Gisela Eckhardt and the Raman laser

Gisela Eckhardt was one of the early pioneers in laser physics, discovering the principle behind the Raman laser in 1962. **Valdas Pasiskevicius**, **Richard Mildren** and **David Burman** tell the largely unknown story of her life – and the challenges she faced as a woman in physics

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There can be few 12 year olds who read serious books about quantum physics. But then Gisela Eckhardt was no ordinary child. Born in the German city of Frankfurt in 1926, she decided to become a physicist after reading and becoming inspired by *The Revolution in Physics* by Ernst Zimmer, which describes how quantum mechanics shows that the world is not deterministic, but governed by probabilities. Eckhardt realized that if she wanted to understand the universe we live in, she had to study physics.

As a girl growing up in the 1930s and 1940s, her path into physics was far from smooth. Like many women of her generation, the young Eckhardt faced formidable barriers and struggles to map out a career in the subject. But she persisted and eventually went to the US, where she joined Hughes Research Laboratories – the research arm of the Hughes Aircraft Company. It was here in 1962 that Eckhardt co-invented the Raman laser and became the first person to explain its physical mechanism – one of the biggest breakthroughs in laser physics since the discovery of the laser itself. And if you've never heard of Eckhardt, you're not alone. In fact, her neglect is a story in itself.

Back in the 1950s, women who studied physics at university and then pursued fruitful research careers were rare. They were the exceptions – not only statistically, but also in the professional qualities they required. Such women had to show a burning and unwavering interest in the field and needed sheer willpower too. The remarkable story that follows is based on many hours of interviews and personal communications we have had with Eckhardt herself, who now lives mainly in Malibu, California, and partly back in Frankfurt. It also draws on documents including witnessed technical lab notes provided by Eckhardt as well as the recorded testimony of Eric Woodbury, who was involved in the discovery of stimulated Raman scattering – the effect underpinning the Raman laser.

Early days

Eckhardt's success in physics stemmed from humble beginnings: her father was an entrepreneur and her mother was a housewife. Apart from being an aspiring physicist, she was also a formidable fencer, ranked third in the under-18s group in her home state of Hessen in 1944. Told that she stood a chance of becoming a national fencing champion, Eckhardt toyed for a while with the idea of continuing with the sport. But after graduating from her local *Gymnasium* (high school), she plumped for physics and was admitted to the prestigious Johann-Wolfgang-Goethe Universität in Frankfurt in 1946.

Eckhardt was one of just a handful of women in the entire university to major in physics. Some of her former male schoolmates, who had also applied to study physics, had told her she was mad, claiming that women had no aptitude for the subject. Even her own family tried to discourage her. But Eckhardt did well and after five successful semesters in Frankfurt, she decided to apply to do a *Diplom* thesis in experimental physics at the university's Physics Institute. (Roughly equivalent to a Master's degree, the *Diplom* was a prerequisite for starting a PhD.)

Eckhardt was one of 10 students to apply for the course but because places were limited, not all could be accepted at once. Applicants were instead divided into three groups based on their age, with the oldest students taking priority. There was, though, one exception. Eckhardt should have been placed in the middle group, but was demoted to the third group and had to wait a further 18 months before she could start. Gender discrimination was alive and well.

In 1950 Eckhardt eventually began her Master's degree, in which she designed and studied an optical filter, known as a "Christiansen filter", that she got to work for the first time with mid-infrared light. All previous Christiansen filters, in contrast, had functioned only at visible frequencies. Before writing her *Diplom* thesis, Eckhardt had shown her experimental results to her adviser, who was also head of the institute, and asked if he'd let her stay on to do a PhD. His response was that it would depend on her performance in her thesis and final exam.

Unfortunately, her adviser had a dim view of women in science, believing that women who went to university were a waste of taxpayers' money. Eckhardt concluded that her only chance of being considered for a PhD at the institute was to get an A grade in both her thesis and exam, which she eventually did in 1952. What made things harder for Eckhardt was that her adviser did not let her publish her work on Christiansen filters, despite it being worthy of publication.

Hughes Research Laboratories

Barrier-breaker Gisela Eckhardt in 1962, when she worked at Hughes Research Laboratories.

