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Technical Note

Polycrystalline i.r. fibres for laser scalpels

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Abstract. The optical and mechanical properties of polycrystalline i.r. fibres in power delivery for laser surgery has been measured in several materials including salts and salt alloys. A viable fibre for 10·6 μm is near development.

1. Introduction

Recent progress in laser technology and surgery has encouraged the design of fibres for power delivery for various laser devices. Table 1 lists the most promising fibre laser scalpels (FLS) which can be used in surgery as well as some characteristics of interaction of laser radiation with tissue. The comparison of the ablation threshold shows that for the CO laser and for the pulsed CO_2 laser this value is small. Nowadays CO_2 lasers are widely used in surgery, but their application is limited by the absence of commercial fibres which have low losses at 10·6 μm as well as high mechanical strength.

The main fibre characteristics for the region 5–20 μm show the advantages of polycrystalline (PC) fibres in comparison with chalcogenide and hollow ones (table 2). They combine low losses (0·1–0·3 dB m^{-1} at 10·6 μm) with high mechanical strength, which allows bends with a radius as small as 1 cm for fibres with a 0·5 mm diameter. These characteristics make polycrystalline fibres suitable in the design of CO and CO_2 laser fibre scalpels [3–5].

It is necessary to improve the operational characteristics of the fibre; that is, to lower the optical losses and to increase mechanical and optical endurance against stresses, temperature, u.v. radiation and radiation of continuous and pulsed CO_2 lasers.

2. Characteristics of promising PC fibres

The comparative analysis of the best samples of PC fibres (table 3) shows that the lowest losses are not achieved in the fibres of the highest strength. Technological difficulties make impossible a combination of low losses and high strength even in the most promising fibres with reflecting cladding. For applications in laser surgery, the best are PC fibres from silver halide solid solutions. Unlike thallium halides, they are non-toxic, practically non-hygroscopic and have higher bending strength. For example, the strongest fibres KRS-13 (0·25 AgCl–0·75 AgBr) allow

Table 1. Characteristics of promising fibre laser scalpels.

Laser	Wavelength (μm)	'A' Tissue absorption (cm^{-1}) [1]	Ablation threshold ($J\ cm^{-2}$) [2]	Types of fibres
XeCl	0·308	200	0·8–0·9	quartz
Argon	0·5145	14	20–30	quartz
Nd:YAG	1·06	4	30–40	quartz
Er:YAG	2·94	2700	0·1–0·5	fluoride glass
CO	5·2–6·2	100–1000	0·5	polycrystalline chalcogenide glass
CO_2	10·6	600	2	polycrystalline hollow, chalcogenide glass
TEA CO_2	10·6	600	0·7	polycrystalline, hollow, chalcogenide glass

Table 2. Characteristics of fibres used for the power delivery.

Wavelength	Fibre	Losses ($dB\ m^{-1}$)	$\frac{\text{Fibre diameter}}{\text{Bending radius}}$ (%)	Threshold intensity ($kW\ cm^{-2}$)
5·2	As_2S_3	0·3–0·9	0·4–3	25
5·2 6·2	KRS-5	1–2	1–5	>5
	KRS-13	1–2	3–10	>5
10·6	As–Ge–Se–Te	2	0·4–3	>1
10·6	KRS-5	0·2	1–5	5–50
10·6	KRS-13	0·2	3–10	>8
10·6	hollow	0·2–3	0·5	30

Table 3. Parameters of crystalline fibres.

Material	Losses at 10·6 μm (dB m^{-1})	Tensile strength (MPa)	Output threshold intensity (kW cm^{-2})	Manufacturer
KRS-5	0·13	36	50*	Matsushita (Japan)
KRS-5	0·20	60	5	IOFAN (U.S.S.R.)
KRS-5 in KRS-6	0·20	30	—	Furukawa (Japan)
KBr in KCl	0·1–1·0	14–21	13·3	Cooper Laser Sonics (U.S.A.)
$\mathrm{AgCl}_{0{\cdot}22}$:$\mathrm{AgBr}_{0{\cdot}98}$	0·07	25	10·7	Sumitomo (Japan)
AgBr in AgCl	0·22	20	—	Sumitomo (Japan)
$\mathrm{AgCl}_{0{\cdot}55}$:$\mathrm{AgBr}_{0{\cdot}5}$	0·15	90	5	School of Physics and Astronomy (Israel)
KRS-13	0·2	150	8	IOFAN (U.S.S.R.)
KRS-13 in AgCl	0·9	150	14	IOFAN (U.S.S.R.)
ZnSe	>0·3	very fragile	—	CVD Incorp. (U.S.A.)

