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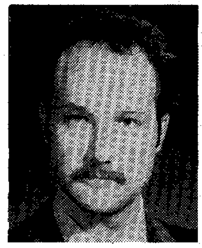

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Undersea Fiber Cable Technology

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(Invited Paper)

Abstract—**Compared with the conventional coaxial undersea cable systems, an optical fiber undersea cable system has a great technical and economical advantage. It is also suitable for digital transmission. In this paper, the optical fiber undersea cable technology (including optical fiber cables and repeaters), which is now in the research and development stage in several countries, is reviewed.**

I. Introduction

Coaxial undersea cable systems have been used as one of the major transmission systems in international telecommunication networks over the past 25 years, and its channel capacity has rapidly been increased about ten times per decade with the growth in overseas traffic. However, this system has nearly reached a limit in its ability to increase the capacities of long-haul transoceanic systems from the standpoint of reliability and economy, although additional growth may be permitted with short-haul cable systems. On the other hand, the research and development on optical fiber communication systems progressed remarkably in the 1970's, and a number of systems using 0.85 μm wavelength have already been put into commercial services. Recently, the experimental systems using long wavelength and single-mode fibers are now actively being developed worldwide.

Optical fiber undersea cable systems are considered to be a very promising technology to surmount these barriers. At the end of the 1970's the research and development effort was directed toward optical fiber undersea cable systems in the countries which had the experiences of developing the coaxial undersea cable systems. Optical fiber undersea cable systems are recognized to be not only economical, but have improved qualities due to digital transmission capability, and will conform to the future digital communication networks.

Undersea cable systems can be roughly classified into two categories. One is short-haul nonrepeatered systems applicable to interisland, for example. The other is repeatered systems which will be applied to medium-haul transmission routes or international long-haul transmission routes. In this paper, the present status and future trends of long-haul repeatered optical fiber undersea cable technology, which will require the most advanced optical fiber transmission technology, will be reviewed, including a comparison with the conventional coaxial cable systems, the structure of optical fiber cables, and the optical repeater circuits and housing now being developed in Japan and other countries.

II. An Optical Undersea Cable System

The principle of transmission systems for undersea cables is basically the same as that for inland long-haul cable systems. However, the fact that the undersea cable is laid into deep sea by a cable ship imposes severe conditions on its mechanical strength. For instance, when the cable is laid under the water some 8000 m deep, water pressure equivalent to about 800 atm is applied onto the cable, and also several tons of tension come

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onto the cable during laying and repairing work. Furthermore, an extremely high system reliability is required because a great deal of time and expense is consumed for the repairing of the undersea cable. On the other hand, the advantage of undersea cable systems compared with inland cable systems is that the temperature variation of the environment is rather small.

Since the first transatlantic cable, capable of carrying 48 telephone channels, was laid in 1956, the development of undersea cable systems has tended to increase bandwidth in order to obtain higher circuit capacities. This has been accomplished by the combination of increasing the cable diameters and reducing the repeater spacings. Fig. 1 shows the repeater spacing versus circuit capacity for coaxial undersea cable systems. At present, systems with bandwidth of 36 and 45 MHz have already been put into practical service. It is likely that the repeater spacing will only be about 4 km in a system carrying around 10 000 telephone circuits. Fig. 2 shows the cable diameter versus circuit capacity. Broader bandwidth systems require larger diameter cables in order to contend with the increasing attenuation at higher frequencies.

The increase in number of repeaters requires extremely high reliability on the components of each repeater. It also gives rise to the problem of the increase of distortion noise and the necessity of higher power feeding voltages. The adoption of a larger diameter cable involves many other difficult problems in economic and technical aspects; it requires more cable costs, a larger cable tank capacity of a cable ship, and gives rise to difficulties in cable handling.

