Theodore H. Maiman

1927–2007

BIOGRAPHICAL *Memoirs*

*A Biographical Memoir by
Andrew H. Rawicz with
Nick Holonyak Jr.*

NATIONAL ACADEMY OF SCIENCES

THEODORE HAROLD **MAIMAN**

July 11, 1927–May 5, 2007

Elected to the NAS, 1980

Andrew H. Rawicz with Nick Holonyak Jr.

A great scientific and engineering breakthrough occurred on May 16, 1960—the invention of the laser. Theodore H. Maiman, assisted by master's student Irnee D'Haenens, pushed the button on a homemade high-voltage power supply and a small tubular ruby-based device shone a short pulse of a powerful red light, projected as a spot on a wall of Maiman's laboratory at Hughes Research Labs in Malibu, California. With the help of D'Haenens and C. K. Asawa, Maiman measured the emitted spectral line width and the outcome was clear: proof of light amplification by stimulated emission of radiation. The laser—mankind's first creation of coherent light—had been born.

On June 22, 1960, Maiman submitted a report of his findings to Physical Review, but within two days he received a rejection letter. The journal's editor Samuel A. Goudsmit wrote, "It would be more appropriate to submit your manuscript for possible publication to an applied physics journal, where it would receive a more appreciative audience."

In an earlier editorial, Goudsmit had written that *Physical Review* was no longer interested in receiving manuscripts discussing the merits of masers. He clearly did not understand that Maiman's report concerned the revolutionary laser—and not just another maser. Maiman then reported his invention in a one-and-a-half page article, "Stimulated optical radiation in ruby," in *Nature* on August 6, 1960. In the 2003 edition of *Nature's* book, *A Century of Nature: Twenty-one discoveries that changed science and the world*, the invention of the laser was prominently featured. In that volume physicist Charles H. Townes wrote,

> *Maiman's paper is so short and has so many powerful ramifications that I believe it might be considered the most important per word of any of the wonderful papers in Nature over the past century. (p. 111)*

Early development and education

Theodore Maiman was born in Los Angeles, California. But his parents moved almost immediately to Denver, Colorado, where his father Abe, an electrical engineer and prolific inventor, had obtained a job at the Mountain States Telephone Company. Abe Maiman always kept a small electronics laboratory either in the basement or the attic of the family's home, and Theodore used it for advancing his technical and scientific knowledge mainly by imaginative destruction (reverse engineering) of some of the mysterious devices lying there, including his father's oscilloscope. With this acquired knowledge he started his first paying job in an electronics shop, repairing appliances and radios; when the owner went to serve in World War II, Theodore, at age 13, took over the shop. In high school he continued in this job, earning money to save for his college education, and he added clarinet lessons to his extracurricular activities as well as playing in the school band. Near the end of the war, at age 17, Theodore enlisted in the U.S. Army, against his father's wishes. He was quickly accepted into the Army's radar and telecommunications training program—experience that strengthened his knowledge of electronics.

Unexplained phenomena, such as the glow emanating from vacuum tubes, piqued Maiman's interest not only in learning how to make things but also in explaining these phenomena and using them practically. As a result he did undergraduate coursework both in engineering and physics at the University of Colorado at Boulder, ending up with a B.S. in engineering physics. After applying to Stanford University for graduate studies and being rejected, he entered the physics graduate program at Columbia University. From there he enrolled in physics courses at Stanford and was ultimately accepted into that school's physics Ph.D. program.

Willis Lamb, a brilliant theoretical physicist at Stanford, took Maiman under his wing and was his thesis supervisor. Lamb had needed a researcher who understood the mathematical formulations of physical hypotheses and would be able to convert them into experiments to prove (or disprove) their validity. Maiman was well suited to such a project, and he quickly learned vacuum systems, methods of measuring vacuum, electrical discharges, and various kinds of instrumentation used to measure the properties of light. All of this knowledge later proved to be very important in his ability to develop strategies to devise a laser.

An experiment proposed by Lamb on subtle spectral transition in helium was difficult, and although Maiman's complex experimental setup initially failed, he did not give up.

