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Warszawa ITME 1993

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PODSTAWOWE WŁAŚCIWOŚCI I ZASTOSOWANIA NOWOCZESNYCH SZKLANYCH WŁÓKIEN OPTYCZNYCH

Przedstawiono rezultaty prac naukowo-badawczych i technologicznych prowadzonych w Zakładzie Szkła Instytutu Technologii Materiałów Elektronicznych w Warszawie.

Prace naukowo-badawcze, zmierzajace do opanowania technologii wytwarzania elementów swiatłowodowych, prowadzone sa w nastepujących obszarach:

1. światlowody ze szkieł wieloskładnikowych,
2. światlowody ze szkieł czystokrzemionkowych,
3. światlowody ze szkieł nietlenkowych.

Opracowano metody laboratoryjnego wytwarzania elementów szklanych wyjściowych dla włókien optycznych. Prace te obejmowały:

- wybór właściwych składnikow chemicznych szkieł,
- przygotowanie optymalnych zestawów surowcowych,
- wytapianie szkieł w tyglach platynowych lub ceramicznych,
- obróbka mechaniczna (szlifowanie i polerowanie) bloków szklanych dla uzyskania prętów na preformy "pręt w rurze".

Opanowano rownież metody wyciągania włókien szklanych o różnych średnicach i przekrojach do różnych aplikacji medycznych, technicznych i ochrony środowiska.

Wysoki stopień opanowania techniki i technologii wytwarzania swiatłowodów pozwolił na wykonywanie elementów swiatłowodowych wyższej generacji, które posiadają zdolność przenoszenia obrazu lub sygnałów sensorowych. Dane o tej technice zostały zilustrowane w niniejszej pracy.

Longin KOCISZEWSKI, Ryszard STĘPIEŃ, Jan BUŹNIAK,
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BASIC PROPERTIES AND APPLICATIONS OF ADVANCED GLASS OPTICAL FIBERS

In this paper it has been presented results of scientific and technological experiments provided in Glass Department of the Institute of Electronic Materials Technology in Warsaw.

Researches on fiber optics elements are carried out in the following areas:

1. light guides from multicomponent glasses
2. light guides from pure silica glasses
3. light guides from nonoxide glasses

It has been elaborated the laboratory methods of manufacturing glass elements which were starting preforms for optical fibers.

Above methods include :

- selection of proper chemical composition of glasses
- preparation of optimum material batches
- melting of glasses in platinum or ceramic crucibles
- mechanical working (grinding and polishing) of glass blocks for getting rods for "rod in the tube" preforms It has been also improved methods of pulling glass fibers of different cross sections for several medical, technical and environmental applications.

A high level of technique and technology skills in manufacturing optical fibers made possible to obtain higher generation of optical fiber elements may possibly transmit image or sensor signals.

Information regarding that technique was ilustrated in the presented paper.

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Основные свойства и применения современных оптических стекловолокон

Изложено результаты научно-исследовательских и технологических работ проведённых в Заведении Стекла варшавского Института Технологии Электронических Материалов.

Научно-исследовательские работы направлённые на освоение технологии изготовления волоконных световодов, ведётся в следующих областях:

1) световоды получённые из многокомпонентных стёкол,
2) световоды из кварцевого стекла (SiO_2),
3) световоды из безкислородных стёкол.

Разработано методы лабораторного изготовления стеклянных исходных элементов для оптических волокон.

Эти работы охватывали:

1) подбор соответствующих химических составов стёкол,
2) приготовление оптимальных сыревых шихт для варки,
3) лабораторная варка стёкол в платиновых или керамических тиглах,
4) механическая обработка (шлифовка и полировка) стеклянных блоков для получения исходного элемента "стержень в трубе" (преформа).

Освоено тоже методы вытягивания стекловолокон с разным диаметром и поперечным сечением для разных медицинских и технических применений, для защиты натуральной человеческой среды.

Высокий степень освоения техники и технологии изготовливания световодов позволил на освоение продукции световодных элементов высшей генерации, которые способны переносить изображение или сенсоровые сигналы.

Многие данные об этой технике изображено в нынешней работе.

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BASIC PROPERTIES AND APPLICATIONS OF ADVANCED GLASS OPTICAL FIBERS

1. Introduction

Since a pretty long time glass has been pulled into fibers of several to several hundred micrometer diameters. They have found many applications, including glass cotton wool, sound deadeners, refractories and semi-insulting fabric. Above said applications took mainly into account high strength and very good insulation properties of the material.

Recently, with discovery and usage of optical parameters of fiber formed vitrified materials, the application range of glass optical fibers has significantly increased. Basing on optical transparency and silicate glass isotropy the fibers have been used as high quality wave guides. Moreover, cladding of fibers enabled total internal reflection of a light wave coming inside, which in turn, allowed to transmit light with minimum losses. A great number of recent researches opens an incredibly wide range of possible applications of light transmitting cable family, making possible elimination of commonly used copper wires.

1.1. Transmission capabilities of optical fibers

The basic condition for wave propagation in an optical fiber is the total internal reflection phenomenon. In order to fulfill this condition rays should be reflected at an angle which is smaller than the critical angle obtained by Snellius's law:

$$\sin \alpha_{cr} = \frac{\text{clad refracting index}}{\text{core refracting index}} = \frac{n_2}{n_1}$$

where n_2 should be smaller than n_1

The value of this parameter depends also on fiber diameter and is defined by the following equation:

$$\frac{2a}{\lambda}\sqrt{n_1^2 - n_2^2} < 2.4$$

$$\sqrt{n_1^2 - n_2^2} = NA \qquad \text{(numerical aperture)}$$

For λ of visual frequencies and fiber diameter /a/ - 100 μm, value of Δnmin is:
$n_1 - n_2 \approx 7 \cdot 10_3 \approx 0.007$

When fiber thickness is 200 μm, Δn equals 0.02.

1.2. Light propagation mechanism

As it has already been mentioned propagation of light at long distances is only possible on condition of the total internal reflection phenomenon occurance. Such phenomenon occurs only when a ray passes from more to less dense environment, (with the smaller light refraction index). There exists such an angle of incidence, called the critical angle /α_{cr}/, where the refraction angle α_2 equals $\pi/2$, what means that the refracted ray goes parallely to the environments' boundaries. The experiments have proved that when the incidence angle $\alpha_1 > \alpha_{cr}$ the refracted ray is not observed.It means, that the total internal reflection phenomenon occurs only then when light passes from optically denser to less dense environment. Fig.1.1 [1.1] shows the case when light is refracted at different angles of incidence when it passes from optically denser to optically less dense material. The critical angle depends on the prpoportion of refractive indices of two environments.The mutual proportion of those properties limits the perfection of light ray propagation through an optical fiber. So, the basic condition is the existance of a fiber internal part with

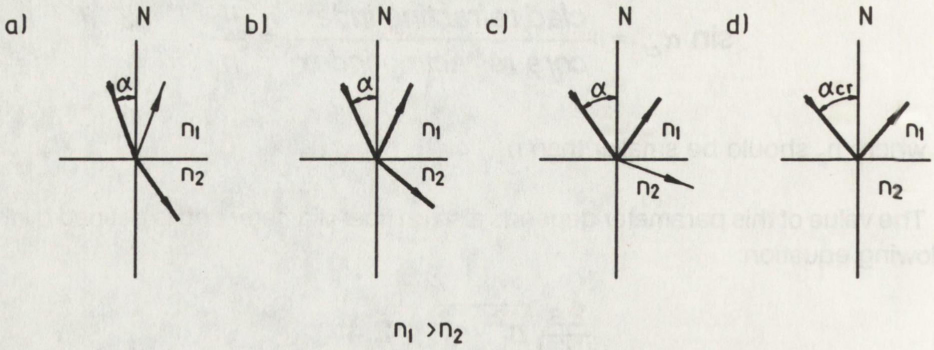


Fig.1.1. Intensity change of a ray reflected at environment's boundaries with different refraction indices.
α_{cr} = critical angle.

higher refraction index and an external layer with lower one. Most often, a fiber is made of possibly most transparent material covered with a glass layer of adequatly lower refraction index.

It is suggested to call the internal part of a fiber- a core, whereas the external part - a clad. The above names refer to a single fiber, and when we talk about a bundle of fibers, creating a light cable, there is also a notion of a jacket, that is an external insulation which protects the bundle from mechanical damages.

However, it should be mentioned here, that the situation described above is idealized and simplified. In fact, we can observe numerous complications which cause light ray deformation leading to its weakening.

The most important of those deformations are:

1. light rays entering a fiber core are weakened because of the material dispersion and of different kinds of absorption
2. some of the rays penetrate cladding and are absorbed there;
3. some rays escape from the core, go through cladding and go away, outside a light cable system.

All those losses are illustrated in Fig.1.2. The figure shows that from the whole solid angle of rays aiming at the end face of a cable only part of them fullfil the law of total internal reflection. The number of those rays depend on a lot of factors such as refracting indices of core and cladding, fiber diameter and the like.

The rest goes outside a cable. The solid angle, embodying the rays fulfilling the total internal reflection law, will be called the acceptance angle α_a.
Sinus value of half of the acceptance angle α_a is defined as the numerical aperture NA /Fig.1.2/

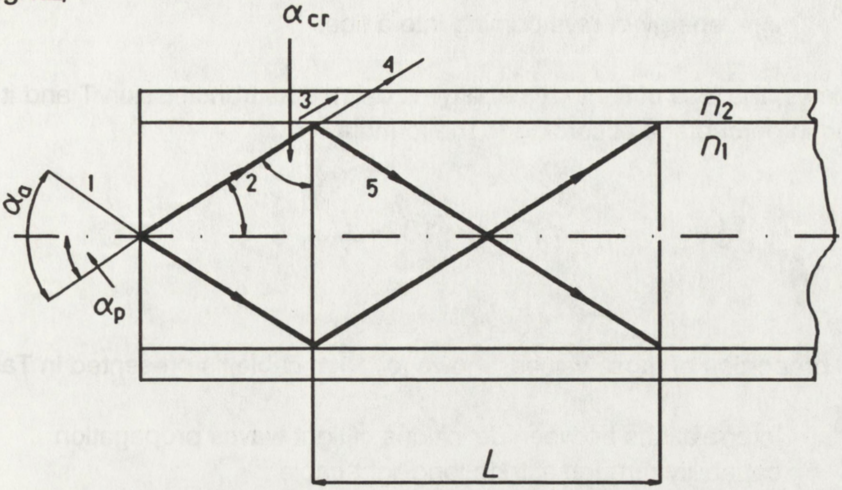


Fig.1.2. Light propagation in optical fiber
1 - meridional ray,
2 - critical ray,
3 - ray accepted by cladding,
4 - ray refracted into the cladding, etc.
α_{cr} - critical angle, α_a -acceptance angle, $\alpha_p = \alpha a/2$.

$$NA = n_0 \sin\frac{\alpha_a}{2} = \sqrt{n_1^2 - n_2^2}$$

where: n_0 - refraction coefficient of the environment of the fiber /for example air with refraction coefficient equal to 1/.

The most important problem in production technology of light cables are material properties and the methods of their processing into devices. The main property of the material envisaged for light cables is its attenuation.

Attenuation is defined in decibels /dB/ according to the following equation:

$$\text{fiber attenuation } dB/km = -10 \log J/J_0$$

where: J - energy of rays coming out of 1 km fiber
J_0 - energy of rays coming into a fiber

Sometimes, the loss of light rays energy is defined as transmission T and it is expressed in percentage according to the formula:

$$T\,\% = 100 * J/J_0$$

Mutual proportion of those values, shown for 1 km cable, is presented in Tab.1.1.

Tab.1.1. Interrelations between definitions of light waves propagation capability through a 1 km long light cable

Attenuation dB / km	Transmission % / km
1	79,3
2	62,9
5	31,7
10	10,0
20	1,0
50	$1 \cdot 10^{-3}$
100	$1 \cdot 10^{-8}$
1000	$1 \cdot 10^{-98}$

It must be realized, that the above listed values result from several properties of a fiber, that is:

1. transparency of a fiber material,
2. structure of a fiber,

3. structural defects of a fiber :
   a) connected with the nature of the material,
   b) resulting from the production process.

A lot of those defects are nowadays eliminated to a large extent what enables production of light cables with attenuation below 1 dB/km.

Material transparency depends mainly on its chemical composition. Till now, melted quartz /SiO_2 /, so called silica glass, shows the lowest attenuation value.

Manufacturing of such a fiber allows to build light cables for numerous applications, whose number increases all the time.

The basic interest, however, focuses on application of light cables in telecommunication. Significant merrits should be expected with transmission of sound and visual signals / a diagram of such a device is presented in Fig.1.3.

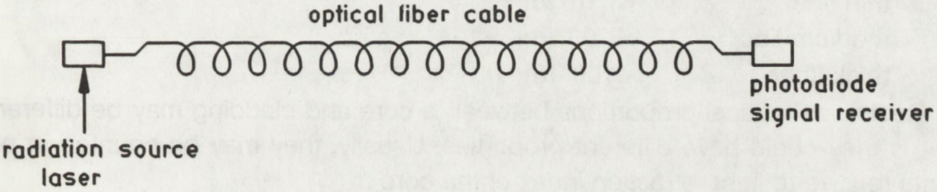


Fig.1.3. General diagram of an optical fiber line.

In 1976, Bell Company proved that experimental telephone wire of 10,9 km length and 10 mm thickness / with 18 connections on the route/ and composed of 114 fibers, working with 44,7 Mbit/s could transmit 46 thousand telephone calls simultaneously.

Taking into account small dimensions, lightness, insensitiveness to electromagnetic and nuclear interferences as well as lack of listening-in possibilities optical fibers are continuously enlarging their application possibilities.

Optical fiber cables are already better than traditional transmission systems made of concentric metal cables, especially in applications requiring high technical parameters. For example, the presently used concentric cable had 30 dB/km losses in transmission system of 100Mbit/s speed, whereas a gradient optical fiber has only 2 dB/km loss. Low level of optical fiber losses at wider transmission bands as well as fiber lightness make them an ideal material for communication connections. Lower attenuation of a signal allows to transmit it to a further distance without the necessity of its processing. Light cables surpass conventional systems mainly because of its smaller weight /99 % smaller at the same effectivness/.

Material properties, structure and texture of optical fibers for light cables are very significant as far as their quality is concerned. Glass materials for optical fiber production should be extremly pure and uniform. An optical fiber should have an appropriate structure and texture.

1.3. Structural and textural phenomena in light cables

The basic role in making a light transmitting fiber effective play such parameters as fiber core thickness, quality of boundary layer in clad-core system as well as fibers arrangement in a cable.

This a notion of a structure which could be:

thin-fiber $\phi < 10\ \mu m$
medium-fiber $\phi\ 10 \div 100\ \mu m$
thick-fiber $\phi > 100\ \mu m$

Reciprocal optical proportions between a core and cladding may be different, that is they could have different proporties. Usually, they may be counted in per cents relative to light refraction index of the core :

$$\Delta = \left(\frac{n_1 - n_2}{n_1}\right) \cdot 100\ \%$$

According to the values received from the formula, we can distinguish the following kinds of structure:

weakcontrast structure $\Delta < 1\ \%$
medium-contrast structure $\Delta = 1 \div 5\ \%$
contrast structure $\Delta > 5\ \%$

and we can also distinguish a fiber of gradual or gradualless fiber clad contrast. Light cables may be finally composed of smaller or bigger number of fibers. So this is single or multifiber texture.

The fibers in a cable may be located disorderly or according to a certain arrangement and particular symmetry. So we have here notion of cable texture, which may be single or multifibered, disorder or arranged. In the last case also the names of integrated or coherent bundles are used.

The above mentioned names are important not only as far as qualification is concerned, but they are also useful as every application will prefer light cables with defined structure and texture, which limit particular symmetry and effectivity of light rays guiding [1.2] /structure influence on wave signal deformation has been illustrated in Fig.1.4/.

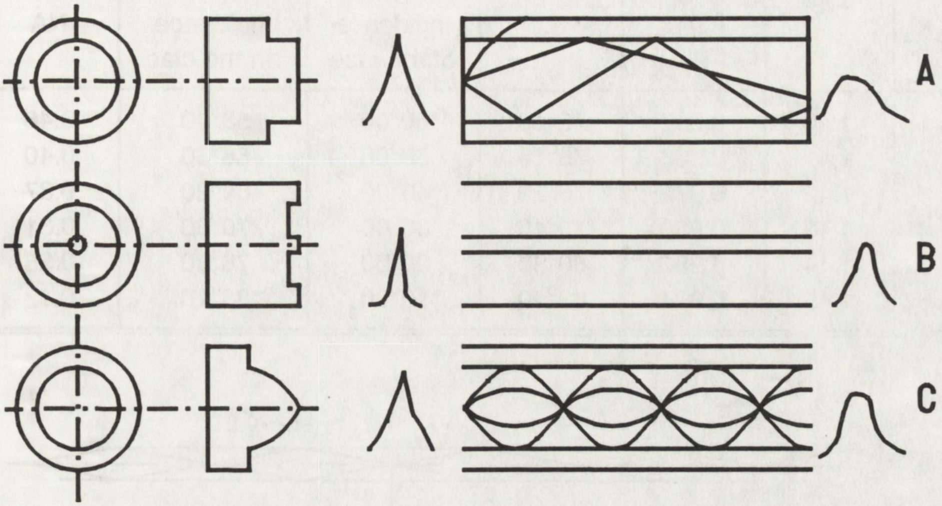


Fig.1.4. Deformation of signal moduled on a light wave running through optical fibers of different structures.

A - contrast structure fiber,
B - optically uniform optical fiber,
C - weak-contrast structure fiber.

Taking into account this criterion we can divide optical fibers into: monomode fibers, multimode fibers with a step refractive index on the core-clad boundary or multimode fibers with continuous index. Monomode fibers /Fig.1.4B/ are able to transmit optical signals with very small losses in an extremely wide transmitted band. The cheapest fiber with the step refractive index /Fig.1.4A/ contains a glass core with uniform refractive index, and the core is enveloped with cladding of lower refracting index.More expansive fiber with the continous refractive index possesses a core with such refractive index that is radially symmetrical and approximately parabolic - the biggest coefficient occurs in the core's centre and then it decreases till the coefficient equals the refractive index of core's cladding /Fig.1.4C/.

Tab.1.2. Dependence of clad refractive index change on critical angle (α_{cr}) value for silica glass fiber (n_1 = 1,460).

N	Clad n_2	n_2 / n_1	α_{cr}	Angle of incidence of the face	Angle of incidence on the clad	NA
1	1.40	0.957	73°10'	60°00'	53°40'	0.46
2	1.41	0.966	75°10'	50°00'	58°30'	0.40
3	1.42	0.972	76°20'	40°00'	64°20'	0.37
4	1.43	0.980	78°40'	30°00'	70°00'	0.31
5	1.44	0.987	80°50'	20°00'	76°30'	0.25
6	1.45	0.994	83°40'	10°00'	83°10'	0.17

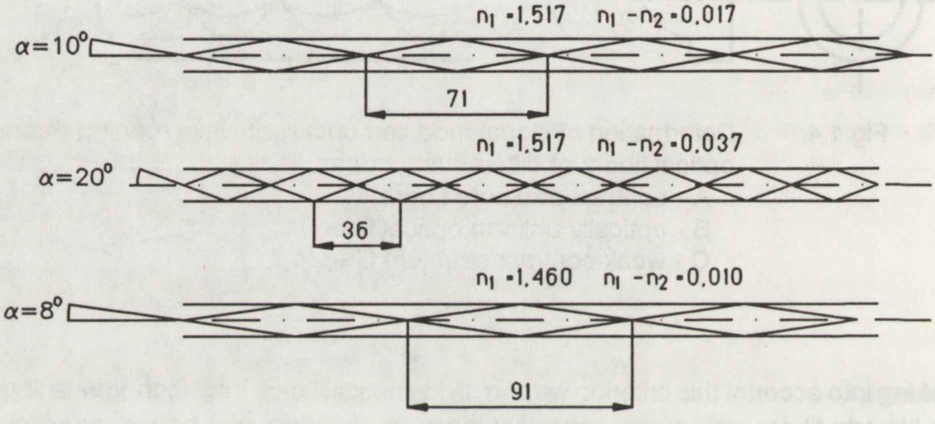


Fig.1.5. Dependence of light propagation change on n_D of core and difference of core and clad optical density.

In a fiber with the step refractive index light signal is trans- mitted by a great number of modes, each of them having a characteristic speed and propagation time. Fibers with continuous index possess a wide transmission band, resulting from the possibility of minimizing propagation delay differences of various modes.Fibers with step index may transmit data of 50 Mbit/s, whereas fibers with continuous index to 500 Mbit/s. Monomode fibers, are still more effective and may transmit data in a range bigger than several Gbit/s.

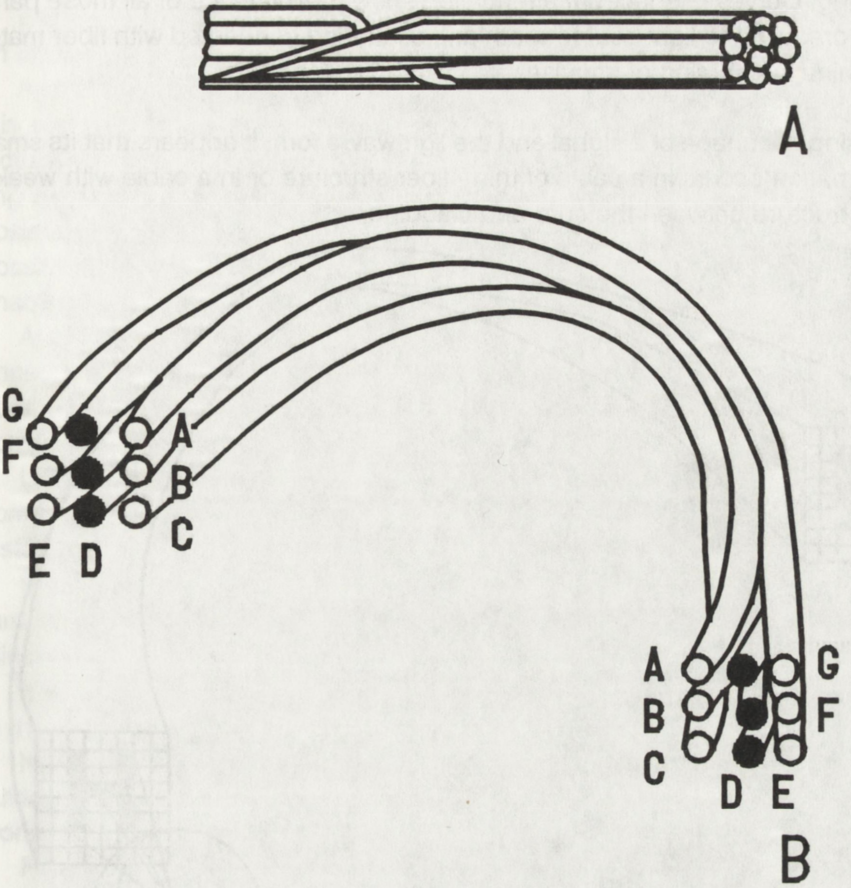


Fig.1.6. Texture of optical fiber bundle.
A - chaotic texture,
B - arranged texture.

