Presenting the (economic) value of patents nominated for the European Inventor Award 2012

Inventor file Federico Capasso
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technopolis [group], March, 2012

Alfred Radauer, Léonor Rivoire, Patrick Eparvier (Technopolis)
Heike Schwanbeck (TU Ilmenau)
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1. The invention

1.1 Historic account

Quantum Cascade Lasers (QCL) is a new type of lasers with a vast range of application fields, in particular in chemical sensing. The technology is considered as truly revolutionary. Commercialisation has already started, with strong growth prospects. The revolution can be traced back to applied physicist Prof. Federico Capasso and his team, who have worked for years at Bell Labs and Harvard to make the invention happen.

Prof. Frederico Capasso was born in Rome in 1949. He decided to study physics and received his PhD, summa cum laude, from the University of Rome in 1973. After doing some research on fibre optics at Fondazione Bordoni in Rome, he joined AT&T’s Bell Labs in 1976. He became Distinguished Technical Member of Technical Staff at Bell labs (1984), Bell Labs Fellow (1997) and held several management positions, such as Head of Quantum Phenomena and Device Research Department (1987 – 2000) and Vice President of Physical Research (2000 – 2002).

At Bell Labs, Prof. Capasso started to work in the field of semiconductor heterostructures and studied ways to use layers of semiconductors for novel devices. Semiconductor heterostructures describe artificial semiconductors that are made up of two different ultrathin layers of semiconductors. The layers are so thin that one can observe quantum effects that lead to new electrical and optical material properties, which are not observable in nature. Prof Capasso recounts:

“We were in particular working with heterostructures grown by a technique called molecular beam epitaxy (MBE), a process by which it is possible to control the thicknesses of the semiconductor layers and which has since became heavily used for producing opto-electronic components such as laser diodes or the quantum cascade lasers....this field started to explode in the early 1980s....I started to work on these artificial materials without any idea that they could lead to QCL lasers....this period lasted around 10 years where I worked on the analysis how electrons behave in the thin layers.”

Prof. Capasso worked in this time together with Alfred Y. Cho, the inventor of the MBE process. The study led eventually to the idea that a laser can be built based on a radically new principle, which would also lead to a number of performance characteristics able to create a revolution in laser physics. In the early 1990s, Prof. Capasso formed a small research group to actually build a quantum cascade laser based on his experimental research results (the theoretical foundations of the QCL lasers were already described in 1971). The collaboration with leading scholars proved essential for the success of the research, whereby the cooperation with Alfred Y. Cho and with Dr Jerome Faist a brilliant postdoctoral fellow, now a professor at the Swiss Federal Institute of Technology – who eventually became also the co-inventors of the QC laser – are to be in particular highlighted.

In 1994, the first patent was eventually filed. Prof. Capasso remembers many of the barriers encountered for development and adoption of the new technology, one of the most pronounced being scepticism that the proposed technology would work:

“For example, the first QCL laser did not work at room temperature, and there was quite some scepticism whether we could deliver on the claim that this would be possible. We did deliver. Within two years, we got it work at room temperature pulsed.”

To help spread the adoption and development of the QCLs, a number of such lasers were built and given to laboratories where leading spectroscopists and chemists were working. Within five years from the invention, around ten such leading groups showed that QCLs were useful for spectroscopy and sensing. These findings opened up the
whole chemical analytical market. Prof. Capasso considered collaboration with these scientists as “…one of the most important decisions made.”

Further milestones were achieved between 1994 and 2001 at Bell Labs, including: demonstration that QCL could cover most of the molecular fingerprint region, simultaneous lasing on multiple wavelengths and broadband lasing, the invention of continuously tunable single mode lasers and application to a wide range of areas, ultrashort pulse QCLs and the fact that Prof. Capasso led the technology transfer and licensing of QCL patents to many start-ups and established firms.

