The First Coupling of a Laser Beam to a Water Jet

How a miniature dental hand tool started a revolution in cool laser machining

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Fig. 1 Water jet guided laser sawing a rough diamond

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Assigned to a project for designing a laser-based dental hand tool, Bernold Richerzhagen visualized combining a water jet and a laser for tooth ablation. His dental tool envisioned a laser within a low-pressure hair-thin water jet that guided the beam by means of total internal reflection in a manner like an optical fiber. Eventually, this fusion of light and water resulted in a new technology capable of machining hard materials with high precision. Starting with a dental tool developed in a Swiss laboratory in 1993, this invention has fostered high-precision laser machining in the aviation, diamond and semiconductor industries amongst others.

Back in 1986, Bernold Richerzhagen decided to focus on bio-medical sciences at RWTH University Aachen. He obtained his master's degree in mechanical engineering with a thesis on artificial heart design. A year later, he joined a research project at the Applied Optics Laboratory of the Federal Institute of Technology, Lausanne, EPFL, to develop a laser-based dental tool. The goal was to develop a laser energy transmission system for dental applications such as the removal of caries.

Cool laser for tooth ablation

During the design stage, Richerzhagen was asked to try a new approach to transmit the laser energy to the target and to cool the tooth during laser drilling. The theory was to guide the laser beam by total reflection within a water jet in the manner of an optical fiber. The laser would provide the heat for ablation while the water would cool the tooth. It was a radical and yet unrealized concept.

In fact, the feasibility of guiding light in a water jet had already been proven: Professor Colladon from Geneva University had shown in 1840 that a stable water jet can be used to guide light [1]. Although nobody had succeeded in combining a laser beam with a water jet, Richerzhagen decided to pursue this option. For one thing, the water jet guided laser offered the advantage of a parallel laser beam. For another, the water jet guiding the laser offers simultaneous cooling with virtually no resulting heat damage to the tooth. This was important since the nerf in the

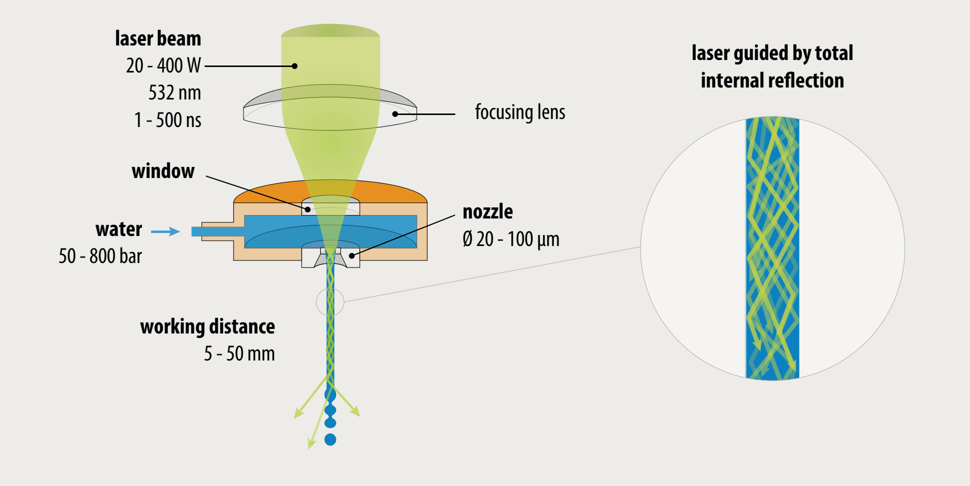

Fig. 2 Concept of a water jet laser beam

tooth is overly sensitive to temperature changes.

In theory, Richerzhagen's concept was based on passing a laser beam through a pressurized water chamber and then focusing it into a nozzle (Fig. 2). His calculations showed that it was possible to focus a laser beam into a water jet nozzle without losses other than the natural absorption in water. The low-pressure water jet emitted from the nozzle would guide the laser beam by means of total internal reflection. This parallel water guided laser would operate on the tooth.