Instead, he did a thorough analysis of his experimental design and as a result drew some major conclusions. A key one was to "simplify." After a year of a painstaking series of improvements, Maiman's measurements showed a clear signal of resonance—the "Lamb shift" in helium had been proven. As Maiman later described in his book *The Laser Odyssey*, in this experimental setup

> *The design included: a servo-tuned parallel-plate microwave cavity that was powered by a war surplus magnetron; a Helmholtz-coil magnetic field activated by a current-regulated power supply and auxiliary square-wave modulation coils; a current-regulated power supply for the helium-excitation tube; a sensitive Q-multiplier tuned low-noise amplifier; and a phase detector.*

Maiman successfully defended his doctoral dissertation in 1955, and later that year Lamb received a Nobel Prize in physics based in part on the laboratory proof of the Lamb shift. In an interesting twist a few years later, after Maiman's invention of the laser, Lamb became interested in the physics underlying laser operation. In a classic paper he predicted a physical phenomenon in laser behavior that came to be known as the "Lamb dip."

Work life

Despite Lamb's advice, Maiman did not try to find an academic position. He was too practical for this, he thought; his aim was rather to work as a research scientist in industry. After an around-the-world cruise of 80 days, he did a short stint at Lockheed's Aerospace Division. Maiman then moved to the Hughes Research Laboratories in Culver City, California, to work in the newly created Atomic Physics Department, whose mandate was to push the practical limits of the coherent electromagnetic spectrum to shorter wavelengths. The U.S. Army Signal Corps had awarded a contract to Hughes to build a state-of-the-art microwave amplifier known as a ruby maser, and Maiman was selected to head this project. The existing maser was a big room-sized device with a very complex cryogenic cooling (liquid-helium temperature) system and a huge electromagnet weighing almost 2.5 thousand kilograms. Despite being large, heavy, and very expensive, this device was not very stable. Maiman's task was to make it smaller, lighter, less expensive, and, most of all, stable.

Within a relatively short time the design of the ruby-based maser was simplified; the weight was reduced more than 200-fold, microwave power was increased, the cost significantly reduced, and the stability much improved. This accomplishment was an indication of Maiman's great talent, which over the course of his career only grew with experience. One of the most important lessons he learned from this exercise was that "cryogenics is a killer; if you can make your product work without very low temperatures, do it." In this case, however, because of the invention of a parametric amplifier with comparable low-signal sensitivity to the maser but with a lower price tag, the newly miniaturized maser was superseded.

Laser time

The possibility of stimulated emission was first postulated by Albert Einstein in 1917. It required electron "population inversion"—a counterintuitive state in which more atoms are in an excited state than in a lower energy state. Nothing happened for years until a young Russian physicist, Valentin Alexandrovich Fabrikant, specified in his 1940 doctoral thesis the conditions needed for amplification of light by stimulated emission. He was not successful in achieving coherent light, but his theoretical and experimental work preceded the demonstration of any laser-like device. Then the laser concept was put on the back burner until 1958, when Arthur Schawlow and Townes published a *Physical Review* article about the possibility of making an infrared laser using hot potassium.[1] Their proposal proved totally unworkable, but it revived the dreams of making a coherent light source. The race to make a laser had begun.

Several groups of first-class scientists in the United States and around the world secured generous funding and started their work to make a laser. The most active were the Columbia Radiation Laboratory (Townes), Bell Telephone Laboratories (several laser teams), TRG, Massachusetts Institute of Technology, and others, most receiving millions of dollars in contract money. Scientists in the Soviet Union paralleled the effort.

Maiman was still finishing his ruby maser project when the laser race left the starting gate. Returning in August 1959 to his earlier ideas about making a laser, he was already eight months behind the competition. He approached managers at Hughes seeking funding to pursue development of a laser, even though such support was easy to secure; Hughes relied on government money for most of its projects, with the only spare funds coming from entries in overhead costs. But, with much reluctance and skepticism, Maiman's bosses gave him $50,000, one half-time technician, and nine months to work on the laser. In contrast, the competitor labs started earlier and some had budgets of millions of dollars and sizeable teams of researchers.

1 Schawlow, A., and C. H. Townes. 1958. *Physical Review* 112(6):1940–1949.

Maiman's practical experience with the maser project dictated several points: the design must be simple, not use cryogenic cooling, and rely on readily available components and materials. And Maiman was confident; he knew well the optical properties of synthesized pink (lightly doped) ruby and seriously considered it a potential lasing medium.

