Dense-WDM Technologies: Furukawa Electric's Contribution

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1. INTRODUCTION

With the successful development of lasers in the 1960s, fiber-optics became the technology of the future for telecommunications, but problems relating to the two most important elements--the light source and the transmission medium--meant that practical applications remained elusive. By 1970, however, a laser diode capable of continuously lasing at room temperature and an optical fiber with a transmission loss of 20 dB/km at last provided the levels of performance required. In a little over 10 years, fiber-optic communications underwent remarkable growth. At that time it was believed that the next generation of systems would be optical coherent communication using heterodyne detection, and many institutions were active in pursuing this line of research. It was in 1989, when high-temperature superconductivity was the rage, that the erbium-doped fiber amplifier (EDFA), an amplifier using erbium-doped fiber (EDF) pumped by a 1480-nm laser diode, forever changed this perception. [1), 2)] In no time the EDFA was in actual use, and has become the key to the technologies of wavelength-division multiplexing (WDM).

Furukawa Electric early recognized the possibilities of fiber-optics and the later EDFA, and was quick to emphasize research in these areas. In 1974 Furukawa led the world in laying outdoor optical fiber cable, [3)] and in 1989 was in the forefront of research on fiber-optic amplifiers. A 1480-nm pumping laser diode in 1989 [2)] and an L-band fiber-optic amplifier [4)] are among the important contributions we have made to fiber-optic communications and the WDM technologies that support it. Another success was scored with the optical fiber amplifier (OFA) repeater system for WDM-based HDTV (high-definition television) programming for the 1998 Winter Olympics in Nagano. Also, realizing that WDM would require OFAs of higher output power, we have been a leader in the pumping laser field in working to increase diode output.

Furukawa Electric places the highest priority on the development of WDM products, and by developing this new technology is creating business and at the same time contributing to the advancement of society.

As an aid to understanding the thrust of this "mini-special" on wavelength-division multiplexing, this article provides an outline of WDM transmission systems and describes the contributions Furukawa Electric has made in the field.

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2. WDM TRANSMISSION SYSTEMS

With the explosion of the Internet, telecommunications capacity is more than doubling every year. This technological revolution has sent line charges plummeting, and the new demand created a virtuous circle that has further spurred technical innovation, centered on WDM. Time-division multiplexing (TDM) and WDM offer the two main means of increasing communications capacity, and as Figure 1 shows, until the commercialization of OFAs, progress depended on increasing the capacity per channel.

WDM itself is not a new concept, and even then was easy to implement. At that time, it was difficult to produce economically light sources having wavelengths stabilized within a narrow range, and filters capable of separating light with narrow channel spacing. The result was WDM using different spectral windows, such as 1310 and 1550 nm.

Figure 2a) shows the basic structure of a conventional optical repeater system in which signals from the transmitters (Tx) are propagated along the optical fibers. When the optical signals have become attenuated, they are relayed by 3R regenerators (repeaters), requiring opto-electrical and electro-optical conversion.

In the WDM system, shown in Figure 2b), signals from transmitters of different wavelength are multiplexed and the multiplexed signal is propagated along the optical fiber. When the optical signal has become attenuated, it is

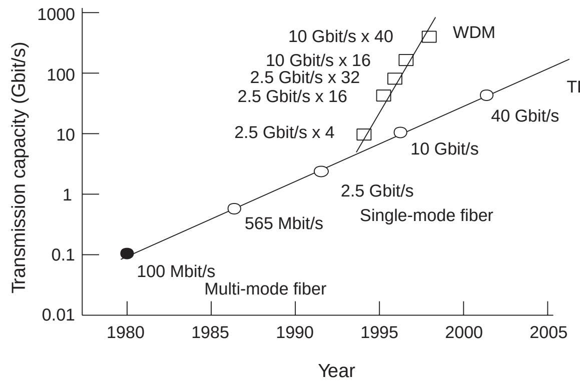

Figure 1 Evolution of transmission capacities

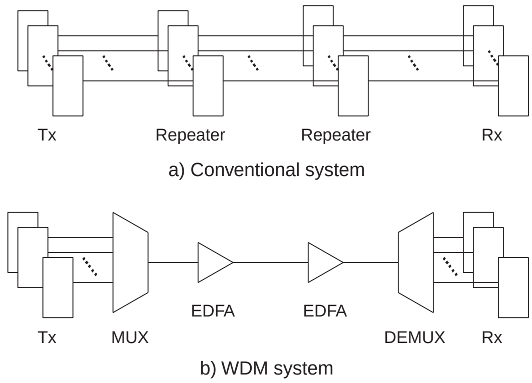

Figure 2 Comparison of conventional optical repeater system and WDM system with optical amplifiers for long-haul applications

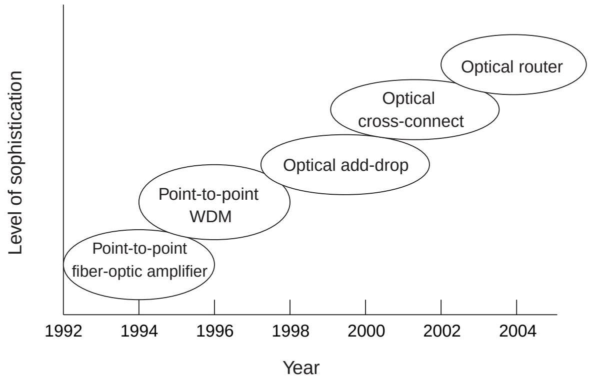

Figure 3 Evolution of photonic networks

amplified by an OFA and, after successive amplifications, is demultiplexed and delivered to the receivers (Rx).

