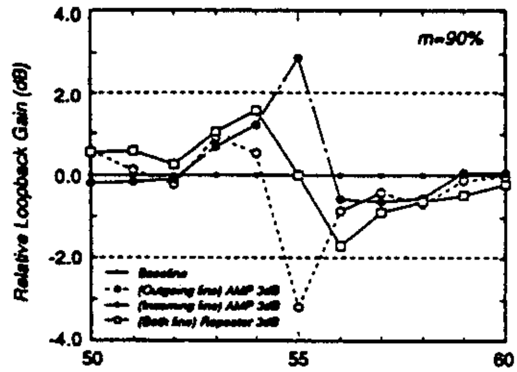

Fig.5: Loopback gain versus repeater number. 3dB degradation in outgoing amplifier, incoming amplifier and both amplifiers is detected.

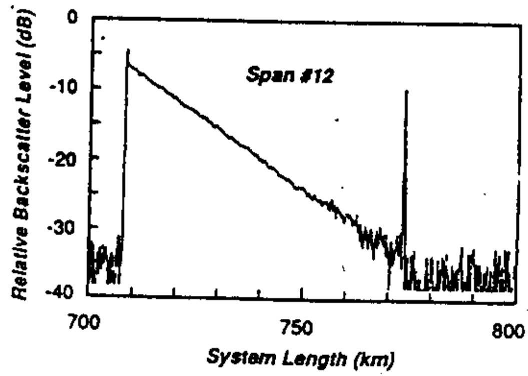

Fig.6: OTDR trace of the span #12.

Four-Wavelength Multiplexed 10Gbit/s IM-DD Signal Transmission Experiments Over 1,500km with 100km EDFA Spacing

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Abstract 10Gbit/s, 4WDM IM-DD optical signal was transmitted through 15 cascaded EDFA repeaters with 100km spacing. The interaction due to FWM was sufficiently reduced with the managed dispersion and the asymmetric channel spacing.

Introduction Wavelength division multiplexed (WDM) technology is attractive as the key of the future large capacity optical communication systems. The advent of the Er-doped fibre amplifier (EDFA) enables the simultaneous amplification of WDM optical signals, and many system experiments have been already demonstrated. Recently, 8×20Gbit/s, 300km transmission [1] and 2×10Gbit/s, 900km transmission [2] were reported. Although the bit-rate distance product of these experiments reaches 18-48Tbit•km/s, it is important to explore longer distance transmission beyond 1,000km so as to extend application areas. In this paper, we describe the experimental results of 4×10Gbit/s WDM transmission over 1,500km EDFA chain. Stability of WDM transmission is briefly discussed by showing the results of long-term Q-factor [3] measurement.

Experiments Fig.1 shows a schematic diagram of the experimental setup. Four DFB-LDs combined with $LiNbO_3$ Mach-Zehnder external modulators were used as the optical transmitters. The modulation bit-rate and the pseudorandom pattern were 10Gbit/s and 2^7-1, respectively. The signal wavelengths were 1553.5nm, 1555.5nm, 1558.0nm, and 1560.0nm for channel 1 to 4, respectively. A 4×4 fused fibre coupler was used to combine these four optical signals, and an EDFA booster amplifier was inserted after the coupler. The WDM signals were transmitted through 1,587km dispersion-shifted single-mode fibre (DSF) with 15 concatenated EDFAs. The average span length was 100km except the last span of 84km. The total EDFA output power was set to +11dBm. The measured zero dispersion wavelength of the system was 1558.2nm.

An optical bandpass filter (OBPF) of 1nm bandwidth was inserted in front of the optical receiver to separate the WDM signals. At the input of the photo detector, an EDFA pre-amplifier combined with an OBPF of 1nm bandwidth was employed to improve the receiver sensitivity. An InGaAs PIN-PD was used as a photo detector of the receiver.

Results and discussions In order to reduce the interaction due to FWM, which efficiency is large at the zero dispersion wavelength, managed dispersion configuration was applied for the experiments. Fig.2 shows a schematic diagram of the managed dispersion. The first half of the repeater span consisted of the normal dispersion fibre, and the accumulated chromatic dispersion was canceled by the latter half of anomalous dispersion fibre for each repeater span. This configuration enables to separate the signal wavelengths and the zero dispersion wavelengths of the constituent fibres in the first half of the repeater span, as the zero dispersion wavelengths of the normal dispersion fibres are longer than the system zero dispersion wavelength. Therefore, the efficiency of the FWM was reduced in the relatively high signal power region. Although the efficiency of the FWM becomes higher in the latter half of the repeater span, because the signal wavelengths and the zero dispersion wavelengths of the anomalous fibres are closer, the total effect was relatively small as the signal power of each channel was effectively reduced by 50km signal transmission. The asymmetric channel spacing also reduced the FWM interaction. As the spacing between channel 2 and 3 was larger than that of the others, the spurious sidemode due to FWM caused no interaction to channel 1 or 4. The FWM between channel 1 and 2 also caused no interaction to channel 3, then, the interaction was effectively suppressed. Fig.3 shows the measured optical spectrum. The spurious sidemode due to FWM is not so obvious after 1,587km transmission.

Fig.4 shows the measured bit error rate (BER) characteristics after 1,587km transmission. The power penalties at 10^{-9} BER of each channel were 3.3dB, 4.9dB, 1.9dB, and 2.3dB, for channel 1 to 4, respectively. As the signal wavelength separation from the system zero dispersion wavelength was large for channel 1 and 2, 27km SMF and 10km SMF were inserted in front of the optical receiver to measure the characteristics for channel 1 and 2, respectively. In order to confirm the error floor level, the Q-factor is measured for each channel. Table 1 summarizes the measured Q value. Note that these numbers were obtained from spot measurement, and that the average Q value of the long-term measurement might be somewhat different from these numbers. Therefore, we investigated transmission stability from long-term Q evaluation. Fig.5 shows an example of the long-term Q performance with 1558.0nm signal wavelength. In this case, the numbers of the multiplexed channels were reduced to two, since there was difficulty to keep the total output power at +11dBm for many hours. But the channel separation was reduced to 1nm, which should considerably enhance FWM and the detailed study on the relationship between instability due to FWM and the channel separation will be published elsewhere [4]. In spite of such narrow channel separation, the standard deviation of the Q was as small as 0.3dB. Therefore, it is estimated that the measured spot Q shown in Table 1 has an accuracy better than ±0.3dB with 67% confidence. As the required Q of 10^{-9} BER is 15.6dB, the WDM signals have a few dB margin except channel 2. The insufficient frequency response of the electrical driver for channel 2 was one reason of the small margin of channel 2 compared to the other channels.

Conclusion We have successfully demonstrated 4×10Gbit/s transmission over 1,500km. The effectiveness of the managed dispersion and the asymmetric channel spacing was demonstrated to reduce the FWM. The system margin of each channel was estimated using the Q-factor, and a few dB margin was confirmed experimentally.

Acknowledgment The authors would like to thank Y. Horiuchi for his help of the fibre chromatic dispersion measurement. They would also like to thank Drs. M. Suzuki, Y. Namihira, K. Sakai, and Y. Urano for their continued encouragement.

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Channel 1	16.99dB
Channel 2	15.95dB
Channel 3	19.20dB
Channel 4	17.91dB