Leading the largest "laser" group at Bell Telephone Laboratories, Townes organized a conference in September 1959 devoted to ideas about making a laser. At this conference Schawlow presented a paper that ridiculed the idea of using ruby as lasing medium. He did not support his contention with any calculations or work out the details. But as we know, "the devil is in the details." Maiman attended the 1959 conference and came away with the following observations, as recorded in his book:

> *Obviously, the attainment of coherent light was turning out to be more difficult than originally envisioned by Schawlow and Townes in their Physical Review paper. They had not successfully instructed anyone on how to achieve a laser, including themselves. New concepts, much more computation, analysis, and ingenuity were going to be needed before anyone would be able to create a laser. (p. 82)*

Maiman was not discouraged by Schawlow's disparaging comments about the ruby and decided to continue his approach. He reworked calculations on properties of the ruby and confirmed his earlier belief that it would be a difficult but viable lasing medium. The size of the ruby crystal, particularly its length, was important. For the ideal crystal constituting the resonance cavity, longer would be better. However, the technology of obtaining synthesized crystals (Czochralski method) was still quite young, and the crystalline defects in long crystals might prevent coherence. Another issue related to length was possible thermal instability and thus mechanical stresses in the crystal. These stresses would degrade the optical parameters of the ruby rod.

> When we got past 950 volts on the power supply, everything changed! The output trace started to shoot up in peaks intensity and the initial decay time rapidly decreased. Voila. This was it. The laser was born.

Therefore Maiman decided to employ a quite short ruby—a cylinder-shaped crystal about 1 cm in diameter and 2 cm in length. The ruby rod had two opposing surfaces polished flat, parallel to each other, and normal to the axis of the rod. For mirrors he used evaporated silver, with a tiny hole in the middle of one of them to let the coherent light out. He then considered the light source needed to lase the crystal medium. Because he wanted to direct maximum pumping light onto the ruby crystal, he chose the strongest spiral photographic flash lamp from GE. He placed the cylindrical ruby crystal inside the spiral lamp, and to get even more light focused on the ruby he constructed a polished aluminum cylinder surrounding the flash lamp spiral. The entire device was small enough to be held in the palm of the inventor's hand.

Figure 1. The first laser and its components. (Photo taken by Theodore Maiman in 2005 in his Vancouver apartment.)

May 16, 1960, was the day. A high-voltage DC power supply was turned on to produce sufficiently high voltage to the flash lamp. The light output from the ruby crystal was directed through a monochromator (Bausch & Lomb) to a very sensitive light detector (photomultiplier), which in turn was electrically connected to a Hughes memoscope (oscilloscope with memory). When Maiman and D'Haenens set the voltage at 500 volts they detected traces of red ruby fluorescence. They increased the voltage several times in roughly 50-volt increments.

As Maiman later reported in his book:

> *When we got past 950 volts on the power supply, everything changed! The output trace started to shoot up in peaks intensity and the initial decay time rapidly decreased. Voila. This was it. The laser was born. (p. 103)*

To confirm that it was really a laser action, the researchers made additional measurements of the spectral width of the emitted light. Maiman got had gotten access to a highly specialized, expensive, high-resolution spectrograph. Using it, they were able to show that only one of two fluorescent modes, referring to two spectral lines, could lase. It was what Maiman had predicted in his earlier calculations, and it was this mode that was present on this 1960 day.

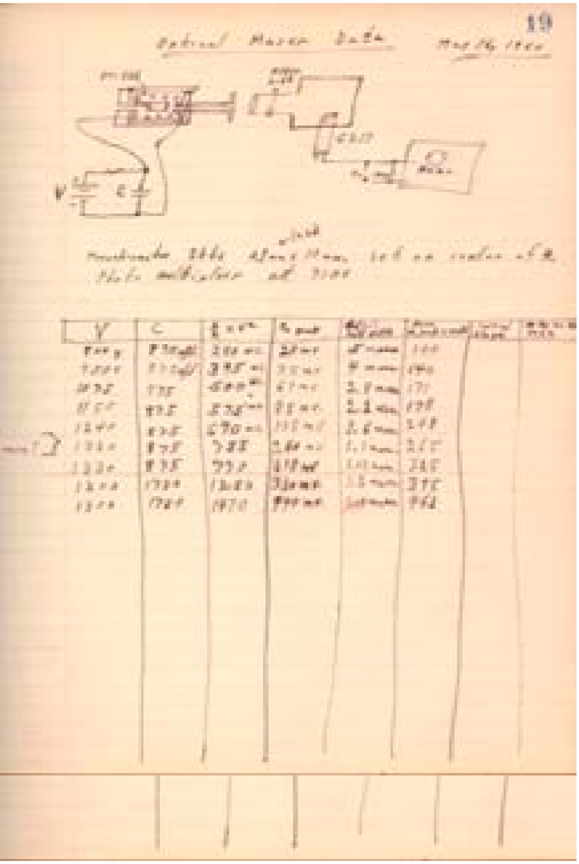

Figure 2. Log book from the experiment that produced the first demonstration of a ruby laser.

