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Rudolf M. Verdaasdonck, Christiaan F. P. van Swol, "What makes a fiber tip do the job: an optical and thermal evaluation study," Proc. SPIE 2396, Biomedical Optoelectronic Instrumentation, (1 May 1995); doi: 10.1117/12.208419

Event: Photonics West '95, 1995, San Jose, CA, United States

What makes a fiber tip do the job: an optical and thermal evaluation study

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1. INTRODUCTION

The success of a medical laser treatment is highly dependent on the optical, thermal and mechanical characteristics of an optical system or shaped tip on the end of a fiber [1]. At present, this can be well illustrated by the laser delivery devices which are developed for the treatment of benign prostatic hyperplasia (BPH) [2]. The designs are based on either side-firing fibers or contact probes coupled to continuous wave (CW) laser systems. For the first, the optical properties are important and, for the latter, the thermal and mechanical properties.

2. FIBER TIP DESIGNS

The normally flat cut or polished fiber end can be modified to other shapes to make it more effective for its application. By melting the probe to a ball shape, the tip becomes atraumatic and mechanical more durable (fig.1, left). Depending on the environment, the ball shape will focus the beam in front of the tip increasing the power density. The ball shape design is easy to use through flexible endoscopes to ablate tissue in front of the fiber e.g. a tumor obstructing a channel in the human body. To irradiate the wall of a small lumen, however, the laser beam must exit the tip sideways. For this purpose various designs of side-firing fibers have been introduced. These designs can be divided into two groups: the metal reflectors and the internal reflectors (fig.1, middle, right). The metal reflectors consists of a bare fiber on which a metal hat it clamped with a gold coated surface that reflects the beam to the side. In case of the internal reflector, the tip of the fiber is polished at such an angle that the incident light exceeds the total reflection angle in the tip and is internally reflected to the side. To protect the fragile tip and to ensure the conditions for internal reflection, the tip is covered with an optical transparent cylindrical shaped dome usually made of silica.

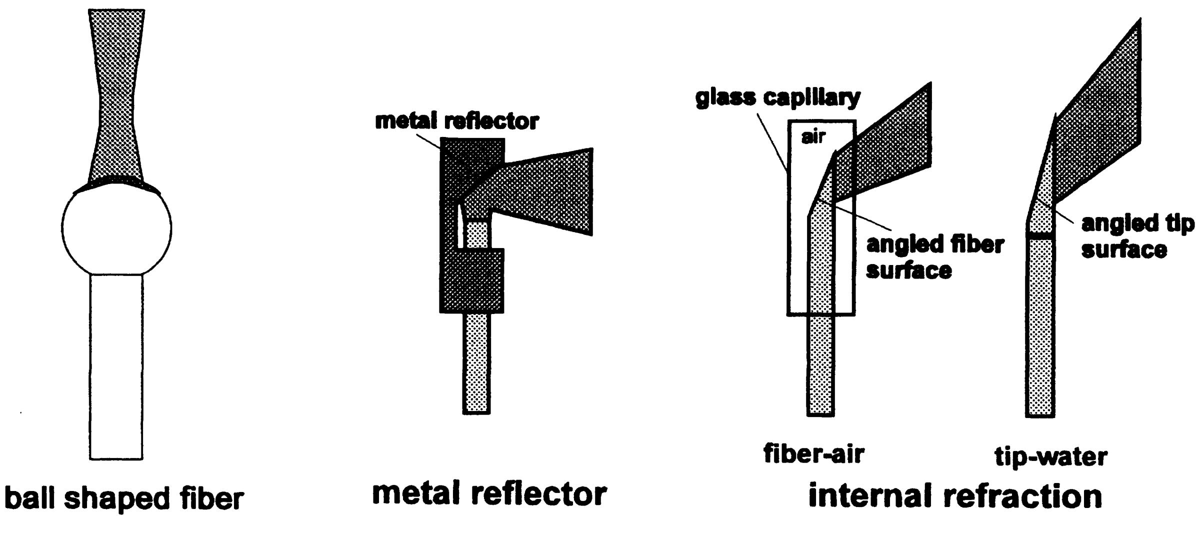

Figure 1. *Designs of fiber tips: ball shaped fiber, metal reflector side firing fiber, internal reflecting side firing fiber*