* with AR coating at ends.

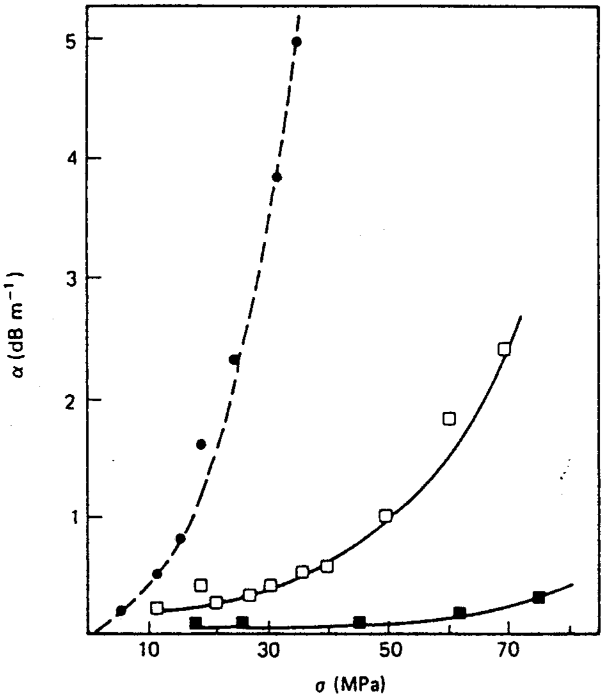

Figure 1. Optical losses in PC fibres induced by stretching stress. (■) KRS-13, λ=10·6 μm; (●) KRS-5, λ=10·6 μm; (□) KRS-13, λ=5·6 μm.

bend radii two to three times smaller than the minimal bending radii of fragile fibres from KRS-5 (TlBr–TlI). In KRS-13 fibres, we achieved the loss level of 0·2 dBm^{-1} at 10·6 μm, which is worse than the value of 0·7 dBm^{-1} obtained for more plastic fibres of 0·02 AgCl–0·98 AgBr composition [5]. But the significantly higher elasticity of KRS-13 fibres provides not only the highest strength, but also the lowest losses induced by stretching the fibre.

The dependence of optical losses in KRS-13 fibres on the stretching stress (figure 1) shows that it is similar to that obtained for KRS-5 fibres, that is $\alpha \sim \tau^2$ [6], but the area of elastic deformation for KRS-13 fibres is wider and the level of induced losses is much less sensitive to the stress. Characteristics of PC fibres can be improved if the air core structure is replaced by the structure core-reflecting cladding. Besides, in cladded fibres it is possible to stabilize the level of losses by the application of a protecting and strengthening polymer coating on the reflecting cladding [7].

In spite of low losses, fibres with reflecting claddings do not show high strength—AgBr in AgCl and KRS-5 in KRS-6 for example (see table 3). That is why we have fabricated fibres with KRS-13 core and AgCl cladding. The fibre external diameter was 960 and 1400 μm, and the core diameter 200 and 700 μm, respectively (see figure 2). Losses in fibres with the greater diameter were 0·9 dB m^{-1} at 10·6 μm. The breaking strength of the core was 150 MPa. In comparison with unclad fibres the lower apertures of cladding fibres allow one to achieve higher intensity by focusing the transmitted laser radiation (figure 3). This parameter is the most important for the application of fibre laser scalpels in surgery and technology.

