Journal of Materials Science and Engineering A 13 (1-3) (2023) 1-12
doi: 10.17265/2161-6213/2023.1-3.001

Development of Glass Optical Fibers 1970-2020, Providing Us the Digitalized Communication World

Tarja T. Volotinen[1] and C. Bertil Arvidsson[2]

1. Univ. of Eastern Finland, Institute of Photonics, Joensuu 80130, Finland

2. Arvidsson Fiber Optics AB, Valla 64161, Sweden

Abstract: New types of communication cables were found to be needed already during the 1960-decade, because the copper cables had, and still would have, too high attenuation and especially limited bandwidth, due to extremely high dispersion at communication signals above 2 Mbit/s. Already the first commercially available multimode optical fibers (1979), developed from pure silica glass with a Ge-doped core, had much lower attenuation at signal frequencies of the order of 2-9 Mbit/s and above it. However, fiber core, cladding and coating materials, cable structures and materials, as well as manufacturing-, measurements- and test methods have been needed to be developed much further to get the reliable fiber cable communication networks. The important development stages and solutions to the most significant childhood problems of the optical fibers and cables are described in this paper. Now over 500 million km of optical fibers are manufactured and installed worldwide for the communication networks. The understanding of how to make the fibers with the very good transmission, mechanical and reliability properties exists at the manufacturers of the fibers and cables.

Key words: Optical fibers, attenuation problems, dispersion problems, mechanical strength problems, reliability, core and cladding materials, transmission properties, mechanical properties.

1. Introduction

1.1 Why were Optical Fibers Needed for the Communication Networks

During 1960-ties, it was realized that new communication cables were needed to provide the signal capacity for our world. For example, the trans-Atlantic coaxial cable was getting too limited for the signal capacity and too old to provide the reliability needed. It had been installed and taken into use during 1860-ties. The metallic coaxial cables had (and still would have) too high absorption at the signal frequencies over 10 MHz, Fig. 1 [1]. The computer equipment had been developed for telecommunication centers, and communication signals were changed from the analog signals (from the 63 kHz telephone channels) to digital multichannel systems (2 Mbit/s 30 phone channels).

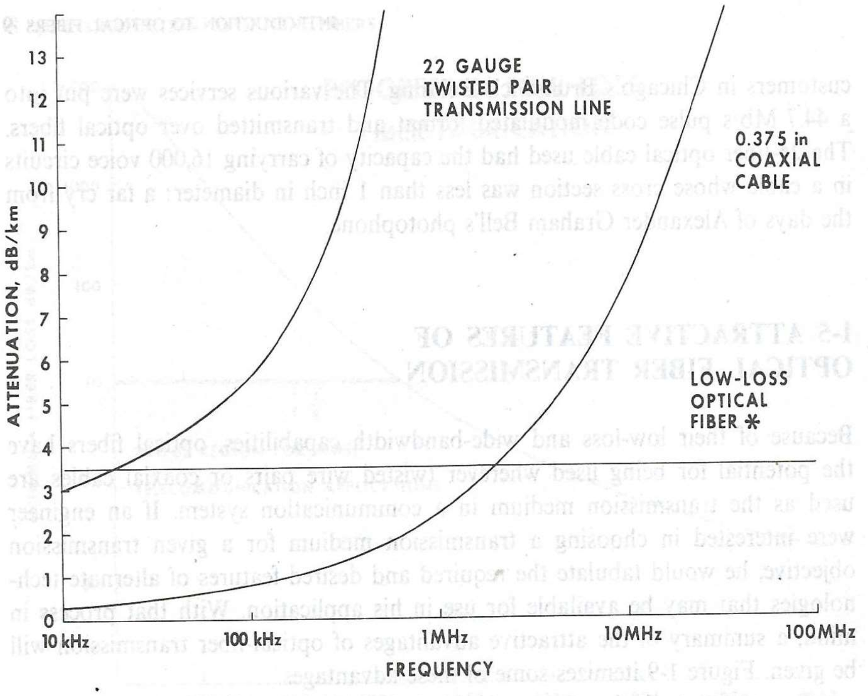
Satellite communication systems had been started also to use, but it caused too long transmission time differences. During a phone call, the signal transmission took 9 s from USA to Europe. It made the phone discussions difficult. The long-distance coaxial cables were very expensive, because amplifiers were needed after every 1,85 km, and thus also electric power cables were installed along the side of communications cables. The amplifiers needed to be protected for the weather and environment, so they were located in small cottages along the cable lines in ground. Thus, the low attenuation and low dispersion optical fiber cables were very welcome for the communication networks. Many other technical benefits were also expected and have been obtained to occur with the optical fiber communication networks. [2].

1.2 First Optical Fibers

K. C. Kao asked: how low attenuation could be reached in glass [3]? The transmission theory for optical fibers was developed in telecom research centers in Japan [2],

---

Corresponding author: Tarja Volotinen, retired associate professor, research fields: optical fibers and colored glasses.



* FIBER LOSS AT A CARRIER WAVELENGTH OF 0.82 µm

Fig. 1 The typical attenuation curves are shown for copper twisted pair, short-distance cables, coaxial long-distance cables, and compared with the first multimode optical fiber cables [1].

USA [1, 4, 5], UK [6] and many other countries, as soon as the low attenuation was realized to be possible to reach [1-9]. In addition to the low attenuation possible to be reached, it was also realized that the bandwidth of transmission signal could be very much higher for optical fibers than for any metallic cables (Fig. 1) [1-2, 10, 11]. The dispersion could be made already so low that the best fibers had bandwidth of 0.2-1 GHz·km at the time when multimode fibers became commercially available in 1979. However, the dispersion, attenuation and other properties varied along the first fiber lengths. The optical fiber digital communication systems up to 34 Mbit/s were tested in 1-10 km long network sections without having any amplifiers already in 1978-1982 in many countries [1-11].