Table 1 Measured Q-factors of the 4WDM transmission experiments

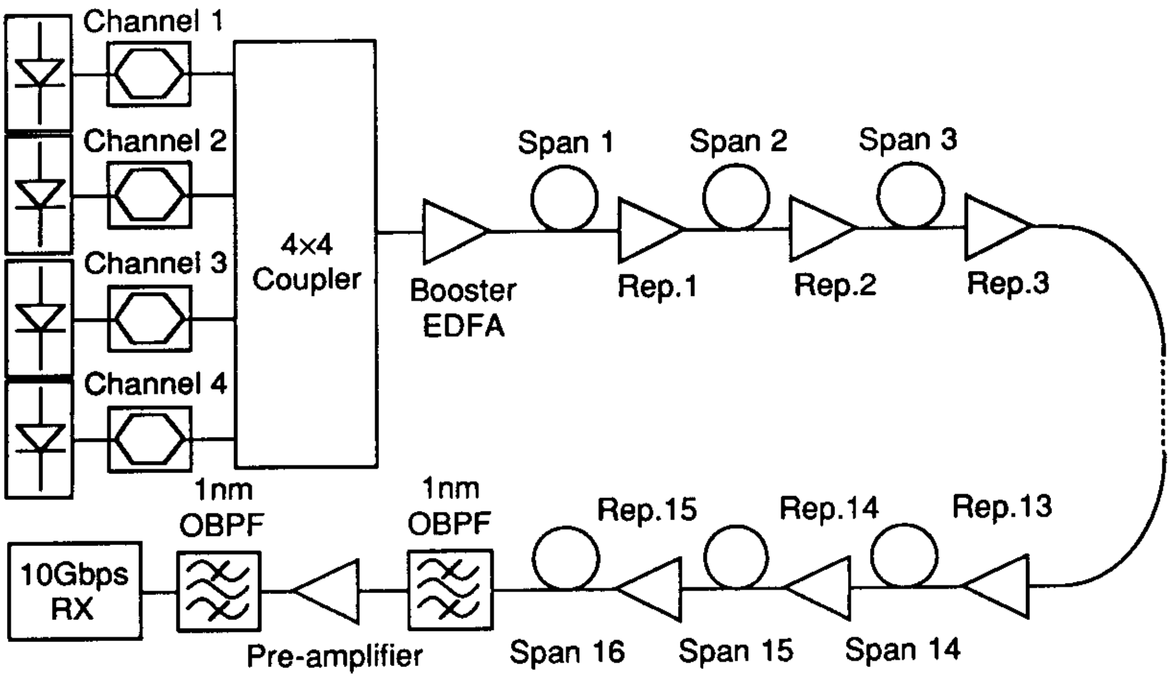


Figure 1 A schematic diagram of the experimental setup

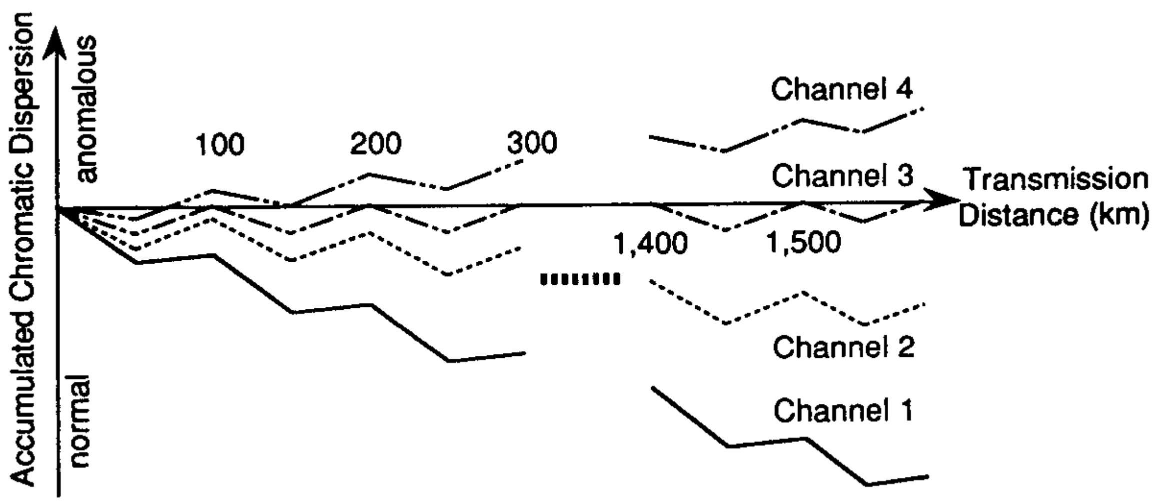
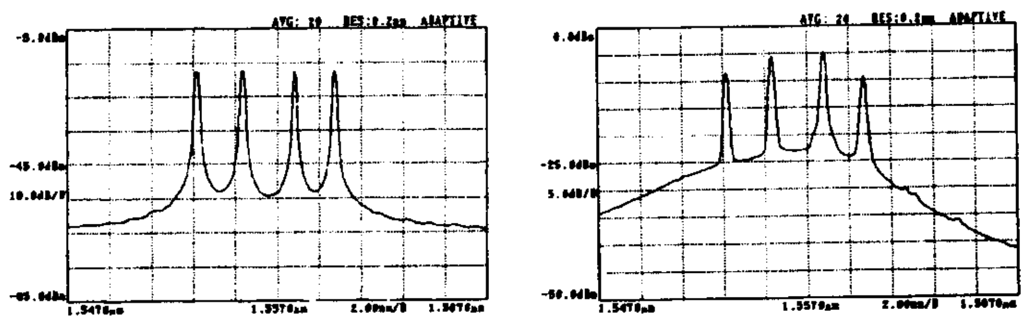


Figure 2 A schematic diagram of the managed dispersion



baseline

after 1,587km

Figure 3 Optical spectrum of 4WDM signal

S2-3

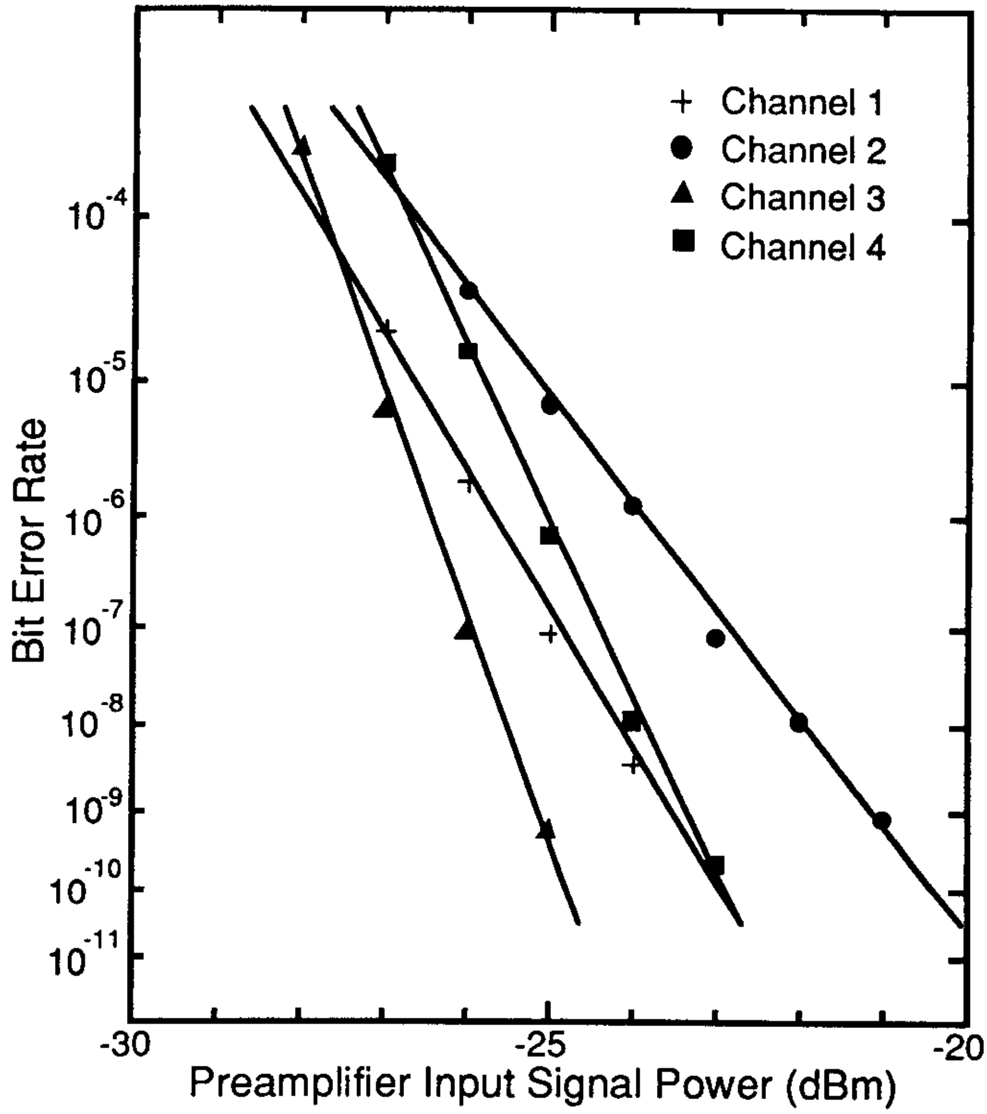


Figure 4 BER characteristics of 10Gbit/s, 4WDM 1,587km transmission

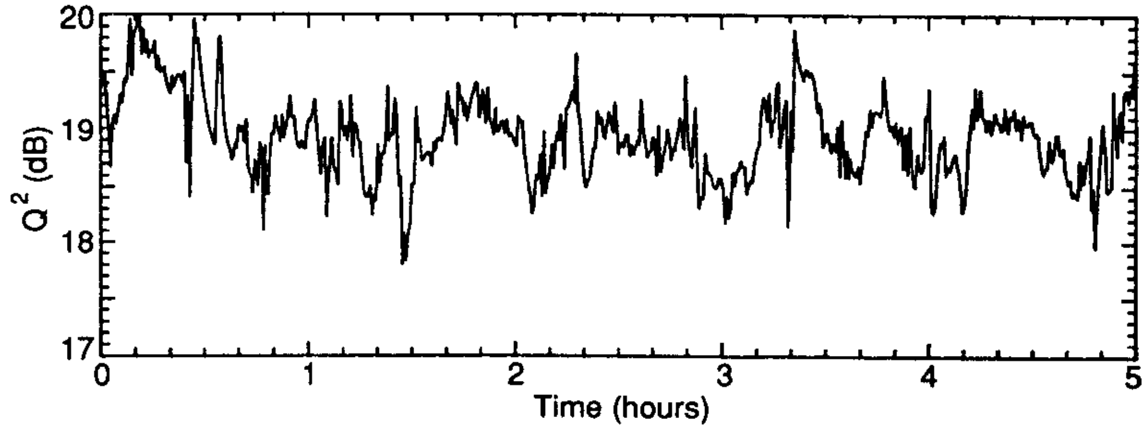


Figure 5 Example of time-varying Q-factor of WDM transmission (channel separation 1nm)

Supplement [3]

Measurements on the Time-Varying Performance for 5Gbit/s Wavelength Division Multiplexed System over 1500km EDFA line

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Introduction Wavelength division multiplexed (WDM) technology is attractive for future ultra-large capacity optical communication systems. As there are other linear and nonlinear interactions such as four-wave mixing (FWM) and cross-phase modulation for WDM system compared to the conventional single carrier system, it is important to study the effect of such interactions on the system performance. The efficiency of the FWM, which is dominant degradation factor, depends on the phase condition of the signal lights and therefore, should be a function of the time if the phase conditions between the signals change independently to other signals. In this paper, we have measured the time-varying performance of two channels WDM system at 5Gbit/s. The Q-factor [1] is used as a measure of the system performance.

