Introduction

Overview

Although the first optical information transmission experiments date back to late in the 19th century, a way has to be found to correctly direct or guide the light before thinking of its application to telecommunications. The emergence of *lasers*, around 1960, led to transmission experiments in the atmosphere. However, propagation instability problems (mainly caused by air index variations) have led researchers to abandon this solution. It is now reserved for short distance communications (infrared remote control, indoor communications, infrared laser link between two buildings), even though it is now being considered again for direct links between satellites.

Optical fibers are very thin angel hair type transparent glass and use the well-known principle of fountains of light. They were used in decorative applications before being used in a more useful way (lighting, endoscopy, remote optical measures). Their application in the field of telecommunications, although considered by theoreticians (Charles Kao) as soon as 1966, was made possible in the 1970s because of the progress in silica fiber-optic production technology, allowing a very light attenuation and an adequate mechanical resistance. It was also enabled by the availability of semiconductor laser diodes, which combine laser performance with electronic component ease of use, in particular because of the progress of III-V compound semiconductors. The development of efficient cables, connectors and passive components, and the availability of industrial connection processes, have also been essential for the development of the first commercial links around 1980.

The 1990s were significant in the development of optical amplification followed by wavelength division multiplexing, leading to an explosion of capabilities in response to new requirements caused by the growth of the Internet. The next revolution should be all-optical networks. Inaugurated by the emergence of the first all-optical switches in 2000, they were only prototypes and this concept remains to be clarified, particularly with standardization of protocols.

With approximately 100 million kilometers produced each year, and despite production activity fluctuations in this field which shows a strongly cyclic characteristic, optical fibers have become a mature technology present in increasingly wide application fields.

Fiber optics advantages

Transmission performance

Very low attenuation, very large bandwidth, possible multiplexing (in wavelength) of numerous signals and users on the same fiber, provide much higher range (over 100 km between transmitter and receiver) and capacity (bitrates of several Tbit/s are possible over a single fiber) systems than with copper wires or radio. However, depending on the considered use, other advantages can be decisive.

Implementation advantages

Including the light weight, very small size, high fiber flexibility, noticeable in telecommunications as well as for cabling in aeronautics, information technology, medicine, manufacturing, home automation, etc.

The most important practical advantage remains electrical (total insulation between terminals, possible use in explosive atmosphere, under high pressure, in medical applications) and electromagnetic safety (the fiber is not sensitive to parasites and does not create them either).

Conversely, the optical power used is weak and not dangerous. We can add total (or almost) invulnerability: it is not possible to hear the signal on an optical fiber without being spotted.

Economic advantage

Contrary to common belief, the global fiber-optic system cost (taking its installation and necessary equipment into account) is, in many cases, lower than the cost of a copper wire system (in particular with the recent increase in the price of copper), and its implementation, notably concerning connections, has become much easier and cheaper than with the first applications.

Fields of use

The main field of use is obviously telecommunications, but fiber optics easily overflow this field and work with a large number of manufacturing applications.

Telecommunications

The two main fields of use, related to network needs, have been urban links, with large capabilities and working without intermediate amplification or remote power-feeding, and submarine links such as trans-oceanic links, or coastal links without repeaters (exceeding 200 km, and over 300 km with optical amplification in terminals). Then, stimulated by the arrival of new operators, regional, national and international terrestrial connections have seen a very strong growth. They are at the base of the ATM network infrastructure.

In the early days of fiber optics, several experiments were carried out in the field of access networks for video communications and broadband service users. Direct fiber optics access or FTTH (fiber to the home) did not spread as expected in the 1980s because of economic constraints and the increase of possible throughputs with twisted pairs (available through ADSL). Intermediate solutions were then developed where the fiber was relayed, at the front end, by existing cables or radio contact. However, the need for increasingly high throughputs has reenergized this market; this movement started in Japan and Sweden and has spread to now represent a large part of the activity for manufacturers, operators and regulation authorities.

Data networks and links

Even for short distances, the use of fiber optics in the information technology field has rapidly progressed, particularly for electric insulation and insensitivity to electromagnetic disruptions. Fiber optics also enable development of multi-terminal networks and high bitrate networks, such as Fiber Channel or 1 Gbit/s (and now up to 10 Gbit/s) Ethernet, were designed for fiber optics from the start. Networks now reach “metropolitan” sizes and work together with railway networks or electricity transport without technical problems.

Industrial systems

There are various applications (telemetry, remote controls, video monitoring, field bus) where fiber insensitivity to parasites and its insulating character are essential advantages.

The massive parallelism of electronic and information technology architectures, the constant increase of frequencies on buses and the resulting electromagnetic accounting problems influence the increasing use of optical support (fibers or planar guides) to interconnect the different computer or embedded system cards ("optical backplane" concept), followed by the different chips from multiprocessor architecture, and even the different parts of a single chip in the future, in a SoC (system on chip) design.

Instrumentation and sensors

Fibers are more and more present in optical instrumentation, where they make it possible to carry out remote measurements in hard to access points. *Sensors* use fiber optics as a sensitive element and transmission support. However, their use remains limited, especially when material integration or total electromagnetic immunity is required. These applications are discussed in Chapter 11.

