The staircase to flexibility

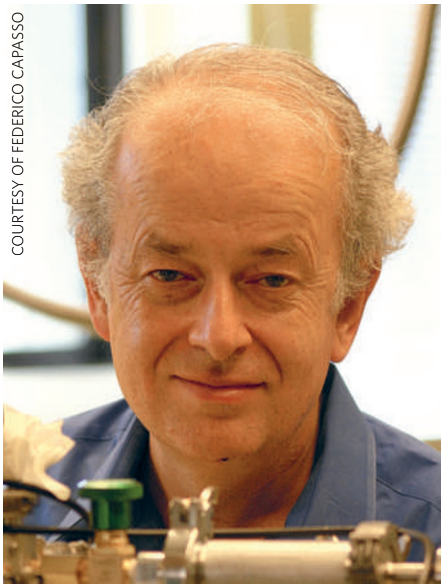
The quantum cascade laser has liberated laser properties from materials limitations, enabling light emission to be tailored over a broad spectral range. *Nature Materials* talks to Federico Capasso about the development of these lasers in his laboratory.

How many lasers do you own?

At home I only have laser pointers and CD players. I don't have a fax machine or a laser printer. Most of the market of the optical mouse is dominated by semiconductor lasers, so that is one more application. For my work here we have quantum cascade lasers (QCLs), we have CO_2 lasers, Ti:sapphire lasers, argon ion lasers and fibre lasers. The laser doesn't have the penetration of the integrated circuit but I would say the functionality of the laser is enormous. Although the volumes are not as high as the transistors, in terms of functionality the laser is probably the device that has the largest number of applications, going from military, commercial, medical to communication. You just name it. It is amazing.

What, in your view, is the impact of the laser?

It is a kind of a truism if people say it was a solution looking for a problem. But that is precisely what it is, it is a solution for many problems. Even today we are finding new things, for example the impact of lasers for metrology, for which Theodor Hänsch and John Hall received the Nobel Prize in 2005. Who knows what is going to be the next one. People have discovered cosmic lasers and so forth. It is peculiar how it has evolved. A few years ago no one would have suspected that population inversion was a necessary condition for laser action, but people now have made lasers without inversion. And take the Schawlow–Townes limit on the minimum laser linewidth. In the past year a theory group at Hamamatsu, followed by experimental work by a group at the European Laboratory for Nonlinear Spectroscopy in Florence, found that the linewidth of QCLs is below the Schawlow–Townes limit. This is kind of stunning because we all thought the Schawlow–Townes limit was a fundamental thing about lasers. There is a continuous rejuvenation of the laser at the application level as well as the fundamental and conceptual level. When Cornell and Wiemann discovered Bose–Einstein condensates and then Ketterle at MIT made an atom laser from these condensates, it was just amazing. Now we can talk about matter waves and you have matter lasers, which is another stunning example of how rich and general the laser concept is.



COURTESY OF FEDERICO CAPASSO

And it was semiconductor lasers that led to all those mass market applications?

Yes. Although the first realization of semiconductor lasers in 1962 was an important milestone, lasers never had any commercial application until heterojunctions came along. This was huge. The heterojunction basically reduced the laser threshold by over an order of magnitude. Without the demonstration in 1970 of continuous room-temperature operation in devices made from heterojunctions, the semiconductor laser would never have seen the market. That is the reason why they gave the Nobel Prize in Physics for 2000, at least in part, to Kroemer and Alferov — it was the single most important development for the semiconductor laser.

Did you follow this development at the time?

When I came to Bell Labs in 1976, the low-loss optical fibres that Corning had made had their minimum losses at wavelengths of around 1.3 μm and 1.5 μm. There was a need to develop a semiconductor heterostructure laser for long wavelengths, and that was not easy. They had to develop these quaternary materials, InGaAsP, and that was a major effort. I was working for the post-office research labs in Italy, and they sent me to Bell Labs to learn about semiconductor lasers. I could have jumped into that area but it was so crowded that I said there is no chance Bell Labs will hire me when there are so many people doing semiconductors at a high level. So I told my boss I wanted to do something else. The post office didn't like it and said if you want to do something different you should resign. So after a year I resigned from my job there and then I moved into avalanche photodiodes and other stuff at Bell Labs. I got interested in heterostructures. Later, when I worked on band-structure engineering concepts, I came back into lasers and started to get interested in how to make a laser in the mid-infrared (IR) wavelength region, where the laser diode shows all its limitations with the emission tied to the bandgap. And that's why I use this term 'bandgap slavery'. Beyond a wavelength of roughly 3 μm the generation of light across the bandgap turns into a big curse if you shrink the gap to get to long wavelengths. That is probably the main reason why the QCL and its use of intersubband transitions is enabling photonics in the mid-IR.

Did you know about early designs by Kazarinov and Suris of intersubband lasers?