A major milestone was also accomplished in 2002 by Professor Faist after he joined the University of Neuchatel in Switzerland: the demonstration of the first room temperature continuous wave (CW) QCL.

After Capasso became professor of applied physics at Harvard in 2003, a second phase of research began. Prof. Capasso’s team reached two particularly important milestones in the development of the QCL technology: First, they were able to show that high quality QCLs can be built with platforms commonly used in the semiconductor industry (see also section 1.2). This result set the basis for industrial scale applicability of the technology. And second, that QCL can be also used at high power levels in CW form, which opened the field of military applications. Prof. Capasso has continued developing in the QCL field since then, and has collaborated also with many of the firms that are now starting to commercialise their various QCL-based products.

Eventually, Prof. Capasso set out also to co-found his own start-up firm EOS Photonics. EOS Photonics is currently developing a spectrometer on a chip that uses QCLs. Around 20 to 30 such lasers are placed in an array on the chip, together with a microcontroller. The chip will be able to emit a large number of wavelengths at relatively large power levels. The advantages of the chip are its small size and its ability to cover a broad range of wavelengths and therefore to detect a large number of chemical compounds at extremely small concentrations (less than a part per billion in volume). Its relatively high power also permits the remote detection of chemicals. Still working full-time at Harvard, Prof. Capasso has stakes in this start-up and is also on the board, but is otherwise not involved in actual business operation.

### 1.2 Technological features

The mid-infrared spectrum is of particular interest for scientists and engineers working with lasers, because this part of the spectrum of light is one where most of the molecules have absorption ‘fingerprints’. By subjecting molecules, in gaseous form, to laser beams in this spectral range, and examining which wavelengths pass through while others are absorbed, it is possible to assess of what elements and molecules a gas or vapour is made up of. Having the hands on a technology for building efficient lasers in this wavelength was/is a key opener for new application fields and markets.

In a traditional diode laser, the wavelength of the laser is determined by the material/semiconductor used for the laser. The material property of the semiconductor in question is called the band gap. This quantity can be defined as the minimum energy that a photon must have to be absorbed or emitted by a semiconductor. There is a general law that says that the smaller the band gap of a material is, the longer the wavelength of a laser based on this material. Consequently, if one were to build a laser for certain large wavelengths such as in the mid-infrared (like from 3 microns to 15 microns), one would need to use or produce a semiconductor with a small band gap. Such semiconductors are, however, difficult to process and temperature sensitive and hence hard to commercialise. Until the advent of the QC lasers, there was no commercially viable laser for the mid-infrared: the then available lasers were expensive, bulky and had to use energy consuming cooling systems. In addition, traditional diode lasers would be locked-in on a particular wavelength, depending on the material used. If one would want to have different wavelengths, one would need to build a laser with a different semiconductor material.
Quantum cascade lasers (QCLs) are radically different from traditional lasers (i.e., semiconductor diode lasers): "While traditional diode laser produces laser light by a recombination of electron–hole pairs across the material band gap, QC lasers use a different process whereby electrons cascade down a series of quantum wells, which result from the growth of very thin layers of semiconductor material. Whereas (in standard semiconductor diode lasers) a single electron–hole recombination can only produce a single photon, in the Quantum Cascade Laser an electron cascading down between many quantum wells, typically 20 to 100, produces a photon at each step." The QCL overcomes the limitations of the diode laser technology and offers a series of advantages:

- The wavelength of a QCL is determined by the thickness of the layers of the semiconductors used in the laser and the resulting quantum effects and not by the band gap. QCLs can therefore reach wavelengths in the mid-IR by using the same type of proven and available semiconductors as generally used in the telecom industry (so there is no need to revert to special materials), and by carefully building the required layer structure.

- Moreover, Prof. Capasso has also demonstrated in his later work at Harvard (see above) in collaboration with Agilent Technologies that high performance QCLs cannot only be made with the MBE process, but also with the Metalorganic Vapor Phase Epitaxy Process (known as MOVPE or MOVCD) which is widely used in the semiconductor industry. The usage of a standard and relatively low cost process established in industry translates into huge industrial scalability possibilities for QC lasers.

