# High Power Lasers: Achievements, Challenges and Opportunities

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## ABSTRACT

Lasers with ever increasing high powers, CW as well as pulsed, have been targets for research and developments from the very invention of the laser. Availability of high powers facilitate many practical applications in industry, medicine and research in quantum electronics. This presentation will summarize some of the key advances that have occurred since early 1960's and provide a guide for what can be expected in the future.

**Keywords:** High power lasers, $CO_2$ lasers, molecular lasers, COIL, quantum cascade lasers

## 1. INTRODUCTION

During the last forty six years since the invention of lasers, there has never been a time when lasers with ever increased power outputs were not desired. Apart from purely scientific reasons for exploring the realm of ever increasing laser power outputs, the search for the high powers has been driven by the needs of novel applications. These applications address both civilian and military needs, including materials processing and modification, medical surgery and diagnoses, cosmetic surgery, target designation, offensive and defensive military weaponry and gas sensing for the ultra low level detection of industrially relevant trace gases and national security relevant chemical warfare agents, toxic industrial chemicals and explosives. Power is not the only relevant performance parameter that determines the utility of a laser in a specific application. Other equally important performance parameters include the wavelength, monochromaticity, wavelength tunability, coherence and output linewidth. However, unless the laser power output meets the minimum necessary requirement for a particular application, other properties are relatively unimportant. Thus, power output often ranks as the key performance specification in describing a laser.

High powers can be either continuous wave (CW) or pulsed. Tremendous progress has been made in both of these arenas, but for the present, I will restrict the discussion to CW high power lasers and especially to those that operate at ambient (room) temperatures.

## 2. HIGH POWER LASERS: FROM MILLIWATTS TO MEGAWATTS

The first laser to be operationally demonstrated was the ruby laser in 1959, which produced pulsed laser output at 694 nm, operating at liquid nitrogen temperature. The first CW laser was the helium-neon gas laser operating on five transitions of neon near 1.1μm and produced about 10 mW of power. The progress towards other CW lasers was swift using gaseous media for the laser action and by early 1963 more than 1,000 laser transitions were reported covering a wavelength range from 400 nm to 120 μm, but the CW power output remained at tens of mW level. During the same period the ruby as well as other solid state laser systems progressed from pulsed operation at low temperatures to CW operation at or near room temperature. However, regardless of the system, optically pumped solids, discharge pumped gas or electrically pumped semiconductor lasers, the room temperature power remained at a few mW. Much progress was made but no system really stood out as the potential system that could generate enough power for many of the industrial applications. Much of the focus, nonetheless, was on exploring solid systems as opposed to the gaseous systems because of deep seated belief that the high active laser ion density provided by the solids compared to the gaseous atom density in a discharge would make the gas lasers less appropriate for obtaining high powers.

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However, all changed in late 1963 when I shifted the focus from atomic gas systems to molecular gas systems, specifically going to the $CO_2$ molecule. Within a fairly short period of time of less than six months, we had the first inkling that gas lasers had finally arrived as high power systems.

Figure 1 shows a handwritten note, circa mid-1964 that I had left for my colleague after a late night coaxing the $CO_2$ laser to start doing its thing! An important thing to note hereIs that in that time frame there were no power meters that could measure CW power of 0,75 W. The first attempt at measurement of the power failed because all that were available at that time were thermopiles with a maximum power handling capacity of about 50 mW! Not knowing what to do at this point, I stuck the back of my hand in the beam and I found out the hard way the effect of 0.75 W laser power at 10.6 μm in a 2 mm diameter beam. I knew then that we had finally reached the goal of finding a high power laser system. The 0.75 W of power was measured in the most fundamental way: absorbing the laser power in a beaker of known quantity of water and monitoring the water temperature as a function of time. The progress from hereon was swift and satisfying.

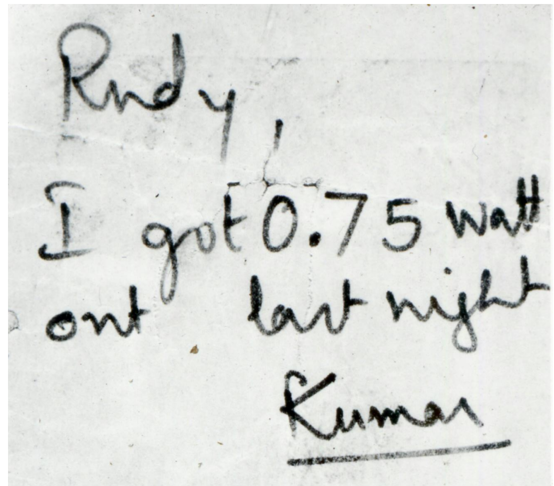



**Figure 1. A handwritten note written by the author of this paper to inform his colleague of the progress**

In less than a year we had progressed to a $CO_2$ laser that produced over 100 W of CW power output and at least for then the race with optically pumped solid state lasers was won.