The first commercially available optical fibers in 1979 were multimode fibers with a Ge-doped core of diameter ca. 62 µm and the cladding diameter was 125 µm. The core had refractive index profile of parabolic shape, made by a type of CVD (chemical vapor deposition) process [1-2, 4-7, 9]. The cladding glass was made of fused silica, dug out from the ground. The coating materials and thicknesses varied, depending on the manufacturer. Now the standard multimode fibers (MM-fibers, 50 µm core, 125 µm cladding and having 2-25 GHz km bandwidth), are used for short communications network sections [12].

The first single-mode fibers, with 8.5-9 µm Ge-doped core and 125 µm cladding, became commercially available a couple of years later. Now the single-mode fibers (SM-fibers) have a slightly thinner, 8-8.5 µm core and 125 µm cladding. In some SM-fiber types, the inner cladding is down-doped in ref. index. The diameter of two-layer coated SM- and MM-fibers is 250 µm for the single core fibers.

The standard SM-fibers with low dispersion and a very low attenuation in the wide wavelength window are used now for all long-distance communications networks worldwide (Fig. 3) [13]. The attenuation has become very low by decreasing the transition metal and other contamination of the core and inner cladding glass to almost zero level. The scattering has been minimized by using such preform manufacture and drawing processes that provide very homogeneous glass structure and constant density. The detailed information about the processes is owned by the successive fiber manufacturers.

Of the order of 500 million km optical communications fibers are installed now yearly for the communication networks. The dispersion of SM-fibers is very low (less than 20 ps/nm·km) in a wide wavelength window (1280-1600 nm) [7, 13-15]. Material dispersion as a function of wavelength has been mainly compensated by the waveguide profile dispersion [7, 13].

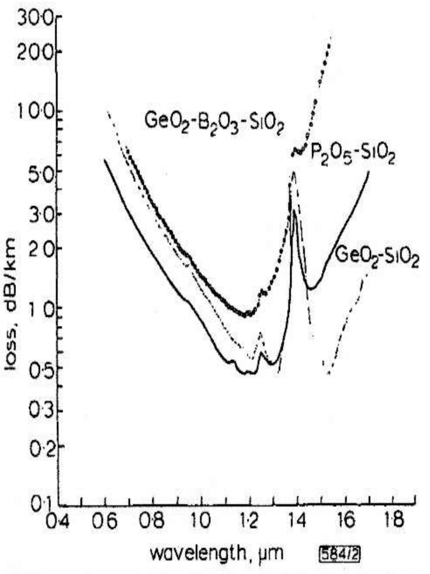


Fig. 2 Absorption loss curves of germania-doped-borosilicate-glass-core fiber, phosphosilicate-glass-core fiber and germania-doped-silica glass-core fiber, whose lengths were 1.2, 1.1 and 0.8 km respectively [10], as were reported for optical fibers in 1976.

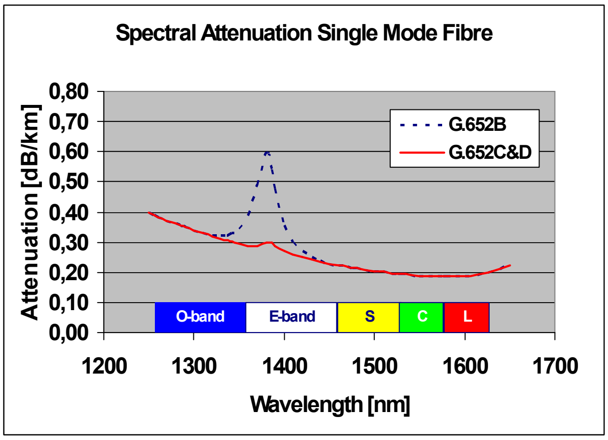


Fig. 3 Attenuation curve for the standard SM-fibers over the wide 5 bands containing wavelength range [13].

PMD (polarization mode dispersion) was a challenge to be improved for many years [14]. In particular, when transmission distances became longer, it was important to control and decrease PMD. In the years right after the millennium change, many papers were presented in particular concerning the spinning technique that could make the core refractive index profile more circularly symmetric [16]. The spinning takes place in the draw tower just below the furnace. This way the velocity difference between the two orthogonal polarization parts of the fundamental transmission mode can be minimized and therefore reduced PMD (max. 0.2 ps/km$^{-1/2}$ over the wide wavelength range) is obtained for the fiber.

The international standardization efforts on the communication fiber properties: dimensions, transmission properties and profile structures, materials, measurement- and test methods, were started during the first testing years. However, it took for a while to get enough experiences and test results to make good enough IEC (the International Electrotechnical Commission), ITU (the International Telecommunication Union) and other international standards. The fiber properties were improved all the time, as well as the light source and detector components to be used in the measurement equipment and especially in communication systems. The measurement-, test- and analysis-methods were needed to be developed for all properties of the fibers and cables [2, 5, 6, 17, 18]. New light sources and detectors were also needed for the fiber measurements.

Splicing of the fibers was at first done by gluing the cleaved ends of fibers into metal V-groove [2, 6-7] and protecting with plastic tubes. But soon the much better fusion-splicing method was developed [2, 6-7] and splice protections were improved.

New cable structures were needed to be developed for the optical fibers to avoid the attenuation increases caused by micro- and macro-bending, and to keep the mechanical stresses of the fibers low. New cable manufacturing equipment and methods were also needed.

However, the most challenging was to make good and reliable enough fibers. All new technologies have some childhood problems, as is described for the fibers in the following chapters.

2. Early Problems and their Solutions in Optical Fibers

2.1 Bend Attenuation Problem in Cables

The optical fibers were drawn 1970-ties (in the beginning) from small, tube-formed glass preforms: 3-5 cm in thickness and 10-50 cm in length. The core part had been done by a CVD process and the cladding part of the fused silica glass. The refractive index profile of the multimode fiber core varied slightly as a function of the preform length. The drawn fibers were only 1 km or 2 km or at maximum 10 km long. Typically, all the fiber properties, especially bend attenuation sensitivity [2, 7], varied as a function of the fiber drawn length. The test methods, fiber optical properties, coating materials and standardization were under development in addition to the development of the preform manufacturing and fiber drawing methods.

The first commercially available MM-fibers 1979 were 1 or 2 km long and quite good and similar in their properties and refractive index profile. However, there came out some problems in cables made of them. Attenuation increased in some of the fibers during the cable manufacturing process [19-23]. It was a very big problem for many years in the SM-fiber cables.

