Undersea Lightwave Transmission Technology and Techniques

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Abstract

This paper tracks the evolution of undersea lightwave transmission technology from digital regenerative systems to the newly developed Erbium-doped fiber amplifier (EDFA) systems, provides a perspective of the evolving technologies using EDFA's, and reviews the impact on the microwave technology and applications community.

Introduction

In the late 1980's lightwave regenerative systems produced a ten fold increase in capacity over it's final analog predecessor. Now in the 1990's multigigabit/sec systems are being installed based on EDFA's.

EDFA's combined with wavelength division multiplexing (WDM) using the conventional non-return-to-zero modulation format or solitons will provide a vast array of solutions to variable bit-rate multichannel, point-to-point and network architectures for both long and short-haul applications.

In the shift from regenerative to optical amplifier based systems the impact on the microwave circuits community is a demand for lower volumes and higher performance circuits, since high speed electronics are only being used in terminal applications.

Regenerative Systems

In the 1970's it became evident that a transoceanic undersea lightwave transmission system could be both technologically and economically viable using low loss silica fiber and available 1.3 µm multi-frequency semiconductor laser diode sources. In the early 1980's deep water sea trials were conducted to demonstrate feasibility and to thoroughly investigate the challenges of deployment, recovery, repair, and other critical issues associated with the implementation of an undersea lightwave system.

The first deep water short-haul system (Optican-1) was installed between Gran Canaria and Tenerife in the Canary Islands in 1985 operating at 295.6 Mb/s. In 1988 the first long-haul transoceanic optical regenerative system was commercially activated. This TransAtlantic Telecommunication (TAT-8) cable operating at 295.6 Mb/s connected the continental US from Tuckerton, NJ-USA, to two points in Europe (Widemouth, England, and Penmarch, France) via an undersea branching unit. This cable system was supplied by AT&T, STC, and Alcatel. The system design employed two working fiber pairs and an additional pair for protection and provided 7560 64 Kb/s circuits, or about 40,000 circuits if configured for voice traffic.

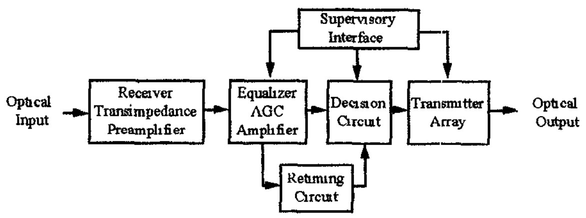

Figure 1 - In-line regenerator block diagram.

In these regenerative systems high speed integrated circuits (ICs) played a vital role in the optical to

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electrical conversion and subsequent regeneration in every repeater (containing six regenerators) as the optical signal traversed the ocean.

A typical in-line regenerator (Figure 1) uses special purpose ICs to perform the six basic regenerator functions, which include a receive optical-to-electrical converter, an automatic gain controlled (AGC) amplifier, timing recovery, decision circuit, an electrical-to-optical transmitter, and finally a supervisory system. The receiver consists of a photodiode and a transimpedance preamplifier that converts the low-level incoming optical pulses to electrical pulses. The linear channel and an automatic AGC amplifier adjust the shape and amplitude of the received data. A timing recovery circuit extracts a local clock signal from the data stream which is used to re-time the data in a decision circuit The laser transmitter driven by the data output of the decision circuit transmits the regenerated pulses onto the out-going fiber. Finally, the supervisory circuit serves to monitor and control certain functions of the undersea plant[1]. Considering the stringent reliability requirements for undersea operation the custom ICs are subjected to an extensive qualification and certification process.

In a digital regenerative transmission system the end-to-end system performance can be characterized by the performance of a single span. In this system bit errors accumulate and the end-to-end system performance can be dominated by the performance of the weakest span. This characteristic greatly simplifies the systems modeling and testing programs.

In less than a decade the transmission capacity of the optical regenerative systems increased from 295.6 Mb/s to an operating rate of 2.5 Gb/s with silica fiber and 1.55 μm single frequency distributed feedback laser sources. In this era there was extensive use of high performance and high reliability ICs to perform the necessary optical to electrical conversion, amplification, retiming, decision making, and regeneration within each regenerator of every repeater.

