PROCEEDINGS REPRINT
SPIE–The International Society for Optical Engineering

Reprinted from

Proceedings of

Optical Fibers in Medicine VI

23–25 January 1991
Los Angeles, California

SPIE Volume 1420

Box 10, Bellingham, Washington 98227 USA. Telephone 206/676-3290.

INFRARED CABLES AND CATHETERS FOR MEDICAL APPLICATIONS

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ABSTRACT

New medical applications of IR lasers can be rather wider with flexible cables and catheters for laser power delivery. Optical parameters of fibers for Er; CO- and CO_2-lasers alongside with design of special optical connectors, efficient coupling units and optics at distal end are reviewed. Applications of cables and catheters for laser therapy and medical diagnostics are analyzed.

INTRODUCTION

The interest for development of flexible cables and catheters for laser power delivery is growing due to the necessity in:

- flexibility of cables for multi-dimensional operations;
- multifiber catheters;
- intracavity laser treatment, including endoscopical laser surgery (intravascular angioplasty etc.);
- "smart" laser fiber systems for controllable laser operations (based on real-time management of laser tissue interaction by means of fiber optic non-contact remote sensing and on laser power delivering by the same cable).

The manufacturing of fiber instruments for non-invasive laser medicine in the region 0.248-2.1 μm transferred from scientific to commercial scale because of availability of commercially manufactured silica fibers. But laser applications in the middle infrared region (MIR): 2.5-12 μm are still restricted by the absence of reliable flexible cables for Er, CO- and CO_2- lasers. These lasers are very promising because of several reasons:

- high absorption in tissue (Fig.1);
- possibility to vary the ratio of ablation efficiency to a thickness of coagulation zone (by pulsewidth variation or by combined use of different wavelength radiation);
- wide experience of numerous physicians in CO_2- laser medical application;
- moderate prices and sizes of these safe lasers in comparison with excimer and other lasers for UV- and visible region.

Besides, the opportunity to use the IR- fibers for remote non-contact temperature control of irradiated zone allows to design the special multichannel catheters or to use the same IR-fiber for laser power delivery and temperature sensing in projects of "smart" laser-fiber-systems (LFS) with exiting idea of automatically controllable welding, coagulation or cutting procedure [1].

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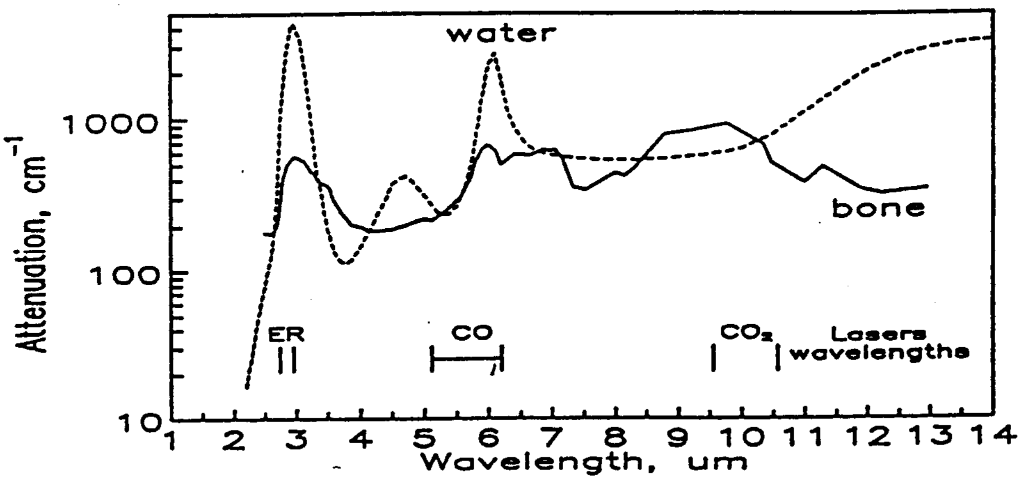


Figure 1. Spectral dependences of attenuation in bone and in water (close to attenuation in muscule tissue).