In many cases, the attenuation problem came out in the fiber sections cut out from longer fibers [19-23]. Both ends of the original fiber had been tested for the bend sensitivity before cutting the fiber and making of the cable. In further tests it was found that there were small differences in the core profile, either core radius, or in the refractive index difference between the core and cladding or in the shape of the core profile [19, 21]. Thus, bend attenuation could be greater or smaller than expected from the bend tests or from core dimeter & profile tests made on the ends of the long original fiber.

The reason for the bend attenuation problems on the quite large (over 10 cm) bend diameters used in cables was thus a too large variation of the refractive index profile and circularity of it, made into the fiber from the preform and or obtained through the drawing. [20, 24, 25].

This problem was slowly decreased with the improvements of the preform manufacturing process and drawing process. The preforms were made bigger and the refractive index profile became more exact and similar and symmetric around the core, along all the preform. Micro-bend sensitivity needed to be improved also and the standards test methods. To get the good enough fibers with low micro- and macro-bend sensitivities, the refractive index profile needed to be improved (Figs. 4 and 5). The inner primary coating needs to be soft enough and the secondary coating slightly harder to protect the fiber from micro-bending. A slightly smaller mode field diameter with slightly higher refractive index difference gives also lower micro-bend sensitivity [19, 21, 24-26], in addition to the low macro-bend sensitivity. The drawing process parameters became better controlled. Also, the core diameter was slightly decreased and the refractive index difference between core and cladding was increased. Thus, the problem for both micro- and macro-bending losses have been solved (Figs. 4 and 5). But it still is needed to keep fiber macro-bend diameters large enough and micro-bending at a low level enough to keep the attenuation over the whole transmission wavelength range as low as needed.

Another problem in the fibers was dispersion variation along the fiber length. The development of the good dispersion properties for the MM-fibers was, and has been until now, very challenging, even though in theory it was known how to reach high bandwidth [2, 4-12]. Successfully, already the first MM-fibers provided much better properties in dispersion and attenuation than coaxial and other metal cables had (Figs. 1. [7] and 2. [10])

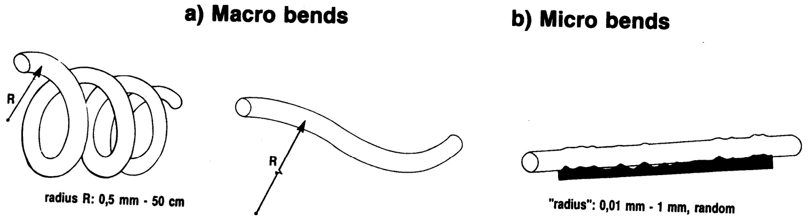


Fig. 4 Macro-bending has bend radius larger than fiber diameter and micro-bending has a smaller one. The micro-bending usually varies along the fiber [19].

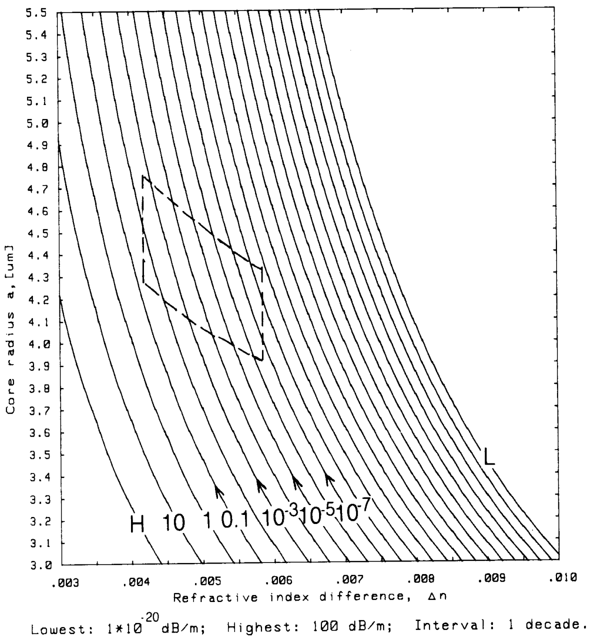


Fig. 5 A typical variation of macro-bend attenuation at 60 mm bend diameter in SM-fibers at 1550 nm wavelength, calculated as a function of the core radius and refractive index difference [19]. The circle represents the SM- fibers available 1990.

One challenge was also the missing of good enough light sources and detectors, as well as the signal capacity of the oscilloscopes and their operation programs [15, 17, 18]. The bandwidth of the first MM-fibers challenged significantly all these factors of the measurement equipment technology. To be able to measure bandwidth of 1 GHz with good enough accuracy and repeatability, the measurement equipment needed to have at least 2.5 GHz measurement capacity. When fast enough lasers and detectors at the 850-950 nm came to the market, also the best ones of the 1-2 km long MM-fibers had bandwidth above 1 GHz km at 904 nm. It could not be measured accurately. However, the most of the fibers had 50-150 MHz·km bandwidth, providing possibilities to test the optical communications cables and networks in practice.

One of the main issues in the silica glass of the first optical fibers, and in the slightly Ge-doped core silica glass, was the accuracy of the refractive index and the homogeneity of the glass structure. Silica glass is well-known of having the possibility to create big differences in density and homogeneity, which both are related to the refractive index [1-2, 4, 7, 26]. The original structure of the fused silica glass, and even by a CVD-process made glass, can become very different, depending on the heat treatments, mechanical stresses and chemical environment during the preform making and especially during the final drawing process of the fiber [2, 4, 9, 26]. It took several decades to reach the high-quality silica and Ge-doped glass now existing in communication fibers.

2.2 Attenuation Problems Found in Fibers

Both optical and mechanical reliability properties of silica glass optical fibers had been tested and partly reported [4, 7] already during the first years when the fibers became commercially available. But some problems showed up later and were greater than was expected.