Meanwhile, due to the progress of optical fiber transmission technology, many of its excellent characteristics have been revealed to date. The characteristics of optical fiber have improved remarkably in the long wavelength range, and the single-mode optical fibers with extremely low loss of 0.5 dB/km at 1.3 μm wavelength and 0.2 dB/km at 1.5 μm wavelength have been realized in 1976 and 1979, respectively. Moreover, material dispersion reaches zero in the region of 1.3 μm in silica based glasses. At this wavelength, the material and waveguide dispersion in single-mode fibers cancel each other to achieve zero total dispersions and very wide bandwidth. Therefore, the optical fibers at long wavelength range are very attractive for a long-haul high-capacity transmission medium. For example, 30–50 km repeater spacings will be possible at the bit rate of 300–400 Mbits/s in 1.3 μm wavelength and around 100 km repeater spacings might be possible at the same bit rate in 1.5 μm wavelength range if semiconductor lasers with single-mode longitudinal oscillation were developed. Furthermore, in the optical fiber undersea cable it is possible to increase the capacity using multiple pairs of optical fibers without increasing the cable diameter. The expected diameter of an optical fiber undersea cable and its repeater spacings are shown in Figs. 1 and 2. It will be easily seen that the optical fiber undersea cable system will have the possibility of low cost compared with coaxial undersea cable systems.

It is not easy at the present stage to compare accurately the construction cost of conventional cable systems with the new optical fiber cable system because the optical fiber and optical device technology is still making progress. Nevertheless, by assuming the optical fiber cable structures and repeater which will be described in the following section, and by predicting their cost, it is estimated that the per channel construction cost of long-haul optical fiber undersea cable with the capacity of around 10 000 telephone channels could be made 30-50 percent lower than the cost of coaxial undersea cable of the same capacity.

Fig. 3 shows the schematic diagram of an optical fiber undersea cable system. The system consists of submersible plant and terminal equipments at both ends of the system. In the terminal equipment, digitally coded telephone and TV signals are multiplexed to high-speed pulse stream by the time division basis. The bit rate can be reduced to about one-third by removing redundancy in the signals using a digital speech interpolation scheme for telephone and a predictive coding scheme for TV signals. The terminal equipments also contain a high voltage power feeding equipment which provides constant current for repeater powering. The submersible plant consists of an optical fiber cable and a number of repeaters which receive, amplify, and regenerate the optical pulse signals and transmit them into the optical fiber.

Table I summarizes the objectives of system design parameters now being developed in various organizations [1]-[3]. The transmission speed of 280 Mbits/s corresponds to around 4000 telephone channels without bit reduction technique. The transmission system length of 6500–10 000 km corresponds to transatlantic or transpacific crossing. The targets of mean time between failure are 8–10 years.

III. Optical Fiber Undersea Cable

The optical fiber undersea cable will be laid in the same undersea environments and also by the same installation and recovery techniques as coaxial undersea cable using a conventional cable ship. Therefore, the mechanical structure and requirements for strain and pressure are almost the same as the conventional coaxial undersea cable. Table I shows the requirements for the optical fiber undersea cable. The maximum hydrostatic pressure, cable modulus, and elongation of cable correspond to a sea depth of 8000 m. The value of bending radius is determined by the installation mechanism of the cable laying ship. The optimum value of dc resistance of the cable is specified by the power consumption of repeater and maximum power supply voltages.

Optical fiber undersea cable is required to maintain its transmission characteristics under high water pressure for a period of more than 20 years. The point of realizing the optical fiber undersea cable lies in how to protect optical fiber from the severe sea-bottom environments for a long period of time. It is reported that when the strain is imposed on optical fiber in a highly humid atmosphere for a long time, optical fiber will degrade considerably in its mechanical strength. Therefore, a variety of structures to prevent the optical fibers from receiving direct water pressure, and also to keep the ambient humidity from going up, are proposed and developed in various organizations.

Fig. 4 shows the cross section of typical optical fiber cable structures that are now being developed by several organizations [3], [4]. Fig. 5 shows one example of the appearance of experimental optical undersea cable. Generally, the fiber core

