LNF-89/055

L. Trasatti

OPTICAL FIBERS AND THEIR APPLICATIONS

Estratto da: NIM A279, 354 (1989)

Nuclear Instruments and Methods in Physics Research A279 (1989) 354–358
North-Holland, Amsterdam

OPTICAL FIBERS AND THEIR APPLICATIONS

Luciano TRASATTI

INFN, Laboratori Nationali di Frascati, Frascati (Roma), Italy

Fiber optics have become in the last few years an extremely attractive method of data transfer. A short review of their properties and of their applications is given, together with some feelings from personal experience of the author.

1. Introduction

Optical fibers have become very popular in a very short time. The reason for this can be easily understood looking at the history of the field: in 1966 the theoretical attenuation limit for light transmission in optical fibers was calculated at the Standard Telephone Laboratories as 20 dB/km. In 1972 the Graded Index optical fiber was invented at Corning Glass, and in the same year an experimental measurement of 4 dB/km was performed, again at Corning Glass. In 1985 we bought from Pirelli SPA for the Gran Sasso Laboratories installation a cable containing 100 single mode fibers with 0.4 dB/km attenuation at a price of about 0.5$/fiber meter.

Such a dramatic improvement in the fiber capabilities has been due to progressively more sophisticated construction techniques and to the possibility of manufacturing extremely high purity glass: to give an example, a 10 km thick block of fiber optic glass would have the same transparency as a normal window pane.

An optical fiber is a hair thin glass cylinder (125 μm outside diameter) made up of an external mantle, or cladding, and of an internal core with a slightly higher index of refraction. Light propagates inside the core by means of total reflection against the separation between core and cladding.

In the original fibers (Multimode Step Index, see fig. 1) the core diameter was of the order of 50 μm. Several propagation modes were possible, generating a modal dispersion which strongly limited the bandwidth × distance product.

An improvement was achieved with the Graded Index Multimode fibers. Here the profile of the refractive index of the core is parabolic and the difference in length between the various propagation modes is compensated for by the different propagation speeds in layers having progressively lower refractive index.

Nowadays the most promising fiber type is the single mode fiber. If the diameter of the core is reduced down to about 10 μm, where it is comparable with the light wavelength (1300 nm), only the longitudinal propagation mode is allowed, practically reducing the dispersion to zero. Again the Pirelli Gran Sasso fibers show a dispersion of 3.5 ps nm^{-1} km^{-1}, depending on the light source frequency spread. Of course you must pay for this, and the balance is the difficulty to couple 1 mW power into a 10 μm diameter cylinder with negligible angular spread. The laser diode (LD) is the appropriate instrument for this, but it is more expensive and more fragile than the common light emitting diode (LED). A typical LD still costs more than 1000$.

In practice, what you can do today is to send 1 Gbit/s signals to a 100 km distant receiver without repeaters. For many applications the limiting factor has become the electronics, which is trying to follow the

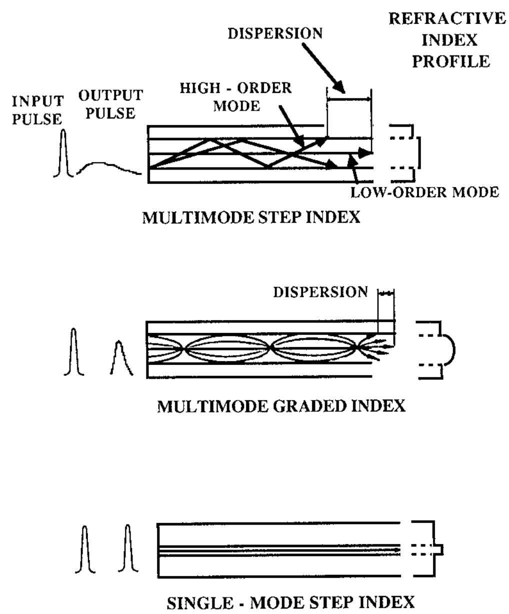

Fig. 1. Optical fiber types: multimode step index, multimode graded index, monomode.

fiber development using galllium arsenide and other high speed technologies.