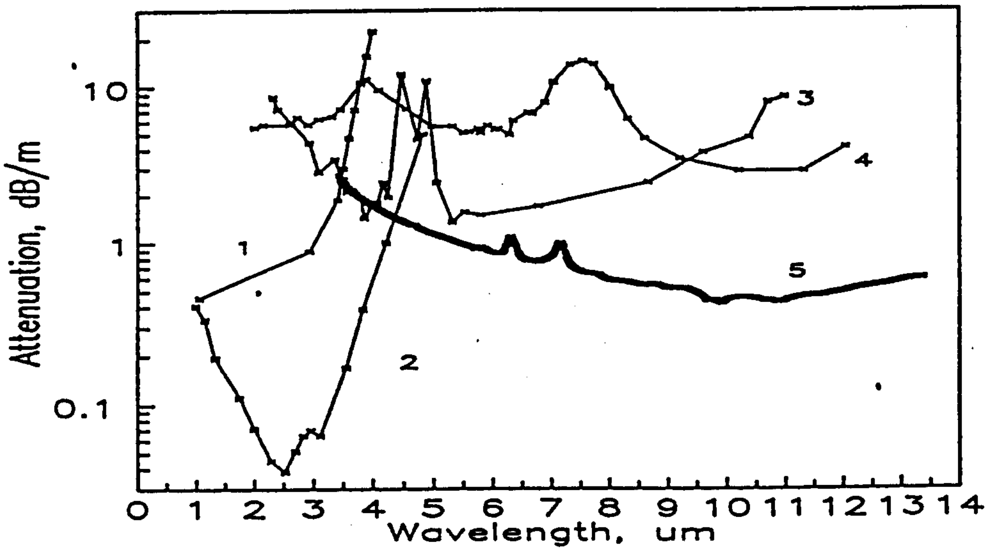


Figure 2. Attenuation spectra of different kinds of waveguides:

1 - sapphire,
2 - fluoride,
3 - chalcogenide,
4 - HCW,
5 - MIR.

COMPARISON OF BASIC IR- FIBER PARAMETERS.

Brief review of optical loss spectra of sapphire, fluoride, chalcogenide, silver halide fibers and hollow circular waveguides is presented at Fig.2. The resulting table 1 shows the optical losses of different fibers for the main medical lasers:

Table 1. Optical losses in lasers fibers (dB/m).

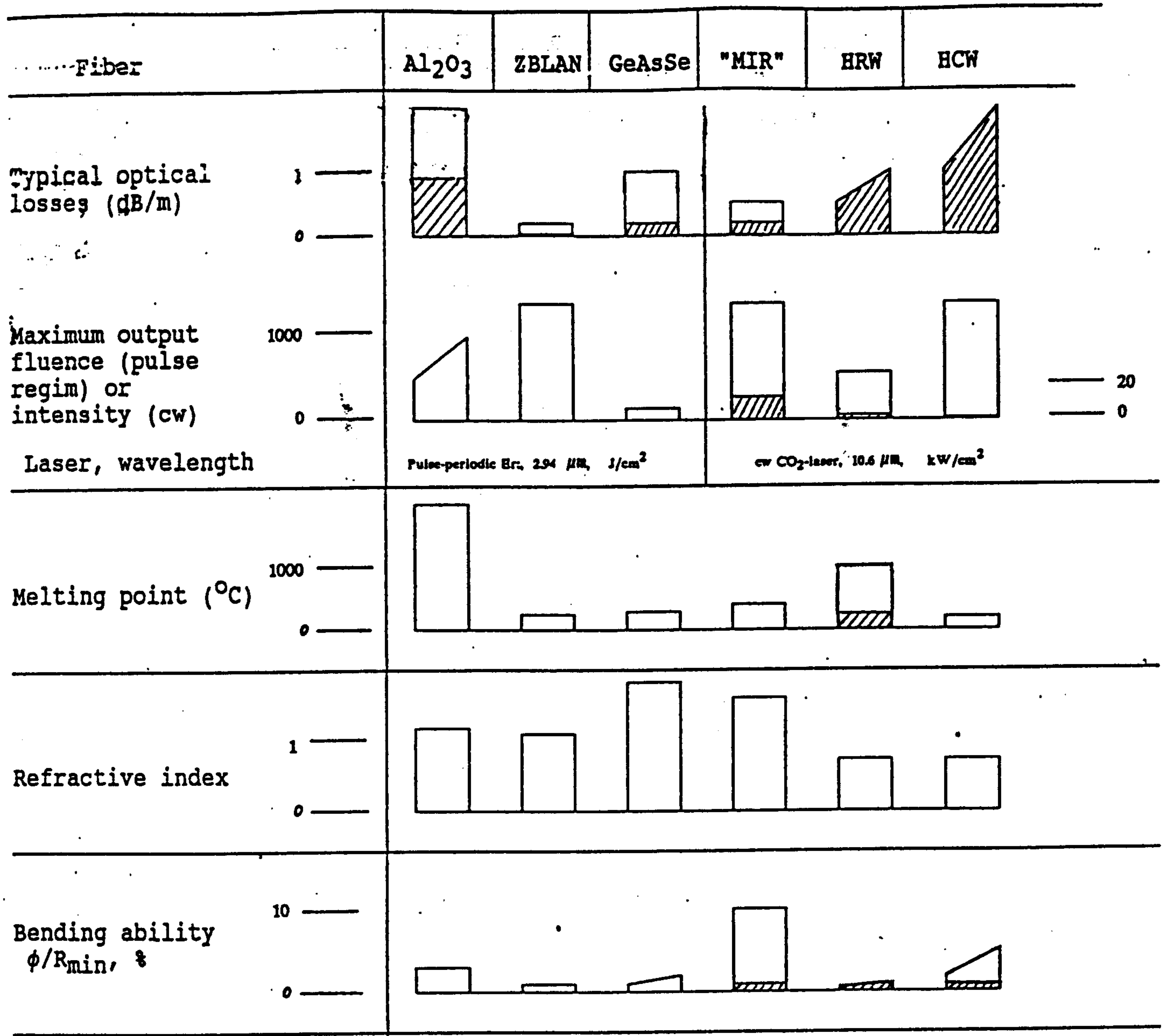
Laser	(μm)	Q/Q-UV	Q/Q-WF	Al_2O_3	ZBLAN	AsSeGe	AgHal	HRW
ArF	0.193	---	---	---	---	---	---	6
KrF	0.248	1	---	---	---	---	---	
XeCl	0.308	0.1	---	---	---	---	---	
XeF	0.351	< 0.1	---	---	---	---	---	
Nd:YAG	1.06	---	< 0.01	---	---	---	---	
Ho:GSCG	2.09	---	< 0.1	---	---	---	---	
Er:YAG	2.94	---	---	0.88	< 0.2	< 0.2	3.0	?
CO	5.2-6.2	---	---	---	---	< 0.2	0.5	< 0.5
CO_2	9.6-10.6	---	---	---	---	> 1.0	< 0.2	< 0.5