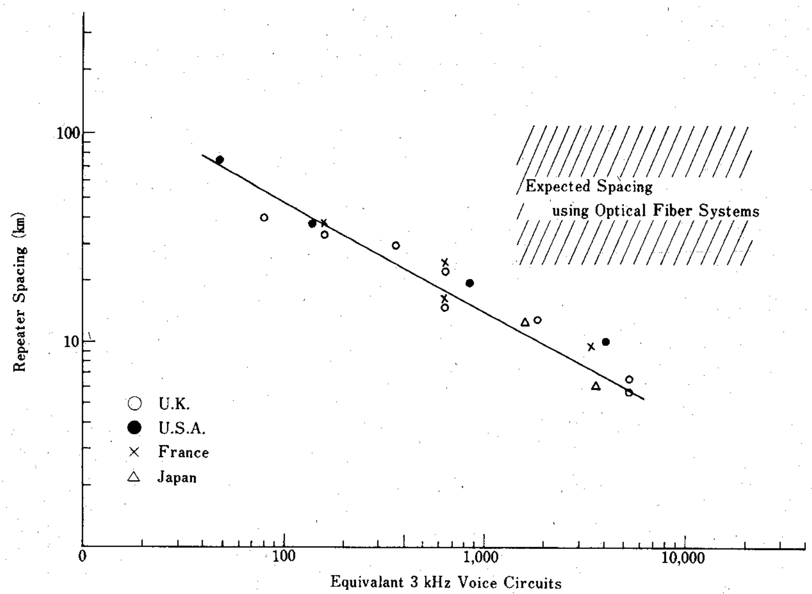

Fig. 1. Repeater spacing versus channel capacity for coaxial undersea cable systems.

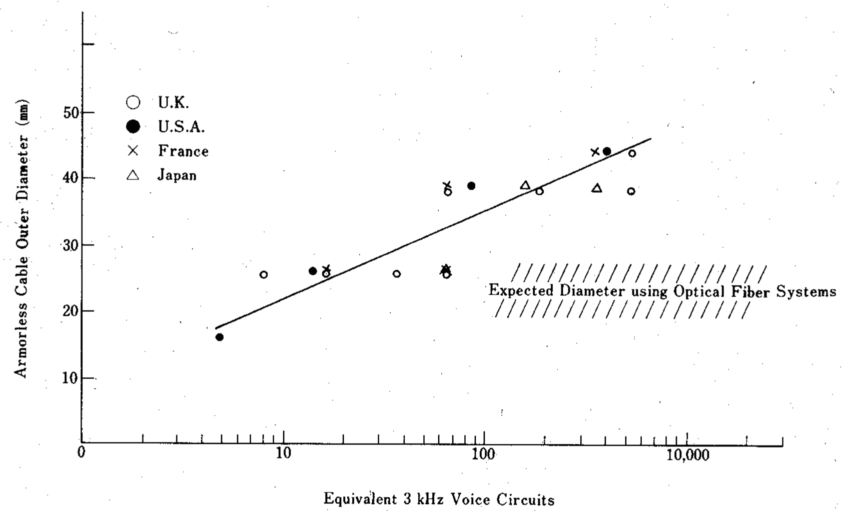

Fig. 2. Cable core diameter versus channel capacity for coaxial undersea cable systems.

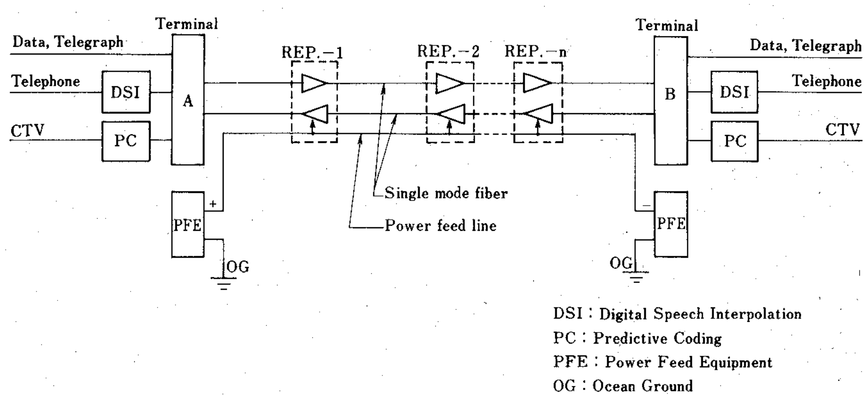

Fig. 3. Schematic diagram of optical fiber undersea cable system.

is placed at the center of the cable to minimize fiber strain due to cable bending and twisting. The fiber core is housed in a thick-walled aluminum or copper tube and/or carefully arranged high tensile steel strand wires which protect optical fibers from high water pressure and give the cable about 8 tons of tensile strength. The aluminum tube can consist of three divided