Eckhardt duly began her PhD in Frankfurt, working once again under the supervision of the institute's head, who wanted her to study heat-transfer processes in glasses at temperatures up to 450 °C. After doing some calculations, Eckhardt realized that meaningful results were possible only if she continued measurements up to 1400 °C. This, however, would require special, platinum containers that would not melt at such high temperatures. When Eckhardt's adviser told her there was no budget for these containers, she arranged with the Glass Technical Society to get the platinum on loan. The adviser, however, refused to accept this deal – without stating why – and instructed her to work in the lower temperature range.

Eckhardt had no choice but to do as she was told, which resulted in three years of largely wasted effort. It was only after her adviser visited the German Bureau of Standards, where he discussed her thesis, that he let her accept the offer and build a set-up that could work up to 1400 °C. After three further years of research, Eckhardt finally gained her PhD in 1958.

Bound for America

Knowing that her chances of securing an academic career in Germany as a woman were near zero, Eckhardt had anticipated working as a research physicist in industry or a government lab after her PhD.

Marja Sundquist

Laser pioneer Gisela Eckhardt at her home in Malibu.

But she soon realized that option was also nigh-on impossible for a woman and so she and her husband Wilfried, who had done a PhD in physics at the same time as her, decided to leave for the US. It was to be a wise choice as at that time America was the most exciting country for doing physics research.

Various agencies of the US armed forces were then recruiting German scientists, and the couple applied for – and both obtained – job offers from government labs. Wilfried, however, also received a superior offer from the RCA Laboratories in Princeton, New Jersey, which he accepted. RCA was then at the forefront of many modern technologies – developing everything from electron microscopes and colour television to videocassette recorders. Gisela, however, was not permitted to work at RCA's Princeton lab because of a company rule forbidding husbands and wives to work in the same RCA division at the same time.

After arriving in the US later in 1958, Gisela turned down a job offer from Bell Labs in Murray Hill, New Jersey, in favour of a post at RCA's semiconductor division in Somerville. Apart from it being closer than Bell Labs to her husband's workplace, salaries were also generally higher there than in the Princeton lab – although RCA's personnel chiefs made sure she earned less than him. Despite that setback, Eckhardt had several successes at RCA. She developed an optical quality-control procedure to determine dislocation densities of silicon-crystal wafers. She invented a new, faster way of polishing them and also solved a major problem with the gallium-arsenide crystals grown at the plant by identifying the nature of a colloidal phase in the crystals using electron microscopy and diffraction.

But all those accomplishments did little to advance her career. After inventing the novel polishing process, Eckhardt asked her department head for a wage rise, explaining that she was being underpaid. Her boss first denied that this was the case before declaring that if she wanted to be paid like a man she'd have to work twice as hard as one. With that, Eckhardt decided it was time to move on. Less than two years after joining RCA, both she and her husband quit the firm – as did almost a third of the other researchers at RCA's semiconductor division, many of them unhappy with the company's management.

Her boss declared that if she wanted to be paid like a man she'd have to work twice as hard as one

Heading west

In January 1960 Eckhardt attended the annual meeting of the American Physical Society in New York, where she presented a scientific paper. Occupying one floor of the conference hotel were many large companies hiring scientists and engineers for their R&D labs. Among them was Hughes Aircraft Company, a leading defence contractor based in California that had been praised as a very fair, employee-friendly company by several friends of Eckhardt and her husband. Keen to move to the west coast, they were flown first-class on TWA – the airline owned by the firm's founder Howard Hughes – to visit its labs and meet potential managers. Put up at the luxurious Beverly Hilton Hotel, both were offered salaries 30% higher than at RCA.

Eckhardt started at Hughes Research Laboratories (HRL) in Malibu in September 1960, working on semiconductors in the quantum-physics department. Hughes Aircraft Company was involved in areas such as microelectronics, semiconductor materials, radars, missile technologies and satellite communications, the sensitive nature of which meant that Eckhardt required security clearance to work in the main building, which took her seven months to obtain as a foreign national. Confined to a room with a separate entrance and no access to the rest of the building, Eckhardt had to be escorted by a woman whenever she wanted to go to a lab or the library. Her husband faced the same restrictions too but they were less severe for him because he required a male escort and more men were around.