As in electrical conductors, transmission signals properties in optical waveguides are given as attenuation dependence in frequncy function.

The above said function depends on fiber attenuation /absorption and diffusion/ and signal scattering (impulse scatter). Both parameters partially depend on the fiber materials /absorption of spectrum in the part close to the infrared is, for example, caused mainly by OH radical oscillation bands., whose second harmonic has a vibration amplitude in 0,93 μm band/. On the other hand, Rayleigh's scattering, caused by thermal fluctuation of the component's atoms, is the basic mechanism of scattering. Curves of spectrum attenuation show the influence of all those parameters. Moreover, the light source width and scattering connected with fiber material determine distribution of impulses.

Analysing the shape of a signal and the lightwavre form it appears that its smallest deformation occurs in a cable of thin - fiber structure or in a cable with weak - contrast structure between the core and cladding.

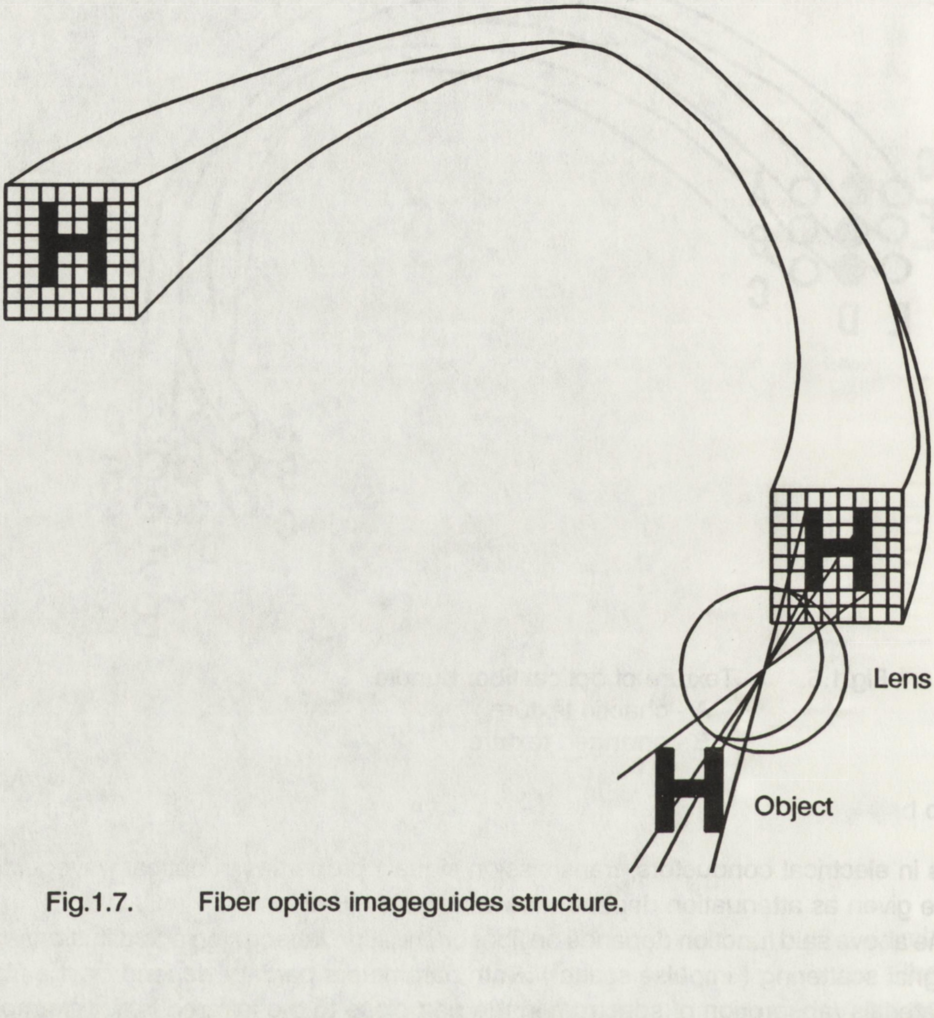


Fig.1.7. Fiber optics imageguides structure.

Those light cables which are to transmit relatively much light on a short way should possess medium or thick fiber structure and should be made of the material with relatively big refractive index. By these means, the acceptance angle of incoming rays which may penetrate into fiber circular surface, is increased.

It should be also noticed that if a bundle of light waveguides serves to transmit an image, it should possess the arranged texture /Fig.1.7./

Application of light waveguides in medicine also create great possibilities. Using this technique we can penetrate inside human body receiving coloured, visible picture of every detail. The appropriate equipment enables sampling or even operating without the necessity of surgical intervention. It is extremely important in diagnosis and therapy f.ex. in the early stage of tumour [1.3] Finally, there are also many possibilities when applying light cables in mechanical vehicles signalization, what enables to increase driving safety.

Application range of light waveguides is presented schematicaly in Fig.1.8a,b,c. Those are the examples of applications introducd by Nippon [2.4].Tab.1.3 illustrates fiber optics application range divided into industrial branches. It also presents components of devices required to implement fiber optics based systems.

Light cables may be also used to signalize functioning of navigation lights or some other devices in airplanes. General Motors applied bundles of fiber optics instaead of conventional cables in order to create vehicle signals control.

Such a system, built into a steering wheel column may, for example, signalize turn of a car, performance of stop lights, switch - on of head lights, functioning of blinkers and the like.

It is expected that after an experimental stage, a great light cables market opens in the world [2.5].

In 1976 an experimental light cable sonar connection was applied on a board of "Little Rock" submarine. The telephone system based on light-cables has been working on that ship since 1973.

Fiber optics telecommunication system consists of elementary segments of several to several dozen km length. An element is made of an optical transmitter with a laser or an electroluminescence diode, optical fiber and receiver with a photodiode. In modern fiber optics telecommunication systems regeneration of the signal, attenuated and deformed by an optical fiber, is performed with help of electrocity. Weak and deformed electric signal, received from the photodiode, is intensified, its shape regenerates, and then it is again changed into optical signal, which is "pumped" into optical fiber. The described device is not uniform; the line is of optical nature, while the regenerator of electronic nature. Therefore, it is a significant barrier for potencial possibilities of the whole system. Integrated optics facilitates the solution of this problem. Instead of changing the electric signal, an appropriate integrated optics system - impulse laser - amplifies optical signal and immediately improves its profile. If we notice that such a laser possess a shape of narrow strip with the width approximately equal to diameter of optical fiber core, we can clearly see how beneficial it is to join integrated optics and fiber optics technique.

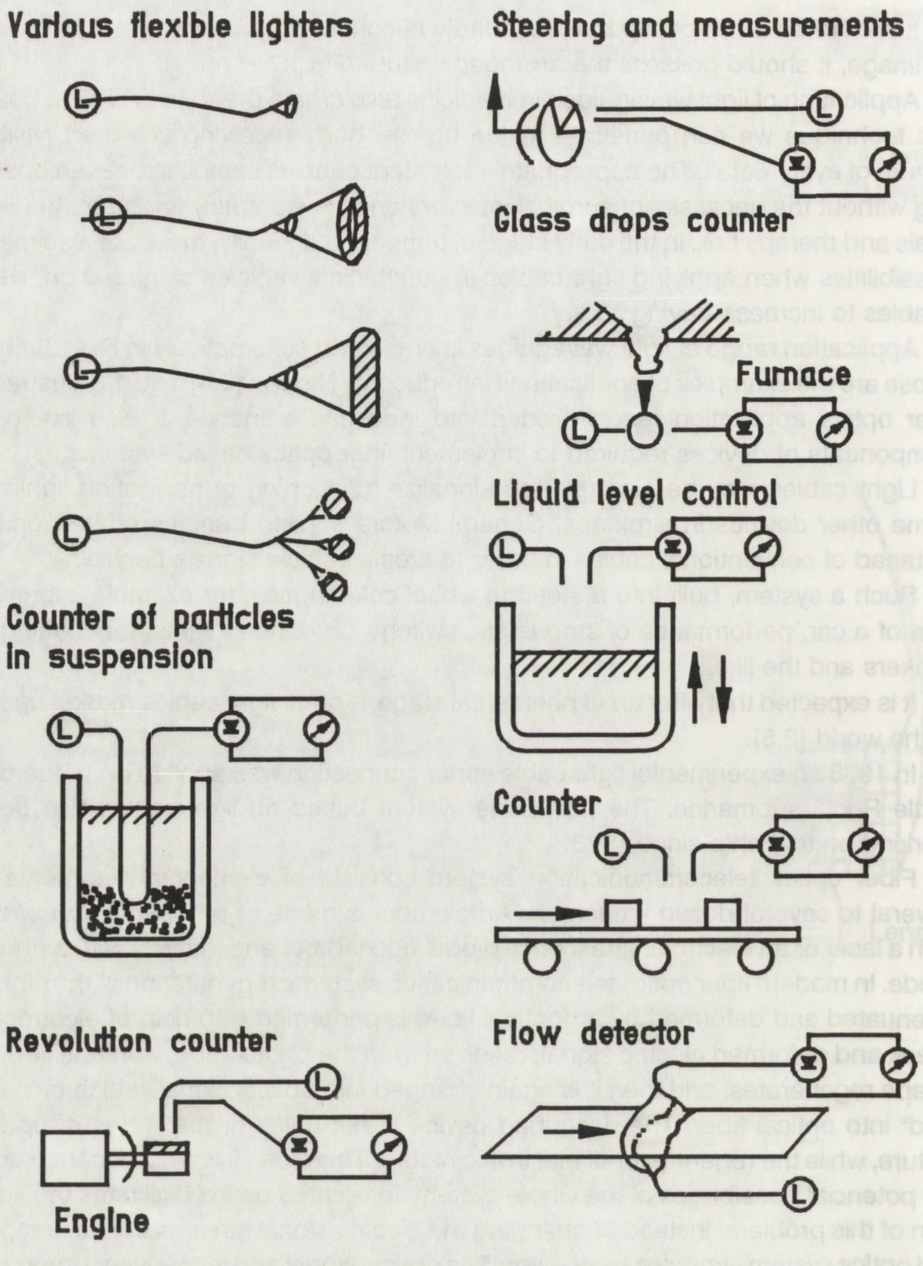


Fig.1.8a. Application range of light waveguides.

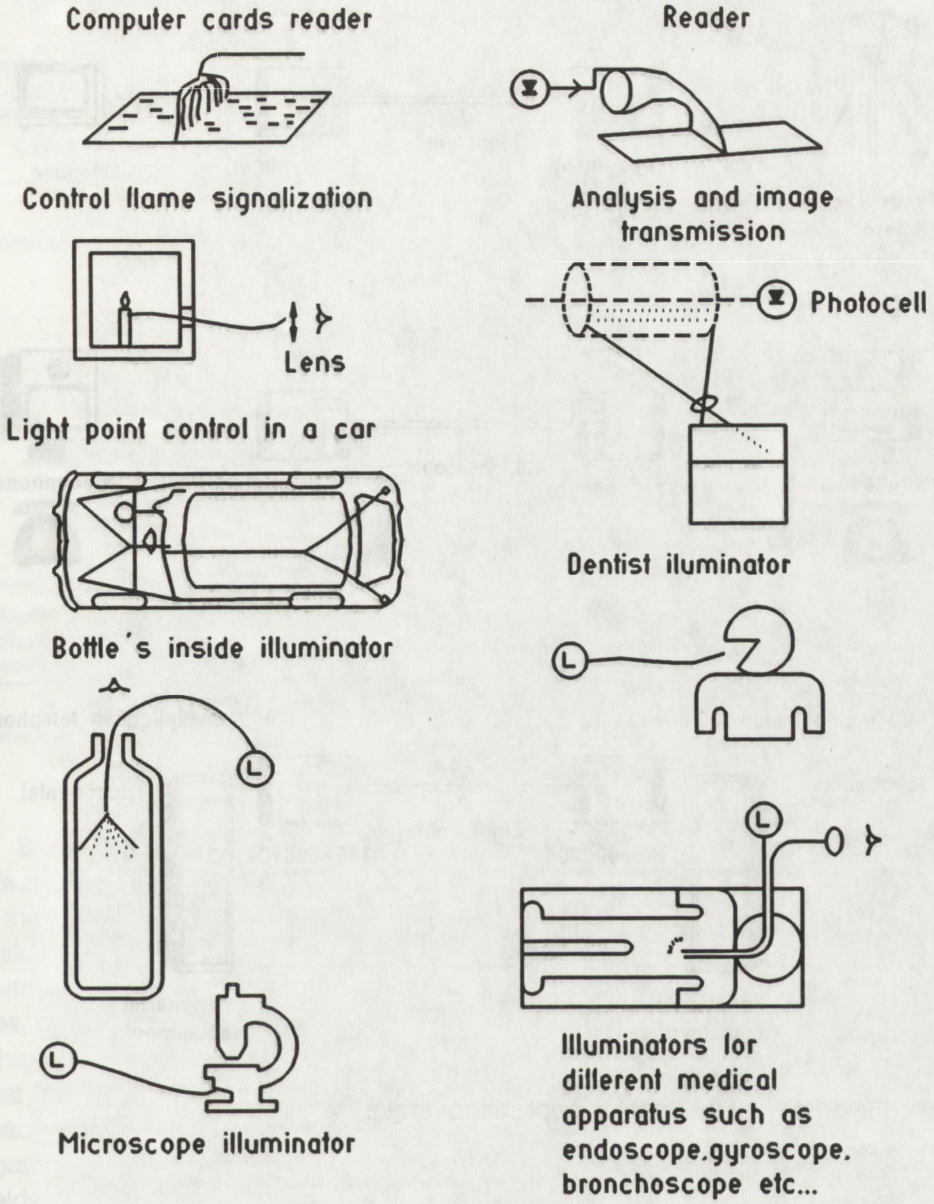


Fig.1.8b. Light cables application range.

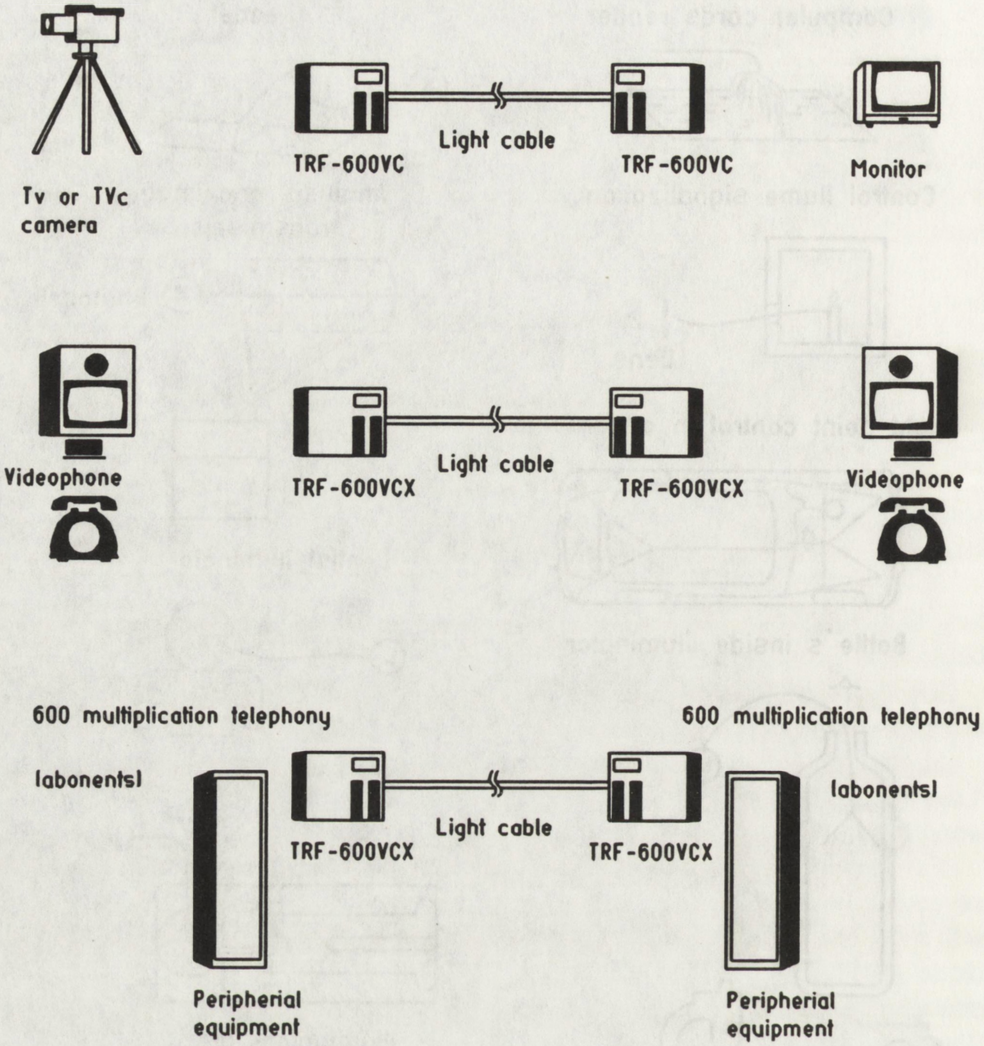
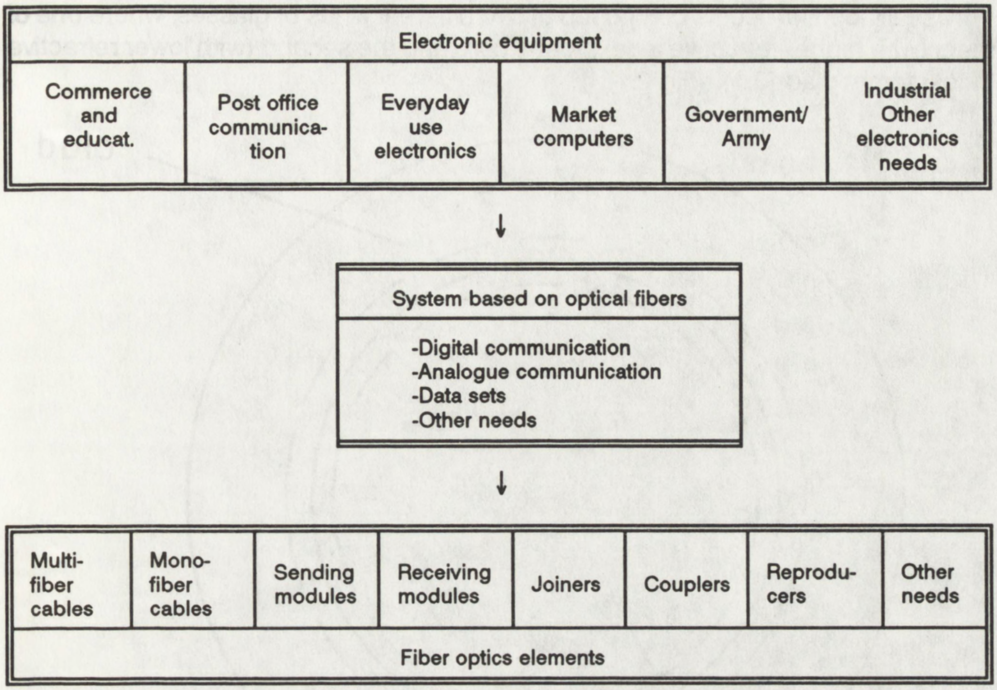


Fig.1.8c. Light cables application range.

Tab.1.3. Fiber optics communication hierarchy



Such cooperation, we think, may be successfully applied in radiestesy. Dowsers are able to find underflows, electrically active mineral deposits, metal objects burried in the ground etc. Fiber-optics cooperating with integrated optics could discover gas leakages from pipelines, test extremely small changes of electromagnetic fields distribution, for example fields of living organisms, serve as very sensitive hydrophones, seismographs etc. In such apparatus optical fibers could serve as sensors, whereas integrated optics systems could play a role of unusual quality amplifiers, that means amplifiers with very low internal noises and with enormous amplifying, reaching hundred billions. With help of such sensitive apparatus, we could investigate such processes as electromagnetic "language" of plants, electromagnetic fields emitted by various organ of human body, for example brain.

Three new optical techniques that is fiber optics, integrated optics and optoelectronics are complementary to one another and in fact together with their development for the first time, there is an opportunity to build optical generation mathematical machines, so complicated, that they may be, could be able to compete with human brain.

2. Material problems

Usually optical fiber is composed of two different kinds of glasses, where one of them (with higher refractive index) forms core and the second (with lower refractive index) forms clad [2.1]. (Fig 2.1).

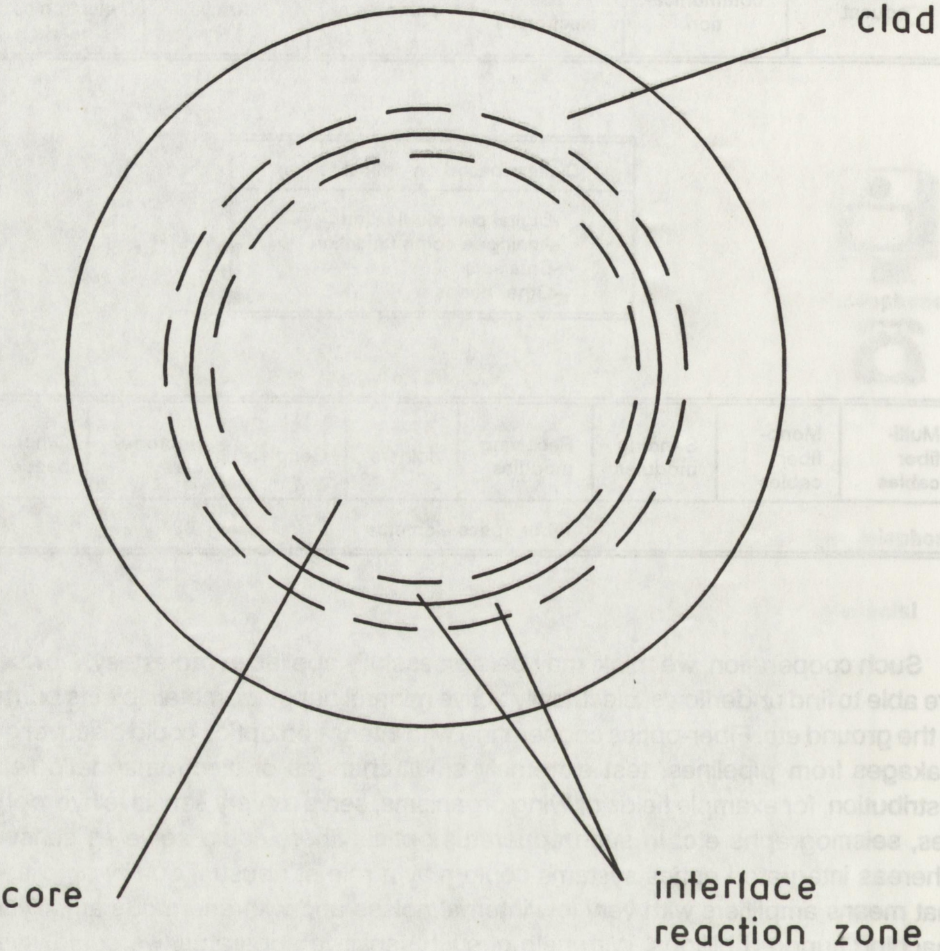


Fig.2.1. Cross section of optical fiber.