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3. INFLUENCES ON FIBER TIP CHARACTERISTICS

3.1 Environment:

The optical effect of fiber tips strongly depends on the difference in the refractive index between the fiber tip and the environment. If this difference is small like the transition from a silica fiber tip (n=1.45) to a water environment (n=1.33), the focusing effect of a ball shaped fiber will be minimal or none [3]. Similarly, in case of an angled polished fiber tip, the small difference in refractive index will not provide the conditions for total internal reflection. The beam will refract from the fiber tip at the front side. Therefore, this design of side firing tips is either with an optical dome to provide an air interface for total internal reflection or the tip is made of a high refractive index material like sapphire (n=1.75).

3.2 Surface of the tip

3.2.1 Surface coatings

Normally, the surface of a (modified) fiber tip is transparent for the laser wavelength for which it has been designed. Except for the Fresnel reflections at the surface, all the light is emitted by the fiber tip and interacts with the surrounding tissue. If the wavelength of the light is poorly absorbed by the tissue (e.g. Nd:YAG), the tissue has to be irradiated for a long time before the ablation process is started. The start of tissue ablation can be accelerated by coating the probe surface with a IR absorber. This layer will absorb part of the light and transfer its heat to the tissue in direct contact with the tip. If the absorbed energy is high enough, the tissue will immediately carbonize and from that point absorb all laser energy providing an efficient tissue ablation.

3.2.2 'dirty' tips

Starting a clinical procedure with a new uncoated fiber tip in combination with a CW laser, it can take some time before the tip will ablate tissue efficiently. However, when tissue starts to carbonize and ablate, carbon particles will adhere to the fiber tip surface and act as the coated layer described before. It has been proven in earlier work [4] that the so called 'dirty' probes are more effective in tissue ablation compared to new 'clean' probes. The carbonized particles on the tip surface will also degrade the tip by formation of small pits and even vaporization of the silica material itself. Usually, the fiber tips have to be remodified after one clinical procedure. E.g. a ball shaped fiber can be easily manufactured on a bare fiber tip using a small high temperature torch.

3.3 Tissue contact

When tissue is irradiated by a laser beam emitted from a fiber at some distance from the tissue surface, coatings on the fiber tip, as discussed above, are useless and will only interfere with an effective energy delivery to the tissue. In this situation the optical properties of the fiber tip are of importance like focusing effects and beams divergence. These parameters will determine the spotsize and energy density at the tissue surface and the related tissue effect. For most side-firing devices the beam divergence is different for the two directions perpendicular on the beam axis [5].

When fiber tips are used in contact with tissue the information in par.3.2 applies. The optical characteristics of the fiber tip are less important since the light is either absorbed at the surface or scattered in the upper tissue layer. The mechanical properties of the fiber tip become more important especially when force is applied to penetrate the tissue [4].

3.4 Pulsed laser energy

Tissue ablation using pulsed laser energy from e.g. a Holmium, a pulsed dye or an Excimer laser, is accompanied with explosive vapor formation [6]. This rapid vapor expansion exerts force on both the tissue and the fiber tip. The construction of the fiber must be designed to withstand this force. The sharp edges of a bare fiber might also be fragile and chip off. A ball shaped fiber, however, is mechanically more resistant for the impacts of e.g. imploding vapor bubbles as verified during experiments with 3 J pulses of a Holmium laser.

Since water vapor formation is the driving mechanism of tissue ablation by pulsed laser, there is no need for a surface coating on the fiber tip. The coating would be blasted away at the very first laser pulse. In this way, fiber tips used with the Holmium laser are self-cleaning when adhering carbonized particles are vaporized every next laser pulse.

4. EVALUATION OF FIBER TIP CHARACTERISTICS

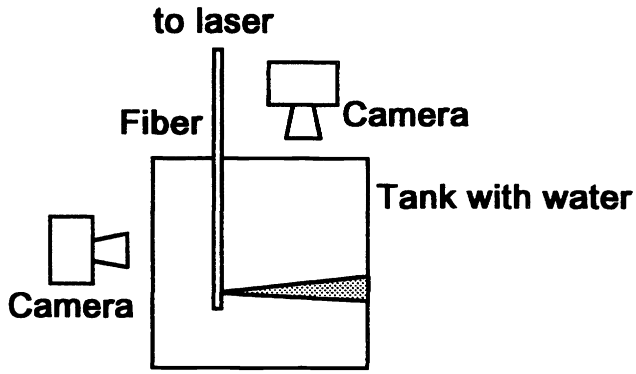
To evaluate the optical, thermal and mechanical properties of different design (modified) fiber tips various setups have been prepared to obtain qualitative and quantitative data. This paper will mainly discuss fiber tip designs for BPH treatment.

