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Conference on Ultrafast Transmission Systems in Optical Fibres

13-17 February 1995

Long-Haul Optical Amplifier Transmission Systems Using the Non-Return-to-Zero Modulation Format

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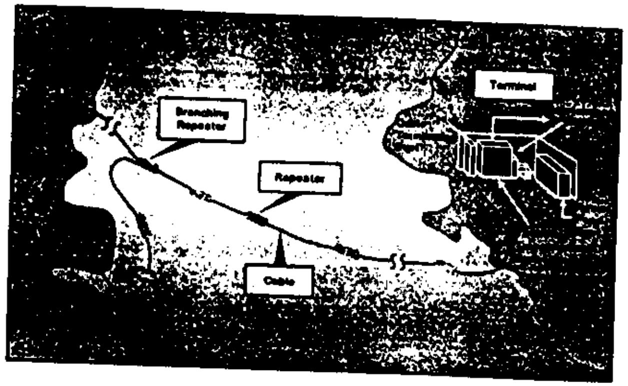
UNDERSEA LIGHTWAVE TRANSMISSION SYSTEM



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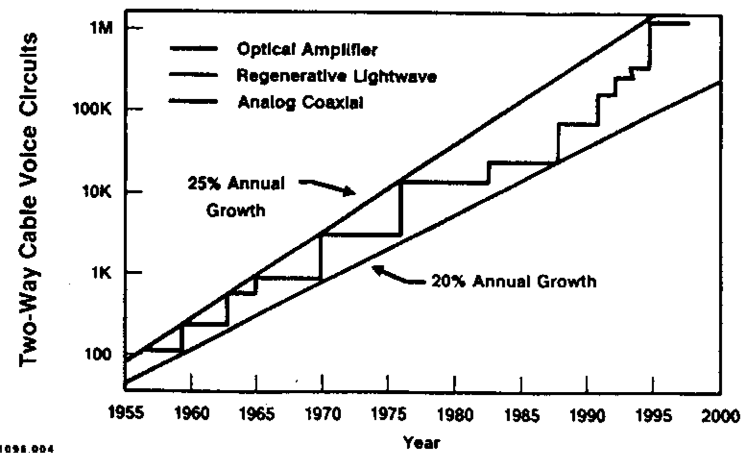
Long-Haul Optical Amplifier Transmission Systems Using the Non-Return-to-Zero Modulation Format

- Undersea Cable Systems
- The NRZ Modulation Format
- System Design
- Measures of System Performance
- Polarization Effects
- Transmission Experiments

Cumulative Trans-Atlantic Telephone Circuits



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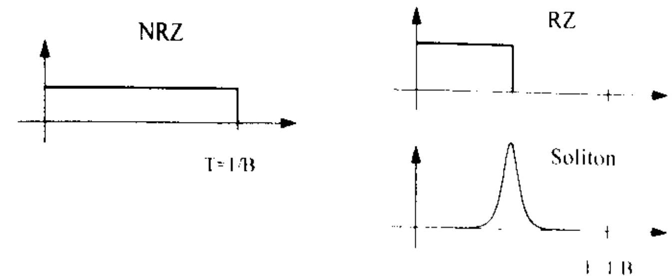
AT&T UNDERSEA CABLE SYSTEMS

SYSTEM	TIME	TYPE	BANDWIDTH OR BIT RATE	NUMBER OF CHANNELS BASIC	NUMBER OF CHANNELS W/TASI (DCMS)	COMMENTS
TAT-1/2 HAW-1	1955/59 1957	SB	0.2 MHz	48	108	COPPER COAX ANALOG Vacuum Tubes
TAT-3/4 HAW-2 H-G-J	1963/65 1964 1964	SD	1.1 MHz	140	315	
TAT-5 HAW-3 H-G-O	1970 1974 1975	SF	6 MHz	840	1,900	Ge Transistors
TAT-6/7	1976/83	SG	30 MHz	4,200	9,450	Si Transistors
TAT-8 HAW-4 TPC-3	1988 1989 1989	SL 280	280 Mb/s	8,000	40,000	OPTICAL FIBER DIGITAL $\lambda = 1.3\ \mu m$
TAT-9	1991	SL 560	560 Mb/s	16,000	80,000	$\lambda = 1.5\ \mu m$
TPC-4 TAT-10/11	1992 1992/3			24,000	120,000	
TAT-12 TPC-5	1995 1995	SL 2000	5 Gb/s	122,880	614,400	Optical Amplifiers $\lambda = 1.5\ \mu m$

2C20962.10-LJ-4/92

NRZ Signal Format

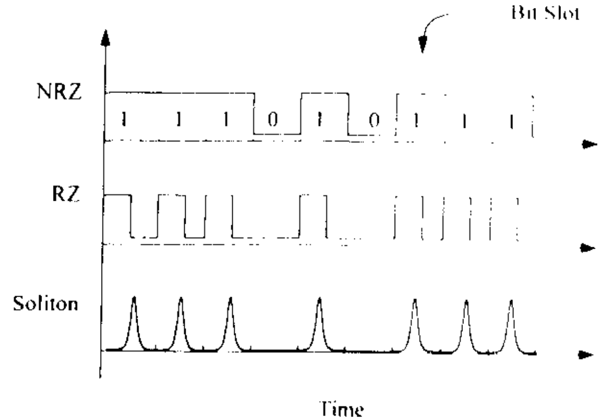
Non-Return-to-Zero (NRZ) is a unipolar binary code. Binary "1" is represented with a pulse, and "0" is represented by the absence of a pulse.



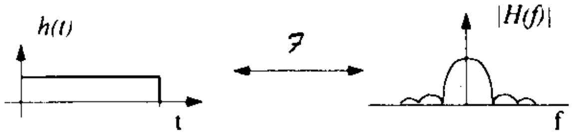
Why Optical Amplifiers?

- Growth Potential - The optical amplifier technology will support next generation system requirements.
- All optical transmission means no high-speed electronics in undersea equipment.
- Simple repeater design translates to a reliable system.
- Flexibility - Amplifier technology can be used in short, medium and long-haul systems.
- A single amplifier design can support different bit rates and wavelength channels.

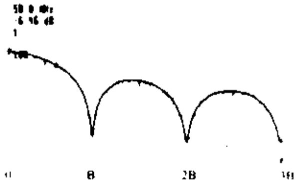
Data Waveforms



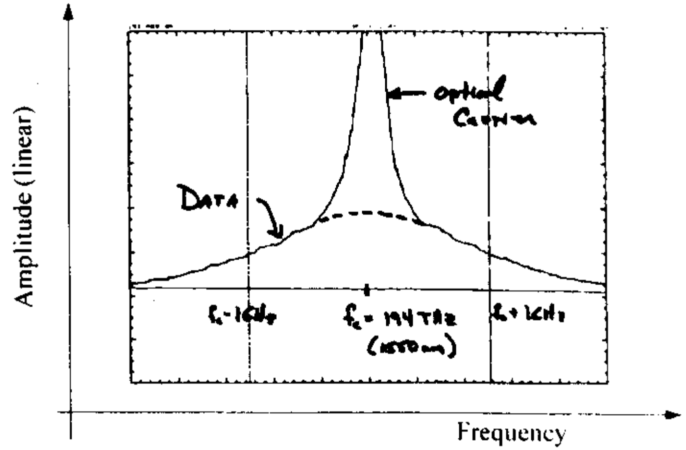
NRZ RF Signal Spectrum



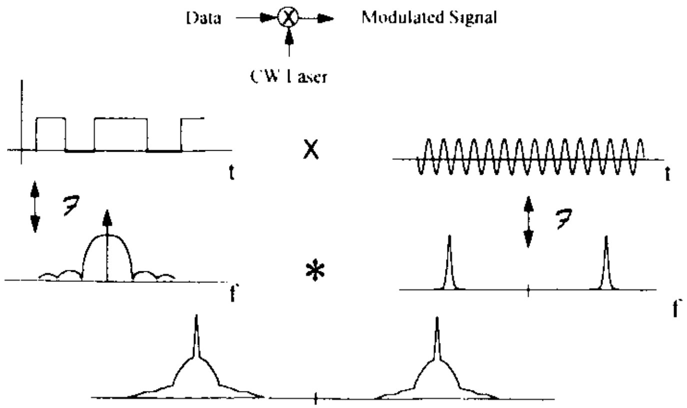
$$P(f) = |H(f)|^2 \left[\frac{p(1-p)}{T} + \frac{p^2}{T^2} \sum_{n} \delta\left(f - \frac{n}{T}\right) \right]$$



NRZ Optical Spectrum - Experimental



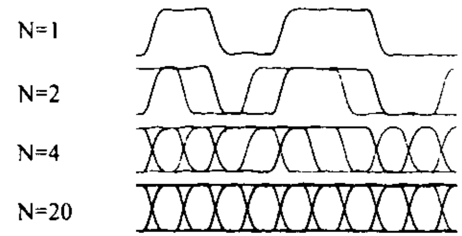
NRZ Optical Spectrum - Theoretical



Eye Diagram *- Graphical method for evaluating impairments such as noise and pulse distortion*

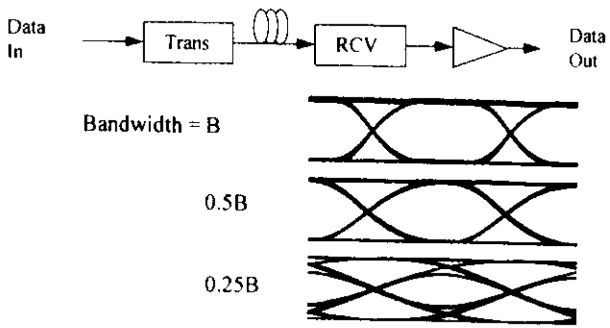
Eye diagrams are useful for observing the worst-case bound on system performance.

If g(t) is the data waveform, Then the eye diagram is the simultaneous display of .... g(t-T), g(t), g(t+T), g(t+2T) .....



NRZ Signal Format - Component Bandwidth

- Theoretical minimum channel bandwidth is 0.5B.
- Practically, (0.6 to 0.7)B is needed for good system performance.
- Transmitter bandwidth > B is needed for adequate rise/fall times.



Modulation Formats - NRZ vs. Solitons

NRZ	*Solitons*
Simple Transmitter	More complex transmitter
More tolerant to power fluctuations	Less tolerant to power fluctuations
Single channel capacity 10Gb/s	Single channel capacity 20Gb/s
WDM $\Delta\lambda$ > 0.5nm	WDM $\Delta\lambda \sim$ 0.1nm
Amplifier gain spectrum more important for WDM	Amplifier gain spectrum less important for WDM
Wavelength stability less important	Wavelength stability more important
Synergy with existing systems	Ultimate in transmission capacity?

AT&T

NRZ Signal Format - Characteristics

- Widely used in high-speed optical communications systems.
- Easy to generate, process, and detect.
- Linear channel bandwidth ~ 0.6B.
- RF spectrum extends to low frequencies; thus, all components must be broad-band.
- No power at the bit rate frequency in the RF spectrum; thus, timing recovery circuit must provide harmonic generation.

What Happened to Coherent Communication?

Receiver Sensitivity -

- Near quantum limited receiver sensitivity has been achieved using EDFA preamplifier front-ends.
- High sensitivity for moderate and high bit rates.

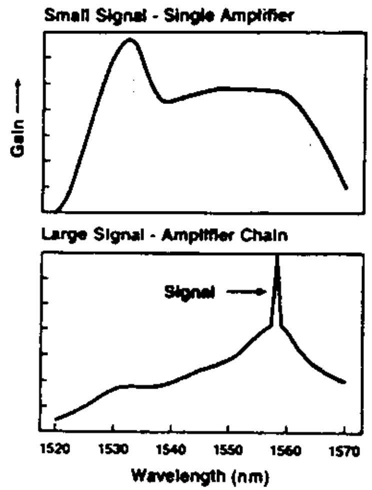
Terminal Complexity -

- Coherent transmitters and receivers are much more complex than existing hardware designed for SL2000 type systems.

Transmission Systems -

- Optical phase is not preserved in long-haul systems due to fiber nonlinearities.

Amplifier Gain Spectrum



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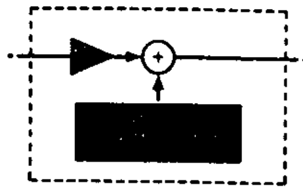
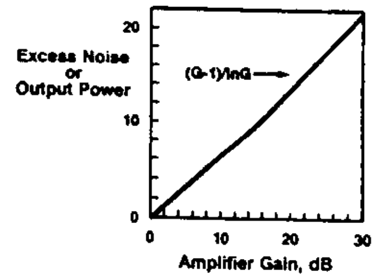
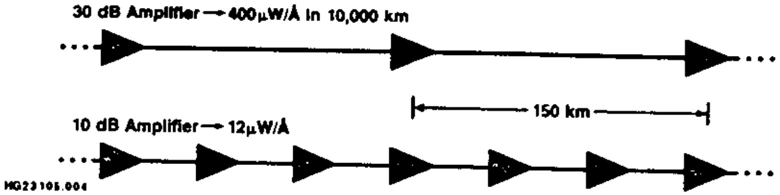
Noise Accumulation In Amplifier Systems







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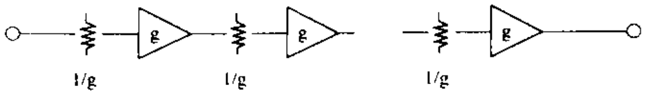
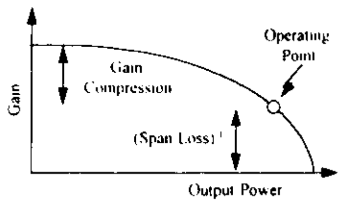
Power Level Control By Amplifier Gain Saturation

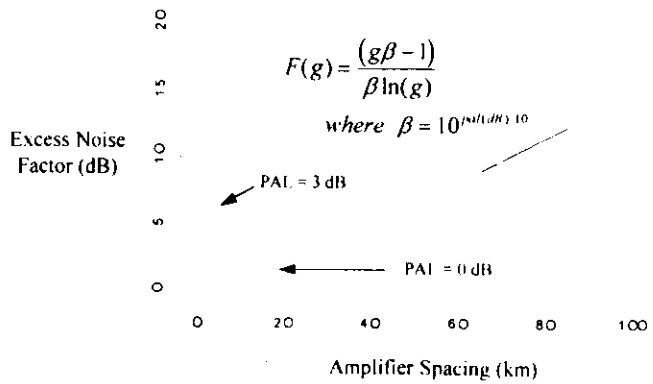


- Amplifiers purposely operated with 5-6 dB of gain compression
- Steady state operation occurs for signal gain = (span loss)$^{-1}$.
- Amplifier saturation provides automatic gain control



*Excess Noise Factor vs. Amplifier Spacing**

(Including the effects of Post-Amplifier-Loss)



$$F(g) = \frac{(g\beta - 1)}{\beta \ln(g)}$$

where $\beta = 10^{\ldots}$

* E. Lichtman, Elec. Lett. Vol 29, No 23

Chromatic Dispersion in an SL2000 Amplifier System.