Experiments Fig.1 shows a schematic diagram of the experimental setup. Two DFB-LDs were used as the signal light sources, and these lights were modulated by $LiNbO_3$ Mach-Zehnder external modulator. The modulation bit-rate and pattern were 5Gbit/s and 2^{15}-1, respectively. The signal wavelength of the channel 2 was set at 1558.5nm, and that of the channel 1 was changed to modify the channel separation. A 3dB fused fiber coupler was used to combine these two optical signals. In order to boost the signals, an Er-doped fiber amplifier (EDFA) was inserted after the coupler. The WDM signals were transmitted through 1,587km dispersion-shifted single-mode fiber (DSF) with 15 EDFA repeaters. The span length was around 100km except the last span of 84km. The repeater output power was set to +7dBm. The zero dispersion wavelength of the system was measured by the phase-error cancellation method [2] and was 1558.2nm.

After the transmission line, an optical bandpass filter (OBPF) of 1nm optical bandwidth was inserted to separate the WDM signals. At the input of the optical receiver, an EDFA pre-amplifier combined with an OBPF of 2nm bandwidth was employed to improve the receiver sensitivity. An InGaAs PIN-PD was used as a photo detector of the receiver. In order to evaluate the system performance, we have measured the Q-factor [1] as a function of time for several different channel spacing. The duration of one Q measurement was around one minute.

Results and discussions Fig.2 shows an example of the change of the Q-factor. The signal wavelength was 1558.5nm only, and the repeater output power was reduced to +4dBm. Fig.3 shows the probability density of the measured Q shown in Fig.2. As seen in Fig.2, the Q fluctuates as the time goes on. The reason of the fluctuation can be attributed to the polarization dependent loss (PDL) [3] of the optical components of the EDFA, polarization mode dispersion (PMD) of the transmission fiber, and the polarization dependent gain (PDG) [4] of the EDFA. The PDL and the PDG cause the optical signal-to-noise ratio (S/N) fluctuation. The PMD causes the optical pulse distortion.

Table 1 summarizes the long-term measurement. As seen in the table, WDM causes the increase of the standard deviation of the Q. Fig. 4 shows the standard deviation of the Q as a function of the channel spacing. As seen in the figure, the smaller channel spacing causes the larger standard deviation of the Q. This can be explained by the additional distortion due to the FWM. As the efficiency of the FWM depends on the phase condition of the optical signal, it may change as time goes on. The worst Q should be observed when the phase matching is satisfied, and the best Q should be observed when the phase is crossed. Therefore, the variation of the Q becomes larger as the distortion due to the FWM becomes larger. As the efficiency is also a function of the channel spacing and the smaller spacing causes the larger efficiency, the variation of the Q becomes large when the channel spacing is small. The experimental results shown in Fig.4 clearly indicate this tendency. Fig.5 shows the change of the Q-factor of 3nm channel separation. As seen in the figure and the table, the large channel separation of 3nm prevents causing large distortion due to the FWM. From these results, it can be said that more than 3nm channel separation is sufficient to achieve stable operation of the WDM system.

Conclusion We have measured the statistics of the WDM system performance for the first time to our knowledge. The results show that the effect of the FWM causes the increase of system performance variation, and that it depends on the channel spacing of the WDM signal.

Acknowledgment The authors would like to thank Y. Horiuchi for his help of the fiber chromatic dispersion measurement. They would also like to thank Drs. Y. Namihira, K. Sakai, and Y. Urano for their continued encouragement.

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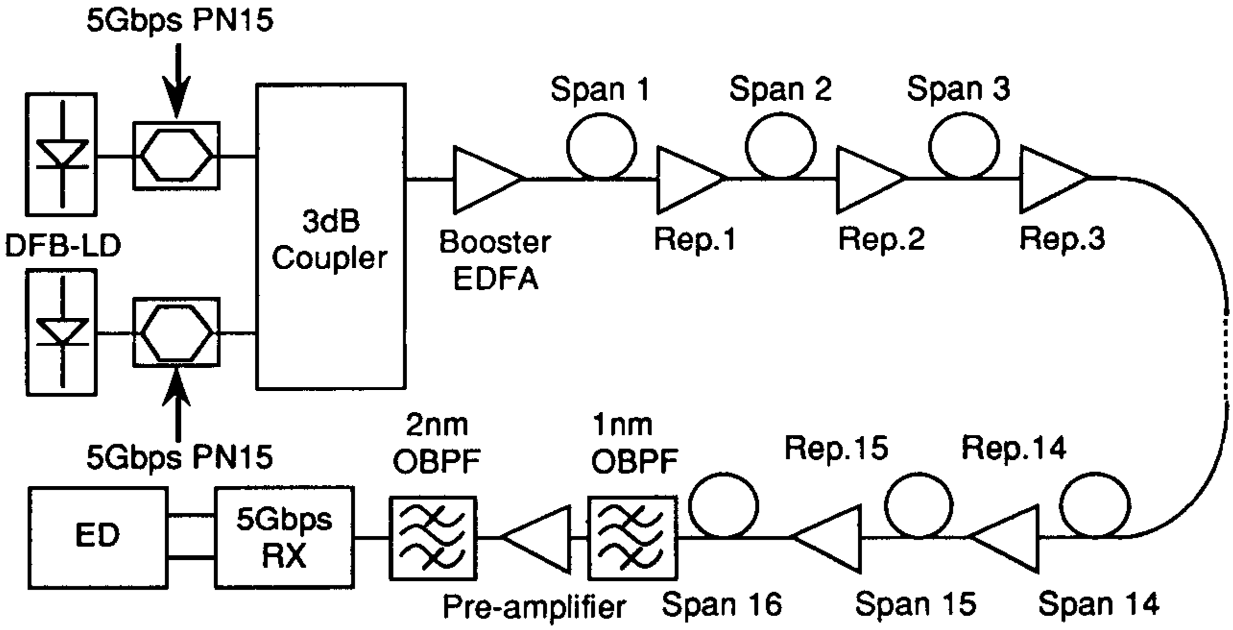