Access of H_2-gas and the attenuation increase caused by it in the optical fibers in installed cables was reported in international conferences in the middle of 1980-ties. Significant increases of attenuation had been seen in laboratory tests, where fibers had been given in H_2-environment [7, 27]. But the problem was found to increase slowly also inside the installed cables, as a function of chemical aging reactions of the fiber coating and cable materials and reported in several fiber optic conferences. Maybe the long length of the fibers could show the absorption that had been so little that it had not been noticed in short glass distances before. The molecules of hydrogen gas are so small in size that they go into silica glass [27] like "a fox runs into a forest". The attenuation is then increased at 1000-1300 nm by the non-coupled hydrogen molecules inside the silica glass [7, 27]. Furthermore, the hydrogen reacts with the silica glass and forms stable OH^--containing molecules that cause permanent attenuation increases at wavelengths above 1300 nm.

The solution to this significant problem has been to use stable coating materials in fibers and cable materials that do not release hydrogen, when they age. For cables to be installed in wet conditions, hermetic structures that prevent hydrogen, are used. One additional solution to keep hydrogen concentration as low as possible has been to use non-hermetic cables structures where it is possible. Thus, a small amount of released hydrogen gas will leak out from the cable and does not go inside the fibers glass. The third part of the solution has been to use such chemical and physical conditions in the fiber glass manufacturing process, that the bonding of the hydrogen ions into the silica glass in the fibers has been made as small as possible. In addition, the deuterium treatment can be applied on coated fibers after drawing. It effectively prevents the formation of the OH-molecules into the silica glass and thus decreases the OH-absorption peak at 1380 nm and prevents the attenuation increase at wavelengths above it [2, 4, 7, 27]. This possible reliability problem is still there, and needs to be and is taken care of, especially in the cables in data centers and close by electric equipment. All electric equipment makes some hydrogen from the air humidity around them.

The other possible issue with optical reliability is the attenuation increase caused by ionizing radiation [28-32]. Silica glass fibers need to be prevented from the radiation access or be well protected from it. Thus, special types of communications network solutions are used in close by the nuclear power stations and other places where the radiation is available.

2.3 Mechanical Properties and Reliability of Optical Fibers

It has been known for several hundred years that silica glass, and all oxide glasses, have higher inert strength than the strength in normal environment, where some humidity exists (Fig. 6.) It has been also known, that silica glass breaks at the largest defect in the stressed part of it, with a significant help from the chemical reaction with water (H_2O). The effect of the normal air humidity decreases the stress needed for a fracture of a glass fiber by factor 3 compared to the inert environment that has no humidity available (Figs. 6 and 7).

Mechanical strength and fatigue in different temperatures and on uncoated and coated fibers had been tested by those laboratories that developed the first optical fibers (Fig. 7). The possibility for some weak spots in the fibers had been noticed and the proof-testing had been taken into use already for the first commercial fibers [4]. The first mechanical problems in optical fibers were related to the cladding glass of fused silica. Such fused silica glass has some weaker sections of the outer surface caused by the impurities and structural variations, containing even a few crystalline particles.

The significant mechanical problems in the first optical fibers started to come out in the beginning of 1990-ties in about 10 years old and even younger communications cable networks [34-39]. It was found out that overall strength of the fibers had decreased significantly in some of the installed cables. International cable conferences and researcher meetings started to show various types of reports about the mechanical strength distribution, fatigue and effects of various chemicals on the strength of the fibers, as well as corrosion of the fiber surface [28-32, 34-47].

Some fibers had become so weak in some installed fiber cables that no re-splicing could be made [36, 39]. Some fibers started to break also in the cables. When the cable drums of the similar cables kept in store for a while, were studied, the same corrosion weakening problem could be found in the fibers [36].

The corrosion problem was found in the fibers that had been used over 10 years in the communication test network in Biarritz [39]. The parts of the fibers that had been located inside the splice boxes and network cabinets had weakened in strength, but no breaks had happened. In UK some cables had got water inside the cable structure and the fibers had become very weak in those parts of the cables [39].

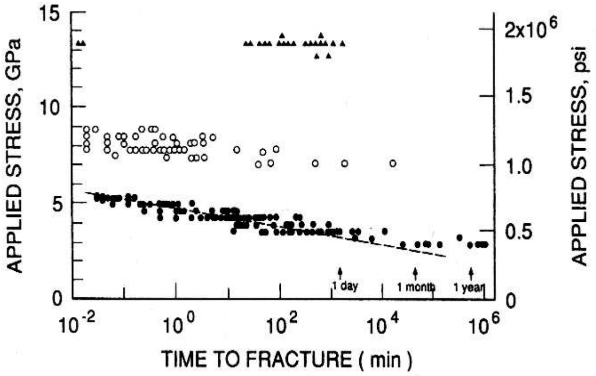


Fig. 6 Static fatigue of uncoated fused silica glass fibers measured in room conditions, dry air and inert environment at 5 %/min stress rate, and reported already in 1967 [33].

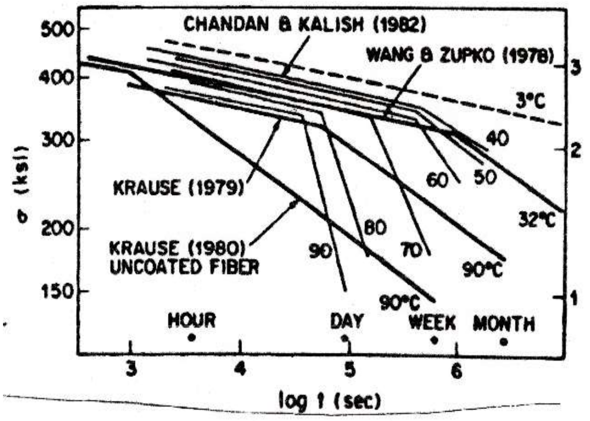


Fig. 7 Temperature dependence of static fatigue of uncoated optical fibers and fibers coated with an UV-cured polyurethane acrylate. The higher the temperature is, the sooner the corrosion starts, seen as the fatigue line direction changes [48].