AT&T/KDD Testbed Data

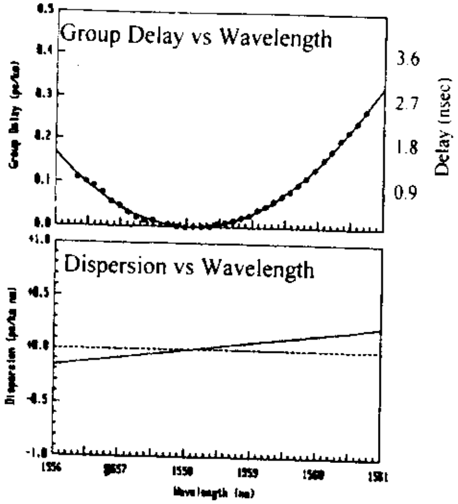
9000km Length,

λ_0 = 1558.08 nm

Example:

For $|\lambda - \lambda_0|$ = 1.5nm, the optical length of the cable is 1 foot longer than at λ_0.

note: One bit is 1.6 in for 5 Gb/s transmission



Optical Fiber Nonlinearities

- **Self Phase Modulation (SPM)**
  - Nonlinear Medium $n = n_0 + n_2 I;\ \Delta\phi = \frac{2\pi}{\lambda} L n_2 I$
  - Causes Spectral Broadening
- **Modulational Instability**
  - SPM + Dispersion Causes Pulse Breakup
- **Four Photon Mixing**
  - Optical Mixing in WDM Systems
- **Stimulated Brillouin Scattering**
  - Power Limit per Channel

HG23238.009

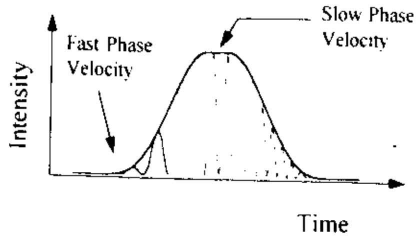
Optical Fiber's Nonlinear Index

$$n = n_0 + N_2 I$$

Index of Refraction — Nonlinear Coefficient — Light Intensity

Nonlinear Phase Shift $\Phi_{NL} \sim N_2 I$

Optical Pulse



Example: L=10,000km, G~10dB

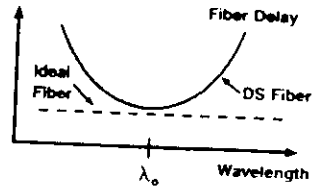
$\Delta T \sim 20$ fsec

$\Delta\Phi \sim 5\pi$ rad

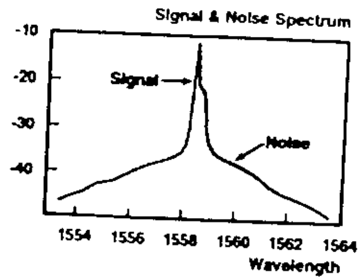
Fiber Dispersion/Nonlinearity Interaction

- NRZ Waveform Distortion Occurs For Operation Away from λ_o

$$B^2 L \sim \frac{1}{D}$$



- Nonlinear Mixing Efficiency Reduced with Dispersion



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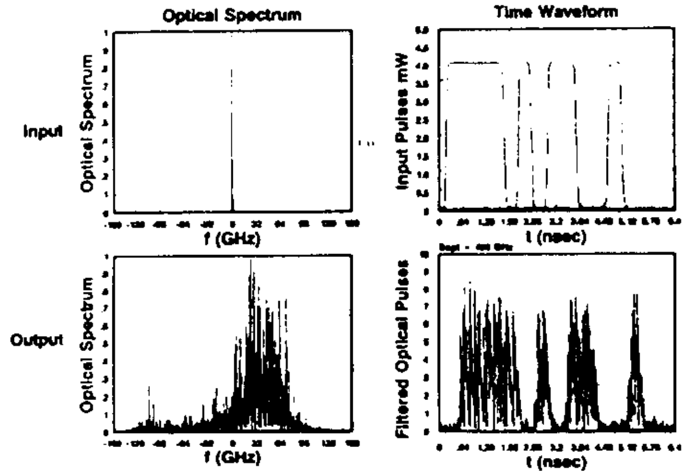
Simulation Of NRZ Transmission*



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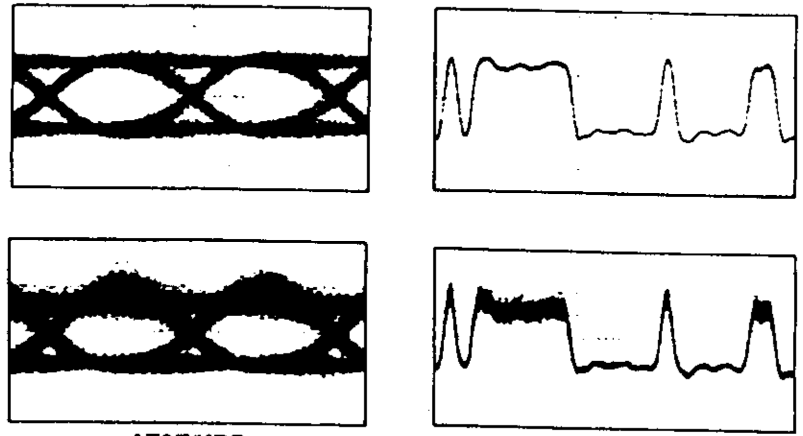
* D. Marcuse, JLT Vol. 9, No. 10, Oct. '91

5-Gb/s Data Waveforms And Eye Diagrams



AT&T/KDD

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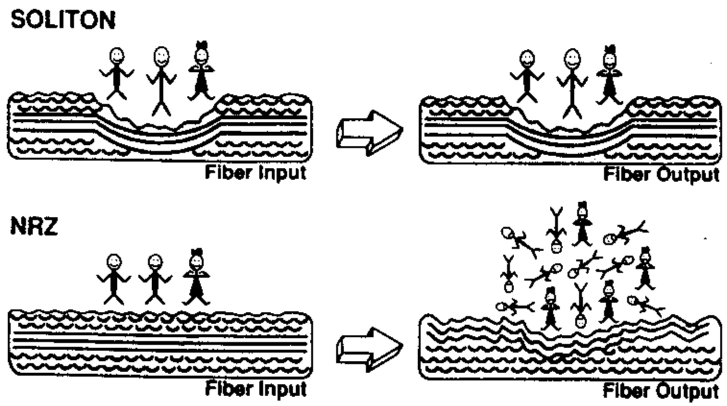
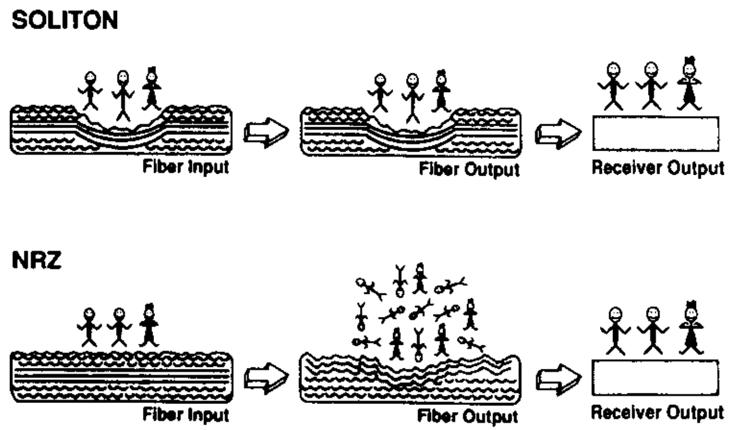
ANTHROPOMORPHIC ANALOG OF SOLITON AND NRZ TRANSMISSION



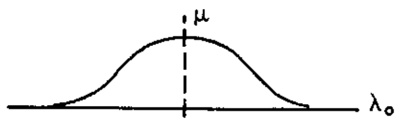
$$-i\frac{\delta u}{\delta z} = \frac{1}{2}\frac{\delta^2 u}{\delta t^2} + |u|^2 u + i(\alpha/2)u$$

ANTHROPOMORPHIC ANALOG OF SOLITON AND NRZ TRANSMISSION



Dispersion Management

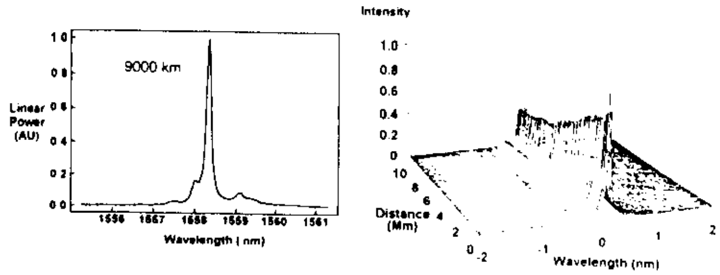
1. DSF Manufactured with $\bar{\lambda}_o > \lambda_p$



1561 nm at Surface Temp
~1560 nm at Ocean Bottom

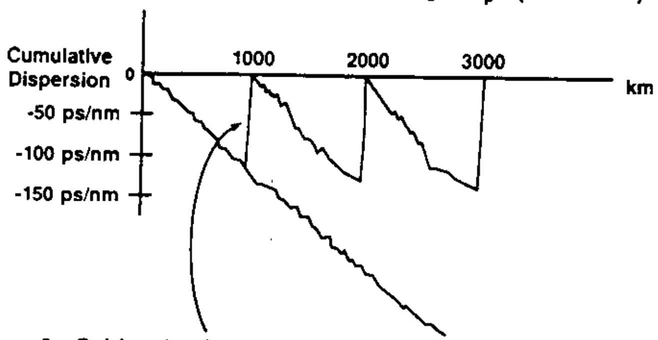
HG32149.003

Optical Spectrum - 5 Gb/s



Dispersion Management

2. Cable Assembled so that at $\lambda_s = \lambda_p$ (1558.5 nm)



3. Cable with Standard SMF Is Added Every ≃ 1000 km so that End-to-End Installed Cable $\lambda_o = \lambda_p = \lambda_s$

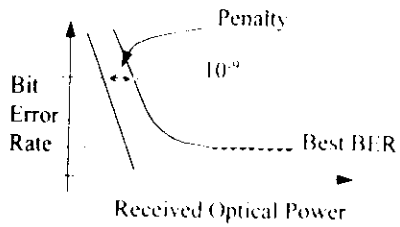
4. Fine Tuning of λ_o on Each Fiber Is Done in Terminal

HG32149.007

Margin in Optical Transmission Systems

Regenerators - Margin is the difference in received optical power and the receiver's sensitivity.

Amplifiers - Margin is defined as the difference in the received SNR and the SNR needed to achieve a 10^{-9} BER.

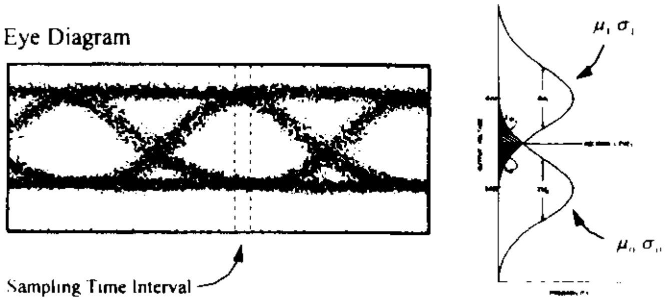


$$\text{Margin(dB)} = SNR_{rcv} - SNR_{spec}$$

Q-Factor is the Electrical SNR at the Decision Circuit

$$Q \equiv \left(\frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \right)$$

Eye Diagram



NRZ Data Waveforms

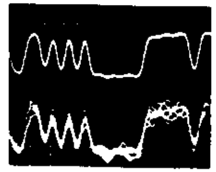
Back-to-back measurements made with different ROP and filtering

Low noise, low distortion →

Large noise, low distortion →

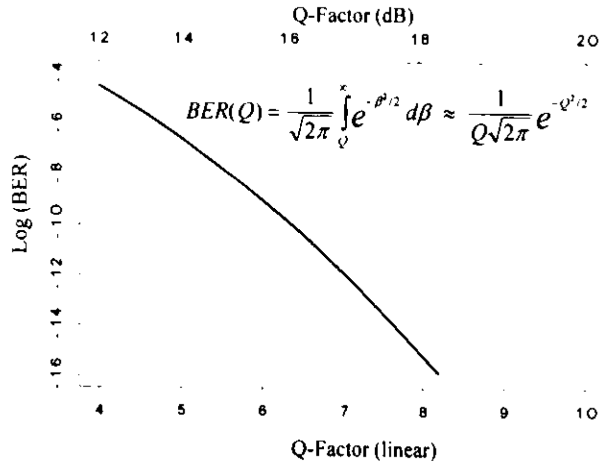
Low noise, large distortion →

Large noise, large distortion →



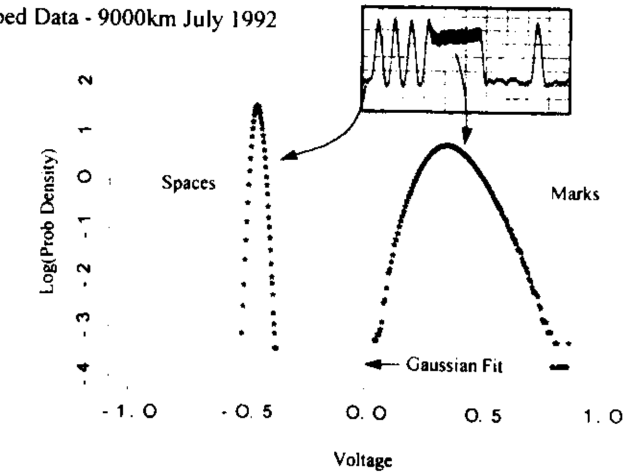
Bit Error Rate vs Q-Factor

$$BER(Q) = \frac{1}{\sqrt{2\pi}} \int_Q^{\infty} e^{-\beta^2/2}\, d\beta \approx \frac{1}{Q\sqrt{2\pi}} e^{-Q^2/2}$$



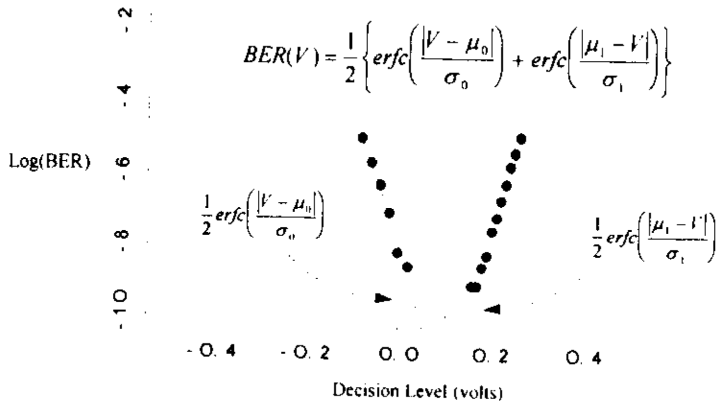
Noise Probability Density Function after 9000km Propagation

Testbed Data - 9000km July 1992

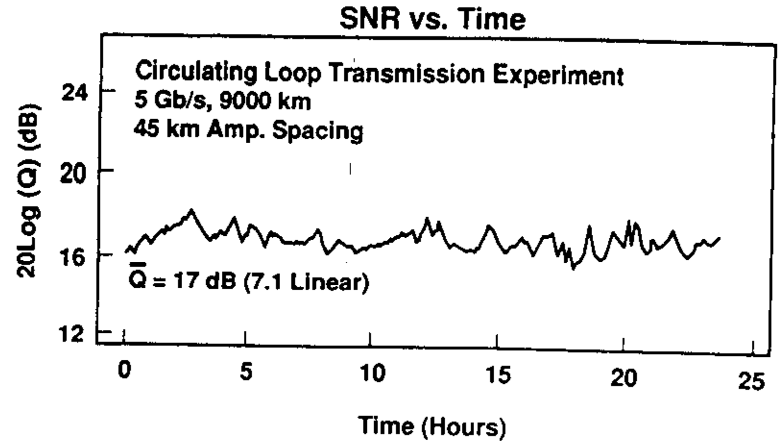


Q-Factor Measurement using the Decision Circuit Method

Testbed Data - 4500km BER vs Decision Level

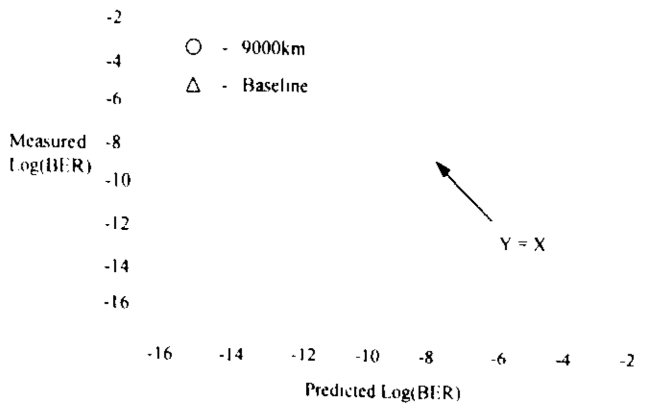


SNR Fluctuations In Optical Amplifier Systems



Measured vs Predicted BER using the Decision Circuit Q-Factor Measurement.