Figure 1 A schematic diagram of the experimental setup

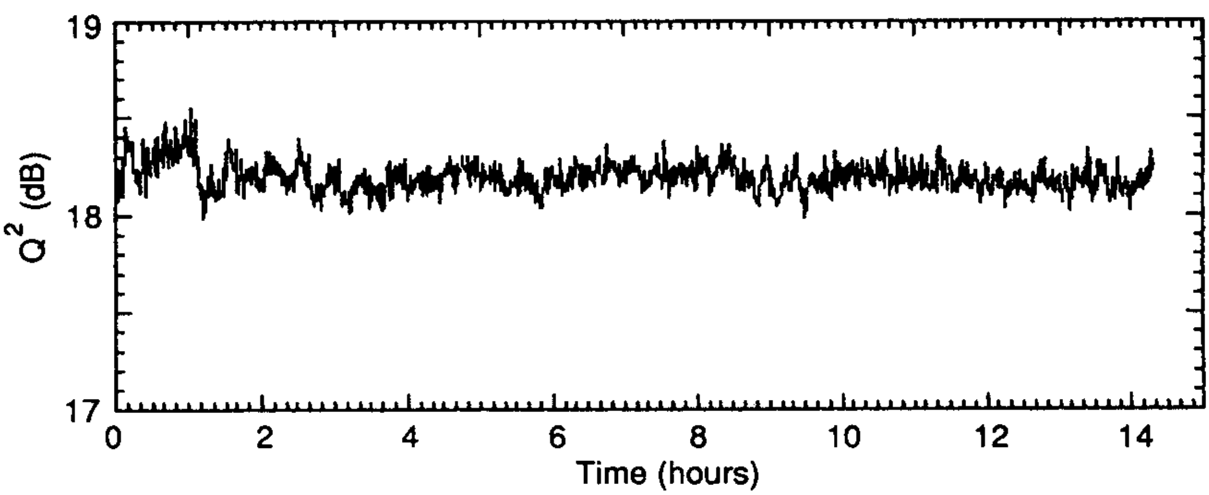

Figure 2 Example of time-varying Q-factor of single carrier transmission

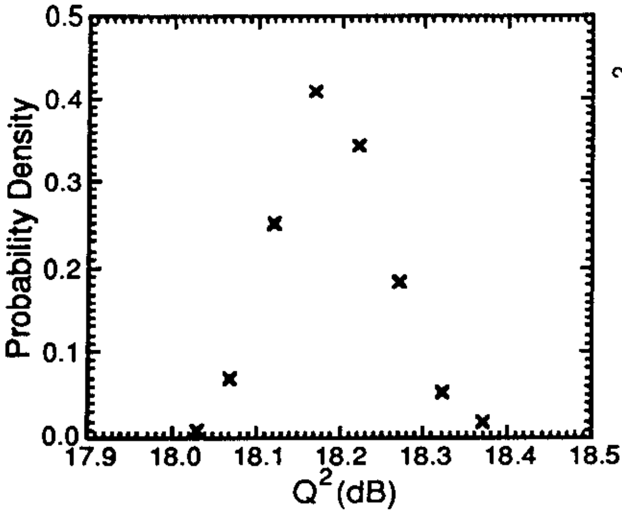

Figure 3 Q^2 probability density of figure 2

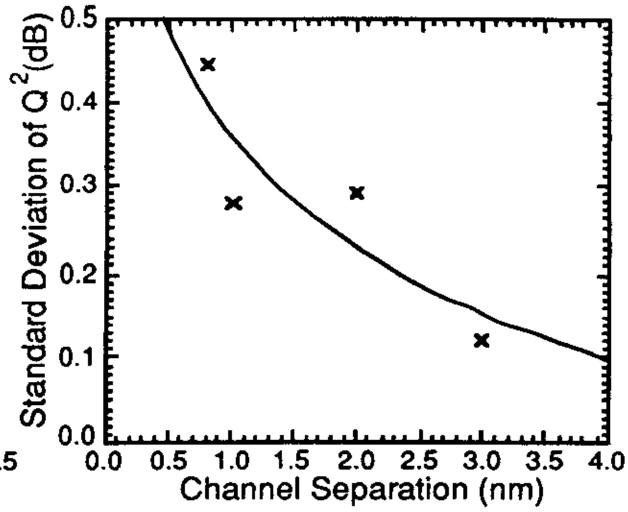

Figure 4 Standard deviation of Q^2 versus channel spacing

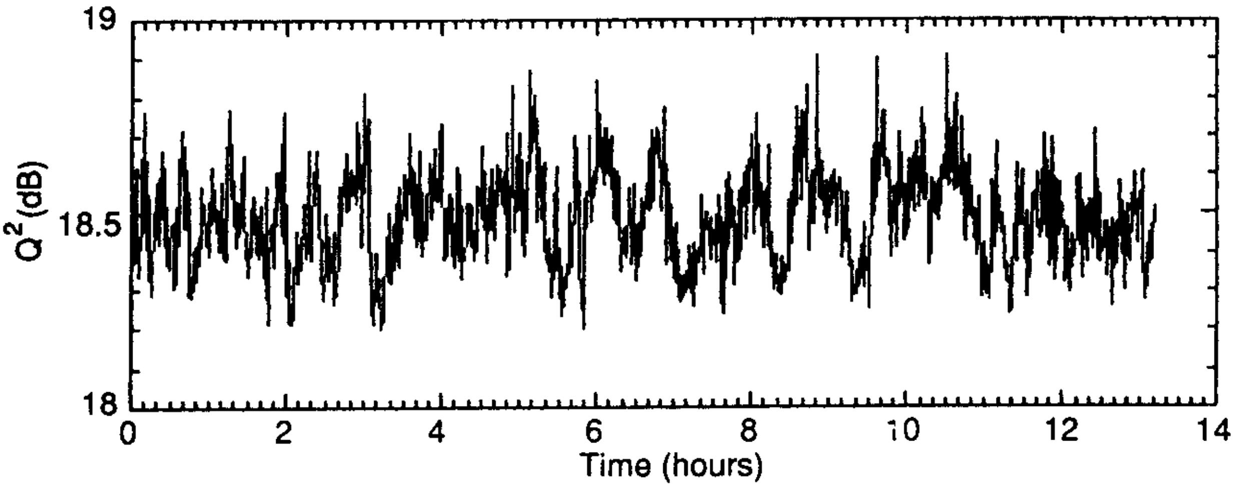

Figure 5 Example of time-varying Q-factor of WDM transmission (channel separation 3nm)

channel separation	Q^2			
	average	σ	max	min
single	18.20dB	0.072dB	18.55dB	17.99dB
3nm	18.49dB	0.119dB	18.91dB	18.20dB
2nm	17.24dB	0.293dB	18.25dB	16.15dB
1nm	17.59dB	0.278dB	18.47dB	16.33dB
0.8nm	17.01dB	0.447dB	18.15dB	15.77dB

Table 1 Summarized results of long-term Q measurement

Eight-wavelength, densely-spaced coherent WDM recirculating-loop experiments at 2.5 Gbit/s over 600 km

S. Ryu and S. Akiba

Indexing terms: Fibre amplifiers, Optical communication, Wavelength division multiplexing

Eight-wavelength, densely-spaced coherent CPFSK recirculating-loop experiments at 2.5Gbit/s have been demonstrated over 600km through 30 cascaded EDFAs. The WDM signals were densely packed in a bandwidth of only 1.4nm, indicating the effective use of optical frequency resources by coherent schemes.

Introduction: Increasing attention has recently been paid to wavelength-division-multiplexing (WDM) lightwave communication systems for expanding transmission capacity and for the construction of flexible transparent systems in future all-optical networks. Most of the WDM experiments have been carried out using intensity-modulation direct-detection (IM-DD) schemes [1, 2]. However, in WDM systems using IM-DD schemes, channel spacings between adjacent channels have to be set relatively large (typically 1 to 3nm) due to the practically available bandwidths of optical bandpass filters (BPFs) for receivers. Such large channel spacings result in an imbalance of signal-to-noise ratios between WDM carriers in in-line amplifier systems due to the accumulation of unflatness in the wavelength against gain characteristics of erbium-doped fibre amplifiers (EDFAs); some countermeasures against the problem have been proposed [1–4].

We have already shown that the problem can also be alleviated by coherent schemes with a densely-spaced carrier arrangement in 2.5Gbit/s, four-channel, 1200km CPFSK transmission experiments [5]. It is also necessary to carry out experiments by increasing the number of channels to show the effectiveness of the densely-spaced WDM systems in in-line amplifier systems. On the other hand, coherent schemes are more immune to the amplified spontaneous emission (ASE) from EDFAs due to the achievement of beat-noise-limited operation between the ASE and local oscillator light in the receiver [6]. Hence, we can reduce the input power to the transmission fibre, and we can expect to alleviate the effect of fibre four-wave mixing (FWM) on transmission performance.

In this Letter, we report the results of eight-wavelength, densely-spaced coherent CPFSK recirculating-loop experiments at 2.5Gbit/s over 600km to show the advantages of the densely-spaced coherent schemes described above in WDM communication systems.

Experiments: Fig. 1 shows the experimental setup which is similar to the previous setup [7]. Eight multiquantum-well/distributed Bragg reflector (MQW/DBR) lasers were used for signal sources. Direct CPFSK modulation was applied at 2.488Gbit/s with a modulation index of 0.8. The wavelengths of the lasers ranged from 1557.8nm (CH 1) to 1559.2nm (CH 8) with an equal spacing of 0.2nm (~25GHz) in an occupied bandwidth of only 1.4nm. An unequal channel arrangement for avoiding the influence of fibre FWM [5] could not be implemented due to the limited signal bandwidth which comes from the use of an optical BPF in the loop. The optical power and state of polarisation of each carrier were adjusted to be the same by an optical attenuator and a polarisation controller following each laser. The signals were then multiplexed, and introduced in a loop. The fibre for transmission was a 39.6km-long dispersion-shifted fibre (DSF) with a normal dispersion of −0.94ps/km/nm, and the dispersion of the fibre was almost perfectly compensated for by a dispersion-compensating fibre in the loop [7]. An optical BPF with a bandwidth of 10nm was inserted in the loop to avoid the build-up of ASE at the gain peak wavelength of the EDFAs (~1563nm) which is an out-of-band wavelength as regards the signals. A DBR laser for a local oscillator had enough tuning capability to capture all the wavelengths of the WDM signals. The bit error rate (BER) performance of the system was measured by a system placed after a coherent heterodyne receiver.

The input power to the fibre in the loop was experimentally optimised to give the best BER performance, and was found to be −2.5dBm which corresponds to −11.5dBm input power for each carrier. Fig. 2*a* and *b* show optical spectra of the WDM signals after approximately 500km and 1000km transmission, respectively. From Fig. 2*a*, we can see that the signal level imbalance for the WDM signals is as small as 3dB, which indicates the advantage of a densely-spaced carrier arrangement in in-line amplifier systems. We did not observe fibre FWM products near the signal wavelengths owing to the low input power to the fibre. In Fig. 2*b*, we can see that the signal level imbalance is further enhanced. The reason for this is mainly attributed to the accumulated filtering effect of the BPF in the loop, and such an imbalance can be removed if we can avoid the use of the BPF by matching the gain peak of the EDFAs with the signal wavelengths.

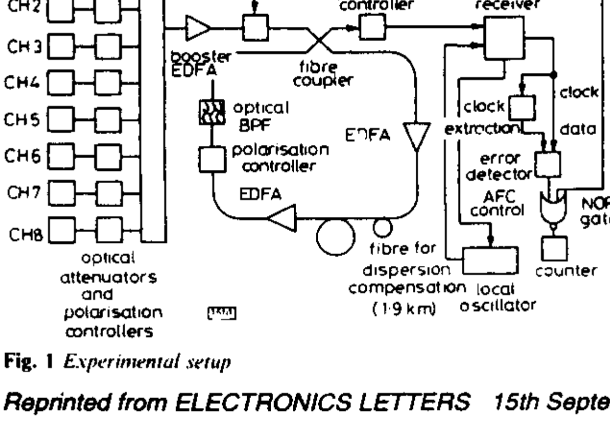

Fig. 1 *Experimental setup*

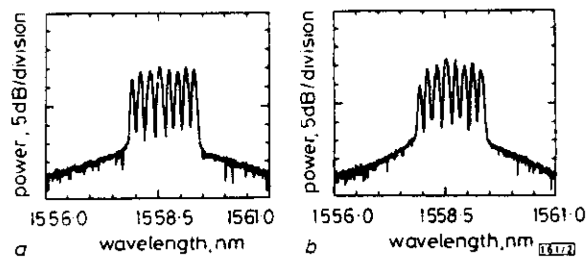

Fig. 2 *Optical spectra after transmission*

a After 500km transmission
b After 100km transmission

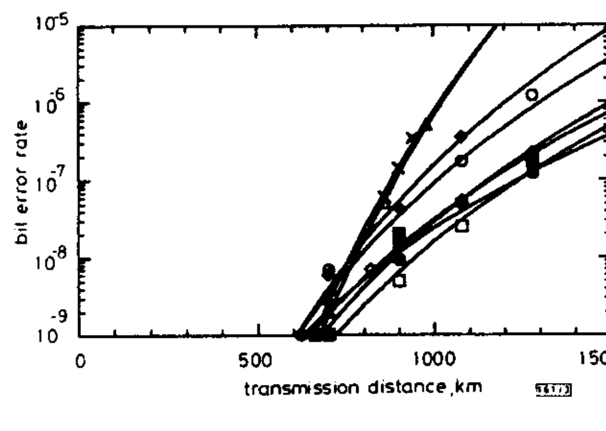

Fig. 3 *BER against transmission distance*

○ CH 1	◆ CH 5
□ CH 2	Δ CH 6
◊ CH 3	● CH 7
× CH 4	■ CH 8

S4-1

The BER performance was then evaluated. Fig. 3 shows the results obtained for the BER against transmission distance characteristics. The achieved transmission distances are almost the same for the eight carriers, and ranged from 600 to 700km at a BER of 10^{-9} although the WDM signals have passed through ~30 cascaded EDFAs for 600km transmission (15 circulations along the loop).