If a 1 meter long $CO_2$ laser could produce 100 W of CW power, the obvious conclusion was that a 10 meter long $CO_2$ laser would produce kilowatts of power. This simple scaling was carried out by Redstone Arsenal group resulting in a multi-kW $CO_2$ laser (figure 2) and the effect on a piece of rock.

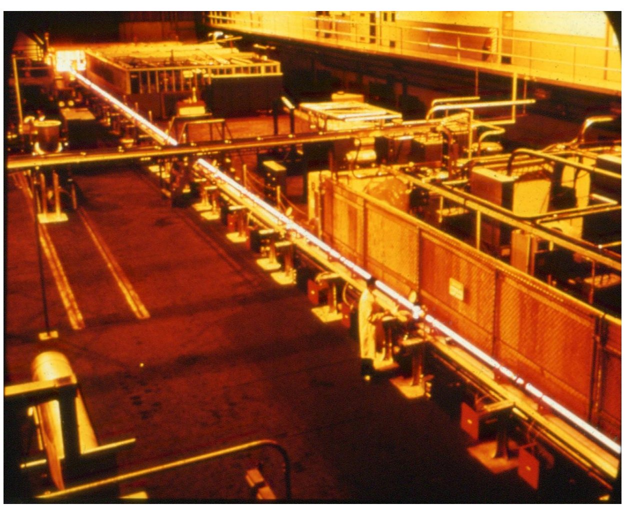


**Figure 2. Multi-kW $CO_2$ laser system built at Redstone Arsenal**

**Figure 3. Effect of directing the multi-kW unfocussed $CO_2$ laser light on to a piece of stone**

Considerable ingenuity was injected into the high power laser systems to make them more compact than the many meters long behemoth shown in figure 2. This included fast flow systems to better understanding of the heat transport within a $CO_2$ laser that resulted in relatively compact, manufacturable and usable $CO_2$ laser systems, an example of which is shown in figure 4 which depicts fast axial flow multi-kW laser systems made by Triumpf.