HRL was an extraordinary place to be at the time, with researchers being given much freedom to follow their interests. The lab hit the headlines in 1960 when Theodore Maiman obtained the first evidence for laser action in pink ruby, which produces light at a wavelength of 694.3 nm (see box opposite). Researchers and engineers at the company immediately started looking for applications, with the first being to use lasers to measure distances – in other words, as "range finders". Unfortunately, the early ruby lasers were pumped by flash lamps, which meant that the lasers produced rather long, randomly spaced pulses of radiation. It is hard to use such pulsed lasers for range finding, as a clean intense echo pulse is required to obtain accurate distance measurements.

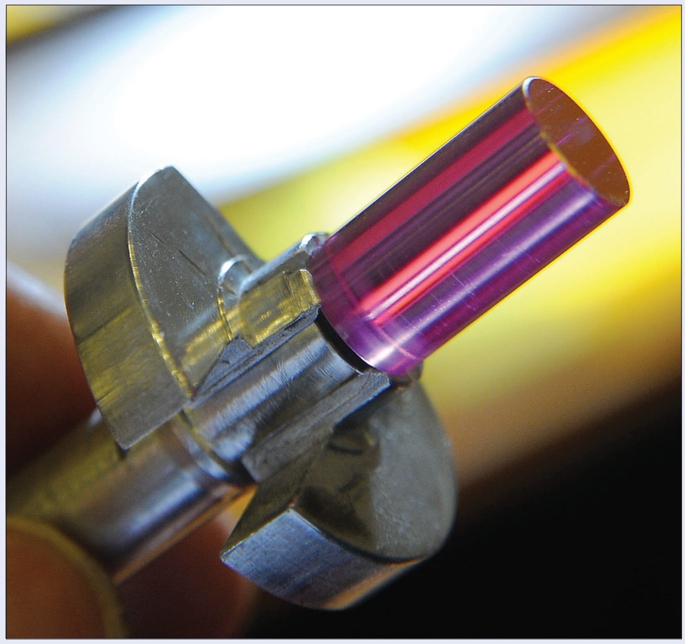
What was needed was a laser that could produce a single, short pulse with plenty of peak power and in 1961 just such a device – known as a Q-switched laser – was demonstrated at HRL by Fred McClung. Based on an idea first proposed by his colleague Robert Hellwarth, it used a high-speed shutter originally developed for cameras monitoring nuclear-bomb tests. What was seemingly just an engineering job to improve range finders eventually became crucial for the first observation of stimulated Raman scattering (SRS) – the process by which the frequency of photons in a laser is reduced by a certain amount when sent through certain materials (see box on p36).

Meanwhile, over at the headquarters of Hughes

Hughes Research Laboratories

Located in Malibu, California, Hughes Research Laboratories (HRL) was an extraordinary environment in the 1960s, where researchers had freedom to pursue pilot projects even without dedicated external funding. When new ideas emerged, it was easy for HRL to assemble a team with complimentary expertise to develop those concepts into something that would attract external funding and a new product line for the Hughes Aircraft Company. It was this luxury of a long development horizon that encouraged HRL to carry out research into lasers, leading one staff member – Theodore Maiman – to obtain the first evidence for laser action, in a material known as pink ruby, on 16 May 1960 (*Nature* **187** 493).

HRL also took a keen interest in ensuring its research staff kept abreast of the latest developments in physics. Richard Feynman, who was based at the nearby California Institute of Technology (Caltech), began lecturing to PhD staff at the lab in the late 1950s and continued to do so for most of his life. He typically lectured for two hours a week, bringing along his own graduate students to avoid having to give them the same lecture at Caltech. Indeed, Feynman was due to give a lecture at HRL on the day it was announced he had won the 1965 Nobel Prize for Physics. In typical company style, the firm hired a limo to pick him up, rolled out a red carpet on his arrival and held a reception in his honour beforehand. In attending many of his lectures on everything from relativity to solid-state physics and biology, Gisela Eckhardt gained access to one of the most brilliant minds on the planet.



Matteis/Look At Sciences/Science Photo Library

Headline-maker The first laser was invented by Theodore Maiman at Hughes Research Laboratories in May 1960.