Testbed Data - July 1992 2^{15}-1 Word



Important Polarization Effects In Optical Amplifier Systems

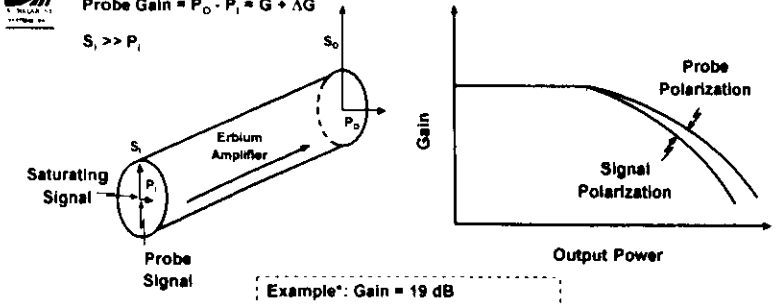
- Signal Polarization Drift - SOP evolves over time, caused by temperature and stress changes of the transmission fiber.
- Polarization Dependent Loss - A component's attenuation has a small dependence on the signal's polarization.
- Polarization Hole-Burning - The amplifier's saturated output power is slightly larger for light in the orthogonal polarization to the saturating signal.
- Polarization Mode Dispersion - The time of flight through the transmission fiber is polarization dependent.

Polarization Hole-Burning In Erbium-Doped Fiber Amplifiers

Signal Gain = $S_o - S_i = G$

Probe Gain = $P_o - P_i = G + \Delta G$

$S_i >> P_i$



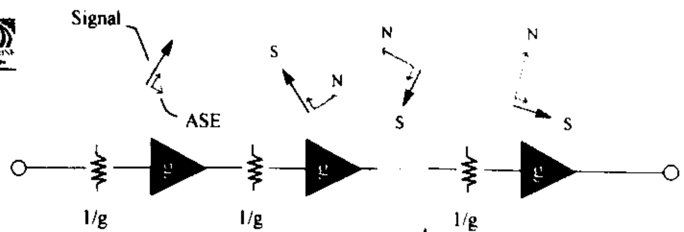
Example*: Gain = 19 dB

Gain Saturation = 3 dB

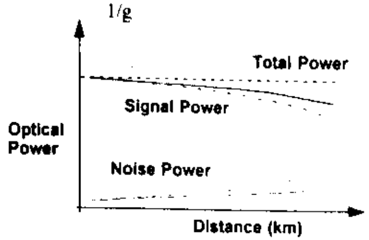
ΔG = 85 mdB

* Mazurczyk and Zyskind, CLEO '93

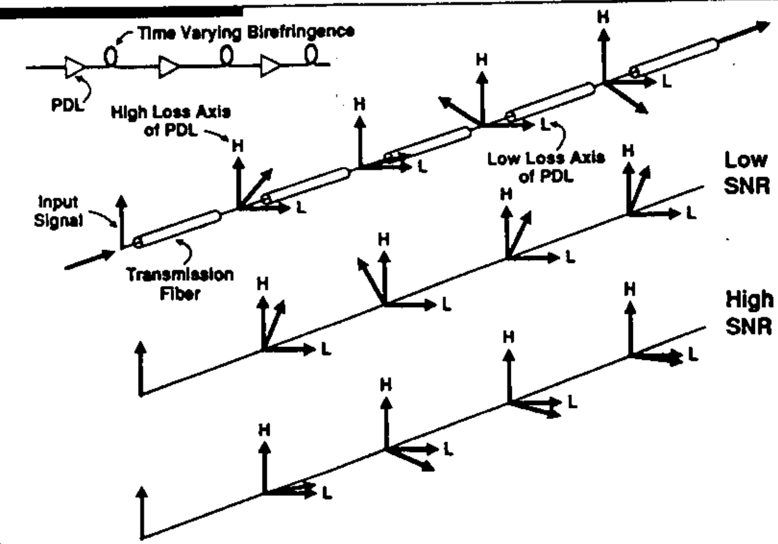
System Impairment Caused by PHB



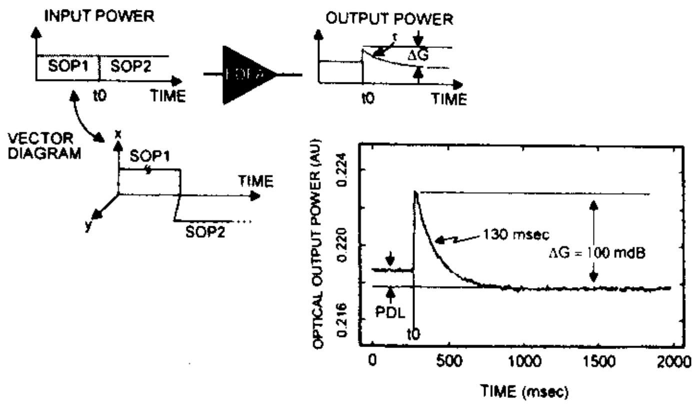
- Amplifiers purposely operated with 5-6 dB of gain compression.
- Steady state operation occurs for signal gain = (span loss)$^{-1}$.
- Orthogonally polarized ASE grows relative to signal.



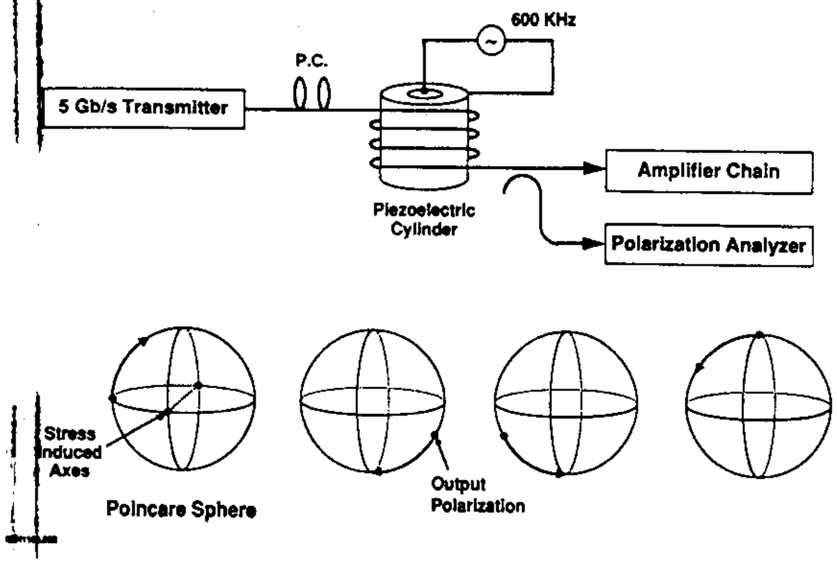
SNR Fluctuations In Optical Amplifier Systems



Time Dynamics of Polarization Hole-Burning



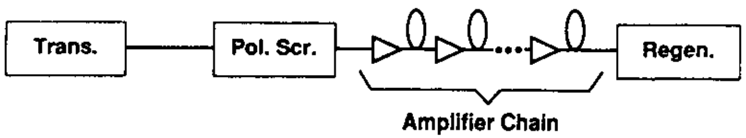
Polarization Scrambled Transmitter

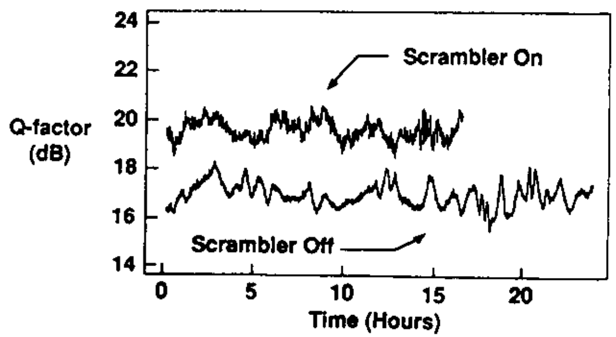


Optical Amplifier Feasibility Demonstrations

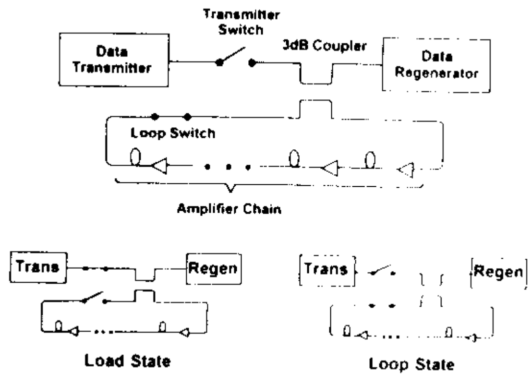
- **Loop Experiments**
  - Cost advantage - smaller amount of equipment needed
  - More flexibility - Can be reconfigured
- **Straight Line Experiments**
  - More accurate representation
  - Most Expensive

Polarization Scrambling Improves SNR Performance In A Chain Of EDFAs

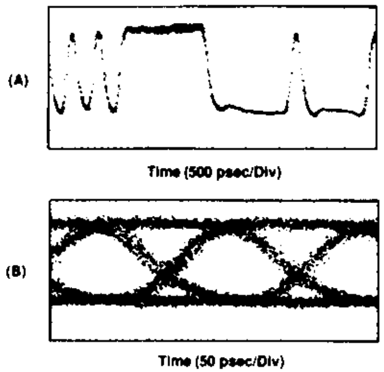




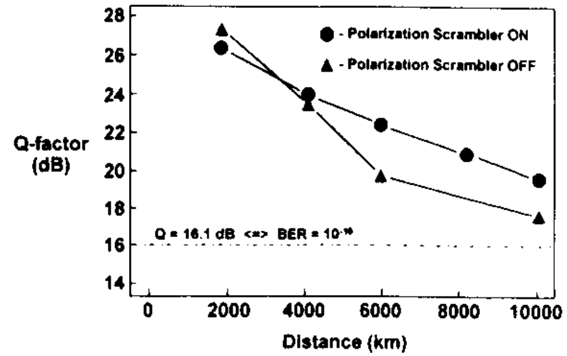
Circulating Loop Transmission Experiment



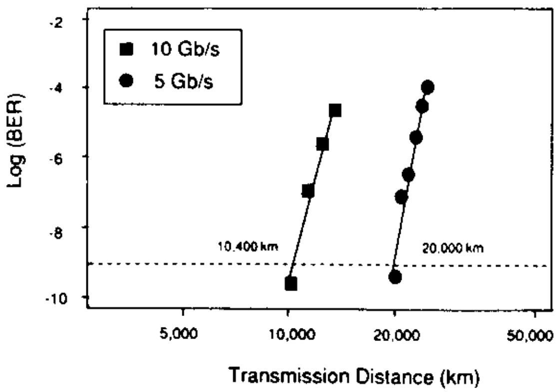
Electrical Data Pattern and Eye Diagram for 9000km Propagation



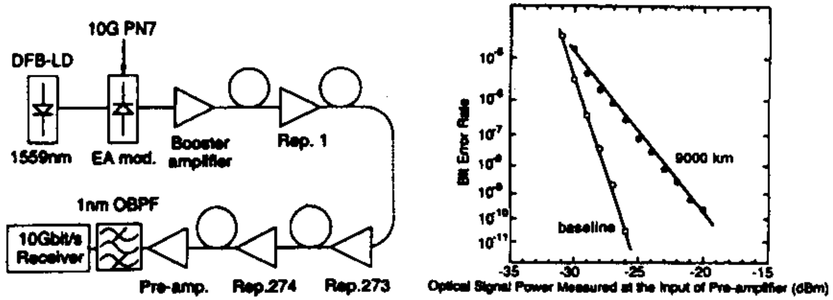
Q-Factor vs Distance for a 5 Gb/s Single Channel Transmission Experiment



Circulating Loop - BER vs Transmission Distance



10-Gb/s, 9000-km TRANSMISSION EXPERIMENT USING AT&T/KDD TRANSOCEANIC SYSTEM TESTBED



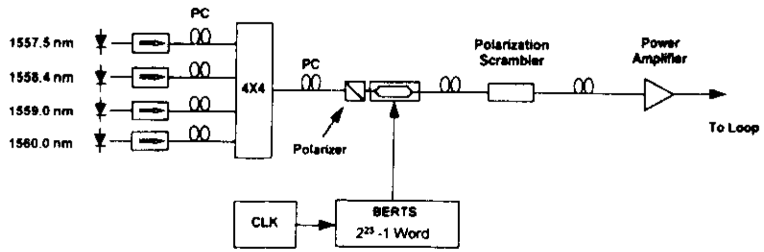
Experimental Setup

BER Measurement

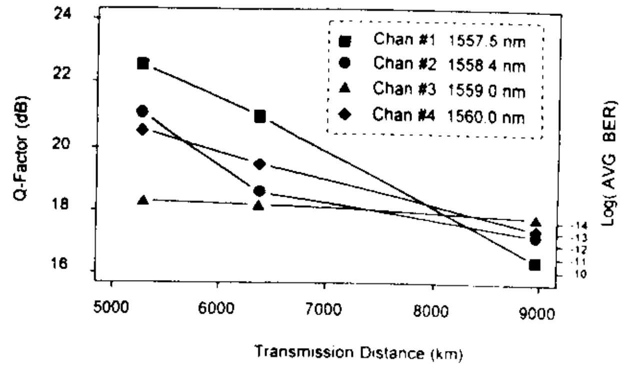
- **Non-Return-to-Zero (NRZ) data at 10 Gb/s**
- **Electroabsorption Modulator:**
  20-dB extinction ratio @ 3.8-V drive
- **9000-km dispersion-shifted single-mode fiber**
- **275 Erbium-Doped Fiber Amplifiers**

Taga et al., (KDD/AT&T), OFC '93, PDI

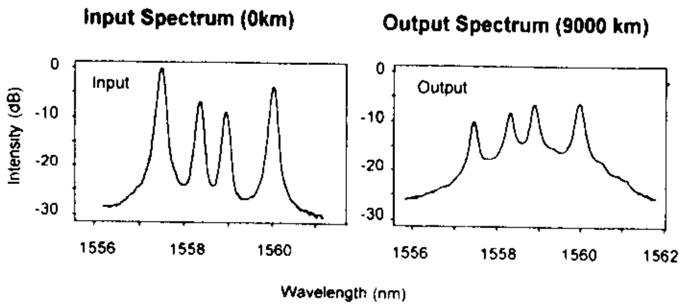
Four-Channel WDM Experiment - Transmitter



