# Water Jet Guided Laser Cutting: a Powerful Hybrid Technology for Fine Cutting and Grooving

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## Abstract

Material laser cutting is well known and widely used in industrial processes, including micro fabrication. An increasing number of applications require nevertheless a superior machining quality than can be achieved using classical laser cutting. An efficient possibility to increase the cut quality is to opt for the water-jet guided laser technology. In this technique the laser is conducted to the work piece by total internal reflection in a thin stable water-jet, comparable to the core of an optical fiber.

The water jet guided laser technique was developed originally in order to reduce the heat affected zone near the cut, but in fact many other advantages were observed due to the use of a water-jet rather than an assist gas stream applied in classical laser cutting. In brief, the advantages are threefold: absence of divergence due to light guiding, efficient melt expulsion, and extremely efficient work piece cooling.

This paper gives an overview of industrial applications of the water-jet guided laser technique. These applications range from the cutting of CBN or ferrite cores to the dicing of thin wafers and the manufacturing of stencils; each illustrates the significant impact of using the water-jet.

**Keywords:** Laser cutting, micro machining, water jet, hybrid cutting process, dicing, semiconductors, solder masks.

## Introduction

*"I [...] managed to illuminate the interior of a stream [of water] in a dark space. I have discovered that this arrangement [...] offers in its results one of the most beautiful, and most curious, experiments that one can perform in a course on optics." – Daniel Colladon, 1842* [1]

### Historical

Daniel Colladon was a 38-year old professor at the university of Geneva (Switzerland) when he conducted light for the first time in order to demonstrate the break-up of free water jets. Hence, the water jet is historically the first optical fiber.

150 years later, more exactly in 1993, scientists of the Institute of Applied Optics from the Swiss Federal Institute of Technology in Lausanne (EPFL), only 50 km from Geneva, succeeded in guiding a laser beam in a water jet injecting sufficient power to ablate metals. Originally the technology was developed to decrease the heat damages during laser-dentistry. In fact, it revealed that the use of a water jet instead of an assist gas stream has many other advantages besides the cooling effect, which has been opening up new applications and markets for industrial laser machining since 1993.

### The Laser Microjet® principle

The basic idea is very simple: take a water jet and couple a laser beam into it (see Figure 1). Just the realization is more difficult. If not there would not have been 30 years between the invention of the laser and the realization of the water jet guided laser.

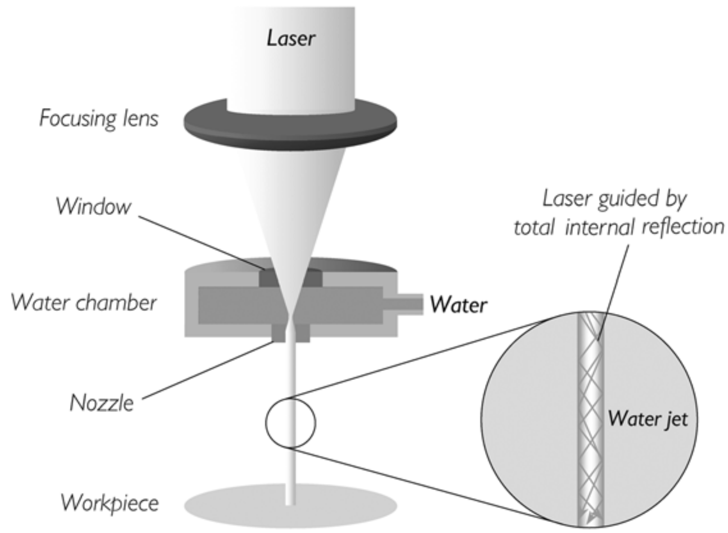


***Fig. 1.*** *Laser Microjet – Principle of the coupling unit: coupling the laser beam into the water jet*

The difficulty consisted in "marrying" two elements – light and water – that do not always like each other. The water "annoys" the laser beam by heating at the position where the light passes. The temperature change induces a negative refractive index change (so-called thermal lensing) resulting in an expansion of the laser beam strong enough to render the coupling completely inefficient. The key for success was the comprehension of this nonlinear optical phenomenon as well as its inhibition by an adapted construction of the coupling unit. This was realized using a highly dynamic flow in the coupling unit, still generating a stable water jet due to the rotational symmetric water inflow. This trick allowed the coupling of high laser powers in a hair-thin water jet, which can be used for laser materials processing.