If we create a diagram of the years of inventions of sources of coherent electromagnetic radiation vs. their frequency (see Figure 3), we notice that on a semi-logarithmic scale they form a nice straight line. The only big outlier is the laser. It should not have been accomplished in 1960. The expected time was 2020, 60 years later!

Aftermath of the invention

For his remarkable contribution to science, Maiman received a number of prestigious international awards and prizes. The first was the Fanny and John Hertz Science Award of 1966, delivered into Maiman's hands by U.S. president Lyndon B. Johnson. In 1984 he was awarded the Wolf Prize—equivalent in prestige, according to many scientists, to the Nobel Prize—as the nominees and their work are highly scrutinized; Maiman received it together with his friend from Stanford University times, Irwin Hahn. The year 1987 brought another prestigious award, the Japan Prize, which was handed to Maiman in the presence of Emperor Hirohito by Konosuke Matsushita, founder of the Panasonic Corp. and of the prize's foundation. Maiman was nominated for the Nobel Prize three times—not successfully, however. He also received many honorary doctorates from eminent universities around the world. The last was in 2002 from British Columbia's Simon Fraser University.

Maiman in Vancouver (1999–2007)

In February 1999, Maiman and his wife Kathleen arrived in Vancouver, British Columbia, as tourists. Their intention, however, was to receive landed-immigrant status and become Canadians, which they ultimately succeeded in doing.

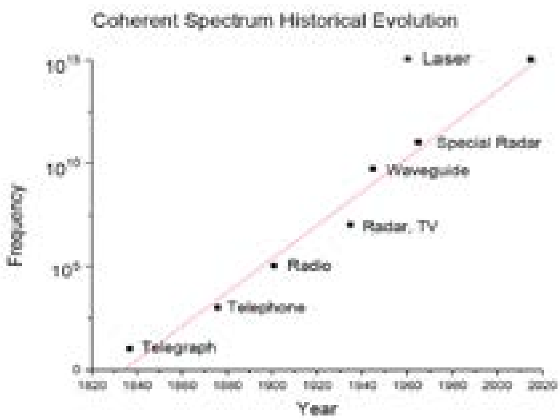

Figure 3. Historical evolution of coherent spectrum.

In May 2000, a celebration of the 40th anniversary of the laser's invention—quite appropriately, its ruby anniversary—was held in the Vancouver Terminal City Club. The event attracted a sizeable crowd of local and visiting people from around the world and from diverse professions, including scientists, engineers, physicians, and dentists, many of whom had directly benefited from the creation of the laser. Irnee D'Haenens, Maiman's assistant at the time of the first laser demonstration, arrived from California (he is shown with Maiman in Figure 4). Also in 2000, Maiman finished writing and published his autobiography, *The Laser Odyssey*.

In April 2001 a short article titled "Laser inventor lives in Vancouver" appeared in the *Vancouver Sun*. This is how I learned about Maiman's presence in our city. After finding his phone number I called and left a mumbled message about how good it would be for engineering and physics students to have him make a presentation on lasers and specifically on his original invention. The message was not well organized, as I felt quite intimidated by this giant in science history. Nothing happened for several weeks, so I almost forgot about it. But one day I got a call from a person who introduced herself as Kathleen Maiman. To my surprise I was invited to the Maimans for dinner. My colleague Alan Guest, chair and founder of the BC Photonics Industry Association, was invited too. The get-together turned out to be very pleasant, with a number of unexpected and funny happenings that showed Maiman's great sense of humor and flexibility. (For instance, we were kicked out of a restaurant because of its "dress code"—I did not have a jacket and tie. Maiman loaned me a jacket and tie of his own, but still the restaurant refused to let us in, as I was wearing sandals and no socks. We went to another place.)

Figure 4. Maiman and assistant Irnee D'Haenens demonstrating the first laser at the 40th anniversary of its invention.

From the conversation it became clear that the Maimans had an immigration problem because, according to the Canadian immigration criteria, they were too old. Of course, the immigration bureaucrats did not realize who Maiman was.