The limit of the transmission distance of the system mainly comes from linear accumulation of ASE due to the low input power to the fibre. In the experiments, two EDFAs were used for one fibre span, which means a doubled noise figure of the system. Hence, if the system configuration is improved, we can expect a further increase in the transmission distance.

Conclusion: We have successfully transmitted densely-spaced eight-wavelength coherent CPFSK signals over 600km through 30 cascaded EDFAs using a recirculating loop, which indicates the advantages of densely-spaced coherent schemes in terms of small signal level imbalance in cascaded EDFA systems and less effect of fibre FWM due to the low input power to the fibre.

 3 August 1994

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INVITED PAPER Special Issue on Ultrafast Optoelectronics

Long-Distance Soliton Transmission up to 20 Gbit/s Using Alternating-Amplitude Solitons and Optical TDM

Masatoshi SUZUKI†, Noboru EDAGAWA†, Hidenori TAGA†, Hideaki TANAKA†, Shu YAMAMOTO†, Yukitoshi TAKAHASHI† *and* Shigeyuki AKIBA†, *Members*

SUMMARY Feasibility of 20 Gbit/s single channel transoceanic soliton transmission systems with a simple EDFA repeaters configuration has been studied. Both a simple and versatile soliton pulse generator and a polarization insensitive optical demultiplexer, which can provide a almost square shape optical gate with duration of full bit time period, have been proposed and demonstrated by using sinusoidally modulated electroabsorption modulators. The optical time-division multiplexing/demultiplexing scheme using the optical demultiplexer results in drastic improvement of bit error rate characteristics. We have experimentally confirmed that the use of alternating-amplitude solitons is an efficient way to mitigate not only soliton-soliton interaction but also Gordon-Haus timing jitter constraints in multi-ten Gbit/s soliton transmission. Timing jitter reduction using relatively wide band optical filter has been investigated in 20 Gbit/s loop experiments and single-carrier, single-polarization 20 Gbit/s soliton data transmission over 11500 km with bit error rate of below 10^{-9} han been experimentally demonstrated, using the modulator-based soliton source, the optical demultiplexer, the alternation-amplitude solitons, and wide-band optical filters. Obtained 230 Tbit/skm transmission capacity shows the feasibility of 20 Gbit/s single channel soliton transoceanic systems using fully practical technologies.
key words: *optical soliton, soliton pulse generator, optical demultiplexer, alternating-amplitude soliton, EDFA, multi-ten Gbit/s long-haul transmission*

1. Introduction

Evolution of optical amplifier technology based on Er-doped fiber amplifiers (EDFA) has brought about a big impact to optical fiber transmission systems and has made rapid increase in capacity and the non-regenerative transmission distance. Recent transmission experiments using NRZ signals have shown possibility of 5 to 10 Git/s long-haul transmission systems based on EDFA repeaters [1] and 5 Gbit/s transoceanic optical amplifier submarine cable systems are planned to be in service in 1996 in the Pacific and the Atlantic Ocean [2]. In multi-ten Gbit/s long-haul lightwave systems using NRZ signals, however, performance degradation due to chromatic dispersion and optical nonlinearity of fibers becomes significant and the transmission distance is considered to be limited to a few thousands of km.

On the other hand, considerable interest has recently been shown in optical soliton transmission schemes proposed by Hasegawa et al [3], because of their highly stable pulse transmission property due to the balance of the chromatic dispersion effect and optical nonlinearity of the fibers. Novel soliton transmission system scheme using lumped amplifiers such as EDFAs [4]-[7] has enabled us to develop a simple and promising transmission system as well as linear optical transmission systems using NRZ signals. ASE-induced timing jitter (Gordon-Haus timing jitter [8]) and interaction between adjacent solitons [9] are major limitations in soliton transmission using optical amplifiers. Several techniques to suppress the timing jitter and the interactions both in frequency domain [10]-[16] and time domain [17] have been proposed and their possibilities of 10 to 20 Gbit/s multi-thousand km soliton transmission systems have been experimentally demonstrated by employing various inline soliton control techniques: 20 Gbit/s, 13000 km transmission in two-channel WDM with sliding frequency-guiding filters [15], 10 Gbit/s unlimited distance transmission using in-line synchronous modulation and narrow band optical filters [17].

In this paper, we have studied the feasibility of 20 Gbit/s single channel soliton transmission over transoceanic distances in details. From view point of practical application, our research interest has been focused on soliton transmission performance enhancement technologies controlling the optical signals at the transmitter and receiver ends, in order not to resort to sophisticated inline controls. In Sect. 2, soliton transmission based on EDFA repeaters and its limitations are briefly described. In Sects. 3 to 5, three simple and practical technologies developed for implementation of multi-ten Gbit/s long distance soliton transmission have been discussed, : 1) a simple soliton pulse generator based on a sinusoidally modulated electroabsorption (EA) modulator [18], 2) a polarization insensitive EA optical demultiplexer to reduce the effect of timing jitter to bit error rate (BER) in optical time-division multiplexing (TDM) scheme, and 3) alternating-amplitude solitons to mitigate not only soliton-soliton interaction but also Gordon-Haus timing jitter constraints [20], [21]. In Sect. 6, the effect of wide band optical filters on timing jitter reduction has been investigated in 20 Gbit/s loop experiments. Finally, single-carrier, single-polarization 20 Gbit/s soliton data transmission over 11500 km with bit error

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rate of below 10^{-9} has been experimentally demonstrated using these simple and practical technologies [22].

2. Soliton Transmission and Its Limitations

2.1 Soliton Transmission Using EDFA Repeaters

Soliton transmission based on EDFA repeaters was first experimentally demonstrated by Nakazawa et al. [4] and followed by insensitive theoretical analysis using guiding-center theory or pass-average solitons [5], [6]. Soliton transmission systems suffer from a number of constraints. The initial pulses must have a transform-limited squared hyperbolic secant ($sech^2$) form. A non-ideal pulse is able to reshape itself into a soliton pulse but it generates a small dispersive wave. The required peak power for excitation of a fundamental soliton pulse in the fiber is given as [3]

$$P_{sol}=0.776\lambda^3 A_{eff}D/(\pi^2 c n_2 \tau^2), \qquad (1)$$

where A_{eff}: effective core area of fibers (μm^2), D: chromatic dispersion (ps/km/nm), τ: width of soliton (FWHM) (ps), n_2: the nonlinear constant of the fiber (m^2/W), λ: wavelength, and c: speed of light. In the lumped amplifier system, stable transmission can be achieved when the repeater span Z_a is enough smaller than soliton period Z_0 represented as [3]

$$Z_0=0.322\pi^2 c\tau^2/(\lambda^2 D). \qquad (2)$$

In this case, optical power at the beginning of each transmission pass should be emphasized so as the pass-average power in the transmission span to be identical to P_{sol} [4]-[6].

2.2 Gordon-Haus Jitter

The Gordon-Haus effect, which is the major limitation on soliton transmission, is well known as a timing jitter resulted from random variation of the soliton center frequency, caused by ASE noise of optical amplifiers and fiber nonlinearity, and the non-zero fiber dispersion [8]. The variance of Gordon-Haus jitter in lumped amplifier systems is given as [7]

$$\langle \delta t^2 \rangle = 0.1959 h n^2 \alpha \beta F(G) L^3 D/(A_{eff}\tau), \qquad (3)$$

where $F(G)=(G-1)^2/G \ln(G)^2$, G: amplifier gain, h; Planck's constant, L: total distance (in thousands of km), and β: the excess noise factor of the amplifier. Equation (3) indicates that the use of lower fiber dispersion and wider pulse width is effective to reduce the Gordon-Haus timing jitter. Taking into account the signal-to-noise ratio at the receiver and interaction between adjacent solitons, however, there is an optimum value for the quantity τ/D [7].

A simple way to reduce the Gordon-Haus jitter have been proposed from two groups [10], [11], which uses narrow-band frequency guiding filters periodically distributed along the transmission line. However, maximum usable filter strength and hence the attainable reduction in jitter is limited, because extra gain around the soliton center frequency, which is need to compensate for the loss at wings of soliton spectrum, amplifies linear waves [13]. As well as inline-synchnorous modulation [17], the sliding-frequency guiding filters can overcome this problem [12], however, it seems very difficult, from engineering point of view, to precisely control the center frequency of each ultra narrow bandpass filter along the transmission pass.

2.3 Soliton Interaction

In soliton systems the pulses interact with each other through the nonlinear index due to overlap of the tails of the pulses or through the radiated dispersive wave. This interaction also cause jitter. Soliton interaction strongly depends on the optical phase difference Θ between adjacent solitons and pulse separation [25]. The optical phase at the distance Z for an isolated soliton with amplitude η_i is represented by

$$\Theta_i=\pi\eta_i^2 Z/4Z_0. \qquad (4)$$

When two adjacent solitons are in-phase ($\Theta=0$), two solitons attract each other along the fiber length and they collide periodically with the oscillation period expressed by

$$\xi p=Z_0 \exp(0.88\Delta), \qquad (5)$$

where $\Delta=T/\tau$ (T: bit period) is the pulse separation. In case of out of phase ($\Theta=\pi$), the pulse separation increases with distance. These soliton interactions can be reduced with increasing the pulse separation Δ. However, in higher speed soliton transmission, the reduction of soliton interaction between adjacent solitons becomes more important, because a relatively large soliton separation, necessary to avoid soliton interaction, limits the bit rate of soliton transmission system due to the Gordon-Haus jitter proportional to

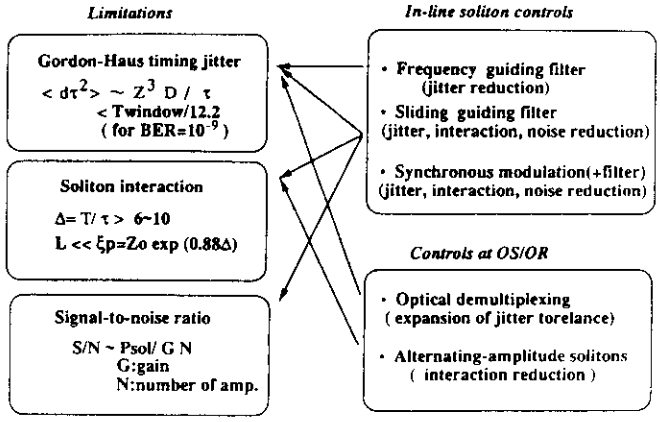

Fig. 1 Limitations in soliton transmission and soliton controls.