## State of the Art

From the coffee machine powered lab-version to today's 1-million-Franc fully automatic machining centers, the process was improved in several steps. The basic idea however remained the same.

The laser source is typically a pulsed all solid state laser at the fundamental wavelength of 1064nm, or a frequency doubled (532nm) or tripled (355nm) laser. Intermitted irradiation is used in order to make sure that the water jet cools the work piece during the time between two laser pulses. The average laser powers range from 50 to 200 W, the pulse lengths range from the nano- to the microsecond, and the pulse repetition rates range, depending on the pulse duration, from 500 Hz to 50 kHz. All lasers are used with fiber delivery, using a step index fiber of 100-200 micron core diameter. The optics, that images the end of the delivery fiber onto the water jet nozzle, allows imaging factors ranging from 4:1 to 8:1. The resulting image size or laser spot diameter on the nozzle is thus 50 to 12.5 micron. It is possible to use conventional lamp pumped or diode pumped lasers, or fiber lasers.

A pressure intensifier pump especially developed for this purpose delivers the water, allowing for a constant water flow with pressures ranging from 2 to 50 MPa. The water is de-ionized (inverse osmosis and ion exchanger), filtered (1 micron), and de-gassed (vacuum membrane). Flow values are typically only 5 to 75 ml/min so recycling is not necessary.

Today's optimized water jet nozzles with diameters of 30 to 150 micron are made out of diamond or sapphire. A current research project aims at a reduction of the laser guiding water jet down to 10 microns diameter. In this range we hit the physical limits of the hydrodynamic stability of free water jets. The lifetime of the nozzles can be several months if the video assisted alignment between nozzle and laser spot is carefully done and regularly controlled.

The jet length that can be used for the light guiding is roughly 1000 times the nozzle diameter. This means for example: a 50-micron water jet can guide the laser beam for 50 mm at optimum conditions and at the optimum pressure. However, this does not mean that such a jet can be used to cut 50 mm thick material. Accordingly a 10-micron jet would still allow 10 mm working distance.

The laser beam completely fills the water jet (spatially) and is guided by total internal reflection at the water-air interface. The only losses are caused by the absorption in the liquid, depending on the applied wavelength, and Raman-scattering at high peak powers. The water jet diameter is 83% of the nozzle diameter because of the usage of sharp edged nozzles and the consequential jet retraction effect (vena contracta).

The generated kerf width is in average 10% larger than the water jet diameter. For example a 30-micron nozzle generates a 25-micron water jet and a 27-micron wide cut. The water jet is thus able to guide the light through the kerf down to the bottom of the cut – a very valuable property.

It is also possible to cut from all positions using the water jet: horizontal, vertical or upside down. The water jet guided laser can also cut in reproducible and controlled manner through a thin water layer, an important property allowing to cut sensitive materials without any contamination.

In general, the water jet laser can be used for any kind of material removal. Limits are set on the one hand by insufficient absorption of the laser light by the work piece (glass, wood, tissues) or to high thickness (copper). On the other hand some applications cannot be performed, such as deep hole drilling where the water cannot be evacuated. However, holes with aspect ratio of less than 3 can be realized. Besides these exceptions the water jet guided laser process has nearly no limits. Very rarely the use of water represents a problem.

## Advantages of the Water Jet Guided Laser

Numerous advantages result from the water jet guidance of the laser, which will briefly be discussed in the following in comparison to classical laser cutting.

The water jet removes the heat introduced by the laser to the material immediately after the end of the pulse. In consequence the work piece stays cool and material changes caused by heating are avoided. In particular we do not observe recrystallization, oxidation or micro cracks. Additionally the material is not distorting or warping. The tolerances of the final products are very small.

The diameter of the laser beam is determined by the diameter of the water jet, which in turn is constant. These stable conditions allow a cutting precision of down to 1 micron.

Due to the light guidance we do not have a focal point and the distance between work piece and nozzle is arbitrary within the working distance of the jet. A distance control is thus not necessary and the cut quality does not vary with the distance.

As the water jet guides the laser down to the bottom of the cut very high aspect ratios can be achieved during cutting. The edges are parallel.

