MIRSURG

Mid-Infrared Solid-State Laser Systems for Minimally Invasive Surgery

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Specific Targeted Research
Theme 3: **Information and Communication Technologies (ICT)**

D4.1: Mid-IR fiber delivery system test results at low power

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Dissemination Level		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Summary
A Mid-IR fiber delivery system was designed and constructed that can be used for a large range of fiber types and laser IR wavelengths. For initial testing, the system has been optimized for the microsecond pulsed 10.6 µm CO_2 laser in combination with hollow waveguides suitable for this wavelength. The transmission loss through the coupling system itself is about 10 %. The transmission loss through a rigid 1000 micron diameter hollow waveguide is only 3 % which is near optimum. However, the more flexible 320 micron hollow waveguide has a loss of around 35 % which increases by additional 10 % when bending it. These results are in accordance which the theoretical predictions. The delivery system will be adapted and tested for other wavelengths in the next phase and optimized towards 6.45 µm. The visualisation setups for the research of the laser-interaction are being tested and optimized using the lasers with similar tissue effects as expected from the 6.45 µm laser.

Introduction
The objectives for the UMC Utrecht in the MIRSURG project for the first year were concentrated on the design and construction of an MIR fiber delivery system and the initial testing of the delivery system measuring the transmission of IR fibers and ablation of tissue.

Design of an IR delivery system
The system was designed to meet the following qualifications:
(a) Can be easily connected to various laser systems (from laboratory setups to commercial medical systems)
(b) Can be used for a large range of wavelengths in the IR (2 to 10 µm)
(c) Can be used for a large range of pulse lengths (ns to ms)
(d) Possibility to use various gas environments at the fiber entrance to reduce optical breakdown in the focus of the laser beam
(e) Accepts fiber termination with universal SMA coupling
(f) Micro adjustment of focus of beam at fiber entrance in x-y-z direction
(g) Rigid and reproducible coupling of fibers after optimal fiber coupling
(h) Accepts fibers in range of 300 to 1000 micrometer
(i) Accepts various fiber types (Hollow and solid)

This has resulted in design and construction of a fiber coupling system as described in detail below.

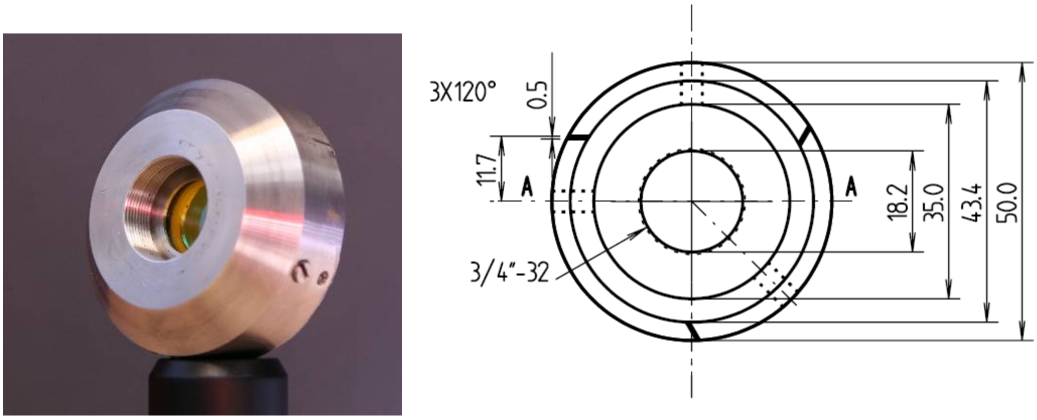


Figure D4.1.1: photo and drawing of front side of entrance of the coupler

A. Beam entrance with possibility to connect to an articulated arm, in particular Coherent/Lumenis Ultrapulse CO_2 lasers to conduct the initial testing.