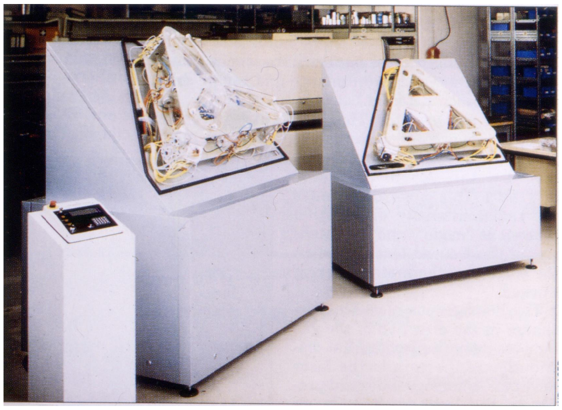


**Figure 4. Fast axial flow $CO_2$ laser system in a triangular geometry built by Triumpf**

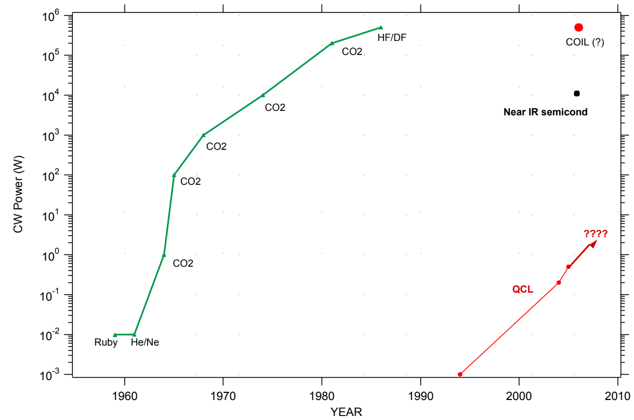
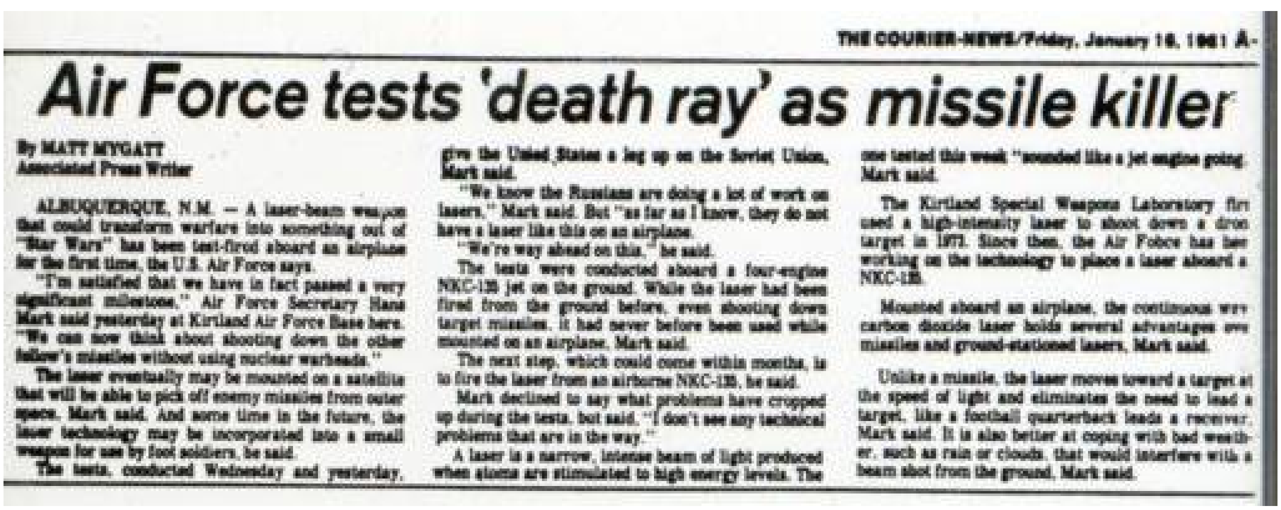



**Figure 5. Summary of CW laser power as a function of time.**

## 3. HIGH POWER LASERS: APPLICATIONS

No sooner than the first laser with more than 100 W power output was reported, a number of commercial manufacturers jumped in applications of the $CO_2$ lasers were to be found everywhere, including metal cutting, drilling and welding, defense related applications, laser surgery, paper cutting and metal forming. An exotic application is shown in figure 6.



THE COURIER-NEWS/Friday, January 16, 1981 A-

**Air Force tests 'death ray' as missile killer**

By MATT MYGATT
Associated Press Writer

ALBUQUERQUE, N.M. — A laser-beam weapon that could transform warfare into something out of "Star Wars" has been test-fired aboard an airplane for the first time, the U.S. Air Force says.

"I'm satisfied that we have in fact passed a very significant milestone," Air Force Secretary Hans Mark said yesterday at Kirtland Air Force Base here. "We can now think about shooting down the other fellow's missiles without using nuclear warheads."

The laser eventually may be mounted on a satellite that will be able to pick off enemy missiles from outer space, Mark said. And some time in the future, the laser technology may be incorporated into a small weapon for use by foot soldiers, he said.

The tests, conducted Wednesday and yesterday, give the United States a leg up on the Soviet Union, Mark said.

"We know the Russians are doing a lot of work on lasers," Mark said. But "as far as I know, they do not have a laser like this on an airplane.

"We're way ahead on this," he said.

The tests were conducted aboard a four-engine NKC-135 jet on the ground. While the laser had been fired from the ground before, even shooting down target missiles, it had never before been used while mounted on an airplane, Mark said.

The next step, which could come within months, is to fire the laser from an airborne NKC-135, he said.

Mark declined to say what problems have cropped up during the tests, but said, "I don't see any technical problems that are in the way."

A laser is a narrow, intense beam of light produced when atoms are stimulated to high energy levels. The one tested this week "sounded like a jet engine going, Mark said.

The Kirtland Special Weapons Laboratory fir used a high-intensity laser to shoot down a dron target in 1973. Since then, the Air Force has bee working on the technology to place a laser aboard a NKC-135.