We immediately created an action plan, which began with Maiman's being invited to Simon Fraser University (SFU) to give a lecture on the invention of the laser. I recommended that he be invited to join the SFU School of Engineering Science (my workplace) as an adjunct professor, which was implemented at once. The next steps were to get Ted involved in the design of photonics and biophotonics courses and to nominate him for an honorary doctorate. In parallel to those activities, two strong support letters were drafted and sent to Canada Immigration—one from me (in my capacity as a professor) and another from SFU's vice-president for research, who was a physicist. At the same time, one of Canada's high-tech industry founders, Dan Gelbart, who used lasers in most products of his company Creo Industries, wrote another support letter and made several phone calls to Canada Immigration, explaining to its officials how important it would be for the country to have someone like Ted here. It all worked, and Ted and Kathleen got their visas extended and ultimately (in 2003) received landed-immigrant status. Earlier, in 2002, Ted received his honorary doctorate from SFU.

Roughly from this time, Ted and I became friends and saw each other quite often (at least once a week), which gave me the privilege and opportunity to learn as much as I could about this great man. In 2002 he was already 75, but if one did not know his birth date one would never suspect this age. He was in great physical shape, but most of all he had an incredibly lively mind, which he would open to people who he liked and trusted. He could be like a young boy, who would play with my dog under the table and make jokes; yet a few minutes later he was ready to discuss serious scientific or engineering problems. He never stopped participating in projects. For example, during the time of our acquaintance he worked on vertical takeoff aircraft. He wanted to improve their efficiency and stability and in the process he built a number of flying models that used toys as components. Being serious about this project, he also calculated the lift and optimized it in quite sophisticated ways, without ever losing his sense of the physics involved. A sample sketch of his hand-written mathematical models is shown in Figure 6.

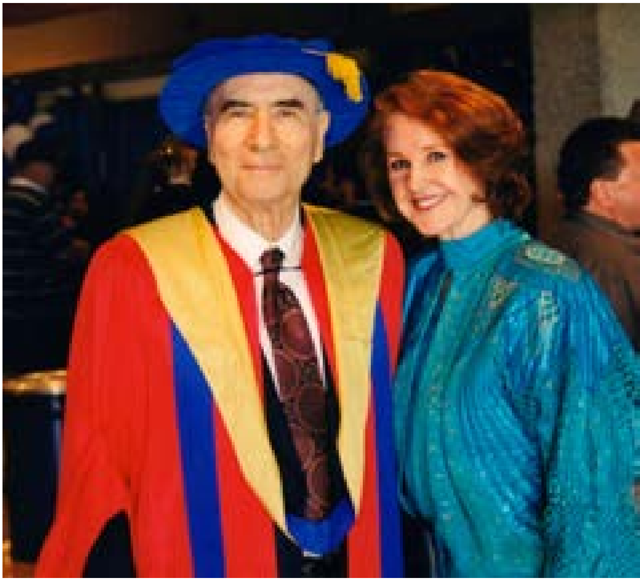

Figure 5. Maiman with wife Kathleen after he received an honorary doctorate from Simon Fraser University.

Why he succeeded

When Ted designed and built and then successfully operated his original ruby laser, it had taken him only eight months to accomplish this task, and he did it with a budget of $50,000 and just one half-time technician, D'Haenens. Some of the competitors had started earlier, had budgets amounting to millions of dollars, and drew on sizeable teams. One of the major conclusions I drew from these historical facts was: if you are to invent/discover something of great value, you do not necessarily need a great deal of money. Too large a budget de-concentrates the project and does not motivate the simplification of your research concepts. Ted's ability to complete engineering tasks with the simplest designs was one of the main reasons for his success.

In addition to his deep native intelligence, Ted had received an excellent combination of elements in his education. His informal education started when he experimented in his father's laboratory and later when he worked as an electronic-appliance repairman. His formal education involved both engineering and physics. Engineering gave him the background for efficient and elegant design, and physics provided a deep and full understanding of what he was doing. His early experiences gave him an intuitive sense of cause-and-effect that in turn saved Ted time in choosing approaches. He was curious and easily motivated, and then persistent (some might say "stubborn") in pursuing his goals.