One of the simple and often used method for obtaining optical fibers, is rod-in-tube technique (Fig 2.2).

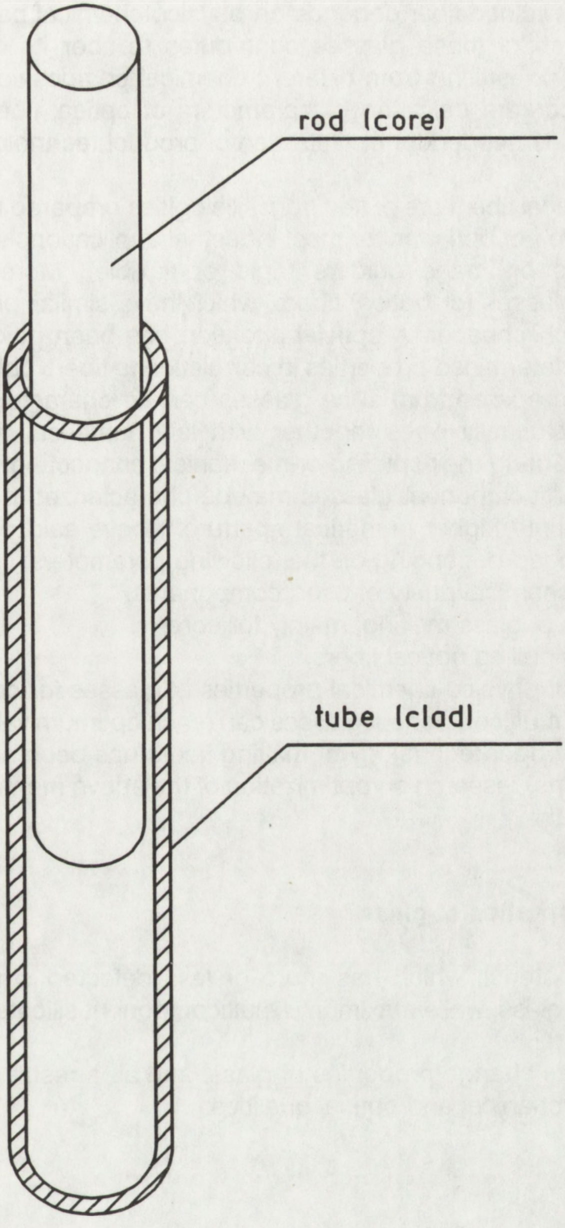


Fig.2.2. Assembly for rod-in-tube technique.

Properties of obtained fiber depends on physico-chemical parameters of used glasses [2.2]. Each of these glasses contributes to fiber its own positive and negative character, resulting from different chemical composition [2.3]. However even the most accurate definition of parameters of optical fiber do not give all information, which is needed for optimization of product technology.

Most of the optical fibers are pulled from silica glass prepared by CVD or MCVD, but those fibers are not optimum for most industrial applications such as computer interlinks, robotics or image guiders (rigid or flexible). More usable are the multicomponent glasses for optical fibers, which have similar properties to silica glass but are much cheaper. A special attention has been paid to materials for starting rods and determined properties in correlation to fibers obtained from them.

Optical fibers prepared from silica glasses can be characterized by very low attenuation, but it usually goes together with low numerical aperture, causing several problems during their splicing or mechanical connecting. Whereas, optical fibers made of multicomponent glasses may be characterized by low attenuation and at the same time higher numerical aperture. Above said properties can be considerably changed depending on the following parameters:

- kind and chemical purity of used components,
- conditions of glass melting, mainly for core,
- method of pulling optical fibers,
- selection of physico-chemical properties of glasses for core and clad.

Optical fibers from multicomponent glasses can reach optimum value of parameters on condition that proper technology of making fibers has been obtained.

For such reasons, research on optimization of the above mentioned technology is extremly important.

2.1. Important properties of glass

Glass is the material, which has more or less defected structure. Minimum defected is quartz glass, while maximum - multicomponent silicate glass. (Fig. 2.3 - 2.5.)

All these defects change properties of glass, and as a result also fiber, mainly in the range of mechanical and optical qualities.

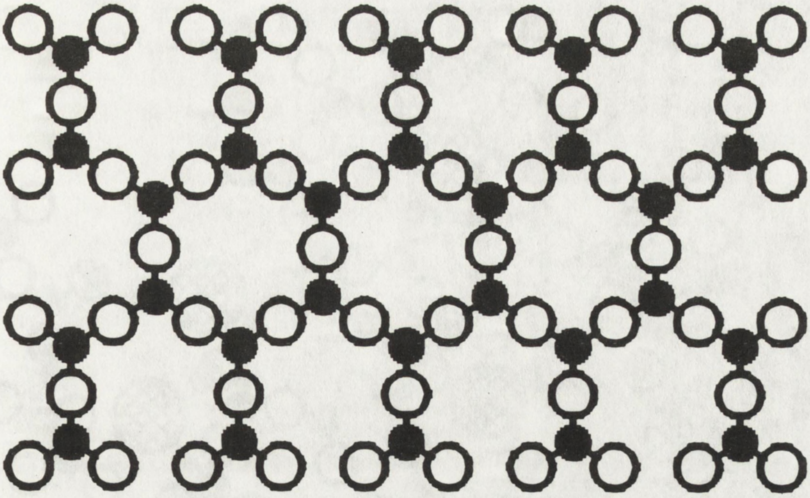


Fig.2.3. Structure of quartz.

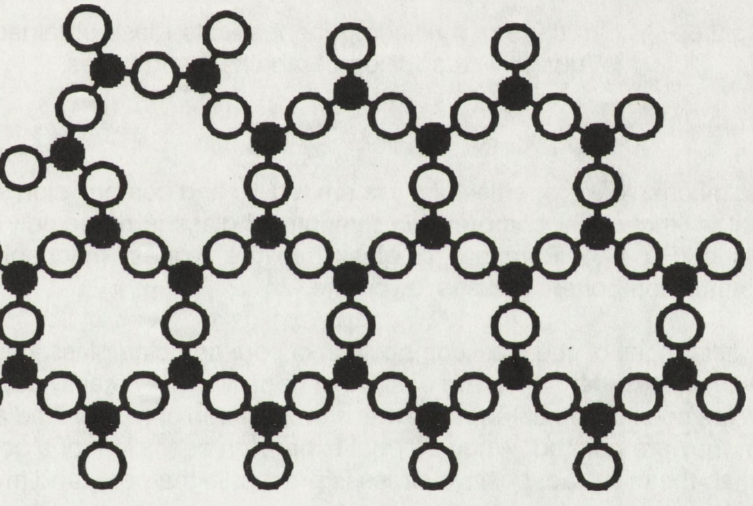


Fig.2.4. Structure of silica glass obtained by melting of quartz.

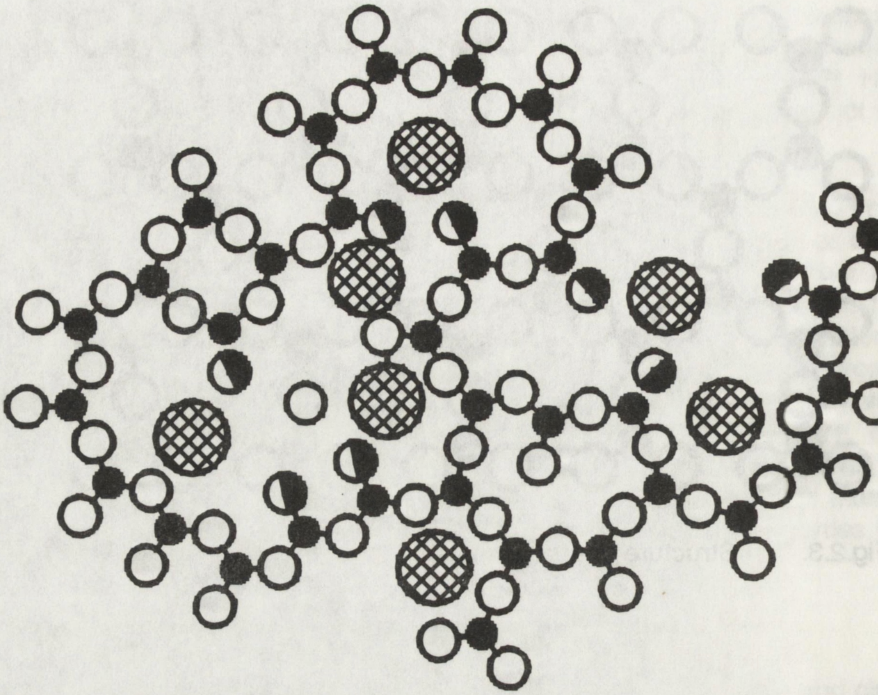


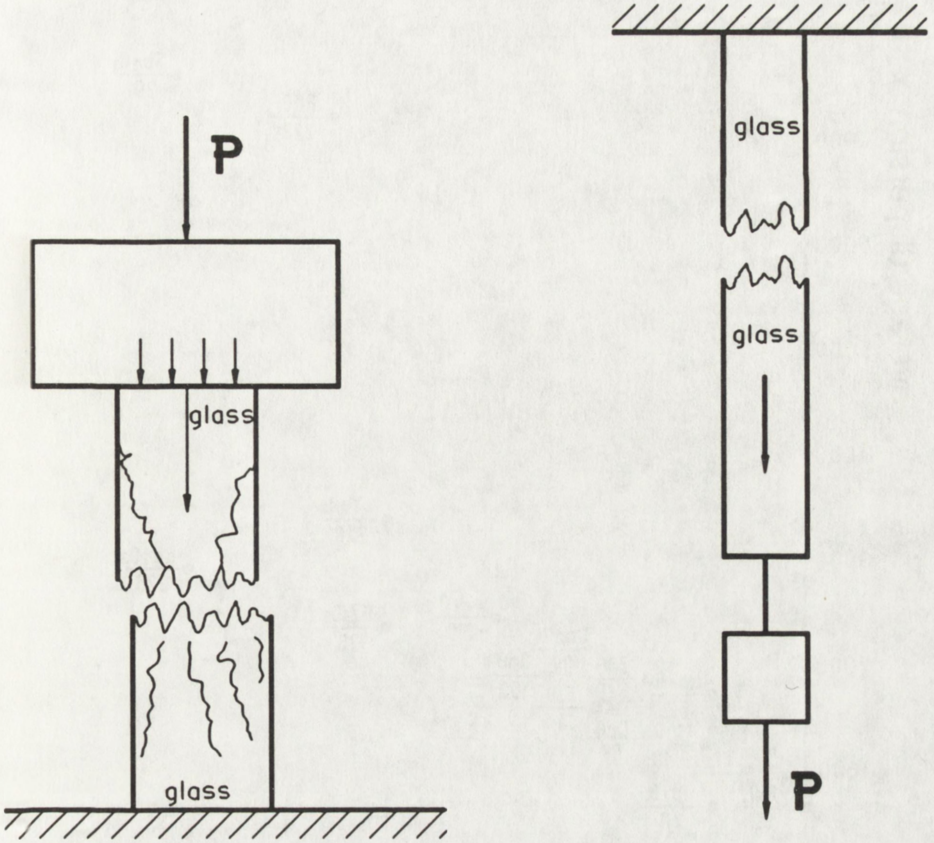
Fig.2.5. Structure of multicomponent silicate glass obtained by melting of quartz with addition of modifiers and fluxes.

Basic mechanical properties of glass are tensile and compression strength. It is important to know, that compression strength of glass is repeatedly higher than tensile one (Fig 2.6). Pure quartz glass has the highest machanical strength whereas multicomponent glasses lower one.

The differences of chemical composition of core and clad glass, causes several stresses in optical fiber, which are positive or negative. They mainly depend on how different are coefficients of thermal expansion between core and clad and in which direction they are pointed. When thermal expansion coefficient of a core (alpha) is higher than the of a clad, positive stress is present in the core, and inversely. This situation is the reason for deformation of fiber, and even causes microcracking.

Sometimes too big differences of alphas between the core and the clad causes also birefringence which generates deformation of light waves.

For purposes of accurate knowledge of above said effects, influence of quality and quantity of individual chemical components on variation of some properties of



compression strength of glass

tensile strength of glass

Fig.2.6. Compression and tensile strength of glass.

glass and optical fiber has been investigated.

The data have been obtained by investigation of influence on variation of the following glass chemical composition (% mole): SiO_2 -68.5; B_2O_3 -15.7; K_2O-10.2. Each time 5.6% mole of one of the following oxides: ZrO_2, BaO, PbO, La_2O_3, Ta_2O_5, GeO_2, Bi_2O_3 has been added to the above said composition. The oxides have been compared to average dispersions (Fig.2.7).

The mixture of components have been homogenized, and then melted in a platinum crucible in an electric furnace. After the process was completed, the glass

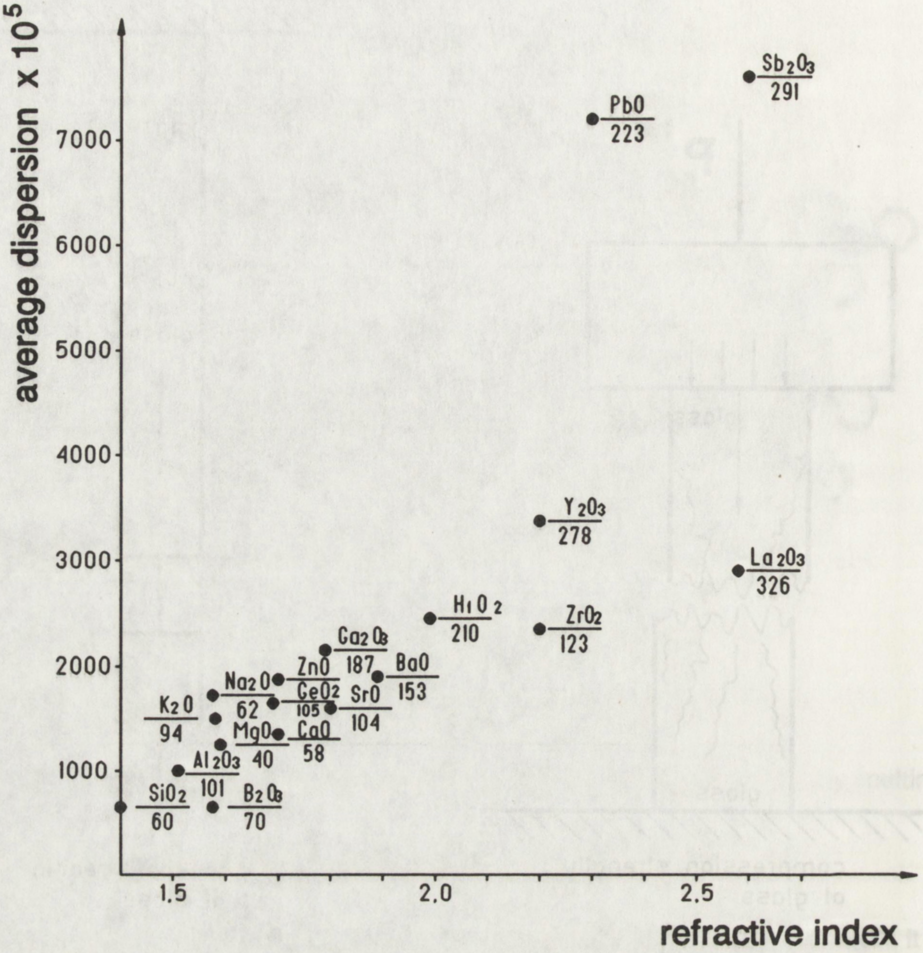


Fig.2.7. Influence of added oxide on refractive index and average dispersion of glass.

was casted into the graphite mould and annealed. Large pieces of the obtained glass were used to prepare sets of samples for tests purposes.

For all the obtained glasses the following examinations have been performed:

- measurement of refractive index,
- measurement of coefficient of thermal expansion,
- measurement of characteristic thermal points,
- transmission of light in the ultraviolet and visible range.

- *refractive index*

Refractive index was measured by ABBE refractometer. Obtained results are shown in Fig.2.8. As we see GeO_2 has the minimum influence on change of refractive index, while oxides of tantalum and bismuth - the maximum.

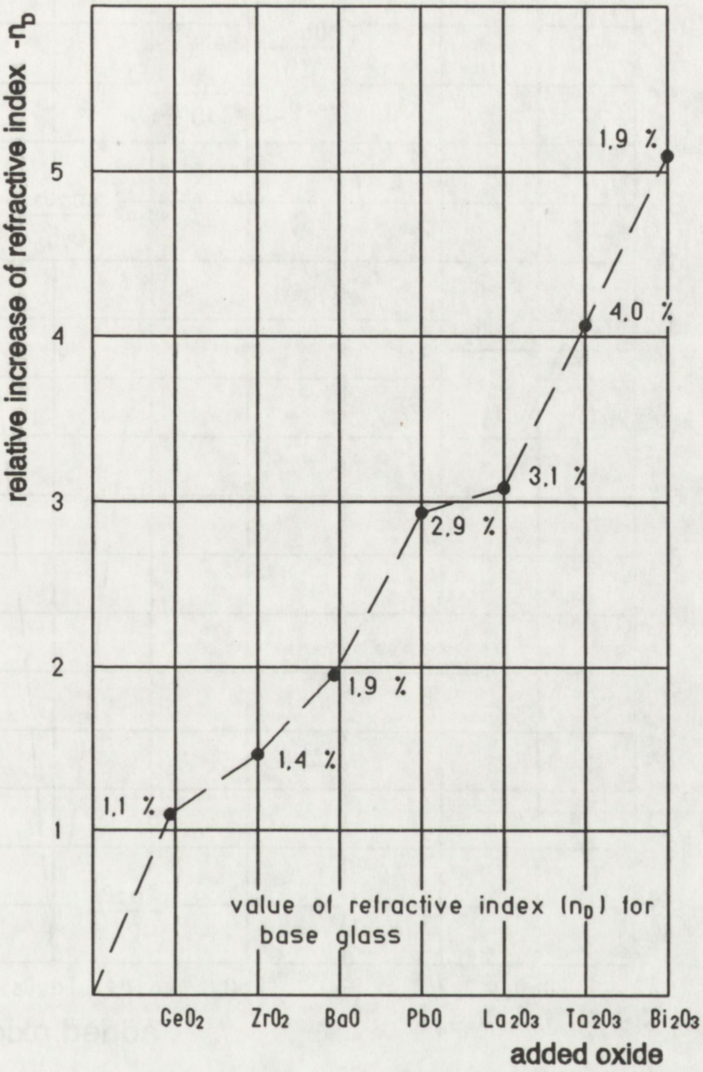


Fig.2.8. Modification of refractive index depending on added oxide.

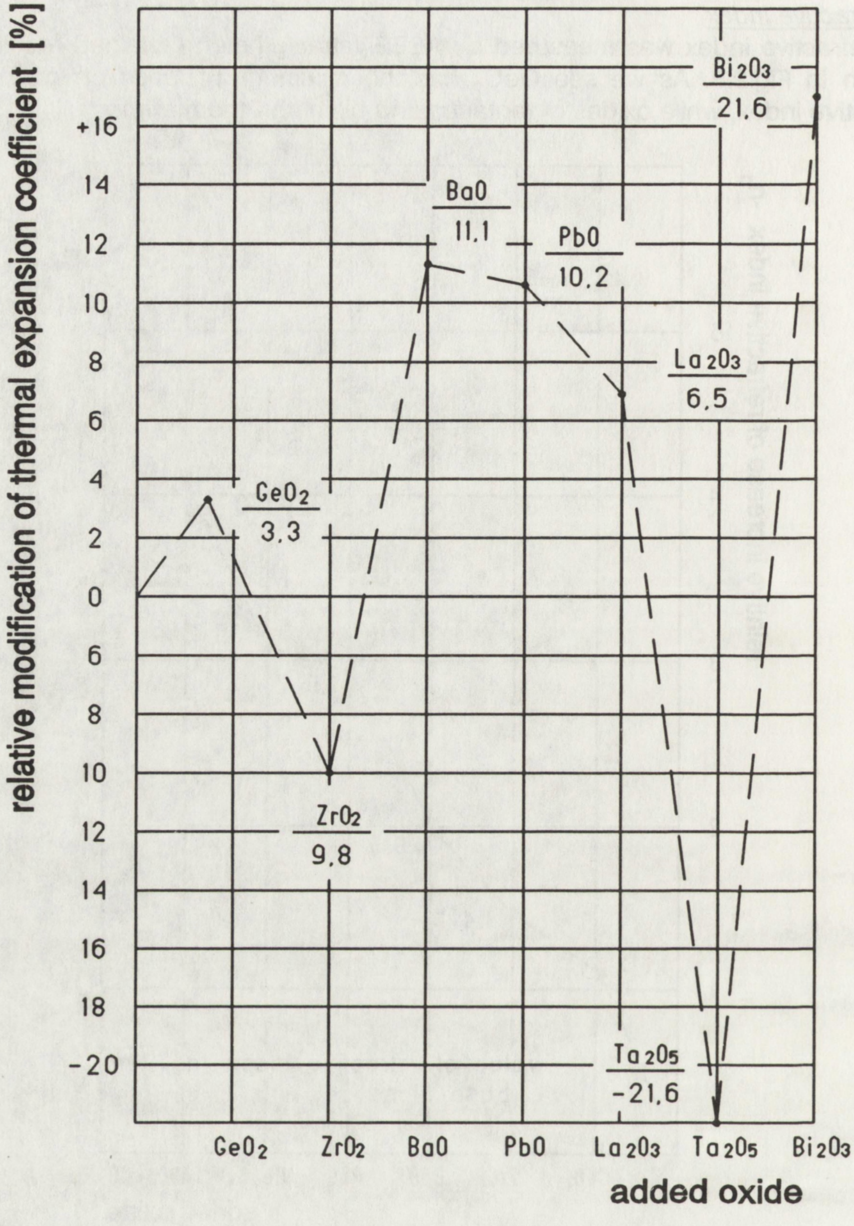


Fig.2.9. Modification of thermal expansion coefficient depending on added oxide.