Mounted aboard an airplane, the continuous wav carbon dioxide laser holds several advantages ove missiles and ground-stationed lasers, Mark said.

Unlike a missile, the laser moves toward a target at the speed of light and eliminates the need to lead a target, like a football quarterback leads a receiver, Mark said. It is also better at coping with bad weather, such as rain or clouds, that would interfere with a beam shot from the ground, Mark said.

**Figure 6. A story that appeared in The Courier News of January 18, 1981 describing a several hundred kilowatt $CO_2$ laser**

More down to earth applications deal with reasons of economy, improved performance and rapid manufacturing as shown in figures 7 and 8 from automotive industry.

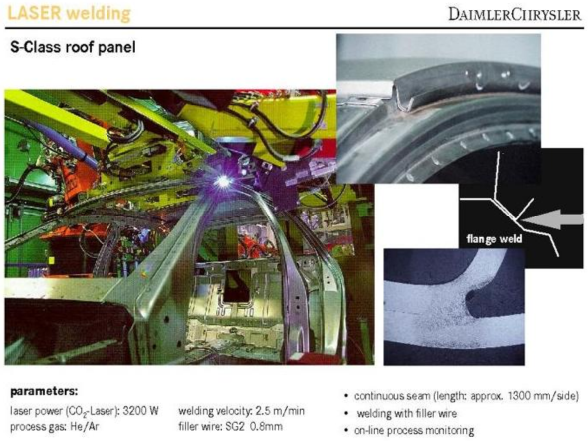



**Figure 7. Auto body welding (courtesy Daimler-Chrysler)**

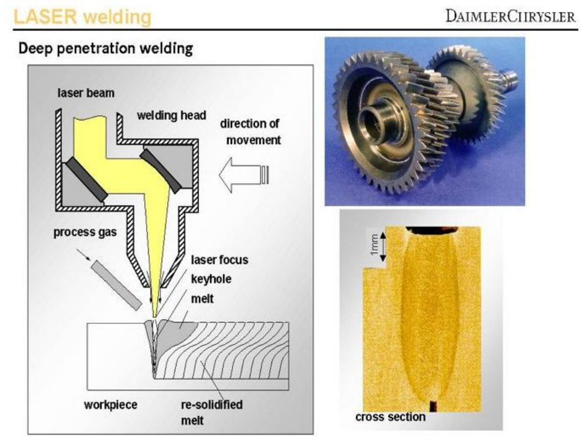



**Figure 8. Deep penetration welding in automotive applications (courtesy Daimler-Chrysler)**

## 4. CURRENT AND FUTURE APPLICATIONS AND NEEDS

Table I gives a composite picture of current and future applications and what is requires and will be required to satisfy the needs. Table II gives a list of potentially useful lasers for the applications outlines in Table I.

**Table I. Summary of laser parameters for various applications.**

| APPLICATION | Power | Wavelength | Tunability | Monochromaticity |
|---|---|---|---|---|
| Materials processing‡ | $>10^3$ W | Not very important | Not very important | Not very important |
| Laser surgery | <100 W | Application dependent | Not very important | Not very important |
| Target designation | <1 W | Important | Not very important | Not very important |
| Laser weapons | $>10^5$ W | App dependent | Not very important | Not very important |
| Spectroscopy | ~ 1 W | Very imp | Very important | Very important |
| Metrology | ~ 1 W | Very imp | Very important | Very important |
| Photolithography | ~10 W | Very imp | Not very important | Not very important |
| Sensing | ~ 1 W | Very imp | Very important | Very important |
| Illumination | ~ 1 W | Application dependent | Application dependent | Application dependent |
| Countermeasures | 10W + | Application dependent | Not very important | Not very important |

**Table II. Summary of laser parameters for various applications.**

| APPLICATION | Power | Lasers of Choice |
|---|---|---|
| Materials processing | $>10^3$ W | $CO_2$, near IR semiconductor lasers |
| Laser surgery | < 100 W | $CO_2$, near IR semiconductor lasers, excimer |
| Target designation | < 1 W | Near IR semiconductor lasers |
| Laser weapons | $> 10^5$ W | HF/DF, COIL |
| Spectroscopy | ~ 1 W | Semiconductor lasers, QCLs, dye, OPO |
| Metrology | ~ 1 W | Semiconductor lasers, QCLs, dye, OPO |
| Photolithography | ~10 W | Excimer |
| Sensing | ~ 1 W | $CO_2$, Semiconductor lasers, QCLs, dye, OPO, etc. |
| Illumination | ~ 1 W | Semiconductor lasers, QCLs |
| Countermeasures | 10 W + | OPO, QCLs |