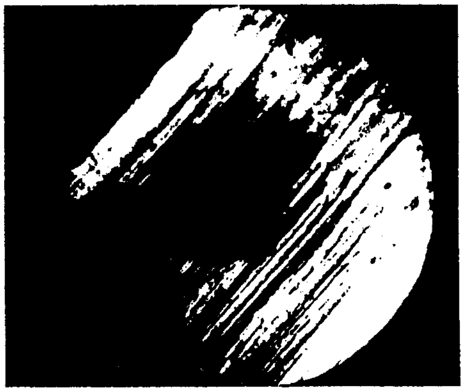

Figure 2. Cross-section of fibres with KRS-13 core and AgCl cladding; $\phi=960$ μm.

While u.v. sensitivity of silver halides restricts applications, we have investigated the absorption induced by u.v. radiation (the radiation of a mercury lamp) in the initial AgCl, AgBr and KRS-13 crystals as well as in fibres drawn from them. The investigations have shown that the induced absorption at wavelengths of 5–6 and 10·6 μm in the initial crystals decreases in the order AgCl, KRS-13, AgBr [8], but the induced absorption in fibres sharply decreases in the order AgCl, AgBr, KRS-13 (see table 4). The high endurance of KRS-13 fibres to u.v. irradiation is, to

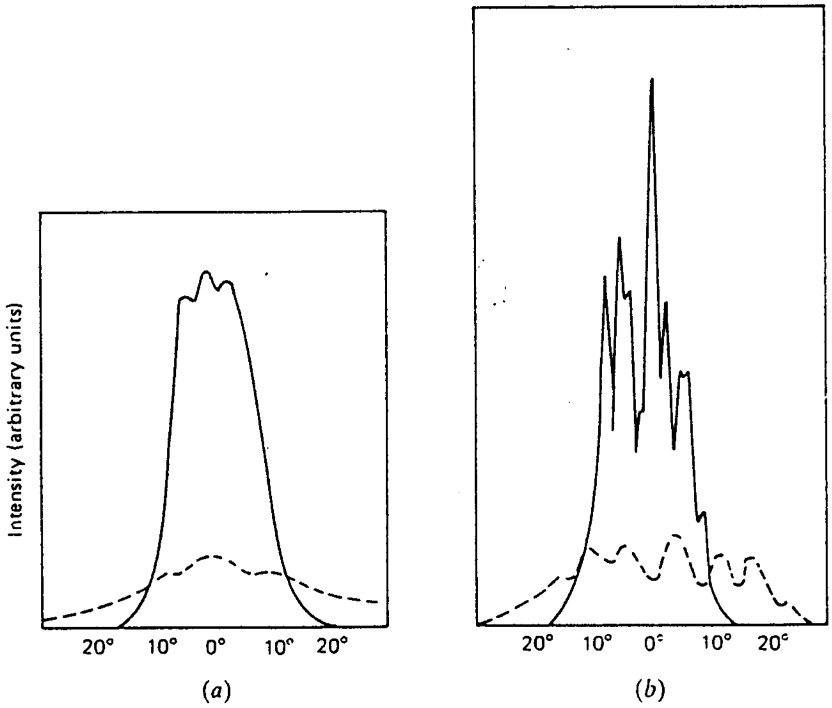

Figure 3. Angular distribution of output intensity of radiation transmitted through clad (solid line) and unclad (broken line) fibres. In (a) λ = 5–6 μm, in (b) λ = 10·6 μm.

Table 4. Increment of absorption (dB m^{-1}×min) in AgHaL fibres reduced by u.v. irradiation (mercury lamp at a distance of 20 cm from the fibre).

Fibre	λ (μm) 5·2–6·2	λ (μm) 10·6
AgCl	62	26
AgBr	4·8	0·45
KRTS-13	0·22	0·06

our mind, the result of peculiarities of the structural defects formed under extrusion of KRS-13 crystals. These defects retard the diffusion growth of silver colloids which are responsible for i.r. absorption.

