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WORKSHOP ON OPTICAL FIBER COMMUNICATION
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OPTICAL FIBER DELIVERY SYSTEMS FOR
LASER MEDICAL APPLICATIONS

presented by

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OPTICAL FIBER DELIVERY SYSTEMS FOR LASER MEDICAL APPLICATIONS

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1. INTRODUCTION

All the laser sources whose applications are already established in medicine are supplied with suitable systems that deliver the radiation up to the tissue to be treated, and when a new laser source has to be introduced in medicine, also its appropriate delivery system has to be detected and supplied. The same problem arises when a laser source finds new fields of applications in medicine, that is its delivery system has to be improved in order to fulfill the requirements dictated by the specific working conditions. Every day new and more precise performances are asked and several patents of special delivery systems are under study. This topic deserves an increasing attention, and in its turn it arouses new interests for the possibilities it will offers in a near future.

To give a detailed description of the systems conveying the radiation from the laser source up to the tissue, three points must be considered: the medium of transmission; its coupling problems,its characteristics of irradiation. The transmission medium is very important because it has to guide the radiation without any losses. Moreover the transmission medium must be flexible and of small dimensions so that it can be used with the more sophisticated techniques in specific therapies and diagnosis problems. As a second point, the coupling device must be efficient, reliable and easy to adjust. As far as the output of the transmission medium is concerned, generally it is used without introducing any variations in its optical characteristics, that depend on the waveguide type and/or on the transmission medium. When necessary, external optical components were added. Only recently, the method of directly shaping the distant end of the transmission medium has been imposed; a method which is much more convenient for its wide range of applications, particularly in surgical or phototherapic treatments, carried out with endoscopic techniques.

I shall consider the fiber-optic systems delivering the radiation from lasers emitting in the visible and in the near infrared regions. The main transmission characteristics will be summarized and the coupling problems will be outlined. Then the topic of the beam shaping from an optical fiber will be treated in detail for its interest in endoscopic and cavitational techniques.

2. TRANSMISSION CHARACTERISTICS AND COUPLING PROBLEMS

The more convenient transmission medium for laser radiations in the visible and near infrared region, is the well known optical fiber, which is able to guide the laser light practically without attenuation. Optical fibers are available on the market,in any diameter and even at a low price. For their flexibility and small dimensions they are a good instrument to facilitate the handling of the laser beam and wherever it is possible they substitute mirrors and lenses. For their guidance properties they also provide a simple method to improve the safety of the laser operator.

In every laser medical center, the optical fibers ase today employed to treat the biological tissue as well as to semplify and make more efficient the laser systems and its ancillary equipments. For safety and handiness reasons the optical fibers are used in open field laser treatments as well as in laser microscope technique. For their flexibility and small dimensions the optical fibers represent the unique solution in endoscopic and cavitational techniques to reach and treat the sick tissue situated in inaccessible zones of the human body (1).

Single fibers, step-index quartz-plastic type, are generally employed. The core diameter ranges from 100 to 600 μm, depending on the laser source and the application type. They are also able to deliver high power radiation.The parameter characterizing the fiber is its numerical aperture, N.A., or its acceptance angle, that is the maximum angle, α, where a ray is "accepted" and therefore guided within the fiber core. It is to be noted that the width of the output beam is nearly equal to the acceptance angle, if the fiber is well feeded. Typical values for the quartz-plastic fiber type are: N.A. $\simeq$ sen α = 0.40 (or 0.27).

Optical fibers do not present any problems in the transmission of the laser light nor in general in the coupling to conventional laser sources. A simple positioner, commercially available, is sufficient for this purpose. It contains a focusing lens, antireflection coated. The fiber end, planar cut and free from cladding, is clamped in a pinzer which is inserted into the positioner. The adjustement of the fiber into the focal spot is easily achieved at low power and refined at high power.

Only in particular cases some difficulties must be overcome to obtain a high coupling efficiency. For instance, if a small diameter fiber must be coupled to a laser with a low spatial coherence, whose beam cannot be focused into a small spot, a particular coupling device must be planned. In fact some Nd-YAG lasers were supplied with a variable section fiber. The largest input allows an easier and more efficient coupling. After the first triconical fiber (2) which was very brittle for its lack of cladding, other tests have been made at IROE (3). Stronger and more reliable tapered fibers have been obtained by means of a cladding and a protection coating, worked in line during the fiber drawing.

