EUROPEAN PATENT SPECIFICATION

Medical laser delivery system with internally reflecting probe

Medizinisches Lasertransportsystem mit intern reflektierender Sonde
Système médical de délivrance de lumière laser muni d’une sonde à réflexion interne

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Description

This invention relates to a medical laser system for delivering laser energy to a treatment site in a liquid medium, the system comprising: means for generating a laser output, and an optical fiber having an input end and a delivery end, with the fiber being so arranged that the laser output is coupled to the input end and exits the delivery end, and with the delivery end terminating in an end surface disposed at a non-normal angle with respect to the longitudinal axis of the fiber, and with the angle (β) of said end surface being such that the laser output will be totally internally reflected off the end surface and be redirected out of the side of the fiber when the index of refraction of the medium adjacent the end surface is close to that of air.

The use of lasers in medical procedures has increased significantly in the last few years. Medical laser devices include a laser engine for generating a high power treatment beam. A means is provided for delivering the treatment beam to the treatment site. The type of delivery means is dependent upon the wavelength of the laser radiation. For example, optical fibers have been developed to carry wavelengths in the visible and near infrared regions of the spectrum.

In most fiber delivery systems, the laser output exits the fiber substantially along its longitudinal axis. Fiber delivery systems have also been developed wherein the output beam is redirected so that it exits the probe at an angle relative to the axis of the fiber. By redirecting the angle of the beam, treatment sites can be reached which are not in line with the fiber. In addition, the probe can be used in a manner more similar to a mechanical knife.

One approach for redirecting the beam is to place a mirrored surface or a prism beyond the end of the fiber. Examples of such approaches can be found in U.S. Patent Nos. 4,445,892 and 4,672,961.

Another approach is to utilize the phenomenon of total internal reflection to redirect the output beam. For example, in U.S. Patent No. 4,648,892, there is disclosed a probe which has a specially configured tip located beyond the end of the fiber. The tip includes a small chamber filled with air having an index of refraction significantly lower than the material which forms an angled surface at the tip. The laser beam is reflected off the angled surface due to the differences in the indices of refraction of the tip material and the air pocket.

A related approach is described in US-A-4,740,047. That document describes a probe having an integrally formed angled end surface. A sealing member is provided and surrounds the end surface. The sealing member functions to trap air and exclude blood and saline from coming into contact with the angled end surface. Because of the difference in indices of refraction between the fiber and the air within the sealing member, the laser beam is totally internally reflected off the angled end surface and exits the side of the fiber.

While the latter approach was effective for redirecting the light energy, it still required an extra sealing member. In addition, the sealing member is subject to failure under the harsh conditions associated with intense laser power.

US-A-4625724 describes a medical laser system of the kind defined hereinafter at the beginning in which the optical fiber has a conical tip which is adapted to form the wall of a vascular duct near the butt ends of two portions of vascular duct which are to be anastomosed. The fiber is made flexible and has a diameter sufficiently small to allow the tip to be positioned within the vascular duct at a position for irradiating the inside of the butt ends of the vascular duct portions. The laser output is of low power. The apex angle of the conical tip is chosen to be substantially 60° on the basis that the tip will be used in contact with air.

According to the present invention, a medical laser system of the kind defined hereinbefore at the beginning is characterised in that the means for generating a laser output is such that the wavelength and energy level of the laser output exiting the delivery end will vaporize a predetermined liquid medium directly adjacent thereto creating a vapor bubble abutting the end surface, the vapor bubble having an index of refraction close to that of air thereby enabling the laser output to be totally internally reflected off the end surface and redirected out of the side of the fiber.

A preferred embodiment of the invention has a laser for generating a treatment beam. The beam is delivered to the treatment site through the optical fiber which is mounted within a probe.

In use, the probe is placed near the tissue to be treated. If the delivery end of the probe is surrounded by air, the treatment beam will be totally internally reflected and exit the side of the fiber. This effect is due solely to the angle of the end surface.