3. Laser-induced damage in PC fibres

Investigations of the damage induced by continuous radiation of CO_2 laser have shown that the fibre begins to melt from the ends. In spite of nearly the same surface absorption for the both ends, melting starts, as a rule, from the output end. As a result the power absorbed in the surface layer is proportional to the square of this sum. The other reason is a speckle pattern at the output end due to the mode interferences in a multimode fibre (figure 4 (*a*)). Evidently, the melting begins at the points with the highest local intensity (figure 4 (*b*)). For KRS-13 fibres the threshold intensity averaged over the whole core cross-section is about 7–10 kW cm^{-2} (see table 3). This intensity can be increased (by cladding the core) up to 14 kW cm^{-2} without cooling or AR coatings on the ends.

The development of a laser scalpel based on KRS-5 fibres by M. Ikedo, H. Ishiwatari and co-workers raises the threshold up to 38 kW cm^{-2} by the high-quality treatment of the end surface and cooling by a flow of dry gas [9]. The record threshold of about 50 kW cm^{-2} was achieved by applying an anti-reflection As_2Se_3/KCl/As_2Se_3 coating on the end surface [10]. The lifetime of such a fibre depends on the level of the delivered power [4].

Investigations on the transmission of pulsed radiation of TEA CO_2 laser through PC fibres have shown that the damage occurs as a rule in the initial part of a fibre at distances from a few millimetres to a few centimetres from the input end. Threshold fibre damage induced by the pulse is significantly lower than in the initial crystals. The beam model of the radiation propagation in the initial part of the fibre shows that this effect can be associated not only with the greater number of defects in fibres, but with the additional focusing of the input radiation by the cylindrical side surface of the fibre. In the focusing region the local intensity is an order of magnitude higher than the average intensity. Estimated values of the threshold in fibres with regard to the additional focusing correspond to the bulk threshold of initial crystals.

The character of damage (see figure 5) and the dependence of the threshold energy and the peak power on the pulse duration (see figure 6) are described by the mechanism of heat explosion [11].

It is well known that pulsed radiation of CO_2 lasers results in more effective ablation of tissue than the radiation of widely used continuous CO_2 lasers [12].

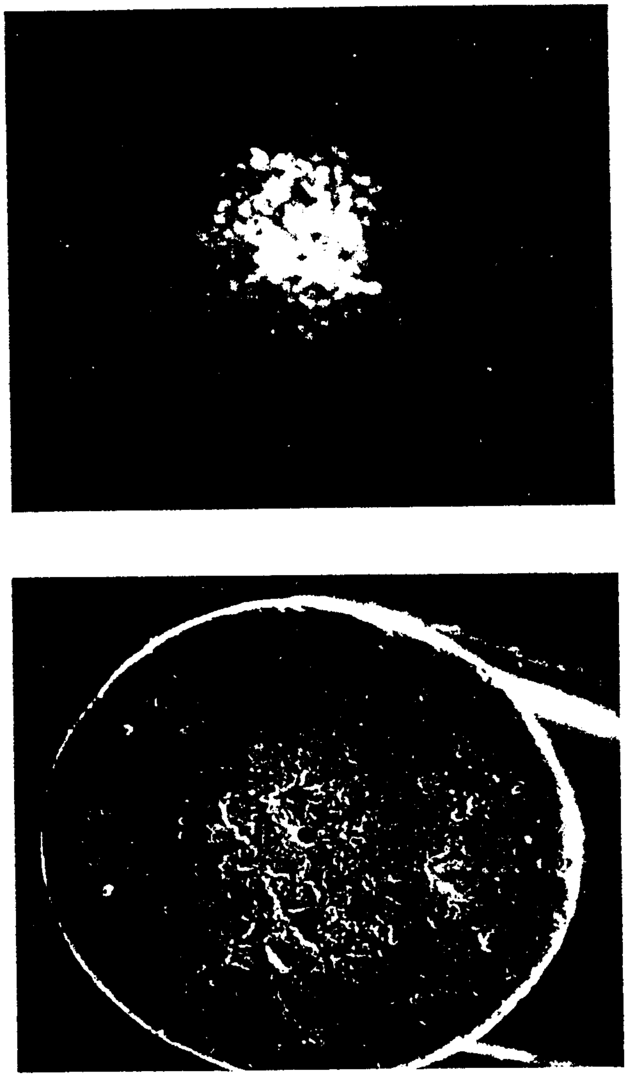

Figure 4. (*a*) Speckle pattern of the output radiation at 10·6 μm at a distance of 7 cm. (*b*) Damage of the output end of a fibre (ϕ=1 mm) by the radiation of a c.w. CO_2 laser.