When WDM is applied to the conventional repeaters, there must be a multiplexer/demultiplexer (MUX/DEMUX) unit plus a repeater for each signal at every repeater point, and while this saves on optical fiber it has little further economic advantage and was never widely used. In a WDM system using OFAs, by contrast, increases in the number of multiplexed channels can be accommodated by simply providing the appropriate number of the previously developed transmitters and receivers and increasing amplifier output, resulting in an extremely economical system. Because such a system allows wavelength multiplexing at narrow channel spacing, it is distinguished from earlier WDM systems by the term dense wavelength division multiplexing (DWDM).

Systems employing OFAs have evolved from the first generation of single-channel systems in which the conventional 3R repeater was replaced by an OFA to the second generation of WDM systems which currently are the mainstay for trunk networks, featuring increased capacity using multiple wavelengths. WDM systems are expected to evolve as shown in Figure 3, and their application will be extended from trunk systems to access systems. Some optical add-drop multiplexers (OADMs), which can add and/or drop some of the optical channels, are already in use at nodes.

Optical cross-connects (OXCs) make it possible to separate the optical signals transmitted by WDM from multiple fibers at the respective demultiplexers and allocate them by channel to output fibers. This makes possible large volume switching of optical signals without opto-electric conversion, resulting in a more economical system configuration.

Topics requiring future research include optical routers for routing signals in the optical domain and repeaters for performing the 3R functions on optical signals, where there are numerous technical problems to be solved before viable products are available.

The key factor technologies for WDM include light sources, fiber amplifiers, multiplexers/demultiplexers, and optical fiber for the transmission medium. Large-capacity OXCs differ in structure according to the type of fiber-optic components that can be used, but they require integrated optical switches, and the ability to use wavelength conversion devices will increase system flexibility. Furukawa Electric is proceeding with the development of all major products including OXCs.

3. KEY FACTOR TECHNOLOGIES FOR WDM

Effective utilization of the bandwidth of OFAs depends on the performance of the demultiplexer. The demultiplexer must have filter characteristics such as to remove from the multiplexed signal the single signal for each receiver and assure that there is no crosstalk from other channels. In the first WDM systems with fewer multiplexed signals, demultiplexers having dielectric multi-layer filters were common, but new technologies based on fiber Bragg gratings (FBGs) and arrayed-waveguide gratings (AWG) [5] have made possible filtering within a narrow range of wavelengths, so that multiplexed channel spacing has been reduced to 50 GHz (approximately 0.4 nm). In this region, even if an ideal filter were available, any attempt to increase the transmission capacity per channel would only result in a broadening of the optical spectrum due to increasing modulation frequency in proportion to transmission capacity, and the point at which this reached the adjacent channels would be the limit of transmission capacity per channel. In actual practice the filter is not ideal, and, when transmission capacity per channel is large, the signal deteriorates due not only to filter crosstalk but also to chromatic dispersion. It is therefore important that demultiplexer performance be improved to take these factors into account.

A demultiplexer can be used as a multiplexer by simply reversing the input and output directions, but since there is no crosstalk problem and insertion loss can be compensated by an OFA, multiplexing can also be provided by an inexpensive star coupler, provided the number of multiplexed channels is small. Furukawa Electric offers a MUX/DEMUX using an AWG that has outstanding narrowband filtering performance.

OADMs may be of fixed or variable wavelength or time by switching. The former type has a fixed-wavelength filter whereas the latter uses a variable-wavelength filter. There are several types of filter for the latter, but most of them are configured using FBGs and optical circulators.

To increase the number of signals multiplexed by WDM, the amplification band of the OFA is broadened and the gain deviation within the band is reduced. To further maintain constant output on each channel, OFA output must be proportional to the number of channels multiplexed. To achieve this, the EDF, gain-equalizing filter and pumping laser must deliver high performance, and Furukawa Electric is committed to in-house development of these key technologies. To achieve flat gain for the OFA, the gain-equalizing filter must be designed in combination with the gain characteristics of the EDF, so that a proprietary design is essential. The gain-equalizing filters used with Furukawa Electric's EDFAs are fabricated using dielectric multi-layer film, FBGs, etalons, etc., and are matched to the spectral gain of the EDFA specifications. Further improvement in OFA functionality additionally requires a variable attenuator to respond to changes in input level, as well as a variable gain-equalizing filter. And as a measure to reduce OFA size and cost, work went forward on the development of integrated components comprising coupler and isolator for the signal light and pumping light.