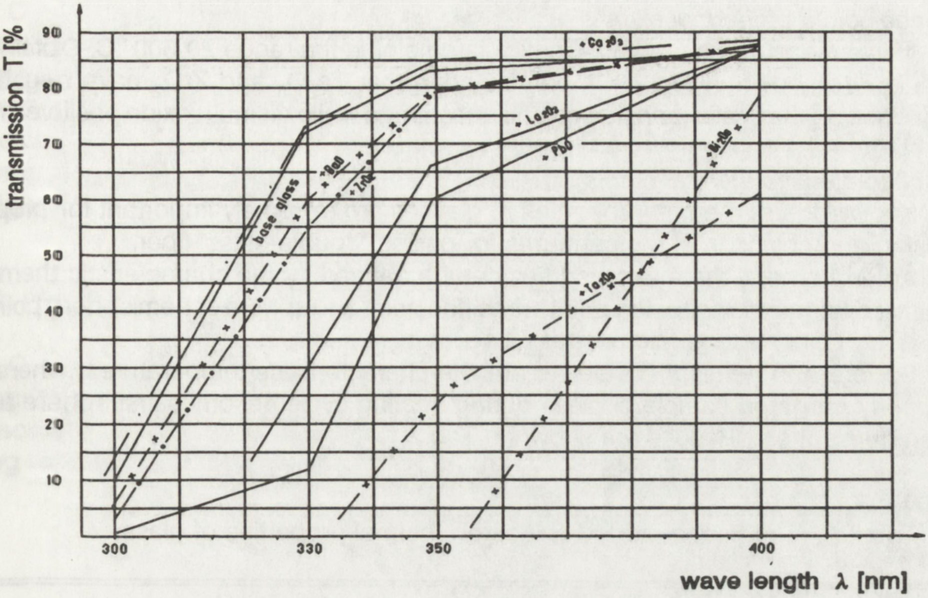


Fig.2.10. Modification of transmission depending on wavelength for various oxides.

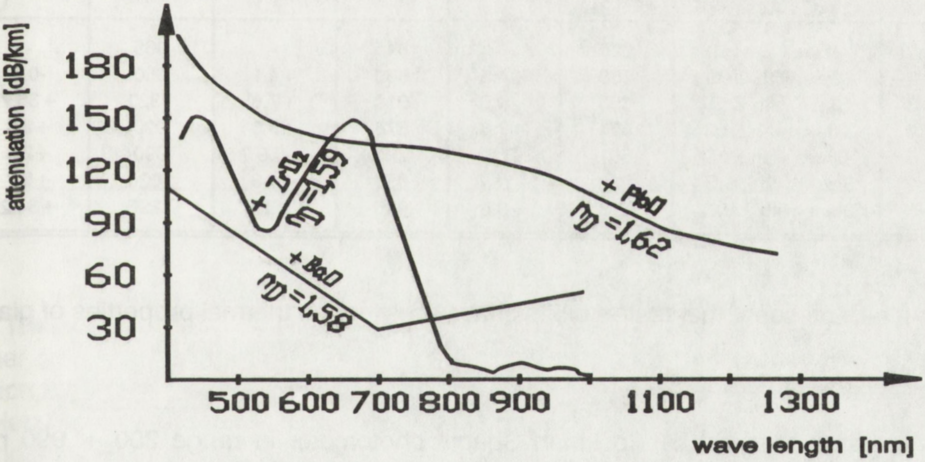


Fig.2.11. Influence of oxide added to core glass on attenuation of optical fiber.

- *coefficient of thermal expansion*

It was measured by Rigaku-Denki dilatometer in the range 20-300 °C. Obtained results are shown in Fig.2.9. It can be seen that Ta_2O_5 and ZrO_2 have negative influence on thermal expansion coefficient change while bismuth oxide positive one.

- *characteristic thermal points*

Knowledge of thermal properties of glasses are extremely important for proper design and selection of temperatures for pulling "double-glass" fiber.

Among others, thermal properties can be defined by the characteristic thermal points: dilatometric softening point, transition point and sphere or hemisphere points taken by Leitz Heating Microscope [2.4].

Sphere and hemisphere points are the characteristics temperatures, where a properly prepared sample of glass during heating cycle becomes first sphere and then hemisphere. Results are shown in Tab.2.1.

Tab.2.1. Effect of added oxides on thermal properties of glass.

No	Properties	Dilatometric Softening Point		Temperature of Sphere		Temperature of Hemisphere	
	Sample characteristics	Indicated Temp. in °C	% to Base Glass	Indicated Temp. in °C	% to Base Glass	Indicated Temp. in °C	% to Base Glass
1	Base Glass	625	-	845	-	965	-
2	Glass with GeO_2	653	+4.5	880	+4.1	960	-0.5
3	Glass with ZrO_2	650	+4.0	910	+7.6	1320	+36.7
4	Glass with BaO	674	+7.8	875	+3.5	990	+2.6
5	Glass with PbO	601	-3.8	795	-5.9	990	+2.6
6	Glass with La_2O_3	730	+16.8	860	+1.8	1020	+5.7
7	Glass with Ta_2O_5	675	+8.0	945	+11.8	1295	+34.2

It can be seen, that tested oxides have an effect on thermal properties of glass.

- *tramsmission of light*

It was measured by Beckman Spectrophotometer in range 300 ÷ 990 nm. Dimensions of samples: 10 x 10 x 25 mm. It was found that curves of transmission are the most important in the range 300 ÷ 400 nm. Over this range, curves for all glasses are similar. Results are shown in Fig.2.10. It was noticed that the most efficient transmission can be observed for the base glass with addition of GeO_2, BaO and ZrO_2. The rest of oxides clearly impair transmission with different intensity.

Correlations between attenuation of optical fiber and stresses inside the core-clad assembly have also been observed. It was also found, that attenuation strongly depends on kind of oxide added to the base glass. Fig.2.11 shows attenuation curves of optical fibers, where a core was prepared from multicomponent glass with addition of Zr, Ba or Pb oxides. Above fibers were pulled down from glasses with similar contents of impurities and have been coated during process by silicon resin Sylgard 182.

2.2. Dispersion

One of the basic parameter limiting properties of optical fibers, both from silica or multicomponent glasses, is their dispersion. Fig.2.12. represents classification of absorption phenoma, while Fig.2.13 illustrates dependences of different glass making oxides on average dispersion.

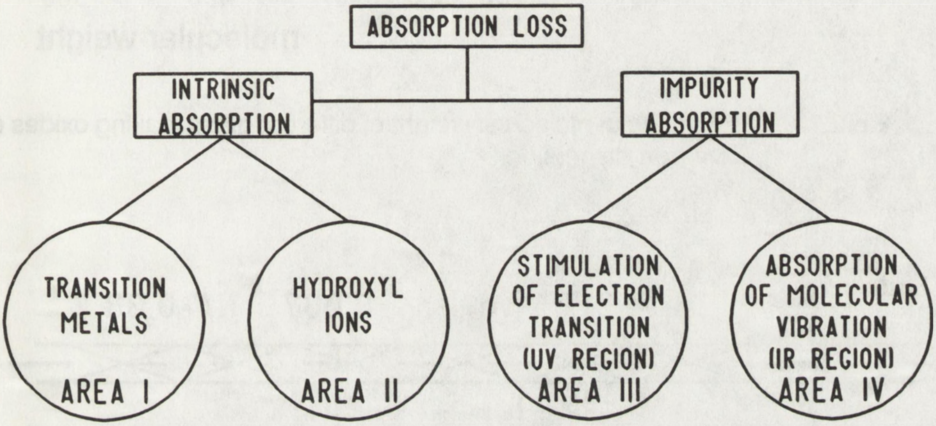


Fig.2.12. Different kinds of absorption effects in glasses and optical fibers.

The lowest dispersion can occur in borosilicate glasses, while glasses with some other oxides have higher dispersion. We can observe two series of metal oxides, which fulfill a principle of proportional increase of average dispersion together with molecular weight. First of these series starts from SiO_2 to Ta_2O_5, whereas the second from BeO until PbO. Among all those oxides, widely used in glass technology, only TiO_2 does not stick to the above defined relationship.

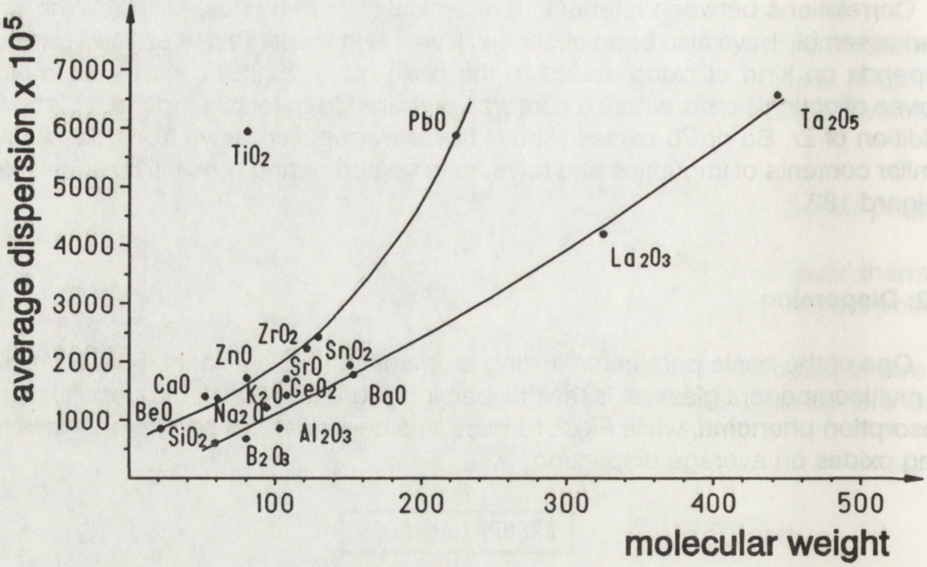


Fig.2.13. Influence of molecular weight of different glass making oxides on average dispersion.

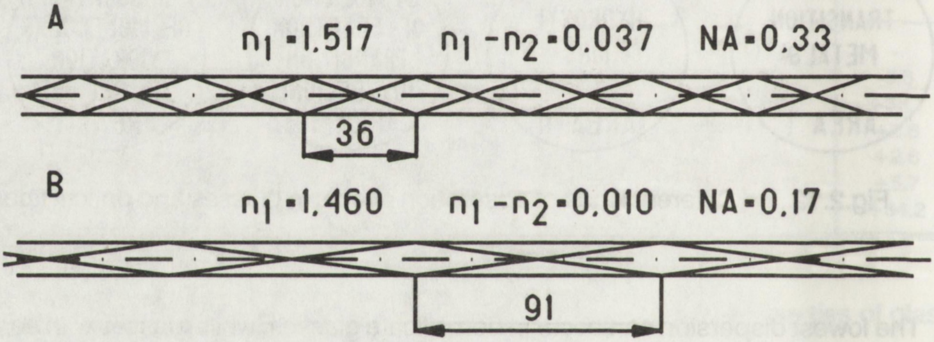


Fig.2.14. Influence of refractive indices on different optical paths and numerical aperture.

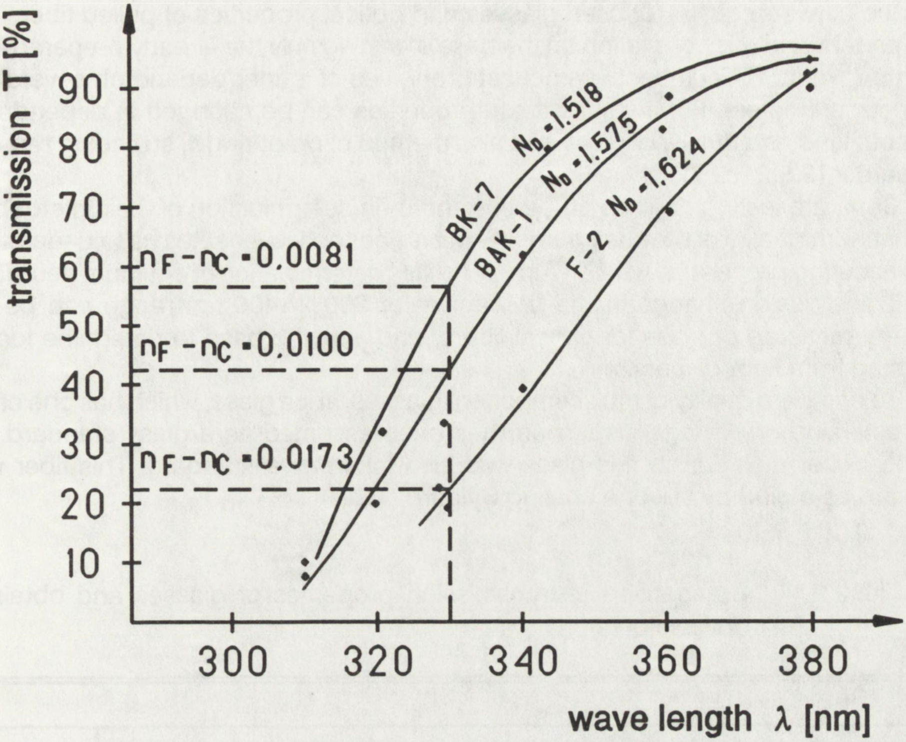


Fig.2.15. Correlation between average dispersion, transmission and refractive index in core glasses for optical fibers.

Optical fibers with higher numerical aperture have a core made of high refractive index glass. Moreover in these fibers a light ray path becomes longer causing higher fiber attenuation. Fig.2.14 illustrates two light ray paths of optical fibers with different numerical aperture. Some glasses with different refractive index but the same impurity level have been investigated. They have also had different average dispersions. It was found out, that these glasses have also had different values of transmission in UV region. These data are shown in Fig.2.15. Thus, it has been stated that transmission of glass in the UV region (300 ÷ 350 nm) is proportional to average dispersion value and that the data may be the base of evaluating attenuation values of fibers made of such glass.

Trials have been made to prove above said thesis by testing properties of glasses and of fibers prepared for them. From methodological point of view such method has several advantages. First of all allows us to understand better interdependence between quality of used glasses and optical properties of pulled fiber. To understand this correlation on the base of testing only the already prepared fiber is much more difficult because optical properties of a fiber depend on several different parameters. For instance these properties can be changed in dependence to both kind and quality of glass and also method of preparing it, so finding reasons is harder.[2.5;2.6;2.7]

Separate testing of glass properties and then determination of their interdependence with quality of the shelf product, that is fiber optics, enables us to understand the occuring processes, what, in turn, simplifies determination of optimum decisions.

Transmission change in the UV region for 200 ÷ 400 nm range can be the quality measure of glass for optical fibers, and also the base to determine losses coming from light dispersion.

To compare quality of multicomponent glasses, silica glass, which has one of the lowest value of average dispersion, has been assumed as a glass standard. An optical fiber pulled from this glass was also taken as a standard. This fiber was coated as a clad by silicone coating Sylgard 182.

Tab.2.2. Comparison of transmission properties of glasses and obtained optical fibers.

Obtained data						
Determined Parameter	Silica glass	Glass X	Glass X + GeO_2	Glass X + ZrO_2	Glass X + BaO	Glass X + PbO
λ (nm)	Transmission T (d = 40 mm) (%)					
300	82	10	14	3	6	1
330	84	73	74	55	62	12
350	85	85	85	80	80	60
370	85	87	87	83	84	70
400	86	88	88	87	87	87
Chemical composition	Contents in ppm					
Fe	5	40	50	40	45	40
Refractive Index n_D for λ = 560 nm						
-	1.460	1.5048	1.5157	1.5209	1.5290	1.5440
Attenuation (in dB/km) of optical fibers for λ = 650 nm						
-	100	200	210	240	220	340
Numerical Aperture NA	0.3	0.47	0.49	0.52	0.54	0.58

The following composition of the base multicomponent glass has been chosen: SiO_2 - 68.5% molar, B_2O_3 - 15.7% molar, K_2O - 10.2% molar. Mixture of raw materials has been melted in a platinum crucible in an electric resistance furnace, then glass has been poured into the graphite mould and annealed. A received glass block has been divided into two pieces. One of them has been used to prepare test samples for optical properties measurements (including transmission) and the other to prepare a "preform" (by grinding and polishing) for optical fiber pulling.

Simultaneously, for comparison reasons, the authors have melted several glasses, each time enriching base glass composition (marked "X") with 5,6% molar of ZrO_2, BaO, PbO or GeO_2. These glasses, after melting have been also optically tested and preforms for pulling fibers have been machined every time too. Also the clad of pulled fibers were silicone coating Sylgard 182. Results are shown in Tab.2.2.

CONCLUSIONS

1. Values of glasses transmission and also values of optical fibers obtained from these glasses, are for UV region proportional to average dispersion (Fig.2.16).

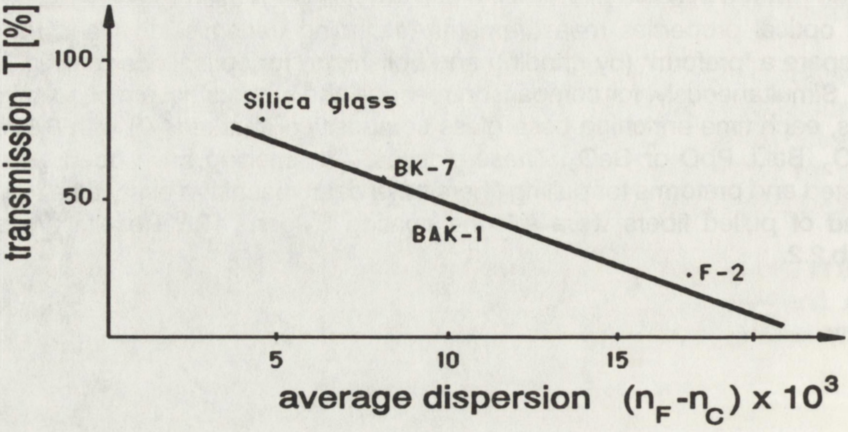


Fig.2.16. Correlation between dispersion and transmission for $\lambda = 330$nm.

2. Setting-up Fig.2.13 of interdependences between oxides molecular weights and average dispersion is useful for forecast of optical properties of glasses and optical fibers obtained from them.
Tab.2.1., shows us that the best properties of optical fibers can be reached by using the glasses with addition of BaO. Glasses with addition of ZrO_2 are also interesting and fibers pulled from glasses with addition of PbO have significantly worse properties.
3. The performed investigations have just signalled possibilities of optimizing properties of optical fibers made of materials with high contamination degree. Carry on of investigation of optical fibers properties, which are obtained from different kind of preforms (i.e rod-in-tube technique) and from less contamined materials, allow us to make additional, more accurate studies on correlation between properties of bulk glass or method of obtaining preforms and optical fibers pulled from them.

3. POSSIBLE APPLICATIONS

One of the major problems connected with further development of fiber optics technology is application-oriented optimization of optical fibers, sensors and devices, cables and systems. This particular direction is stimulated largely by extending applications of optical fiber technology in highly specialized LANs working in adverse industrial environments. The quality indicator of this optimization process should include, among others the following levels: application oriented material factors, application oriented mechanical and optical structure of a fiber, and all aspects of environmental conditions - the system is designed to work in.

Here we will confine ourselves mainly to material and structural factors. In some special cases of application the predicted environmental conditions could even substantially modify the desired work characteristics of fiber optic devices like: survivability, lifetime, reliability, average time between failures, susceptibility to non-expected harmful reactions of the environment, linearity and dynamic ranges etc. The material and structure optimization of an application - oriented optical fiber enhances these characteristics in adverse environments.

We are seeking here for nonstandard special-purpose optical fibers to be applied as microdevices and sensors, that have substantially different or better characteristics than the ones made of standard avaiable telecommunication oriented CVD/VAD optical fibers in the particular application environment. The term "nonstandard" concerns here a new methodology of fiber design, new rules for material choice, and a new method of fiber pulling

3.1 Devices and sensor - new manufacturing method

Among the groups of special purpose optical fibers (mainly device and sensor oriented, definitely not designed for a long distance, low loss transmission) we are considering the following types: multicore, with shaped noncircular cores, with segmented cores, attenuation and/or dispersion tailored, ultra low or high birefringent,with direct polarizing/modulating possibilities, active amplifying, with nonhomogeneous cores and claddings; with air holes (capillaries) frozen into the fiber structure, made of highly specialized glasses - magnetostrictive, conducting or semiconducting, photochromic, piezoelectric; conductor containing fibers, heater containing fibers, etc. Among these various kinds of optical fibers we are seeking eventually the optimum candidates for system design to meet devices and sensors needs optoelectric systems working in any kind of hostile environments. Our special fibers to be applied as passive devices, active devices for signal processing and as sensors, used to be manufactured by a hybrid multistage technology mainly from multicomponent high-purity glasses. The main three stages of the technological process have included:

1) manufacturing of single-mode or multimode optical fiber core preforms of very complex refractive index profiles or of complex shape by a hybrid multicrucible technology,
2) manufacturing of optical fiber special preform (so called intermediate preform) by a multirod-in -tube collapsing process,
3) pulling process of monomode or multimode special optical fiber with the aid of classical CVD tower equipment with a graphite furnace. Thus, during the process we operate with two or even three intermediate preforms: core preform, structural preform and specialty fiber preform. The costs of such a method are high but it really gives all basic kinds of above mentioned specialty fibers of highest interest to a system designer.

We are suggesting a new technology of special purpose optical fiber pulling which is much simpler and considerably cheaper than the previous ones. No preform at all or only a single one is involved in this process. In the simplest solution of the process, the appropriate parts of the fiber are composed of separate glass rods. These homogeneous rods melting in the hot zone of a furnace are building a continuous fiber structure. Thus, very complex cross-sections of fibers are possible. The number of separate stages of the technological process is greatly reducted. Essentially we have here only one-stage process. The most complex versions of fiber assembling technology involves two-stage pulling process.It concerns monomode special purpose optical fibers. The major technological parameters of assembling process are: refractive, mechanical and thermal properties of glass rods, distribution of the rods in a fiber, assembling methodology, controlled nonsymmetricity of stress distribution.

Several kinds of special optical fibers have been used to build application oriented sensors and fiber optic devices for microoptics circuitry. Among the devices that are going to be presented we could mention the following (not all them will be described here fully):

I. Evanescent optical field sensor for measurement of optical properties of fluids and some gases. The sensor has an axial circular or square hole in the fiber and ring-like optical core. It is extremely rugged against some types of environmental influences in comparison with classical constructions of evanescent field optical fiber sensors.
II. Optical fiber double-ring-core sensor for enhanced or suppressed microbending/vibration/acoustical characteristics. The fiber in the sensor has two axial ring-like cores separated by one axial and two ring-like clad-

dings. The output of the sensor measured integrally or subtractively gives the desired sensitivity to microbending.