Besides, in the pulsed removal of tissue the zones of coagulational necrosis and carbonization becomes significantly smaller. These raise interest in the application of pulse CO_2 lasers in surgery and demand further investigations of the mechanisms of laser-induced damage in the accumulating regime.

For a single pulse with the duraciton of $\tau=40$ μs, the threshold values of E_d exceeded 33 J cm^{-2} (the pulsed energy was insufficient to achieve threshold values of E_d). This value agrees with the growth of the threshold energy with pulse duration (see figure 6). Pulse irradiation results in the reduction of the fibre beam strength. This effect manifests itself in the fact that at $E_N < E_d$ the damage occurs

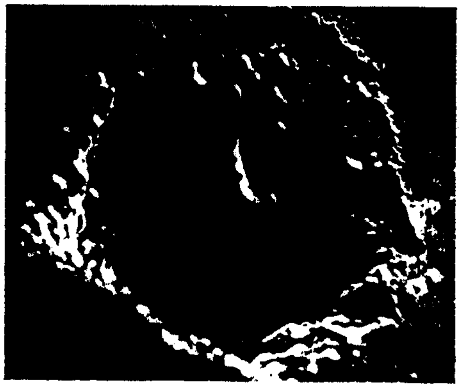

Figure 5. Crater at a side surface of KRS-5 fibre produced by a pulse from a TEA CO_2 laser.

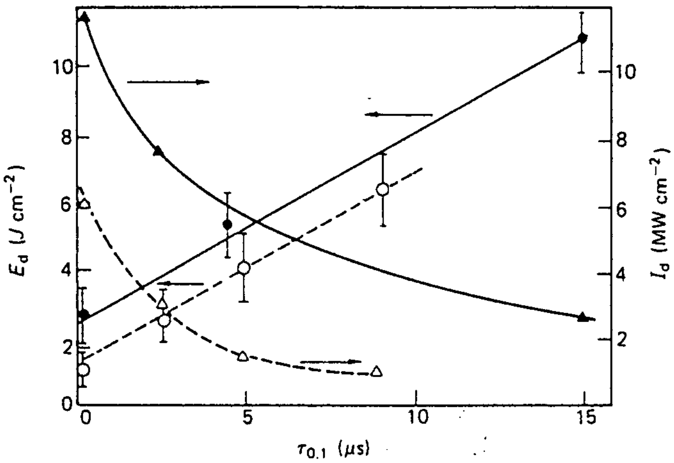

Figure 6. Threshold energy E_d and peak intensity I_d dependence of KRS-13^{-d} and KRS-5 fibres on the pulse duration τ.

at the transmission of a pulse with the number $N > 1$. That is why the damage threshold in the pulsed regime can be characterized by the critical number of laser pulses N_d which is necessary for the damage of the prescribed value of E_N. Table 5 shows the results of N_d (E_N) for two types of fibres and at two durations of laser pulses. Note that with an increase of pulse duration, the tendency of the growth of E_N threshold becomes quite clear, like the case of single pulse damage.

The preliminary data on KRS-13 core AgCl cladding fibre show the value of the pulse damage threshold which is two to three times higher than that for the unclad fibre.

Table 5. Endurance of KRS-5 and KRS-13 fibres to the pulsed radiation of a TEA CO_2 laser with a pulse repetition rate of 10 Hz. ϕ: fibre diameter; τ: pulse duration; E_0: output energy; E_N: output energy density; t_d: time until damage; N_d: number of pulses until damage.