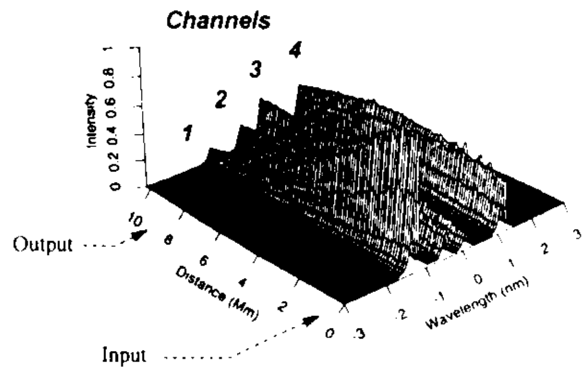
WDM Experiment - Q-Factor vs Transmission Distance



Four-Channel WDM Experiment - Optical Spectra



WDM Experiment - Optical Spectrum



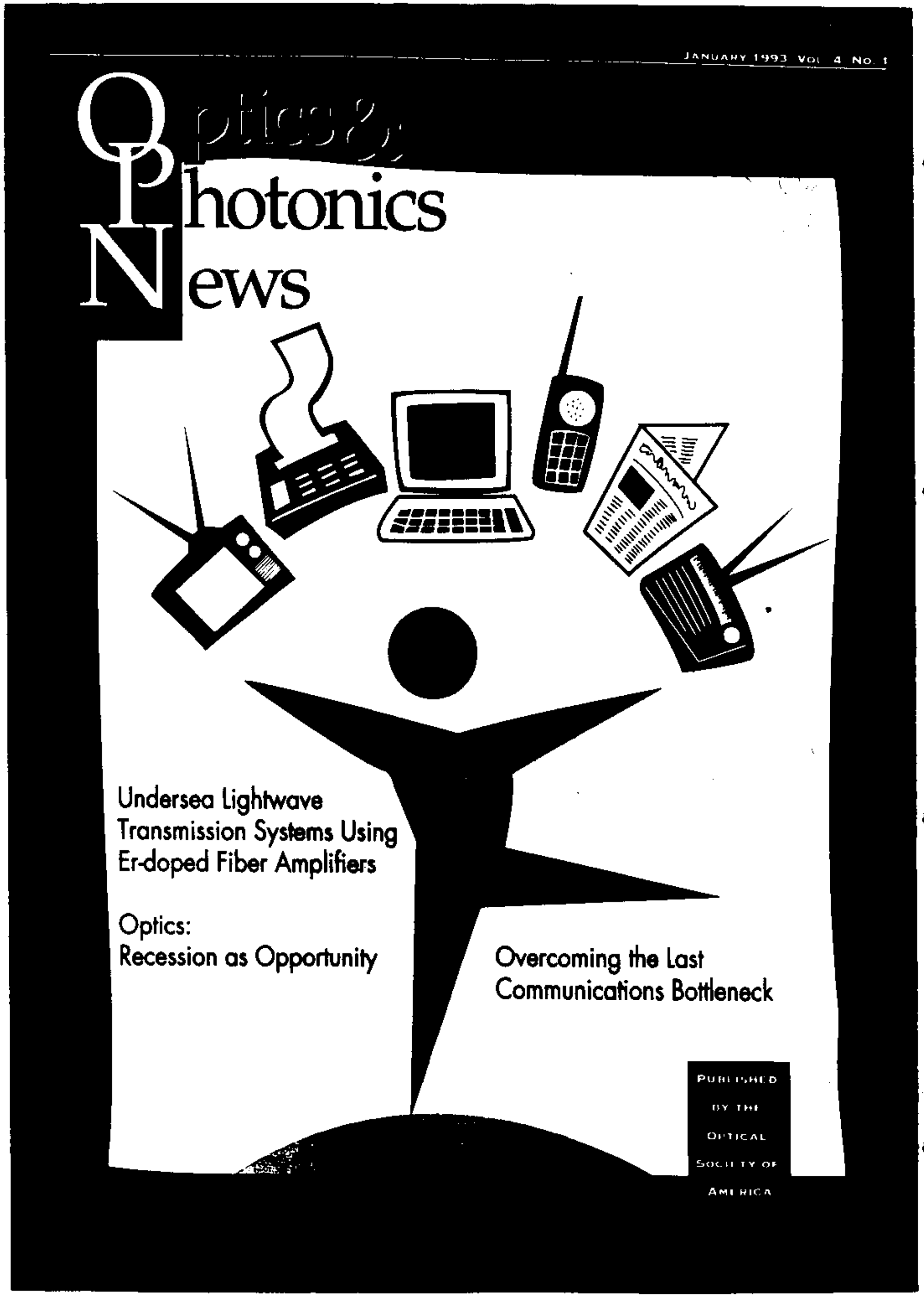
Four-Channel WDM Transmission Experiment Over Transoceanic Distances.

- Laboratory demonstration of WDM using NRZ transmission over transoceanic distances.
- 4x2.5 Gb/s achieved over 9000km.
- Average Q-Factor better than 6.6:1 or (16.4 dB).
- Experiment performed at low power, and low chromatic dispersion.
- FEC could be added for additional margin, and/or channels.

Long-Haul Optical Amplifier Transmission Systems Using the Non-Return-to-Zero Modulation Format

- Optical amplifiers give all optical transmission. No intermediate electronic regenerators.
- Consistent with long term direction of photonic technology.
- Flexible transmission for various bit rates.
- Designs have been experimentally verified.
- The first systems have been installed, and use the NRZ transmission format.

AT&T



Undersea Lightwave Systems Using Er-dop

The erbium-doped fiber amplifier (EDFA), a research curiosity in the late 1980s,[1,2] will be the backbone of future undersea lightwave communications by the mid-1990s. Erbium-doped fiber amplifiers will have a profound impact on the design, operation, and performance of transoceanic cable transmission systems. The first amplifier systems to be installed in the mid-1990s will increase the capacity of undersea systems four-to-eight fold over the most advanced digital fiber system in use today. Later generations of erbium-doped fiber amplifier systems promise to satisfy the international transmission needs into the 21st century.

EDFAs have several characteristics that make them an ideal choice for many lightwave applications, including long-haul transmission:

- EDFAs can be made with a variety of gains in the low-loss 1550 nm wavelength window of telecommunications fibers, with nearly ideal noise performance;
- EDFAs amplify high-speed signals without distortion or crosstalk between wavelengths, even when the amplifier is operated deep in gain compression;[3]

BY NEAL S. BERGANO

Transmission
ed Fiber Amplifiers

- EDFAs are a fiber device, splicing naturally with telecommunications fiber, and are insensitive to polarization effects; and
- The EDFA's pump laser diodes are manufactured from the same InGaAsP semiconductor family that has proven undersea reliability with millions of device hours on 1.3 µm and 1.55 µm signal lasers; All other EDFA components are passive devices, making amplifier designs simple and ensuring that EDFAs can be made with high reliability.

Given these advantages, the next generation of undersea cable transmission systems will use EDFAs in repeaters to boost signals periodically as they travel across the world's oceans.[5] EDFAs will make possible a significant improvement in the capacity of undersea lightwave cable systems installed in the mid 1990s.[6] The first EDFA-based systems will use the Non-Return-to-Zero (NRZ) modulation format at bit rates up to 5 Gb/sec with dispersion-shifted fiber that is matched to the operating wavelength. AT&T, with its partners, plans to install and operate transoceanic cable systems using EDFA repeaters by 1995-96 in the Atlantic and Pacific.

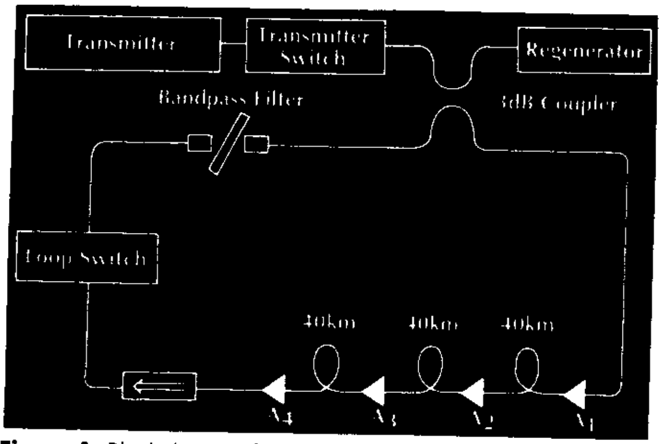


Figure 1. Block diagram for the circulating loop experiment. Long-length transmission is simulated with a 120 km amplifier chain. Optical data is transmitted through the amplifier chain and diverted back into the input using optical switches, trapping the data in the loop.

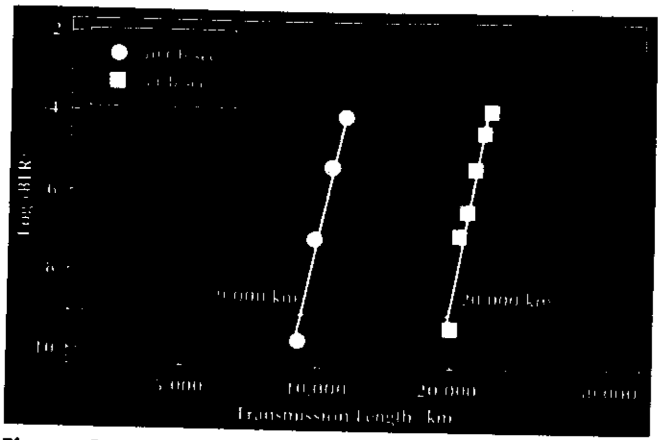


Figure 2. Bit error ratio vs. distance for the circulating loop experiment. At 10 Gb/sec, a transmission distance of 9000 km was obtained at a BER of 4×10^{-10} and a distance of 20,000 km at 5 Gb/sec.

Undersea Cable Systems

The first successful transoceanic cable system was deployed in 1866 in the North Atlantic and provided telegraph service from North America to Europe. An experienced telegraph operator could send up to 17 words per minute, at a cost of 5 dollars per word.[7] It took about 90 years from the time of the first successful telegraph cable to the first transatlantic telephone cable. The first transatlantic telephone cable was commissioned in 1956 and provided 48 voice channels using coaxial cable and repeaters with vacuum tubes.[8] Today, undersea cables provide the international connectivity of terrestrial communications networks with fiber optic cable systems. A modern system such as Transpacific Cable 4 (TPC-4) is nearly 9000 km long, with repeaters spaced about every 130 km, and operates at an information rate of 560 Mb/sec per fiber pair, providing 80,000 equivalent voice channels.

Since the first telephone cable systems were installed, the capacity of transatlantic cable's circuits has increased at an annual rate of 20-27%.[8] New innovations, rather than a single technology, have allowed capacity to keep pace with demand. Coaxial systems technology progressed through the '60s and '70s to include better cables and transistor amplifiers, eventually providing 10,000 voice circuits in systems deployed in the late 1970s and early 1980s. With the promise that optical systems could supply the capacity needed for many years to come, the R&D efforts of the major suppliers of undersea systems switched to fiber optics in the 1970s. The first fiber systems were installed in the Atlantic and Pacific oceans in 1988-89 and operated at 280 Mb/sec per fiber pair.[10] These were actually hybrid optical systems in the sense that the repeaters converted the incoming signals from optical to electrical, regenerated the data with high-speed integrated circuits, and retransmitted the data with a local semiconductor laser. The transmission capacity of the regenerated fiber cables eventually doubled, and repeater spacing increased with the switch from 1.3 μm multi-frequency lasers to 1.55 μm single-frequency laser diodes.

The first fiber systems greatly improved the quality of international telephony; however, the ability of the regenerator systems to exploit the large fiber bandwidth were limited by the capacity bottleneck in the high-speed electronics of undersea repeaters. Undersea lightwave systems with EDFA repeaters will remove the electronic bottleneck, and provide the first clear optical channel connectivity (or lightpipe) between the world's continents.

Feasibility Demonstration

Based on quantitative data gathered from transmission experiments and management's vision, the focus of R&D efforts changed from electronic regenerators to optical amplifier repeaters. This untested technology seemed to be at odds with the strict design requirements of undersea systems. Developing an EDFA cable system would involve extensive resources, both people and equipment, for a five-year period (from conception to installation). Before resources could be committed, an experimental proof that could demonstrate high data rate, long length transmission at low error rate was needed. This created a dilemma; a transoceanic length experiment would require more equipment than could be supplied without a major development, and a development could not be justified without proof of EDFA technology's feasibility. Our solution was a circulating loop amplifier experiment where we could measure the Bit Error Ratio (BER) at equivalent transoceanic transmission lengths.[11]

Circulating loop experiments were performed as early as 1956 to study digital pulse propagation in wire pair cable,[12] jitter accumulation in digital fiber systems,[13] and soliton pulse propagation.[14] Our contribution was a new set of techniques that allowed a BER measurement.[15] In the circulating loop experiment, an optical data signal is transmitted through a modest length system of a few hundred kilometers and diverted back into the system's input using optical switches, trapping the data in the loop. The data circulates for a specified time, after which the state of the switches change, and the experiment repeats. BER is determined by dividing the number of errors detected in the N^{th} pass by the total number of bits sent in that observation period. An undersea digital system is expected to operate with a BER of 4×10^{-10} (or less than one error per billion bits) over its lifetime. The amount of time needed to record a BER in the loop experiment is increased by the duty cycle (arising from the error counting interval being a small percentage of the total time for the experiment). To obtain a BER of 10^{-10} for the 120 km loop at 9000 km required error counting for 18,000 runs, or about 13 minutes real time.

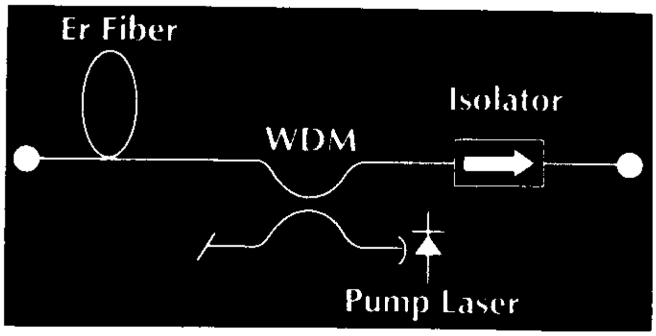


Figure 3. Typical configuration for a moderate gain EDFA. The coupling loss into the amplifier is minimized by placing the WDM after the erbium fiber, so that the pump and signal propagate in opposite directions. An optical isolator in each amplifier prevents the build-up of amplified spontaneous emission (ASE) from traveling in the reverse direction from the signal.