III. Twin and quadruple core optical fibers and sensors. Interferometric sensors that can measure simultaneously temperature and stress/vibration. They also can be highly selective, i.e. immune against one of these (or other) reactions of the environment.

IV. Matrix cored devices and sensors,

V. Highly selective, distributive, directional, single mode and multimode couplers, branchers made of multicoreoptical mosaic fibers.

Mosaic optical fibers create a totally new class of filamentary lightguides. They are assembled in a proper way of initially separate glass rods. The general idea of this assembling is presented in Fig.3.1a. The region A is a core one. The region B is a cladding one. The figure presents a cross section of an assembled preform and eventual possible shapes of simplest versions of a mosaic optical fiber. All modifications of this main idea use the same assembling technique to obtain a mosaic preform. Moreover, all modifications could be assembled from the rods (here areas A and B) of the same size (or multiplied basic size).

We will confine ourselves to the discussion of various modifications of basic assembling technique for the preform and potential properties of mosaic optical fibers. We will consider them not from technological point of view here but will debate the topologies of possible cross-sections and some consequenses of these topologies. Thus, we will not speak here of any rods or preforms but only of core-cladding and auxilliary areas, and other special regions located in a fiber cross-section. All these regions are playing a significant role in tailoring of a fiber transmission properties.

The aim of these topological considerations is to show more fully, from various sides, the curious properties of mosaic optical fibers. We will abstract here as far as possible from any technological problems. The debate will go in agreement with the structures presented in Fig.3.1.

We are building them here literally of particular topological areas in all versions of considered mosaic optical fibers. The basic topology, presented in Fig.3.1a., gives an ordinary squere core or circular core optical fiber. The simplest possible modifications of this structure allow us to create mosaic optical fibers of tailored cores, what was presented in Fig.3.1m. The examples show strip-like and squere-strip-loop-case. These are mainly sensor oriented fibers.

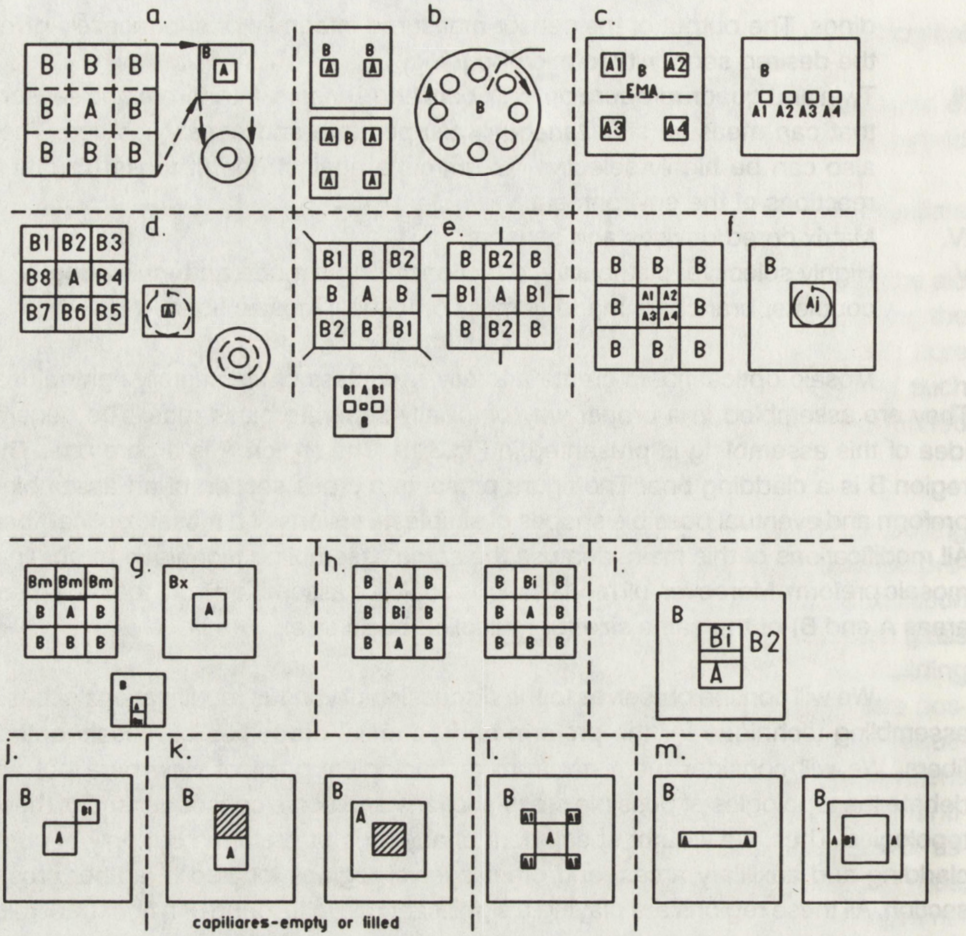


Fig.3.1. General idea of assembled mosaic optical fibers. Simplified cross-sections of core-cladding regions are presented. A-core, AA-cores of the same refractive (mechanical properties, A1,A2..Ai-hectorocore fibers, Bifibers with nonhomogeneous cladding, a) Basic solution of assembled mosaic optical fiber with a single core cladding geometry. Fibre could remain square /rectangular or be made circural.

b) Double, quadruple or multiple core mosaic optical fibers. Exact mosaic structure, analogous to the presented in Fig.3.1.a, not shown here. The cores are exactly homogeneous (all are the same) or have different dimensions.

c) heterocore mosaic opticalfibers. Circural or linear geometries of cores distribution are possible. EMA (extramular absorbtion) is applied between certain cores. Selective distribution of EMA enables directed coupling and excludding of coupling from some areas of the fiber.

d) Nonhomogeneous cladding mosaic optical fiber. The changes are in refractive, mechanical, absorbtion etc, properties of the cladding.

e) Other solutions to nonhomogeneous cladding mosaic optical fiber with stress applying areas. Directions of desired stress distributionis shown by arrows. Also classical solution of Panda type fiber is possible.

f) Nonhomogeneous core mosaic optical optical fiber. Nonhomogeneous concerns either refractive or mechanical/thermical properties of the core. The distribution and smoothness of nonhomogeneity is confined by mosaic period.

g) Mosaic optical fiber with "active" cladding responing to environmental conditions: Bm-magnetostrictive, Bph-photohromic, Bpi-piezoelectric, Bc-conducting and semiconducting and semiconducting,Bh-heating, resistive.

h) Leaking core mosaic optical fiber. The core (or multiple cores) are located outward. Also solutions are possible with refractive "opening" of the core from one side to the ambient. In this case the refractive properties of B1 are nearly the same as A.

i) and j) Mosaic optical fiber with auxilliary overflow core, single and multiple. Changing the aperture of exciting beam or level of power results in power flow to auxilliary core.

k) Mosaic optical fiber with a capillary. One element of a mosaic is lacking in the structure. Planar or axial symmetry solutions are possible.

m) Strip-like and ring-case core mosaic optical fibers as simplest modifications of the basic structure from Fig.3.1.a.

We can distinguish a few major directions of modifications of this basic mosaic topology. These are:

- shaped core optical fibers,
- tailored cladding optical fibers,
- multicore optical fibers,
- specialized material mosaic optical fibers,
- optical fibers with built-in nonguiding areas.

Figs 3.1b - 3.1c show multicore mosaic optical fibers. One of these is a homocore and the second is a heterocore fiber. The homocore fibers possess at least two different cores. The differences are in refractive properties, dimensions, and other physico-chemical properties of the core regions. Moving core regions give circular, linear or more complex distributions of the cores in the cladding area.

Internal coupling processes are essential in a fiber with more than one core. The coupling is even more complicated in a fiber with multiple cores. In order to prevent coupling between particular cores, EMA, which insulates optically some mosaic areas, is applied. For example, EMA applied between two cores in a fiber presented in Fig.3.1b. (the one of a circular geometry) gives a waveguide where the coupling is possible clockwise and anticlockwise is not. This is on condition that only this core of the fiber is excited which is adjacent to EMA layer and axial crosstalk is impossible. The crosstalk is here of the diffusion type.

Figs 3.1d, 3.1e, and 3.1g. show an optical fiber with nonhomogeneous cladding. This seems to be a totally new idea to build such fibers for device and sensing purposes. The cladding has tailored optical or other physico-chemical properties, which depend on both "r" and "ϕ" cylindrical coordinates. The nonhomogeneity can concern its refractive properties. For instance, we can place narrow refractive index trapes in the cladding. This case will be discussed in a more detailed way from the technological and application point of view. The aim of these refractive traps is to remove certain angles of propagation for higher order modes from a multimode optical fiber. This process could be total or partial.

Other aims of applying a nonhomogeneous cladding is to introduce mechanical stresses influencing the propagation of a wave in the core. All applied stresses could interact mutually, add or substract to create a desired distribution around the core. Any nonhomogeneous distribution of stress in the core results in optical birefringence and other effects like optical nonlinearity and bistability.

Various glassy materials could be applied for the cladding. The core is surrounded, in this case, by an auxiliary optical cladding to prevent too high losses of the fiber - (Fig.3.1g). Certain areas of the cladding possess magnetostrictive, conducting, photochemical, piezoelectric, etc, properties. These fibers are typically sensor oriented.

A fiber with a nonhomogeneous optical core, in terms of refractive or mechanical properties, is a dual solution to a step-index fiber with tailored noncircular core. This idea was presented in Fig.3.1f. Both geometries are here possible: square and perfectly circular. We obtain here a circular core fiber which simulates (it is almost perfectly equivalent) a noncircular core fiber.

Also typically sensor oriented are fibers with "outward" located cores - only partially or totally. This idea was presented in Fig 3.1h. Two optical cores are located totally outward, in the first case and isolated mutually by a weak refractive index barrier. Usually the cores are covered from the outside by a thin auxilliary cladding to prevent too high losses of such a fiber. The core is isolated by a tailored gradient index optical barrier, in the second case presented by Fig.3.1h. The side BB1B of the considered fiber acts as an evanescent field sensor of strictly tailored directional characteristics.

The solutions presented by Figs 3.1i-j and 3.1l, are called mosaic optical fibers with overflow cores. The optical overflow cores are located symmetrically or nonsymmetrically against the main core and coupled weakly or strongly. Various refractive or lossy barrieres are placed in between these cores to tailor the coupling characteristics. The coupling depends on the mode order guided in the main core or on modal angle of propagation (in a multimode case).

The mosaic optical fiber could also contain an empty space. This is realized by a lacking rod in a particular mosaic area. The mosaic optical fiber could also contain other nonguiding areas like a conducting wire, heater etc, to give still other families of special-purpose optical waveguides - Fig 3.1k.

The well know multicrucible technology is so far the main method of manufacturing nonconventional optical fibers with comlex refractive index profile, noncircular cores and complex distribution of stresses near the core-cladding boundary. This technology possesses its internal confinements. Among them is a long lasting high temperature stage of the process durring which the glasses are totally melted in crucibles. The desired viscosity of glasses reach 10E7-10E8 poise in these conditions. High temperature facilitates greatly the diffusion processes between core and cladding glasses what causes a considerable broadening of the refractive boundaries. The multicrucible technology can not use freely some glasses characterized by high tendency toward crystallization. Some of these glasses possess, however, desired properties for fiber optics applications.

In the existing references concerning optical fiber technology we have not encountered a metdhos similar to the one suggested in this work. This method bases on composing of multielement waveguiding structures. The process of fiber manufacturing begins with an assembling of a preform from separate glass rods. We are suggesting here a name mosaic optical fibers for this technology, because the preform's cross-section resembles a precise optical mosaic.

The basic structure of a mosaic optical fiber possesses only one axially positioned core (glass A) surrounded by a homogeneous cladding (glass B). The homogeneity concerns refractive index distribution nD and thermal expansion coefficient α (Fig.3.1a.) The following conditions are fulfilled in this structure:

$nDA > nDB$ and $\alpha B < \alpha A$, $\Delta\alpha = 100(\alpha A-\alpha B)/\alpha A < 15\%$. Avoiding too big stresses requires, however, $\Delta\alpha < 10\%$ in the basic structure. Two examples are given of mosaic optical fibers possessing the basic structure: a single core optical fiber of a big numerical aperture and a very low internal level of mechanical stresses, and a single core optical fiber with big NA and big difference of thermal expansion coefficients between core and cladding glasses.

3.1.1 Characteristic of optical mosaic technology and structure

To simplify the description of a new technological method we are assuming here a standard square module. This dimensional module will be valid for assembled preforms as well as for ready optical fibers. Thus, the dimensions of the rods are normalized, so are internal structures of a resulting fiber. The basic element of the mosaic throughout this particular work will be a square. A square module does not exhaust the possible sets of mosaics. Other applied modules were hexagonal and octagonal.

The process of manufacturing mosaic optical fibers consists of the following stages:

a) melting of core and cladding glasses,
b) casting long rectangular prisms,
c) cutting the blocks to square cross-section rods,
d) grinding and mechanical polishing of the rods,
e) high temperature pulling the rods to standard dimensions of the mosaic,
f) assembling a multirod preform of wanted core-cladding structure. The preform is assembled of the rods of the same dimensions but different refractive/mechanical/thermal properties.
g) high temperature pulling the mosaic preform to obtain a mosaic optical fiber - oversized, multi- or monomode,
h) covering the fiber with a protective organical jacket of high strength.
i) cutting the fiber to application lengths and preparing end-faces.

The simplest mosaic preform consists of nine rods (8 for a cladding and one for a core). The glass rods are assembled to give a 3 x 3 mosaic square. The core rod assumes the central position in the preform. Technological reasons require dimensions of the preform to be around 15 x 15 mm. Thus, the individual rod has the cross-sectional dimensions 5 x 5 mm in this basic assembly. This preform is then pulled to a fiber. The fiber has dimensions in the range of 75 ÷ 100 μm, i.e. the thinning ratio is 150 ÷ 200 times. The core assumes the dimensions 25 ÷ 30 μm in these conditions. A ready fiber leaving the furnace is immeditely covered by a thermo-cured layer of a silicone resin varnish and next by an acrylic UV-cured lacquer. The external dimensions of a fiber are 250-350 μm, what makes all manual operations with a filament of this size much easier in laboratory conditions. It is also necessary to manufacture oversized optical fibers for some groups of applications. These fibers have approximately 1mm in diameter with a core as thick as 250 ÷ 350 μm and thinning ratio as low as only 15 times.

Tab.3.1. Glasses for a single-core mosaic optical fiber with big NA and suited physical properties.

	Glass composition in % weight								n_D for 293 K	Alpha for 293-573 K •10E--7K^{-1}
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	BaO	CaO	Na_2O		
core A	48	12	5	-	12	10	5	8	1.603	80.63
cladding B	44	30	17	9	-	-	-	-	1.486	76.76

fiber data: Δn_D=0.117; NA=0.60; $\Delta\alpha$=3.87; $\Delta\alpha/\alpha$A=4.8%;

Tab.3.1 shows chemical composition of used glasses for the core and cladding of an investigated fiber. Also basic properties of these glasses were presented: nD value for 293K and thermal expansion coefficient for temperature range 293 ÷ 573K. Tab.3.2 presents the same data for the second considered example of basic solution to mosaic optical fiber.

Tab.3.2. Glasses for a single core mosaic optical fiber with big NA and big internal stresses.

	Glass composition in % weight								n_D for 293 K	Alpha for 293-573 K •10E--7K^{-1}
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	BaO	CaO	Na_2O		
core A	40	11	3	-	13	15	10	8	1.633	86.13
cladding B	44	30	17	9	-	-	-	-	1.486	76.76

fiber data: Δn_D=0.147; NA=0.68; $\Delta\alpha$=9.37; $\Delta\alpha/\alpha$A=10.9%;

The examples were chosen to illustrate only new features of the suggested assembling mosaic technology of optical fibers. We are interested here particulary in technological tailoring of very subtle transmission properties of these fibers including refractive ones and distribution of internal stresses. The described structures are modifications of the basic structure and comprise: twin-core fibers - homocore and heterocore, and single-core fibers with highly nonhomogeneous distribution of stresses in the cladding - with elliptical symmetry of stresses and with helical distribution of the field of stresses.

A twin-homo-core optical fiber (doubled basic structure)

The mosaic preform structure consists of 25 elements. The dimensions of a single element is 5 x 5 mm, thus, the dimensions of a preform is 25 x 25 mm. Thinning this structure 200x during the pulling process gives a fiber 125 x 125 mm with cores of 25 x 25 mm in dimensions. The cores A1 and A2 are made of the same glass or of different glasses (the difference is in chemical composition) possessing exactly the same values of n_D and alpha parameters, what is shown in Tab.3.3.

Tab.3.3. Twin-core fiber (homocore solution).

	Glass composition in % weight										
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	La_2O_3	BaO	CdO	ZnO	n_D	alpha
cladding B	44	30	17	9	-	-	-	-	-	1.486	76.76
core A1	19	10	-	1	3	19	38	9	1	1.754	82.49
core A_2	20	10	-	-	3	19	39	9	-	1.753	82.54

fiber data: $\Delta n_D(A1-A2)=0.001$; $\Delta\alpha(B-A2)=5.78$; $NA1=NA2=0.91$; $\Delta\alpha/\alpha A2=7\%$;

Twin-hetero-core optical fibers

Tab.3.4 presents the technological data of utilized materials for assembling and pulling of a mosaic twin-core optical fiber. The cores possess considerably different numerical apertures. The mechanical properties of all used glasses to build this structure are fairly similar, thus the internal stresses are low.

Tab.3.4. Hetero-twin-core mosaic optical fiber with homogeneous physical properties.

	Glass composition in % weight										
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	La_2O_3	BaO	CdO	Bi_2O_3	n_D	alpha
cladding B	44	30	17	9	-	-	-	-	-	1.486	76.76
core A1	21	10	-	1	3	19	39	7	-	1.743	80.18
core A_2	47	12.5	11	-	-	-	-	-	29.5	1.574	80.20

fiber data: NA1=0.91; NA2=0.52; $\Delta\alpha$(A-B)=3.44; $\Delta\alpha/\alpha$A2=4.3%;

Tab.3.5. Hetero-twin-core mosaic optical fiber with high level of internal stresses.

	Glass composition in % weight									
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	BaO	CaO	Na_2O	n_D	alpha
cladding B	44	30	17	9	-	-	-	-	1.486	76.76
core A1	41	12	5	-	12	10	5	8	1.603	80.63
core A_2	40	11	3	-	13	15	10	8	1.633	86.13

fiber data: Δn_D(A2-A1)=0.03; NA1=0.6; NA2=0.68;
$\Delta\alpha$(A1-A2)=5.5; $\Delta\alpha$(A2-B)=9.37; $\Delta\alpha$(A1-A2)/αA1=6.8%;
$\Delta\alpha$(A2-B)/αA2=10.9%;

Another twin-hetero-core mosaic optical fiber was pulled of glasses whose parameters have gathered in Tab.3.5. The assembling geometry is exactly the same as presented in Fig.3.1b and Tab.3.4. The applied glasses have considerably different coefficients alpha, what results in different fields of stresses around each core. The core made of A2 glass of greater alpha2 coefficient is more stretched in its cross- section than the core made of A1 glass. These mechanical stresses are "frozen" in the fiber during its cooling process.

A mosaic optical fiber with elliptical distribution of stresses

This complex mosaic optical fiber is built of four kinds of glasses, what was presented in Fig.3.1e. The full set of glasses includes one core glass A and three cladding glasses B, B1 and B2. The cladding glasses possess almost equal refractive indices but different expansion coefficients - Tab.3.6.

Tab.3.6. Single-core mosaic optical fibers with elliptical distribution of internal stresses on c-c boundary.

	Glass composition in % weight								
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	BaO	CaO	Na_2O	n_D	alpha
core A	48	12	5	-	12	10	5	8	1.603	80.63
cladding B	44	31	16	9	-	-	-	-	1.485	73.58
cladding B1	44	30	17	9	-	-	-	-	1.486	76.76
cladding B2	38	39	15	8	-	-	-	-	1.483	70.11

The cladding glasses B1 and B2 are placed in the corners of the suggested structure. They differ considerably among themselves as far as a value of alpha is concerned. The core (A) -cladding (Bi) interfaces are mechanically stressed due to these differences in alpha. The value of these stresses is much bigger in the direction B2-A than in B1-A. The whole core interface is stretched nonhomogeneously as it was presented schematically in Fig.3.2a.

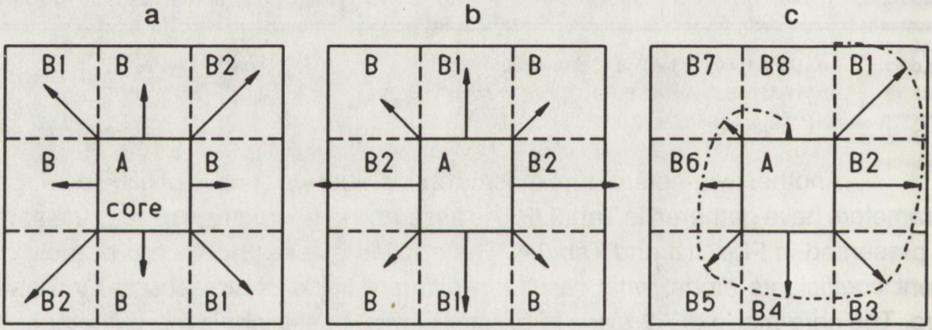


Fig.3.2. Distribution of internal mechanical stresses around the corecladding interface in mosaic optical fibers with nonhomogenous claddings,
a) and b) four-glass fibers with elliptical distribution of stresses,
c) nine glass fiber with helical distribution of stresses.

The second version of a pulled mosaic optical fiber with elliptical distribution of internal stresses was performed according to a design structure presented in Fig.3.2b. Much bigger stresses are applied here to the sides of a square core.

These stresses are stretching ones. Smaller stresses act in the corners, i.e. differently than in the previous case. Both fibers were performed of the same set of glasses what enables easy comparison of the results of these stresses on transmission properties of fibers. In both cases (and in all cases debated proviously) of properly designed optical fibers stresses in the cladding have squeezing nature.

A mosaic optical fiber with helical distribution of stresses around a core.

Tab.3.7 presents basic technological data of a manufactured mosaic optical fiber with helically nonhomogeneous cladding - the same kind was presented in Fig.3.1d. Nine different glasses have been applied here to build this very interesting mosaic optical fiber. Fig.3.2c shows schematically the distribution of stretching stresses near the core-cladding boundary.

Tab.3.7. Single core mosaic optical fiber with helical distribution of core-cladding boundary stresses.