TABLE I
OBJECTIVES OF SYSTEM DESIGN PARAMETER OF OPTICAL FIBER UNDERSEA CABLE SYSTEM

Country Organization		U.S.A. (BL)	JAPAN (NTT and KDD)
System	Transmission Length	8,000km	1,000 − 10,000km
	Water Depth	7,500m	8,000m
	Transmission Speed	274 Mb/s	260 − 400Mb/s
	Wave Length	1.3μm.	1.3μm
	Number of Subsystems	3 max	2 − 3
	Power Supply Current	1 A/unit	1A
	Reliability (MTBF)	8 years	10 years
Repeater	Repeater Span	25-50km	25 − 50km
	Parts	mono-IC	mono − IC
	DC Power Consumption	4 W/one way	3 − 5W/one way
	Supervision	loop back	loop back method
	LD Redundancy	up to 3 stand by	0 or 1 standby
Cable	Optical Loss	less than 1 dB/km	less than 1 dB/km
	Tensile Strength	8.0ton	7.5 − 10 ton
Housing		gimbal less structure	gimbal structure

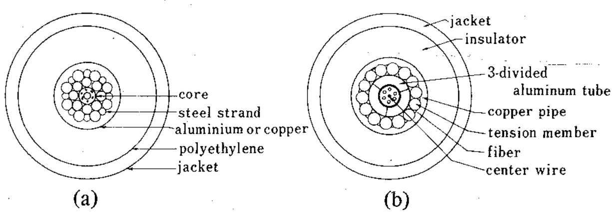

Fig. 4. Cross sections of optical fiber undersea cable.

pieces as shown in Fig. 4(b). Then, an aluminum or copper tube is formed around the steel strand wire structure. This tube acts as a barrier to water diffusion and is also used as a power feed path. Around this tube, thick polyethylene is formed as an insulator. The thickness of the polyethylene is determined to give a sufficient electrical field strength in the insulation at the expected maximum power supply voltages. For shallow water use, the cable will be armored with one or two layers of armor wires.

It is necessary to keep the variation of optical fiber characteristics as small as possible during the cable manufacturing process. It was reported by several organizations that no significant change in attenuation was observed during the cable fabrication process [5], [6].

At Bell Laboratories, an experimental optical undersea cable was tested using an ocean simulating facility which simulates an ocean environment without requiring the service of a cable ship. The pressure corresponding to about 5000 m water depth was applied and the temperature was varied from 3-30°C. There was no observed change in loss of optical fiber in the test[6]. In the United Kingdom and Japan, the experimental optical fiber undersea cable was tested by laying it in the ocean using a cable ship and the results were generally satisfactory. More detailed experiments are scheduled to be conducted in the future.

When tension is applied to the undersea cable during the installation or recovery processes, the cable elongates as shown

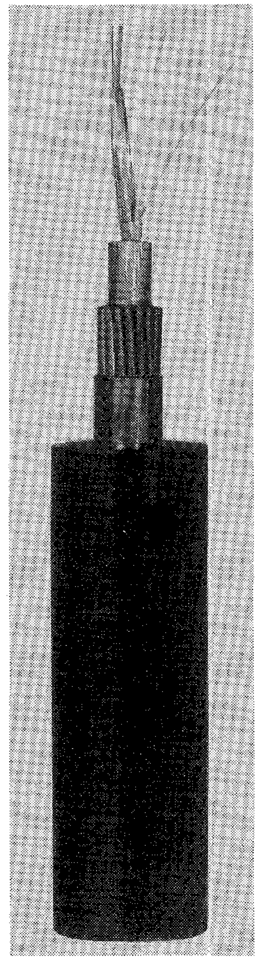

Fig. 5. Experimental optical fiber undersea cable.

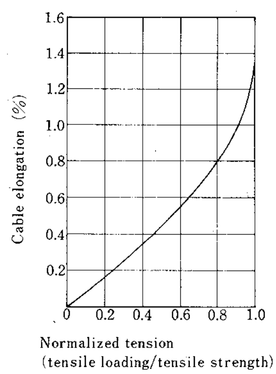

Fig. 6. Tension versus elongation characteristics of optical fiber undersea cable.

in Fig. 6. The optical fiber in the cable will have to sustain the strain corresponding to degree of elongation, that is, about 0.4-percent elongation under laying conditions and about 0.8-percent elongation under recovery conditions for repair. Usually, a short-time proof test is adopted to guarantee the strength of the optical fiber. However, in actual recovery conditions, the undersea cable must be subjected to high tension for about two successive days in the worst case. Therefore, optical fiber will have to be produced which is capable of meeting the high-proof test levels, perhaps more than 1 percent. To manufacture the optical fibers of a long length which can sustain such strain is now a pressing problem. Parallel with this, studies on a cable structure which would mitigate the elongation of optical fibers are also under way.