4.1 Methods for measuring optical properties

4.1.1 Beam photography

A photograph of the beam will give a good first qualitative impression of the beam divergence and secondary beams although this information can not be quantified. The beams are visualized in air using (cigarette) smoke and a laser beam of a visible wavelength (Argon, Cu-vapor/dye). For a water environment, a small amount of ink is diluted in water to provide some scattering of the beam. Using white scattering particles like interlipid is not advised since it will diffuse and distort the beam. The beams are photograph from different directions (see figure 2).

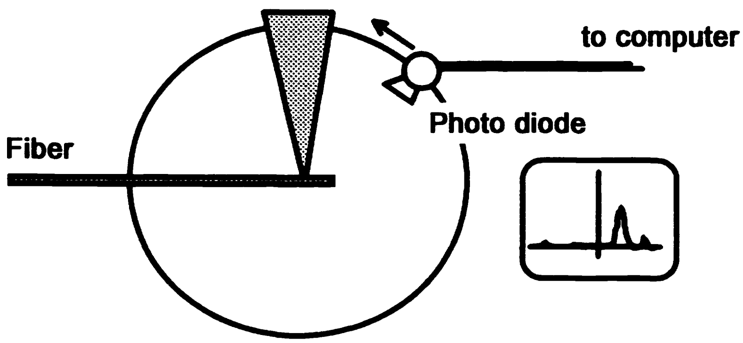
Figure 2:
Setup for beam photography



4.1.2 Circular scanner

To determine the relative power density distribution around a laser device, a photodetector is scanned at a particular distance 360 degrees around a fiber tip as shown in figure 3. The inset shows an example of the measurement. Especially, secondary beams which are not intended in the design, will show up as small irregularities in the curve.

Figure 3:
Setup of circular scanner



4.1.3 Plane scanner

To quantify the power density distribution and beam divergence of the primary beam, the beam is scanned in one plane along the axis of the beam. A 100 μm large aperture sensor is scanned in the x and y direction through the beam. With the obtained data, the beam profiles can be presented in various manner as shown in figure 4.