Fibre	ϕ (mm)	τ (μs)	E_0 (mJ)	E_N (J cm^{-2})	t_d (min)	N_d ($\times 10^3$)
KRS-5	1·0	10	25	3·2	>30	>18
			50	6·4	>30	>18
			83	10·6	3	18
			83	10·6	5	3
		40	100	12·8	>30	>18
KRS-13	0·7	10	25	6·4	>30	>18
			50	12·8	1	0·6
			50	12·8	2	1·2
		40	40	9·4	>30	>18
			80	18·8	25	15
			80	18·8	15	9
			86	20·2	3	1·8
			140	32	5	3
			140	32·3	12	7·2

4. Optimization of FLS parameters for surgery

Because the absorbing capability of living tissue is similar to that of raw potatoes, we measured the dependence of the energy, W, of pulsed radiation (CO_2) necessary for the ablation of raw potatoes for durations τ (see figure 7). It is clear from the figure that an increase of E leads to a decrease of W. The other peculiarity is a two to three times increase of W as τ grows from 3 to 8 μs and the independence of W in the range 8–40 μs. In the figure we also display the levels of E_N and E_p energy densities corresponding to the fibre damage thresholds and to the threshold of plasma formation for the sample under investigation.

Suitability of fibre laser scalpels for tissue removal can be determined from the dependences $E_N(\tau)$ and $W(E, \tau)$. Figure 8 shows the dependence of tissue mass m, removed during one pulse, on the pulse duration τ:

$$m = ES/W\,, \tag{1}$$

where $E = E_N$ is the pulse damage threshold of a fibre and S is the fibre cross-sectional area. The increase of m by an order of magnitude for increases of pulse duration from 3 up to 40 μs is restricted only by heat diffusion from the zone of irradiation. Hence, the large pulse durations can be used only for the formation of a deeper coagulation zone. This conclusion agrees well with the results of our experiments on the dissecting of human stomach walls *in vitro*. The experiment was conducted on a cooled sample four hours after the operation with pulse repetition rates of 20–40 Hz.

Though at $\tau = 3$ μs the energy of ablation W is minimal, the threshold of the fibre damage F_N is too low. This regime is of little use because of the 'explosive' character of the tissue removal. The holes have broken edges, the damage to the neighbouring tissue is greater the higher E.

At $\tau = 40$ μs, when the threshold of fibre damage was maximal, we observed another drawback—the significant diffusion of heat from the irradiated zone. As a

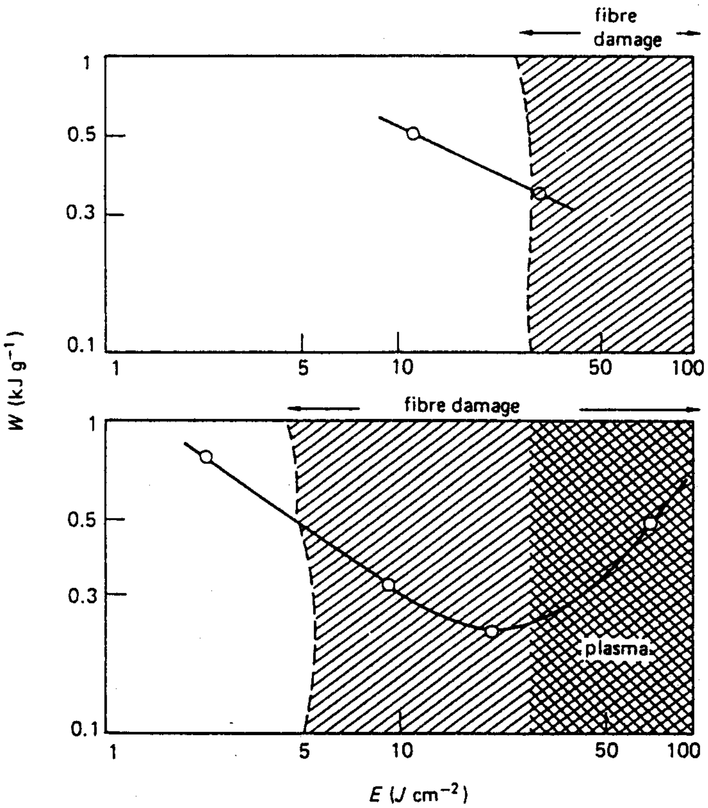

Figure 7. Dependence of specific energy W used for the ablation of raw potatoes on the energy density. Top part, $\tau_{0\cdot 1}$=40 μs; bottom part: $\tau_{0\cdot 1}$=3 μs.