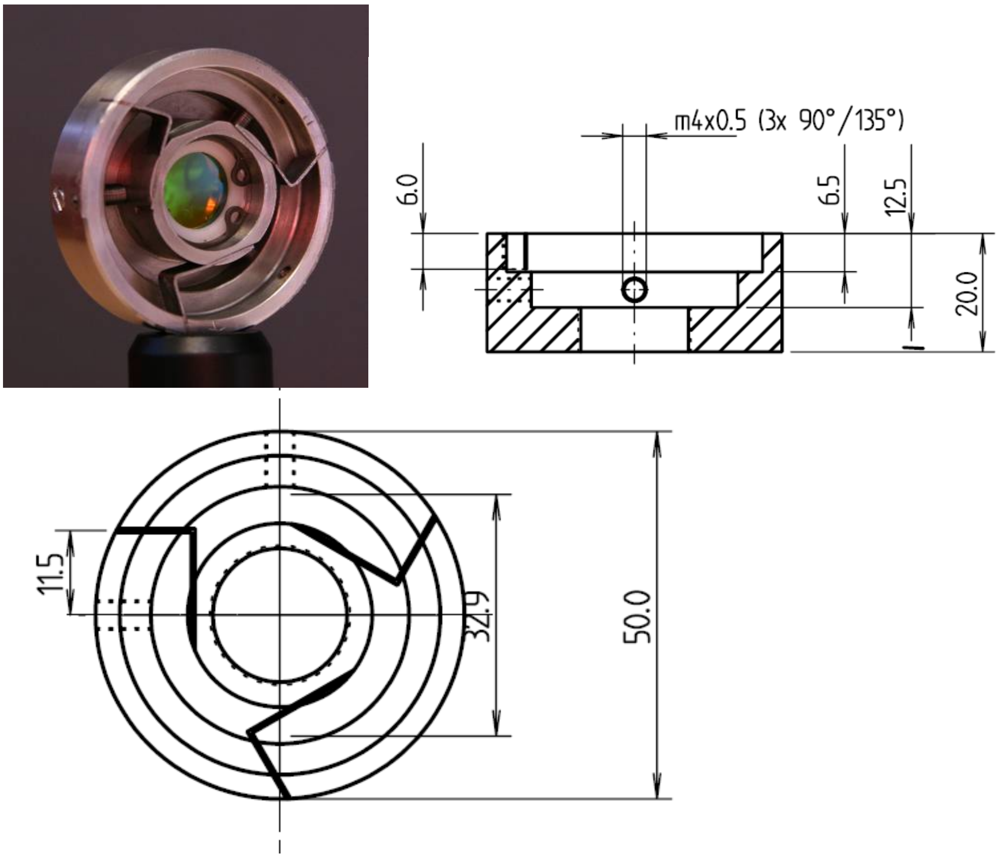


Figure D4.1.2: photo and drawings of back side of entrance with lens holder and x-y positioning system

B. Lens holder with adjustments for x-y direction using a three point spring blade system. The translation of the lens at mm scale will result in a translation of the focal point in x-y direction at µm scale. This approach makes it possible to build the construction of the SMA fiber coupling more simple and reliable.

C. The lens is made of ZincSelenide (ZnSe) and has a focal length of 120 mm and will accept laser beams up to 10 mm diameter. Typically, with this focal length, a 6 mm diameter beam with 1 mrad divergence will be focussed to a spot of 250 µm. ZnSe is a durable and water resistant material that is transparent for the long range from 1 to 20 µm in the IR. However, the refractive index is high (2.4) which results in high reflection losses (>30% for the two lens surfaces).

