Quantum Cascade Lasers:
Well-timed next avenue for lightsource R&D?

Patent Landscape Report

Sebastian Gorgon (sg911@cam.ac.uk)

4 November 2019

1 Objective

This patent report is aimed at assessing whether conditions exist at this time for an established laser manufacturer to expand their R&D to include Quantum Cascade Lasers, with a primary focus on the intellectual property environment.

2 Technology overview

Lasers are sources of light with characteristics impossible to obtain via different methods. Since their invention in the 1960s, they have found numerous applications in a large range of industries. It is the details of the composition of the optical and electronic components that determine the colour, intensity, and temporal profile of the light generated. Therefore, huge amount of time and money has been invested in designing new laser platforms, each with its own niche of commercial targets.

Some of the most successful to date have been semiconductor lasers. Thanks to their small size and low power requirements they are omnipresent in the world, primarily in optical disk readers (CDs and DVDs), and in laser pointers. They consist of a sandwich of at least two different materials, and the interplay of their energetic structures at the interface(s) enables electrons and holes injected from the power source to recombine across the band gap. This produces coherent laser light which can be coupled out of the device thanks to cavity effects engineered into the active region.

Soon after, it was noted that quantum confinement effects become relevant when the thickness of those layers is small enough. This led to the invention of quantum well lasers in 1974 at Bell Laboratories, described in patent US3982207A, which was filed in 1975. Thanks to their non-classical behaviour, these lasers exhibit emission with a much sharper spectral profile, which is crucial to many applications in sensing and telecommunications. The great commercial applicability of this technology justified the extreme precision required in fabrication of the complicated layer stacks.

The Quantum Cascade Laser (QCL) is the most sophisticated among the semiconductor lasers. In a QCL multiple photons of light are obtained from each electron injected from the power supply. This leads to great improvements in efficiency and beam intensity, as in all other semiconductor laser types each recombining electron only generates a single photon. The external bias applied to the lattice stack allows for energy level alignment, with the adjacent wells having matching lower and upper level (Fig. 1). This causes to the electron to be funnelled from one well to the next, hence "cascade" in the name, every time releasing a useful light photon.

In order to achieve such emission, the chemical composition and thickness of

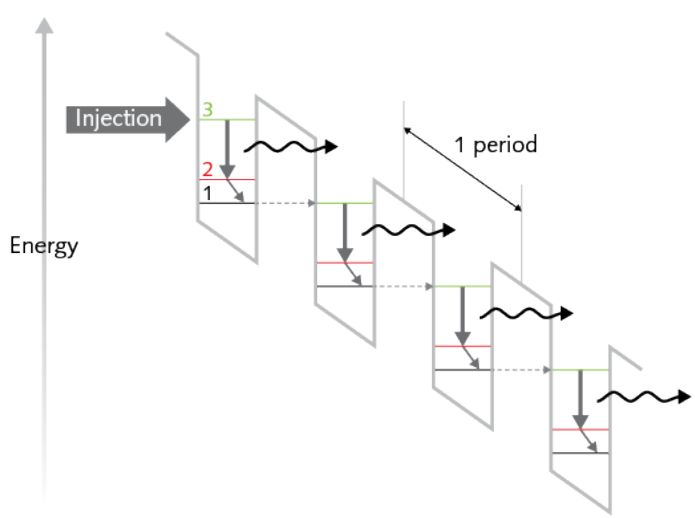

Figure 1: QCL operating mechanism. Electrons injected at the highest energy level cascade down emitting infrared photons (green to red transition). The layer structure is arranged so that the lower lasing level matches the upper lasing level in the adjacent period.

the tens or hundreds of layers need to be designed with enormous precision, and fabricated using atomic deposition methods. This makes them quite complex, but equally, enables great flexibility and room for vast development for a range of applications. The most prominent among these is sensing, including atmospheric pollutant detection, and medical diagnostics, thanks to their extreme sensitivity unachievable via other methods. If reliable emission in the Terahertz regime is realised, non-invasive industrial inspection techniques may become a lucrative and diverse target for deployment.

3 Methodology

H01S5/34 was identified as the key CPC as it corresponds to semiconductor lasers with quantum well or superlattice structures. H01S5/3401 sub-symbol explicitly mentions QCLs, but also includes other types of lasers without a pn-junction, so is not an exclusive QCL classification. Furthermore, several relevant patents were found not to bear any of these two symbols.

Given the specificity of the nomenclature related to this type of laser, every relevant patent carries its full name in the abstract. Therefore it was found that performing a search with the term “quantum cascade laser” as a title/abstract keyword returned a list free of items related to other technologies.

Due to this report’s focus on finding new areas of innovation in the design of QCL systems, this list was refined by requiring a match to either the H01S5/3401 symbol mentioned above, or B82Y20/00 which corresponds to nanooptics, where many key steps in the development of the device architecture have been classed.