The coupling dilemma

In practice, Richerzhagen faced two challenges. The first, rather easier, was to transfer energy from a laser source to the dentist's handheld tool. The second, more demanding, was to develop a coupling unit that would merge the laser beam in a water jet.

Using lasers available at the EPFL lab, Richerzhagen constructed his first prototype with other components such as a water pump and a water jet nozzle. After several experiments, Richerzhagen determined that a 300-micron optical fiber connected from the laser source to the dental tool resulted in minimal power losses. To obtain the needed power density, he developed a system with a mirror and multiple lenses to focus the 300-micron beam down to 100 µm.

Richerzhagen's first coupling unit consisted of an enclosed water chamber with a window on one side and a nozzle on the other side. The laser beam would pass through the window and water and be focused on the entry of the nozzle. It would then exit as a laser beam in a water jet (Fig. 3). Richerzhagen's coupling unit had mixed results. Though his calculations and simulations showed that the laser beam should pass through the nozzle, even low energy pulses damaged the nozzle bores. The beam was apparently getting defocused, hitting the nozzle edge and damaging it (Fig. 4).

Richerzhagen was faced with a serious problem of low transmission and quickly damaged nozzles. The laser beam should be reflecting internally within the water jet. Such total internal reflection results from refraction, a phenomenon that causes the laser beam passing from water into air to bend toward the surface. If the beam hits the water surface below a 'critical' angle, it reflects within the water like an

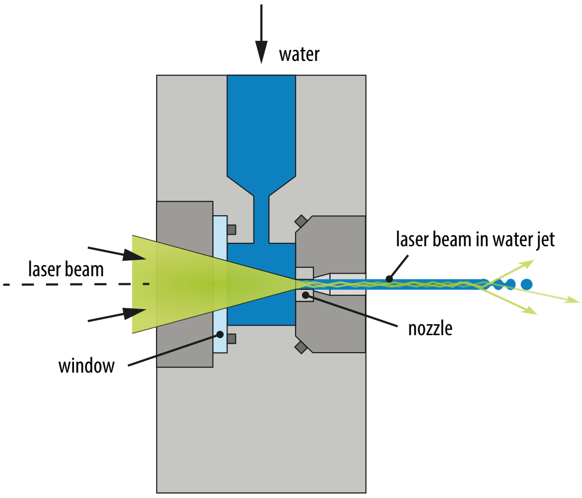

Fig. 3 Coupling unit

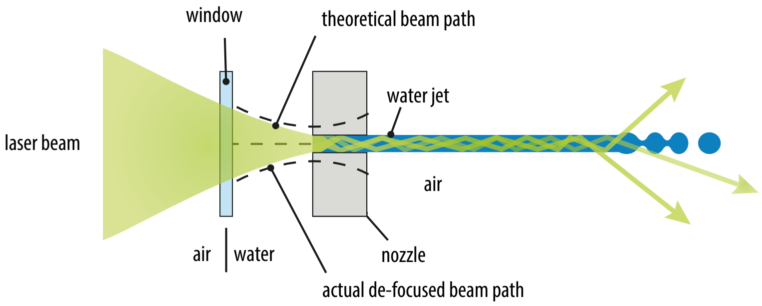

Fig. 4 Theoretical versus actual defocused beam path

Company

Synova

Synova SA, based in Duillier (Switzerland), develops and manufactures 5-axis laser machining systems based on its proprietary Laser Microjet technology. This hybrid method of machining combines a laser with a 'hair-thin' water jet that precisely guides the laser beam by means of total internal reflection. The company has supplied over 350 machines designed for applications such as drilling coolant holes in turbine blades, faceting raw diamond stones and dicing semiconductor wafers.