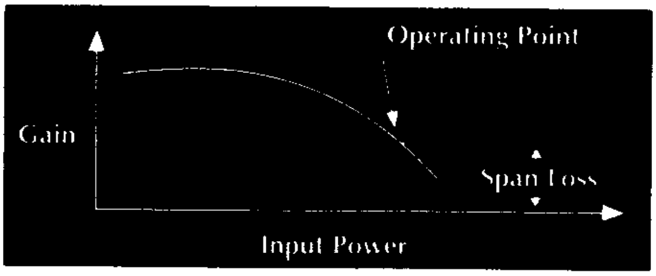
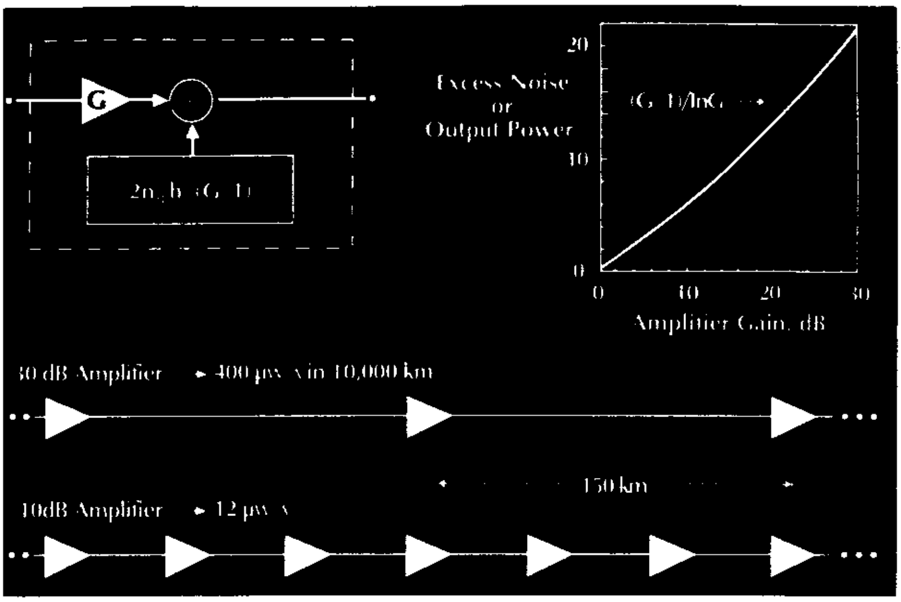


Figure 4. Gain vs. input power of an EDFA. Span loss is indicated by the horizontal line. Self regulation is achieved by making the EDFAs small signal gain several dBs larger than the fiber span's attenuation, which creates a stable operating point where amplifier gain equals span loss.

In our original BER circulating loop experiment, the loop consisted of an amplifier chain, isolator, acusto-optic switch, optical bandpass filter, and 3 dB coupler. The amplifier chain had four 10 dB EDFAs pumped counter to the propagating signal and three 40 km spans of dispersion-shifted fiber (Figure 1). The transmitter/regenerator pair was capable of operating at 2.5 Gb/sec, 5.0 Gb/sec, or 10 Gb/sec. Figure 2 shows the BER vs. transmission distance. At 10 Gb/sec, a transmission distance of 9000 km was obtained at a BER of 4×10^{-10}, and a distance of 20,000 km at 5 Gb/sec. This experiment yielded the results necessary to start development of an EDFA undersea transmission system.

Since that time, several long experiments have been reported, where hundreds of amplifiers were concatenated to form amplifier chains up to 10,000 km.[16] Recently, we reported the results of a joint experiment between AT&T and KDD where error-free transmission was measured for a 5 Gb/sec NRZ signal through 9000 km of dispersion-shifted



...ure 5. Amplifier noise is proportional to the linear gain coefficient, therefore, the amount of ...ise accumulated in a chain of amplifiers increases with gain. A system with 150 km spacing ...cumulates 33 times more noise per unit bandwidth than a system with 50 km repeater spacing ...suming 0.2 dB/km fiber loss).

...er and 274 EDFAs.[17] These long experiments give direct ...nfirmation of the feasibility and design of transoceanic ...tical amplifier cable systems.

...E ERBIUM-DOPED FIBER AMPLIFIER

...typical configuration for a moderate gain EDFA is shown ... Figure 3. The amplifying medium is a short length of ...gle-mode fiber whose core has been lightly doped with the ...e earth element erbium. The pump and signal light are ...mbined in a wavelength selective coupler (also called a ...avelength Division Multiplexer, WDM). The coupling loss ...o the amplifier is minimized by placing the WDM after the ...bium fiber, so that the pump and signal propagate in ...posite directions. An optical isolator in each amplifier ...events the build-up of amplified spontaneous emission ...SE) from traveling in the reverse direction from the signal. ...ch amplifier is pumped by at least one 1480 nm semicon...uctor laser diode. Several references discuss the EDFA ...nstruction and optimization.[3,18,19]

In a long system design, the amplifier is characterized by ... input/output relationship and its noise figure. The input/...tput relationship of an amplifier is typically displayed as ...in vs. input power, as shown in Figure 4. Compression of ...e gain occurs when the input signal becomes large enough ... make the rate of stimulated emission comparable to the rate ... absorption by the pump light, which limits the output ...wer.

The natural gain compression of the EDFA can provide ...f regulation of the power in a chain of amplifiers. Self ...gulation is achieved by making the EDFA's small signal ...in several dBs larger than the fiber span's attenuation, ...hich creates a stable operating point where amplifier gain ...uals span loss. If the input power to the amplifier decreases, ...en its gain increases, and visa versa, thus keeping the power ...el stable. The design of the amplifier chain can also take ...vantage of the EDFA's natural bandpass characteristic.[20] When the amplifier is operated with several dBs of gain compression, the gain peak occurs at the long wavelength edge of the small signal passband near 1558 nm. The natural bandwidth of the amplifiers should be wide enough to pass the data signal, yet small enough to avoid signal compression due to the ASE saturating the amplifiers.

The classical definition of amplifier noise figure is the ratio of the signal-to-noise ratios (SNR) at the output ampli-fier's output to that of the input. A good working definition in terms of measurable EDFA quantities can be expressed as:

$$NF=10\log\left[\frac{P_{ASE}}{h\nu GB_0}\right] \qquad (1)$$

where NF is noise figure in dB, P_{ASE} is the optical noise power, measured in bandwidth B_0, h,v is photon energy, and G is gain expressed as a linear ratio. EDFAs pumped at 1480 nm can be made with noise figures of 4.5-6 dB, and when pumped at 980 nm, the noise figures can approach the ideal value of 3 dB.

SYSTEM CONSIDERATIONS

Three major factors limit transmission performance of an amplifier system: optical noise, chromatic dispersion, and fiber nonlinearities. Unlike regenerator systems, where transmission penalties are reset, these effects accumulate along the amplifier chain and must be managed by the system design.

Amplifier noise accumulation can be limited by placing repeaters close enough so that the required gain is less then about 10 dB.[21] An EDFA generates an amount of noise proportional to the amplifier's gain. As a consequence, the amount of accumulated noise at the end of the system depends on the repeater gain and fiber loss. For the purpose of noise accumulation, a simplified amplifier model is an ideal gain block, followed by an additive noise source (Fig. 5), with the noise spectral density N of:

$$N=2n_{sp}h\nu(G-1) \qquad (2)$$

where $h\nu$ is photon energy, G is gain in linear units, and n_{sp} is the excess noise factor related to the amplifier's noise figure.

Consider the system with fiber loss of 0.2 dB/km, shown in Figure 5. A 150 km repeater spacing would require 30 dB amplifiers, whereas a 50 km spacing needs three times as many 10 dB amplifiers. A 30 dB amplifier (1000 × gain) generates 100 times more noise per unit bandwidth than a 10 dB gain amplifier. Thus, the 30 dB gain system would have 33 times more noise than the 10 dB gain system. The excess accumulated noise in a system with lumped amplifiers of gain G is:

$$\text{Excess Noise}=\frac{G-1}{\ln G} \qquad (3)$$

and is plotted in Figure 5. The relationship between accumulated noise and amplifier gain imposes an interesting trade; longer systems require shorter repeater spacing to keep the same output SNR.

Ironically, EDFA systems are limited by a nonlinear transmission medium and amplifier gain saturation is advantageous. This is just the opposite from analog cable systems where the cable is linear and amplifier saturation is detrimental. Single-mode fibers are slightly nonlinear resulting from the dependence of the fiber's index on the intensity of the light propagating though it. This behavior is expressed as:

$$n = n_0 + \frac{N_2 P}{A_{eff}} \quad (4)$$

where n_0 is the linear part of the refractive index, N_2 is the nonlinear coefficient (~2.6×10^{-16}cm^2/Watt), P is the light power in the fiber, and A_{eff} is the effective area over which the power is distributed[22] (about 50 µm^2). This nonlinear behavior causes only minute changes in the group velocity of the fiber. For example, the presence or absence of a 1 mW signal changes the index by 35 trillionths of a percent. The equivalent length change over 10,000 km is about 3.5 µm, and is of no consequence to system performance; however, the power dependent index of refraction leads to the nonlinear phenomena of self-phase modulation, cross-phase modulation, and four-wave mixing.[23]

For very long systems, the nonlinear refractive index essentially couples the signal and noise, which complicates the span engineering in an optical amplifier system.[22] When the system is operated at the dispersion minimum, the data signal and the amplifier noise (with wavelengths similar to the signal) travel at the same velocity. The signal and noise waves have long interaction lengths (or are phase matched) in the nonlinear fiber, and thus can mix together to form new frequencies. Under these conditions, noise, dispersion, and nonlinearities must be considered together. This nonlinear behavior, in a long undersea system, is managed by tailoring the dispersion accumulation so that the phase-matching lengths are short and the end-to-end dispersion is small. For example, fibers with slightly different dispersion values can be concatenated to form the transmission spans, where the accumulated dispersion along the cable passes through the minimum dispersion value occasionally. Thus, the nonlinear mixing is minimized by reducing the interaction lengths, and the distortion of the data is minimized by ensuring that the total dispersion returns to zero at the end of the system.

FUTURE SYSTEMS

The attraction of optical amplifier technology is its potential for growth of future systems and the synergy of future systems with the first generation system. The first generation of long EDFA systems will use the NRZ modulation format and have a transmission capacity of 5 Gb/sec per fiber pair. Unlike regenerative systems, there exists the possibility of upgrading the capacity of the amplifier system by making changes to the equipment at the shore, such as higher bit rate terminals. When the bit rate of the signal is increased, the degradations caused by noise, dispersion, and nonlinearities become more severe. It may be possible to manage these limitations with more sophisticated terminal equipment. For example, an error-correcting code with 14% bit rate overhead would allow the BER on the undersea amplifier chain to be as high as 10^{-4}, while maintaining virtually error free performance for the customers.[24] The deleterious effects of signal distortions could be reduced by using adaptive equalization and decision circuits at the system's receiver end. Studies of adaptive nonlinear cancellation of intersymbol interference at the decision circuit, where the decision point is changed bit-to-bit offer promise to reduce the BER in systems limited by polarization and chromatic dispersion.[25]

Ultimately, undersea optical amplifier systems may use wavelength division multiplexing with soliton modulation to obtain bit rates in the tens of gigabits per second region. Solitons rely on the fiber nonlinearities to balance the effects of chromatic dispersion, thus creating a special nonlinear optical pulse that is non-dispersive in time and frequency.[26] This latter property makes possible the use of more than one wavelength on a single fiber. Recently, Mollenauer *et al.*, proposed a technique that takes full advantage of the soliton's nonlinear behavior of shifting its own frequency under the influence of a guiding frequency filter.[27] As the soliton propagates down the amplifier chain, optical bandpass filters with slightly different center frequencies "slide" the soliton away from the noise generated in the amplifiers, apparently defying the effects of noise accumulation. Some day, these techniques might yield bit rates in excess of 50 Gb/sec per fiber pair, with amplifiers that will look similar to those used in the first generation of EDFA systems.

While the erbium-doped fiber amplifier will have a significant impact on the design, operation, and performance of transoceanic cable transmission systems, of equal importance is the impact that undersea systems will have on EDFA technology. The development of optical amplifier undersea cable systems will transform EDFAs from a research curiosity to a mature technology.

ACKNOWLEDGMENTS

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OFC'93

10Gbit/s, 9,000km IM-DD Transmission Experiments Using 274 Er-doped Fiber Amplifier Repeaters

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Introduction The Erbium-doped fiber amplifier (EDFA) will make possible reliable transoceanic optical communication systems that are transparent to bit-rate. Such systems have the potential to be upgraded after installation by making changes to the terminals. Several experiments show the capability of the EDFA for long distance communication systems[1,2,3,4]. The collaboration between KDD laboratories and AT&T Bell laboratories has demonstrated the feasibility of EDFAs for transpacific optical communication systems at 5Gbit/s[2]. In this paper, we present the results of an intensity modulated, direct detection (IM-DD) 10Gbit/s, 9,000km transmission experiments.

Experimental Setup Fig.1 shows a schematic diagram of the experimental setup. The transmitter used a DFB-LD emitting at 1558nm with a hermetically packaged electro-absorption (EA) modulator to generate the 10Gbit/s, 2^7-1 pseudorandom NRZ signal. A booster EDFA was added to compensate for the EA modulator's insertion loss.

The amplifier chain consisted of 274 in-line EDFAs and dispersion-shifted fiber spans. The average amplifier spacing and the average fiber loss were 33km and 0.22dB/km, respectively. The total system length was 9,040km and the averaged zero-dispersion wavelength was 1559nm. The output power of each repeater was set around +2dBm at the signal wavelength of 1559nm. An optical filter was not employed in the signal transmission line.

An InGaAs PIN-PD was used in the optical receiver. An Er-doped fiber pre-amplifier with a 1nm optical bandpass filter was inserted before the receiver to boost the receiver input power. Then, the receiver has a pre-amplifier configuration, a baseline receiver sensitivity of -25.6dBm was achieved at a BER of 10^{-9}.

Results Fig.2 (A) and (B) show the eye diagrams at the optical receiver output. As seen in the figures, the eye of 9,040km transmission shows pulse compression slightly compared to the eye of baseline. Fig.3 shows the measured BER versus optical pre-amplifier input signal power. In the figure, ○ and ● denote the measured data for the baseline and the 9,040km transmission. As shown in Fig.3, the power penalty at a BER of 10^{-9} due to the 9,040km transmission was 4.6dB. The maximum optical signal power to the optical pre-amplifier was limited to -20dBm by the restriction of the photo-current of the PIN-PD in the optical receiver.

Discussions Fig.4 (A) and (B) show the modulated bit-stream of baseline and 9,040km transmission, respectively. They were measured by a photo-detector with 20GHz bandwidth. Optical noise accumulation and nonlinearities in the transmission fiber lead to signal distortion, thus reducing eye margin and increasing transmission penalty. Fig.4 (B) shows the classical characteristics of noise accumulation where the noise level on the marks rail is large compared to the spaces rail. This causes the compression of the eye and reduces the threshold margin of the transmission. The isolated "1" pulse shown in Fig.4 (B) shows the effect of nonlinearities in the transmission fiber apparently, where the pulse becomes peakey and compressed compared to the baseline. This causes the narrowing of the eye and reduces the phase margin of the transmission. As a result, these two aspects are likely major factors to increase the transmission penalty.

Conclusions We have successfully transmitted 10Gbit/s IM-DD signal over 9,000km using 274 Er-doped fiber amplifier repeaters. The 90Tbit•km/s bit-rate•distance product is the largest value reported to date for a straight line transmission experiment. We observe eye closer caused by noise accumulation and fiber nonlinearities. The results show the technological possibility of the EDFAs for the future long-distance large-capacity optical communication systems.

Acknowledgements We express our thanks to Mr. Y. Horiuchi, Mr. Y. Yoshida, Mr. T. Kawazawa, Mr, S. Takagi, and Dr. Y. Namihira of KDD, and Dr. J. J. Kassig and Mr. W. J. Bredesen of AT&T for their kind help and advise on the experiment. We also thank Dr. K. Ono, Dr. T. Yamamoto, Dr. Y. Takahashi, Dr. K. Sakai, Dr. Y. Matsushima, and Dr. S. Akiba of KDD, and Dr. J. M. Sipress and Dr. P. K. Runge of AT&T for their continued encouragement.