Several reasons for the strength decrease problem came out in the research work reported worldwide [28-32, 39-47]. The most severe corrosion problems were found to be related to the fused silica glass cladding that was not free enough of contaminations and had not enough homogenous silica glass structure. In addition, some coating materials had been used, which contained chemical components that increased corrosion of the silica glass surface. Some coating materials were found to age and provide new chemical components that were corrosive for the silica glass. The third issues that were also needed to be solved were: the details of the proof test procedure of the fibers, tests methods of the mechanical properties and aging tests of the fibers and cables, as well as to find out the reliable and correct life-time calculation theory to be used for the life-estimation of the installed fiber networks [40, 43]. It was needed to estimate the number of fiber fractures during the life-time of 30 years, in some cases up to 45 years.

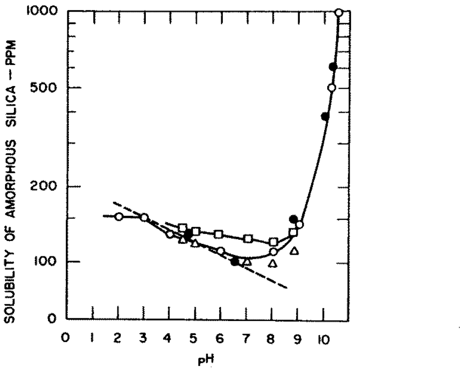
The first solution for this serious reliability problem was to replace the weakened cables with the new cables made of fibers that had a by-CVD-process made, pure and homogeneous silica glass structure of the cladding. The fused silica was stopped to be used in communications fibers. Very much research and testing of communications fibers were made worldwide, of which some examples are Refs. [28-32, 39, 41-47].

Secondly, the chemical conditions, at the cladding glass surface must stay at pH-level of 7.0 inside the cables (Fig. 8). It is the least corrosive environment for the good quality homogeneous silica glass and can be created by the stable coating materials and chemistry of all items included in the cables.

Third part of the necessary solutions to provide the long-term stability of the fibers mechanical properties is provided by keeping the mechanical tensile stresses of the fiber surfaces below such level that would cause the breaking of the largest defects that have survived the fiber proof test without breaking. Typically, the maximum tensile stress allowed in the cladding surface inside the cable is 1/4 or 1/3 of the proof test stress depending on the cable network type and the life-time required. During installation of the cable a slightly higher stress, up to ½ of the proof test stress is allowed for a short time (~ a few minutes). These standard recommendations are based on the lifetime calculation methods developed by the worldwide research work during 1990-ties of which some reports are referred in Refs. [39, 40, 43].

The basic mechanical properties of the silica glass fibers were based on the knowledge, that was available already in 1980—when the communications fibers came to the market. However, the purity of the fiber silica glass and accuracy of the refractive index have been further developed much better than 1980-ties. Also, the structural homogeneity of the ultrapure, well manufactured cladding glass of the fibers has become much better than is required in any other glass application.

Thus, it was needed to create reliable and meaningful aging test and mechanical measurement methods for all types of the mechanical properties needed for the communications fibers: strength distribution, inert strength, strength in normal standard environment, and for the effects of the environment available in communications networks. Furthermore, a reliable life-time calculation method was also needed [39, 40, 43]. The proof-test conditions and method were needed to be as realistic as possible to take away the most serious defects from the fibers, but save the surviving parts as good as possible.



Solubility of amorphous silica versus pH: O, Alexander, 25°C; ●, Cherkinskii and Knyaz'kova (160) 19°C; Δ Baumann, 20°C; □ Baumann, 30°C; Dashed line from Cherkinskii equation: log $C_M = -2.44 - 0.053$ (pH).

Fig. 8 Solubility of amorphous silica glass versus pH. [9]. The solubility is lowest at pH = 7. The original references of the data are given in the Ref. 9.

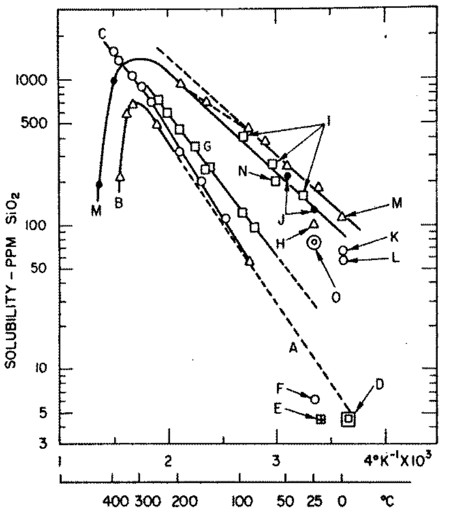
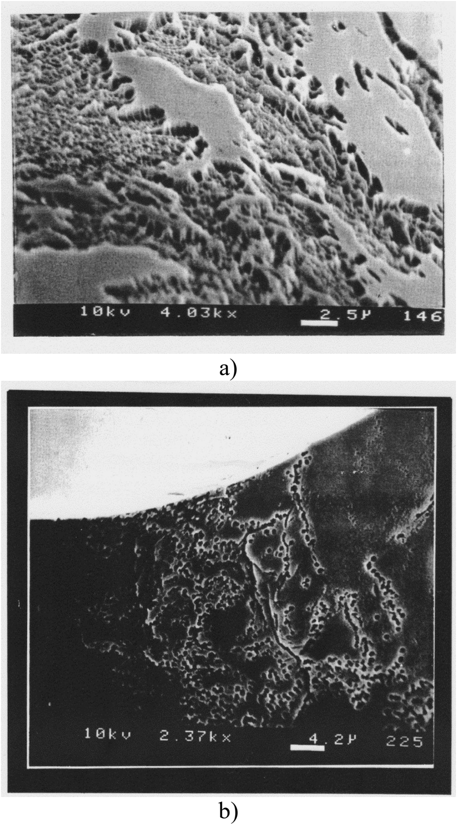


Fig. 9 Solubility of the various forms of silica in water and salt solutions, showing that the solubility is dependent on the silica glass purity and structure [9]. The least soluble is the crystalline silica, i.e., quartz, in pure water, as is shown by the dashed curve A. The original info is given in Ref. 9.



a)

b)

Fig. 10 SEM (scanning electron microscope) pictures of the corrosion in the silica glass gladding surface of optical fibers aged 9 months in tap water at 80 °C. (a) an overall corrosion of the cladding surface, caused by the chemicals from the coating and the tap water, and (b) a contamination location corroded faster than the surrounding silica glass [35].