- QCLs can be made widely tuneable by using the same semiconductor material and not fixed to a narrow range of wavelengths determined by the semi-conductor material. Using an analogy of a zoom lens for a camera, the QC laser can tune the wavelength along most of the mid-IR spectrum.

- QC lasers are very forgiving when it comes to their operating temperature. There is less need to monitor the operating temperature and less need for expensive cooling provisions, as these lasers can operate at room temperature and above up to more than 100 degrees, while maintaining reasonably high power.

- Because the QCL laser produces, as stated above, a photon every time the electron passes a stage made of quantum wells (hence up to 30 photons in one ‘cascade’ for a 30 stage device), where as a traditional laser can only produce one photon with one electron–hole recombination, there is, according to Nesdore, “...a step change in performance of lasing efficiency enabling QCLs to emit several watts of peak power in pulsed operation and in continuous wave.”

The use of QC lasers has resulted in the possibility to measure, with relatively compact devices, in real time and remotely, gases in extremely small concentrations (1 part per trillion in volume, whereas before only 1 part per billion was the state of the art). The features of the technology give rise to a number of application fields, particular in critical chemical remote sensing applications (see below when the market is discussed).

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2. The market

There is general consensus that the potential market for QC lasers is huge, given the vast broad range of possible application areas. The technology is at the beginning of its life cycle, with the first commercial applications having hit the market in the time period of 2004 to 2006.

By 2008, the market had already developed into a niche market with strong growth prospects: QCLs were offered by several small start-ups such as Alpes Lasers (SUI) or nanoplus (GER). Alcatel-Thales (FR) and Hamamatsu (JP) entered the market later, and a number of other start-ups in the U.S. and Europe were set up. In 2008, the market leader was Alpes Lasers (Switzerland) with a market share of around 80%. The firm is co-owned by one of the inventors of the QCL, Prof. Jerome Faist. The estimated market volume was 1,000 sold QCLs in 2008 globally, and the estimates were that QCL sales would increase to 100,000 units sold p.a. by 2010. In 2012, many of the predictions have come true or surpassed them and Prof. Capasso assesses that “…the field is literally exploding and the technology is taking off. Every month there is a new development”. This view is also shared by Prof. Antoine Mueller from Alpes Laser as well as other document sources. The largest market player is now Hamamatsu.

According to the experts and the desk research, there are currently >20 firms globally of various size which actively work on QC laser solutions. A list of these firms is provided in the table below. The largest of these firms is Hamamatsu Photonics in Japan (which produce and develop, however, also other types of photonics technologies). Around 15 of these firms have, according to Prof. Capasso, already products on offer commercially.

Figure 1 List of QCL companies

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<td>1</td>
<td>Ad Tech Optics</td>
<td>14</td>
<td>ILX Lightwave</td>
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<td>2</td>
<td>Aerodyne Research Inc.</td>
<td>15</td>
<td>Lasertel Inc.</td>
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<td>3</td>
<td>Alpes Lasers</td>
<td>16</td>
<td>Maxion Technologies</td>
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<td>4</td>
<td>Argos LLC</td>
<td>17</td>
<td>Naval Research Laboratories</td>
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<td>5</td>
<td>Block Engineering</td>
<td>18</td>
<td>Nanoplus GmbH</td>
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<td>6</td>
<td>Boston Electronics</td>
<td>19</td>
<td>Physical Sciences Inc.</td>
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<td>7</td>
<td>Cascade Technologies</td>
<td>20</td>
<td>Pranalytica</td>
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<tr>
<td>8</td>
<td>Coming Inc.</td>
<td>21</td>
<td>Physical Sciences Inc.</td>
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<td>9</td>
<td>Daylight Solutions</td>
<td>22</td>
<td>Picarro, Inc.</td>
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<td>10</td>
<td>Ekips Technologies, Inc.</td>
<td>23</td>
<td>PNNL.</td>
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<td>11</td>
<td>EOS Photonics</td>
<td>24</td>
<td>Q-On</td>
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<tr>
<td>12</td>
<td>Epitaxial Laboratoty Inc.</td>
<td>25</td>
<td>Sandia National Lab</td>
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<tr>
<td>13</td>
<td>Hamamatsu</td>
<td>26</td>
<td>Wavelength Electronics</td>
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The market consists basically of two main market segments, defence and civil use, making the QC laser technology an example of a dual use technology. The different