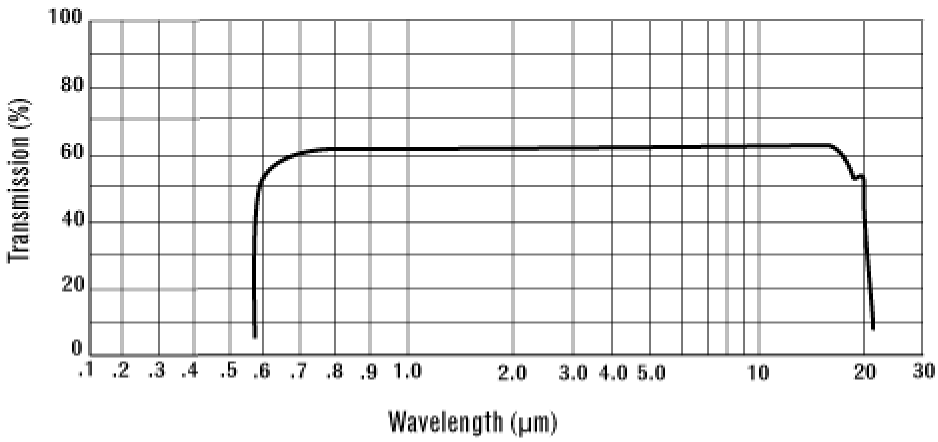


Figure D4.1.3: transmission of ZincSelenide in through the IR range

By use of special anti-reflection coatings the transmission can be improve to over 90%. However, these coating are wavelength dependent and need to be adapted to the type of laser used. For this phase of the project the lens/coupler is optimized for the CO_2 laser to perform the initial testing and feasibility studies. The lenses with other coatings can be easily exchanged for the wavelengths of interest (e.g. 2, 3 and 6.45 µm).

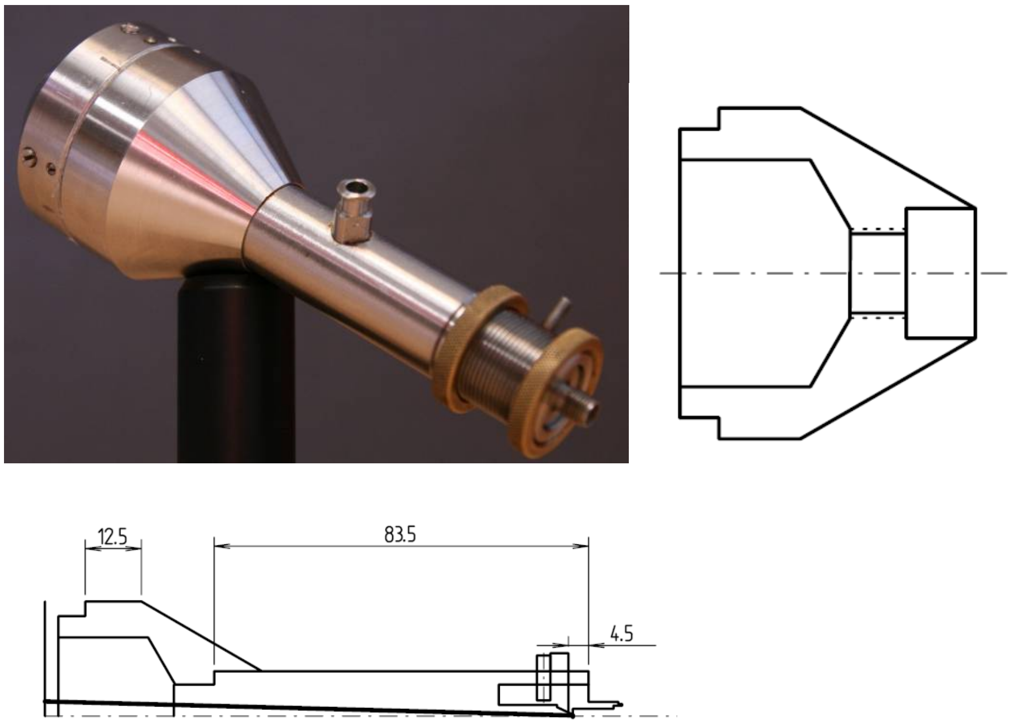


Figure D4.1.4: photo and drawings of the SMA fiber coupling side

D. SMA coupling: The distal end of the coupler consist of a metal tube in which metal cylinder can be move in the z direction over 10 mm length for fine adjustment of the focal point. The metal cylinder is translated and fixed by turning two rings against a notch that sticks out through an opening at the side. The metal cylinder accepts SMA terminated fibers.
The metal tube has a luer-lock on the side to connect to a gas flush, so the inside of the coupler van be filled with a special gas to reduce optical breakdown due to the high fluence at the focal point especially using short pulses in the ns range. The inside is not air tied at present. The gas could leak out along side the lens or SMA cylinder. However, when necessary, using membranes (e.g Teflon) and vacuum lubricant, it could be made air tied to a particular pressure level.
The gas flush can also be used to flush gas through the inner core of hollow waveguides. This is beneficial during clinical application to prevent liquids and/or ablation products to either the distal end of the hollow waveguide.