The following mechanical properties of optical fibers are needed to be taken care of for communication cables, according to the exsisting standard requirements for the fiber properties, test- and measurement methods [28-32, 34-48]:

- Prooftest: the tensile stress and time applied into the fiber, the waiting time between the drawing of the fiber and the prooftest and the conditions used for the pre-conditioning and the proof-test. It is assential to get the normal humidity content through the coating layers into the cladding glass surface before the prooftest is performed. The speed depends on the coating material (Fig. 11). The pre-conditioning is usually performed for one night.
- The strength distribution and fatigue parameter (n-value) for the fiber high strength and low strength parts. The distributions shall be measured at standardized room conditions on the fiber samples well pre-conditioned in the same environment before the testing.
- Effect of the humidity and temperature on the strength and fatigue.
- Effect of the coating materials on the strength and fatigue.
- Effects of the mechanical stresses inside the cable, during manufacturing of the cable, during installation of the cable and during the life-time of the cable.
- The aging behaviour of the fibers in all those chemical and physical conditions that are relevant for the long term use of the fibers inside the cables, splice boxes and network cabinets etc.

Effect of the chemical conditions and access of the water/humidity inside the cables (pH-value, etc.). e.g. polyoleofine fat is used to avoid the access and forming of the water drops inside the cables. Water drops are dangerous because they may cause serious local stresses and may thus brake the fibers, when the temperature goes below 0 °C.

- The maximum tensile and bending stresses allowed being applied into the fiber inside the cable after its installation.
- Lifetime-estimation method and all the parameters needed to calculate the fracture rate of the fibers in the installed cable network during the life-time of 30-50 years. It is better to have slightly lower stresses than the maximum allowed.

Most of the fibers installed after the 1995 have behaved well (i.e. have had a lower fracture rate than expected), i.e. better than has been required. It is difficult and more expensive to make and install cables so that the final stress inside the fibers is at the limit. It is much better and cheaper to make and install a cable so that the all reaquirements are completely fullfilled. In such cases, also the fiber fractures and other problems are avoided.

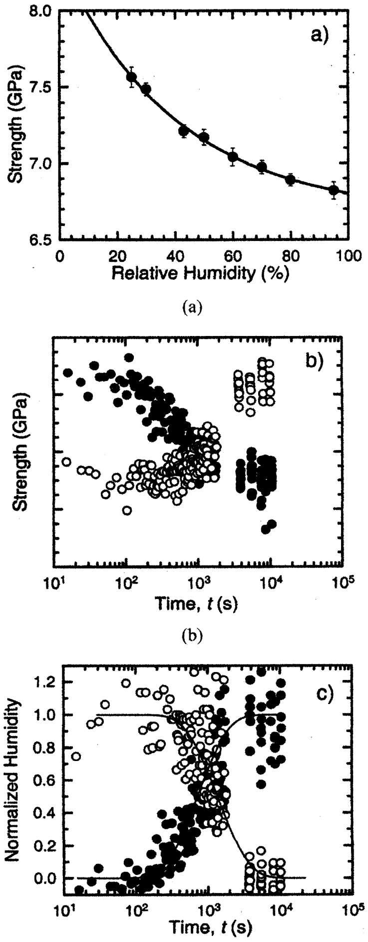


Fig. 11 (a) The strength of a fiber with a good quality coating materials is dependent on the relative humidity. (b) The strength as a function of time after changing humidity, where (spot) is for wetting i.e. going from 25% to 95% RH at 25 °C and (ring) is for drying, i.e. going from 95% to 25% RH at 25 °C. (c) Normalized humidity as a function of time, [42].

2.4 Lifetime of Optical Fibers

A lot of analyses and discussions were needed between experts and scientists worldwide, before a standard could be determined for the way to calculate the lifetime of the optical fibers in communication networks, a lot of research projects, such as COST218, COST246 and COST270 projects in Europe [39] and scientific SPIE conferences in USA and Europe [28-32, 34-47, 49-50].

It is very important that there are enough data to get the relevant strength distribution, that represents the fiber strengths. Also, the tests (the proof test of the fibers and the mechanical strength measurements of the proof-tested fiber pieces) need to be done in the standard room conditions after pre-conditioning the fibers.

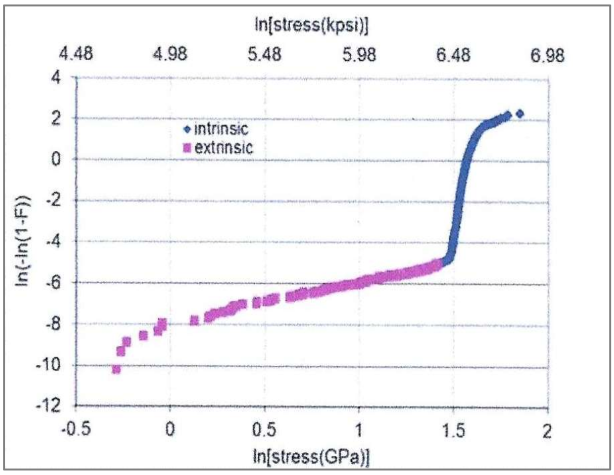


Fig. 12 Combined 10μgauge length Weibull strength distribution representing 198.9 km of fiber, i.e., 19163 pieces of 10.38 m gauge lengths, spanning a 2-year production window tested at 2.5 %/min strain rate in standard room conditions. The Weibull parameters for the high strength distribution are: median strength S_0 = 4.84 GPa, m = 47.5. The m = 2.15 is the weak spot distribution [49].

Many discussions and a lot of confirming mechanical property tests results of the further developed good quality optical fibers were needed between the scientists to come to the final solutions, how to calculate the lifetime of the optical fibers in the cable networks. One example of mechanical strength distribution of fibers is shown in the next Figs. 12 and 13. The lifetime, the time to reach the certain fracture probability has been calculated by using the standard equation IEC TR62048. The equation used now as standard is the same as W. Griffioen proposed in his Ph.D. thesis report [40] 1994.