But a more complete comparison demands to take into account the whole set of practical requirements, which are evident for laser fibers:

- Small optical losses
- High laser damage thresholds for cw and pulse regime
- High flexibility (R core / R cladding $\leq 1/1.2$)
- High numerical aperture (NA > 0.2)
- Nontoxic and nonhygroscopic materials
- Stable AR coating of the ends, especially for materials with $n \geq 2$.
- Optimal and reliable coupling with laser beam.

The comparison of enlisted parameters in Table 2 provides the possibility to choose the proper fiber for Er- or CO_2- laser. The choice of fiber for CO- laser could be done between chalogenide and silver halide MIR-fibers. Fortunately, MIR-fibers are transparent at 5.2 - 6.2 μm with level of losses nearby 0.5 - 1.5 dB/m. Ge-As-Se fibers possess smaller losses 0.2 - 0.5 dB/m for CO- laser (Table 1) but these fragile and toxic fibers (Table 2) could not be under serious consideration for medical applications. CO- laser is also one of the most promising for medical applications [2] due to simultaneous generation of more than 30 lines in the region 5.2 - 6.2 μm, where the tissue absorption varies from 200 to 2000 cm^{-1} (Fig.1). This unique feature allows to use CO- laser for combined effect of efficient ablation along with reliable haemostasis instead of similar "Combolaser" systems based on Nd:YAG and CO_2- laser [3].

Table 2. Basic physical properties of IR-fibers



Fiber	Al_2O_3	ZBLAN	GeAsSe	"MIR"	HRW	HCW
Drawbacks		Fragile, Wet Corrosion	Fragile Toxic	UV-sensitive	Necessity in polarized beam	
Commercial source		Infrared Fiber Systems		CeramOptec Systems		
	---	IRIS Fiber Optics Le Verre Fluore	---	Matsushita	---	Sharplan

NEW RESULTS IN DEVELOPMENT OF IR- FIBERS.

The main news of the last year is transfer of IR- fiber development from science to producibility concerning especially MIR-fibers manufactured by Soviet-German-American Joint Venture "Ceram-Optec Systems" and by "Matsushita", Japan, and hollow circular waveguides "Flexilase", manufactured by "Sharplan", Israel and based on polymer tubes coated inside by 1 - 3 μm metallic layer and by 0.025 μm dielectric layer.

The promotion in development of **sapphire, fluoride and chalcogenide fibers** was not so substantial for their medical applications.

Hollow plastic circular waveguides provided by "Sharplan" to their CO_2- lasers are the good practical step to a more convenient medical operations. But too large spot size (ϕ 1.9 mm) restricts the output intensity < 1 kW/cm^2 and than the bending of Flexilase fiber reduces the power transmission [4].

Hollow rectangular waveguides can handle more than 100 W of CO_2- laser and provides the intensity in 0.5 mm spot (after focusing) more than 40 kW/cm^2. This high intensity, high transmission under moderate bending and twisting, absence of problem with laser-induced damage in delicate IR-optics plus opportunity to use the HRW itself for cooling stream of gas determine the promising future in applications of HRW cables in external laser operations, especially for such laser power consuming procedures like cutting, evaporation and so on. HRW can be also used with TEA CO_2- lasers [5] for realization of the most efficient use of laser energy in pulse-periodic regim (more than 120 mJ in 80 ns pulse) for cutting with minimal thickness of necrosis zone. MIR-fibers can be also used for optimized pulse regim of TEA CO_2-laser but for pulse energy less than 100 mJ. Main advantages of HRW cables in comparison with standart joint mirror articulated arms are their flexibility and absence of expensive joint mirrors and these cables could be used with all medical lasers-from 0.193 to 10.6 μm [5]. Specific feature of HRW is necessity in polarized beam for high transmission, but it means just a simple modification of a typical medical lasers. Multiple bending of HRW confirms high reliability of these cables - no changes in transmission after 70.000 cycles of bending at 8 cm radius [6].