This list has been exported in full, along with the metadata, directly from the Worldwide database of the European Patent Office (Espacenet), and subsequently analysed in Python. A script has been designed to account for people being listed as co-inventors in various permutations, and for different variants of company names. The analysis is available to access at `https://github.com/sebgorgon/patents/blob/master/patents.ipynb`.

4 Patent landscape

The QCL has been invented by Federico Capasso and his team at Bell Laboratories, and first reported in 1994 (doi:10.1126/science.264.5158.553).

US5936989A is the original patent reporting the QCL design. It was filed in April of 1997 by Lucent Technologies, who owned Bell Laboratories at the time, and listed Capasso and 6 members of the group as inventors. It has been granted

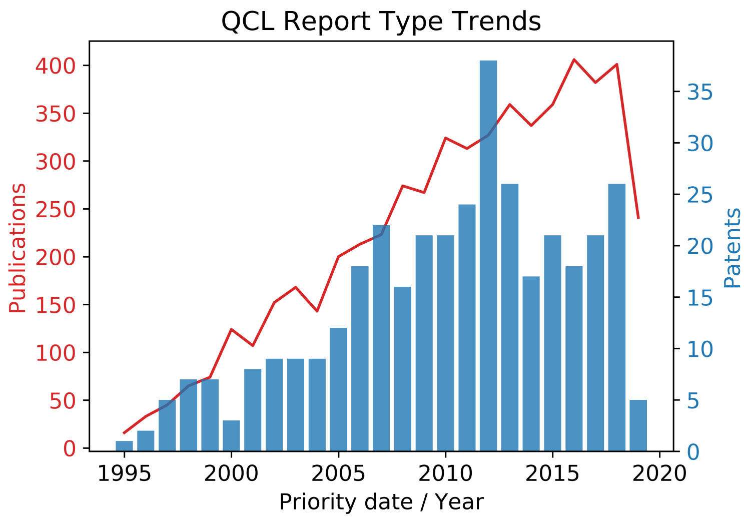

Figure 2: Number of QCL technology-related patents (blue) and scientific publications (red) by year.

in August of 1999. Interestingly, it has not been rolled out outside the USA. This may indicate the IP owners' belief that constructing a commercially profitable manufacturing facility in a different jurisdiction was unlikely at that point in the QCL development. Indeed, many technological challenges remained, and in the following years some of them were addressed by Capasso, and by others.

4.1 Volumes and trends

The search performed under the constraints described above returns a total of 366 patents (Fig. 2).

In the years following the QCL invention, some relatively trivial applications of the technology have been patented, and steady growth in volume has been seen. Capasso is listed as an inventor on just over half of the patents (13/25) filed between 1994 and 1999. In 1996 AT&T performed a divestiture from Bell Laboratories, and thus Lucent Technologies is listed as the applicant on Capasso's patents from that year onwards. The key patent from that time is JPH11284287A, from 1998, which described a method for obtaining simultaneous double-colour emission from a QCL. This has paved the way to a useful range of applications in multiple-wavelength devices.

In the early 2000s the patent numbers stayed at almost a constant 10 per

Layer	Thickness (Å)
$In_{0.66}Ga_{0.34}As$	28
$Al_{0.65}In_{0.35}As$	17
$In_{0.64}Ga_{0.36}As$	25
$Al_{0.65}In_{0.35}As$	17
$In_{0.64}Ga_{0.36}As$	24
$Al_{0.56}In_{0.44}As$	20
$In_{0.60}Ga_{0.40}As$	22
$Al_{0.56}In_{0.44}As$	22
$In_{0.60}Ga_{0.40}As$	20
$Al_{0.56}In_{0.44}As$	23
$In_{0.60}Ga_{0.40}As$	18
$Al_{0.56}In_{0.44}As$	25
$In_{0.60}Ga_{0.40}As$	17
$Al_{0.56}In_{0.44}As$	28
$In_{0.60}Ga_{0.40}As$	17
$Al_{0.56}In_{0.44}As$	28
$Al_{0.65}In_{0.35}As$	11
$In_{0.68}Ga_{0.32}As$	11
$Al_{0.65}In_{0.35}As$	11
$In_{0.68}Ga_{0.32}As$	42
$Al_{0.65}In_{0.35}As$	11
$In_{0.68}Ga_{0.32}As$	40
$Al_{0.75}In_{0.25}As$	13
$In_{0.68}Ga_{0.32}As$	36
$Al_{0.75}In_{0.25}As$	22

Figure 3: Layer parameters reported in US20120039350A1.

year, before picking up a large increase in 2005, reaching a high of 38 in 2012. Since then the number hovered around 20-25 per year.

Most of the patents from that period report incremental improvements in the design of the structure for specific applications, as in US20120039350A1 for example, by fine tuning of layer thicknesses and their chemical composition (Fig. 3).

It is interesting to note, that those fluctuations have not been matched by the trends in published scientific articles related to QCL technique development. The literature shows a remarkably steady linear increase year-on-year with no significant speed-up or slow-down over the 27 year period. This persistent growth is on one hand indicative of a healthy pick-up of innovation between manufacturers and academics, which shows there is a good demand for novel QCL devices within the academic community, while on the other hand the lack of an accelerating increase shows there is potential still yet to be harnessed.