If a laser must be coupled to more than one fiber, mechanical or optical scanner are now employed. Fiber-optic beam splitters could be very handy, but they must be made on purpose. Indeed Y or star coupler are today available but only in fibers for optical communications, that is in graded-index fibers of very small diameter.

Recently, new laser sources, such as f.i. excimer laser, array of LED or of semiconductor lasers (4), are found to be usefull in medical applications. In these case too, a suitable systems collecting all the emitted light and addressing it into a single fiber, must be designed and built on purpose.

Finally it is worthwhile to mention also the problem of the connection between two fibers. A rapid change of a piece in the fiber, without disconnecting the fiber itself from the laser source, can be sometime necessary in various cases; for instance when you want to work with a fiber having a special end (lens, scattering or conical ends) or when it is advisable to change rapidly the diameter of the fiber, in particular small diameter endoscopes. With low power radiation, connectors commercially available can be used to join two fibers of equal diameter. However at high powers even the low insertion losses of the connector can create some heating problem. Therefore particular arrangements have been proposed; employing fibers having an output end focusing the radiation on the second fiber. Analogously two fibers of different diameter can be joined by means of an additional piece of fiber with graded diameter (5). As a conclusion, we can say that today there are no more problems in connection with the transmission medium. At least for delivering high power laser radiation at very short distances. Only when an optical fiber delivery system must be employed for connecting sources and operative rooms, distant apart more than some tenth of meters, substantial losses must be taken into account. Some problems still exist in coupling very small diameter fibers to particular laser systems and also the connection fiber to fiber has yet to be developed in a more satisfying way. An effort must be done in the direction of giving a greater flexibility to the fiber optic delivery systems now in use. A laser operator in the operative room would find it extremely convenient to work with a multipurpose delivery system, so easy to handle that referring to outside personal for any minor change would be avoided.

3. BEAM SHAPING OF AN OPTICAL FIBER

Single fibers are generally used both for surgical and for phototerapic treatments. In some cases and only in open field treatments also bundles of a limited number of fibers have been proposed. For instance in dermatology, a system has been developed by 7 fibers whose input ends are aligned in a stright line, while the output ends are arranged in hexagonal close-packed array (6). The system is able to irradiate successively different spots of large lesions, without scanning over them mechanically. In all other cases, a single fiber is sufficient also because it has been proved that it is possible to modify the output end of the fiber itself in such a way that the required type of irradiation can be obtained (7). In contrast to the conventional method of adding external optical components, this method offers the advantages of being employable in endoscopic techniques, of being safer for the patient and more reliable from a technological point of view even with high power laser radiation.

The modification of the output beam of the optical fiber is achieved by giving the fiber tip another shape than the flat end. This technique is well known in optical communications where however the input end of the fiber is modified with the purpose of increasing the coupling efficiency to LED or semiconductor lasers and the fibers themselves are of gradient-index type, or very small diameter. In medicine, on the contrary, the near and the far fields at the output from a suitably shaped step-index fiber of very large diameter are of greater interest and much work would be done. At IROE this specific subject has been developed in the frame of the C.N.R Special Programs: "Laser in Medicine" and "Biomedical Technologies".

A variety of different shapes can be given to the output end of an optical fiber as we will see in the following pages. For some of these terminals both the optical characteristics and the fabrication techniques will be rewieved. All the optical fibers with special terminals are hikely to find an immediate application as soon as they are available.