Optical Amplifiers

During this same period significant strides were being made on a potentially more revolutionary technology employing semiconductor laser-diode pumped EDFA's to take advantage of the wide bandwidth offered by low loss single mode and dispersion shifted fibers[2,3,4,5] . In 1994 the first optically amplified system (Columbus-II B) operating with a single channel (1558.5 nm) at 2.5 Gb/s was commissioned between West Palm Beach, Florida and Magens Bay, St. Thomas, USVI. Optical amplifier systems require no optical-to-electrical conversion in the repeaters, resulting in a smaller demand for the specialized regenerator ICs. In these new systems high speed electronics are only required in the terminal stations. High speed circuits will certainly play a vital role in upgrading existing systems and in the installation of the ever increasing higher capacity systems[6].

In 1996 the first generation of long-haul transoceanic optical amplifier systems will be fully activated. TAT-12/13 forms a ring network in the north Atlantic with two transatlantic cables of 5900 km and 6300 km, and two interconnection cables, each a few hundred kilometers in length. A set of cables in the TPC-5 cable network form a similar architecture in the Pacific. These systems use 1480 nm pumped EDFA's and transmit a single 5 Gb/s data channel per fiber pair. The TAT-12/13 cable network will provide 120,960 fully protected 64 kb/s circuits.

Figure 2 shows the basic block diagram of an EDFA with the associated energy level diagram for 980 nm and 1480 nm pumping and the absorption and emission spectra[7]. High output power semiconductor pump lasers are readily available at both these wavelengths. The emission (gain) spectrum shows that significant gain occurs in the 1550 nm region, coinciding with the low-loss window of single mode fibers. This feature makes EDFA's ideal for long-haul transmission. The basic operation of an EDFA is as follows: A pump laser, coupled to a short section of erbium-doped fiber via a wavelength selective coupler, excites the erbium ions to produce population inversion. The amplification of the incoming signal results from the stimulated emission of the excited erbium ions. The optical isolator serve to prevent oscillations in the amplifier in the presence of spurious optical reflections. The simplicity of the optical amplifier makes it ideal for undersea applications. Some of the other attributes of the EDFA are; wide optical gain bandwidth, high small signal gain, high output power, low noise figure and bit rate and modulation format independence.

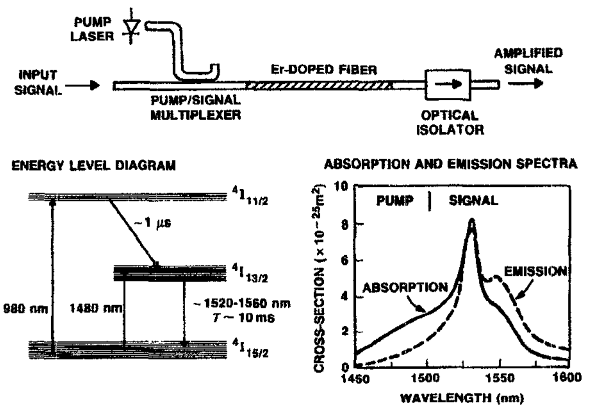

Figure 2 - EDFA Block Diagram with Energy Level Diagram and Absorption and Emission Spectra.

Optical amplifiers are considered useful in transmission systems as booster amplifiers, receiver preamplifiers, and in-line repeater amplifiers. A booster amplifier typically employs a two stage, dual pumped design to produce very high output power for use in long unrepeatered applications. The receiver preamplifier typically employs a counter propagating (opposite to the direction of the signal) 980 nm pumped design to produce almost full population inversion and low noise figure for use in applications were the incoming optical signal is small. The in-line amplifier typically employs a simple, economical design with low noise, modest output power due to fiber nonlinearities, significant compression level to provide automatic gain control and protection against pump failures or degradation. The gain bandwidth of a concatenated chain of amplifiers decreases with distance and is a limiting factor in multichannel long-haul transmission. Amplifier designs and system topologies are under development to increase the usable bandwidth of long-haul optical amplifier systems.