IV. Optical Undersea Repeater

A repeater is made up of regenerator circuits, supervisory circuits, the housing that protects the optical and electrical units and fibers from hydrostatic pressure, and the cable coupling that connects the housing and optical fiber undersea cable.

In conventional coaxial submarine cable systems, the main part of undersea repeater circuits consists of a rather simple linear amplifier. On the other hand, in optical undersea repeaters, the regenerative repeater is adopted, whose basic circuitry is the same as that developed for the inland optical digital transmission system. However, a high degree of reliability and particular supervisory circuits are required for the undersea repeaters.

In Fig. 7, the block diagram of an optical regenerator under development is shown. The incoming optical signal is detected by the avalanche photodiode which converts the optical signal into an electrical signal. The electrical signal is amplified, equalized, and applied to the decision circuit. The timing information is also extracted from the signal, and presence or absence of pulse is determined at the decision circuit. The regenerated pulses drive the laser diode whose output is coupled to the next optical fiber. Besides the above mentioned circuits, automatic gain control circuits and supervisory circuits are included.

If the mean time between failure is assumed to be about 10 years as the conventional coaxial cable systems, the reliability requirement for one repeater will be about 30 FITS for the transoceanic cable system which includes about 200 repeaters. The reliability of the repeater is mainly determined by the reliability of electrical circuits and optical devices, especially laser diodes. The highly reliable electrical circuits call for a reduction of the number of components and soldered junction points, and it would be impossible to attain the required reliability if the discrete components were used because the number of active components would be about 10 times more in a regenerative repeater compared to a conventional linear repeater. As a consequence, the integration of electrical circuits will be inevitable. It is expected that one regenerator circuit will be made up of about five integrated circuits.

The research and development of the laser diode which operates at long wavelength region has been carried out actively in many countries and a laser diode using InGaAsP quarternary semiconductor material is considered to be most suitable. Reliability tests of InGaAsP lasers have been conducted and the results show that the lifetime of a long wavelength laser is expected to be the same or longer than that of the laser diode of short wavelength. However, the accumulated data are not enough and the degradation mechanism is not yet clarified at present. It may be required to introduce the redundancy techniques, that is, to implement a sparing scheme for laser diodes. Two methods are considered to implement the sparing scheme; one is to switch the laser automatically in the repeater by detecting the deteriorated laser, the other is to monitor the degradation of the laser at the seashore terminal and switch the laser by command control signal from the seashore station. In either case, it is necessary to switch the output of the laser diode to the optical fiber mechanically or electrooptically.

As for the photodetector operation at long wavelength region, an avalanche photodiode (APD) using germanium has already been developed and used in the experiment. Also, APD's using InGaAs compounds are studied in order to improve the noise characteristics. Although the sensitivity of a photodiode is less than that of an APD, the use of a p-i-n diode is also proceeded from the standpoint of high reliability and low power supply voltages. In the future, the optical integrated circuits such as the integration of laser diode and drive circuits or that of photodetector and preamplifier will be introduced into the repeater.

The repeater circuits are accommodated in the pressure housing which protects the circuits from high water pressure and mechanical forces during installation and recovery. The pressure housing is connected to the cable by a coupling device. Figs. 8 and 9 show one example of a repeater structure, which is under development at Kokusai Denshin Denwa (KDD), Japan [7]. The pressure housing is almost the same as that which has been used for coaxial submarine cables for many years. However, a regenerative repeater dissipates more power than an analog repeater and it is desirable from the standpoint of component reliability to reduce the thermal resistance between inner housing and outer pressure housing [8].

The optical feedthrough assembly, through which optical fibers are introduced into the pressure-proof case, must be newly developed for optical undersea repeaters. The factors which should be considered in the design of optical feedthrough are airtightness in high water pressure, low optical attenuation, and stable performance. Fig. 10 shows an experimental optical fiber feedthrough. The thin metal is coated on the surface of optical fibers, which are inserted into the copper pipe and sealed off with solder. The copper pipe is also used as a power feeding line.

There are two types of cable coupling structure; one is to use a flexible gimball joint structure and the other is to use a rigid gimballess joint structure. The structure must be compatible with the cable handling equipment on the cable ship. The optical fiber undersea cable and repeaters are connected aboard a cable ship. In order to accomplish this connection in a rather short time and to maintain it stable for a long time, the joint chambers are provided on either side of the repeater housing in the case as shown in Fig. 8.