4. FORWARD-RADIATION SYMMETRIC TERMINALS

Let us consider, at first, fiber terminals which give rise to an output beam with the intensity maximum directed along the fiber axis but with an angular intensity distribution different from that of a flat-end fiber. Some symmetric terminals are sketched in Fig.1 together a qualitative drawing of their radiation pattern, that is of the intensity detected far from the fiber end and plotted versus the output angle a. Enlarged tapered terminals of type (b) produce a beam narrower than that from a conven-

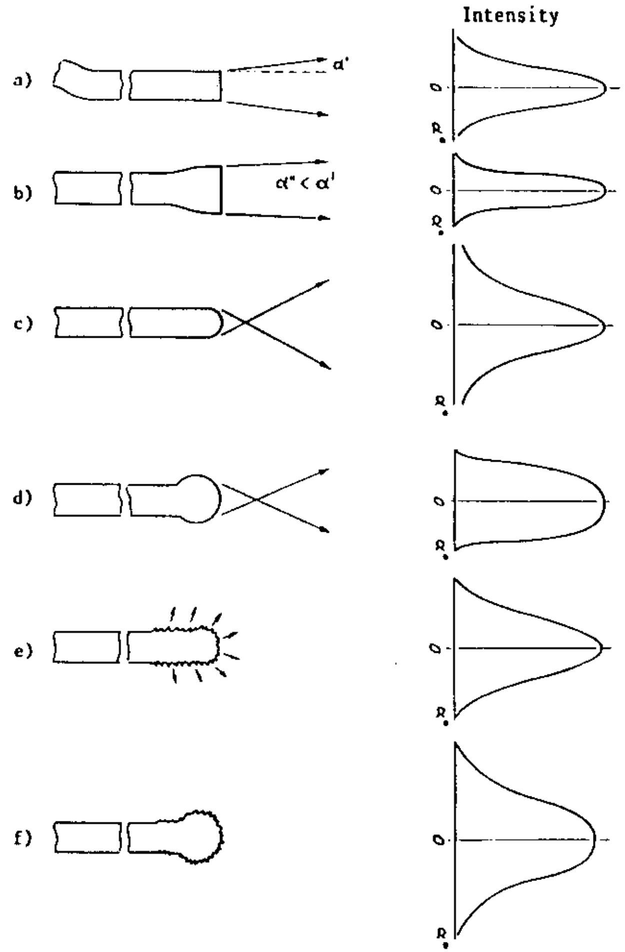

Fig.1. Sketches of different forward-radiation terminals of optical fibers. a) flat-end terminal, b) enlarged terminal, c) arc-microlens terminal, d) bulb-microlens terminal, e) scattering flat-terminal, f) scattering lens-terminal. On the right a qualitative drawing of the intensity distributions is plotted versus the output angle α.

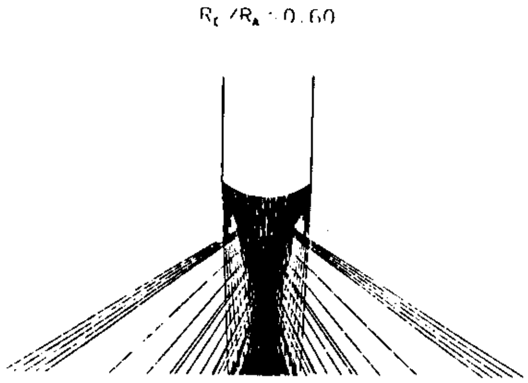

Fig.2. Ray tracing of the output beam from an arc microlens with $r_a = r_c/0.6$ (d=0.6)

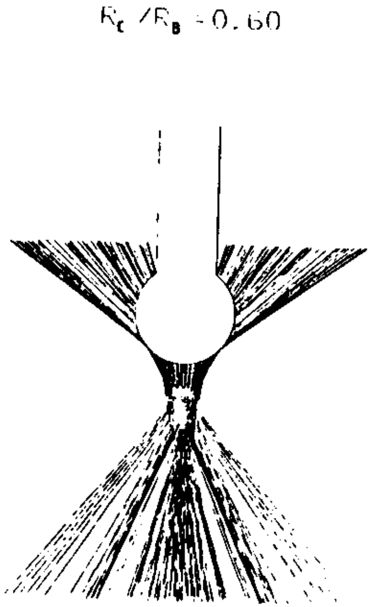

Fig.3. Ray tracing of the output beam from a bulb microlens with $r_b = r_c/0.6$

tional flat-end fiber (a) (3). Arc (c) and bulb (d) microlenses produce beams both wider than that from (a). Scattering flat-end terminal (e) and scattering lens-ended terminals present beams more wider than that from the corresponding not-scattering terminals. They are obtained by dipping the fiber tip in HF acid solution.