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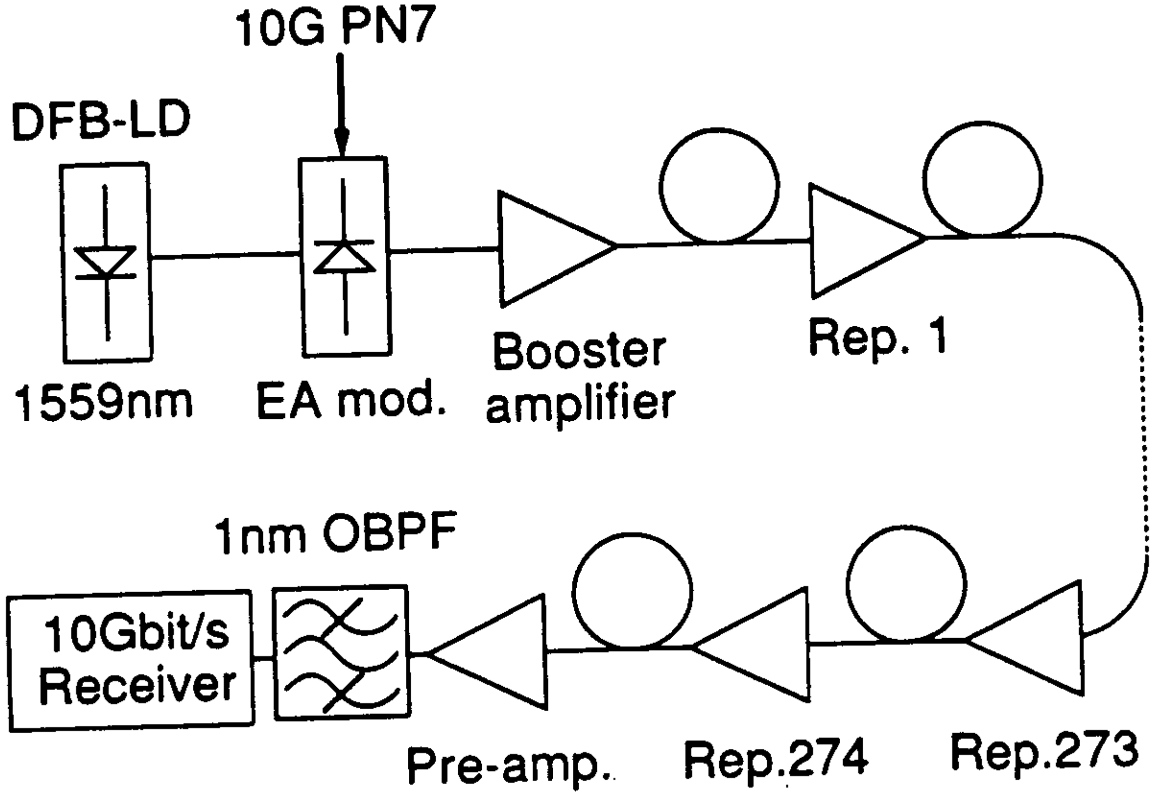
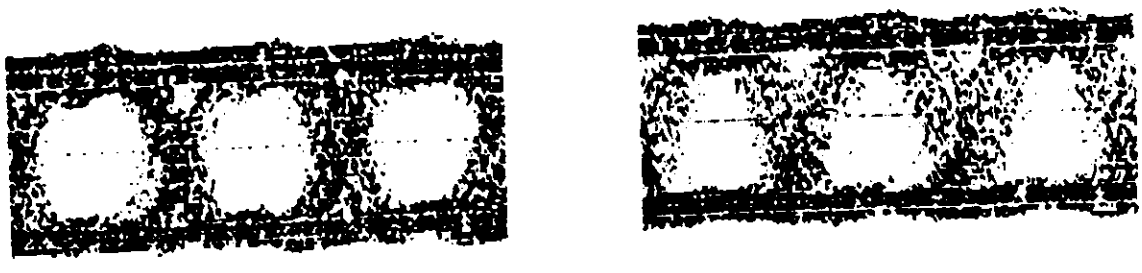


Figure 1 Schematic Diagram of the Experimental Setup



(A) baseline (B) 9,040km

Figure 2 Eye Patterns of 10Gbit/s Receiver

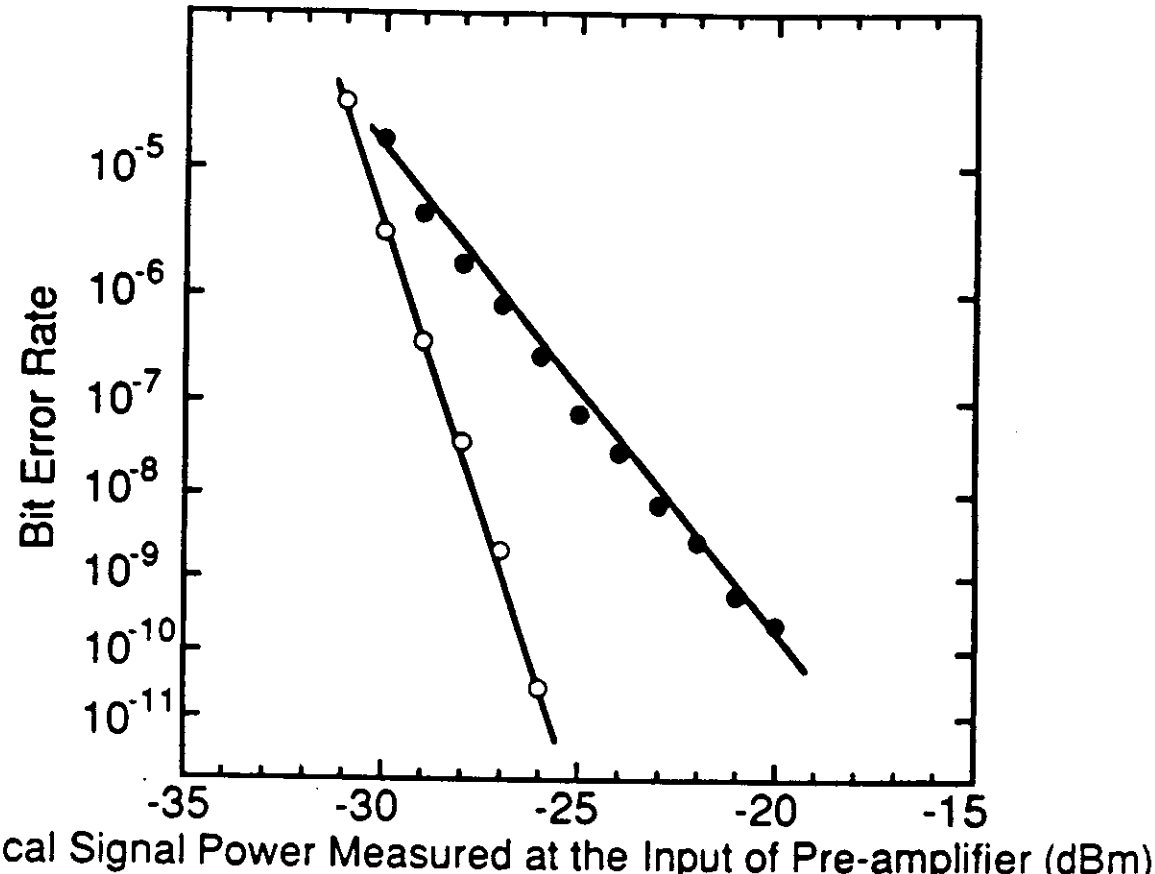


Figure 3 BER Characteristics of the Experiments

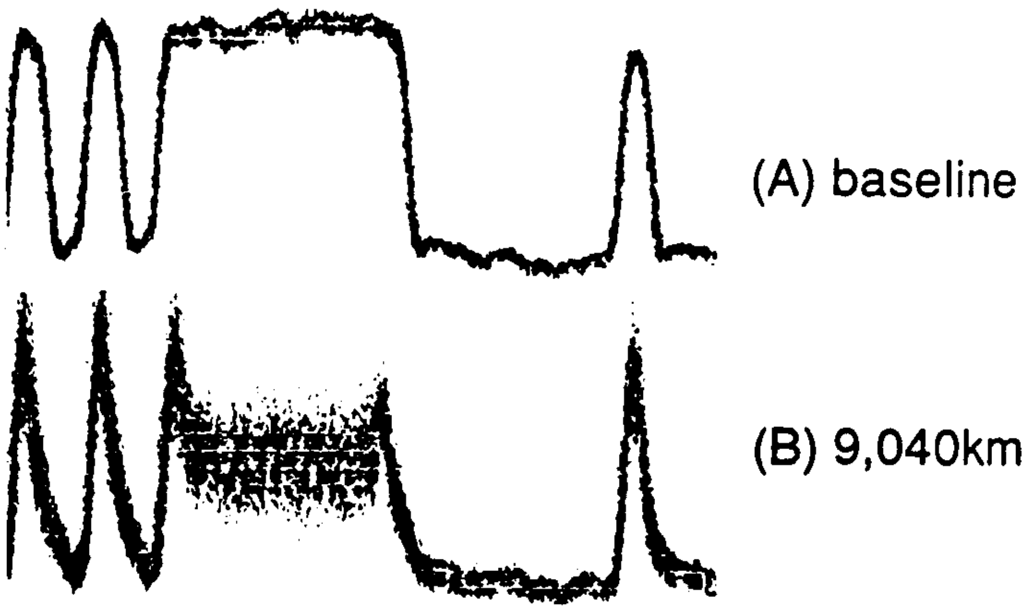


Figure 4 Pulse Sequences measured with 20GHz Bandwidth

Topical Meeting on Optical Amplifiers and Their Applications 1994

Four-Channel WDM Transmission Experiment over Transoceanic Distances

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Abstract

We have transmitted four 2.5 Gb/s *N*on-*R*eturn to *Z*ero data signals over a 9000 km *E*rbium-*D*oped *F*iber-*A*mplifier chain using a circulating loop transmission line. At 9000 km the average Q-factor was better than 6.6:1 (or 16.4 dB) for all four channels.

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INTRODUCTION - The advent of the *E*rbium-*D*oped *F*iber-*A*mplifier (EDFA) transmission system has kindled an interest in *W*avelength *D*ivision *M*ultiplexing (WDM) for long-haul data transmission. Recently there have been reports of many channel experiments over short distances[1], and two channel experiments over 4500 km.[2] Here we report a four channel WDM experiment at 2.5 Gb/s operating with several dBs of margin over transoceanic distances. The transmission performance (expressed as a mean Q-factor[3]) is reported as a function of transmission distance. The optical spectrum is measured as a function of transmission distance, which shows the importance of the EDFA's gain spectrum in WDM transmission systems.

EXPERIMENT - The transmission measurement was performed using a four-wavelength transmitter, a circulating loop[4] transmission line, and a conventional single-wavelength receiver. Four DFB lasers with individual isolators and polarization controllers were multiplexed onto a single fiber using a 4x4 fused fiber coupler (Figure 1). The four wavelengths were modulated with a 2.5 Gb/s, 2^{23}-1 *N*on-*R*eturn to *Z*ero (NRZ) data signal using a Lithium Niobate intensity modulator. The relative powers were set by adjusting the polarization controllers on each laser: thus, changing the loss through the modulator's polarizer. Following the intensity modulator a high-speed polarization modulator scrambled the state-of-polarization in the GHz range to avoid excess noise accumulation caused by polarization hole-burning in the EDFAs.[5] The wavelength separations of the four channels were made unequal to reduce the effects of four-wave mixing interference between channels.

The 370 km amplifier chain was constructed with eight amplifier spans, each with 46 km of dispersion shifted fiber. Each 1480 nm pumped EDFA had a small signal gain of about 15 dB and a noise figure of 5.5 dB at the operating point. The transmission fiber was AT&T dispersion shifted single-mode fiber with an average spliced loss of 0.2 dB/km, an effective area of 55 μm^2, an average zero dispersion wavelength of 1563 nm, and polarization mode dispersion less than 0.15 ps/km^0.5. The chromatic dispersion of the transmission line caused each channel to slip in time: thus, the signals became de-correlated after a few loops. The average combined signal power for all four channels was +2.5 dBm. One extra EDFA was added to compensate for the attenuation in the loop's acousto-optic modulator switch and the 3 dB coupler, making a total of nine amplifiers within the loop.

The regenerator used a 980 nm pumped EDFA preamplifier, an EDFA automatic gain controlled amplifier, a set of 1 nm optical bandpass filters, a p-i-n diode optical-to-electrical converter, and a phased locked loop timing recovery circuit. At 2.5 Gb/s the receiver sensitivity was -41 dBm for a 2^{23}-1 pattern, and the optical dynamic range exceeded 40 dB. The individual channels were separated by using a combination of up to three 1 nm filters.

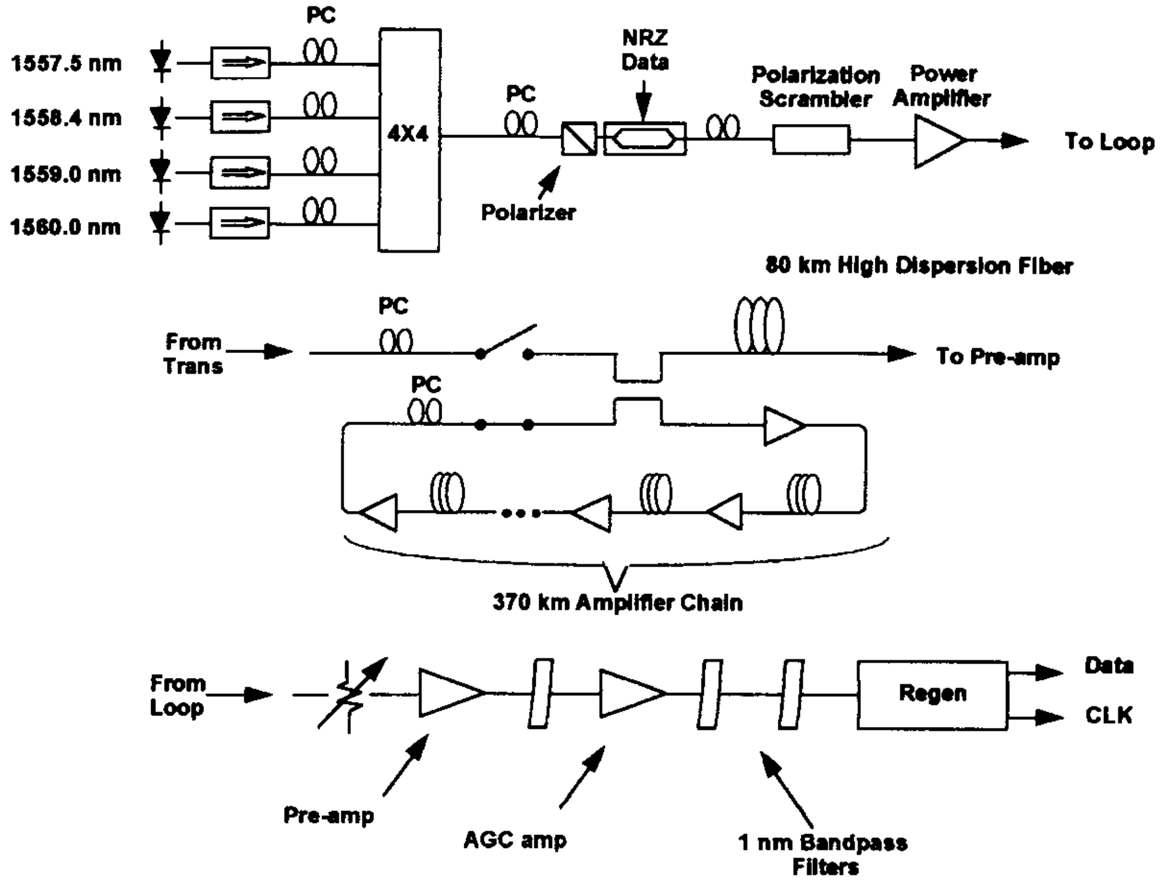

Figure 1 - Experimental setup showing the transmitter (top), circulating loop (middle), and the receiver (bottom).