V. Supervisory and Fault Locating System

In order to maintain the undersea cable system in normal conditions, it is necessary to supervise the operating state of repeaters. Moreover, if the failure occurs in the submersible plant, it is required to locate the faulty position accurately and quickly.

The supervisory systems for the undersea repeater can be classified into two schemes. One is to utilize the optical fiber itself as a transmission line of supervisory signals and the other is to prepare a special transmission line for supervisory signals.

Fig. 11 shows the remote-control type optical loopback method [9]. The output of the laser diode in the repeater is coupled to the input photodetector of the reverse direction

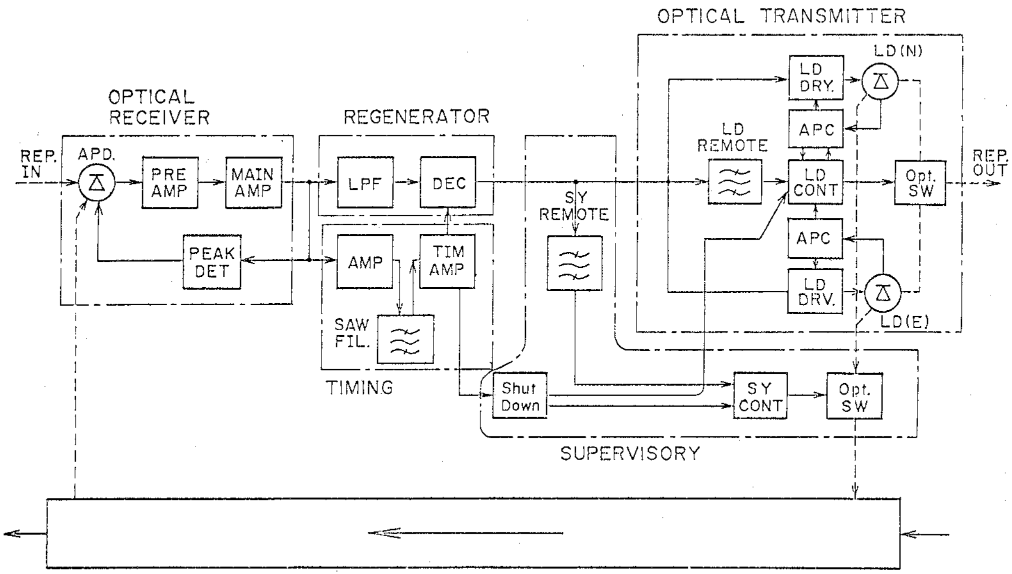

Fig. 7. Block diagram of optical regenerator.

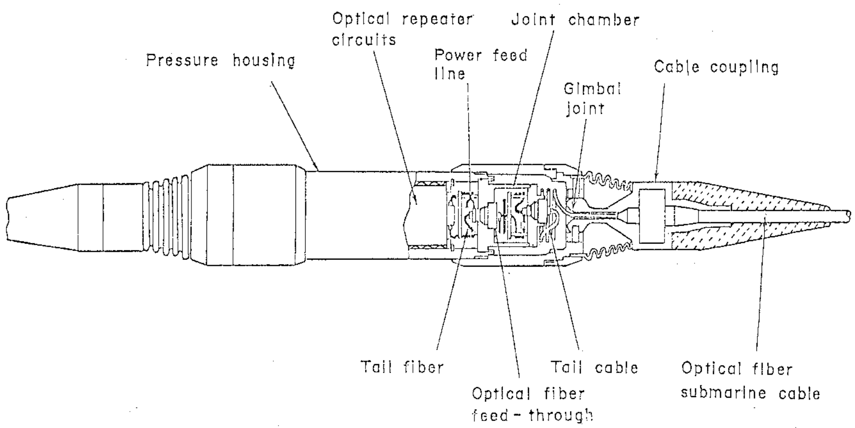

Fig. 8. Repeater housing structure.