The biggest advantage besides the cooling effect is the cleanliness of the cut. For the first time it is possible to cut without any microscopic or macroscopic contamination. Even materials that tend to contamination and redeposition can be cut extremely cleanly.

The ablation products are bound to the water in a way that for example no hazardous materials are released to the atmosphere. They can simply be filtered out of the wastewater.

The water jet ejects the melt. It has a much higher kinetic energy than any assist gas flow. When cutting thin materials, the efficiency is considerably increased compared to classical “dry” laser cutting. For this reason we can easily use Q-switched lasers for cutting of thin materials. Using a continuous water jet guided laser at 600 W, cutting speeds of more than 4 m/s were reached in thin nickel foils.

The water jet exhibits a small and constant force onto the work piece, much smaller than the force applied by an assist gas stream. In consequence, micrometric structures can be cut without vibrations.

The cut width at comparable laser power is smaller than for conventional laser cutting. 27-micron cuts using 100 W are realized without any problems, 40 microns with 200 W.

The water jet enables the use of infrared lasers in applications where conventional machining, even with UV lasers, results in significantly worse cut quality. This results in higher usable laser powers at better cut quality, lower investment and lower running costs.

The efficient melt expulsion and the immediate cooling enable the process to generate cavities with very smooth walls. Trenches with a depth precision of only 3 microns can be manufactured. Peak-to-valley wall roughness of less than 1 micron upon cutting can be realized.

It is also possible to use mounting tapes where the work piece stays fixed after the cut. The tapes are designed in a way, that the laser does not cut it, and the water including the ablation products can penetrate the tape because of its porosity.

There is nearly no area where the water jet guided laser does not offer improvements compared to conventional laser cutting. In conclusion the water jet laser is the tool of the future in precision material machining.

## Applications

Nearly all usual laser applications except deep hole drilling can be performed with the water jet guided laser. Besides this fact new applications open up that can only be performed using the combination of water jet and laser.

In following are some examples that illustrate the progress achieved by allying the water jet guided laser.

**Cutting of medical stents**

Stents are used in medicine to open up congested blood vessels. They support and dilate the tissue and allow thus a normal blood flow. Usually they are made out of stainless steel or nickel-titanium. The contours, which have to be cut in these thin tubes, are very small. Up to now mostly classical laser cutting or chemical etching are applied. Classical laser cutting of stents however requires important post treatment by mechanical and chemical cleaning and polishing steps. The water jet guided laser inhibits material changes – an important property for this application as product failure is fatal. The Laser Microjet cut tubes are already so clean that the post treatment steps can be considerably shortened (see Figure 2).

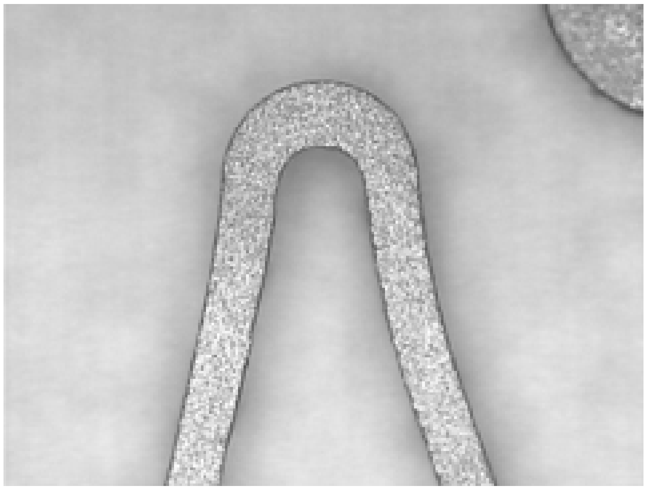

***Fig. 2.*** *200 um thick and 120 um width Nitinol stent cut with the Laser Microjet (no further process)*

The small radius of only 14 microns enables fine contours. Cutting speeds of more than 12 mm/s allow high throughput. The important advantages of the water jet guided laser in this application are: no heat influence, small beam radius, high speed, the smallest forces as well as the absence of contamination.