2. Applications

2.1. Telecommunications

High speed (565 Mbit/s) apparata are available off-the-shelf from telecommunication firms. These systems are highly standardized [1] but they are not very flexible. A telecommunication apparatus uses a time division multiplexing (TDM) technique to divide the available bandwidth among different users, cyclically assigning a time slot to every channel. This is strictly a point-to-point system: every user talks only with the corresponding user on the other side, and no interconnection (networking) is possible. A set of standard frequencies is defined: 565 Mbit/s, 140, 34, 8, 2, down to the 64 Kbit/s of a digital telephone channel. Note the 8 Mbit/s figure, because it ignores completely the computer network standard 10 Mbit/s frequency (ETHERNET and ref. [2]): this is a sign of the fact that the telecommunication people up to now have never exchanged frequencies and ideas with the computer people. This situation leads to very difficult interactions between the two fields, which could benefit a lot from a more cooperative approach. Moreover, telecommunication equipment tends to be extremely reliable, but also extremely expensive.

2.2. Networks

When you try to transfer a network designed to run on a coaxial cable to optical fibers, several problems show up immediately. The most striking is the lack, in the fiber optic field, of the "T". The detectors are simply not efficient enough to allow the usual high impedance tap, like you do with an oscilloscope on a coaxial cable. Here, every connection must be paid for in terms of dBs, and one is forced to use X and Y couplers with splitting ratios of at least 10/90. If you try to connect several users to the same fiber this is definitely a problem.

The equivalent of the coaxial cable is the optical star, where several fibers are joined together to mix their light signals. Of course, the loss in the power budget is a factor of N, where N is the number of rays emerging from the star, and therefore the number of users. A commercial implementation of ETHERNET on optical fibers is available, using the star technology. To understand the difficulties involved you must remember that the ETHERNET Collision Detection mechanism is analog, relying on a threshold discriminator.

Another typical difference is the fact that optical fibers are normally used in a monodirectional configuration: when you talk about a fiber optic connection, you typically have two fibers, one for each direction, instead of the single bidirectional copper conductor. Star couplers, X, Y connectors are also directional devices.

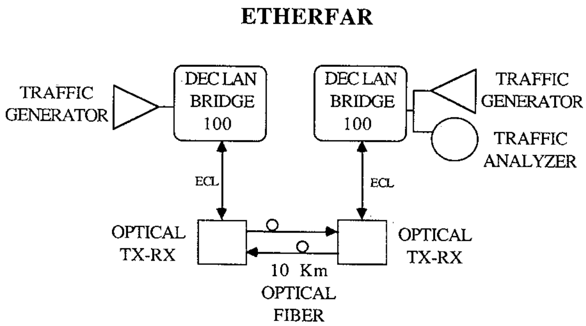

Fig. 2. 10 km ETHERNET connection experimental setup.

Nevertheless, the intrinsic capacity of fiber systems to cover long distances without repeaters gives rise to a wide range of possibilities.

At the Frascati National Laboratories we have used two stretches of single mode optical fibers to extend the total ETHERNET span from the standard 2.8 km to 10 km [3]. The experimental setup is shown in fig. 2. Two standard local DEC ETHERNET LAN BRIDGE 100's have been interfaced to two optical transmitter–receiver systems without any software modifications. In this situation, the ETHERNET 45 μs protocol limit is exceeded, and delivery of packets is not any more guaranteed. This is not a problem in itself, since, anyway, a bridge does not guarantee the delivery of all packets sent, and the higher levels of software must be capable to recover a loss. The actual amount of packet losses has been measured up to quite unrealistic line

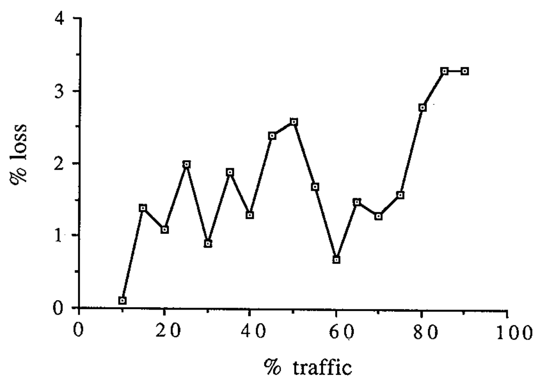

Fig. 3. 10 km ETHERNET connection: 1500 byte packet loss vs line occupancy.

occupancies (see fig. 3), and found reasonably small; less than 2% up to about 40% line occupancy.

In the meantime the first fiber optic network has finally been standardized: FDDI (Fiber Distributed Data Interface, see ref. [4]). This network, which has generated a lot of talk and which has taken a relatively (to the fiber development) long time to be approved, is based on multimode optical fibers, covering a 100 km span at a speed of 100 Mbit/s (Note again: not the telecommunication G703 standard 140 Mb/s!) with optical repeaters at every station. This is a simple and cheap configuration, although not very up to date. In other words, exactly what you expect of a standard. Many people will have to conform.