	Glass composition in % weight										
kind of glass	SiO_2	B_2O_3	K_2O	Al_2O_3	ZrO_2	BaO	CaO	Na_2O	n_D	alpha	local%
core A	48	12	5	-	12	10	5	8	1.603	80.63	-
cladding B1	44	30	17	9	-	-	-	-	1.486	76.76	4.8
cladding B2	42	35	17	6	-	-	-	-	1.484	75.77	1.3
cladding B3	44	31	16	9	-	-	-	-	1.485	73.58	2.9
cladding B4	44	33	16	7	-	-	-	-	1.484	72.98	0.8
cladding B5	47	32	16	5	-	-	-	-	1.483	72.44	0.7
cladding B6	41	39	6	4	-	-	-	-	1.482	72.06	0.5
cladding B7	45	31	15	9	-	-	-	-	1.484	70.45	2.2
cladding B8	38	39	15	8	-	-	-	-	1.483	70.11	0.5

fiber data: $\Delta\alpha/(A\text{-}B8)/\alpha_A=13.7\%$; NA=0.6; $\Delta\alpha\max(B1\text{-}B8/\alpha B8=9.5\%$

3.1.2. Technological confinements for mosaic optical fibers

The first basic condition of waveguiding in a mosaic optical fiber is existence of a proper refractive index profile. The core glasses contain some additions of high refractive index oxides like ZrO_2, La_2O_3, Bi_2O_3, PbO, BaO. The claddings are built of light borosilica glasses.

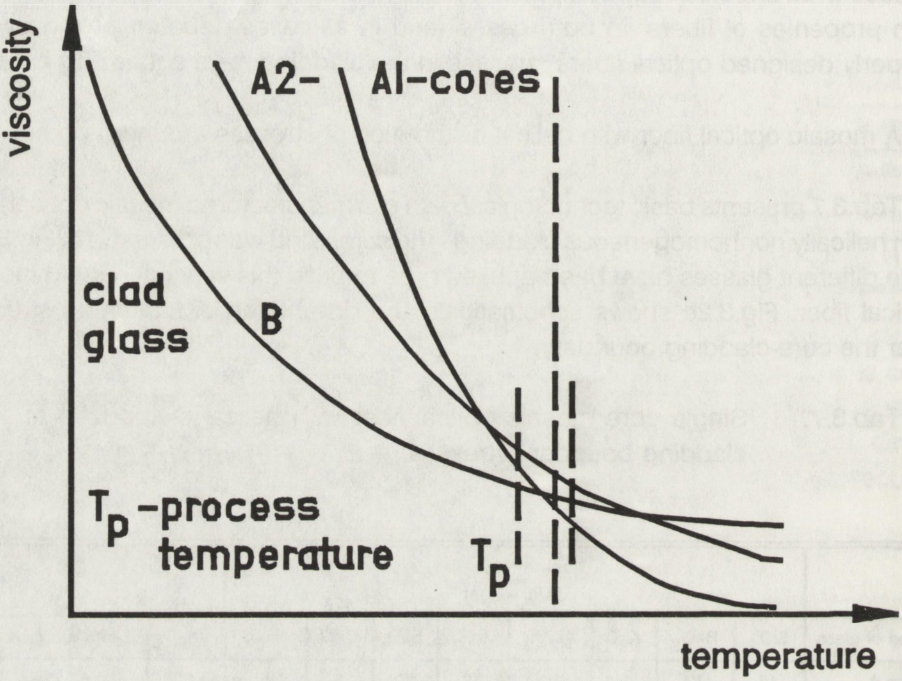


Fig.3.3. Viscosities of the glasses for mosaic optical fiber.

The second basic condition for a mosaic optical fiber pulling is existence of squeezing stresses near the external surface of a mosaic structure. This is obtained by application of cladding glasses having lower expansion coefficient than core glasses. During the cooling process of a fiber, its axial part (the core) contracts more than external areas (cladding layers). The core is subject to stretching forces, when cooled below its glass Tg transition temperature. The cladding layers are in a squeezing area of the field of stresses distribution and keep the fiber as a homogeneous unity. The basic confinement to be considered here is connected with the tearing strength of considered cladding glass. Simple calculations show that, from practical point of view, the difference between core-cladding expansion coefficient should be confined to a value not exceeding 10 ÷ 15 %. Not properly composed glasses for a mosaic optical fiber, from expansion properties point of view, results in too big stretching stresses frozen in the cladding area. This decreases greatly the internal strength of such a mosaic fiber and in some cases makes impossible fiber pulling.

The third basic condition for assembling - mosaic optical fiber technology is the choice of glasses with properly intersecting viscosity curves as functions of temperature $\log\eta = f(T)$. This intersection points, for all glasses bulding the fiber structure, should be as close as possible to an optimum temperature of the technological process. This situation was shown schematically in Fig.3.3. Too big differences in the viscosities make the pulling impossible. Big differences in the viscosities of mosaic glasses used, require bigger temperatures of the pulling process what activates considerably diffusion processes between core-cladding regions and makes impossible step-index mosaic optical fiber of high value of NA.In some cases we are interested not only in step-like changes in nD but also step-like changes in alpha parameter. The sufficiently active enough diffusion processes equalize not only nD but also the value of expansion coefficient alpha.

The last confinement is connected with recrystallization tendency of used optical glasses for assembling mosaic preforms. This tendency is especially strong in low silica core glasses of high values of refractive indices. To avoid the recrystallization problems the time of high temperature process should be as short as possible, and the temperature of the process as low as possible.

3.1.3. Application considerations for mosaic optical fibers

Several kinds of mosaic optical fibers have been pulled using the basic idea presented in Fig.3.1a. They have been manufactured of high-purity multicomponent glasses debated in previous section of the paper. The fibers possessed very similar mechanical and optical characteristics (loss, dispersion and others) as these pulled by other methode like: rod-in-tube and multicrucible ones. At first sight the mosaic optical fibers were almost impossible to be distinguished from classical ones. Thus, we have proven that this technology is effectively possible and gives optical fibers of sufficiently high quality to be applied in optical equipment.

Other kinds of more complex mosaic optical fibers have also been pulled. These included: twin-core and quadruple core optical fibers, ring-core-case fibers, multimode optical fiber of gradient refractive index and nonhomogeneous cladding, multimode step-index optical fiber with refractive traps in the cladding. The refractive profiles of these two last fibers were presented in Figures 3.4 - 3.5. Eventually we have tried to manufacture some more or less usefull devices and sensors from the mosaic optical fibers.

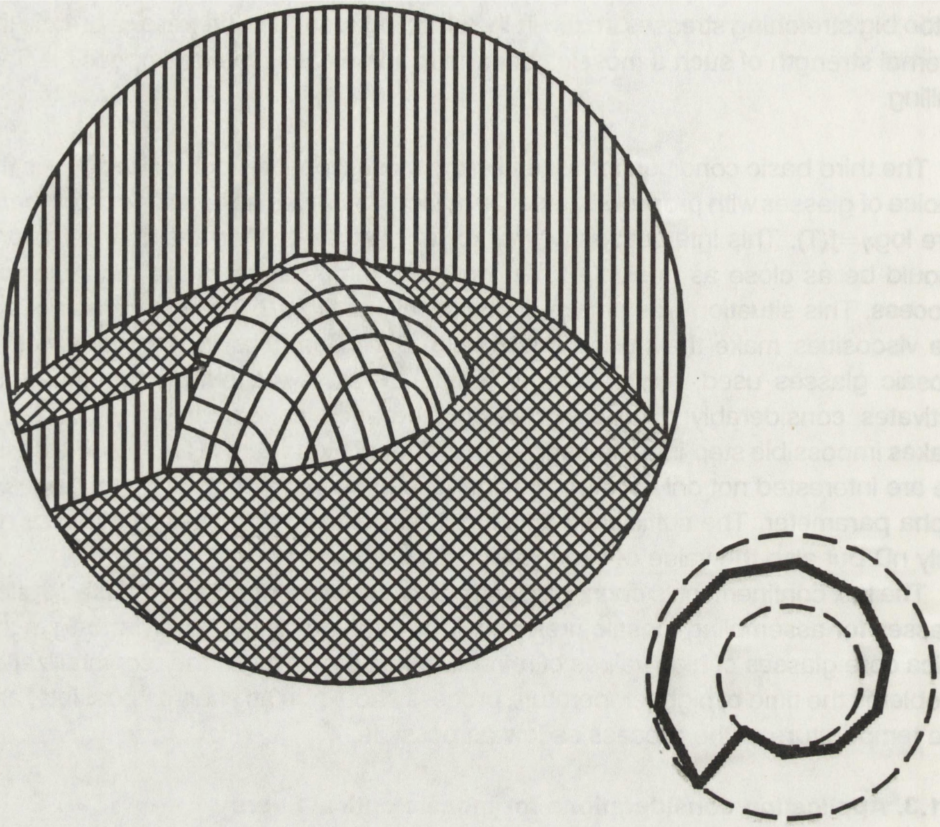


Fig.3.4. Measured refractive index profile of a pulled gradient multimode mosaic optical fiber with optically nonhomogeneous cladding.The refractive index is rising in the cladding continuously anticlockwise. A refractive index ramp is visible in the cladding. The fiber is of a type presented in fig.3.1.d. The losses of the fiber depend considerably on the conditions of excitation. The inset shows numerical aperture of this fiber.

There were manufactured two classes of multimode mosaic optical fibers with linearly changing properties of optical cladding in the function of the angle in circular coordinates. The value of refractive index was rising continuously in the cladding in one of these fibers. The value of mechanical expansion coefficient alpha was rising continuously in the cladding of the other fiber, giving rise to a helical distribution of stresses in the core. All these fibers possess a shear plane in the cladding where an abrupt ramp of physico-chemical properties is observed. The numerical aperture seen on a plane parallel to the fiber end-face looks like a snail's shell. The fiber has different refractive properties from various sides and these differences are retained by the light-guide in short lengths not exceeding a dozen of meters or so.

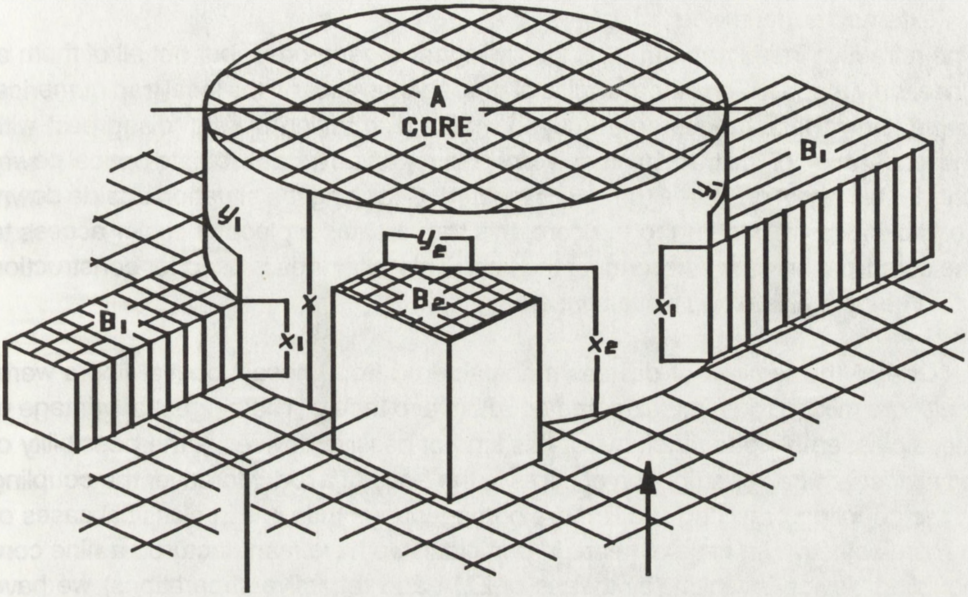


Fig.3.5. Refractive index profile of mosaic optical fiber with nonhomogeneous step-index cladding. The cladding contains narrow refractive index traps, responsible for power radiation in certain direction and at certain angles. The parameters of this fiber are:

X - maximum difference of refractive indices between core and cladding,
xi - local refractive index differences,
yi - local widths of refractive index traps; the traps are located on a background optical cladding,
A - core,
B_i - traps in the cladding.

Another solution of nonhomogeneous core mosaic optical fiber possesses one or more narrow refractive index traps in the cladding. These traps touch the core and change locally numerical aperture of the fiber. A multimode fiber of this kind behaves differently for two different ranges of its length:

a) long lengths when a steady state modal distribution is obtained in a fiber - considered lengths in the range of at least a few kilometers,
b) short lengths - here of our bigger concern for device and sensor applications - steady state modal distribution is never obtained unless we apply a special external modal mixers.

The refractive index trap removes locally higher order modes, but not all of them at once, only these which modal angles of propagation exceed the local trap numerical angle. Only these modes are removed whose distribution of field "disagrees" with the localization of the trap. In other words, the removed modes radiate optical power only in this direction where the trap is located. Changing the situation upside down, i.e. looking from cladding to the core, this trap creates a place of easier access to the core from an area surrounding the fiber. This latter idea is used for construction of some optical leakage wave sensors.

One of the families of devices manufactured from mosaic optical fibers were: multicore mixing rods, matrix-cored couplers and tapers. The biggest advantage of mosaic assembling technology for this kind of passive devices is the possibility of an almost arbitrary distribution of cores in the body of a rod. Moreover the coupling in the coupling or mixing rod is more homogeneous than it is in classical cases or is more selective, in case of need. In particular, we have manufactured a nine core coupling device in which (by means of EMA and refractive separations) we have obtained $C_x=5C_y$, where C-is directional coupling in %. It means that the coupling in "x" direction was five times greater than in "y" direction (Fig.3.6.). The directional separation ratio (DSR) could be easily varied in these devices in the range 0-30 dB.

A mosaic optical fiber was pulled of a glass with high bismuth content. The composition of this particular glass was given in tab.3.4. The fiber possessed auxialiary nonguiding region-axially localized capillary (Fig.3.1k.). The internal surface of the capillary was activated with hydrogen to gain semiconductor properties in the surface layer. This internal surface was somehow isolated optically from the core not to increase the losses of a fiber too much. The semiconductor layer was utilized in fibers of short lengths to heat dynamically the core.

In the other solution we have kept high vacuum in the capillary and investigated the effects of interaction between optical guided wave and avalanche multiplication of electrons in the semiconductor layer.

A mosaic optical fiber was pulled with double ring cores, Fig.3.7. The fiber was designed for a microbending vibration/acoustical sensor. Some versions of this class of fibers have additionally refractive index traps (isolators, directional windows) to increase/depress the sensitivity in certain directions. The output of the sensor measured integrally or subtractively gives additional in the sensitivity to microbending. Thus, we are obtaining here the desired level of sensitivity on two separate ways: technological and signal processing. This kind of fibers has uncomparable selective sensitivity to microbending/acoustical fields.

Optical fibers, devices and sensors presented in this work have recently found or will soon find their practical applications in optoelectronic systems working mainly in adverse environments. These environments include: electrical high power engineering, airborne and space systems, onboard marine systems, coal mining, industrial robotics and others. The more detailed data about these optimized fiber optic systems for adverse environments could be found elsewhere [3.1, 3.2].

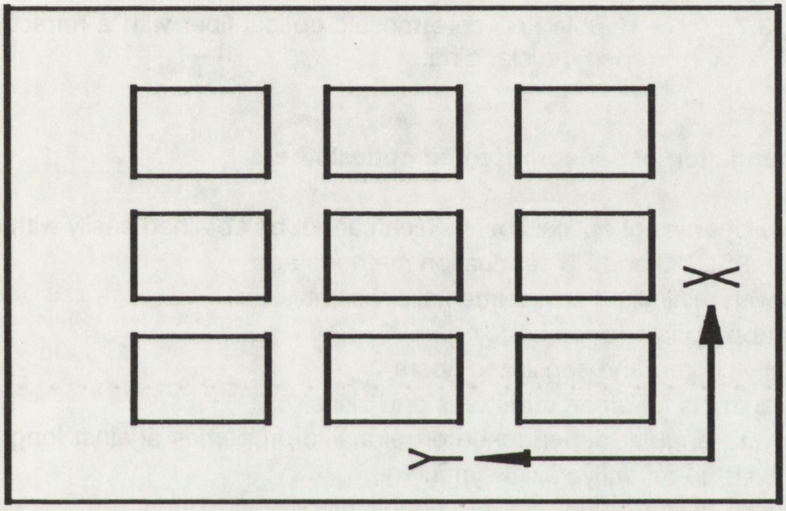


Fig.3.6. A nine-core mosaic optical fiber selective coupler/mixing rod.

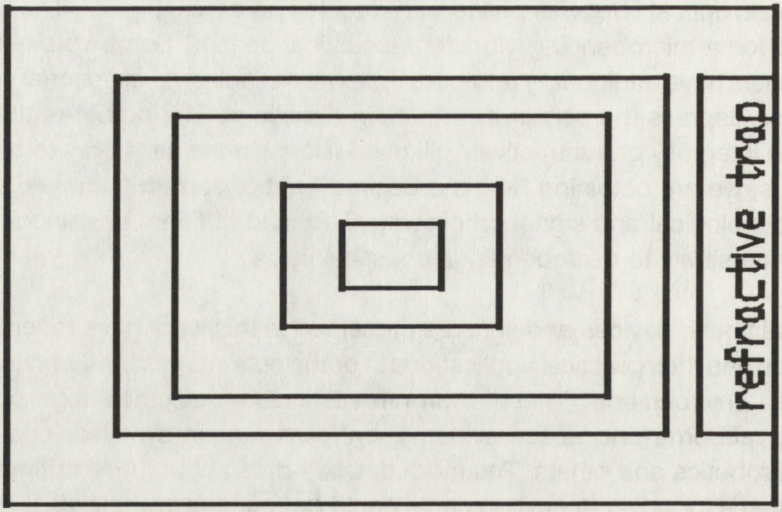


Fig.3.7. A double ring core mosaic optical fiber with a refractive index trap in the cladding.

3.1.4. Foundation of sensor oriented optical fibers

Basic properties of optical fibers which cannot be obtained easily with classical CVD, VAD, PSL,DC and RiT fabrication methods are:

- fibers with minimized environmental sensitivity,
- fibers appropriate for embedding,
- specially coated and sensitized fibers,
- fibers suitable for smart structures and skins,
- fibers with angular dependence of refractive properties against long axis, i.e. fibers with no refractive axial symmetry,
- fibers with helical cores and with noncircular cores,
- multicore optical fibers.

Ordinary monomode as well as multimode telecommunication oriented optical fibers, which have been used so far for sensors, gave many families of useful devices. In this domain we are now working on a real life applications in industrial, military and biomedical environments. We believe that a further considerable progress in sensing capabilities of this technology is possible with an optimized, application oriented optical fibers. That is why the main aim of this paper is to present one group of special optical fibers developed in our laboratory. These are defibered optical bundles by mosaic assembling technology.

Let us assume that we are going to measure distributed stresses in a large block of concrete. Let us also assume that hundreds or even thousands of fiber optic sensing paths are to be distributed in this block to give a reliable telemetric network. How to do that? How to handle these thousands of separate optical fibers? And what more, the environment for embedded glass fibers is very harsh in a concrete. It is very basic and, adding to this dampness, gives ideal conditions for glass optical fiber solubility.

Thus, we envision here the following technological and engineering problems while designing an optical fiber network for this kind of adverse environment. The initial one is material choice for all parts of nonstandard optical fiber: core or multiple cores, optical cladding, buffers - mechanical and/or sensitivity enhancing/depressing (sensitizing layers),outer protections etc.

The next stage is material processing and fiber pulling/manufacturing. Sometimes we have a fiber of pretty complex internal structure that requires a multistage pulling/manufacturing process. The multistage manufacturing process of a fiber incorporates some stages that are nontypical during standard fiber preparation. These stages we call special fiber sesitization. Thus, we have here numerable additional technological factors affecting fiber construction.

Returning back to our initial example, we need optical fibers that are extremely resistant to base environments. They should be also resistant to naturally - bonded moulding sand, erosive slag, gravel or shingle. The embedding process should take into account shrinkage processes during setting of concrete.

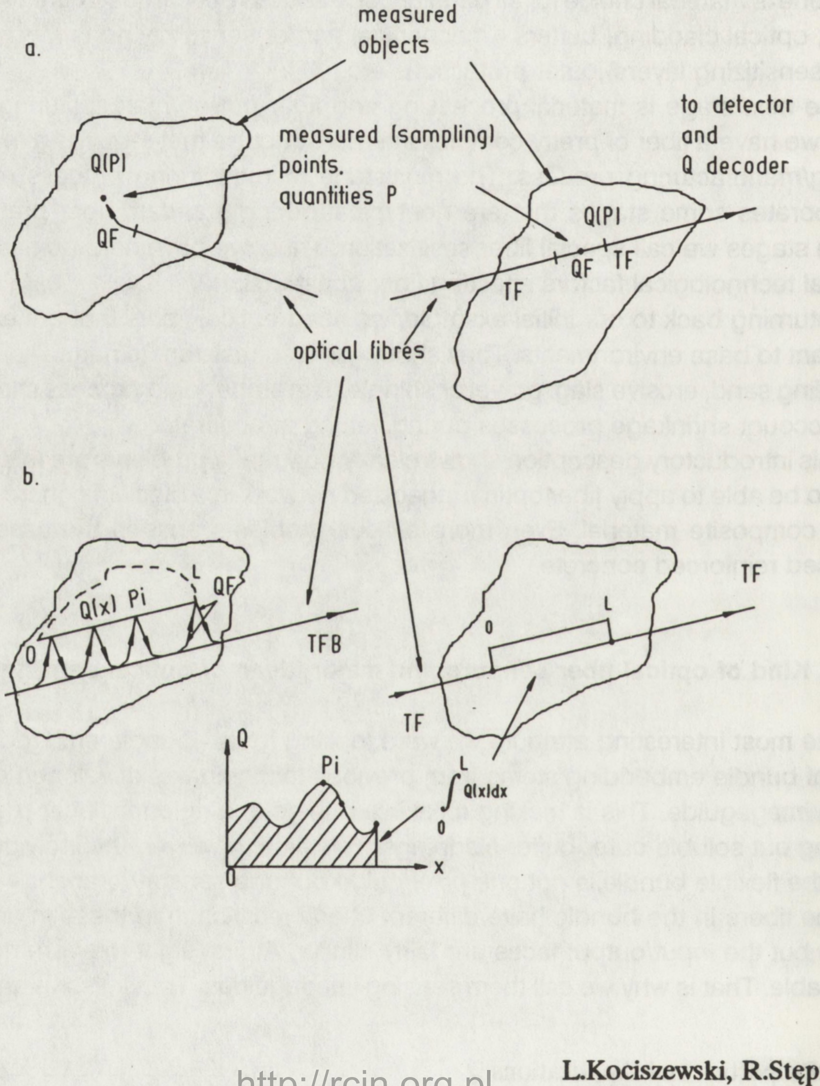
This introductory description shows clearly how many problems are to be solved here to be able to apply fiber optic ruggedized network in a block of concrete or any other composite material. Even more difficult problems arise in the case of prestressed reinforced concrete.