Aircraft Company in Culver City, Eric Woodbury and William Ng were working on amplifying Q-switched pulses using a copy of the laser at HRL. They were keen to incorporate it into future product lines, such as laser range finders, or to complement radar technology, of which the firm was a leading supplier. Their careful measurements, however, revealed a mysterious, powerful radiation emerging at a wavelength of 767 nm in addition to the expected ruby radiation at 694.3 nm. They reported this finding in July 1962 but gave no explanation for the mysterious new radiation (*Proc. Inst. Radio Eng.* **50** 2367).

Mystery explained

The word got out to HRL, where McClung quickly reproduced the results with his Q-switched laser. He then asked Eckhardt, who at the time was investigating gallium-arsenide crystals using infrared spectroscopy, if she could take the absorption spectrum of a ruby laser in the infrared. The working hypothesis was that the radiation was produced by electrons moving between previously unidentified energy levels in the ruby – but when Eckhardt ran the infrared spectrum, there were no absorption bands corresponding to such a transition.

Having asked if there were any other materials in the laser beam path, she was told about the shutter, which consisted of a cell containing liquid nitrobenzene. Having ample experience in Raman spectroscopy, Eckhardt not only ran the spectrum but also looked up the energy-level diagrams of all the substances inside the laser cavity: ruby, quartz and nitrobenzene. Comparing these diagrams with the energy of the new laser lines, she realized that there was an explanation: a Raman-active vibration in nitrobenzene, the energy of which corresponds exactly to the difference between that of the ruby laser and the mysterious light.

This new hypothesis was initially greeted with some scepticism because Eckhardt was not a laser specialist. But she then proposed three crucial and ingenious experiments that quickly proved unequivocally that her explanation was correct (1962 *Phys. Rev. Lett.* **9** 455). Her discovery of SRS with a ruby laser was important not only because it was a new kind of laser – the Raman laser – but also because it allowed laser radiation at one wavelength to be efficiently shifted to another wavelength; in fact, SRS gives us access to an almost unlimited number of wavelengths.

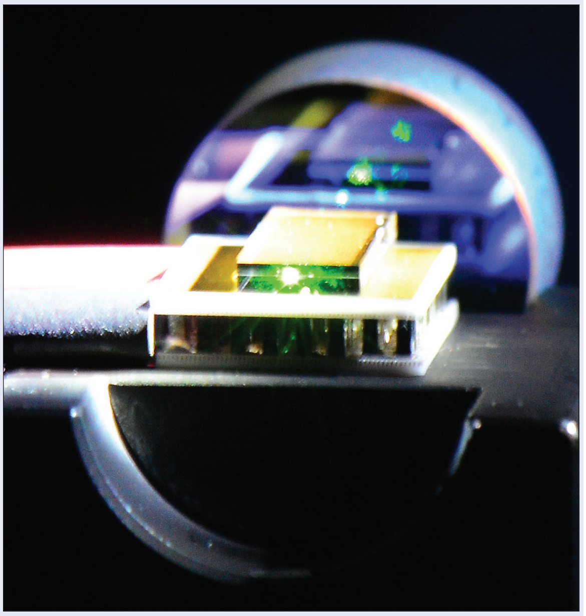
The ability to build lasers operating in regions of the spectrum beyond ruby opened the door to many potential new applications. One early idea was to use Raman lasers as range finders for military purposes because they could easily create laser light at a wavelength that is less likely to damage the human eye. A 1 μm infrared laser beam, for example, which can easily penetrate the eye and damage the retina, can be shifted to a wavelength of 1.5 μm, which is largely absorbed by the cornea – a vital distinction that can avoid unnecessary accidents.

The Hughes Aircraft Company quickly realized the importance of Eckhardt's laser discovery and asked her to write a patent disclosure. The patent application was filed in October 1962 with Woodbury and Eckhardt as co-inventors. Rejected three times by the US Patent Office, which claimed the invention was not novel, the patent was finally granted in 1968 – although only after three prominent experts had filed affidavits at Eckhardt's behest: Nobel laureate Charles Townes, Bela A Langyel (the author of the first book on lasers) and Sergio Porto (a key name in Raman spectroscopy).