RESULTS AND DISCUSSION - Figure 2 shows the transmitted and received spectrum after 9000 km. Pre-emphasis of the high and low wavelength channels was used to correct for the non-ideal gain characteristic of the EDFAs.[6] The pre-emphasis was arranged to equalize the Q-factors at a transmission distance of 9000 km, which corresponds to the distance across the Pacific ocean. The power per channel launched into the transmission fiber (as averaged over distance from 0 to 9000 km) was less than 0.5 mW.

The Q-factor vs transmission distance is shown in figure 3. Each data point on the curve represents an average of at least 10 measurements. At 6300 km (the transatlantic distance) the Q-factors ranged from 18.2-21 dB, and at 9000 km the Q-factors were 16.4-17.8 dB. The performance of channel #1 degrades the fastest as the transmission distance is increased, which is a result of the lower gain in that channel. The gain peak of the amplifier chain was near channel #3.

The differential gain experienced by the four wavelengths can be easily observed in the spectral contour plot of Figure 4. Here the optical spectrum is plotted as a surface over the wavelength, distance plane. At the launch end the power in channel #3 is the smallest, and as the signal propagates through the amplifier chain its power grows at the expense of the other channels.

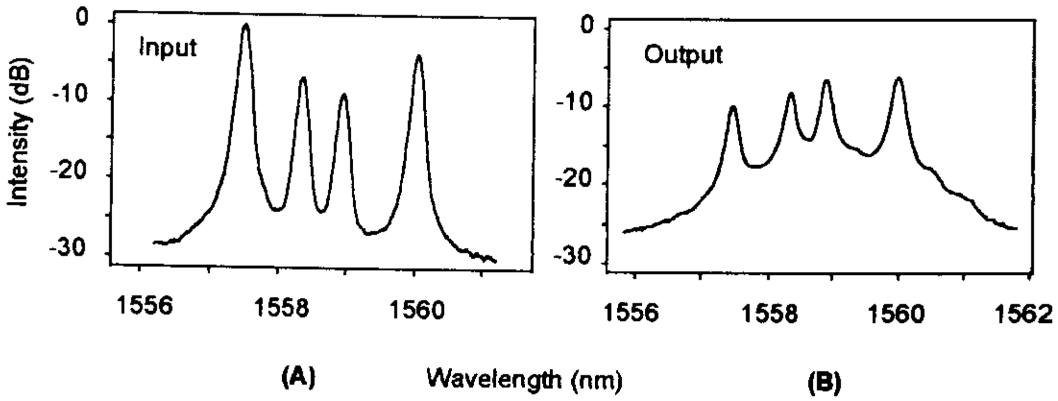

Figure 2 - A) Input spectrum showing the amount of pre-emphasis. B) Spectrum after 9000 km propagation.

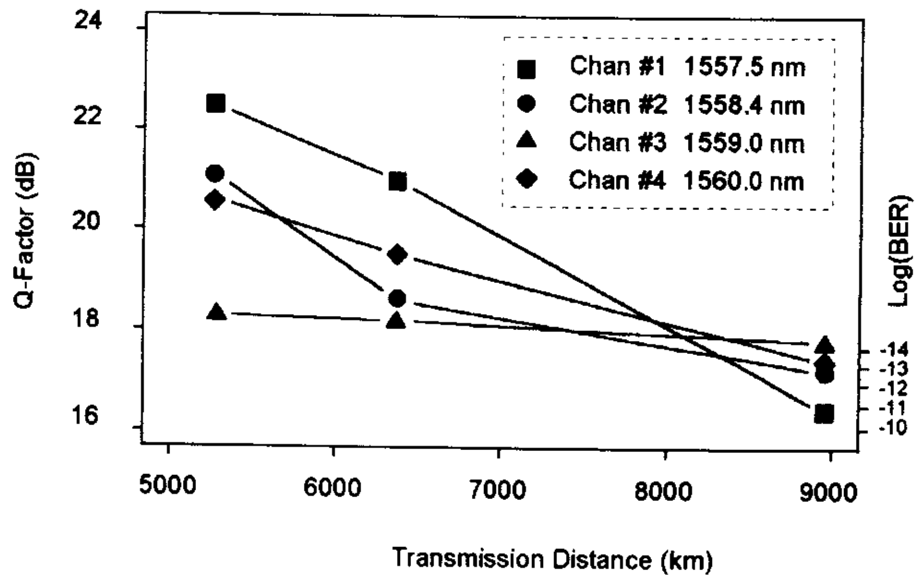

Figure 3 - Q-factor (in dB) vs transmission distance for the 4 WDM channels. The translation between Q-factor and bit error ratio is indicated with the right hand axis.

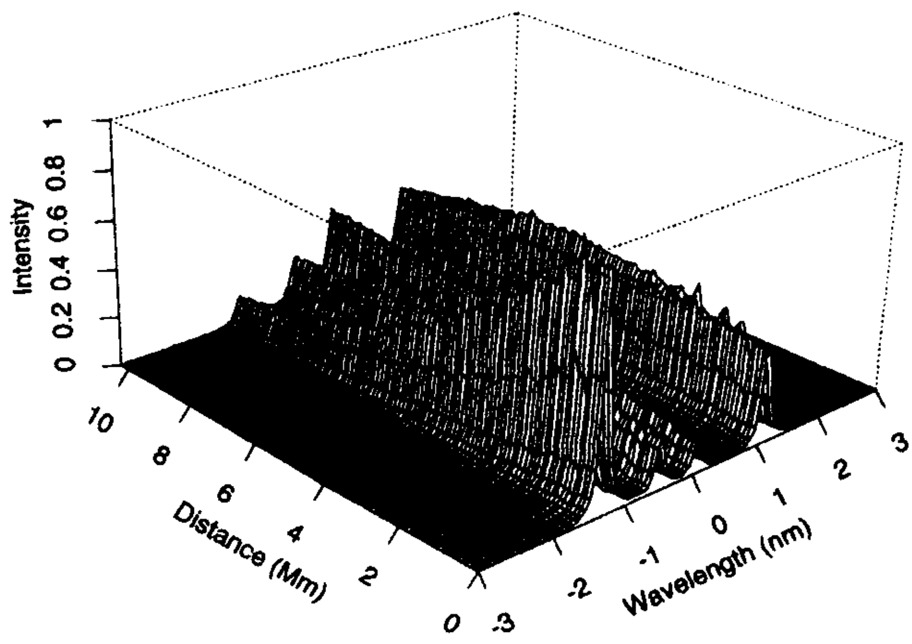

Figure 4 - The measured optical spectrum vs transmission distance. Signal intensity is displayed above the wavelength/distance plane.

CONCLUSIONS - A 4 x 2.5 Gb/s WDM experiment was performed with more than 3 dB of margin at transatlantic distances. The weakest channel had a bit error ratio better than 10^{-10} at 9000 km. Channel pre-emphasis was used to reduce the effects of unequal gain for the four different channels. Unequal wavelength spacing was used to limit the effects of channel cross-talk (or nonlinear four-wave mixing).

The transmission performance could be improved by incorporating terminals that use *F*orward *E*rror correction *C*oding[7] (FEC). FEC would improve the system margin by 4-5 dB per channel, above and beyond any improvement made using optical techniques.

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Polarization Hole-Burning in Erbium-Doped Fiber-Amplifier Transmission Systems

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ABSTRACT - Polarization hole-burning can reduce the received signal-to-noise ratio of a data signal propagating through a long chain of Erbium-doped fiber-amplifiers. The impairments caused by polarization hole-burning are greatly reduced by scrambling the transmitter's polarization. An improvement in Q-factor of 4.5 dB was measured for 9000 km, 5 GB/s NRZ transmission.

INTRODUCTION - Long optical fiber transmission paths that use *E*rbium-*D*oped *F*iber-*A*mplifiers (EDFAs) are subject to degraded performance caused by *P*olarization *H*ole-*B*urning (PHB) in the amplifiers[1 2]. PHB results from an anisotropic saturation created when a polarized saturating signal is launched into the erbium doped fiber. This effect was first observed by Taylor[3] as an excess noise accumulation in a chain of saturated EDFAs, and was later isolated in a single amplifier and identified as PHB by Mazurczyk and Zyskind[4]. In a chain of saturated amplifiers, PHB can cause the amplified spontaneous emission noise to accumulate in the polarization orthogonal to the signal faster than along the parallel axis. The deleterious effects of PHB can be avoided by polarization modulation (or scrambling) of the signal at a rate faster than the EDFA can respond. This paper reviews PHB, its effect on lightwave systems using EDFA repeaters, and how polarization scrambling improves system performance.

POLARIZATION HOLE-BURNING - The effect of PHB is to depress the gain of an EDFA for light with the same polarization as a saturating signal. Consider a section of the EDFA with a polarized input saturating signal S_I and a small input probe signal P_I in the orthogonal polarization (Figure 1). The amplifier's gain (in dB) as measured with the saturating signal is $S_O - S_I = G$, and the gain in the orthogonal polarization as measured with the probe is $P_O - P_I = G + \Delta G$. This excess gain ΔG is what we call the PHB. The amount of PHB in a single amplifier is only about 0.07 dB for an EDFA with 3 dB of gain compression, and becomes larger as the amplifier goes deeper into gain compression.[5] This small gain difference went unnoticed in single amplifier measurements for several years. In addition to the PHB effect that tracks the saturating signal, there is a *P*olarization *D*ependent *G*ain (PDG) that tracks the pump polarization. Unlike PHB, the polarization axes of the PDG are uncorrelated to the saturating signal: thus, PDG effects system performance differently than PHB.

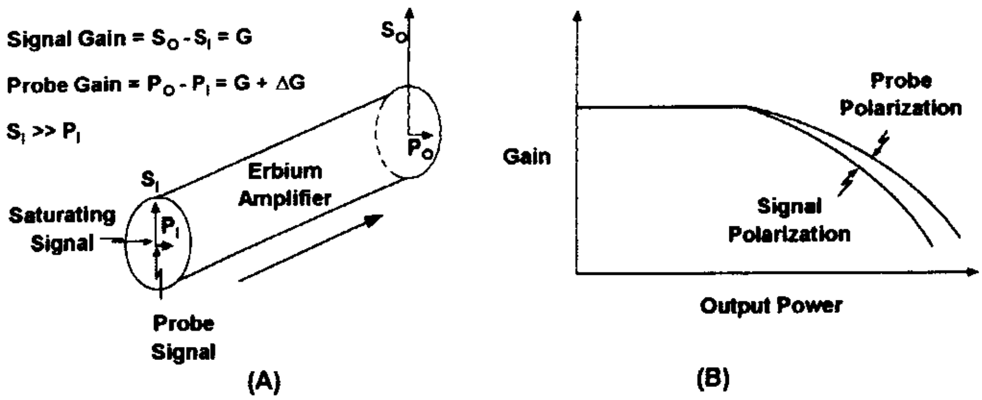

Figure 1 - (A) Polarization Hole-Burning in an section of an EDFA. $S_{I,O}$ is a saturating signal and $P_{I,O}$ is a small probe signal with the orthogonal polarization. (B) The EDFAs saturation characteristic for the signal and the probe.

PHB arises from the randomly distributed orientations of erbium ions in the glass matrix and the selective de-excitation of those ions by a polarized signal. On a microscopic level the erbium ion's anisotropy causes the local PHB effect to be maximum where the saturating signal is linearly polarized whereas at points where the polarization is elliptical the PHB effect is reduced.[6] Unlike bulk glass amplifiers, EDFAs typically have birefringence resulting from various internal and external mechanisms such as bending, non-circular waveguide geometry, or internal stress. The birefringence causes the polarization of the saturating signal to evolve along the length of the amplifier. This produces an averaging, which reduces the measured PHB's dependence on the launch polarization of the saturating signal.[7]

Figure 2 shows an experiment for measuring PHB in a single amplifier.[8] A saturating signal at 1558.8 nm and a probe signal at 1558.3 nm were combined in a 90/10% coupler. The saturating signal was CW and the probe was modulated at 100 kHz to allow for AC voltmeter detection. The polarization of two light sources were controlled using a variety of manual and automated polarization adjusters. The 10% output was detected through a polarizer to establish a polarization reference angle, arbitrarily defined to be zero for the signal angle θ and probe angle ϕ. The gain measurement was made with $\theta = 0°$ while ϕ is varied over a range that includes 0° and 90°, then the measurement was repeated with $\theta = 90°$. This double measurement procedure allowed the separation of *P*olarization *D*ependent *L*oss (PDL) and PDG effects from the PHB. The 17 meter EDFA under test was pumped in the counter propagating direction with 14 mW of 1480 nm pump light, and had 3 dB of gain compression and 19 dB of gain at the operating point.

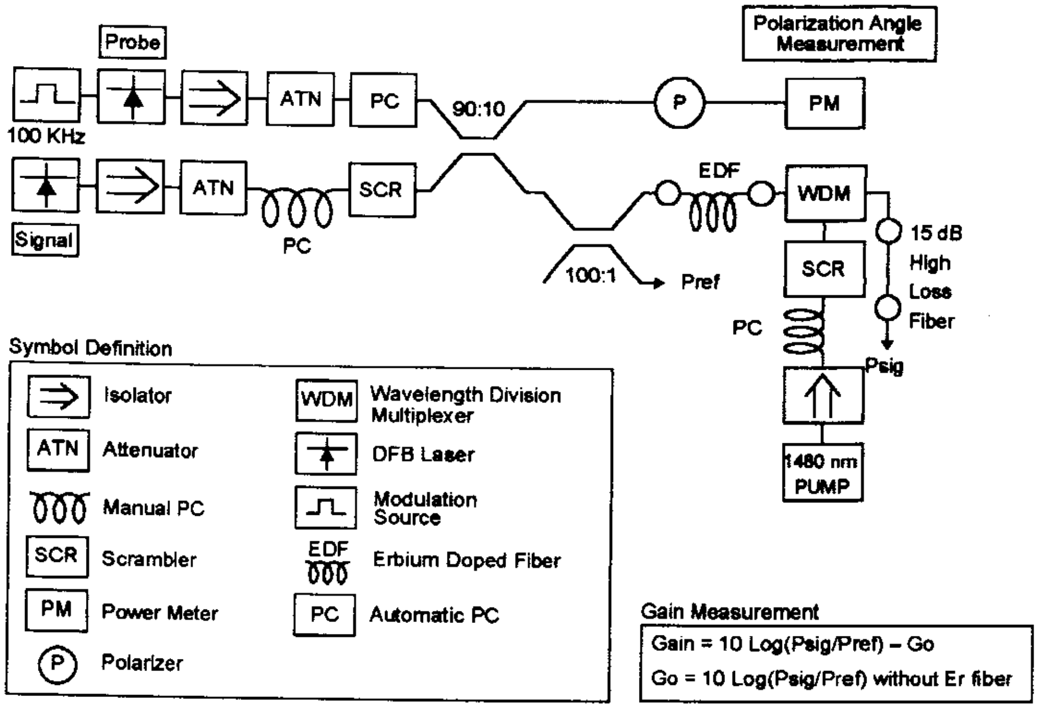

Figure 2 - The test apparatus to measure PHB in a single amplifier.