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D/τ. Optical TDM scheme can reduce the effect of timing jitter on BER and alternating-amplitude solitons can reduce the soliton interaction maintaining small pulse separation [20]. We discuss the optical TDM and alternating-amplitude soliton in Sects. 4 and 5 in details. Figure 1 summarizes the limitations is soliton transmission and methods to reduce limitations by using soliton controls.

3. Soliton Pulse Generation by EA Modulator

To realize optical soliton transmission systems, it is of primary importance to develop a practical soliton pulse generator providing transform-limited sech^2 shape pulses. We have proposed external modulation of a constant output power from a CW laser using a sinusoidally modulated semiconductor electroabsorption (EA) modulator without any optical resonators [18]. By using the pulse compression effect due to nonlinear attenuation characteristics of InGaAsP EA modulators [27] to the applied voltage, a nearly transform-limited optical pulse train can be generated just with sinusoidal modulation. The pulse shape obtained by the EA modulator is of between sech^2 shape and Gaussian shape. Figures 2(a) and (b) show an example of a measured optical waveform and a power spectrum, of 10 GHz pulses generated from an InGaAsP EA modulator driven by $5.2\,V_{p-p}$ modulation voltage, respectively. The FWHM of the pulse was 15 ps and spectral width was about 23 GHz. The time-bandwidth product of 0.34 is in good agreement with the theoretical prediction assuming quasi-transform limited pulse of between sech^2 shape and Gaussian shape. The pulse width of as small as 10% of the modulation period can be obtained as increasing the bias voltage, almost independently of the repetition rate. These features result in high controllability in terms of pulse width and repetition rate. Since the pulse generation takes place in one device without any filters and cavities, this simple technique can simultaneously satisfy high quality, robustness, compactness and versatility required for a practical soliton pulse generator in multi-ten Gbit/s range.

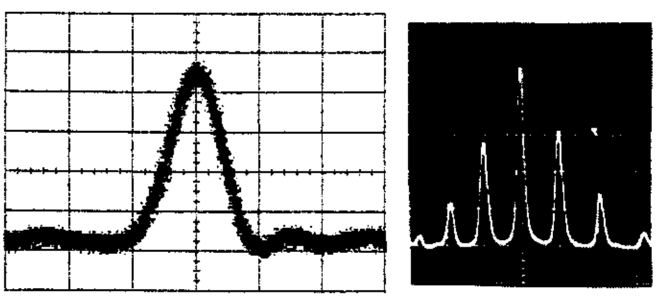

Fig. 2 Optical waveform and spectrum for a 10 GHz pulse generated by sinusoidally modulated InGaAsP EA modulator.

4. Optical Time-Division-Multiplexing/Demultiplexing

4.1 Optical Demultiplexing for BER Improvement

When timing jitter is a dominant limitation to transmission characteristics, an acceptance time window T_{window} or phase margin of the error detector must be at least 12.2 times wider than the standard deviation σ of the jitter for a Gaussian distribution, in order to obtain the BER of less than 10^{-9}. Electronic error decision circuit can not usually utilized the full bit time period $T=1/B$ (B: bit rate) as an acceptance window because of the performance limit of decision circuits, and it is typically limited 2/3 times T. Optical time-division-multiplexing/demultiplexing is an efficient way to extend the acceptance window up to the full time bit period, if an optical demultiplexer provides a square-shape optical gate with duration T. Figure 3 illustrates the improvement of BER characteristics by using the optical demultiplexing with duration T. The jitter-limitted BER of 10^{-9} in direct error detection with acceptance window of 2/3 $T(=6.1(2\sigma))$ can be reduced to be as small as 5.8×10^{-20} by the optical demultiplexing with square-shape optical gate with duration T, which corresponds the acceptance window of 18.3 standard deviations $(9.15(2\sigma))$ of Gaussian distribution in pulse arrival times. Since the timing jitter is the dominant limitation on soliton transmission, we can expect drastic improvement of BER characteristics by employing such an optical demultiplexing.

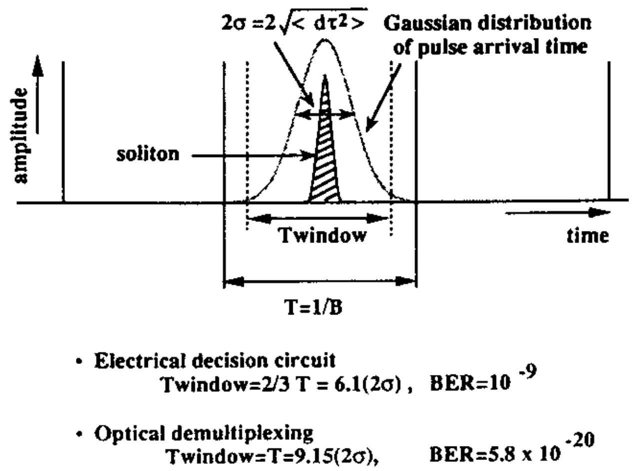

Fig. 3 Optical demultiplexing for improvement of BER characteristics.

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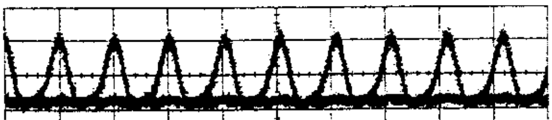
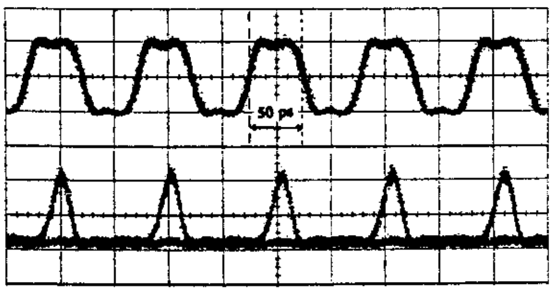
4.2 Optical EA Demultiplexer

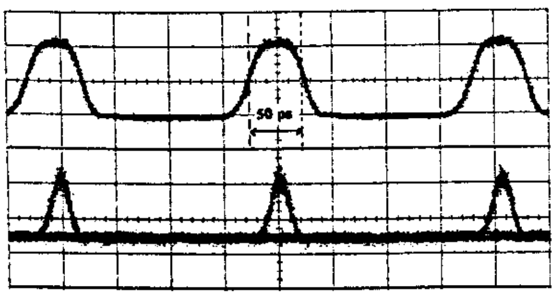
Polarization insensitivity, high extinction ratio, and high controllability of the optical gate width are strongly required for a practical optical demultiplexer. In several optical demultiplexing schemes, an optical demultiplexer using a sinusoidally driven EA modulator [19] is a promising and practical optical demultiplexer in multi-ten Gbit/s optical TDM system, because of its polarization insensitivity, high stability, high controllability of gate width, and single frequency driving scheme. The EA modulator can provide a square shape optical gates with variable duration by changing the sinusoidal modulation voltage and bias voltage, because of the nonlinear attenuation characteristics for reverse bias voltage and for nearly constant response for positive bias voltage [19]. Figure 4 shows 2 : 1 and 4 : 1 optical demultiplexing experiments for data coded 20 Gbit/s signals using an InGaAsP EA modulator with polarization dependent loss of 0.1 dB.



(a) 20 Gbit/s multiplexed pulses.



(b) optical gate for 2 : 1 demultiplexing and 10 Gbit/s demultiplexed pulses.



(c) optical gate for 4 : 1 demultiplexing and 5 Gbit/s demultiplexed pulses.

Fig. 4 2 : 1 and 4 : 1 optical demultiplexing experiments for data coded 20 Gbit/s signals using a sinusoidally driven InGaAsP EA modulator. (50 ps/div).

Figures 4(a), (b), and (c) show 20 Gbit/s multiplexed signals, optical gate for 2 : 1 demultiplexing and 10 Gbit/s demultiplexed signals, and optical gate for 4 : 1 demultiplexing and 5 Gbit/s demultiplexed signals, respectively. Even though the EA modulator was driven with the single frequency of 10 GHz and 5 GHz, the InGaAsP EA modulator could provide a nearly square shape optical gates with full bit period of 50 ps for the desired subchannel, and more than 20 dB rejection of the other subchannels, almost independently of incoming signal polarization. Because of this single and low frequency driving scheme, before multiplexing, this optical demultiplexer has potential for 4: 1 demultiplexing for higher bit rate such as 40 Gbit/s or more.