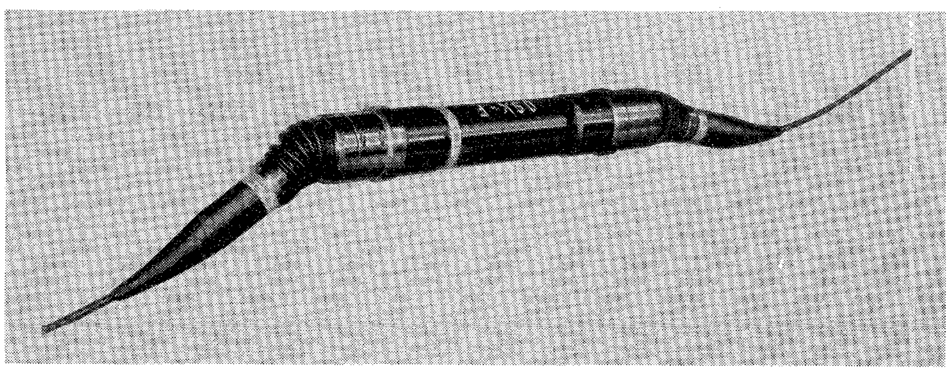

Fig. 9. Experimental optical undersea repeater.

repeater through the optical switch. The loopback circuit is established by closing one of the specific switches in the repeater which is selected by command signal from the seashore terminal. Then, the test signals consisting of pseudorandom sequences are transmitted and the bit error rate is measured at the receiving end. By repeating such measurements successively to all repeaters from both seashore terminals, the degraded or faulty repeater can be identified.

The other supervisory scheme proposed is one which utilizes the central metal wire of the undersea cable for low speed transmission of electrical supervisory signals [2]. Each repeater contains a supervisory signal regenerator and associated circuits. Supervisory signals first identify the specific repeater being addressed and then determine the configuration of the repeater, that is, which of the lasers is in operation, which loopback connections for fault localization exist, and so on. The oper-

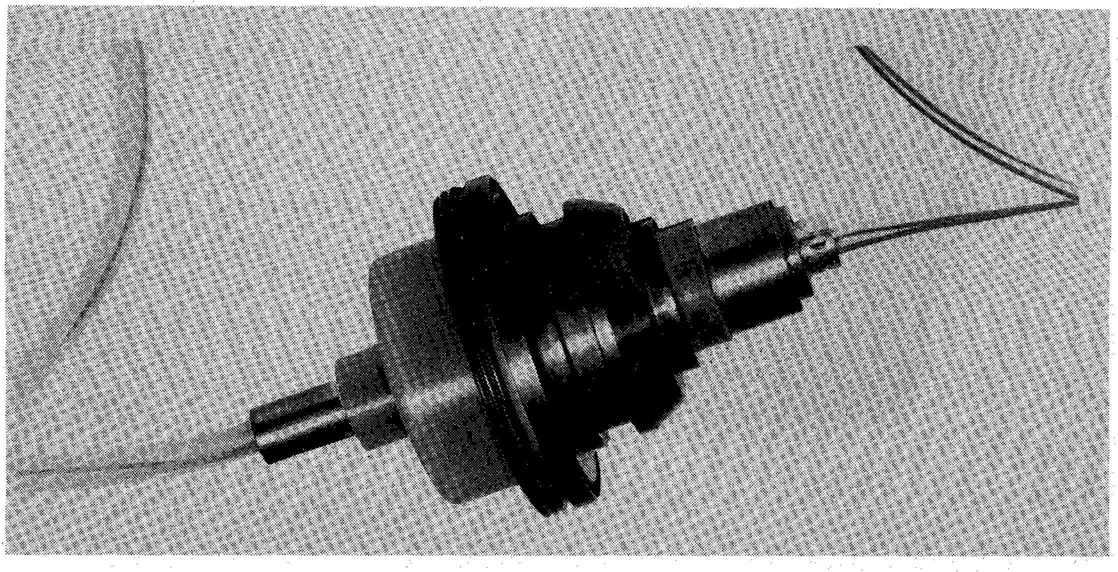

Fig. 10. Experimental optical fiber feedthrough.

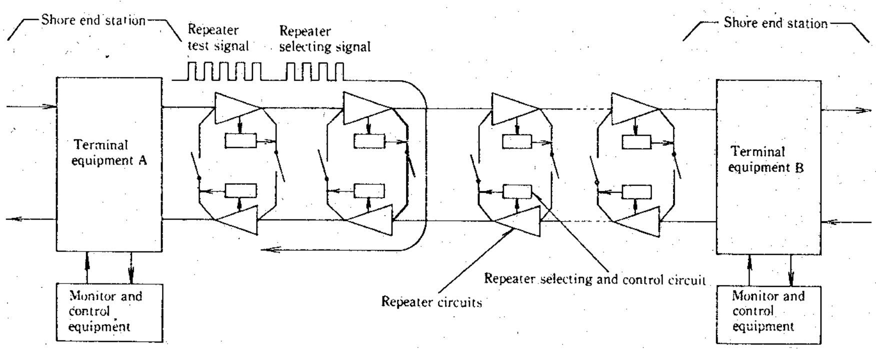

Fig. 11. Remote-control type optical loop-back method for repeater supervisory.

ating conditions of lasers and photodetectors can also be monitored in this scheme.