Efforts are also being spent to use the more innovative technologies in the network field. STARNET, an INFN collaboration (LNF, Roma I, Roma II, CNAF, ISS, see ref. [5]) is designing a Metropolitan Area Network (MAN) based on the use of single mode optical fibers and passive star couplers, for a distance range greater than 100 km and speeds starting from 140 Mb/s, with an innovative topology. STARNET is a collection of 2 km diameter stars, where a single star (see fig. 4) is made up of a number of stations (DIASPAR) and optical adapters (TRIFFID) with the data channel converging into a passive optical star coupler in a flooding configuration (i.e., only one station at a time has control over the full data channel). The bandwidth allocation mechanism is handled by a central controller (TRANTOR) which communicates with the single stations through physically separated fiber optic links. Although this configuration increases the number of fibers, it allows to achieve an extremely efficient bandwidth utilization, with packets lined head to tail in the center of the optical star.

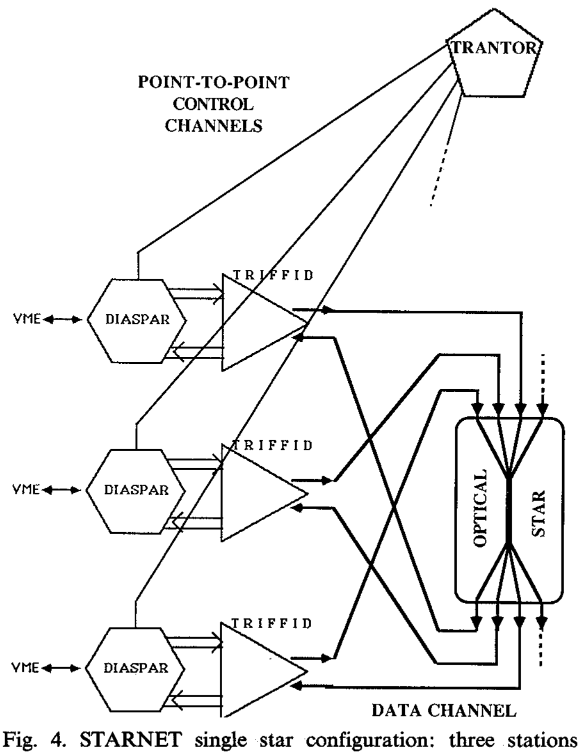

Fig. 4. STARNET single star configuration: three stations (DIASPAR + TRIFFID) + star controller (TRANTOR).

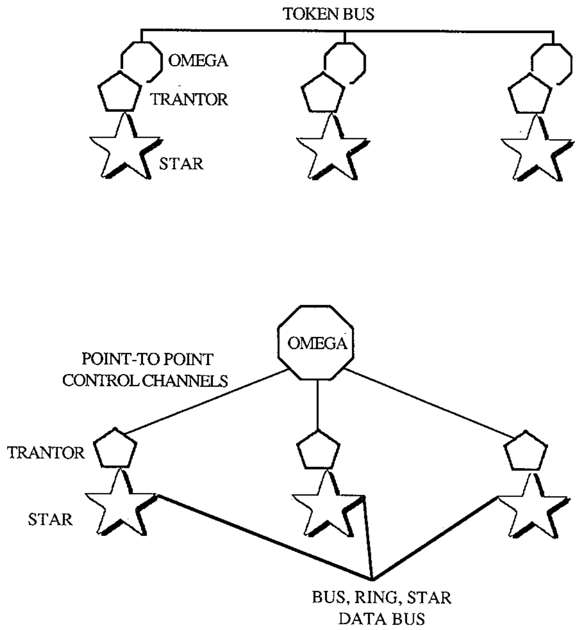

Fig. 5. STARNET multiple star interconnection: (top) data bus with token mechanism and (bottom) separate star connection for the control channel.

The method of connecting several stars and the general configuration of the network are still under discussion. The original proposal mentioned a token mechanism to interconnect the stars along a bus (see fig. 5 (top)). A star controller (TRANTOR) gives the authorization to transmit to all the stations of his star which have requested it and then, through a bus controller (OMEGA), sends a token message to the next star in line, thus releasing the bus. However, the token mechanism, while very simple conceptually (see for example ref. [6]), becomes extremely cumbersome in the implementation due to reconfiguration and diagnostic problems. Moreover, the mechanism itself is such that the token is slowed down by the data being sent on the line, making it very difficult to implement priority mechanisms and to guarantee reasonable response times for high priority messages. Another consideration is directly related to optical fibers costs: the cost of a cable is much higher than the cost of the fibers it contains, due to shieldings, protective coatings and to the installation process itself. The cost of an installed 10 fiber cable exceeds the cost of a 2 fiber cable by only 10% [7].