In many surgical procedures, the delivery end of the probe will be immersed in a liquid medium. The liquid medium might be blood or other natural body fluids. In the alternative, the area might be irrigated with saline. Since the index of refraction of these liquids is much closer to the index of refraction of the fiber, total internal reflection of the beam would not be expected. However, the wavelength and power of output pulses of the treatment beam are selected so that the water in the liquid medium surrounding the delivery end of the fiber will be vaporized. The vaporized liquid creates a bubble in the fluid medium that surrounds the fiber. The index of refraction of the bubble is substantially similar to the index of refraction of air. Thus, as soon as the bubble is formed, the treatment beam will be totally internally reflected at the angled surface and will exit the fiber along the side edge thereof.

The creation of the vapor bubble is based on the absorption of the laser energy by the fluid medium. The fluid media discussed above consist primarily of water. Figure 1 is a logarithmic graph plotting the absorption coefficient (in units cm⁻¹) of laser energy in water with respect to wavelength. As can be seen, the absorption
coefficient is significant above 1.5 microns and there are two absorption peaks at 2.1 microns and 3 microns. Applicants have tested a preferred embodiment of invention that has a pulsed, high power, Ho:YAG laser with an output wavelength of 2.1 microns. The 2.1 micron output is closely matched to one of the absorption peaks in water. Ho:YAG pulses having an energy as low as 25 millijoule will create a bubble sufficient to redirect the light.

Other gain media which may be suitable to create this effect would include Thulium:YAG at 2.01 microns, Erbium:YAG at 2.9 microns and Nd:YAG, particularly at the 1.44 micron wavelength. As the wavelength of the laser output moves away from the absorption peaks in water, the energy per pulse needed to create the bubble will increase.

The creation of a vapor bubble at the end of a laser delivery probe in a liquid medium has been reported in "Noncontact Tissue Ablation by Holmium:YSGG Laser Pulses in Blood," Lasers in Surgery and Medicine, van Leeuwen et al, 11:26-34, (1991). As described in the article, the bubble begins to form as early as 15 microseconds into the pulse. In their device, the bubble reached its maximum extent at about 250 μs. The bubble then began to disintegrate and disappears by about 450 μs. In the preferred embodiment of the subject invention, the duration of the laser pulses are on the order of 300 μs, well within the window of existence of the bubble.

It should be noted that the discussion in the van Leeuwen article concerns the on-axis penetration depth of the laser beam and the role which the vapor bubble plays in increasing that depth. The article is unrelated to the use of such a bubble to create a total internally reflecting probe.

As can be appreciated, using the subject approach, total internal reflection of the beam off an angled surface can be achieved without the use of any additional structural elements attached to the end of the fiber. By this arrangement, an extremely simple and reliable device can be manufactured and used.

Further objects and advantages of the subject invention will be appreciated from the following detailed description taken in conjunction with the drawings in which:

Detailed Description of the Preferred Embodiment

Turning to Figures 2 and 3, there is illustrated a schematic view of a medical laser system 20 embodying the subject invention. The system 20 includes a laser source 22 for generating a treatment beam 24.

The system 20 further includes a probe 30. Probe 30 includes an optical fiber 32. The optical fiber 32 is typically formed from a glass. Fiber 32 has an input end 34 and a delivery end 36. The output beam from the laser 22 is coupled into the input end 34 of the fiber 32 with suitable optical elements.

In accordance with the subject invention, the delivery end 36 of the fiber includes an angled end surface 40.

The angle β is selected so that substantially all of the light output travelling down fiber 32 will be totally internally reflected at surface 40 and be redirected out the side of the fiber. This angle β can be readily determined if indices of refraction of the fiber and the medium surrounding the fiber are known.

The approach for determining this angle β begins with a determination of the angle of the ray R, relative to the surface normal 42, which must be met or exceeded to produce total internal reflection. The angle of total internal reflection (TIR) may be calculated using the following formula:

\[ \alpha (\text{TIR angle}) = \sin^{-1}(n_2/n_1) \]  

where \( n_1 \) is the index of refraction of the fiber core and \( n_2 \) is the index of refraction of the medium surrounding the fiber. As will be discussed below, in the subject invention, the vapor bubble surrounding the end of the fiber will present a medium having an index substantially similar to air, which is close to unity.