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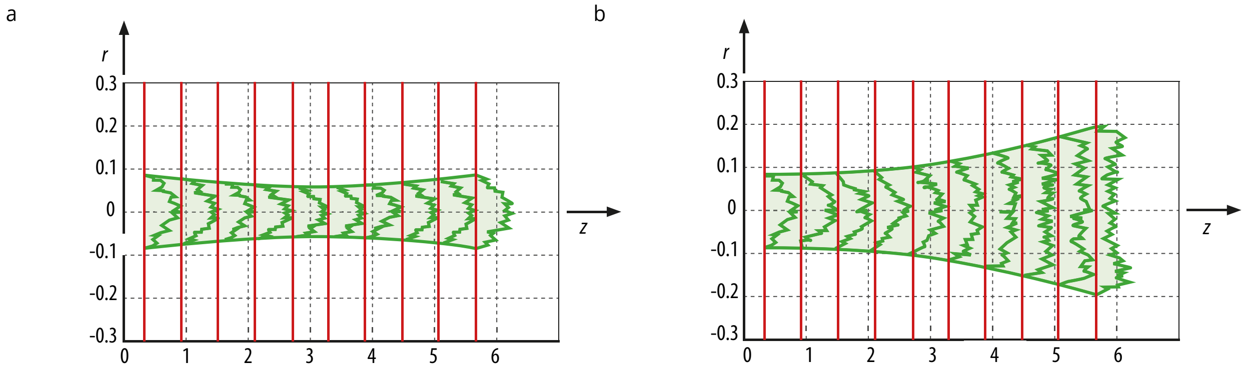

Fig. 5 Beam waist at the start of pulse in water (a), and at the end (b; from [4])

optical fiber. The priority was to identify the external factors preventing the laser beam from focusing within the nozzle. The investigation to solve this problem would last a couple of years and result in several interesting discoveries.

Proof of thermal defocusing

His first experiment was designed to study what takes place when a transparent chamber containing water absorbs energy from a laser pulse. This experimental set-up used two laser sources, a ND:YAG laser with a 200-microsecond pulse width and a second continuous low-power helium-neon laser. A photo diode registered that the helium-neon signal experienced a loss in power intensity during the 200-microsecond pulse. This led to the conclusion that a rise in water temperature resulted in a weakening of the helium-neon signal.

This was clear proof that during each 200-micron pulse, the water absorbed a small part of the laser energy. This energy was converted to heat. The increase in water temperature resulted in a change in the refractive index, which is a measure of the bending of the beam when it passes through media with different indices of refraction. A certain time after the laser pulse, the water cools down due to heat exchange processes such as convection and conduction. As a result, the refractive index returns to its original level. This 'thermal-induced' lens loses its effect. This phenomenon is known as thermal blooming or thermal defocusing.

So defocusing caused the beam to widen and the position of the focal point to shift, Richerzhagen assumed. Thus, a significant part of the energy was outside the theoretical focal point. This energy struck the front surface of the nozzle and damaged it. This process took place during the laser pulse and clear traces of the laser radiation were found on the damaged nozzles.

The next step was to measure the impact of thermal defocusing on the laser beam profile.

Fattened laser beam waist

Richerzhagen designed an experimental set-up with imaging optics and a high-speed camera to capture the change in laser beam waist at the start and end of a 200-microsecond pulse as it passed through a water chamber. The entire set-up was automated. The 200-microsecond laser beam pulse passed through a water vessel with two glass windows. Its focal point was on the output window. Imaging optics magnified the beam waist to a resolution of 2.2 microns while the camera operated with adjustable shutter speeds down to 1 microsecond. The camera recorded ten frames at different axial points from the start till the end of the 200-microsecond laser pulse.

The images were startling. They showed that the laser beam waist diameter which was less than 0.2 millimeters at the start of the pulse doubled to 0.4 millimeters at the end of the laser pulse (**Figs. 5a, b**). It was clear proof that thermal defocusing was altering the profile of the laser beam.

The problem now shifted to the domain of optics because, as a PhD student, Richerzhagen wanted to confirm his observations by theoretical calculations. For this purpose, there was a need to measure the change in refractive index of water as a function of its temperature. This would eventually enable him to take the measures needed to eliminate the thermal defocusing effect.