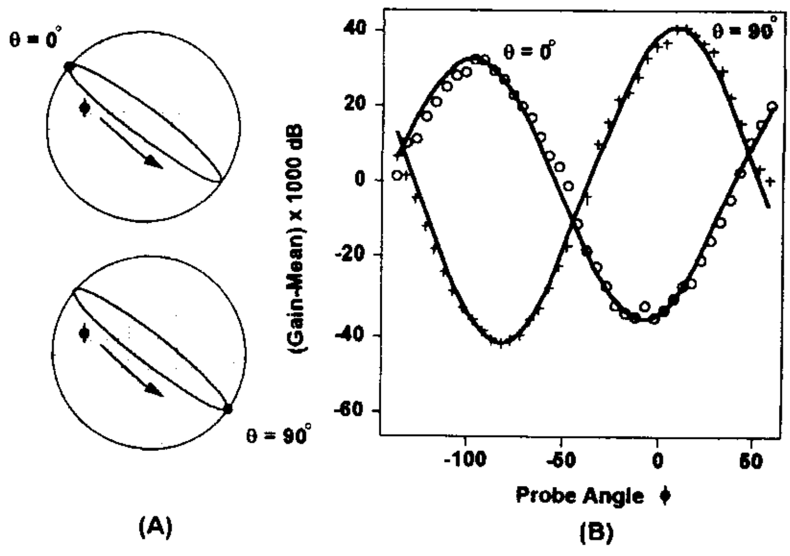

Figure 3 - (A) Typical polarization trajectory for the measurement of PHB. (B) Gain measurement made for depolarized pump.

Figure 3 shows the variation of the gain with the angle ϕ for $\theta = 0°$ (circles) and $\theta = 90°$ (crosses), and a Poincare sphere representation of a typical polarization trajectory for the measurement. In this experiment the degree of polarization of the pump laser was made small by scrambling its state of polarization using a PZT element[9]. For this data the PHB was 0.07 dB as given by one half of the peak to peak deviation of the difference of the two curves. The magnitude of the pump induced polarization dependent gain was estimated by repeating the measurement with the highly polarized pump. Coincidentally, the pump effect was also about 0.07 dB.

EDFA Transmission Systems - In optical amplifier transmission systems, the natural gain compression of the EDFA provides an automatic gain control function. However, operating the amplifiers in gain compression causes the PHB effect. The automatic gain control is accomplished by designing each amplifier in the chain to have a small signal gain that is a few dB larger than the attenuation of the span (Figure 4). The amplifier's output power achieves an equilibrium where the gain for the *total* signal is equal to the span losses; thus near the beginning of the system (where the accumulated ASE is small) the amplifier's gain equals the span loss for the *signal*. However, the ASE noise in the orthogonal polarization to the signal *sees* an excess gain of ΔG in each amplifier and therefore accumulates faster than the standard noise accumulation theory[10] would predict. Since the gain of each amplifier depends on the total input power, noise grows at the expense of the signal at an even greater rate than when PHB is absent. A second impairment mechanism can occur if the signal couples with the orthogonal noise. For example, the orthogonal optical waves can couple from the PDL in the amplifier's components that are distributed down the amplifier chain with random orientations. The system impairments caused by PDG are similar to those caused by PDL[11], since the axis of the PDG is coupled to the pump polarization and is not correlated with the signal's polarization.

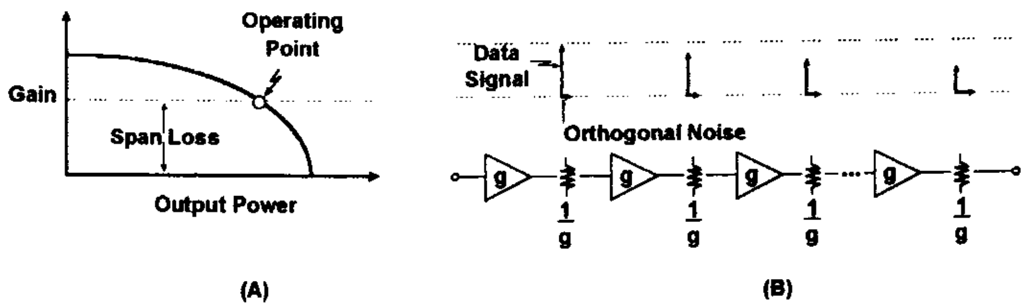

Figure 4 - (A) The gain saturation in the EDFA creates a stable operating condition where the gain for the total signal (both polarizations) equals the loss of the spans. (B) PHB causes the noise in the orthogonal polarization to have an excess gain of ΔG per amplifier stage.

Fortunately, in long-haul EDFA transmission systems, scrabbling the transmitter's polarization reduces the transmission impairment caused by PHB because the dynamics of the EDFA gain are relatively slow.[12] When the signal's polarization is scrambled faster than the amplifier can respond to, there is no preferred polarization axis for the gain to be depleted, and the transmission performance returns to the expected value. The characteristic time constant associated with PHB was measured by switching the SOP of an amplifier's input signal, and measuring the resulting transient behavior of the output power[13] (Figure 5). Following the polarization switch, the input wave momentarily experiences the higher gain of the orthogonal SOP. The change in output power from its initial increased level, to its final steady-state value is related to the gain difference caused by PHB.

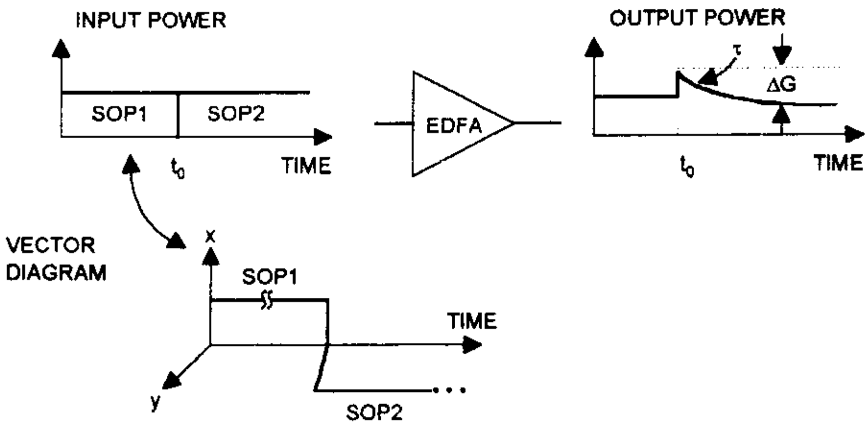

Figure 5 - The dynamics of polarization hole-burning were measured by injecting a signal into an EDFA with pure polarization modulation. The gain difference ΔG and time constant τ was obtained from the output waveform.

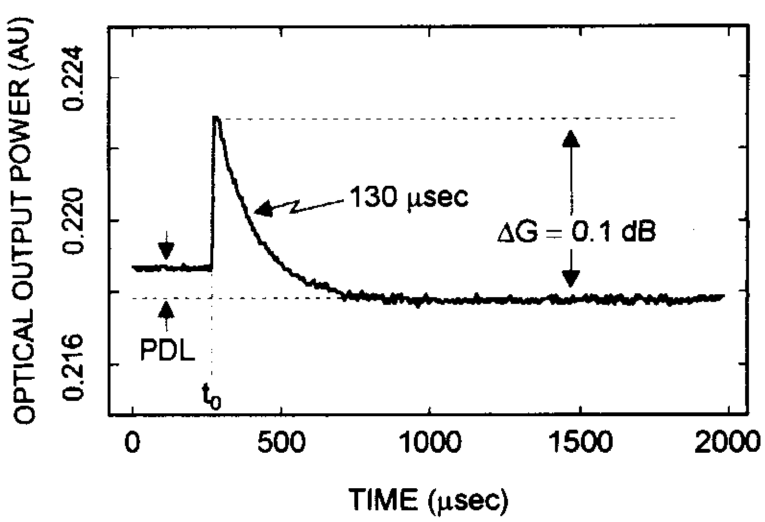

Figure 6 - Transient response of an EDFA to the polarization switch. The time constant was 130 μsec, and the gain difference was 0.1 dB.

The polarization switching was accomplished experimentally using a circulating loop[14] where the polarization controllers were adjusted so that the SOP of the first round trip is orthogonal to the initial condition. The EDFA under test had 9.5 dB gain at 4 dB gain compression, 5 dB noise figure, 12 mW pump power, and 2.2 mW average output signal power, at the measurement wavelength of 1558 nm. PHB is clearly seen in Figure 6 as higher output power (or excess gain) following time t_0. The transient part of the curve, where the high and low gain polarization axes interchange, almost exactly matches an exponential characteristic with a 130 μsec time constant.

This 130 μsec value is similar to the large-signal transient response of the EDFA which was measured to be ≈180 μsec. With the launch SOP adjusted to find the maximum PHB effect, the gain difference was 0.1 dB. The difference in output power before t_0, and the final steady-state value was caused by the polarization dependent loss in the components (labeled PDL in the figure).

To reduce the negative effects of PHB on transmission systems, the SOP of the transmitted optical data signal should be scrambled at a rate that is high compared to the amplifier's response time. Therefore, polarization scrambling should interchange the optical signal between orthogonal polarizations at a frequency higher than 1/130 μsec or about 7 kHz. Thus, the frequency of polarization scrambling (on a great circle route around the Poincare sphere[15]) should be greater than 3.5 kHz to reduce the negative effects of PHB. While scrambling in the kHz range improves system performance, it also causes *A*mplitude *M*odulation (AM) of the data signal resulting from polarization modulation to AM conversion through the PDL elements in the system. Considering this phenomena, it is more desirable to scramble at rates faster than the data's bit rate so that the AM modulation occurs outside of the receiver's bandwidth.

The first report of polarization scrambling to improve the performance of long EDFA transmission systems used a two wavelength transmitter.[16] Since that time other reports have confirmed the results using high-speed lithium niobate scramblers,[17 18] and low speed scramblers.[19] Figure 7 shows a block diagram of the two-wavelength depolarized transmitter. Two distributed-feedback lasers generate the carriers (λ_1 and λ_2) with a wavelength separation of 0.3 nm (or Δf =37 GHz), centered at 1558.3 nm. This separation was chosen to be wide enough so that the information bandwidths of the two carriers do not overlap, yet narrow enough so that they both propagate down the amplifier chain. The two wavelengths are modulated using a Mack-Zehnder intensity modulator; then their polarizations are separated with the PMD in a high-birefringence (HiBi) fiber. With λ_1 and λ_2 adjusted for equal power, the degree of polarization at the output of the HiBi fiber was less than 5%.

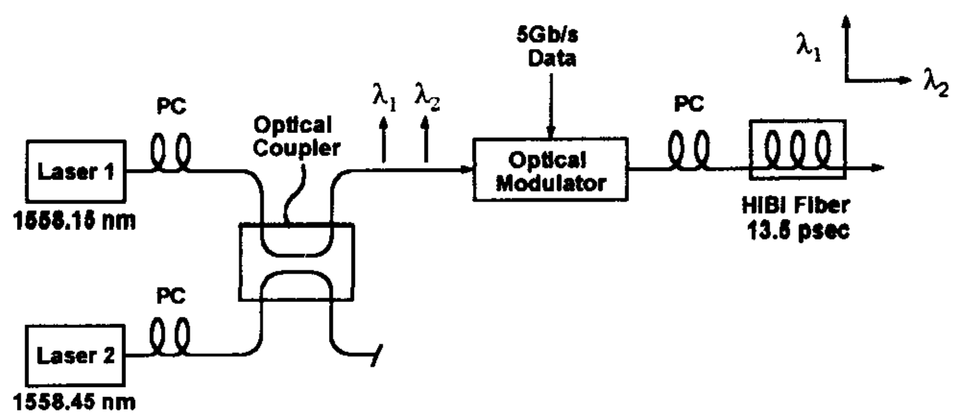

Figure 7 - Block diagram for the two-wavelength, depolarized transmitter.

The transmission performance of the new transmitter was measured using a circulating loop, at a transmission distance of 9000 km and a 5 Gb/s NRZ pseudo-random signal of 2^{15}-1 bit length. The loop's 1460 km amplifier chain consisted of 32 amplifier spans, each with 45 km of dispersion-shifted, single-mode fiber. Thus, 9000 km transmission was accomplished with 6 circulations around the loop. On average, each EDFA had 9.5 dB gain, 5 dB noise figure, 12 mW 1480 nm pump power in the Erbium fiber, and 2.2 mW average signal output power. The DS fiber had an average zero-dispersion wavelength of 1561 nm and an average spliced loss of 0.21 dB/km. The zero dispersion wavelength of the entire chain was set to 1558.3 nm by placing short lengths of conventional single-mode fiber (i.e., λ_0 = 1310 nm) every 500 km along the length of the chain.

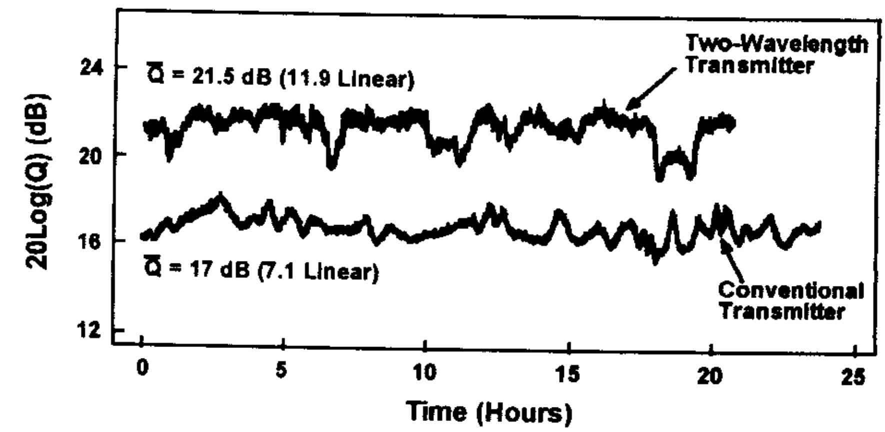

Figure 8 - Q-factor vs time. Top curve was measured with the two-wavelength, depolarized transmitter. Bottom curve was measured with a standard transmitter.

Figure 8 shows the Q-factor[20] vs time, using the new transmitter as compared with a conventional, single-wavelength transmitter. The only difference between the two sets of measurements was the transmitter; all other parameters were held constant. The two average Q-factors over two 24 hour periods were 21.5 dB for the two-wavelength depolarized transmitter and 17 dB for the conventional transmitter. Thus, we realized a 4.5 dB improvement in SNR by making a change to the terminal equipment only.

CONCLUSIONS - Although PHB is a very small effect in a single EDFA, its effect on the overall performance of an optical amplifier transmission line can be several dBs in received Q-Factor. This illuminates the basic difference between optical amplifier and regenerative transmission systems that subtle effects in the amplifiers and/or fibers can *accumulate* to cause significant impairments of the system's performance. Fortunately, the PHB responds slowly to changes of the input polarization; thus, scrambling the state-of-polarization of the input signal greatly reduces the negative effects of PHB on system performance.

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