The next step in the process is to determine the maximum angle θ along which rays will propagate within the fiber. While a portion of the rays will propagate close to the fiber's central axis, a significant portion of the energy will be guided off the walls of the fiber. The angle of maximum propagation θ is a function of the index of refraction of the material forming the core of the fiber versus the index of the refraction of the material forming the surrounding cladding and is given by the following formula:

\[ \cos \theta = \frac{n_{\text{clad}}}{n_{\text{core}}} \]  

The selection of the angle β for the end surface is then made so that any rays propagating at maximum angle θ with respect to the axis of the fiber will equal the TIR angle (α) when striking the end surface. All rays propagating along the fiber at less than the maximum propagation angle will exceed the TIR with respect to the end surface. Based on simple geometric principles, angle β is then given by:

\[ \beta = 90 - \alpha - \theta \]
In use, the probe 30 is inserted into the patient adjacent the site to be treated with the laser energy. The probe can be used in either a dry or a fluid environment. The fluid medium should consist primarily of water and be located around the delivery end of the fiber. The fluid medium can be blood or other body fluids. Alternatively, the fluid can be provided by irrigating the site with a saline solution. Saline irrigation is common in surgical procedures such as arthroscopic knee surgery.

Once the surgeon has positioned the fiber alongside the region to be treated, the high power treatment beam 24 can be activated. In accordance with the subject invention, the character of the treatment beam is such that if a fluid medium is present at the delivery end of the fiber, the fluid medium adjacent the end surface 40 will be vaporized creating a vapor bubble 50 as shown in Figure 3. Once this vapor bubble 50 is created, the index of refraction on the outside of surface 40 will be similar to air and the treatment beam will be totally internally reflected and exit the side of the fiber.

As noted above, the creation of a vapor bubble at the end of a laser delivery fiber has been previously reported. It appears that the bubble begins to form very quickly, on the order of 15 μs. The length of time the bubble exists will be related to the time the laser energy is being transmitted through the fiber. Because the creation of the bubble is dynamic, and therefore a steady state could not be easily achieved, it is believed that the laser should be operated in a pulsed mode. The pulsed mode also has the advantage of increasing the peak power so that the water molecule will be rapidly vaporized.

As noted above, the power necessary to create the bubble is dependent on the absorption of the light in water and therefore the wavelength of the laser light. Applicants have successfully tested the subject invention using a pulsed Ho:YAG laser emitting a wavelength of 2.1 microns. Pulse energies as low as .25 millijoule are sufficient to create a vapor bubble that will cause the light to be totally internally reflected. Typical operating powers for arthroscopic knee procedures are in the range of one to two joules per pulse. Pulses in this range were generated having a duration of 300 μs which gave peak power levels on the order of 3000 to 6000 watts. In this range, the vapor bubble was created and lasted close to one millisecond so that substantially all of the pulsed power was totally internally reflected and redirected out of the side of the fiber. The laser was operated at 5 to 20 Hz.

Other wavelengths of light that are readily absorbed in water could be used to carry out the subject invention. The amount of power necessary to create the bubble is inversely proportional to the absorption of the light energy in the fluid medium. As noted above, thulium, erbium and neodymium would be suitable lasers species. These materials can be doped into various hosts such as YAG, YLF and YSGG. In the future, should a fiber be developed to safely carry longer wavelengths, other gain media, such as CO₂ at 10.6 microns could be used.

Figures 4 and 5 illustrate a probe 60 which has been fabricated and tested in accordance with the subject invention. The probe consists of a holder 62 for surrounding and supporting the fiber 64. The fiber was formed from quartz having a 400 micron diameter core surrounded by a 40 micron thick layer of doped quartz cladding. The quartz fiber was surrounded by a silicone buffer layer and a nylon jacket. In order to increase the lifetime of the fiber, the buffer layer near the end of the fiber is stripped and the fiber is encased in an adhesive injected through hole 70. The end of the fiber is also polished and annealed. A tapered venting channel 72 is provided for venting vapor and debris from the end of the probe. The process of strengthening the fiber and providing venting channels is described in greater detail in our copending European application Publication No. 0 441 606.

The end of the probe is provided with an opening 80 through which the treatment beam can be directed. In accordance with the subject invention, the end surface 82 of the fiber is angled in a manner to create total internal reflection of the treatment beam. It has been empirically determined that the optimum angle β for the end surface is on the order of 37 to 38 degrees. This angle is consistent with the calculation set forth above using a 2.1 micron wavelength beam, a quartz fiber with a doped quartz cladding and assuming that the index of the vapor bubble is close to that of air. With the end surface set at about 37 degrees, the treatment beam 90 exits the fiber with a profile as illustrated in Figure 5.