Polycrystalline MIR- fibers have been under investigations and under transfer to producibility in several directions:

- development of technology of core/clad structure extrusion,
- improvement of bare core fiber extrusion for reduction of reproducible level of optical losses,
- testment of stability of optical losses, (aging),
- investigation of UV-induced optical losses mechanism,
- investigation of fiber overheating under laser power delivery and design of cable connectors.

The cross-section of core/clad structure is based on $ArCl_{0.25}ArBr_{0.75}$ core and $ArCl_{0.75}ArBr_{0.25}$ cladding compositions is presented by Fig.3. Chemical etching of surface reveals a complicated structure of fiber, consisted from mixture of crystallized and amorphous regions (Fig.3b). The geometry of this mixture reflects the viscous character of extrusion process and can be responsible for one of λ^{-2} scattering mechanisms in fiber due to the possible difference in refractive indexes of the phases. Our assumption of existence of such scatterers was made in 1987 [6]. Unfortunately such evident advantager of core/clad fiber as smaller divergence and protection of optical properties from side surface deteriorations are still not realized for good quality of core/clad boundary (Fig.3) because of high level of optical losses in comparison with bare core fiber. For CO_2- laser launching NA < 0.1 minimal losses were 1 dB/m only (Fig.4).

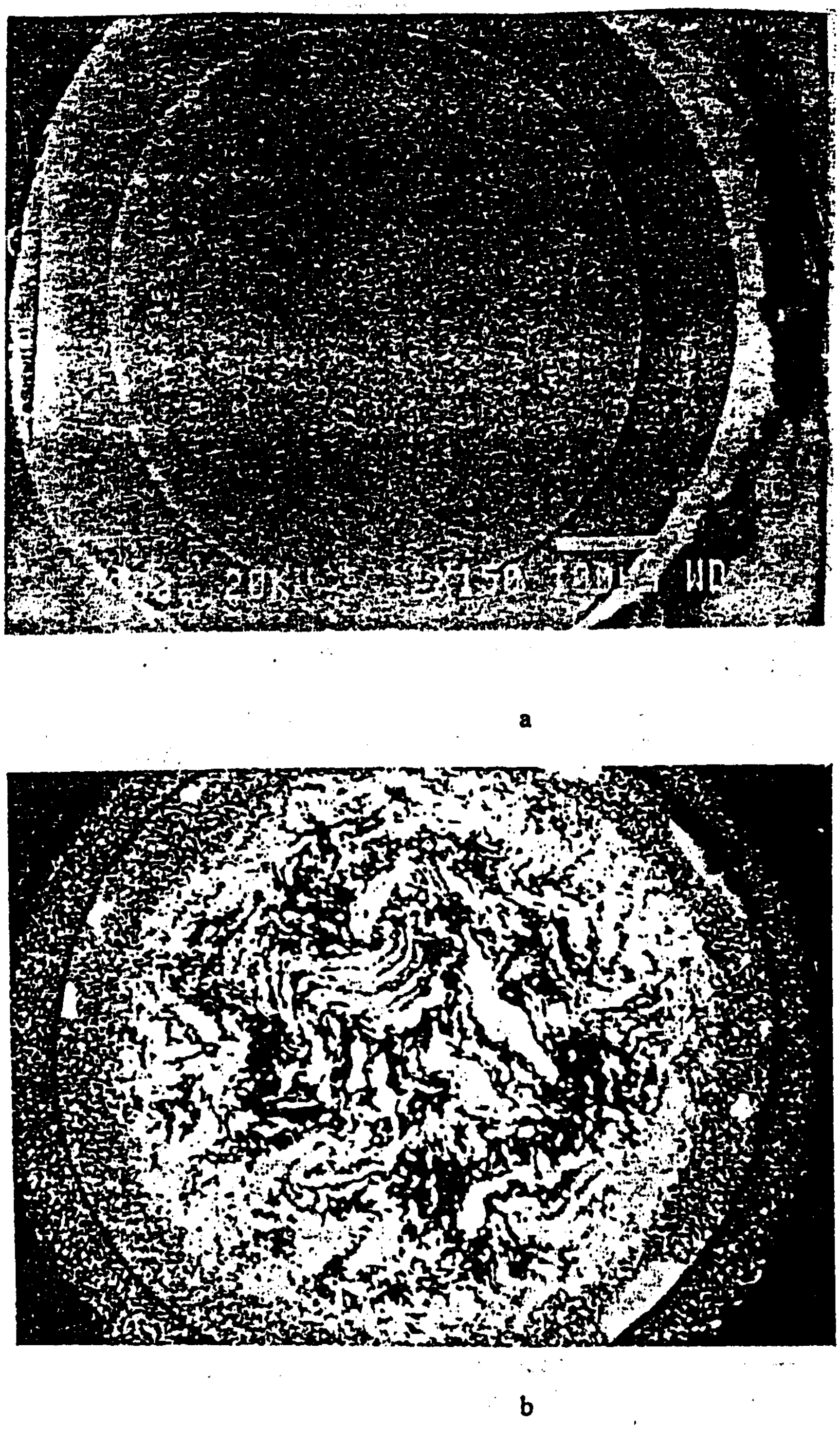


Figure 3. Cross-section of ϕ 0.7 mm core-clad MIR-fiber:
a - SEM-picture,
b - chemically etched surface (optical microscope)