Study of fibers suitable for IR laser delivery.
Fibers suitable for the IR range (2-20 µm) stay far behind the characteristics, like transmission and strength, of silica fibers used for the visible range (0.3 to 2 µm). In general, potential IR fiber materials can be divided in the categories as shown in table D4.1.1 with typical transmission losses as shown in figure D4.1.5 [ref 1].

Main	Subcategory	Examples
Glass	Heavy metal fluoride-HMFG Germanate Chalcogenide	ZBLAN - (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) GeO_2-PbO As_2S_3 and AsGeTeSe
Crystal	Polycrystalline –PC Single crystal – SC	AgBrCl Sapphire
Hollow waveguide	Metal/dielectric film Refractive index < 1	Hollow glass waveguide Hollow sapphire at 10.6 µm

Table D4.1.1

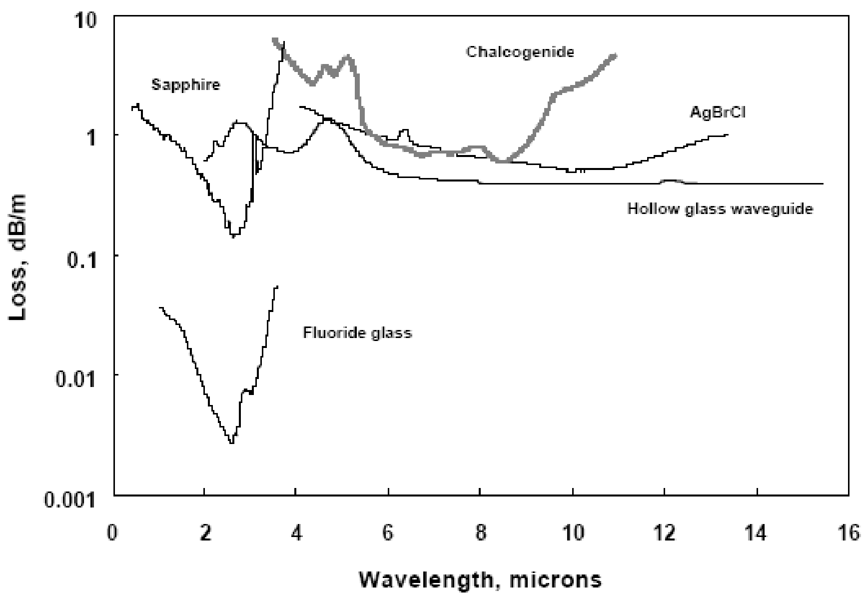


Figure D4.1.5: Typical transmission losses of the materials used for IR fibers.

For the MIRSURG project, the interest will be in fibers capable to transmit 6.45 µm and made of material that can be used in a clinical environment. Based on literature study, personal contacts with leading scientists in IR fiber development (e.g. James Harrington and Abraham Katzir) and companies producing IR fiber optics, we are concentrating on the following sources for fibers that can be used for our present feasibility study and later the 6.45 µm wavelength:

source	**website**	**contact**	**type**	**material**	**brand**	**λ range**
Rutgers University	http://irfibers.rutgers.edu/	J. Harrington	hollow		HSW	3 - 10 µm
Polymicro Technologies	www.polymicro.com		hollow			3, 10 µm
Omniguide	www.omni-guide.com		hollow		Omniguide	10 µm
Tel Aviv University	http://www.tau.ac.il/~applphys/	A. Katzir	solid	AgClBr		3 - 10 µm
CeramOptec	www.ceramoptec.com		solid	AgClBr	OptranMIR	4 - 13 µm

Table D4.1.2: sources for IR fibers for the MIRSURG project

These fibers are available at present for the CO_2 laser to conduct feasibility studies with the coupler for ablation of biological tissue with various pulse/energy parameters. The OptranMIR fibers may be directly suitable for the use at 6.45 µm. The hollow waveguides (HWG) might need to be produced with a coating for 6.45 µm.