Water temperature and refractive index

He found that the existing quantitative data on the relationship between water temperature and the change in refractive index at 1064 nm did not serve his purpose. For this reason, he needed to measure the refractive index as a func-

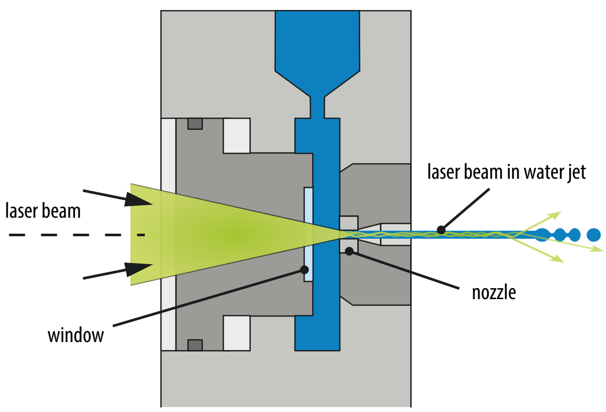

Fig. 6 Modified coupling unit

Fig. 7 Coupling unit prototype

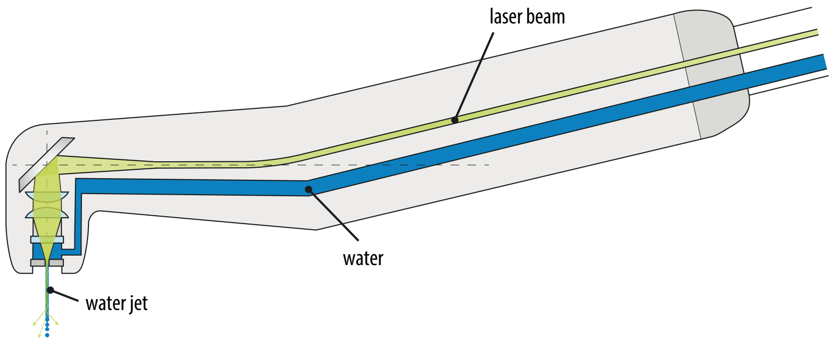

Fig. 8 Schematic of water-cooled dental tool

tion of water temperature in a controlled laboratory environment. The laser wavelength was set at precisely 1064 nm. The goal was to have accurate data that could be supported by a theoretical simulation.

Richerzhagen designed a set-up based on a modified Michelson interferometer, a configuration used for optical interferometry. The laser source was coupled to a monochromator, to ensure that the laser wavelength was within a very tight wavelength spectrum to assure a strong interference effect. The lenses and aperture corrected any astigmatism caused by the monochromator. The glass vessel was thermally insulated, so that the water temperature remained constant during the one-minute measuring process. An external circuit keeps the water heated.

The measurement cycle was long. After heating the water in the glass vessel to a specific temperature, there was an hour wait for the water temperature to stabilize. The measuring process consisted of moving the mirror in the water a specific length and measuring the interference signal. Measurements were carried out for water temperatures from 20 – 60 °C to record the refractive index for each temperature. The results were significant enough to be published in the journal Applied Optics in 1996 [2] and to become part of the Handbook of Chemistry and Physics.

Theoretical simulation

Having found the most accurate method of establishing the relationship between the refractive index and the water temperature, Richerzhagen went a step further. He decided to confirm the hypothesis of thermal defocusing and reproduce his experimental measurements of beam profiles under thermal defocusing through numerical simulation. In the process, he metamorphosed from engineer to scientist, using a methodology based on combining finite element analysis with raytracing. In a simplified form, his simulation was based on a laser beam passing through a grid of finite elements and its path being influenced by different refractive indices axially and radially.

The simulation results were extremely close to those obtained in his earlier practical experiments, without any fitting factor. The findings were of such significance to be published in Applied Optics [3] and Optical Engineering [4], in 1996. The agreement between measurement and theory enabled him to make reliable theoretical predictions of the thermal defocusing effect. Although his research was trail blazing, he did not lose track of his primary goal: developing a coupling unit that did not damage nozzles.

Improved coupling unit

In his goal was to stabilize the water temperature in the chamber when a laser pulse passed through it, he had to resort to a solution based on fluid dynamics. After much experimentation, he established that any stagnation of the water in the area where the laser beam passes through must be avoided. The conflict was that the literature says that a quasi-stationary state is necessary to achieve a stable and laminar flow towards the water jet. Laminar flow is smooth. It occurs at lower velocities. At such velocities, water flows without lateral mixing. Adjacent layers slide past one another like playing cards. The velocity depends on the viscosity and density of the fluid and dimensions of the nozzle aperture.