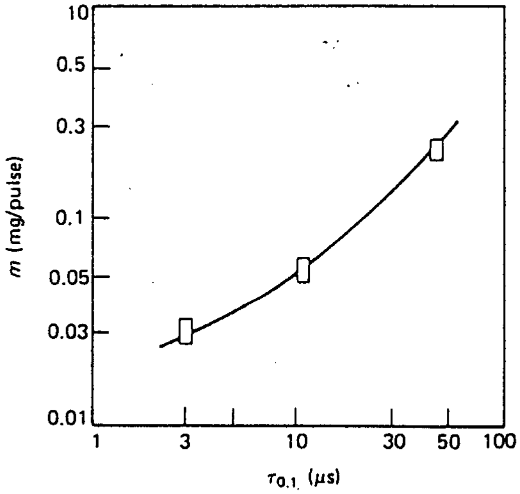

Figure 8. Dependence of tissue ablation by a single pulse (with maximum energy transmitted by the fibre) on pulse duration.

result, weak carbonization of the hole edges was observed. This effect is usual when employing continuous CO_2 lasers.

The best results were obtained with pulses in duration 10–20 μs. The dissection of a stomach at $E = 15$ J cm^{-2} had clear and dry walls with a slight white coating. We observed no carbonization. Owing to the absence of heat transfer from the irradiated zone there was no swelling and deformation of the cutting zone, which is usually observed with continuous radiation.

The advantages of fibre laser scalpels (even in external surgery) are great flexibility of the fibre cable and simplicity of design due to the absence of mirror-joint devices. But the main advantage of a fibre power cable is the possibility of its application for operations in internal cavities and for angioplastics [12]. In such operations, CO_2 laser radiation can be delivered only by crystalline fibres because their sizes and bend radii are sufficiently small in comparison with the hollow fibres, though the latter are able to deliver more powerful radiation [13].

For the angioplastics and other internal-cavity operations we need on the one hand high density of radiation power at the output, and on the other hand, the absence of tissue destruction in the vicinity of the affected zone (for example, the walls of the vessel during the plaque ablation). For these purposes we can use fibres with microlenses at the output end. Figure 9 shows that the intensity in the focus of a microlens formed at the output end of KRS-13 fibre is significantly higher than the intensity obtained from the flat end, and behind the focus it decreases quicker because of greater divergence.

5. Conclusion

The design and investigation of crystalline fibres from silver halides have shown that their optical and mechanical characteristics are most promising for the flexible fibre laser scalpels with CO_2 lasers. Better characteristics of such power fibre cables

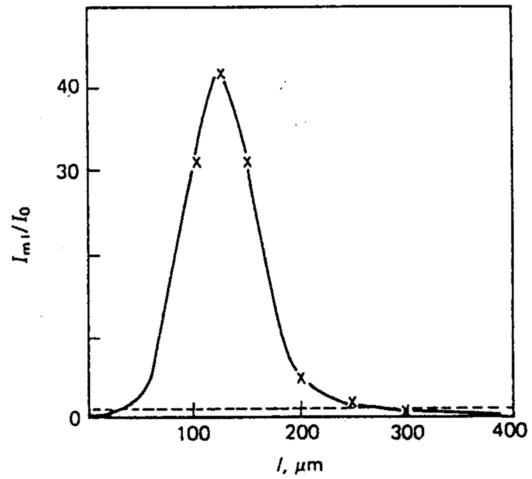

Figure 9. Dependence of the ratio of the output intensity I_l of radiation transmitted through a fibre with an output microlens to the intensity I_0 after the flat-surface end on distance from the end. The diameter of the KRS-13 fibre is 980 μm and the radius of the KRS-5 fibre is 750 μm.

can be achieved by the improvement of the fabrication technology of clad fibres. It is also necessary to develop the technology of anti-reflection coatings on the ends of fibres.

6. Achnowledgements

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