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3 http://www.wsi.tum.de/Portals/0/Media/Publications/48d84a9e1-a861-4fc1-bb46-a2b4aa3e08/PhotonikIntl_2008_02_60_Birner_QCL.pdf

market segments and application areas are at different stages of maturity and commercialisation:

- One important defence application is countermeasures against heat-seeking missiles. A QCL can be used to divert and mislead a heat-seeking missile closing in on its target. The technology is already on trial, with, for example, the firm DAYLIGHT SOLUTIONS working closely with the defence industry on the realisation.⁵

- Other security and defence-related application areas include the detection of explosives and harmful chemical agents, the detection of illegal drugs or the detection of infectious diseases. For example, Block Engineering from Massachusetts, U.S. has introduced remote sensing QCLs, which can detect various substances on surfaces 6 inches to 2 feet away.

In the civil area, the following application fields can be distinguished:

- The most important current field of application is, as said, chemical (gas) sensing and analysis in industrial process control. Environmental monitoring follows en suite, as QCLs can be used for atmospheric monitoring and pollution emission monitoring. Both industrial process and environmental monitoring are application areas that are already commercially exploited. The Scottish firm CASCADE Laser Technologies offers, as one example, lasers for the monitoring of industrial emissions for SOx, NOx, CO and other pollutants.

- Not yet commercially exploited are applications in the healthcare market. QCL lasers can be used for breath analysis. By analysing trace particles of substances in the breath of a human, it is envisaged to accurately diagnose certain types of diseases. This area is thought by Prof. Capasso to be the one with the highest potential.

- Other possible areas of application include collision avoidance systems in cars or infrared illumination (e.g., via flashlights) in the night.

In terms of industry revenue, Mr. Capasso assessed the market in 2007, in one of his presentations, at around US$ 50 million to US$ 100 million, and for the future – based on market reports for gas sensing equipment– as much as US$ 7 billion.⁶ Antoine Mueller from alpes Laser assesses that “…the market for chemical sensing is globally worth some US$ 20 bio and growing, and the QCL share of this will be more than half within five years.” Prof. Mueller considers the competitive position of Europe in general in this growing industry as good, on par with that of the U.S. and ahead of Asia (the U.S. is, however, in the lead with a particular type of QC lasers called external cavity lasers).

A recent analysis by Wintergreen Research puts the market for Mid Infrared (IR) Sensors (of which QCLs are a part of) at US$ 509 million in 2011 word-wide, poised to increase to US$ 5 billion by 2018:⁷ “This strong growth is anticipated to come as units are less expensive and more effective in the same amount of space. Wireless sensor networks are useful almost everywhere, creating the opportunity to implement controls and manage every aspect of human activity in ways that have not even been imagined hitherto.”

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⁵ [http://optics.org/news/2/10/7](http://optics.org/news/2/10/7)
3. The role of patents and Intellectual Property Rights (IPR)

3.1 Motives and benefits of patenting and employed IPR strategy

Prof. Capasso considers IPR and patenting essential:

“It has enabled me to found my own business...it has enabled the technology’s wider adoption. One example is licensing which is especially important if you are a small firm with a niche solution and you need to partner with a big one who delivers the whole system. It is also important for the large firm, when it, for example, realises that some IP created is not useful for the current strategy pursued by the firm, but it would be useful for another company (so you can transfer the IP through licensing or sale)...that’s what also happened at Bell/Alcatel-Lucent who licensed the technology to a number of key players...if there were no IP, I would think this would be really scary...after all, what would you own?”