Lens-ended optical fibers have been proposed in medicine because the characteristics of their output beam can be employed for different purposes (8). The focusing in the neighborough of the terminal microlens can be used to increase the power density on the biological tissue, allowing the production of sharp cuts or microholes, without placing the fiber end in direct contact with the tissue. In this way the damaging of the fiber tip, due to the sticky and absorbing debris can be reduced. The strong beam divergence behind the focus can be used in laser endoscopy of a more rapid vaporization or phototherapic treatments of large tumoral areas situated in cavities. Lens-ended optical fibers have been theoretically studied and experimentally tested (9). In addition a new fabrication technique has been developped at IROE that allows an immediate fabrication or repair even by an inexperiented operator in the operative room. For this reason some details of results obtained will be reported here in the following. Both arc and bulb microlenses present different optical performances by varying their radius of curvature. As an example, Fig.2 shows the ray tracing of the output beam of an arc microlens with $r_a = r_c/0.6$, and Fig.3 shows that one of a bulb microlens with $r_b = r_c/0.6$ where r_c is the radius of the fiber core and r_a and r_b are the radius of curvature of the microlenses. The focusing properties are evident as well as the consequent widening of the beam behind the focusing. It has been found that all the bulb terminals (and some arc terminals) have a secondary beam in a backward direction, in addition to the main forward beam. This is due to that part of the rays which is reflected at the airdioptre interface; it does come out, but in a different direction than the one of the main beam. The intensity of this secondary beam is a few percent of the main beam . (Fig.4)

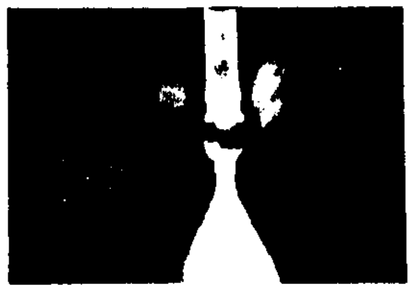

Fig.4. Photograph of the laser beam coming out from a bulb terminal (d = 0.67).

The intensity distribution in the near and in the far field has been theretically evaluated and experimentally detected. The focal spot size, s and the focal length, f, of the microlens terminals, derived from the measurements of the near field, have been plotted in Fig.5 as a function of the parameter d (the ratio between the radius of the fiber core r_c and the microlens radius of curvature. The focal spot size ranges from 1/2 r_c(d=1) to 2 times the fiber core radius (d=0.5). Then it increases rapidly with $r_{microlenses}$.

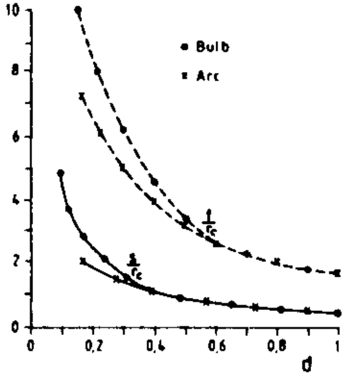

Fig.5. Focal spot size s (continuous line) and focal length f (dashed line), normalized with respect to the fiber core radius r_c, vs the parameter d= r_c/r microlens for arc and bulb microlenses.

The radiation patterns the angular intensity distribution have been also detected from the far field measurements. As an example, Fig.6 shows the radiation patterns of an arc microlens terminal with d = 1 and of a bulb microlens terminal with d = 0.45 compared with the radiation pattern of the same fiber with a planar cut (d=0).

To complete the characterization of the microlens-ended fibers, also the possible losses due to rays totally or partially reflected at the air-dioptre interface have been theoretically evaluated and experimentally tested. Fig. 7 shows the ratio between the power P_m emitted from the microlens in the main forward beam and the one P_f emitted

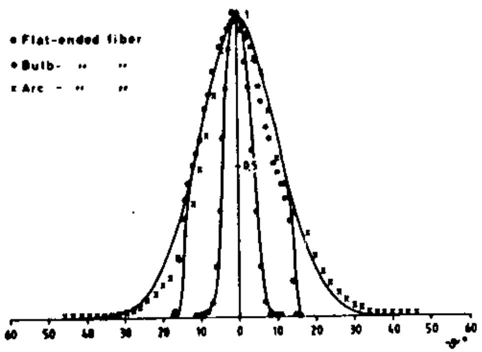

Fig.6. Theoretical (solid lines) and experimental (dots and crosses) radiation patterns for an arc microlens with d = 1, a bulb microlens with d = 0.45, and a flat end (d = 0).