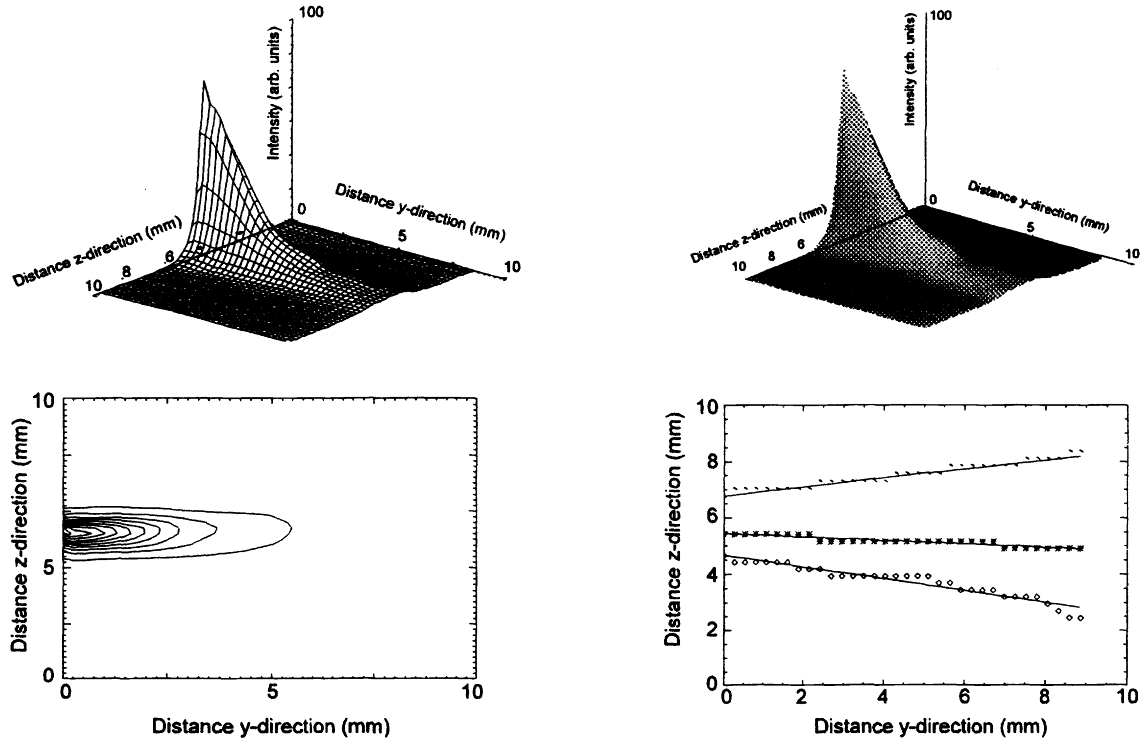


Figure 4: Various plots of the same parallel scan of a side firing fiber (Bard, UroLase), wire frame, surface map, contour map and plot with $1/e^2$ divergence lines.

4.1.4 Transmission measurements

For a clinical-relevant transmission measurement for especially side-firing fibers, the measurement conditions should be comparable with the clinical application. The fiber tips are used under water (particularly in the prostatic urethra) and with relatively high input powers (ranging from 20 to 80 Watt). Therefore the measurements are performed with a specially developed power meter [7] shown in figure 5 called 'Aquarius'.

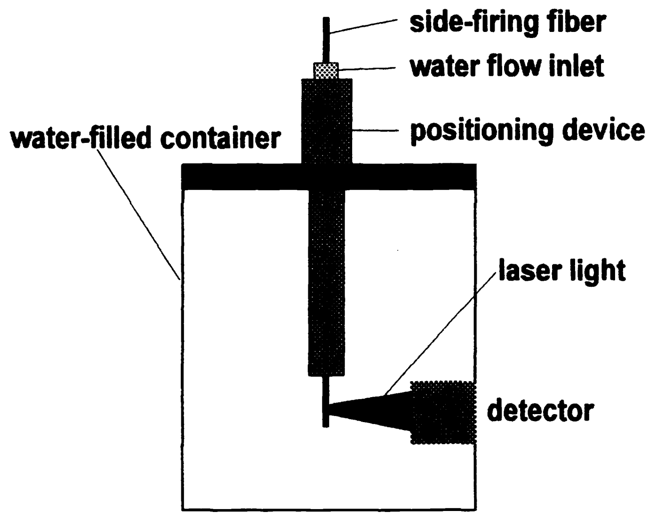


Figure 5:
Power meter 'Aquarius' specially designed for side-firing fibers

The detector head is positioned inside a water-filled container. The fiber is placed in such a way that it emits the laser light perpendicular to the wall of the container and to the surface of the detector head. The distance of the fiber to the detector is about 5 mm. Unlike an integrating sphere power meter only that beam is measured that will cause the clinical effect (the so-called primary or therapeutic beam). Possible secondary beams caused by scattering will not be considered. A water flow can be incorporated along the fiber axis. In this way the measured power is a good representation of the power that actually reaches the tissue and that causes the therapeutic effects. The power meter also permits power measurements in sterile conditions so the change in transmission during a clinical treatment can be monitored.

The transmission before use of the eight different side-firing fibers is presented in figure 6. The transmission was calculated relative to that of a bare fiber with the same diameter. Measurements were done at 4 different power settings: 10, 20, 40 and 60 Watt.