5. Alternating-Amplitude Solitons

5.1 Interaction Reduction by Alternating-Amplitude Solitons

We have experimentally investigated the effect of pulse separation on soliton interaction at 5 Gbit/s. In our loop experiments [24], transmission distance for 10^{-9} BER was increased from 10000 km to over 13000 km with increasing pulse separation from 6.4 to 8.3 as shown in Fig. 5. For multi-ten Gbit/s soliton transmission, however, it is important to search for methods to reduce soliton-soliton interaction maintaining small pulse separation, because large separation of pulses leads increasing of Gordon-Haus jitter. So far, soliton transmission experiments have been done by using equal amplitude solitons. However, interaction between adjacent solitons cannot be avoidable for small pulse separation as described in Sect. 2. It has been theoretically proposed that soliton interaction can be reduced by using unequal amplitude solitons and that the pulse separation can be reduced by a factor of 2 by using unequal amplitude solitons for the neighboring two solitons [25], [26]. For data coded solitons with pseudorandom bit sequence, we have

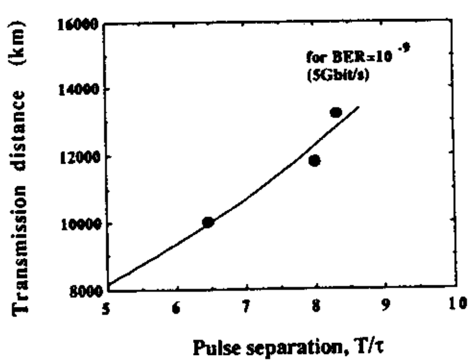


Fig. 5 Effect of soliton interaction (Transmission distance for 10^{-9} BER vs. pulse separation at 5 Gbit/s).

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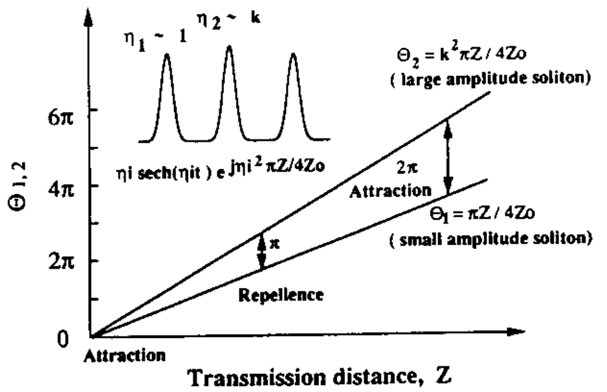


Fig. 6 Optical phase variation vs. transmission distance in alternating-amplitude solitons.

experimentally confirmed that alternating-amplitude solitons with consecutively arranged large and small amplitude solitons can reduce the soliton interaction significantly [20], [21]. Alternating-amplitude solitons allow us to use relatively wide pulse for keeping small Gordon-Haus effect.

The relative phase of the larger and the smaller amplitude solitons is varied with distance according to Eq. (4), due to the different phase velocities of different amplitude solitons. Using amplitude ratio k between the alternated amplitudes normalized by the smaller amplitude and soliton period Z_0 for smaller amplitude soliton, the relative phase at transmission distance Z can be roughly represented as

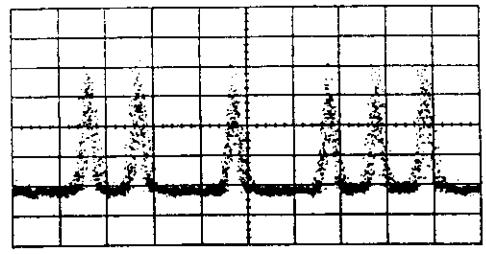
$$\Theta = (k^2 - 1)\pi Z/4Z_0. \tag{6}$$

Figure 6 shows the phase variations for large and small amplitude solitons versus transmission distance. The phase difference between two solitons increases with increasing the distance, and consequently, the attraction (in-phase) and repellence (out-of-phase) occur periodically along the fiber length and soliton interactions can be reduced [25], [26]. The distance for π phase shift for alternating amplitude solitons of $k=1.1$ and $Z_0=300$ km (typical soliton period for 10 Gbit/s) is 5700 km and 2800 km for $Z_0=150$ km, respectively. Eventually, the use of alternating-amplitude soliton at the transmitter corresponds to introduction of distributed inline phase modulation in the transmission pass. This technique is very effective to reduce soliton interaction in a simple manner and quite attractive for implementation.

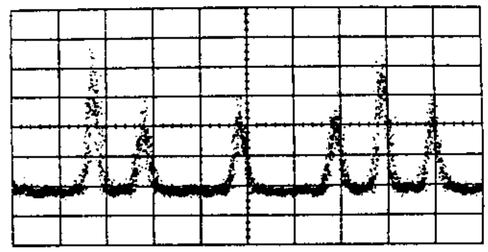
5.2 Experimental Study of 10 Gbit/s Alternating-Amplitude Solitons

Figures 7 (a) and (b) show examples of the waveforms after 9100 km transmission using the fiber loop [20] for optical TDM 10 Gbit/s constant-amplitude solitons and alternating-amplitude solitons, respectively. The initial amplitude was preserved even after long distance transmission and it is clearly found the timing jitter of alternating-amplitude solitons is smaller than that of constant-amplitude solitons. Figure 8 shows BER after 9100 km transmission as a function of amplitude ratio k, for 10 Gbit/s signals with pulse separation $\Delta=4.4$. For relatively small pulse separation, the interaction was reduced and BER was also reduced with increase in amplitude ratio, but, relatively large amplitude ratio such as $k=1.2$ resulted in BER degradation, which might be due to signal-to-noise ratio degradation for small amplitude solitons.

From view point of total performance, the proper value of k depending on pulse separation should be selected. For the case of $k=1.09$ and $\Delta=4.4$ as described above, the maximum transmission distance for 10^{-9} BER was limited to 9300 km [20]. We varied the pulse separation and investigated the optimum k value for the maximum transmission distance. Figures



(a) constant-amplitude solitons.



(b) alternating-amplitude solitons.

Fig. 7 Waveforms after 10 Gbit/s, 9100 km transmission (100 ps/div).

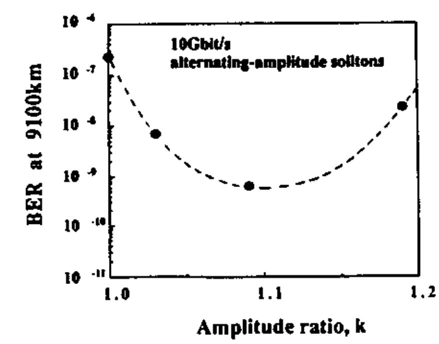


Fig. 8 BER after 9100 km transmission of 10 Gbit/s alternating-amplitude solitons as a function of amplitude ratio k.

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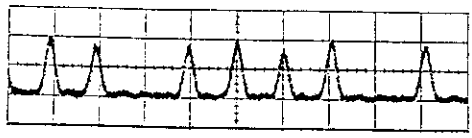
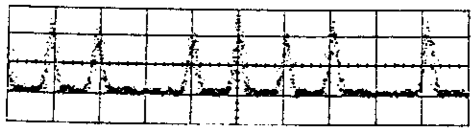
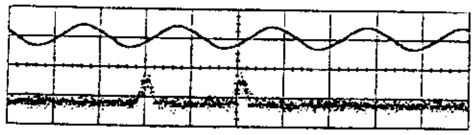


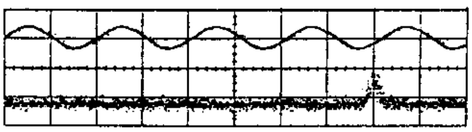
(a) initial 10 Gbit/s pulses.



(b) received 10 Gbit/s pulses after 11650 km transmission.



(c) Demultiplexed large amplitude solitons (ch1) and clock after transmission.



(d) Demultiplexed small amplitude solitons (ch2) and clock after transmission.

Fig. 9 Waveforms for 10 Gbit/s, 11650 kym transmission (100 ps/div).

Table 1 Summary of 10 Gbit/s transmission experiment using alternating-amplitude solitons.

pulse separation Δ	amplitude ratio k	fiber dispersion (ps/km.nm)	maximum distance (km) (for 10^{-9} BER)
4.4	1.09	0.47	9300
4.8	1.08	0.43	11600
5.5	1.06	0.43	12200

9 (a), (b), (c), (d) show the initial waveforms for 10 Gbit/s optical TDM alternating-amplitude solitons with $k=1.08$ and $\Delta=4.8$, 10 Gbit/s received waveforms after 11650 km transmission, demultiplexed large-amplitude solitons (ch1) and the 5 GHz extracted clock at 11650 km, and demultiplexed small-amplitude solitons (ch2) and the clock, respectively. BER for both channels was less than 10^{-9}. In these experiments, we observed tendency that BER for small amplitude solitons (ch2) was slightly greater than that for large amplitude solitons (ch1), and this results indicate the maximum transmission distance is limited by degradation of signal-to-noise ratio rather than the timing jitter. The best BER characteristics were obtained for amplitude ratio of $k=1.06$ and $\Delta=5.5$. The BER less than 10^{-9} was obtained after 12200 km transmission. Table 1 summarizes the experimental results of maximum transmission distance for 10^{-9} BER for various k and Δ and indicates a reasonable tendency that k value becomes close to unity with increasing the pulse separation. Note that the difference of fiber dispersion is one cause of large difference of the maximum transmission distances. The relative phase of adjacent solitons at 12200 km is estimated to be $5\pi/4$ and this value is not so large, but, these experimental results show the effectiveness of alternating-amplitude solitons for performance enhancement of soliton-based transmission systems.

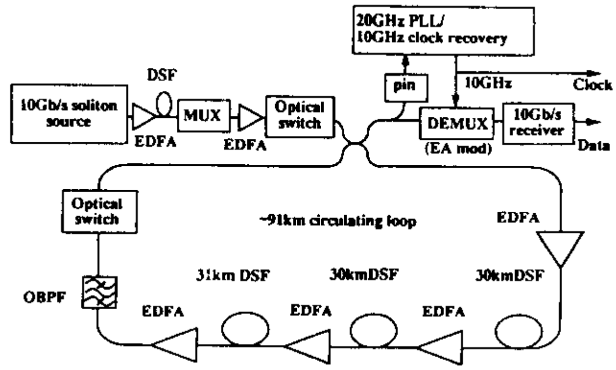


Fig. 10 Experimental setup for 20 Gbit/s transmission.