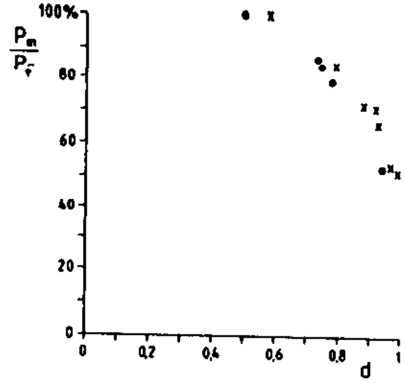

Fig.7. Forward output power P_m of arc and bulb microlenses, normalized to the output power P_f from a flat-ended fiber, plotted as a function of d.

from the same fiber with a flat end. It turns out that the hemispherical microlens has the higher losses while microlenses with d smaller than 0.6 does not introduce any additional losses.

Considering the results, one can easily infer that for medical applications, but not only, lens-ended fibers with d= 0.6 are the best compromise. In fact they have the focal spot size reasonably small, the largest beam width and small losses.

The fabrication techniques of integral microlenses at the end of the optical fiber are based on the heating and melting the fiber tip that assumes a round shape, by surface tension. All the previous techniques made use of external sources, such as the gas microtorque, CO_2 laser, electronic arc discharge etc. Some of them needed specific and elaborate inhouse ficilities. We have developed a new technique, that unlike the previous ones, uses the energy of the laser radiation delivered by the fiber to heat and melt the tip of the fiber itself, Fig.8 (9), (10). The distal end of the fiber, free from cladding and with a flat cut, is placed perpendicularly very close to the surface of a target, capable of absorbing the laser light and with low termal conductivity. The fusion of the target area immediately below the fiber gives rise to a small incandescent microfurnace, that re-emitts part of the absorbed energy in a spectral region (i.e. in the middle infrared) where the fiber core material is higly absorbing. As a consequence the fiber tip melts. Pure silica fibers (core diameter 80 ÷ 600 um) have been used mainly with Argon laser radiation. A few tests have been made also with Nd-YAG laser. The target was a sample made of a compound of Kaolin, calcium carbonate, borax, with a 20% percentage of ferrous oxide. Laser power at the output from the fiber (1 ÷ 3 Watt) exposure time (1-5 sec) and fiber tip to target distance (≃1 core diameter) are the main parameters of the process. By varying one of them it is possible to fabricate microlenses, arc and bulb type, of different radius of curvature.

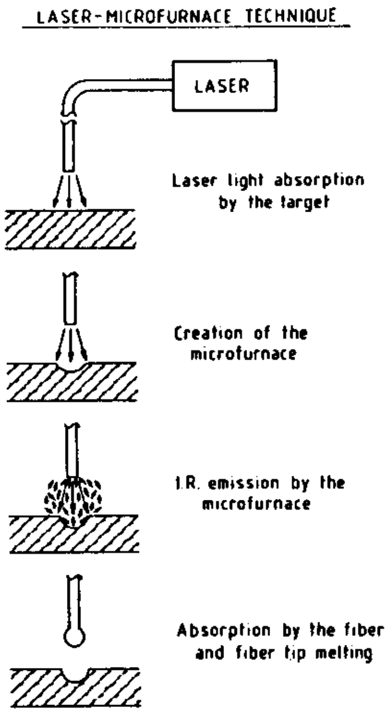

Fig.8. Working principle of the new lens-ended optical fiber fabrication technique