However, the installed fibers break less than the expected from the lifetime estimations. Most of the installed cables provide slightly lower tensile stress on the fibers. Secondly, also some improving of the largest defects may occur under a longer time. It was also found in the scientific analyses several places in the world [39].

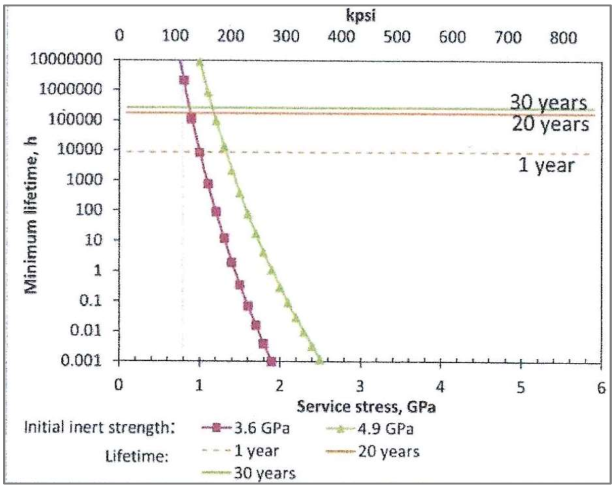


Fig. 13 Minimum lifetime vs. service stress in standard room environment, calculated for 10 m fiber sections (Fig. 12) of 3.6 GPa and 4.9 GPa initial inert strengths. The initial inert strength 4.9 GPa corresponds to the Weibull facture probability (ln-ln(1-F)) = -6 at 2.7 GPa, and 3.6 GPa corresponds to the -8 probability, as were obtained in the tensile test at strain rate 2.5 %/min in Fig. 12 above [49].

3. Conclusions

Good quality optical fibers, with very low attenuation and dispersion in a wide wavelength window, and with high mechanical properties and reliability, have been developed during past 45 years for communications networks. The “childhood problems” in both optical and mechanical properties have been solved as is described above. Thus, optical fiber communication networks provide us the reliable high-capacity communication with pictures and on-line-films, TV- and computer-networks etc. The optical fiber networks do not warm up our climate, because the signal is travelling inside the fibers.

Author information: Both authors have more than 30 years of work experience in the fiber optic cable industry: T Volotinen 1978-2022 and B Arvidsson: 1990-. Hopefully, this article helps young engineers, who are starting to work with optical fibers, cables or networks, understand the properties of fibers and keep the fiber networks reliable.

References

[1] Cherin, A. H. 1983. *An Introduction to Optical Fibers* (2nd ed.). Singapore: McGraw-Hill Book Company.

[2] Murata, H. 1996. *Handbook of Optical Fibers and Cables* (2nd ed.). New York: Marcel Dekker, Inc.

[3] Kao, K. C., and Hockham, G. A. 1966. "Dielectric Fiber Surface Waveguides for Optical Frequencies." *Proc. IEE* 113: 1151-8.

[4] Li, T. 1985. *Optical Fiber Communications. Fiber Fabrication (Vol. 1).* Orlando FL: Academic Press Inc.

[5] Keiser, G. 1983. *Optical Fiber Communications*. New York: McGraw-Hill Inc.

[6] Midwinter, J. E. 1979. *Optical Fibers for Transmission*. New York: John Wiley & Sons Inc.

[7] Allard, F. C. 1990. *Fiber Optics Handbook for Engineers and Scientists*. New York: McGraw Hill Inc.

[8] Senior, J. M. 1985. *Optical Fiber Communications Principles and Practice.* London, UK: Prentice-Hall International, Inc.

[9] Iler, K. 1979. *The Chemistry of Silica*. New York: John Wiley & Sons.

[10] Osonai, H., Shioda, T., Moriyama, T., Araki, S., Horiguchi, M., Izawa, T., and Takata, H. 1976. "Effect of Dopants on Transmission Loss of Low-OH-Content Optical Fibres." *Electron. Lett.* 12 (21): 549-50.

[11] Snyder, A. W., and Love, J. D. 1983. *Optical Waveguide Theory.* Bristol, UK: Chapman and Hall.

[12] Shubochkin, R., Braganza, D., Sun, Y., Balemarthy, K., Lingle, R. Jr, Kamino, J., Mazzarese, D., and Vaidya, D. 2016. "Next Generation Wideband Multimode Fiber for High-Speed SWDM Datacom Links." In *Proc. of 65th IWCS International Cable and Connectivity Symposium*, pp. 489-94.

[13] Map of IEC designation to ITU-T Recommendations and IEC60793-2-50:2015 Designation. Partly Refers also to IEC DTR 63309 © IEC:2020.

[14] IEC 60793-1-48. *Polarization Mode Dispersion*.

[15] Hecht, J. 2002. *Understanding Fiber Optics* (4th Ed.). USA: Prentice Hall.

[16] Palmieri, L. 2006. "Polarization Properties of Spun Single-Mode Fibers." *Journal of Lightwave Technology* 24 (11): 4075-88.

[17] Marcuse, D. 1981. *Principles of Optical Fiber Measurements*. New York: Academic Press.

[18] Derickson, D. 1998. *Fiber Optic Test and Measurement.* New Jersey: Prentice-Hall Inc.

[19] Volotinen, T. 1990. "Influence of the Standard Single Mode Fibre Bends on Cable Properties Investigated by the $\alpha 11_b(\lambda)$ Method." Ph.D. thesis, Helsinki University.

[20] Volotinen, T., and Stensland, L. 1988. "Method for Single Mode Fibre Bending Studies in Short Fibres and Cables." In *Proc. 37th of The International Wire and Cable Symposium (IWCS)*, pp. 710-21.

[21] Volotinen, T., Stensland, L., and Björk, A. 1992. "A New Method of Testing Optical Fibres and Cables." *Ericsson Review* 69 (4): 100-14.

[22] Volotinen, T., Stensland, L., and Björk, A. 1991. "Testing of Some Single Mode Fibre Cables and Ribbons by the $\alpha 11_b(\lambda)$ Method." In *Proc. of the 40th IWCS*, pp. 535-9.

