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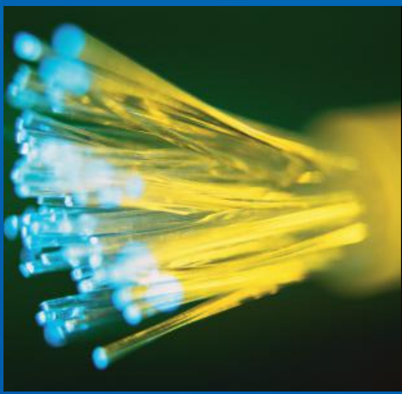
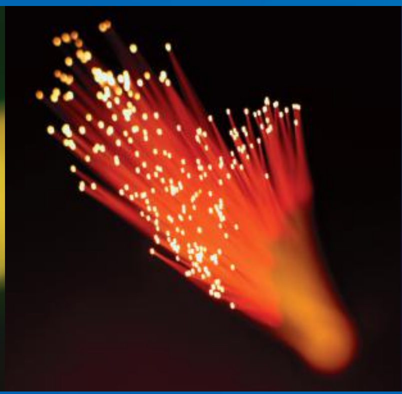

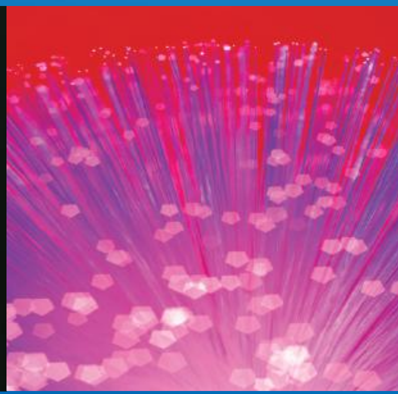

Optical fibres, cables and systems

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Foreword

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As we approach the half century mark for the dawn of the era of optical communications, it is appropriate to take stock of the journey of discovery and application of this empowering technology. As with most new technologies, the engineering challenges associated with its assimilation into the existing infrastructure have been as significant as the scientific advances within the invention of the laser itself. ITU-T has been active in the standardization of optical communications technology and the techniques for its optimal application within networks from the infancy of this industry. However, it is not always easy to find out what has been covered, and where it can be found. This manual attempts to aggregate all of the available information on ITU-T's work.

The manual is intended as a guide for technologists, middle-level management, as well as regulators, to assist in the practical installation of optical fibre-based systems. Throughout the discussions on the practical issues associated with the application of this technology, the explanations focus on how ITU-T Recommendations address them. It provides the organized insights of those who have created and lived with the evolution of the technology for several decades.

The first ITU-T Handbook related to optical fibres, *Optical Fibres for Telecommunications*, was published in 1984, and several others have been produced over the years. It is an honour to present you with the latest version, which is another example of how ITU-T is bridging the standardization gap between developed and developing nations. I trust that this manual will be a useful guide for those looking to take advantage of optical cables and systems and I welcome feedback from readers for future editions.

The success of efforts such as this, and the underlying standardization upon which it is based, depends on attracting and involving the pioneers of new technologies in a spirit of collaborative competition to establish the best practices for the common good. Participation is open to all.

I would like to express my appreciation to the experts from the ITU membership, who have provided us with valuable proposals and to those who have contributed to the new version. My particular appreciation goes to Mr. Gastone Bonaventura, former Vice-Chairman of ITU-T Study Group 15, the leading Study Group on Optical Networks, and his team of collaborators.

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PREFACE

The invention of the laser and its demonstration is dated 1960. It was suggested in 1966 that optical fibres might be the best choice for using laser light for optical communications, as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires. The main problem was the high losses of optical fibres: fibres available during the 1960s had losses in excess of 1 000 dB/km. A breakthrough occurred in 1970 when the losses could be reduced to below 20 dB/km in the wavelength region near 1 000 nm. At about the same time, GaAs semiconductor lasers, operating continuously at room temperature, were demonstrated. The simultaneous availability of compact sources and of low-loss optical fibres led to a worldwide effort for developing optical fibre communication systems.