With increased OFA output power has come a change in the performance requirements for the laser diodes used for pumping. Practicable diodes have been developed for wavelengths of 980 and 1480 nm. In terms of fiber amplifier noise, the value is about 2 dB lower for 980 nm, and the overall energy conversion efficiency--from the power driving the diode to the amplified optical signal--is higher, so that at one time it was assumed that it would be the 980-nm laser diodes that would be used for pumping. The reliability problem has already been solved for 980-nm diodes, but the conversion efficiency from pumping light to signal light is low and only a narrow range of wavelengths is available for use as pumping light, resulting in a limitation on OFA output. The 1480-nm laser diodes, on the other hand, have a broader available range of wavelengths and wavelength-division multiplexing of the pumping light is possible [6)] so that for high-output OFAs, this technology is used. As things stand today, 1480-nm diodes are indispensable, and their applications are being further extended to remote pumping for OFA used in submarine cables as well as to Raman amplifiers. [7)] In anticipation of the need for higher-power OFAs because of the larger number of channels in DWDM systems, Furukawa Electric has from the earliest stage been involved in developing 1480-nm laser diodes, and is also working on 980-nm laser diodes and has solved its reliability problems. It now markets pumping laser diodes of both wavelengths.

Work on the development of distributed-feedback (DFB) laser diodes has also been undertaken based on technology acquired with pumping diodes.

If existing systems using single-mode fiber are to be upgraded by DWDM, compensation must be provided for the large chromatic dispersion in the optical fiber at 1550 nm. This can be done using either dispersion-compensating fiber (DCF) or fiber Bragg gratings (FBGs), [8)] each of which had its advantages and disadvantages. Furukawa Electric is working on both approaches but at present it is the DCF that is commercially available.

Performance requirements for the optical fiber used as the transmission medium have been increased by the OFA. In conventional fiber-optic communications systems, waveform degradation and noise were eliminated at each repeater and were thus non-cumulative, but this is not the case in systems using OFAs. Thus while chromatic dispersion is managed for the system as a whole, a new problem arises of fiber nonlinearity due to polarized mode dispersion (PMD) and the Kerr effect. The most problematical of the nonlinear phenomena is four-wave mixing (FWM), which is more severe the lower the chromatic dispersion. When chromatic dispersion is high, on the other hand, this causes degradation of the signal waveform by group velocity dispersion (GVD). A proposal to solve this, a new type of fiber, known as non-zero-dispersion shifted optical fiber (NZDSF: ITU Recommendation G.655), has been proposed. As OFAs practically remove limitations on the optical signal level launched into the fiber, it is possible to make the optical signal as strong as possible to lengthen repeater spacing if there is no nonlinear phenomenon in the fiber. But in actuality the input signal level is limited by the nonlinearity of the optical fiber. Since nonlinearity is greater the higher the optical power per unit area, consideration was given to enlarging the core region, but this would only increase the chromatic dispersion slope. On the other hand there is a tendency toward expansion of the WDM band, and a demand for a decrease in the chromatic dispersion slope, and this has led to a number of designs from research institutions around the world for optical fiber suited to WDM.

At Furukawa Electric we are working to develop NZDSF with larger core diameter, as well as reverse-dispersion fiber (RDF) [9)] having chromatic dispersion characteristics that are the reverse of those of single mode fiber. Using single mode fiber in the high power region and RDF in the low power region reduces nonlinearity as well as chromatic dispersion for the system as a whole over a wider range of wavelengths and thereby configures a transmission path suited to long-haul, large-capacity DWDM. We have further confirmed that no problems are encountered in the cabling process. The results of tests on a transmission system using this configuration have been reported, and we believe that it will become a model for the next generation of transmission links. [10)]

Optical cross-connects (OXCs) require integrated optical switches. At present the only reliable types are mechanical, and large switching arrays configured in this way tend to be bulky, but many designs are being proposed using new technology. Work is in progress on waveguide-type optical switches that change the refractive index without moving parts by utilizing electro-optical (EO) acoustic-optical (AO) and thermal-optical (TO) effects and on mechanical switches [11)] based micro-electro-mechanical systems (MEMS), and some of them have advanced to the on-site testing stage.

If wavelength conversion becomes possible, identical wavelengths from different optical fibers could be converted so that the wavelengths do not overlap, and then sent out over the same output fiber, thereby improving the performance of OXCs. Wavelength conversion devices based on semiconductor optical amplifiers (SOAs) are under development, but there are many technological problems to be overcome before practicable units become available.

4. CONCLUSIONS

The mini-feature on WDM is presented as a way of summarizing Furukawa Electric's current activities in the WDM field. We hope it will guide you to the many fine components we have developed for WDM systems.

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