Initial testing of fiber coupling system

For this phase of the project, we have performed our initial testing with hollow waveguides provided by Prof Jim Harrington of Rutgers University. They have licensed their technology to Polymicro from which the fibers can be bought directly. The fibers have a bore diameter of 1000 µm and 320 µm.

The fibers were cleaved at the input and output end to obtain a flat surface and the protective (plastic) coating on the outside was removed for several mm. The input end was terminated with a SMA adapter and connected to the coupler. The output end was positioned around 5 cm in front of an energy meter (Coherent). Using the x-y-z- adjustment capabilities, the coupler was aligned for maximum transmission.

The transmission was tested in four conditions:

- straight
- 90 degree bend with a fixed radius
- 180 degree bend with a fixed radius
- 360 degree bend with a fixed radius

The measurements were performed 3 times and averaged. The transmission losses due to the lens surfaces of the coupler are around 10 % and are excluded from data.

Energy pulses in the range of 10 to 50 mJ (20 to 100 µs pulse length) were launched into the fiber with a repetition frequency of 100 Hz (resp. 1 to 5 W average power)

The results are summarized in the following graphs:

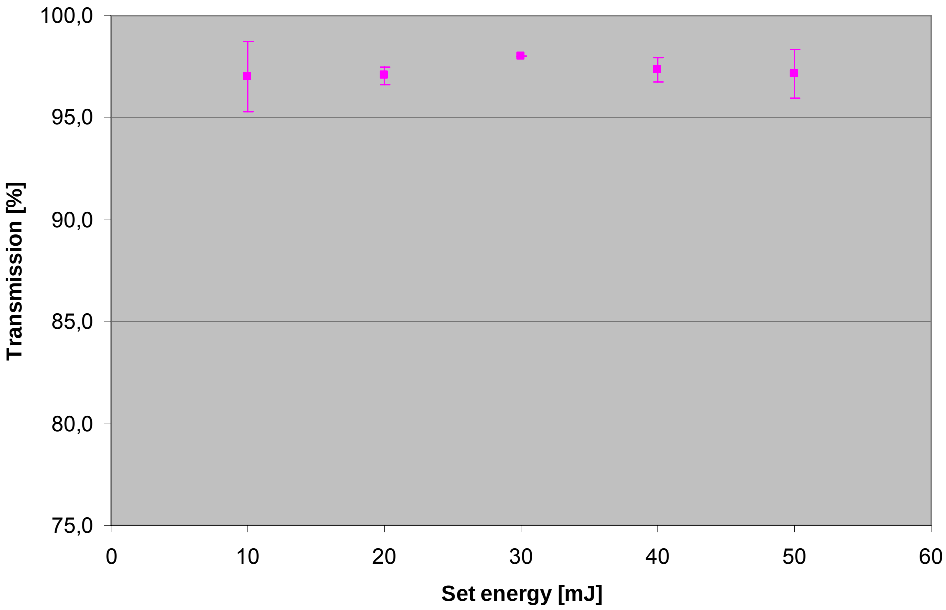


Figure D4.1.6: transmission through a 1000 µm bore diameter HWG with a length of 550 mm