Prof. Capasso believes that the future IP in the area will be driven by specific applications. Against this backdrop, the business strategy pursued for his firm is to create sub-systems, where the firm can have good IP, and enter collaboration agreements with big firms.

3.2 Patent statistics and patenting trends

The analysis of the patent statistics shows, unsurprisingly, that Prof. Capasso and his co-inventors were the first to apply for patents on the QC laser technology. The patents nominated were applied for first in the U.S. in 1994, 1996, 1997 and 1998, the priority years of the inventions. Later, respective patent applications were filed also in Europe in 1995, 1996 and 1999 on the same inventions. Patent protection was eventually granted in the U.S., Japan and Germany as well as nine other European countries, and all patents granted are still in force. This shows that Prof. Capasso and his co-inventors succeeded in creating a well-sized portfolio of patents for a number of important international markets. As broad geographical scope of patent protection for an invention is usually associated with a high value of the invention, this result can be seen as a first indication that the QCL patents analysed describe a valuable piece of technology.

Another indication of patent value is the number of times a patent is cited by other patents as prior art. The understanding is – as with scientific publications – that the more a patent is cited within a given technology field, the more important (and hence valuable) it is for this field. The patents in question were cited 80 times up until February 2012, which can be considered considerable. The main citing applicants are the Japanese firm HAMAMATSU PHOTONICS and the U.S.-based firm DAYLIGHT SOLUTIONS who themselves have been actively applying for patents since 2001 (respectively 2005) in the QCL technology area.

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8 Patents are a territorial concept. This means that if an inventor wants to obtain patent protection in two countries, he or she has to apply for each of the two countries for a patent. However, application procedures have been to an extent internationally harmonised. One effect of such harmonisation allows inventors to apply for a patent in one country first and decide only later, without violating the rule that the invention has to be something novel, whether he/she also wants to have a patent on the invention in other countries. This gives the inventor some time to think about commercialisation prospects and eventually to save money on the different application fees. The year in which the patent was first applied for in any country is called the ‘priority year’.

9 Patents filed in different countries, but on the same invention, denote a so-called patent family. As subsequent international patent applications have to state the initial patent application in order not to lose their novelty feature, one possibility to identify the members of a patent family is to group all patents together which cite the same priority filing/patent application.
Based on analysis of patents with the word ‘QCL’ in their title, abstracts or claims shows that the leading patent applicant for QC is ALTEC LUCENT/ATT with 31 patent applications so far. Up until 2000, there were relatively few organisations trying to patent QCL technology, namely Fraunhofer (Germany) and the U.S. National Science Foundation. It is only after 2000 that other, commercial, applicants entered the field: the already mentioned HAMATSU PHOTONICS (JP) with 20 patent applications, the INSTITUTE OF SEMICONDUCTORS (China) with 16 patent applications, DAYLIGHT SOLUTIONS (U.S.) 8 applications. Given this development, one can theorise that the area of application for a particular patented technology has broadened over time.

A look at the development of patent applications, which make reference to QCL technologies in their description of their inventions, substantiates such a hypothesis. Based on this broadened search, one can see that there have been more than 100 patents applied for each year since 2005. Overall, most patents were applied for in the U.S. (567), which is more than double the figure of Japanese applications. However, especially since 2005, one can also observe a surge in Japanese applications. Chinese applications have also increased, but respective filing activity is considerably behind the U.S. and Japan. Under the broadened search terms, we find new actors in the top-10 applicant list such as Canon (51 patent applications), Panasonic (26) or Sony (22). These results reflect the advances made of the QCL technology on its way to becoming a broadly commercially applied technology. Alcatel Lucent is listed second in this top-10 list, which once again underlines the strong technology position of the firm.