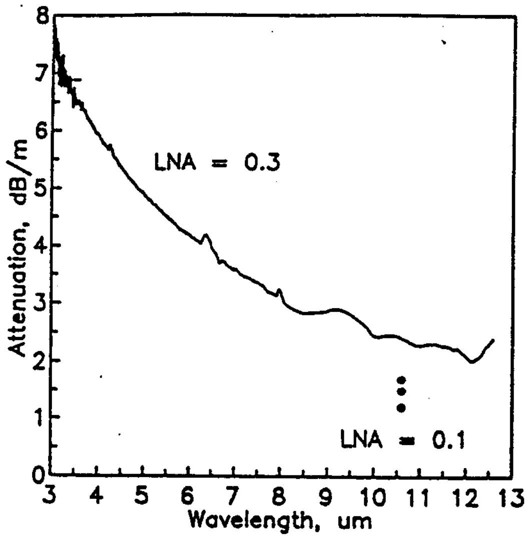


Figure 4. Spectral attenuation of core-clad MIR-fiber

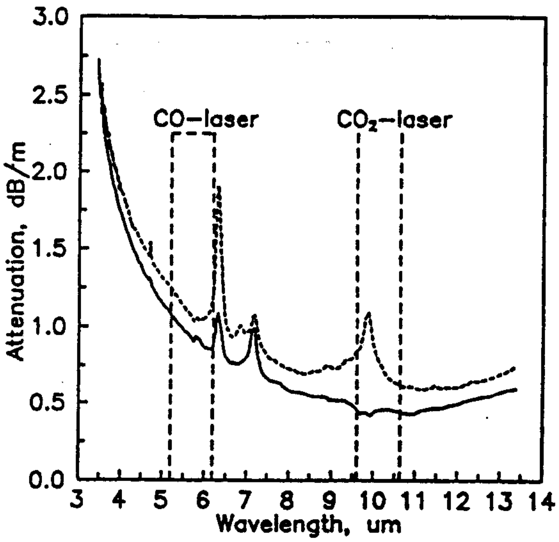


Figure 5. Improvement of optical losses spectra of MIR-fibers, manufactured by CeramOptec Systems

The development of bare core fiber extrusion technology provides the better optical losses spectra (Fig.5). Since last year these fibers are commercially available at the market. For clarification of question of shelflife of 1st version of this product some samples were tested during several mounths (Fig.6).
Attenuation spectra were measured with FTIR-spectrophotometer "Bruker-IFS-113" in 3-13 μm region by cut off method. Fiber was kept in non-hermetic loose polymer tube for 9 months. Spectra of fiber is shown at Fig. 6. The first spectrum was measured immediately after fabrication process, the second spectrum was measured in 5 months after extrusion and the third - after 9 months after extrusion.

The most interesting region is from 5 to 11 μm because most impurities peaks are in this region. The peak at 6.28 μm connected with atmospheric water. It depends on adsorption of water on the fiber. The peak at 7.15 μm connected with chemistry of silver halide solid solutions, because it exists in all spectra of AgHal fibers. A peak among 8 and 9 μm is not usual for MIR- fibers and it determines by purity of fiber fabrication method. Using another method it is possible to avoid this peak (Fig.5).

The deterioration of losses is depend on set of technological parameters, and last results with novel MIR-fibers (lower line at Fig. 5) reveals the opportunity to save the small optical losses by proper choice of technological parameters along with cable design and exploitation conditions.