6. 20 Gbit/s Single Channel Soliton Transmission over 11500 km

As for 20 Gbit/s transmission, feasibility of transmission of transoceanic distance has been only demonstrated by 20 Gbit/s, over 13000 km transmission experiment in two-channel WDM using sliding frequency guiding filters [15]. This technique however, requires precise adjustment of the center frequency of each optical filters. It seems more practical especially for undersea cable application, however, if we could obtain similar performance without using such ultra-narrow band sliding-guiding filters. In this section, we have investigated the jitter reduction effect of relative wide optical BPFs and demonstrated the feasibility of single-channel 20 Gbits/s soliton data transmission system over 10000 km based on conventional optical amplifier repeaters, by using the EA modulator-based soliton source, the optical time-division demultiplexing, and alternating-amplitude solitons.

6.1 Experimental Setup

Figure 10 shows the experimental setup. The 10 Gbit/s soliton source consists of a DFB-LD operating at 1553.6 nm, a sinusoidally driven InGaAsP electroabsorption (EA) modulator for pulse generation, $LiNbO_3$ intensity modulator and EDFAs. The 10 Gbit/s $2^{11}-1$ pseudorandomly modulated 15 ps-wide pulse sequence from the soliton source was slightly compressed to 11.5 ps with a time-bandwidth product of 0.33 by using higher order soliton effect in 11 km long

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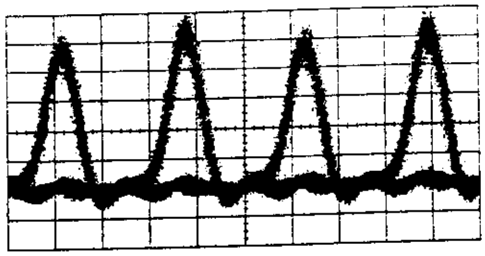


Fig. 11 Initial 20 Gbit/s alternating-amplitude solitons with $k = 1.05$ (20 ps/div).

dipesion-shifted fiber. This 10 Gbit/s pulse train was time-division multiplexed to 20 Gbit/s with the same polarization. The amplitude of the two subchannels was alternated between large and small using a passive optical multiplexer [20]. Figure 11 shows eye pattern for 20 Gbit/s alternating-amplitude solitons with $k=1.05$ from the transmitter. Two acoustic-optic (AO) switches were employed in the experiment to control the optical signal transmission through the fiber loop. The 91 km circulating loop consisted of three spans of 30 km dispersion shifted fibre (average dispersion: 0.22 ps/km/nm, average loss: 0.21 dB/km), four EDFAs pumped at 1480 nm, and a second-order Butterworth-type optical bandpass filter (OBPF). The average optical power launched into the transmission fiber was set to 0 dBm. The soliton period was estimated to be about 250 km. The transmitted signal was optically time-division demultiplexed to 10 Gbit/s by a nearly polarization insensitive InGaAsP EA modulator driven by the recovered 10 GHz sinusoidal clock signal from the 20 GHz phase-locked-loop. The EA demultiplexer provided an almost flat 50 ps-wide optical gate to the desired subchannel and more than 20 dB rejection to the other subchannel.

Frequency-guiding filters can reduce the timing jitter, but, the use of narrow-band filters lead to eventual instability of solitions because of the extra gain around soliton center frequency to compensate for the loss of soliton spectrum through the filtering [12], [13]. Narrow band filter about 1 nm bandwidth could not be used unless the filter center frequency is sliding with distance along the transmission line [12]. In our experiment, we used relatively wideband OBPFs with different bandwidths of 2.1 nm and 3.0 nm. These second-order Butterworth-type optical bandpass filters have been well developed for ASE noise reduction in conventional EDFA repeaters and have rather flat-top transmission characteristics. The peak curvatures of the OBPFs were 2.7×10^{-5} GHz^{-2} for 2.1 nm bandwidth and 7.6×10^{-6} GHz^{-2}, for 3.0 nm bandwidth, respectively. These values are over 10 to 40 times more gradual than that of the sliding frequency guiding filters and fixed frequency guiding filters placed after every EDFA used in the reported 10 Gbit/s transmission experiments [15], [16].

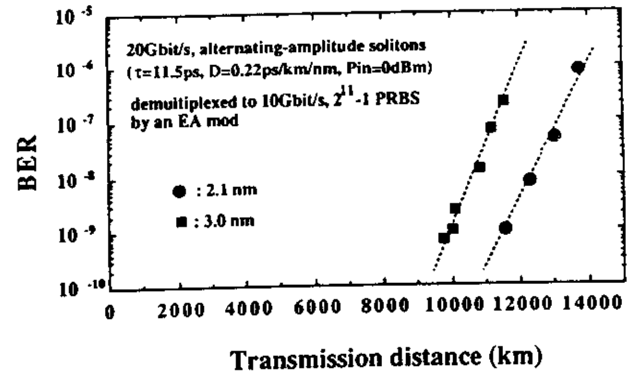
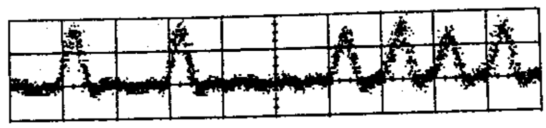


Fig. 12 Bit error rate for demultiplexed small amplitude solitons vs. transmission distance in 20 Gbit/s alternating-amplitude soliton transmission experiments using second order Butterworth OBPFs with 2.1 nm and 3.0 nm bandwidth.

(a) before transmission.



(b) after 11500 km transmission.

Fig. 13 Measured 20 Gbit/s waveforms for transmission experiments using 2.1 nm OBPF (50 ps/div).

6.2 Results and Discussion

Figure 12 shows the measured BER characteristics for small amplitude solitons (the worse subchannel) as a function of transmission distance in 20 Gbit/s alternating-amplitude soliton transmission using two different OBPFs. The transmission distances for the BER of less than 10^{-9} were 9700 km for 3.0 nm-OBPF, and 11500 km for 2.1 nm-OBPF, respectively. Figures 13 (a) and (b) show waveforms before and after 11500 km transmission using 2.1 nm-OBPF. As expected from the theory of frequency guiding filters [10], [11], the observed timing jiter in the experiment using 2.1 nm-OBPF was well suppressed as shown in Fig. 13, and the jitter reduction effect of 2.1 nm-OBPF was larger than that of 3.0 nm-OBPF. As shown in Fig. 13, the initial amplitude ratio was preserved even after 11500 km transmission, which manifests that the OBPF used in the loop did not function as a strong frequency guiding filter [11]. Nevertheless, the OBPF with 2.1 nm bandwidth could reduce the timing jitter to one third of the one without guiding filtering effect, assuming 50

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ps acceptance time window of our error detection system. Since we cannot use too narrower band filter, the bandwidth of 2.1 nm is estimated to be close to an optimum value for second-order Butterworth filters. These results indicate that, in 20 Gbit/s single channel soliton transmission using short soliton pulses, even relatively wide-band OBPFs conventionally used for ASE noise reduction can effectively reduce the timing jitter. It is recently pointed out that a frequency shift of the optical carrier produced by an AO switch used in the loop is equivalent to the sliding of the in-line filter [28]. In our experiment, the total frequency shift at 10000 km transmission distance is as small as 0.48 times the soliton bandwidth. Compared with the corresponding value of 3.4 times the soliton bandwidth for the sliding filters reported in [15], this value is too small for the purpose of separation of the signal spectrum from the noise spectrum. In this experiment, the effect of the AO switch is estimated to be small. Note that the oscillation period of soliton-soliton interaction for constant amplitude solitons is estimated to be 11500 km and alternating-amplitude solitons avoided soliton-soliton interaction significantly. 230 Tbit/skm transmission capacity is more than five times the reported rate-distance product for single channel 20 Gbit/s soliton transmission [23].

7. Conclusion

We have studied the feasibility of 20 Gbit/s single channel soliton transmission over transoceanic distances and have demonstrated fully practical technologies. We have developed a simple and practical soliton pulse generator and an almost ideal polarization insensitive optical demultiplexer which can provide a almost square shape optical gate with duration of full bit time period, using sinusoidal modulation of an EA modulator. This optical demultiplexing scheme results in drastic improvement of BER characteristics. Alternating-amplitude solitons have been experimentally studied and it has been confirmed that alternating-amplitude solitons can reduce soliton interaction significantly. As the use of alternating-amplitude soliton at the transmitter corresponds to introduction of distributed inline phase modulation along the transmission pass, this technique is effective for performance enhancement of soliton transmission systems in a simple manner. The jitter reduction effect of relatively wide-band OBPFs conventionally used for ASE noise reduction has been investigated. Finally, we have experimentally demonstrated the feasibility of single-carrier, single-polarization 20 Gbit/s soliton data transmission over 11500 km with BER of below 10^{-9} using these key technologies. 230 Tbit/skm transmission capacity is more than five times the reported rate-distance product for single channel 20 Gbit/s soliton transmission and these results show the feasibility of 20 Gbit/s single channel transoceanic soliton communication systems.

Acknowledgement

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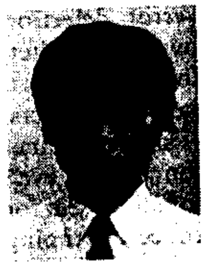

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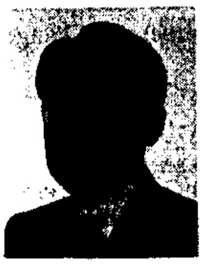

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