**Stencil drilling**

Stencils are employed for example during the production of printed circuit boards to apply the solder paste, or during the production of flat panel displays (LCD and Plasma). Standard methods for stencil production are conventional laser cutting and for thin precision stencils, dry etching. The trend towards ever-smaller apertures, increasing aperture number, thinner stencils and higher tolerance requirements make the water jet laser cutting attractive. Smallest ligaments do not bend, nor does the stencil warp. The small beam radius of 14 microns allows for sharp edges (see Figure 3).

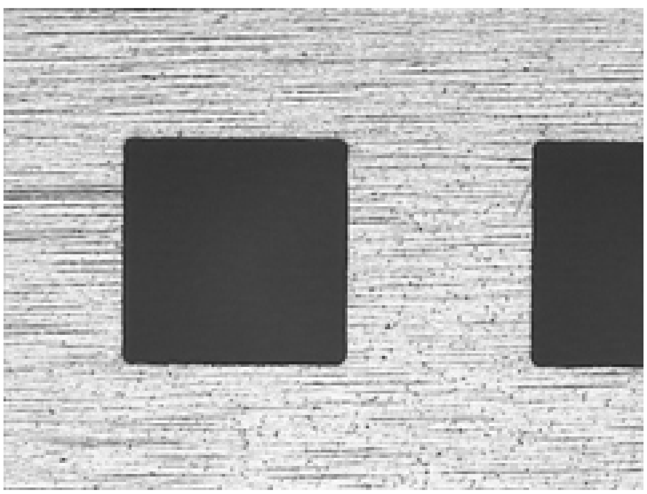

***Fig. 3.*** *475 um wide square apertures in 200 um stainless steel, rate 4000/hour*

No oxidation occurs, nor contamination, and practically no burrs remain to remove. The wall angle is programmable in order to assure easy solder paste release. The image processing capabilities of the machine can be used for inspection and – that's unique – if necessary, for repair of only partially cut apertures. The drilling speed is up to 20 apertures per second in 50-micron thick stainless steel foils. The important advantages of the water jet guided laser in this application are: absence of thermal load of the sample, small tool radius, burr- and contamination free cut, large working distance, high ablation efficiency and small product tolerances.

**Cutting air gaps in ferrite cores**

Ferrite cores are used in transformers and other coils. Certain types of ferrite cores (toroidal cores) need an air gap. The standard manufacturing method is sawing with a diamond blade or breaking and gluing. The water jet guided laser allows for automation of this process resulting in very small product tolerances and minimal running costs. The cut is absolutely parallel, free of contamination, without chippings and highly precise (see Figure 4).

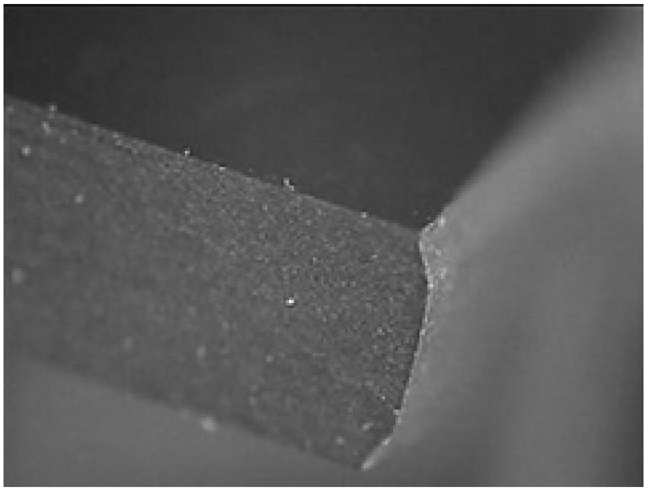

***Fig. 4.*** *Edge of a 10 mm thick ferrite core cut with the Laser Microjet*

The cut depth is virtually unlimited (more than 20 mm are possible). The following advantages are at the origin of the superiority of the water jet guided laser in this application: large working distance, light guidance in the cut, no heat load of the sample, no contamination, very high production tolerances.