## 5. PROGRESS TOWARDS HIGH POWER QCLS

As can be seen from the Table II, QCLs have enormous opportunities, however, CW room temperature power outputs in the vicinity of 1 W or more may be needed. QCLs, which were first demonstrated in 1994 by Capasso and his colleagues at Bell Laboratories, are coming of age thanks to the enormous progress that has occurred in high power operation through the work carried out in Professor Razeghi's laboratory. Nonetheless, much more needs to be done to make QCLs appropriate for practical applications listed in the Tables I and II. Some encouraging advances are shown in Figures 9 and 10 which show results of power output and tunablity with epi-down mounting and external grating tuning setup.

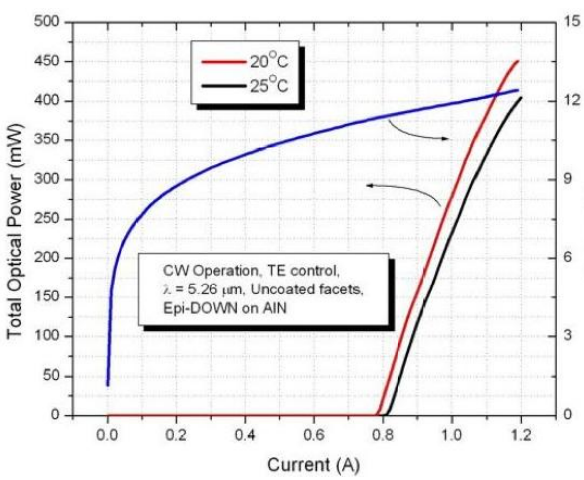



**Figure 9. Epi-down mounted QCL CW power output at RT**

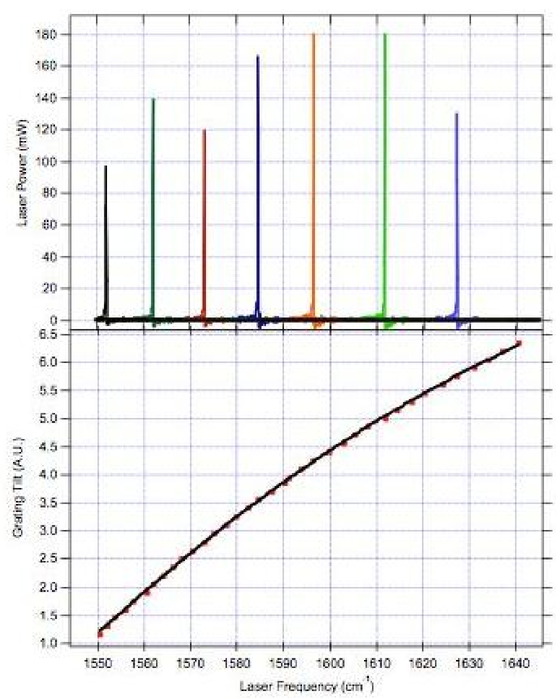



**Figure 10. Broad tunability of a external grating cavity QCL at 6.3 μm.**

In Figure 10, the top part shows FTIR spectra of the external grating cavity QCL at seven chosen wavelengths, indicating single frequency operation with FTIR resolution limited (<0.08 $cm^{-1}$) linewidths.

These studies are directed towards using QCLs as sources of radiation application that would lead to a man portable chemical warfare agent sensor having sub-ppb detection capability with $< 1:10^7$ false alarm rates.  A proposed final configuration for the CWA sensor is shown in the figure 11.


**Figure 11.  QCL based laser photoacoustic spectrometry based CWA sensor that will be man-portable and have very high sensitivity as well as very low false alarm rates.**

## 6.  CONCLUSIONS

I have attempted to show that much progress has been made in high power lasers but many new applications now demand new types of lasers without sacrificing some of the high power capabilities.  Referring back to the figure 5 where in the right hand bottom corner I have plotted power output characteristics of QCLs, I leave the community with the question:  how quickly can we get to the point where QCLs become as ubiquitously used as sources of infrared radiation as the $CO_2$ lasers are?

## 6.  ACKNOWLEDGEMENTS

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