They definitely proposed to have an intersubband laser between discrete energy levels, and to inject electrons with tunnelling. It was a superlattice, but would have had a hard time lasing. But I don't want to criticize. That paper was published in 1970, and it is the second paper on superlattices after the paper by Esaki and Tsui. But it could not have worked for a number of reasons, one being that the energy-level diagram was a bit too naive. What we realized was that specially designed doped electron-injector regions need to be alternated with undoped regions, and that you need to engineer the lifetime so that the lowest state could empty fast. You have to empty the final state of the laser transition much faster than the lifetime of the upper state otherwise you can't get strong population inversion. So we added a third level below the final state of the laser transition. The lower level is separated from the final state of laser transition by an optical phonon, so that the final state empties very fast because of resonant optical phonon scattering. Still, Kazarinov's and Suris's design had two important ingredients, the intersubband transition and the pumping by resonant tunnelling.

What were the key steps in the realization of QCLs?

The QCL was the culmination of our work on band-structure engineering where you design everything bottom-up quantum mechanically from wave functions through energy levels to lifetimes. In some sense this work could perhaps only have happened at Bell Labs. At that time we were the absolute world's best in molecular beam epitaxy. We had all the knowledge of quantum design, and we had strong knowledge of solid-state physics. The QCL is at the cross roads of quantum mechanics, crystal growth, solid-state physics and photonics. Bell Labs was the right crucible where these ideas could not only be developed fully but demonstrated. In particular, I had worked years before on a so-called staircase avalanche photodiode, where the idea was that an electron going down a heterostructure staircase at each step could gain energy and create an electron–hole pair. And that idea of the staircase avalanche photodiode came back in a different context to generate light. The other thing was the great set of collaborators we had then, like Al Cho, Jérôme Faist and so on. And there was one important decision that we made. We started to design a device to emit in the far-IR because of the notion that if the energy levels are spaced too far apart the lifetime is shorter and it is harder to lase.

But, we had forgotten that to work in the far-IR is far more difficult than to work in the mid-IR. So, at some point, Jérôme and I said we should design something in the mid-IR where we had much better detectors and so forth. That was a very good decision.

Was it difficult to sustain such a long-term effort?

The work probably started around 1986, when we demonstrated resonant tunnelling in AlInAs/GaInAs quantum wells at room temperature. AlInAs/GaInAs has a heterojunction with a large discontinuity that can accommodate a reasonable amount of energy states, which is important for QCLs. Then, in around 1990 we made an attempt with the Kazarinov–Suris structure, but it didn't work. I then realized why it didn't lase and it took two more years, so the whole thing took about ten years. Of course I was doing other things; if I had done it for ten years full-time probably Bell Labs would have fired me, although they were extremely supportive. Every year or so we would give a high-level presentation to the vice president of research, which at that time was Nobel Laureate Arno Penzias. I remember Penzias saying, "Why are you pursuing this? What's in it? This is so far out". But they let me continue and that kind of support was crucial.

Did you realize the applications of QCLs?

When we demonstrated the first laser in 1994 we had no clue really about the technological importance of this. I was just excited about demonstrating this new laser. When it came out, it lased mostly at 4 K. But within two years we went to room temperature and that was when we said this is for real now. I was talking to someone who said, "Federico, in the mid-IR there is no good semiconductor laser, there are only these lead-salt lasers that were not going to room temperature". So we then had our first paper with the Stevens Institute of Technology in Hoboken, where we demonstrated wavelength modulation spectroscopy of N_2O. Then I was contacted by Pacific Northwest National Laboratory, which had a group doing spectroscopy, in particular the detection of warfare gases and the high-sensitivity detection of trace gases. They were interested in these applications, and in a sense that was the first technology transfer of the QCL. There are now 17 companies commercializing QCLs and QCL-based systems (such as sensors), including major ones like Hamamatsu.

What do you think are the future directions of QCLs?

Let's talk first about power. We are part of a Defense Advanced Research Projects Agency programme to develop very-high-power efficiency lasers. When QCLs started the power efficiency was about 4%, much lower than conventional semiconductor lasers, so QCLs tend to be power hungry that's for sure. But through this programme we got power efficiencies approaching 15% for continuous-wave operation at room temperature. We have lasers with 3 W of power. But the real question is can we make QCLs at telecom wavelengths. With GaN-based QCLs, calculations show that you could make a high-power, high-temperature laser. And the other interesting thing is that because the linewidth of the QCL is so small one can make a chirp-free telecom laser. Also, of course, the question is can we do metrology, can we do ultrashort pulses and the kind of things that Hänsch and Hall have done, but in the mid-IR. It would open new frontiers in molecular spectroscopy. And the area of spectroscopy is a huge open field. There, atmospheric science is one of the most exciting applications because QCLs enable broadly tunable spectroscopy, where you can detect almost any compound.

INTERVIEW BY JOERG HEBER

Coherence comes full circle

Coherent synchrotron radiation has revolutionized the study of molecules and materials. Talking to *Nature Materials*, Gerhard Materlik, CEO of the Diamond Light Source, discusses the many uses of synchrotron sources and free electron lasers.

How important is the discovery of the laser to you?

Oh it is fantastic, it is one of the most important developments and inventions. It shows that coherence matters, because before the 1950s almost nobody had thought about coherence. Understanding coherence is a very important aspect when you do imaging. In the X-ray range, for example, we had already dreamed about holography and always felt you needed coherence for that. Until, when we finally invented atomic-resolution X-ray holography, we noted that almost every illumination is coherent over the dimension of the atom. If you want to image atoms and manage to get small samples you will be fine, but usually