When the trouble should occur in the undersea cable portion, it is also necessary to locate the faulty position accurately. The fault locating methods may be different depending on the state of troubles. When the power feeding is possible even in the failure, the above mentioned supervisory system will localize the fault to within one repeater section and then the fault locating scheme using backscatter phenomena in optical fiber or electrical pulse echo in metallic wire cable will be used to pinpoint the fault position.

VI. Present Status and Trends of Development

The research and development of the optical undersea cable system are actively conducted in the countries which have the experience of developing coaxial undersea cable systems, that is, the United States, the United Kingdom, France, and Japan.

Bell Laboratories is actively engaged in the exploratory development of a high-capacity optical undersea cable system named SL with the intention of applying it to the transatlantic in 1988 as the international traffic will continue to grow at a rate of 20-30 percent annually. The expected circuit capacity is 12 000 channels per pair of optical fibers. This corresponds to a digital transmission bit rate of 274 Mbits/s and a bit rate reduction of 3. The bit rate reduction will be performed by speech processing such as digital TASI. This system can be made up of one to a maximum of three subsystems depending on load requirements. Since the subsystems are electrically independent, this system can be made with one or both ends split so that different subsystems can go to different countries [2].

In the United Kingdom, the 9.5 km optical fiber undersea cable was installed to an average depth of 100 m in Loch Fyne, Scotland, in February 1980. This system comprised five jointed lengths of cable, and four multimode fibers and two single-mode fibers are incorporated in the cable. No significant change in attenuation was observed for a period up to 3 months after the lay. A 140 Mbit/s bothway digital repeater was inserted into one pair of multimode fibers. This trial represented the first practical use of long wavelength single-mode fiber in a real underwater environment which might be experienced in the North Sea [5].

French PTT is also proceeding with the research and development of optical fiber undersea cable systems. The experimental link program is to develop a 20 km nonrepeatered system by the end of 1982 and a medium-haul repeatered system by the end of 1983. The goal is to install an approximately 200 km optical undersea cable system at a depth of around 2500 m between France and Corsica by about 1984–1985 [10].

In Japan, the research and development of optical fiber undersea cable systems has actively progressed to the point where these systems will be applied to domestic and international links. Nippon Telegraph and Telephone is studying a nonrepeatered system providing 96–1440 voice channels with a pair of fibers for short-haul routes and a repeatered system providing high capacity for long-haul routes. A field evaluation test for a nonrepeatered system of about 10 km was started in autumn 1980. A commercial system will be installed in 1983. The trial repeatered system will be evaluated in a field test in 1982. The first commercial system will be installed for relatively short-circuit length in 1985 [8].

KDD is also proceeding with the research and development of optical undersea cable systems with the intention of applying them to international long-haul routes, for example, to transpacific cable systems. To this end, the field test of experimental repeatered systems will be conducted in 1982 and the long-haul commercial system is expected to be available by the end of this decade.

VIII. Conclusion

The optical fiber undersea cable system has a potentially great technical and economical advantage over the conventional coaxial undersea cable system and will be realized by combining the long wavelength, single-mode fiber transmission technology with the established undersea cable technology. In the development of an optical undersea cable system, the most advanced fiber optic technology will be introduced. There remain many difficult technological problems to be solved before the system will be put into practical use. The most important problems are the realization of the highly reliable optical and electrical devices and the low loss, high strength, and long span optical fibers. The fiber optic technology has been progressing very rapidly and the technological difficulties will be overcome in the near future. The high capacity optical fiber undersea cable system using single-mode fiber at 1.3 μm wavelength will be developed in the mid 1980's for medium distance and in the late 1980's for long distance, such as transoceanic application. The optical fiber transmission technologies such as single-mode transmission at 1.5 μm wavelength, wavelength division multiplex technology, and coherent communication technology should be taken into account in the future.

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