The design of an optical amplifier transmission system is complicated by the fact that impairment mechanisms (such as noise, chromatic dispersion and fiber nonlinearities) accumulate over the entire length of the system. This is different from the regenerative systems where the performance of the weakest span usually dominates the end-to-end performance. The end-to-end signal to noise ratio budget is the primary system design parameter for optically amplified systems. The problem of predicting the end-to-end performance is complicated and requires extensive computer simulations, circulating loop experiments, and even full length straight away testbeds[8,9,10].

Current Technology and Techniques

Since the EDFA exhibits wideband gain, and is bit rate and modulation format independent, this technology provides system designers with a wide range of options for system topology, upgrade and total capacity. WDM is currently the primary vehicle to achieve those objectives. 100 Gb/s over 6300 km with twenty 5 Gb/s data channels has been achieved in the laboratory using the conventional non-return-to-zero modulation format[11]. This experiment used long period fiber gratings to flatten the amplifier chain, and bit-synchronous polarization and phase modulation to overcome the effects of polarization hole burning and polarization dependent loss. High capacity (40 Gb/s over 9,000 km with eight 5 Gb/s channels using guiding filters) performance was also demonstrated using solitons.[12] Common to both these experiments was proper management of the transmission fiber dispersion to reduce cross phase modulation and four-wave mixing, and tailoring of the per channel power to suppress non-linear interactions.

As the bit rate of individual channels, number of channels, and the total system capacity increases there will be a great need for specialized high speed and high performance electronic circuits for data modulators, multiplexers, demultiplexers, decision circuits, frequency dividers, clock distribution networks, logic gates, error correcting codes, and subsystems for maintenance and network control. The principal requirement of these ICs and subsystems will be to provide optimum performance over wide bandwidths with minimum intersymbol interference and high signal to noise ratio. With the low demand for volume, cost will always be an underlying issue.

In addition to high capacity for point-to-point applications, WDM also offers a vast array of networking capability to provide high capacity to several countries connected to a common network. Africa ONE, a proposed undersea optical ring around the coast of Africa will connect some 40 countries on the continent and then to Europe, Asia, and the Americas, (Figure 3) is one example of the wide range of options that this new technology can provide. This system will provide broad flexibility for present communication requirements and evolve to accommodate the variable growth demands of individual countries. There has been phenomenal growth in the deployment of undersea lightwave communications in response to strong market demand for high capacity communication systems. It is estimated that by 1998, almost 129 countries will be connected to undersea lightwave transmission networks[13].

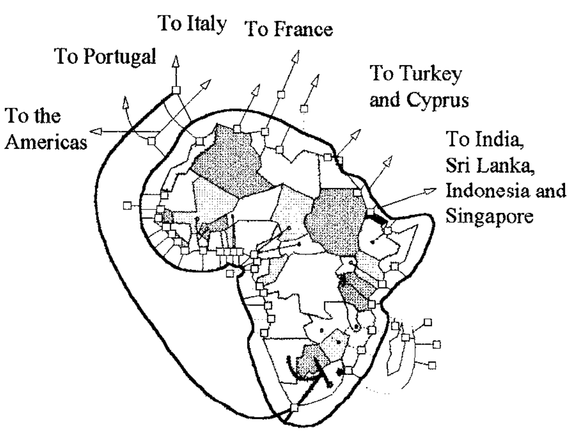

Figure 3 - A Proposed Africa ONE Network.

Conclusions

The recent introduction of EDFA's into the undersea transmission technology business has revolutionized the industry. Options are becoming available for upgrading installed systems with only terminal modifications using WDM technology. Different modulation formats will provide system designers with a wide range of options for implementing variable bit-rate multi-channel, point-to-point, and network architectures for both long and short-haul applications.

There are numerous technological hurdles to overcome to fully realize the commercial potential of this fiber amplifier technology both in the optical and electrical arenas. However, laboratory experiments continue to produce record breaking results, indicating increasing understanding and innovative implementations.

Acknowledgments

I would like to thank J. M. Sipress, P. K. Runge, and F. W. Kerfoot for their continued support and encouragement. I would also like to thank N. S. Bergano for his help and technical insights.

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