The real research phase of fibre-optic communication systems started around 1975. The enormous progress realized over the 30-year period extending from 1975 can be grouped in several distinct phases. Over this time period the BL product [B is the bit rate and L is the repeater spacing, where the repeaters perform optical to electrical to optical conversion] doubled every year. In every phase BL increased initially but began to saturate as the technology matured. Each new phase brought a fundamental change.

The first phase

The first phase of lightwave systems operated **near 850 nm** and used GaAs semiconductor lasers with *multimode fibres*. After several field trials during the period 1977-79, such systems became available commercially in 1980. They operated at a bit rate of 34-45 Mbit/s and allowed repeater spacings of up to 10 km. The larger repeater spacing compared with 1-km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

This phase of lightwave systems was specified in two Recommendations. The first one is ITU-T G.651, where the characteristics of a multimode optical fibre operating at 850 nm are specified. The second one is ITU-T G.956 (now ITU-T G.955) where are specified the characteristics of the optical systems operating at 850 nm and suitable for the bit rates of the plesiochronous digital hierarchy (PDH).

The second phase

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave systems in the wavelength region near 1 300 nm, where fibre loss is below 1 dB/km. Furthermore, optical fibres exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of InGaAsP semiconductor lasers and detectors operating **near 1 300 nm**.

The second phase of fibre-optic communication systems, based on InGaAsP semiconductor lasers and detectors operating near 1 300 nm became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mbit/s because of dispersion in multimode fibres. This limitation was overcome by the use of *single-mode fibres*. A laboratory experiment in 1981 demonstrated transmission of 2 Gbit/s over 44 km of single-mode fibre. The introduction of commercial systems followed. By 1988, second-generation lightwave systems, operating at bit rates of up to 1.7 Gbit/s with a repeater spacing of about 50 km, were commercially available.

This second phase of lightwave systems was also specified in some Recommendations. In particular, Recommendation ITU-T G.652 specifies the characteristics of a single-mode optical fibre operating at 1 300 nm. Recommendation ITU-T G. 957 specifies the characteristics of optical systems operating at 1 300 nm and suitable for transmitting the bit rates of the synchronous digital hierarchy (SDH) up to STM-16. Moreover the text of Recommendation ITU-T G.956 (now Recommendation ITU-T G.955) was extended to include also PDH systems operating at 1 300 nm.

The third phase

The repeater spacing of the second phase lightwave systems was limited by the fibre losses at the operating wavelength of 1 300 nm (typically 0.5 dB/km). Losses of silica fibres become minimum near 1 550 nm. Indeed, a 0.2 dB/km loss was realized in 1979 in this spectral region.

However the introduction of third phase lightwave systems operating **at 1 550 nm over single-mode fibre** was considerably delayed by the large fibre dispersion near 1 550 nm. Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading occurring as a result of simultaneous oscillation of several longitudinal modes. The dispersion problem can be overcome either by using *dispersion-shifted fibres* designed to have minimum dispersion near 1 550 nm or by limiting the laser spectrum to a single longitudinal mode. Both approaches were followed during the 1980s. By 1985, laboratory experiments indicated the possibility of transmitting information at bit rates of up to 4 Gbit/s over distances in excess of 100 km. Third generation lightwave systems operating at 2.5 Gbit/s became available commercially in 1992. Such systems were capable of operating at a bit rate of up to 10 Gbit/s. The best performance is achieved using dispersion-shifted fibres in combination with lasers oscillating in a single longitudinal mode.

Also, this phase of lightwave systems was specified in some Recommendations. Recommendation ITU-T G.653 specifies the characteristics of a dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.652, ITU-T G.955 (ex-G.956) and ITU-T G.957 were revised / extended in order to include optical systems operating at 1 550 nm. Recommendation ITU-T G.974 specified the characteristics of the optical systems to be used for the submarine applications.