3.1.5. Kind of optical fiber sensors and major ideas of optical sensing system

The most interesting attribute we were looking for is - bundle embedding. The idea of bundle embedding stems from previous technologies developed originally for an imageguide. This is making a flexible bundle of a rigid multifiber preform by etching out soluble outer buffer claddings. This time, however, the individual fiber, from the flexible bundle,is not one pixel guide but one sensory branch.

The fibers in the bundle have different characteristics than these in an imageguide but the input/output faces are fairly similar. At first sight they are nondistinguishable. That is why we call them sensing imageguides. Transmissive and reflective sensing imageguides are possible. Another cause that justifies this name is that as a result we obtain a two or three-dimensional distribution of sensed property of surrounding space/matter. This image is one of the invisible images that describes a real physical state of investigated object. This "image" (matrix) information could then be processed in almost the same way as ordinary optical image.

The major difference between both imageguide techniques - classical and sensing is that the latter could be singlemode contrary to the first one. The consequence of this is that the sensing imageguide technique can operate with polarization, phase and coherent detection techniques, which are inaccessible to the first one.



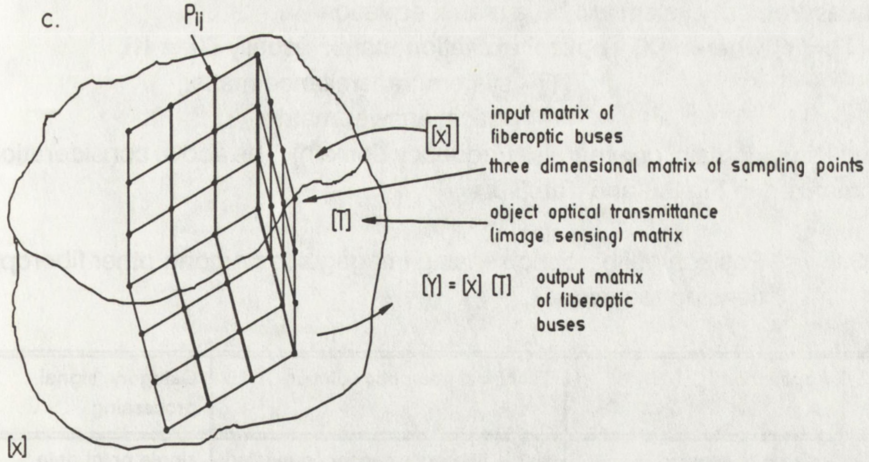


Fig.3.8. Categories of fiberoptic sensing techniques

a) single point sensing,
b) distributed sensing,
c) volume matrix (image) sensing
QF - sensing fiber (quantity Q),
TF - transmissive fiber,
TFB - fiberoptic bus,
P_i - sampling points.

Let us consider now the position of a matrix fiberoptic sensing among other fiberoptic sensing techniques (Fig.3.8). While performing "one point sensing" we need a short piece of a fiber sensitive to the measured quantity Q. Let us call this fiber QF. Then, we need to transmit this measurement data to a detector and decoder. Several measurement geometries are possible: active, passive, transmissive, reflective, direct,indirect (optrode).

While performing distributed sensing we can chose two solutions: discrete multipoint sampling of the measurand or line integrating. To solve this problems we have to apply an appropriate fiberoptic bus.

While performing a three-dimensional sensing we can also chose the above two solutions:sampling and integrating. To solve this problem technically (using fiberoptics) we have to employ in a general case a matrix of fiberoptic buses. The answer of the measurement system will be a matrix equation

$[X] \bullet [T] = [Y]$ where: $[X]$ - optical excitation matrix, usually $|X| \equiv |1|$,
$[T]$ - system transmitance matrix,
$|Y|$ - optical answer matrix

(sampling - time domain, or integrals - frequency domain). The above considerations are summarized in Fig.3.8 and Tab.3.8.

Tab.3.8. Position of fiberoptic sensing imageguides among other fiberoptic sensing techniques.

No.	Application	Technical fiberoptic solution	Category, signal processing
1	one point sensing	single fiberoptic sensor connected with optical transmission line to a detector and decoder, numerous physical, chemical and biomedical quantities to be measured	single point data collection two main categories: narrow-band and/or wideo-band
2	distributed sensing	monomode and multimode optical buses: line integrating sensors, multipoint sensors	multisource (distributed) data collection
3	(image) matrix sensing, thermomechanical, aging	monomode and multimode sensing imageguides	(novel understanding of) image processing

3.1.6. Technological background

One of the basic manufacturing methods of sensor oriented optical fibers requires a circular core glass rod and a circular glass tube. Sometimes more than one tube is needed (Fig.3.9) to sensitize and/or insulate individual fibers in the bundle. The chemical and physical properties of these components have to be chosen very precisely to give an optical fiber. These properties comprise: mechanical, fit of dimensions, thermal and optical. Sensor oriented optical fiber technology requires special materials for the glass tubes.

Danner technology is the basic method of glass tube manufacturing.A large tank furnace contains molten glass. Molten glass from a tank furnace flows to a day tank. The day tank possesses a rotating gas presure nozzle to facilitate tube formation. This method, however, possesses a couple of drawbacks that make is not extremely

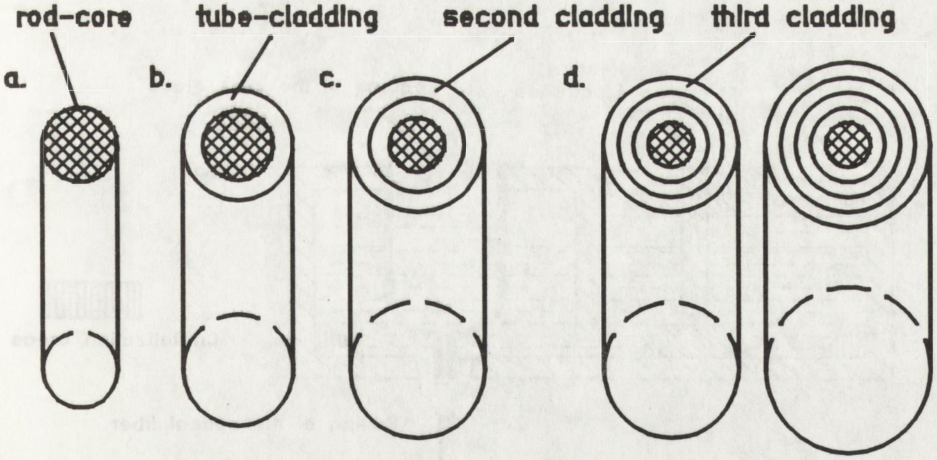


Fig.3.9. Rod and multi-tube construction of sensor oriented optical fibers.
a) core rod,
b) first optical cladding,
c) second sensitizing cladding,
d) third or fourth cladding-EMA and/or soluble layers.

useful for optical fiber technology. The main one is the necessity of using large amounts of molten glass in the tank furnace. The minimum amount is several tons. When one wants to change the glass for scientific experiments it is necessary to: remove totally the previous glass from the tank furnace to wash it with glass. The process is costly and time consuming and could not be accepted for frequent changes.

There are several internal confinements of Danner method as far as tube manufacturing for optical fiber technology is concerned:

- it is difficult to pull thick wall tubes (with wall thicknesses above 3 mm). This causes some difficulties in single mode fiber manufacturing,
- the tube internal and external dimensions oscillate around average values. Thus, a post-technology calibration machining is necessary,
- Danner method does not give tubes of ultimate purity, common impurities are Cu^{2+}, Fe^{2+}, Ti^{4+}.

A method which avoids some drawbacks of Danner tube technology is a double crucible technique. This method allows one to manufacture small optical tubes and fibers using much less amount of loaded glass. Fig.3.10 illustrates the multicrucible idea for optical fiber manufacturing that was used in our laboratory.

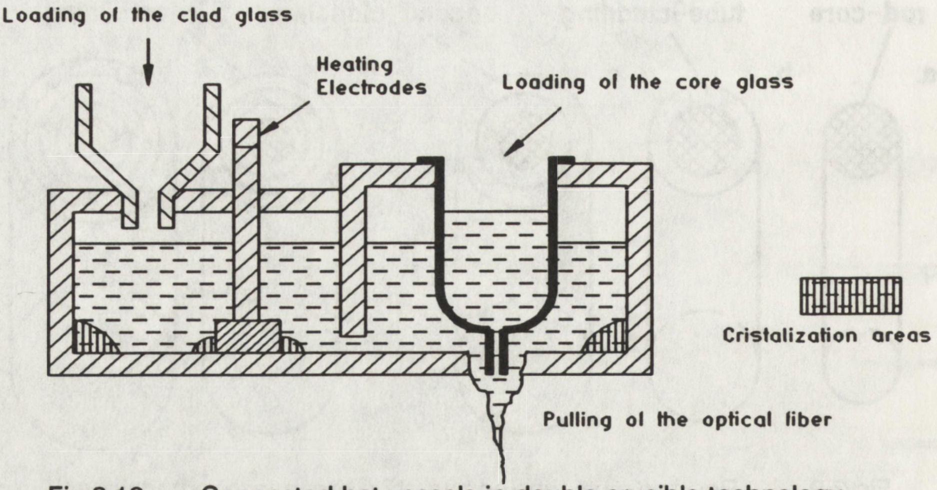


Fig.3.10. Connected hot vessels in double crucible technology.

This system allows in-line manufacturing of a continuous optical fiber. The raw materials of high purity are loaded to intermediate hot chambers and then ready glasses are used in a system of connected hot-vessels to pull a fiber. This way decreases possible sources of glass contamination and eventually results in a fiber of higher quality (good optical properties and acceptable elasticity).

Application of shaped nozzles in the crucibles allows one to pull specialty optical fibers of tailored cores and claddings. Among these fibers one is able to pull square/rectangular fibers, elliptical and multilayer with ring-case cores, This was presented exemplary in Fig.3.11. The confinements of this method include: great difficulty to pull fibers of too complex core shapes; only low temperature process acceptable.

Recently introduced mosaic-assembling technology of optical fibers [3.3] has turned out to be very suitable for manufacturing of sensor oriented optical fibers. The mosaic assembling technology (MAT) is used here for preform manufacturing. The idea of MAT was presented in Fig.3.12. The output components that build a fiber in this method are:

- for a core (Fig.3.12a) - a rectangular (or of other noncircular shape) glass rod made of high-silica or compound glass (including non-silica glasses),
- for successive claddings (Fig.3.12b,c,d) - modular glass rods or battens of dimensions fitting the modular core.

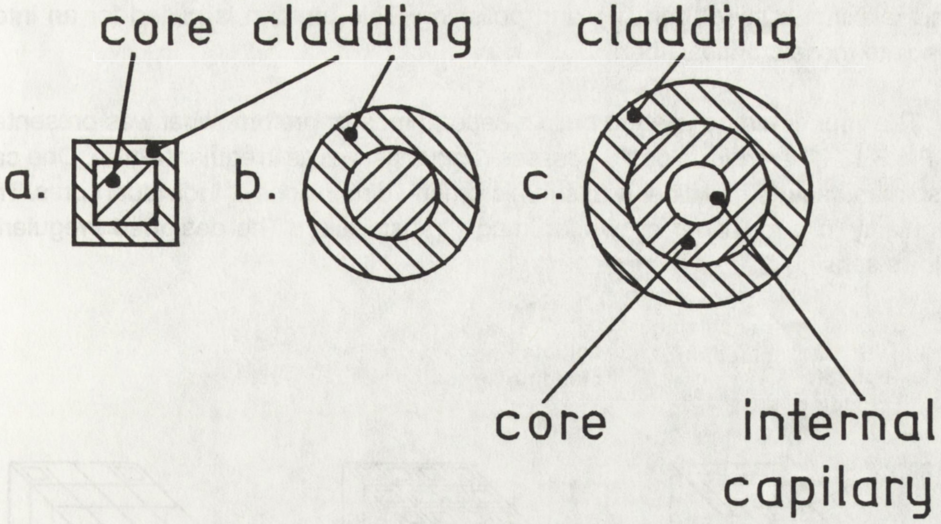


Fig.3.11. Cross sections of specialty optical fibers manufactured by modified double crucible technology.

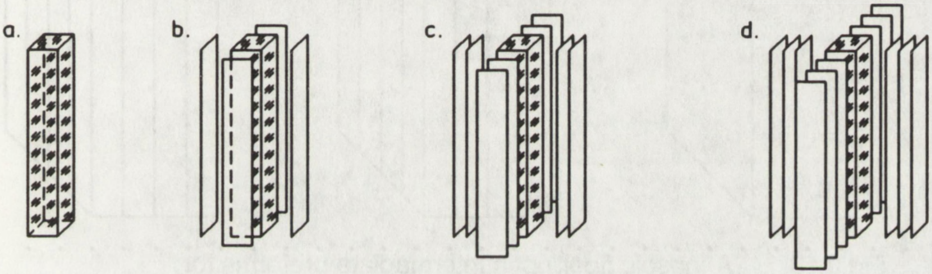


Fig.3.12. Necessary components for specialty optical fiber preform assembly
a) basic modular core glass rod,
b) glass battens and strips for optical cladding,
c) components for sensitizing cladding,
d) components for EMA and soluble claddings.

These cladding battens are assembled and/or attached/glued to core modular rod to build an output mosaic preform. The core rod (a) and cladding slab (b,c,d) are manufactured in a classical way by: glass melting, block forming, glass cooling and relaxing, cutting, grinding and polishing. This preform is pulled for an intermediate mosaic optical fiber.

The fiber could be used to build a second mosaic preform what was presented in Fig.3.13. The preform could possess regular as well as irregular texture. One can also manufacture multifiber with submicrometer dimensions of individual cores. The regularity in a multifiber allows for image transmission. The designed irregularity allows sensing.

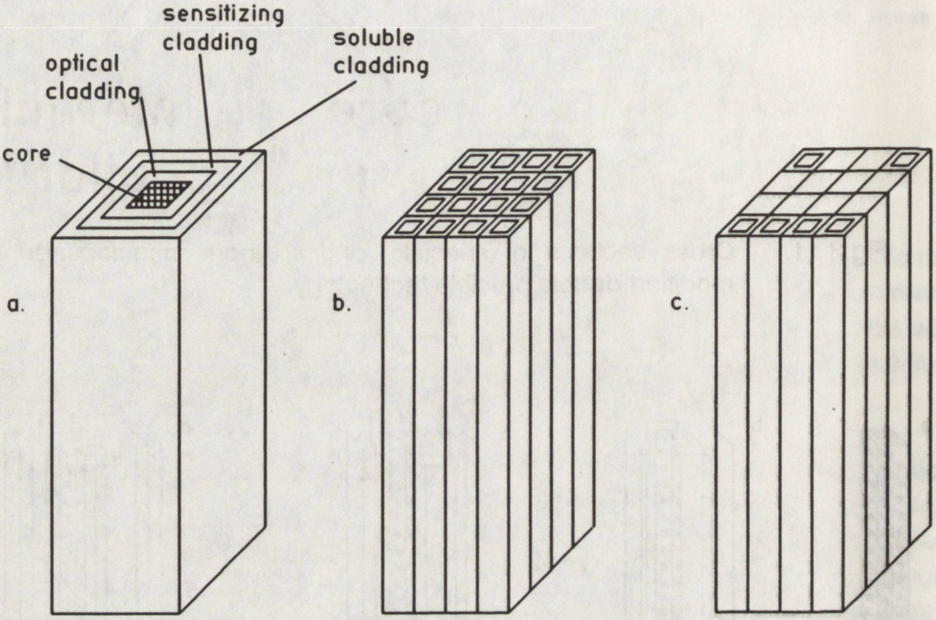


Fig.3.13. A mosaic fiber optic intermediate preforms for:
a) pulling of single core specialty fiber,
b) regular multifiber,
c) irregular multifiber.

The mosaic assembling technology of optical fiber preforms and sensor oriented multifibers has the following attributes:

- possibility of very precise fit of all individual components to build a preform and a fiber,
- precise geometrical fit obtained during cutting, grinding and polishing processes,
- precise chemical composition of glasses molten in small amounts in high-quality clean-room-laboratories and/or silica crucibles.

- greater flexibility of the method for research purposes, what is important during the initial stage of material optimization for a particular fibers,
- ease to obtain regular and irregular structures of optical fiber preforms with soluble buffer claddings between individual guiding structures (or between groups of isolated cores) to defiber the preform and obtain flexible sensing-imaging coherent bundles. The latter process was presented in Fig.3.14.

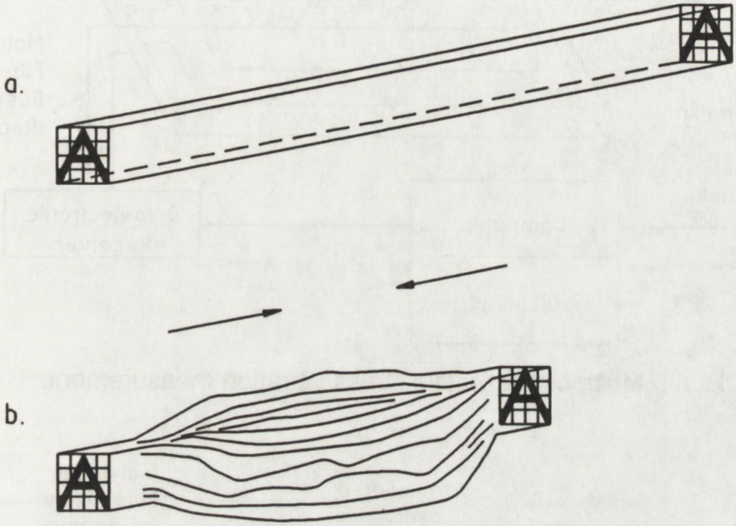


Fig.3.14. A square optical fiber mosaic multirod (a sensing imageguide) -
a) preform,
b) defibered coherent sensing bundle.

3.1.7. Application of fiberoptic sensing systems

Sensing oriented coherent bundles are designed to play a key role of measuring loops in the optical network. The loops can work as interferometric ones, reflectometric, polarimetric, evanescent wave spectroscopes, colorimeters and many others. They can be excited in series (one by one, row by row, column by column or any other designed and coded way) or in parallel to give different optical outputs and various network's measurement possibilities and circuit geometries. Some of these sensing geometries and capabilities for our bundles have been gathered in.

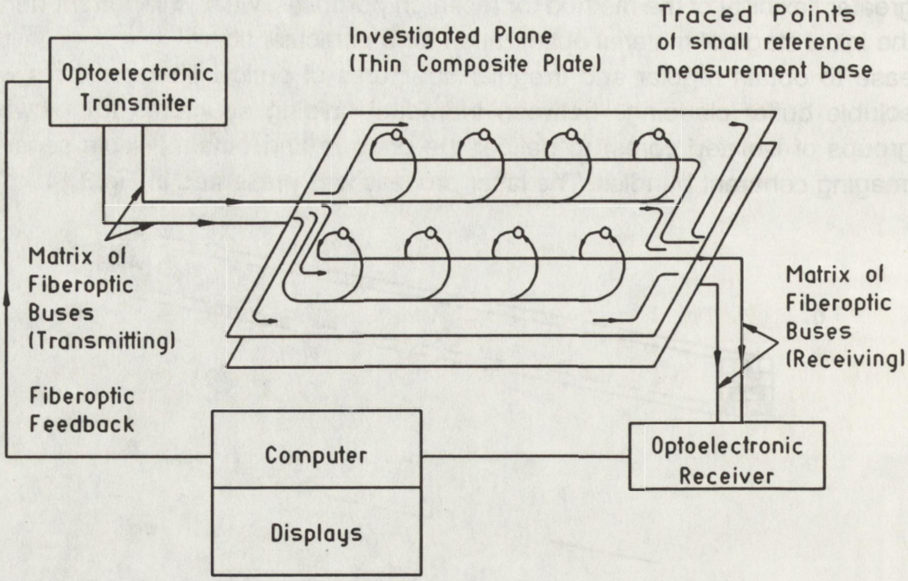


Fig.3.15. Multipoint reflective stress/vibration measurement.

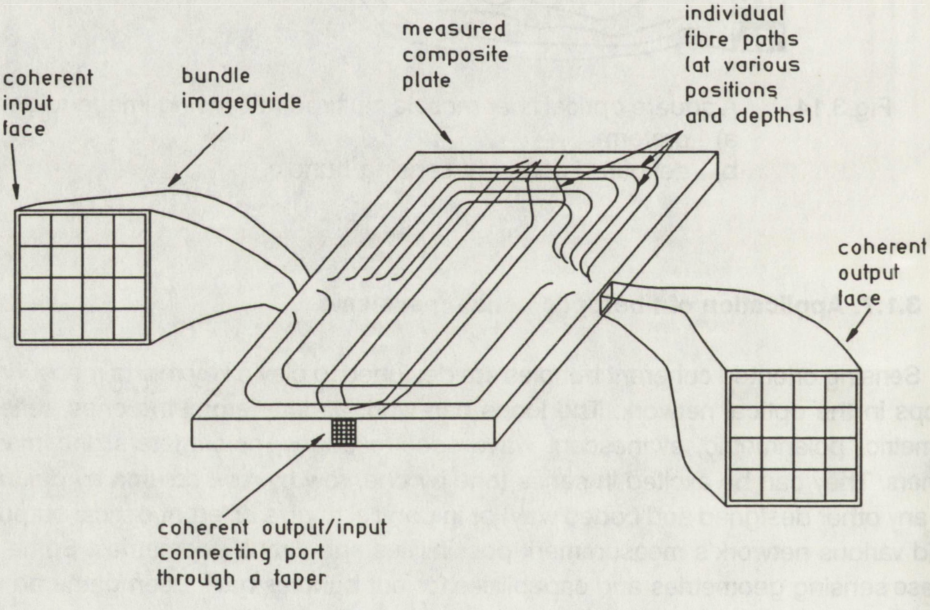


Fig.3.16. Fiberoptic sensing imageguides.

Fig.3.15 presents an idea of fiberoptic network consisting of multiple reflective buses. Each single bus traces several points on a single plane. The planes are made of thin lead plates covered on one side by a thin layer of composite material. All the measurement system is placed in an ionizing environment of a low power of dose (0.1 - 10 rads per minute) [3.4 ; 3.5].The role of a system is double: 1) gathering all scintillations appearing in the field of vision of receiving heads of distributed optical fibers; 2) performing periodically some polarimetric measurements by optical reflective method. A real fiberoptic sensing imageguide working embedded in a

Tab.3.9. Applications of fiberoptic sensing imageguides.