4.2 Key patents

One prominent current area of development in QCLs is working towards extending the achievable emission wavelength beyond the, by now well-established, mid-infrared range. Several patents were filed within the last 5 years constraining the activity in relation to some, but not all, methods of achieving Terahertz emission, most importantly in US20160322788A1.

Apart from the layer composition, where most innovation took place thus far, other optical elements are key to efficient and tunable QCL operation. An important improvement was patented by Daylight Solutions in US7535656B2, expiring in 2026, which describes currently the most well-performing lenses. Their commercial system is patented in US7848382B2, further building on the earlier work by Capasso related to multiple-wavelength emission. While not necessarily obstructing, it is an important demonstration of the potential limited protection a patent may provide to a new type of a system developed.

4.3 Key players

The original inventors are still active in the field today. Capasso, now at Harvard University, and Faist, currently working for Swiss company IRSWEEP AG, both filed patents which were published this year. There is significant work undertaken in Japan also, with Hashimoto (based at SUMITOMO) and Edamura (at HAMAMATSU) both filing in 2017 as well. Akikusa, who is the 5$^{\text{th}}$ most prolific inventor in the field, last filed in 2013.

Looking at the last decade alone, clear leaders are readily apparent. SUMITOMO filed all of its 36 patents during that period, compared with 14 from HAMAMATSU, which still form more than half of its entire portfolio.

Company	**Country**	**Patents held**
SUMITOMO ELECTRIC INDUSTRIES	JP	36
HAMAMATSU PHOTONICS KK	JP	26
LUCENT TECHNOLOGIES INC	US	18
DAYLIGHT SOLUTIONS INC	US	16
CANON KK	JP	11
THALES SA	FR	9
AGILENT TECHNOLOGIES INC	US	7

Table 1: Ranking of companies by amount of QCL-related patents held.

Inventor	Country	Patents held
CAPASSO, FEDERICO	US	34
EDAMURA, TADATAKA	JP	25
FAIST, JEROME	CH	21
HASHIMOTO, JUN-ICHI	JP	20
AKIKUSA, NAOTA	JP	18

Table 2: Ranking of inventors by amount of QCL-related patents held.

4.4 Protection range

In terms of territorial jurisdiction protection ranges, the USA is the dominant player, with a combined 70% of patents applying on its territory (Fig. 4). Japan follows with 23%, and then the EU and China have similar volumes.

This distribution is largely unchanged over the entire relevant period, save for the growth in share of European filings, and a decrease in that of China's seen in the last decade.

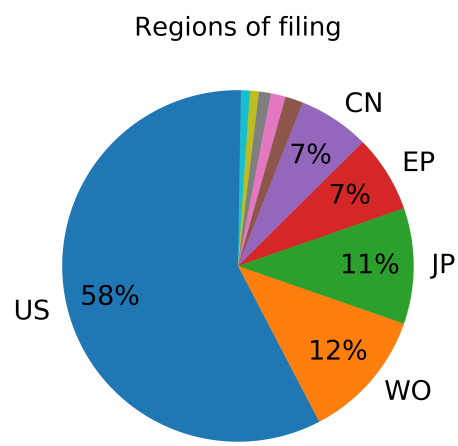

Figure 4: Regions of jurisdiction where the patents reported in this search were filed.

5 Recommendations

It is an exciting time of flux in the field of novel semiconductor lasers.

We find ourselves in a position extremely similar to Bell Laboratories in the early 1990s: the groundwork design of the QCL is that of the quantum well laser, especially its confining layer structure. The patent blocking that technology expired in 1993, which is very likely to have provided the impetus necessary to focus the efforts and funds at many companies on new inventions inspired by that system.

The original QCL patent expired in April 2017, and thus the core of the technology belongs in the public domain now. Other key innovations remain protected only for the next few years, most notably patents related to simultaneous multiple-wavelength emission. More recent patents provide valuable insights into avenue of R&D within competitor firms, while not impeding progress that can be made elsewhere due to their extreme specificity.

As can be seen from the patent volumes, there exists a firm basis for innovation with clear room for further expansion.

Another important factor to consider is the cost of entering the field. While the atomic deposition processes required for manufacture of the layer stacks are costly, semiconductor lasers give a solid foundation from which it is possible to develop rapidly. The main area of expertise the company would need to contest is in fact computational simulation of the quantum cascade, to streamline the process of layer design. This is very encouraging, as the expense of hiring a small team of theoreticians is miniscule compared with developing the manufacturing capabilities, which thanks to the semiconductor laser side we largely possess presently.

Therefore, I would highly recommend expanding the company's R&D focus into the field of QCLs. The IP landscape is very favourable for unconstrained innovation, and it has just become that within the last 2 years. If we are to make the entry, this is the perfect time to do it.