The fourth phase

A drawback of third phase 1 550 nm systems is that the signal must be regenerated periodically by using electronic repeaters spaced apart typically by 70-80 km. This situation changed with the advent of fibre amplifiers in 1989.

The fourth phase of lightwave systems makes use of **optical amplification** for increasing the repeater spacing **and** of wavelength division multiplexing (**WDM**) for increasing the aggregate bit rate. The advent of the WDM technique started a revolution that resulted in doubling the system capacity every 6 months. In most WDM systems fibre losses are compensated periodically using erbium-doped fibre amplifiers typically spaced 70-80 km apart. Such amplifiers, **operating in C-band (1 530-1 565 nm)**, were developed after 1985 and became available commercially by 1990. A 1991 experiment showed the possibility of data transmission over 21 000 km at 2.5 Gbit/s and over 14 300 km at 5 Gbit/s, using a recirculating-loop configuration. This performance indicated that an amplifier-based, all-optical, submarine transmission system was feasible for intercontinental communication. By 1996, not only transmission over 11 600 km at a bit rate of 5 Gbit/s had been demonstrated by using actual submarine cables, but commercial transatlantic and transpacific cable systems also became available. Since then, a large number of submarine lightwave systems have been deployed worldwide.

In order to specify the characteristics of optical fibres and systems operating with optical amplifiers and the WDM technique, many new Recommendations were developed in ITU-T. Recommendation ITU-T G.655 specifies a non-zero dispersion-shifted single-mode optical fibre. Recommendations ITU-T G.694.1 and ITU-T G.694.2 specify the spectral grids for DWDM and CWDM applications. Some Recommendations specify the characteristics of optical systems devoted to particular DWDM applications: Recommendations ITU-T G.959.1 (inter-domain applications without line OA), G.698.1 (metro access applications without line OA), ITU-T G.698.2 (metro core / regional applications with line OA), ITU-T G.696.1 (backbone applications with line OA), ITU-T G.973 (submarine applications without line OA), and ITU-T G.977 (submarine applications with line OA). Recommendation ITU-T G.695 specifies CWDM systems for access / metro access applications.

The fifth phase

In the current development of lightwave systems, which is considered as the fifth phase, there are several directions of evolution.

The first one, **mainly related to the long-haul systems**, is towards increasing the capacity transmitted on an optical fibre:

i) by transmitting more and more channels through the WDM technique in the C-band (1 530-1 565 nm), by reducing the channel spacing. Commercial terrestrial systems with the capacity of 1.6 Tbit/s (160 optical channels at 10 Gbit/s) are now available with a channel spacing of 25 GHz;

ii) by deploying the optical channels not only in the C-band, but also in the short wavelength S-band (1 460-1 530 nm) and in the long wavelength L-band (1 565-1 625 nm). The Raman amplification technique could be used for signals in all three wavelength bands. Moreover a new type of fibre, known as the dry or low water peak fibre has been developed with the property that fibre losses are small over the entire wavelength region extending from 1.3 to 1.65 µm. Availability of such fibres and new amplification schemes may lead to lightwave systems with a larger number of WDM channels on a single optical fibre;

iii) by increasing the bit rate of each channel within the WDM signal. Starting in 2000, many experiments used channels operating at 40 Gbit/s. Moreover starting from 2006 some experiments demonstrated the feasibility of systems operating up to 110-130 Gbit/s per channel. Most of these new systems require an extremely careful management of their dispersion and new techniques to deal with polarization time variant effects (1^{st} and 2^{nd} order PMD, PDL, etc).