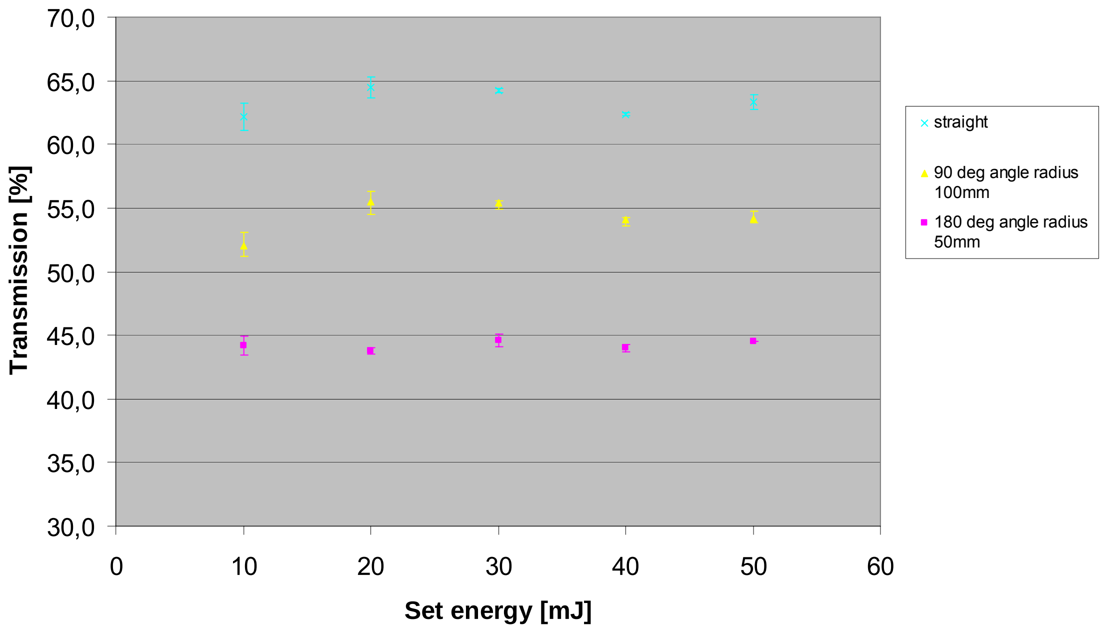


Figure D4.1.6: transmission through a 320 µm bore diameter HWG with a length of 800 mm for the conditions: straight, 90 degree angle bend and 180 degree angle bend.

The 1000 µm fiber was too rigid to bend so was only measured in straight position. The transmission losses through the 1000 µm fiber are only a few percent since a hollow waveguide does not have reflection losses due to refraction at surfaces. The spot of the laser (~250 µm) could easily fit in the fiber. However, a fiber that is too stiff to bend is not practical in a clinical environment considering e.g. endoscopic application.

The 320 µm fiber was far more flexible but the transmission losses are considerable. From theory of hollow waveguides, it is known that the transmission losses highly depend on the bore diameter dictated by $1/\alpha^3$. So for the length of 80 cm the losses are 35 %. This result is a higher then theoretically expected (20%) which is attributed to the additional losses at the input end since the spot diameter in the same order as the fiber diameter so any irregularities and misalignment become critical. Bending the fiber will result in additional losses as also predicted by theory of HWG and are around 10 % for a 90 degree bend.

For solid fibers that will be tested in a later phase of the project, it can be expected that the losses at the in- and output fiber end will be higher but there will be no additional losses due to bending the fiber. The Omniguide hollow waveguides fibers might have better performance for bending but it is not sure they will be available for the 6.45 µm wavelength. Comparison of the various fibers will prove which fibers will perform best. Also the pulse characteristics of the lasers will dictate which fiber can withstand high energy densities at the input end.

Testing of equipment and research methods for future tissue studies with the IR light

For the future research of the interaction of the 6.45 µm wavelength with biological tissue various imaging techniques will be used. To test the experimental setups and visualisation techniques, various feasibilities experiments have been performed using pulsed lasers with characteristics that resemble the expected tissue effects for the 6.45 µm wavelength: the 10 µm pulsed CO_2 laser and 3 µm Erbium which both have a high absorption in tissue water.

A. High speed imaging setup:

To observe the interaction in close up with high resolution in time, a high speed camera (Photron) is used which is capable to capture images up to 20.000 frames/second (50 µs). This camera is being used in the studies of interaction of various lasers in the UMC Utrecht. The figures below show some examples of application.