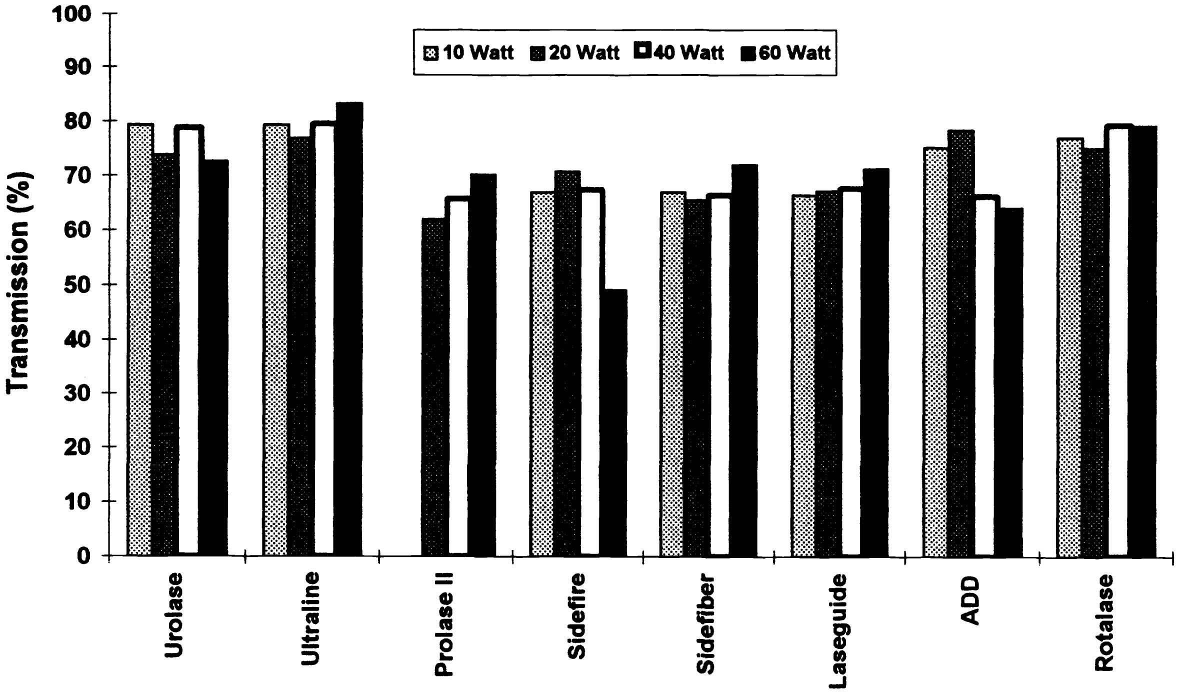


Figure 6: Results of the transmission measurements with the 'Aquarius' power meter.

4.2 Temperature measurements and thermal imaging

4.2.1 Thermocouple measurements

A simple way to get a qualitative impression of the thermal behavior of a fiber tip is attaching a thermocouple on the tip if possible on any metal part available as performed before [8]. During laser exposure, the fiber tip will also be heated by parts absorbing secondary beams or by coatings absorbing the light directly.

4.2.2 Thermal Imaging

Imaging the temperature distribution around a fiber tip could reflect the positions were light is being absorbed. Normally, a thermocamera would be used if the fiber tip is used in an air environment. However, most of the fiber tips evaluated are used in an water environment. The special thermal imaging techniques has been developed by the author which enables imaging of the temperature distribution around a probe in a water environment [9]. In figure 7 such images are shown of two all metal side firing probes. These images, reproduced here in black and white, normally show discrete color bands separated by black lines representing 'isotherms' [10].