Finally, optical fibers still play a role in light transportation. Traditional applications (lighting, visualization, endoscopy) or more recent applications (laser beam transportation for industry, measurement, medicine) have seen their performance improve, and their cost decrease, thanks to the development of fiber-optic technologies.

Elements of a fiber-optic transmission system

Interfaces

In a point-to-point link as well as in a network, we find (see Figure 1):

– the optical transmitter interface which transforms the electric signal into optical signal. It mainly includes the optoelectronic transmission component, which can be a light-emitting diode (LED) or a laser diode (LD), components studied in Chapter 6. The interface also contains adaptation and protection circuits; it is connected to the cable by a connector or by an optical fiber pigtail that needs to be connected. Modulation is generally a light intensity modulation obtained by modulation of current going through the transmission diode or, at a very high bitrate, by an external modulation;

– the optical receiver interface containing a photodiode which converts the received optical signal into an electric signal. It is followed by a head amplifier, which must be carefully designed as its noise is generally the one limiting the minimum optical power that can be detected, and thus the range of the system (see

Chapter 7). According to the application, we then find filtering or digital reshaping circuits.

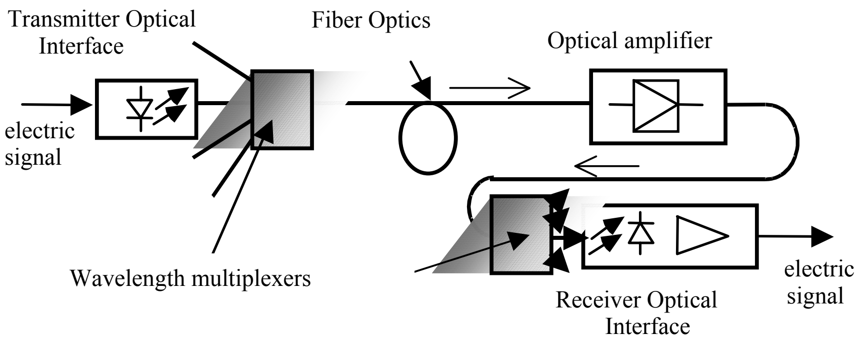

Figure 1. *Point-to-point fiber-optic link*

Repeaters

When the link length requires it, one or several *repeaters* are inserted. Ancient link repeaters (installed prior to 1995) contained receiving and transmission interfaces, linked by amplification and regeneration circuits for digital transmissions, leading to signal interruption. Nowadays, terrestrial and submarine links use erbium-doped fiber amplifiers (see Chapter 8), and are entirely optical over distances exceeding 10,000 km.

Wavelength division multiplexing

Wavelength division multiplexing (WDM) enables the multiplexing of several signals in the same fiber-optic, even if they are from geographically different origins or in opposite direction. If wavelengths are close, they can be amplified by the same optical amplifier.

This was first used in local area networks or user links, as well as in sensor networks. It now increases even already installed optical cable capabilities significantly.

Dozens, and even hundreds of Gbit/s per fiber are reached in commercial links. Achieved in the laboratory ten years ago, the Tbit/s (10^{12} bit/s!) now corresponds to long distance infrastructure requirements; the last laboratory benchmarks have exceeded 10 Tbit/s and the theoretical limit has not yet been reached.

Fiber-optic networks

All optical networks can be developed which are not simple point-to-point links combinations interconnected by electric nodes. Optical network nodes can be passive (splitters, multi-branch couplers, wavelength division multiplexers) or active (switches, time-division multiplexers) components using integrated optics or micro-technologies (MEMS).

The development of large scale optical switching is one of the major issues today. In fact, the speed of optical transmissions is such that the bottleneck is now located in the network node electronics. However, specific architectures and protocols for optical routing must be developed.

Transmitted signals

The vast majority of applications (telecommunications, information technology) consist of digital transmissions, with bitrates from a few kbit/s to more than 10 Gbit/s. However, analog applications still subsist in video and telemetry fields.

There are more particular cases, such as retransmission over fiber optics of carrier microwave frequencies to 30 GHz, or even modulating a laser diode. This technique (already used for producing active antennae, notably for radars) is beginning to be used in satellite telecommunications stations or for retransmission of microwave signals in future access networks combining fiber and radio.

Fiberless infrared connections

Even though this book is mainly dedicated to fiber-optic telecommunications, we can mention the development of infrared wave use for line-of-sight communications at very short distance: remote control, hi-fi accessories, mobile robotics, which are traditional applications, as well as wireless local area networks. While benefiting from the practical advantages of “wireless”, infrared can transport high throughputs and resolve certain disruption and confidentiality problems raised by radio links. They are well adapted to indoor propagation (within a building, not going outside). Different protocols were defined, with the most well known being IrDA for interfacing PCs and various peripherals to 4 Mbit/s.

Direct links between buildings with 0.8 µm laser beams have recently been developed, used as microwave point-to-point beams. These free space optics (FSO) systems avoid the cost and delay of cabling. These beams are very directional because of a telescope system (lens), and work at low power (a few mW), but can be interrupted by strong fog. Very high (2.5 Gbit/s or more) bitrates can be transported over a few kilometers with no obstacles, interferences or a need for a license, contrary to radio. Important development in these systems is expected.

There are also link projects between satellites by laser beams in spatial vacuum over thousands of kilometers, obviously requiring great precision in the orientation of transmitters.