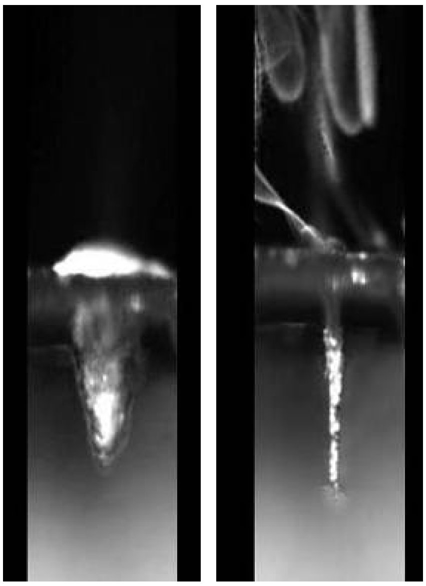
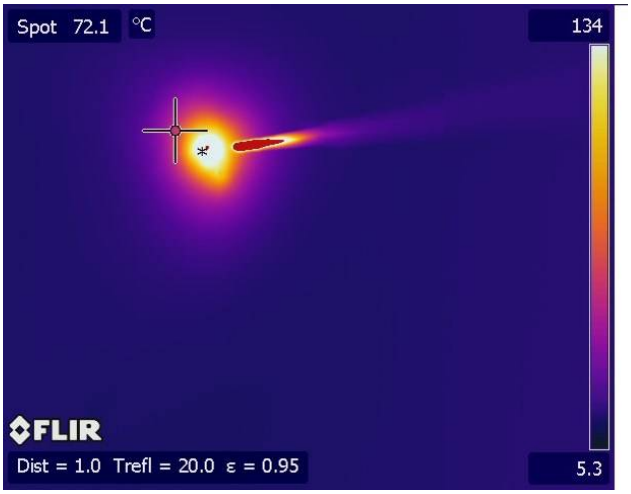


Figure D4.1.7: Example of imaging tissue ablation at 10.000 frames/sec: (left) Ablation of transparent tissue model showing the expansion of the ablation crater during vaporisation of the tissue. (right) After the laser pulse, the crater collapses and steam/aerosols are ejected. The scale of the images is 2 x 8 mm.

B. Thermal imaging

For precise tissue ablation, the energy should be used efficiently for the ablation process which minimal secondary thermal effects in the environment. Using thermal imaging techniques, the dispersion of thermal energy around the ablation area can be observed using a thermo camera (FLIR) on biological tissue as shown in figure D4.1.8 left. With a special setup, temperatures below the surface can be obtained. Using a special technique based on color Schlieren imaging, the temperature distribution can be visualised in a transparent tissue model. Additional thermocouple measurements will provide absolute temperatures (see figure D4.1.8 right).



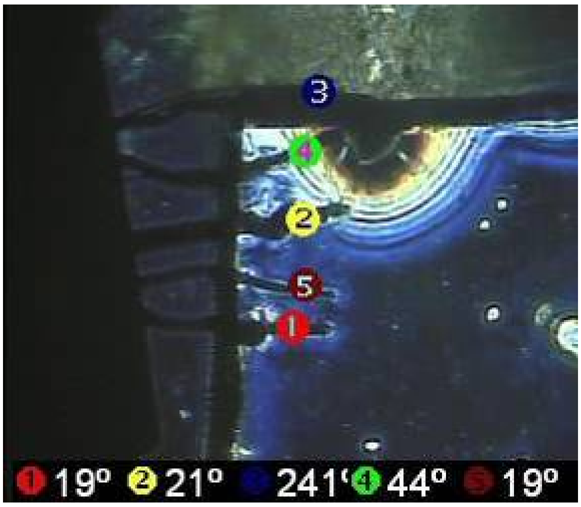


Figure D4.1.8: Examples of thermal images during laser exposure of tissue. Left: Image obtained with a thermal camera showing the hot spot on tissue irradiated by by a laser light from a fiber. Right: Image obtained with a COlor Schlieren Technique showing temperature gradients around the ablation crater from the side in a transparent tissue model. The absolute temperatures are measured with thermocouples and superposed on the bottom of the image.

Activities for next phase

A. the fiber coupler will be optimized for various fiber types and wavelengths. Lenses with coatings for othe wavelengths will be obtained.

B. depending on the laser systems that become available in the near future, IR fibers suitable for those particular lasers will be obtained and optics of the coupling system will be adapted to the fibers.

C. High speed imaging and thermal imaging studies will be conducted of laser tissue interaction using the CO_2 laser with hollow waveguide.

Ref 1: J.A. Harrington, Infrared Fiber Optics and Their Applications, CRC press (2003)