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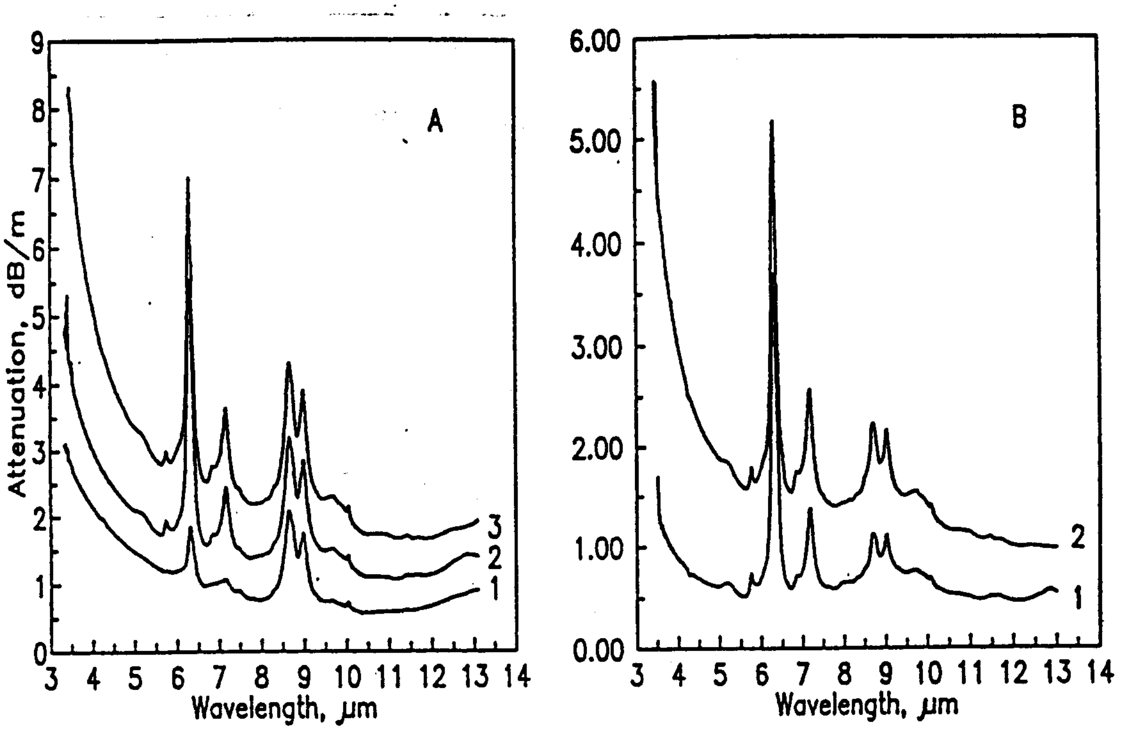

Figure 6. Spectra of attenuation of silver halide fiber:

a: 1- immediately after extrusion
2- in 5 months after extrusion
3- in 9 months after extrusion

b: 1 - different spectrum between spectrum 2 and 1 (a)
2 - different. spectrum between spectrum 3 and 1 (a).

SILVER COLLOIDS ABSORPTION.

Absorption and scattering on silver colloids is one of the possible optical loss mechanism in MIR-fibers. Changes of temperature and mechanical stresses under extrusion and exploitation could lead to colloids formation alongside with well-known UV-induced process. Silver colloids have characteristic peak of extinction in visible region. Decay of this peak could cause the additional losses in IR region. To distinguish silver colloids extinction from other optical losses mechanisms the losses spectra of UV-irradiated fibers could be analyzed.

If the dose of radiation is not too large the dimension of silver particles is small ($x<<1$). In that case all losses connected with silver particles is restricted mainly to the excitation of the first spherical surface plasmon mode, exited in metal particle. The efficiency of absorption of spherical particle can be calculated using Mie's theory [7]:

$$Q_{abs}=12\,x\,\frac{\varepsilon_m\,\varepsilon_2}{(\varepsilon_1+\varepsilon_2\,\varepsilon_m)^2+\varepsilon_2^2}$$

where x - diffraction parameter, ε_m - dielectric constants of medium.

Dielectric constants of metals in IR region satisfy simplified Drude free-electron theory equations:

$$\varepsilon_1 = 1 - \frac{\lambda^2}{\lambda_p^2}; \quad \varepsilon_2 = \frac{\lambda^3}{\lambda_p^2} \cdot \frac{1}{2\pi c\tau}$$

where λ_p - wavelength of plasma frequency, τ - relaxation time, c - velocity of light. For small metal particles relaxation time depends from dimension of particle and include two terms [8]: $1/\tau = 1/\tau_0 + V_f a$, where $1/\tau_0$ - bulk metal damping constant, V_f - Fermi velocity.

In the case when prevail losses caused by absorption on silver colloids the power flow in fiber is determined by simplified transport equation: $dP/dz \approx -\pi a^2 n_v P Q_{abs}$,

where P - power inside fiber, a - radius of colloids, z - longitude coordinate, n_v - number of colloids; and the absorption loss is $\alpha_{abs} \approx \pi a^2 n_v Q_{abs}$.

So, if the added losses during UV radiation connected only with absorption, these losses could be calculated using the above equality.

Series of experiment was conducted to compare that simplified theoretical view, obtained above, with experiment. Fibers that were used in experiment was extruded from pure $AgCl_{0.25}Br_{0.75}$ crystals. For silver particle nucleation the fiber was irradiated without any filters by a Hg pressure lamp. Transmission spectrum before and during UV irradiation was measured by infrared Fourier spectrometer "Bruker IFS-113v". After finishing of irradiation the fiber was cut off and transmission spectrum of input piece of fiber was measured. That part of fiber was protected from UV radiation. Fig. 7 shows the additional fiber losses produced by UV radiation.