Stimulated Raman scattering

The birth of the laser in 1960 not only led to a range of futuristic devices, but also opened up the new field of "nonlinear optics", in which light of one frequency becomes distorted in a material and exits with a completely different frequency. The first nonlinear optical effect to be seen involved using certain crystals to exactly double the frequency of infrared light passing through them, with this "second-harmonic generation" being responsible for most green, blue and ultraviolet lasers used today.

Stimulated Raman scattering (SRS) was the next such effect to be discovered. Rather than generating a harmonic at a *higher* frequency, SRS allows the frequency to be *lowered* by a fixed amount – giving physicists access to a much wider range of laser frequencies. The effect has been used extensively to extend laser capability by, for example, generating high-quality beams in "difficult" parts of the spectrum in the yellow or the so-called eye-safe region in the infrared. The effect is seen in a huge number of materials and is exploited in many other fields too. SRS can, for example, probe for chemical structures, store and read out quantum information, and amplify signals in optical data systems. It also plays a key role in areas of extreme physics such as in ultrafast supercontinuum generation (for example, white light lasers) and laser fusion.



Dr Aaron McKay, Macquarie University

New direction This diamond Raman laser at Macquarie University in Australia was a big step forward in ultrabright beam generation in 2014.

Eckhardt was rewarded with a nominal fee of $100 for assigning the patent, which was not uncommon in those days. Incredibly, it went on to earn Hughes a staggering $1.5bn in contracts and royalties, mainly for its range finder line.

Living legacy

Half a century later, Eckhardt's discovery has influenced many areas of technology. Light amplifiers based on SRS are today key components in providing long-distance transmission of data between continents. SRS has also led to laser-based systems for eye surgery plus many applications in the defence, chemical, environmental and biomedical fields. It's even used to make laser "guide stars" – artificial stars that can enhance the resolution of ground-based telescopes.

These days, more than 30 papers involving SRS are published every month, covering everything from chemical detection, new optical materials and quantum memories to random generators, frequency combs and on-chip light amplifiers and lasers. One particularly exciting area is the diamond Raman laser, which exploits the extreme properties of diamond to generate laser beams of unprecedented power and brightness. Few researchers, however, are probably aware that the suitability of diamond as a Raman laser material was first proposed and demonstrated in 1963 by a group at Hughes Aircraft Company, of which Eckhardt was the lead researcher (*Appl. Phys. Lett.* **3** 137).

Her career shift, which reflected the unique creative environment at Hughes Research Laboratories, is one reason why Eckhardt's crucial contributions to Raman lasers are often forgotten

Eckhardt herself did not stay in the field of Raman lasers for long, partly due to the many research freedoms enjoyed by HRL staff. By 1968, when her patent was finally approved, the field was exploding with large Raman laser research programmes being established in the US and elsewhere in areas as diverse as the development of blue-green lasers for submarine communications and high-power lasers for missile defence. She had already moved into plasma electronics, where she became an expert as well – helping to develop devices that could convert alternating current (AC) into direct current (DC) and vice-versa. Most power lines these days use AC voltages but Eckhardt and other Hughes scientists already realized how much more efficient DC would be to transmit electricity; its converters offered a way of turning the DC back into the AC that customers use.

Her career shift, which reflected the unique creative environment at HRL, is one reason why Eckhardt's crucial contributions to Raman lasers are often forgotten. After becoming renowned in plasma electronics, Eckhardt went on to run her own business ventures in California. As a fitting tribute to her achievements, Eckhardt, then aged 86, was invited to give the keynote address at the Europhoton 2014 conference in Switzerland on the 50th anniversary of her discovery.

So while Woodbury and Ng discovered laser lines with longer wavelengths than the ruby laser line in the output of their ruby laser, it was Eckhardt who proposed the correct explanation for the effect and it was she alone who proposed the experiments that proved it. Without her persistence, SRS would not have been discovered at HRL and, more likely, Bell Labs would have beaten them to the finish line. This episode in the early history of nonlinear optics reveals some of the many barriers to success that confronted Eckhardt and recognizes the important contributions she made. Without doubt similar challenges were faced by other female scientists of the time too. ■