No.	Sensing scheme, measuring circuit	Measuring optical loop geometry	Basic type of	Signal processing	Chosen parameters, basic properties
1	Interferometer	Simultaneous multiloop switched loops	Reflective transmissive, phase,	Interloop interf. interf.between single meas. loop and refer. loop monomode	Sensitiv. for strain and temp. meas. comparable to classical interferom., but distribution measur.
2	Polarimeter	Switched loops	Transmissive, polarization, phase/amplitude monomode, low-mode	Polarization shift keying between optical loops	Faraday rotation
3	Reflectometer	Loop correlation	Amplitude phase	Inter-loop incremental reflectometry, (real time domain)	Multi-path OTDR
4	Microbending	Different. loops	Amplitude diff.loop loses	The same methods as in classical black-and white image processing	Selectivity, resonant
5	Evanescent wave spectroscopy	Single wave or multiwave opt. loops	Singlemode or low-mode, amplitude	Black-and white image processing	Wavelength switching

composite plate is presented in Fig.3.16. The plate is equipped with edge imageguide taper connectors. The input laser beam is scanned through the input face of a sensing imageguide to read the state of succesive fiberoptic loops/ branches. The optical outputs detected and decoded are then compared/ correlated and analysed by a computer to give an unusually good picture of stress and temperature distribution in the probe plate.

3.2. Image guide

Conventional optical fiber image guides are of major types: rigid and flexible. The image guides are manufactured from several kinds of glasses using two main methods:

- pulling a fiber from rod-in-tube assembly,
- pulling a fiber from a set of two crucibles.

Formed optical fibers are next glued with the aid of an organic glue enabling the integration of image-guiding structure. Ribbon integration is performed on a drum. This methods operates with fibers of 10 ÷ 20 μm in diameter what gives a resolution of the image guide in the order of 25 ÷ 50 pairs of lines per mm. To obtain the resolution exceeding 50 pairs of lines per mm with this method is very difficult. It is connected with the necessity of receiving very high rates and accuracy of winding drum rotation. Also there are some difficulties with proper protection and gluing of very thin optical fibers.

Tab.3.10. Some data of technological process for the high resolution mosaic fiber optic image-guides.

Fiber diameter in mm	Drum velocity (0,4 m drum dia.) in mm/min	Thicknes of integrating layer in μm	Comments
10	16000	0.015	non-homogeneous layer
20	3800	0.5	
40	1060	2	

Tab.3.10. presents a relation between fiber diameter and necessary parameters of the technological process. It is apparent here that there are great difficulties in going with the diameter beneath 20 μm. Line velocities for such a process get

enormous and the gluing integrating layer tends not to be homogeneous and sufficiently thick.

3.2.1. Manufacturing of the high resolution optical fiber image guides

The above mentioned and other difficulties connected with these methods made us try to look for another solution. There are some possibilities in this range associated with recently developed mosaic - assembling optical fiber technology [3.6]. With the aid of mosaic assembling technology one is able to manufacture optical fibers of square, regular multiangle and circular cross sections. The fibers are manufactured from glass preforms assembled with proper number of modular glass rods. The intermediate fibers are assembled to give intermediate image-guiding structures. Mosaic technology allows to build coherent structure containing almost no disturbances. Some properties of mosaic method are better then those obtained from classical methods.

The fibers and coherent matrices are obtained by a multistage hybrid technology from multicomponent glasses of the highest possible purity. The process comprises the following main technological stages:

- glass melting for core and cladding
- casting core bars and pulling cladding tubes
- assembling bar in tube and pulling rods
- intermediate preform assembling; intermediate preform is assembled also of rods of the same dimensions but different physico-chemical properties (including refractive properties)
- assembling and consolidation of preforms
- preform pulling to obtain an intermediate optical fiber - fiber covering with integrating-gluing organical substance - fiber cutting and end face polishing.

The whole process was outlined in Fig.3.17.

Thus, as the output of our methods we have a few kinds of intermediate preforms: cladded preform, structured preform, and a preform of tailored structure. These preforms are consolidated in a high temperature furnace and next pulled in to continous glass fibers. The main parameters of the technological process for preform manufacturing are:

- relative refractive index distribution in the preform,
- mechanical and thermical properties of all used glasses. (see 3.1.2)

The glasses presented in Tab.3.11 can be used to manufacture mosaic fiber image guides of high resolution.

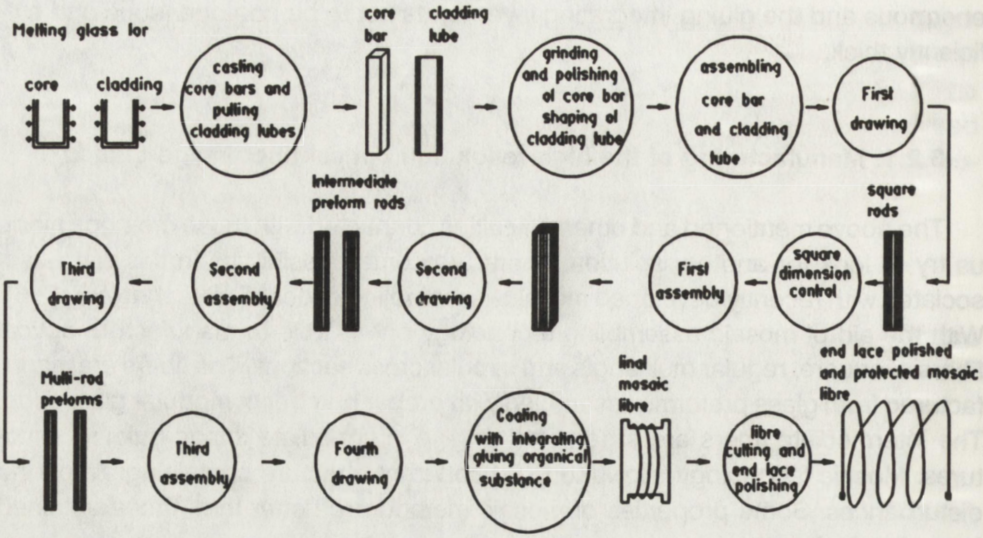


Fig.3.17. A general diagramme of the mosaic-assembling optical fiber technology.

Tab.3.11. Exemplary parameters of glasses.

Glass composition in % of weight	Core glass A	Core glass B	Clad glass A
SiO_2	48	40	44
B_2O_3	12	11	30
K_2O	5	3	17
Al_2O_3	–	–	9
ZrO_2	12	13	–
BaO	10	15	–
CaO	5	10	–
Na_2O	8	8	–
glass properties			
refractive index n_D(293K)	1,603	1,633	1,486
coefficient of thermal expansion $\alpha(293K \div 573K) \cdot 10^{-7} K^{-1}$	80,63	86,13	76,76

3.2.2. Physical and technical limits to miniaturization of fiber optic image-guides

Thin medical imageguides are nowadays of very big concern for cardiological, angiological and oncological applications. As the coherent bundle based on fiber optic image-guides contribute significantly to these dimensions, we are going to discuss here the miniaturization of this bundle.

3.2.2.1. Dimensional and refractive limits for optical fibers designed for image-guides

The most fundamental confinement stems from the waveguide nature of optical fiber transmission. Image transmission by almost nondependent channels (giving rise to image pixels at the output plane) is possible only with the aid of a bundle consisting of multimode optical fibers. There are some similarities and differences between optical fibers designed for broadband digital transmission and image guidance. These were presented in Tab.3.12.

Tab.3.12. Similarities and differences in parameters of optical fibers designed for broadband digital signal transmission and image-guidance

No	Parameter	Image-guide	Broadband transmission channel
1.	modal status	multimode, low mode visible band 0.4-0.7μm	single-mode in band 1.3-1.6μm, multi-mode in band 0.4-0.7μm
2.	core diameter	typically 1-3μm exceptionally 1-3μm	typically 5-8
3.	numerical aperture	as big as possible NA (0.7-1)	as small as possible NA 0.1

The condition of a single mode transmission for a chosen fiber defines its numerical aperture and core diameter. This boundary in the visible spectrum, was presented in fig.3.18. Actually we have several boundaries, one for different value of refractive index in the core. Fig.3.18. presents only three of them. The most critical condition, as far as the biggest boundary value of core diameter is concerned, is present exactly at the long wave length edge of a visible spectrum. These critical wave lengths in the core are: $\lambda=0,42$ and $\lambda=0,48\mu$m in these conditions and critical values of "a" parameter are 0,11 and 0,13, where a-core diameter.

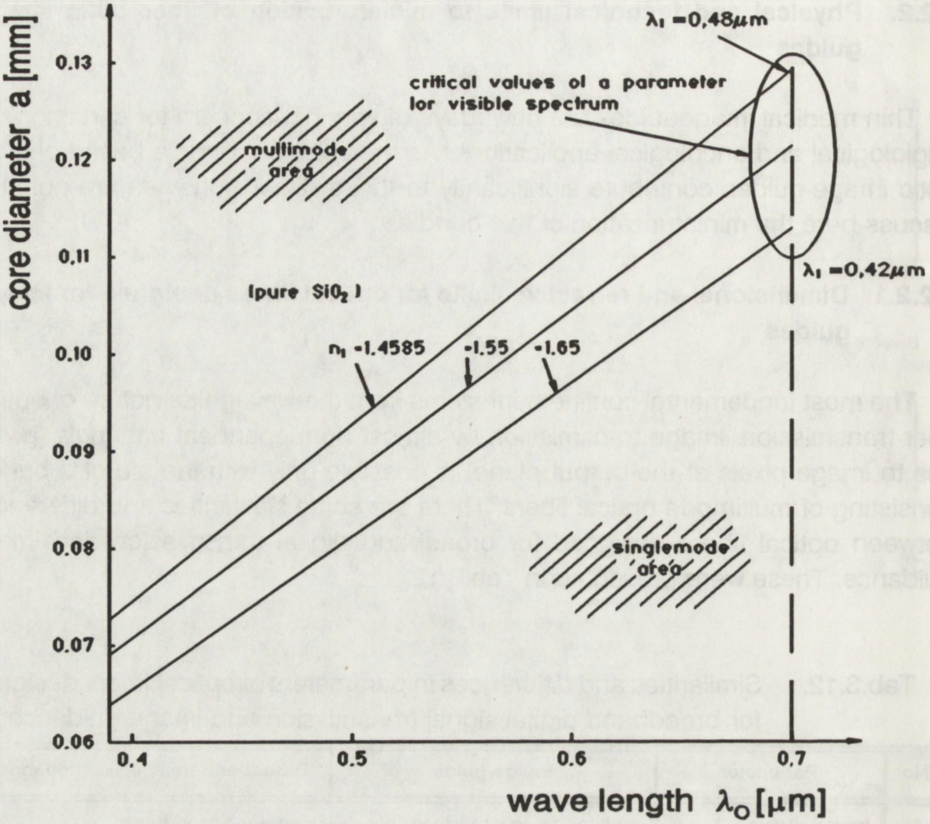


Fig.3.18. The boundaries between single mode and multimode guidance conditions in optical fibers designed for visible spectrum. Multimode propagation conditions are needed for high quality image guidance. Data:

V - normalized fraquency $V=akNA=ak_1 2\,\Delta n$,
n_1 - core refractive index,
Δn - relative difference between refractive indices of core and cladding $\Delta n=(n_1 - n_2)/n_1$,
a - core diameter in μm,
$k=2\Pi/\lambda_o$ - wavenumber in free space,
k_1 - wavenumber in core
$k_1 =2\Pi/\lambda_1, \lambda_1$ - wavelength in the core $\lambda_1 = \lambda_o /n_1$.

We are considering futher only multimode area from Fig.3.18. for high quality image guidance. But a question appears, how deep one should go into this multimode area, not to loose too much on dimensions of an individual fiber. In other words, how far away from the single mode boundary we have to choose the point of work for our high quality image-guide.

Tab.3.13. presents the results of simple calculations for optical fibers designed for visible band and nearing the single mode cut-off condition. Critical values of core diameter were calculated for different NAs and normalized frquencies V.

Tab.3.13. Physical limits of geometrical dimensions in the visible wavelength bandwidth for the high resolution optical fiber mosaic image-guides.

Normalized frequency $V = akNA$ $\lambda_o = 0{,}7\mu m$	Critical value of core diameter in μm			Number of modes propagated by fiber	Comments
	theoretical value of numer. apert.				
	0,4	0,87	1,0		
	theoretical angle of vision in degs				
	47	120	180		
2,4 for $\lambda_o = 0{,}4\mu m$	0,38	0,18	0,	2	limiting condition for short wavelength edge of bisible spectrum, quoted here to compare with long wavelength edge, best case for long wavelength edge, $a_{\Lambda}\ \Delta = 0{,}11\ \lambda_1 = 0{,}42\mu m$
2,4	0,65	0,30	0,26	2	
2,4	0,67	0,31	0,27	2	long wavelength edge of visible spectrum, worst case $a_{\Lambda}\ \Delta = 0{,}13;\ \lambda_1 = 0{,}48\mu m$,
3	0,84	0,38	0,33	6	too small number of modes for high quality image transmission
4	1,11	0,51	0,45	12	acceptable number of modes for high quality image transmission, guidance.
6	1,67	0,77	0,67	20	dimensions still of concern for a miniature high quality image guide,
10	2,79	1,28	1,11	approx.50	too big core dimensions for a miniature high resolution image guide.

We have made two choices from Tab.3.13. We have assumed in the first of them that the fiber should propagate at least 10 guided modes, while in the second this number amounted to 20. Thus our choices for core dimensions were $a_1 = 0{,}5\mu m$,

$a_2=0,7\mu m$, with fibers of NA < 1.

It is understandable why we need multimode transmission for a high quality image guidance.

Single mode transmision is inherently connected with observable interference effects, very low power and very small aperture angle - all of these features destroying the direct image information. To obtain the image of high quality we need optical fibers of big enough NA value and considerable number of guided modes present in a fiber. A considerable range of values for transmission angles is needed to transmit nondistorted information about a diffuse image.

3.2.2.2. Enhancing contrast and optical resolution in fiber optic image guides.

We have also summarized the basic ways of expanding technical limits in coherent bundle fiber optics image-guides and gathered the results in Tab.3.14.

Tab.3.14. Some ways of expanding technical limits in coherent bundle fiber optic image-guides.

No	Undertaken measures	Technical consequences	
		Positive result	Negative result
1.	very short endpieces	elimination of crosstalk	not very important, more difficult construction of both endpieces
2.	smallest possible core diameter	miniatrurization of image-guide and better optical resolution for thin cladding	nearing the single mode condition, image degradation for boundary conditions, smaller transmission
3.	smallest possible cladding thickness	increasing core packing density	increasing crosstalk, contrast degradation of image
4.	highest possible value of NA	increasing of contrast and angle of vision	decresing of sight directionality
5.	highest possible packing density	increasing image resolution	increasing crosstalk
6.	highest possible optical resolution		decreasing transmission, nearing single mode cut-off
7.	material choice for core: a.SiO_2 glass	high strength of fiber, high flexibility	only small NA possible
8.	multicomponent glass	very high NA possible	smaller strength of fibers, lower flexibility

Fig.3.19 presents optical resolution characteristics for coherent bundles of optical fibers with different (total) external diameters,chosen in the range 0,7 ÷ 5 μm. these characteristics are presented in classical references [3.7] most frequently for fibers with diameters going down from 75 μm only to 5 μm. One can see that the resolution exceeding a few hundreds of line pairs per mm is readily achievable with considerable value of contrast.

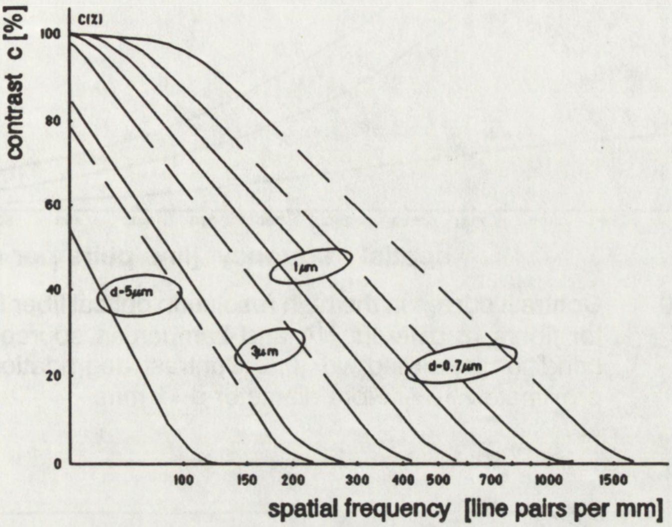


Fig.3.19. Contrast curves obtained in the high resolution optical fiber image-guides for various fiber diameters and NA=1 -solid lines present worst case orientation of bar-chart and coherent bundle, worst case condition: wd=0,5, -broken line present best case of orientation with condition wd=1.

Changing the numerical aperture below the boundary value 1, deteriorates contrast in the transmitted image. This effect was presented in a coherent guide manufactured of fibers with external diameter d=1 μm. The contrast does not reach 100% for zero spatial frequency because of stray light effect and core packing fraction effect, (Fig.3.20).

Another important effect connected with continuously diminishing core diameter is abruptly decreasing core packing fraction in the bundle F_C is measured as a ratio of core surface to elementary cell surface. Two cell geometries are possible: square and triangular. Two asymptotic values of F_C are 0,78 and 0,91 for these two geometries. Simple calculations of F_C for our high resolution image guide are presented in Fig.3.21.

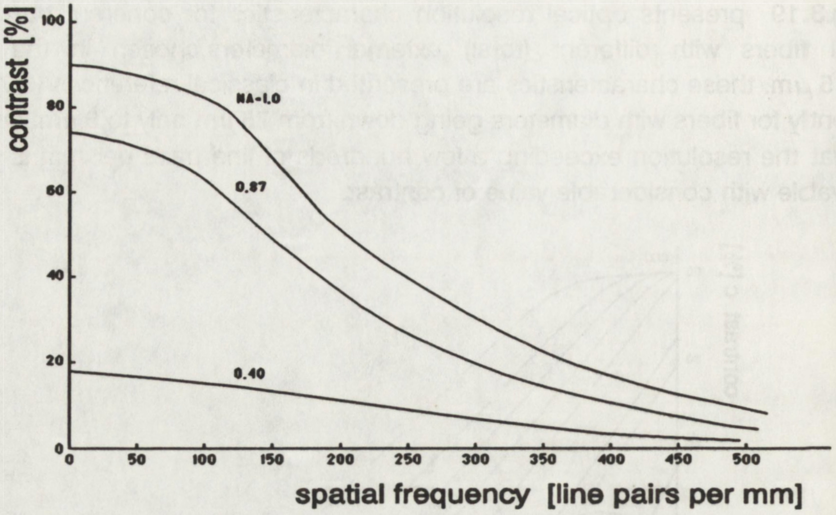


Fig.3.20. Contrast curves in the high resolution optical fiber image-guides for fibers of different NA and Lambertian source. Worst case condition is fulfilled wd=0,5. Contrast degradation is here approximately 10%. Fibre diameter d=1 mm.

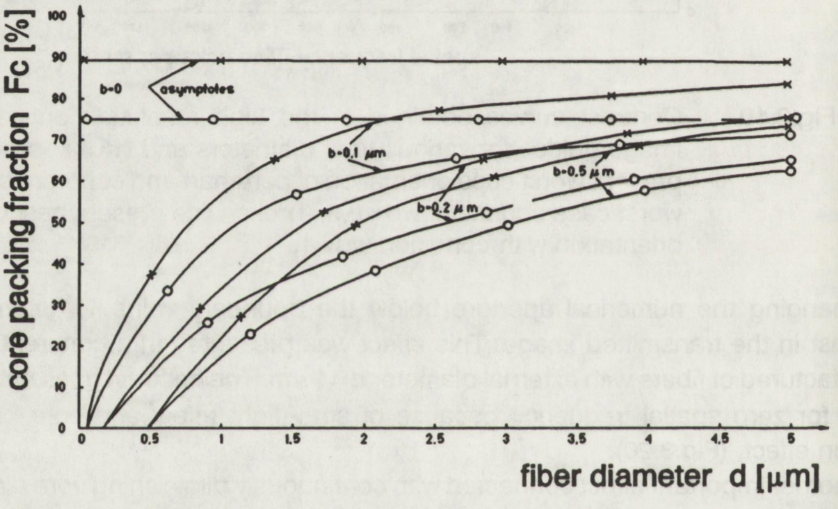


Fig.3.21. Core packing fraction in bundle end-faces as a function of fiber diameter d for various cladding thicknessess b in the high resolution image-guides made by mosaic technology. Elementary cell shapes marked on the curves by squares and regular triangles.

Our choices for cladding thickeness were as follows:

- for a_1 = 0.5 μm; b_1 = 0.10 μm to obtain d = 0.7 μm;
- for a_2 = 0.7 μm; b_2 = 0.15 μm to obtain d = 1.0 μm.

Also bigger values for these parameters were tried but they are not of interest here as they add significantly to a single cell dimensions.

3.2.3. Medical applications mosaic made imageguides

The major directions of development in medical endoscopy are indicated now by:

- miniaturization of high power optical channels acting under a direct visual supervision, and
- exploding applications of optical fiber medical sensors.

Tab.3.15. Assumed technical parameters for a medical micro-angioscope.

No	Parameter	General design requirements	Our choice
1.	external diameter of cathether in mm	not bigger than 1 or 1,5	1 and 0,7
2.	cathether cross section	circular	flat and circular
3.	cathether length in m	up to 1	0,5 and 1
4.	diameter of a through channel in mm	not smaller than 0,3	0,3 equivalent noncircular
5.	diameter of high optical power channel in μm	not bigger than 200 or 150	approximately 100
6.	diameter of optical fiber sensory channel in μm	not bigger than 150	75, nonstandard fiber,
7.	cathether flexibility	stiff enough to be operational from 1 m distant end, equivalent of 2-3 mm polyethylene cathether	
8.	diameter of imageguide in μm	not more than 500	400 for TV image quality, 200 for half-TV image quality
9.	designed for:	mainly for plaque removal in coronary arteries	other possible application under experimental investigations including oncology.

Two medical disciplines are here of major concern: angiology and oncology, trough several others are also of importance like gastroenterology, gynecology, cardiology, neurosurgery etc. The endoscope of the nearest future requires a reliable assembly of:

- small diameter optical power channel; actually at least two or even three such channels acting in near UV, visible and near infrared and medium infrared bands
- capable to cooperative with excimer, visible, Nd: YAG and CO lasers,
- micro-image-guide of high resolution and high image quality, - a multisensor fiber optic probe.

The equipment should also possess two additional channels: inflating-sucking, and forceps. The overal diameter of the endoscopic probe should not exceed much more than 1 mm, for some medical applications, for instance those used in arteriore-canalization procedures.

The early version of fiber optic angiocathetter has to be supplemented with a fiber optic image guide, to be an instrument of a real usefullness for contemporary and future cardiology. We have gathered the major technological requirements for such instrument in Tab.3.15.

We also included here our choices for the design. The most important parameter here is external dimensions of the cathether (endoscopic probe). To reach the coronary arteries its external diameter must not exceed approximately 1 mm. Thus, we have only so small place for our disposal to accomodate, in a comparatively stiff package of very thin walls, the following channels: image guide, optical power, sensor and open channel.

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