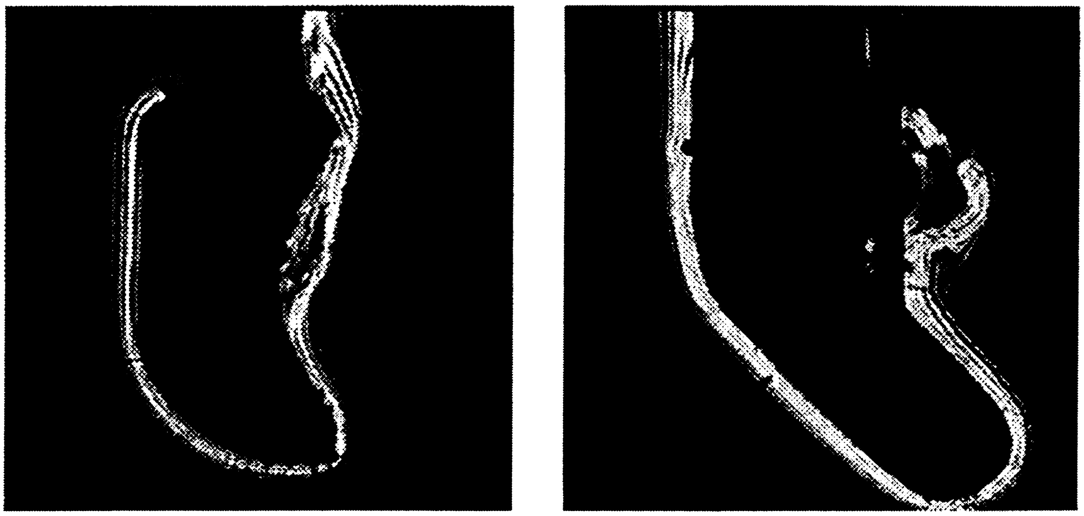


Figure 7: Thermal images of metal side-firing fibers; left: Bard, Urolase, right: Matteoli bridge.

4.3 Tissue ablation and penetration: mechanical properties

The speed of tissue ablation can be measured focusing a laser beam at the top of a tissue laser and measuring the light transmission through the tissue at the bottom to see the advance of crater formation and to detect the moment of total perforation [11]. When using the fiber tip in contact with tissue, probe penetration in relation to exerted force and tip diameter using the 'penetration tower' setup (fig. 8) as used before [4,12].

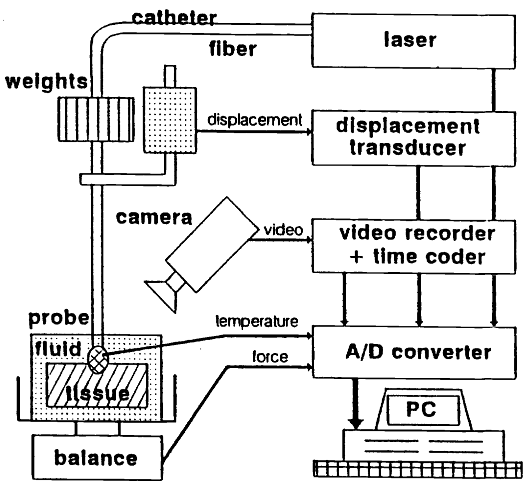


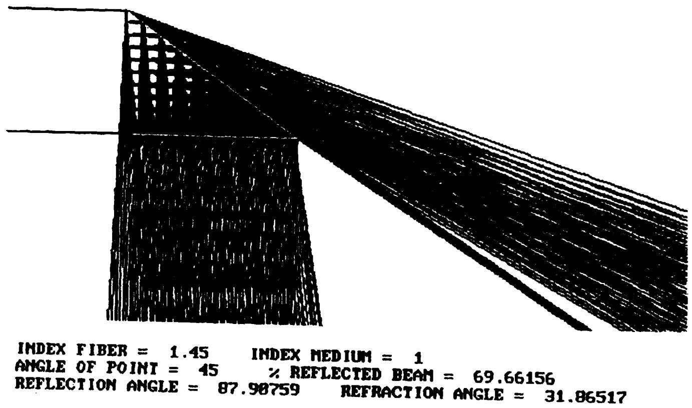
Figure 8:
'Penetration Tower' setup

5. RAY-TRACING

Theoretical calculations can be very helpful to predict and optimize the optical behavior of a particular probe design. The optical behavior of hemispherical, ball shaped and tapered fiber tips of silica and sapphire have been discussed before [3,13]. For side-firing fibers based on internal reflections the deflection angle and the intensity of primary and secondary beams in relation to the angle of the fiber tip were determined using a specially developed ray-tracing program. The program will produces graphs as shown in figure 9.

The results are presented in figure 10. To get all emitted energy in the primary (reflected) beam only, the angle of the tip must be smaller than 42 degrees.