Claims

1. A medical laser system for delivering laser energy to a treatment site in a liquid medium, the system comprising: means (22) for generating a laser output (24), and an optical fiber (32) having an input end (34) and a delivery end (36), with the fiber (32) being so arranged that the laser output is coupled to the input end (34) and exits the delivery end (36), and with the delivery end (36) terminating in an end surface (40) disposed at a non-normal angle with respect to the longitudinal axis of the fiber (32), and with the angle (β) of said end surface (40) being such that the laser output will be totally internally reflected off the end surface (40) and be redirected out of the side of the fiber (32) when the index of refraction of the medium adjacent the end surface (40) is close to that of air, characterised in that the means (22) for generating a laser output is such that the wavelength and energy level of the laser output exiting the delivery end (36) will vaporize a predetermined liquid medium directly adjacent thereto creating a vapor bubble (50) abutting the end surface (40), the vapor bubble (50) having an index of refraction close to that of air thereby enabling the laser output to be totally internally reflected off the end surface (40) and redirected out...
of the side of the fiber (32).

2. A system according to Claim 1, characterised in
that laser output is in the form of pulses.

3. A system according to Claim 2, characterised in
that the energy of each of said pulses exceeds .25
millijoule.

4. A system according to Claim 2, characterised in
that the duration of the pulses is on the order of 300
microseconds.

5. A system according to Claim 4, characterised in
that the energy of each of said pulses exceeds one
djoule.

6. A system according to Claim 1, characterised in
that the means (22) for generating a laser output is
a pulsed Ho:YAG laser.

7. A system according to Claim 6, characterised in
that the energy of each of said pulses exceeds .25
millijoule and the duration of the pulses is on the
order of 300 microseconds.

8. A system according to Claim 1, characterised in
that the end surface (82) is oriented at an angle on
the order of 37 degrees with respect to the longitudi-
nal axis of the fiber (64).

9. A system according to Claim 1, characterised in
that the end surface (82) of the fiber (64) is polished
and annealed.

10. A system according to any preceding claims, char-
acterised in that the liquid medium is saline.

Patentansprüche

1. Medizinisches Lasersystem für die Zuführung von
Laserenergie zu einer Behandlungsstelle in einem
flüssigen Medium, wobei das System aufweist: eine
Einrichtung (22) zur Erzeugung einer Laseraus-
gangsenergie (24) und eine optische Faser (32),
die ein Eingangsauge (34) und ein Abgabauge
(36) aufweist, wobei die Faser (32) derart angeord-
net ist, daß die Laserausgangsenergie in das Ein-
gangsauge (34) eingespeist wird und an dem Ab-
gabauge (36) austritt, und wobei das Abgabe-
auge (36) in einer Endfläche (40) endet, die in
einem nicht rechteckigen Winkel mit Bezug zu der
Längsachse der Faser (32) angeordnet ist, und der
Winkel (π) der Endfläche (40) derart ausgelegt ist,
daß die Laserausgangsenergie intern an der End-
fläche (40) totalreflektiert wird und an der Seite der
Faser (32) herausgeleitet wird, wenn der Bre-
chungswinkel des der Endfläche (40) benachbarten
Mediums nahe bei demjenigen von Luft liegt,
dadurch gekennzeichnet, daß die Einrichtung (22)
zur Erzeugung der Laserausgangsenergie derart
ausgelegt ist, daß die Wellenlänge und das Ener-
gieniveau der Laserausgangsenergie, die an dem
Abgabeauge (36) austritt, ein vorbestimmtes, flüs-
siges Medium, das in direkter Nähe zum Abgabe-
auge vorhanden ist, zur Verdampfung bringt,
wodurch eine Dampfblase (50) erzeugt wird, die an
der Endfläche (40) anliegt und einen Brechungsin-
dex aufweist, der nahe bei demjenigen von Luft
liegt, wodurch eine interne Totalreflexion der Las-
erausgangsenergie an der Endfläche (40) und eine
Neuausrichtung derselben für den Austritt an der
Seite der Faser (32) ermöglicht ist.