**Cutting of hard materials (CBN, PCD, hard metal)**

Hard materials like cubic boron nitride (CBN), diamond or silicon nitride are mostly applied for abrasive tool production. One possibility for the use of hard metal is moulds for ceramics applied during the production of catalyst. The thickness in all these materials is typically some millimeters. The difficulty for classical machining of these materials is their extreme hardness. For this reason electrical discharge machining (EDM) and laser machining are widely used in the tooling industry. Both methods however require important post treatment of the edges. The water jet guided laser offers in this field important advantages: the edges are perfectly rectangular, without contamination or deposit and free of heat influence. The surface quality is as good as after EDM. It is possible to generate 5 micron wide and 2 mm deep trenches in hard metal that no other process in the world can produce. This enables in the end new catalysts with higher efficiency for the car manufacturing industry.

**Thin foil cutting for packaging**

A special application with very high potential is the high-speed cutting of thin metal foils, which are for example used in food packaging. Up to now they are piled up and punched, or cut one by one using knifes. The trend to more and more diversified packages and shorter product cycles requires considering alternative cutting methods. Because of the very efficient melt expulsion caused by the water jet, high laser powers are equivalent to high cutting speeds. The conventional laser can quickly melt the material. However, the assist gas stream is much to weak to expel the material at the same speed. In consequence the molten zone resolidifies without cut formation, an effect that the water jet avoids. Aluminum, nickel and stainless steel foils with thickness ranging from 10 to 80 micron can be cut with good quality and speeds of more than 4 m/s. The used laser is a diode pumped continuous wave laser with a power of 1 kW.

**Dicing of semiconductor wafers**

Integrated circuits, also called micro-chips, are manufactured using semiconductor materials like silicon (see Figure 5), gallium arsenide (see Figure 6), indium phosphide, gallium nitride (see Figure 7), low-k wafers (see Figure 8), etc.