Another piece of evidence for the broader application of the technology is the fact that QCL referring patents can today be found in more and more internationally defined technology classes. The respective ranking of IPC classes reveals that most patent applications are in measurement engineering (class G01 ‘measurement; testing’). In 1999, there were, in addition, the first applications in the class A61B (‘diagnosis, surgery, identification’). Since around 2000 there is an increasing number of application areas, as each year there are around ten new IPC classes where QCL laser technology is mentioned.

The combined evidence of the patent statistics suggests a strong and qualitative growth of patenting activities concerned with QCL lasers. Furthermore, it can be seen that the development can be traced back to Prof. Capasso’s patents, and citation as well as other indicators indicate a high value of these patents.

Prof. Capasso’s role is also underlined by the fact that he is the leading inventor with 44 patent applications in the field. His impact in the research field is also large: According to the Web of Science, Prof Capasso has 542 publications that have been cited to date 18,844 times. Prof. Capasso had some 232 publications relating directly to QCL lasers. The 1994 publication on QCL of Capasso and his co-inventor has been to date cited 2,215 times, making this publication the most cited one of Prof. Capasso.

4. Conclusions and success factors

The collected evidence shows that the invention of the QCL is a valuable invention with great economic promise and a wide area of application fields. The inventor of the laser, Charles Townes, said 1994 that QCL "…represents a remarkable combination of excellent solid-state and laser physics with new solid-state technology. It opens the door to very important new laser possibilities, ones I hope will be pursued and achieved.” A recent article in the widely read Chemical and Engineering News of
American Chemical Society re-iterated this assessment, pointing to a number of already working QCL solutions.\textsuperscript{11}

Asked about critical success factors Capasso underlined in particular the role of Bell Labs as an institution and argued that the invention would have hardly been possible in any other place. In an article by Jon Gertner in the New York Times, the secrets of Bell Labs were described to be:\textsuperscript{12}

- The fact that the institution provided the researchers the time necessary to pursue their research, in order to come up with a true radical innovation, is the first aspect to be noted: “In his recent letter to potential shareholders of Facebook, Mark Zuckerberg noted that one of his firm’s mottoes was “move fast and break things”. Bell Labs’ might just as well have been “move deliberately and build things”.”

- The fact that Bell Labs assembled a critical mass of talented people in close physical proximity. The geographical proximity was in particular important; as the general assessment was that the existence of phone lines could not replace actual physical contact. This general belief is also reflected in the architecture, were hallways, buildings and rooms were designed in such a way that they foster the exchange of ideas and communication.

- There was an embodied consensus among all working researchers at Bell Labs, even for those who were in pursuit of pure scientific understanding, “…that the ultimate aim of their organisation was to transform knowledge into new things.”

- The application focus was also reflected in organisational issues, such as that satellite facilities of the lab were regularly installed at the phone company’s manufacturing plants. This was supposed to help transfer the new ideas into new things, but it also provided a ‘backwards’ knowledge transfer channel, where engineers and workers at the plants could feed back their assessments and ideas to the researchers. However, with manufacturing being off-shored, this particular point has lost importance.

- In terms of human resources policy and organisation, Bell Labs approach was to provide as little top-down leadership as possible, i.e. provide freedom to the researchers and trust them that they would eventually come up with sth. worthwhile. Younger researchers were provided a supervisor as a linking pin between them and famous scientists in order to overcome a barrier of authority should the young researchers question or challenge some of their famous peer’s views.

- Eventually, inter-disciplinarity was a clear organisational goal which further triggered the exchange of ideas and ultimately created “…a creative culture of interdisciplinary collaboration with very little bureaucratic overheads.” That proved essential not only for QCLs but for many of the other of the various famous inventions created at Bell Laboratories.