Another experiment was made using laser calorimetry method [10] for separation the absorption and scattering components of losses in irradiated and unirradiated pieces of fiber at CO- laser wavelengths 5.2 - 6.2 µm. Before irradiation the total losses was α_t = 2.5 dB/m, absorption losses was α_{abs} = 1.1 dB/m, after irradiation total losses became α_t = 12.1 dB/m, absorption losses became α_{abs} = 9.2 dB/m. Main part of additional losses was connected with absorption and probably was caused by small silver particles. Experimental loss spectrum and theoretical formula for absorption colloidal losses were used for nonlinear least squares fitting. Characteristic radius of silver particles that grow during UV irradiation and concentration of these particles was given from that adjusting procedure. Size distribution of colloids haven't been taken into account.

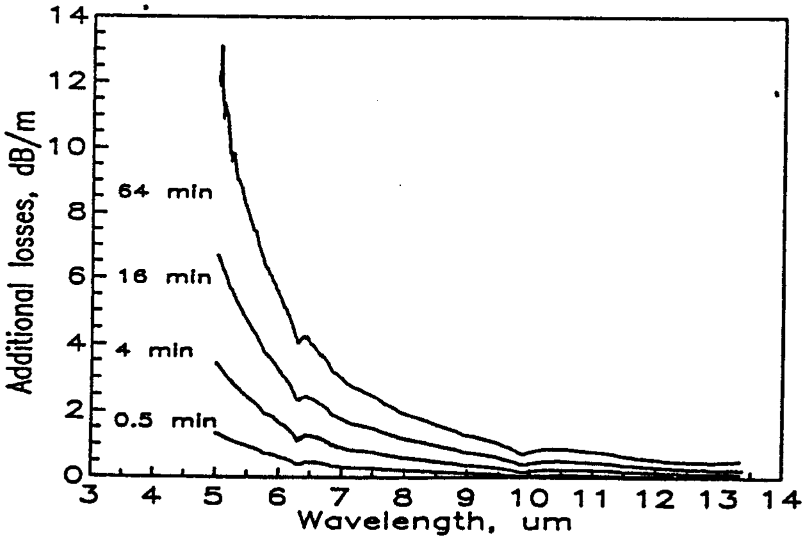

Figure 7. Dependence of UV-induced losses on time of irradiation (for 250 watt Hg-lamp at 30 cm from the fiber).

The main result is that the dimension of silver colloids grew quickly till 3 nm - 4nm after irradiation during first 30s and then practically does not change. The following increase of losses is determined may be by the rise of colloids concentration from 10^{14} cm^{-3} till $10^{15}cm^{-3}$.

This first experimental results confirm our assumption [9] about mechanism of retarding of silver colloids formation in superfine (10nm - 100nm) structure of fiber extruded from such solid solutions as $AgCl_{0.25}Br_{0.75}$. The multiple structure defects slow down substantially the interstitial silver diffusion in difference with easy diffusion in large grain size structure of AgCl or AgBr fibers.

FIBER LASER POWER HEATING AND CABLE DESIGN.

To evaluate the permissible laser power level transmitted through the fiber or to choose an optimal cable design and working condition one should know exactly the fiber temperature distribution.

We have solved the modified heat equation for a long and thin rod with bulk (distributed as G Exp(-az), where a is an extinction coefficient, plus r G Exp(-a(L-z)) because of Freshnel reflection) and surface (on fiber tip) heat sources. The special feature was the considerable role of the heat transfer through the lateral fiber surface and the constant value of the cross-sectional temperature profile we have assumed.

Temperature measurement was conducted by non-contact method in fiber. As one can see (Fig. 8) a temperature of fiber near a tip varies as $T_S \exp(-kz)+T_B(z)$, where k is approximately 0.5-0.6 mm^{-1}, T_S and T_B