To ensure a laminar flow based on these fluid dynamics, he redesigned the water chamber. It simultaneously allowed a homogenous flow as well as high speed in the area of the laser path. This key milestone was achieved by transferring the features of flow laminarization to the nozzle itself. This design change resulted in a very thin chamber stabilizing the temperature of the water when the laser pulse passed through it. It achieved a constant, homogeneous acceleration of the water from the chamber until it passed through the nozzle without any turbulences. Everything was compact. The laser passed through the window and water chamber, focusing directly into the nozzle. It coupled with the water jet that was ejected from the nozzle. The process worked.

The improved coupling unit design (Fig. 6) and prototype (Fig. 7) was the first system to guide a high-power laser beam in a water jet to ablate material. With this invention, Richerzhagen had demonstrated the feasibility of a water jet guided laser capable of ablating material for the first time in history in 1993.

Fig. 9 Bernold Richerzhagen with a laser system for turbine blade machining

Integration of water-guided laser in a dental tool

After more than two years of research on thermal defocusing and experimenting with coupling unit designs, Richerzhagen produced a water jet guided hand tool for dental applications (Fig. 8). The integration of this new process in a handheld tool for dental drilling showed its superiority in many ways. The laser energy for tooth ablation was available at a length of more than four centimeters. The water jet ensured a constant cooling of the tissue. As a result, the dentist has a greater working distance between the hand piece and the tooth which enabled deeper cavities in the tooth.

The successful execution of the dental laser hand tool project provided the basis for Richerzhagen to complete his doctoral thesis by May 1994. While working on his PhD project, he submitted his first patent application (FR 2 676 913, May 1991) in the name of the project sponsors. This application described a water jet guided system based on the initial concept of having a large chamber for quasi-stationary flow of water that has not led to success. He later registered first a German patent in 1994 and then a European patent (EP7629481) in his own name in 1995, supported by the EPFL.

Richerzhagen deserves credit for his multidisciplinary approach in resolving the coupling problem. His hard work paid off; he was eventually able to apply the water guided jet laser principle in other industrial sectors. Starting from the dental hand tool and coupling unit design, he founded a company, Synova, in 1997 to manufacture laser cutting machines using water jet coupled lasers.

Extension of water jet guided laser technology in industry

Since its inception, Synova has supplied more than 350 machines worldwide in industry sectors ranging from automotive and aviation to diamonds and semiconductors (Fig. 9). However, the results of the fundamental research carried out on the coupling unit are still valid. To ensure the successful coupling of any laser in liquid jets, a thin, disc-type water chamber is needed to control the thermal effects. The work done on the dental hand tool is still paying dividends today.

Richerzhagen has laid the basics for a machining technology that is being increasingly applied in many industry sectors to process various materials, often high-tech materials such as ceramic matrix composites or CVD tools requiring a high quality of surface finish. Leading research institutes globally have taken interest in the technology and its potential applications. The future looks bright for the evolution of this technology.

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[1] *J. Hecht*: 'City of Light – The Story of Fiber Optics', cf. p. 12, Oxford University Press, 1999, ISBN 0-19-510818-3

[2] *B. Richerzhagen:* Interferometer for measuring the absolute refractive index of liquid water as a function of temperature at 1 .064 pm, Applied Optics **35** (1996) 10, 1650-1653

[3] *B. Richerzhagen:* Finite element ray tracing: a new method for ray tracing in gradient-index media, Applied Optics **35** (1996) 31, 6186-6189

[4] *B. Richerzhagen, G. Delacrétaz, R. P. Salathé:* Complete model to simulate the thermal defocusing of a laser beam focused in water, Opt. Eng. **35** (1996) 7, 2058-2066

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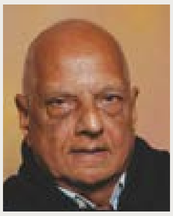

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