2. System nach Anspruch 1, dadurch gekennzeich-
net, daß die Laserausgangsenergie in der Form
von Impulsen vorliegt.

3. System nach Anspruch 2, dadurch gekennzeich-
net, daß die Energie von jedem der Impulse 0,25
Millijoule überschreitet.

4. System nach Anspruch 2, dadurch gekennzeich-
net, daß die Dauer der Impulse in der Großenord-
nung von 300 Mikrosekunden liegt.

5. System nach Anspruch 4, dadurch gekennzeich-
net, daß die Energie von jedem der Impulse 1 Joule
überschreitet.

6. System nach Anspruch 1, dadurch gekennzeich-
net, daß die Einrichtung (22) zur Erzeugung der
Laserausgangsenergie ein gepulster Ho:YAG-
Laser ist.

7. System nach Anspruch 6, dadurch gekennzeich-
net, daß die Energie jedes Impulses 0,25 Millijoule
überschreitet und daß die Dauer der Impulse im
Bereich von 300 Mikrosekunden liegt.

8. System nach Anspruch 1, dadurch gekennzeich-
net, daß die Endfläche (82) in einem Winkel im
Bereich von 37° mit Bezug zu der Längsachse der
Faser (64) orientiert ist.

9. System nach Anspruch 1, dadurch gekennzeich-
net, daß die Endfläche (82) der Faser (64) poliert
und gegläut ist.

10. System nach einem der vorhergehenden Ansprü-
che, dadurch gekennzeichnet, daß das flüssige
Medium salzhaltig ist.

Revendications

1. Système de laser médical pour fournir de l'énergie
laser à un site de traitement dans un milieu liquide,
le système comprenant: un moyen (22) pour géné-

5
rer une sortie de laser (24), et une fibre optique (32) ayant une extrémité d’entrée (34) et une extrémité d’amenée (36), la fibre (32) étant disposée de telle manière que la sortie de laser est injectée dans l’extrémité d’entrée (34) et sort par l’extrémité d’amenée (36), l’extrémité d’amenée (36) se terminant par une surface d’extrémité (40) disposée à angle non droit par rapport à l’axe longitudinal de la fibre (32), l’angle (β) de ladite surface d’extrémité (40) étant tel que la sortie de laser sera totalement réfléchie, à l’intérieur, au niveau de la surface d’extrémité (40) et sera redirigée en sortie sur le côté de la fibre (32), lorsque l’indice de réfraction du milieu adjacent à la surface d’extrémité (40) est proche de celui de l’air, caractérisé en ce que le moyen (22) pour générer une sortie de laser est tel que la longueur d’onde et le niveau d’énergie de la sortie de laser sortant de l’extrémité d’amenée (36) vont vaporiser un milieu liquide prédéterminé directement adjacent, créant une bulle de vapeur (50) attenante à la surface d’extrémité (40), la bulle de vapeur (50) ayant un indice de réfraction proche de celui de l’air, ce qui permet à la sortie de laser d’être totalement réfléchie, à l’intérieur, au niveau de la surface d’extrémité (40) et redirigée en sortie sur le côté de la fibre (32).

2. Système selon la revendication 1, caractérisé en ce que la sortie de laser est sous forme d’impulsions.

3. Système selon la revendication 2, caractérisé en ce que l’énergie de chacune desdites impulsions dépasse 0,25 millijoule.

4. Système selon la revendication 2, caractérisé en ce que la durée des impulsions est de l’ordre de 300 microsecondes.

5. Système selon la revendication 4, caractérisé en ce que l’énergie de chacune desdites impulsions dépasse 1 joule.

6. Système selon la revendication 1, caractérisé en ce que le moyen (22) pour générer une sortie de laser est un laser impulsionnel Ho:YAG.

7. Système selon la revendication 6, caractérisé en ce que l’énergie de chacune desdites impulsions dépasse 0,25 millijoule et la durée des impulsions est de l’ordre de 300 microsecondes.

8. Système selon la revendication 1, caractérisé en ce que la surface d’extrémité (82) est orientée avec un angle de l’ordre de 37° par rapport à l’axe longitudinal de la fibre (64).

9. Système selon la revendication 1, caractérisé en ce que la surface d’extrémité (82) de la fibre (64) est polie et recuite.