Therefore, wasting some of the enormous bandwidth allowed by a 10 fiber cable for the sake of simplicity, and using dedicated fibers for a point-to-point communication between the separate stars and a general central controller (see fig. 5 (bottom)), the bandwidth is optimized, the system is general more simple and the protocol more flexible. Priorities are easily assigned to different kinds of messages and an ISDN structure is easily implemented. An additional advantage is that the data bus topology is now completely free: a bus, a star, a ring or a tree are all equally compatible with the system, as long as every star has its separate control channel to the central controller.

2.3. Gran Sasso Laboratories

During the design of the basic facilities of the new Gran Sasso Laboratories, the problem of interconnecting the underground tunnels with the external facilities was solved laying down a fiber optic cable containing 100 single mode fibers 8.6 km long. This enormous amount of bandwidth will be used for all communication needs:

- Two 2 Mb/s PCM channels demultiplexed from a 34 Mb/s standard link will connect the PABXs, serving the telephone exchange and a number of 64 Kb/s channels for computer interconnection;
- Private and public ETHERNET channels will be connected through bridges using the scheme outlined above;
- Slow and standard television channels will use dedicated fibers;
- Some experiments (ICARUS) will use private high speed links to carry outside all of the raw experimental data: a 140 Mb/s fiber will deliver to the outside the full bandwidth of a VME crate;
- Some of the fibers will be used for network tests (e.g. STARNET);
- Some of the fibers will be left for future expansions: I expect that the ingenuity of the experimenters will use all that is left in a very short time.

2.4. Laboratory

The applications of optical fibers are not limited to large installations. Small and inexpensive systems can be very helpful even in the laboratory.

As far as point-to-point connections are concerned, a variety of possibilities is available in a wide range of price/performance.

The UA1 group at CERN developed a relatively slow (16.6 Mbit/s) but very cheap and integrated system called PATROL [8]: you buy two small boxes which have a fiber on one side and a 16-bit parallel bus on the other and you just feed the data on one side and pull them out on the other.

In increasing order of complication and price you find the AMD TAXI chips (100 Mb/s), which contain everything but the optical interface, and the Siemens system which does not contain the clock generation and recovery circuits, but can handle 200 Mb/s. New systems are becoming available every day.

Analog signals can also be sent on optical fibers. In an INFN(LNF)–CNR(IMAI) proposal to INFN Group V [9] an analogic 100 MHz optical fiber system will be installed in the base of a PM tube working in an extremely noisy environment (high power pulsed laser) to prevent electromagnetic interference.

3. Conclusions

What are the advantages of optical fibers over copper cables? I will try to make a short summary:

- High bandwidth and low attenuation: the most striking characteristic of optical fibers is their high bandwidth $\times$ distance product, which outdistances by far the conventional cables.
- Optical fibers are small and low-weight: when you hear about future high energy physics experiments, with a number of channels of the order of 10^5, this characteristic could become vital.
- Absence of crosstalk also means that it is almost impossible to bug a fiber optic channel, at least without the user realizing it immediately.
- Absence of electromagnetic interference; we have seen at least one example of how useful this can be.
- It is possible to build completely dielectric fiber optic cables: it has not been done very often, due to stretching problems, but it can be done.
- There are no ground or dc problems.
- It is possible to localize a fault within a very short distance, given the appropriate instruments: thus maintenance is facilitated.

I think that in the next few years we shall see an interesting competition between copper and glass: and if the service electronics and electrooptics keep up with the development pace of the optical fibers themselves, glass is sure to gain a large part of the market.

References

[1] CCITT Digital Networks transmission systems and multiplexing equipment, Recommendations G.700-G.956, Geneva (1985).

[2] ISO 8802/3: Local Area Network CSMA/CD Access Method (1985).

[3] Giampiero Di Pirro and Luciano Trasatti, ETHERFAR, a long distance fiber optic ETHERNET connection, Frascati Internal Report LNF 88/31 (R) (1988)
[4] FDDI Token Ring Media Access Control, American National Standard, X3.139/1987.
[5] STARNET, experiment proposal to INFN Group V (1986).
[6] ISO 8802/4 Standard (1985).
[7] Private communication from Pirelli SpA.
[8] P. Cennini, communication at this Conference.
[9] TIEMPI, experiment proposal to INFN Group V (1988).