The second direction of evolution is the **reduction of the number of expensive optical/electrical/optical (O/E/O) conversions** within the optical transport networks (OTN). The two main reasons for the reduction in the number of O/E/O conversions are that DWDM systems are becoming capable of carrying light signals for thousands of kilometres without electrical regeneration and that photonic cross-connect (PXCs) and optical add-dDrop multiplexers (OADMs) are becoming available with the capacity, space requirements, power consumption, reliability and cost, suitable for their use in the telecommunication networks. With this evolution it is possible to foresee that all optical networks (AONs) could extend to all potential routes of the backbone network of a medium size country with optical paths up to around 2 000 km.

The third direction (an alternative to the second one) is the implementation of multiple O/E/O regenerators at a cost comparable to that of an optical amplifier. This is today a realistic objective, thanks to recent advances in photonic integrated circuits and silicon photonics. 40 WDM channels, 40 Gbit/s each channel, have been recently demonstrated on the same chip. Following this way of evolution, the O/E/O regenerators could be put practically in all the nodes of the network. The additional cost could compensate the technical problems related to the implementation of an AON (impairments accumulation, network planning rules, optical monitoring, etc.).

In the framework of these evolutions several Recommendations have already been prepared and the preparation of others is under way. Among those completed it is possible to quote Recommendation ITU-T G.656 for a fibre with non-zero dispersion for wideband optical transport, the extension of Recommendation ITU-T G.959.1 to include also 40 Gbit/s systems, and Recommendation ITU-T G.680, which allows operators to take OADMs and PXCs from different vendors and integrate them into an AON without having to add expensive O/E/O conversions.

In parallel with the above stated developments of the DWDM systems for the backbone network, passive optical networks (PON) have been developing. A PON is an optical access network that extends from an operator central office into individual homes, apartment houses and business offices. A PON can be deployed in a FTTH (fibre to the home) architecture or in a FTTB (fibre to the building), a FTTC (fibre to the curb) or a FTTCab (fibre to the cabinet) architecture, depending on local demands. In order to reduce the need for separate fibres for the two direction of transmission, the PON systems can take advantage of WDM signal multiplexing technique, where downstream and upstream channels are transmitted at different wavelengths.

Optical fibres for the access network are specified in Recommendations ITU-T G.657 and ITU-T G.651.1. PON systems specifications are included in the ITU-T G.983 x-series of Recommendations and in the ITU-T G.984 x–series of Recommendations.

Applications of optical technology in the telecommunication networks

Given that the first-generation systems had a capacity of 34-45 Mbit/s per fibre in 1980, the capacity of optical systems has jumped by a factor of more than 10 000 over a period of 20 years. In the same time period, the applications of optical technology progressively moved from short distance links (a few tens of km) to the very long distance links of the backbone networks, completely substituting the traditional copper conductors. In the last few years the optical technology also started to be deployed in the access networks.

This wide range of applications is not only based on the above-quoted development of optical fibres and systems. It has been also necessary to develop and to specify many other aspects related to the practical implementation of the optical plant.

Optical fibres must be inserted in cables, which are laid in different ways: buried, in ducts, aerial, in sewers, submarine, etc. For each of these ways of laying, it is necessary to properly design the cable in order to respect well-defined mechanical (bending, tensile strength, crush, impact, torsion, etc.) and environmental conditions (moisture permeation, water penetration, vibration, temperature variations, fire safety, etc.).

In the same way, it is necessary to define the installation techniques to maintain the dynamic strain below the specified maximum allowable fibre strain, in order not to reduce the predictable lifetime of the fibres.

Moreover, the optical plant needs a lot of complementary hardware (passive nodes, optical distribution frames, joint closure, cabinets, etc.), which needs a detailed development and specification both for technical and economical reasons.

The ITU-T has published a complete set of Recommendations dealing with the above subjects: Recommendations of the ITU-T G-series on optical fibres and systems and Recommendations of the ITU-T L-series on construction, installation, jointing and termination of the optical cables.

The content of this ITU-T Handbook is mainly based on the content of those ITU-T Recommendations.

TABLE OF CONTENTS

Page

Page

Page

Page

Page

Page