[23] Volotinen, T., Stensland, L., and Björk, A. 1991. "The $\alpha 11_b(\lambda)$ Method: A Way to Investigate the Bending and Bend Sensitivity of Single Mode Fibres." In *Proc. of the OFMC (The Optical Fibre Measurement Conference)*, pp. 20-3.

[24] Arvidsson, C. B., Shah, P., Schmid, S. R., Alexandersson, R., and Björk, A. 2011. "Microbend Evaluation of Selected G652D & G657 Fibers and Ribbons before Cabling." In *Proc. Of the 60th IWCS.*

[25] IEC TR 62221. *Microbend Sensitivity.*

[26] Izawa, T., and Sudo, S. 1987. *Optical Fibers: Materials and Fabrication*. Tokyo, Japan: KTK Scientific Publishers.

[27] Rush, J. D., Beales, K. J., Cooper, D. M., Duncan, W. J., and Rabone, N. H. 1984. "Hydrogen Related Degradation in Optical Fibers-System Implications and Practical Solutions." *BT Technology Journal* 2 (4): 84-93.

[28] Paul, D. K., Greenwell, R. A., and Wadekar, S. G. 1988. *Proc. of SPIE Conference: Fiber Optics Reliability: Benign and Adverse Environment II* (Vol. 992).

[29] Greenwell, R. A., and Paul, D. K. 1992. *Proc. of SPIE Conference: Optical Materials Reliability and Testing: Benign and Adverse Environments* (Vol. 1791).

[30] Paul, D. K., and Yuce, H. H. 1993. *Proc. of SPIE Conference: Fiber Optics Reliability and Testing: Benign and Adverse Environments* (Vol. 2074).

[31] Yuce, H. H., Paul, D. K., and Greenwell, R. A. 1995. *Proc. of SPIE Conference: Optical Network Engineering and Integrity* (Vol. 2611).

[32] Matthewson, M. J. 1999. *Proc. of SPIE Conference: Optical Reliability and Testing* (Vol. 3848).

[33] Proctor, B. A., Whitney, I., and Johnson, J. W. 1967. "Strength of Fused Silica." In *Proc. R. Soc. London, Ser. A 297 A*, pp. 534-57.

[34] Volotinen, T. T., Yuce, H. H., and Frantz, R. A. 1993. "Ageing Behaviour of Fibers." *SPIE* 1973: 161-74.

[35] Volotinen, T. T., Yuce, H. H., and Frantz, R. A. 1993. "Effects of Glass Preparation on the Surface Corrosion of Fused Silica Optical Fibers." *SPIE* 2074: 83-94.

[36] Griffioen, W., Volotinen, T., Wilson, P., Gouronnec, A., and Svensson, T. 1995. "Handleability of Aged Optical Fibers." In *Proc. of the 44th IWCS*, pp. 857-64.

[37] Bonanno, N. J., Hartman, H. C., Contreras, R. W., Yuce, H. H., Volotinen, T. T., and Varachi, J. P. Jr. 1993. "Handling Behaviour of Aged and Unaged Fibers during Splicing Operation." In *Proc. of 9th NFOEC (National Fiber Optic Engineering Conference)*, San Antonio, Texas, US.

[38] Haslov, K. B. J., and Skovgaard, N. H. 1994. "Degradation of Stressed Optical Fibers in Water: New Worst-Case Lifetime Estimation Model." *J. Am. Ceram. Soc.* 77 (6): 1431-6.

[39] Volotinen, T., Griffioen, W., Cadonna, M. and Limberger, H. 1999. *Reliability of Optical Fibres and Components, Final Report of COST 246*. London, UK: Springer-Verlag.

[40] Griffioen, W. 1994. "Optical Fiber Mechanical Reliability." Ph.D. thesis, Royal PTT Nederland.

[41] Mrotek, J. L. A., Matthewson, M. J., and Kurkjian, C. R. 2001. "Diffusion of Moisture through Optical Fiber Coatings." *Journal of Lightw. Techn.* 19 (7): 988-93.

[42] Mrotek, J. L. A., Matthewson, M. J., and Kurkjian, C. R. 2003. "Diffusion of Moisture through Fatigue- and Aging-Resistant Polymer Coatings on Lightguide Fibers." *Journal of Lightw. Techn*. 21 (8): 1775-8.

[43] Matthewson, M. J. 2002. "Environmental Effects on Fatigue and Lifetime Predictions for Silica Optical Fibers." *Proc. of SPIE* 4940: 80-92.

[44] Shiue, Y. S., and Matthewson, M. J. 2002. "Apparent Activation Energy of Fused Silica Optical Fibers in Static Fatigue in Aqueous Environments." *Journal of European Ceramic Society* 22: 2325-32.

[45] Matthewson, M. J. 2000. *Proc. of SPIE Conference: Optical Fiber and Fiber Component Mechanical Reliability and Testing* (Vol. 4215).

[46] Matthewson, M. J., and Kurkjian, C. R. 2002. *Proc. of SPIE Conference: Optical Fiber and Fiber Component Mechanical Reliability and Testing II* (Vol. 4639).

[47] Limberger, H. G., and Matthewson, M. J. 2002. *Proc. of SPIE Conference: Reliability of Optical Fiber Components, Devices, Systems and Networks* (Vol. 4940).

[48] Chandan, H. C., and Kalish, D. 1982. "Temperature Dependence of Static Fatigue of Optical Fibers Coated with a UV-Curable Polyurethane Acrylate." *Journal of the American Ceramic Society* 65: 171-3.

[49] Volotinen, T., Konstadinidis, K., Cusanello, V., Tretheway, E., Lago, R., and Mazzarese, D. 2014. "Mechanical Reliability of Short Optical Fiber Links in Data Centers." In *Proc. of the 63rd IWCS*, pp. 47-54.

[50] Matthewson, M. J., 1998, Chemical Kinetics Models for the Fatigue Behavior of Fused Silica Optical Fiber", *Mat. Res. Soc. Proc. Vol. 531,* pp 143-153.