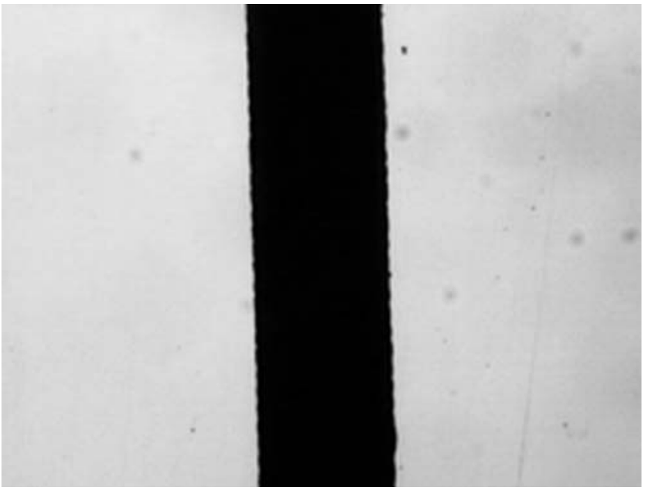

***Fig.5***. *27 um cut in 100 um thick Silicon*

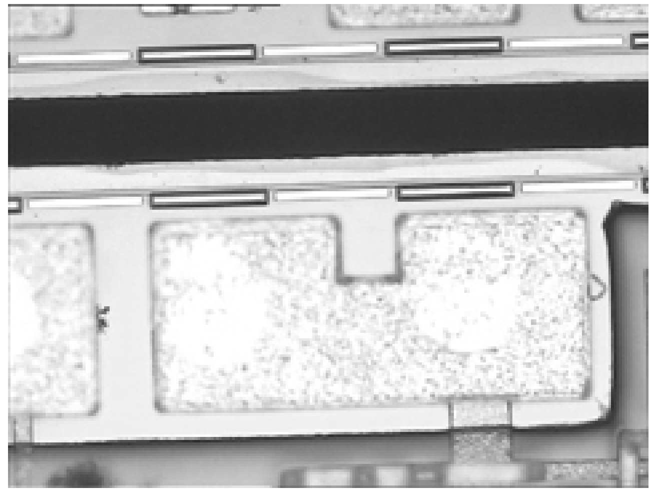

***Fig.6.*** *26 um cut in 100 um thick GaAs*

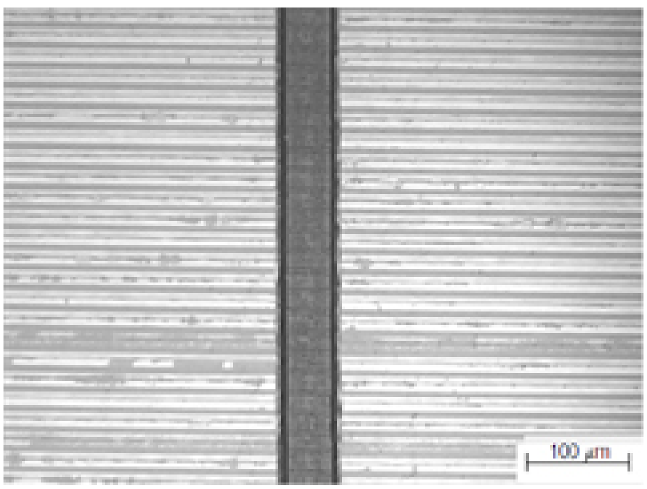


***Fig. 7.*** *10 um deep and 49 um wide groove where the GaN layer is completely removed*

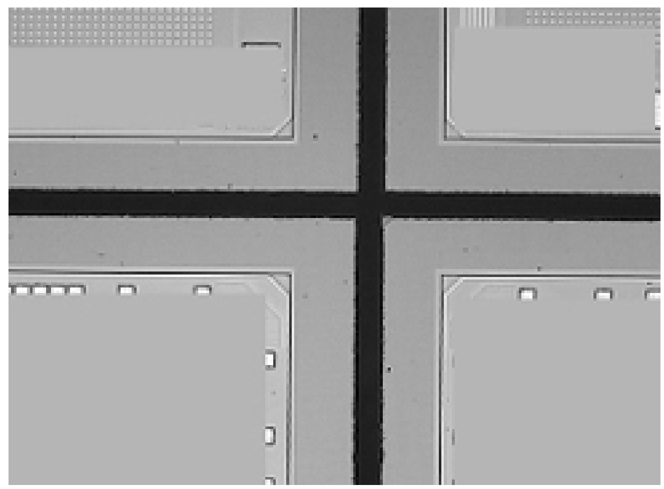

***Fig. 8.*** *35 um cut in a 100 um thick low-k wafer*

Once that all structures have been generated on the wafer, it has to be cut for separating the dies or chips (dicing). The established method for this step is abrasive sawing with a diamond blade. Today the requirements for dicing increase constantly due for example to ever-thinner substrates and very fragile layers. Conventional laser cutting was in the past not able to penetrate this market because of important quality problems. The new UV laser sources will not change the situation as fundamental problems like surface contamination, edge roughness and small efficiency are still present. The water jet guided laser however produces cuts that are unimaginable for a conventional laser process: surface contamination is lowered by several orders of magnitude to practically zero. Cut quality and cutting speed are far ahead of the values of the classical laser. Even if in the next years 100 W average power UV lasers came to the market, they would never reach the quality that the water jet guided laser obtains already today using infrared and green laser sources.

## References

[1] Daniel Colladon, “On the reflections of a ray of light inside a parabolic liquid stream”, Comptes Rendus 15, pp. 800-802, 1842

## Biographies

**Bernold Richerzhagen**

Bernold Richerzhagen received his M.Sc. in mechanical engineering from Aachen Polytechnic in Germany (RWTH) and his Ph.D. in micro-technology from the Swiss Federal Institute of Technology Lausanne. He became CEO of Synova SA in 1997. He is acknowledged as the inventor of water-jet-guided laser technology.

**Frank Wagner**
After working during his studies in the fields of ultra-fast laser development (M.Sc.) and of UV-laser ablation (PhD), Frank Wagner was hired as head of the Process R&D Group at Synova Inc in 2000. Main interest is the research and development of the water-jet guided laser technique.

**Roy Housh**
Roy Housh received his BSBA with dual majors in Business Administration and Marketing from Emporia State University, Kansas, as well as his MAE from the University of Maryland. He is also a Scholar Fellow of the International House at Washburn University. Mr. Housh has worked exclusively in global trade since finishing his studies. He joined Synova in January of 2001, and is currently International Sales Manager in charge of worldwide sales at Synova.

**John Manley**
After graduating from Glendale College A.S. Industrial Automation and RSI Tech. Mechanical HVAC M.E., John Manley worked ten years in aerospace manufacturing and thirteen years in semiconductor equipment/process engineering. He then joined Synova as manager of the USA subsidiary.