5. SIDE-RADIATION SYMMETRIC TERMINALS

Optical fibers with tapered terminals are sketched in Fig.9 a,b,c. All of them have a shape symmetric with respect to the fiber axis and of consequence present an output intensity distribution with axial rotation symmetry. They are characterized by a wide radiation pattern having a central minimum (11). The energy is distributed along cones coaxial to the fiber axis. Both cone and truncated cone terminals have been constructed and tested in our laboratory on silica plastic fibers with core diameter of 600 μm and 300 μm. Truncated cones are resulted less brittle than cones and therefore more appropriate for a practical application if vertex angles very narrow are required. By varying the geometrical parameters of the taper, end face and vertex angle, one can vary the direction of the output intensity maximum (12). As an example Fig. 10 shows the radiation pattern of a large cone terminal. The maximum has an off axis direction of ∼60°. Truncated cone and cone terminals are obtained with a chemical etching by dipping for different times, a flat-end fiber suitably prepared in advance in a 40% fluoridric acid solution.
Cone ended optical fibers with large vertex angles are particularly suitable for laser treatments (surgical or phototherapic) of narrow cylindrical cavities.
In a successive step, also the conic terminals with small vertex angle, can be made scattering terminals, thus obtaining still more wide output beams.

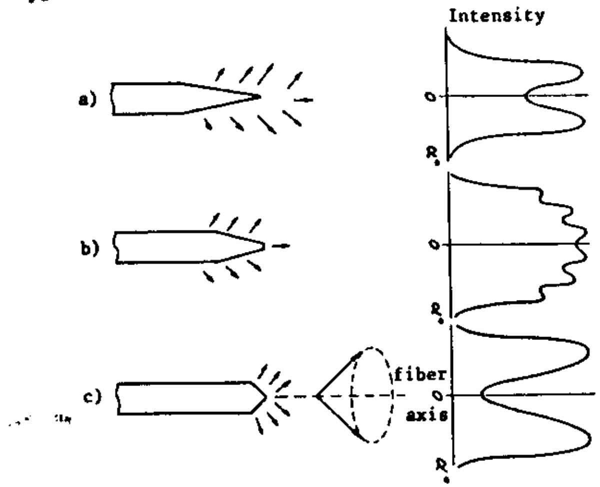

Fig.9. Sketches of different side-radiation symmetric terminals of an optical fibers

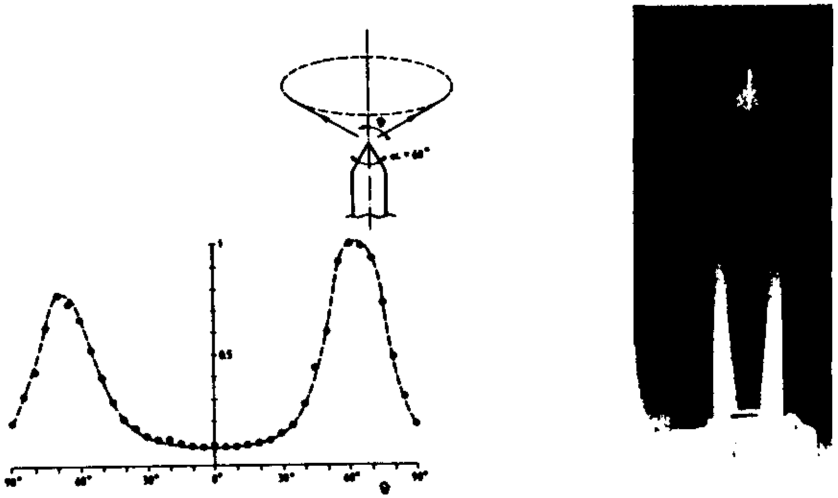

Fig.10. Radiation pattern of the cone ended optical fiber with a large vertex angle (60°). The maximum has an off axis direction of ∼ 60°

6. SIDE-RADIATION ASYMMETRIC TERMINALS

Endoscopic or cavitational techniques may require the treatment of a sick tissue situated sideways with respect to the fiber axis e.g. on the wall of a cylindrical cavity or on the wall of a vessel. In such a case a fiber able to radiate the laser energy much more sideways than forward could be very effective. Some different side radiation asymmetric terminals are sketched in Fig. 11.