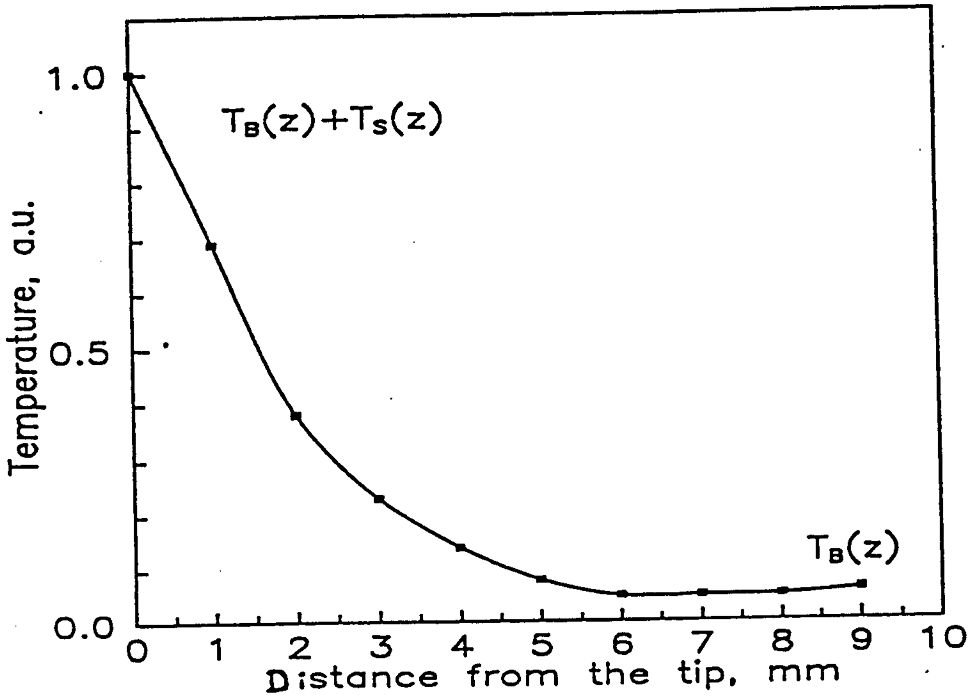

Figure 8. Typical static temperature profil near a heated tip (additional to an air temperature) T_B and T_S are proportional in incindent power. The value T_S/T_B depends on the surface absorption and the extinction coefficient T_S/T_B is usual larger than 10.

are contributions of surface and bulk sources. Thus, the tip temperature of the fiber with usual losses 0.3 - 0.5 dB/m is determined mainly by heat sources at the surface of fiber tip. For example, after the tip processing with the polished ceramic knife the fiber can transmit at least 20 - 25 Watts of the CO_2- laser radiation without the danger of fiber tip damage. The fiber tip heating in this case is only 100°C while the damage temperature is about 400°C. The presence of absorbing layers or surface defects decreases the secure transmitted CO_2- laser power level up to 10 - 20 times.

The considerable effect of mentioned above factors on tip damage makes it necessary to protect the tip by external window, made of any non-toxic and non-hygroscopic IR- material with high melting temperature and low-reflection losses. This window may be in an optical contact with fiber tip to eliminate a temperature rise due to a Freshnel reflection. The other well known way is to deposit AR- coating on the fiber tip [11].

Design of connectors, handpieces and coupling systems for laser power delivery has to be done also from the point of view of minimal overheating under high-power level. Control of temperature distribution of different connectors and cables based on MIR- fibers and HRW- waveguides has been done with IR- imaging camera under delivery of power of cw CO_2- laser at 9.5 μm. This CO_2- laser with unusual wavelength has been manufactured by Zeiss due to higher absorption of this radiation in bones in comparison with typical 10.6 μm (Fig.1). Temperature of MIR- fibers with optical losses 0.4 dB/m at 9.5 μm increased under delivery of 10 W (20 W at the input) within 1-2°C, and only polymer tubes were heated for higher temperature due to their smaller temperature conductivity and absorption of light scattered by fiber. Time constant for MIR- fiber heating till stationary state was nearby 5 s and for MIR- cable with SMA- type connector - several minutes.

The overheating of connectors for HRW cables was due to Freshnel reflection of coupling optics, but the overheating at the beginning of HRW was much higher due to unpolarized beam of used laser.

APPLICATIONS.

First applications of new IR- laser fiber systems are under development in different areas of medical treatment. One of the first clinical applications of CO_2- laser with MIR- fibers has been made in welding of lymphous and venous vessels in 1988 [12].

For such operations like welding or coagulation of tissue it's necessary to deliver 1-2 W of cw CO- or CO_2- laser. Even to remove the fibrous tissue inside the eye it's sufficient to insert the scalpel probe with 1.6 mm diameter and only 2 W at the output diamond window fitted to the tip of MIR- fibers [13]. CO_2- laser with MIR- fiber ("Medilas 10 S") was also used to necrotize the cancer in the rectum, trachea and bronchi with 7 W at the output of endoscope. 10 W at handpiece output of the cable is sufficient to remove the condilomas without bleeding [14].

The experimental testment of CO- laser with polycrystalline fiber showed the advantages of the use of its wavelengths in cutting of rabbit lung with reliable haemostasis and sealing of lung air passagers only (with 0.5 kW/cm^2 intensity in the focal spot). The 2.5 mm diameter vein has been coagulated and cutted also without bleeding during 15-20 s [2].

CO_2- lasers with HRW- cables are under experimental applications now [15], and they will certainly have wide medical applications, especially in external laser power consuming operations.

CONCLUSIONS.

New stage of development in technology and design of IR- cables is characterized by transfer from science to producibility of several products: MIR- fibers, hollow rectangular and hollow circular waveguides for delivery of radiation of Er:, CO- and CO_2- lasers. To accelerate this development the medical

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experimental and clinical test of new IR- laser-fiber systems has to be made along with improvement of IR-LFS itself.

Future wide applications of MIR- fibers for non-contact temperature measurements in endoscopical diagnostics and for design of "smart" LFS is determined by their best transmission in the middle infrared region [15] and needs in design of correspondent sensor cables and catheters.

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