Figure 9:
Example of ray-tracing of a 45 degree fiber tip showing the sideward reflected and forward refracted beam



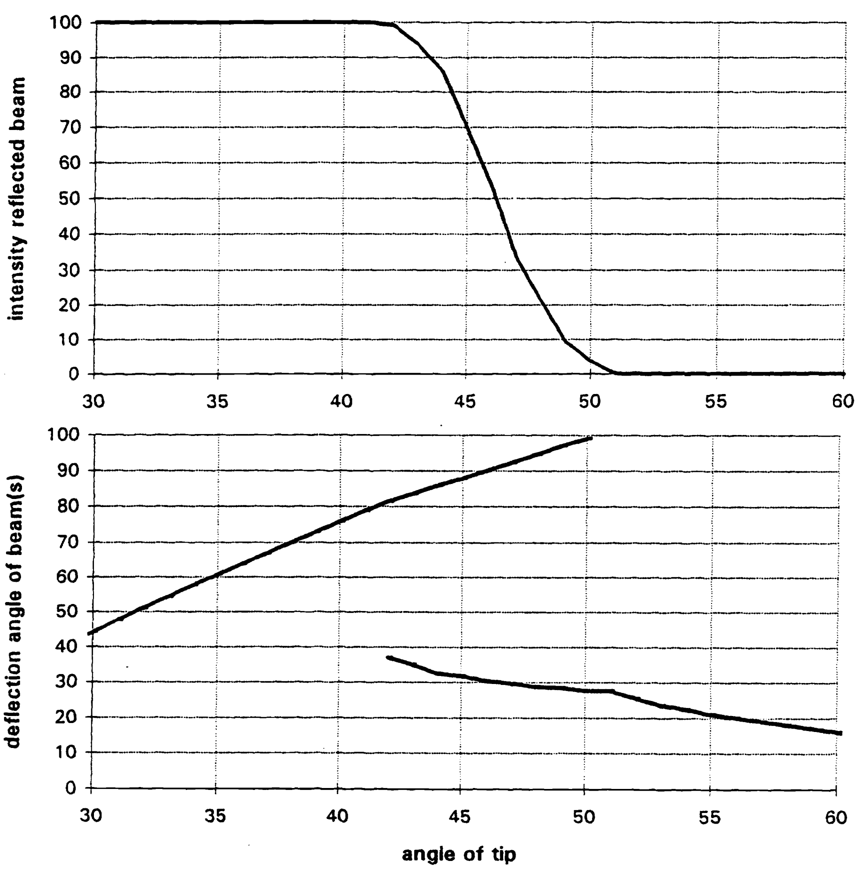


Figure 10*: Intensity of the reflected beam (top) and the deflection angle of the refracted and deflected beams (bottom) in relation to the angle of the fiber tip.*

6. EXAMPLES OF CLINICAL APPLICATIONS

6.1 Urology Application

Many side-firing laser devices have been designed for the treatment of Benigne Prostate Hyperplasia (BPH) in the last two years and are also clinically applied. Evaluation of these fiber tips shows that they are unique with regard to the angle at which the light is deflected off axis and to the size and shape of the spot at the urethra wall [2,5],. These measurements can be used to determine an optimal dosimetry with the best fitted parameters for each device. For some it may be best to irradiate the prostate at a fixed position while others have to be moved to 'paint' the prostatic tissue for a satisfying coagulation and later desobstructive effect in the urethra. Besides side-firing fibers also contact probes in combination with pulsed laser are being investigated.

6.2 Neurosurgery Application 1

For other applications, such as neurosurgery, effective and precise ablation of tissue is required from the fiber tip. This can be achieved by the combination of laser wavelength, pulse length and shape of the (multi)fiber tip. By precoating an atraumic ball-shaped fiber, only tissue in contact with the probe surface is instantly vaporized by <1 s exposure with CW lasers with a small lateral coagulation zone. This method is successfully applied in endoscopic ventricular fenestration. An cyst wall obstructing the fluid circulation between ventricles in the brain is perforated totally by punching tens of holes in the membrane. When the mechanical strength of the membrane is weakened sufficiently, it can be removed with a mechanical tool without the risk of inducing bleedings.

6.3 Neurosurgery Application 2

Using a preferred arrangement of multifibers [14], the desired shape of a cut can be made in tissue using a 308 nm excimer laser without thermal damage, though one has to be cautious for the mechanical trauma due to explosive vapor formation. A ring shaped multifiber catheter, with a suction through the inner lumen, is used to punch a circular hole in a vessel wall to create a high flow bypass in the brains without occlusion of the receiving artery. This technique is used to perform surgery on patients suffering from brain ischemia or a dangerous arterial aneurysm [15].

7. CONCLUSIONS

Knowledge of the optical, thermal and mechanical characteristics of fiber tips enables the appropriate choice of the fiber delivery system and the dosimetry for a successful clinical laser application

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