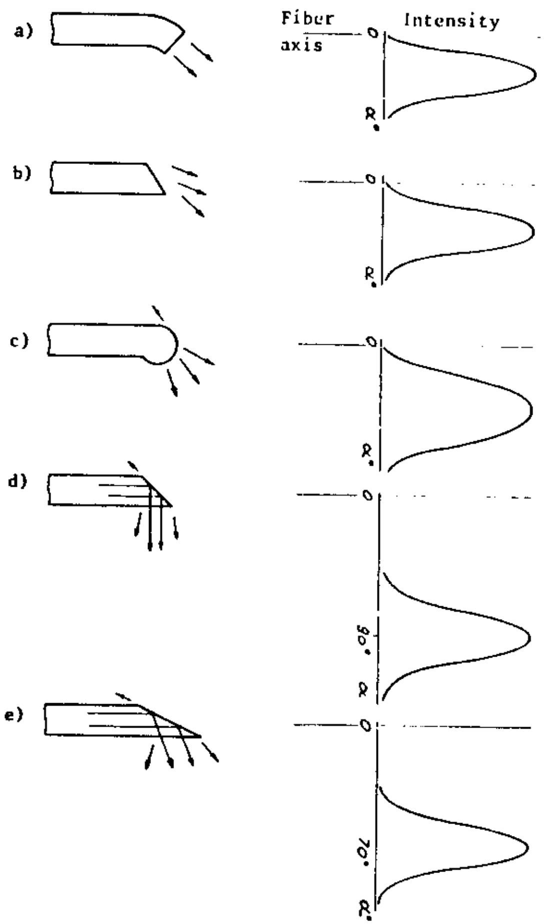

Fig.11. Sketches of different side-radiation asymmetric terminals. a) J-shaped terminal, b) beveled terminal, c) tilted lens terminal, d) and e) total reflection terminals.

Similar output beams are obtained by a J shaped terminal (13)and a beveled terminal operating by refraction. Both terminals slightly deflect the output beams. Tilted-lens terminals (12) show an output beam with a deflection angle which depends on the tilt angle. They can be tilted untill ~90°. In this case the main beam is directed in the expected direction (+90°), and a secondary beam of less intensity is directed in the opposite versus. Fig. 12 show a 90 tilted lens terminal radiating mainly in the +90 direction.

Fig.12. Asymmetric lens-end terminal with a tilt angle of ~90° radiating mainly towards 90° with respect to the fiber axis.

The last type of side radiation terminal shown in Fig. 11 has a different working principle (12,14). The beam comes out from the fiber after a total reflection on the end face which has been beveled at the critical angle (45°). This type of terminal totally reflects mostly of the energy at an angle close to 90 with respect to the fiber axis. Optical fibers with beveled ends are fabricated by optically lapping and polishing while tilted lens ended fibres are fabricated by melting the fiber flat-end with a conventional microtorche.

7. CONCLUSIONS

The optical fiber delivery system represents a unique instrument for endoscopic and cavitational laser treatments. Optical fibers commercially available are employed to transmitt the laser beam from the source to the operative room, without attenuation problems if the distance is very short. In other cases, attenuation losses must be considered and appropriate fiber to fiber connectors for high power laser must be provided.

The beam shaping of a single optical fiber obtained by modyfing the shape of the fiber tip is today a simple and interesting technique which find application in surgical and in therapic laser treatments (15). Lens-ended fibers have been employed in microsurgery for their focusing properties, and can be used in bronchology, gastroenterology, etc, for their beam widening properties. Scattering terminals can be used in phototherapy attempting to obtain an uniform intensity distribution over 360°. They can also be proposed to radiate into liquid media.

Side-radiation terminals with axial rotation symmetry, particularly the large cone terminals, are suggested for the laser treatments of obstructions on the walls of narrow cylindrical cavities. They are convenient to save energy and to avoid irradiation of healty tissues. Applications in treatment of blood vessels, in bronchology, in gastroentherology, in urology are expected.

Asymmetric side radiation terminals can be of interest in cavities where the sick tissue is placed on one side of the wall and therefore inaccessible with a conventional flat end fiber. They are particularly convenient also in cavities where the zone cannot be reached only making use of the curvature permitted by the endoscope. Tilted--lens optical fibers f.i. have been already employed in urology (Urology Division Florence Hospital) to reach tumoral areas placed strongly off-axis with respect to the endoscope. Asymmetric side radiation terminals are more than ever of interest when an optical fiber delivering the laser radiation must be used in combination with very small but rigid vision systems (f.i. Selfoscopes), or in very delicate organs like eye, brain, hearth, and blood vessels.

Acknowledgement

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