A keen sense of humor and play permitted him to keep his tasks at a distance, to avoid losing objectivity. The following excerpt from the speech that Ted gave at the award ceremony of his honorary doctorate from Simon Fraser University speech, shows this illustrious man's essence:

> *For those of you who are willing to take the risk of blazing new trails, you need to appreciate a reality of life: you will find that the more you deviate from conventional wisdom and the well-beaten paths, the more your consensus of agreement will diminish.*
>
> *Naturally, if you achieve your goal in spite of going against established views, it is especially sweet. But even if your goal is not achieved, there is still a rich reward for your choice. You will experience the thrill and excitement of an adventure. I assure you it will not be boring.*

Figure 6. A sample of Ted's hand calculations of necessary lift for a vertical takeoff aircraft.

A great loss

In 2006, Ted was in a car accident in which his vehicle was damaged to the point of disrepair. Physically, nothing seemed to have happened to him, but the post-accident trauma may have triggered a rare disorder called mastocytosis. Ted died on May 5, 2007, leaving a profound legacy, in the form of the laser, that affects so many aspects of

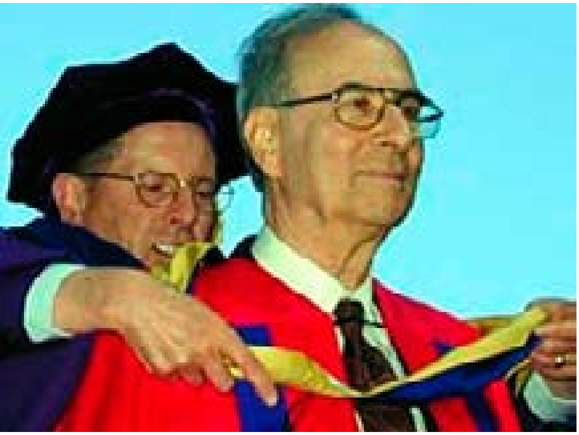

Figure 7. Maiman receiving a Doctor Honoris Causa degree from Simon Fraser University.

all of our lives. He deeply affected my and my wife's lives on a personal level as well. Kathleen remains our good friend. D'Haenens passed away seven months later, after attending a memorial for Ted organized at Simon Fraser University.

Ted's first laser was fired again in Vancouver at the "Laser Celebration" symposium, held on May 15 and 16, 2010. The symposium gathered first-class researchers who primarily use lasers in their work, and they all agreed that without Ted's invention their research would be impossible. One of Ted's great friends, Nick Holonyak—who is John Bardeen Endowed Chair in Electrical and Computer Engineering and Physics at the University of Illinois at Urbana-Champlain and inventor of the semiconductor laser—apologized for not being able to attend this symposium due to illness. He instead wrote a very touching contribution, which was read to the symposium's audience. He agreed that his letter should be included in the NAS memoir, and it follows.

Ted Maiman and the laser: 50 years later

By Nick Holonyak, Jr.

As is often said, everyone has a story. All of us who've had an opportunity to contribute to the science and technology of the laser in the beginning, in its infancy, have our own stories of how we arrived at various basic discoveries, of whose work mattered to us and whose did not. As we now approach the 50th anniversary of Ted Maiman's ruby laser—the first laser (May 1960)—we have a rare opportunity to look back at this golden moment and recall how it influenced our thinking and our work.

I want to mention first that in studying oscillators (microwave oscillators—klystrons, magnetrons, multipactors) I go all the way back to 1951–52, to a time before there was a molecular oscillator. At that time, there was even speculation that if coherent light could be generated, it might not be visible to the human eye because of how it evolved, seeing over the course of human evolution only incoherent light. This sounds ridiculous now, considering that the eye is a photon detector, and the laser generates photons, no matter if in coherent-wave form. They are still seeable photon "lumps" of energy. In 1951–52 the idea of a molecular oscillator wasn't too strange. In fact, it was a known idea. But a light-frequency oscillator was beyond comprehension—simply speculation. Some attempts were even being made to prove, based on incomplete theoretical ideas, that there was a physical limit on the upper frequency of oscillation, and hence no possibility of a laser.

It can't be said that anyone knew in the 50s how to reach the visible—i.e., how to build a laser. Ruby as a laser material was dismissed by most workers, but not Maiman. He knew something and felt something that others missed, or dismissed, and, as we know, he demonstrated the first laser (May 1960) using ruby and his own work and knowledge (U.S. Patent 3, 353, 115). Employing his own thinking, he was not misled by the wrong conclusions of others. Ted Maiman's ruby laser was not a sterile existence proof, an ethereal form of proof so acceptable to mathematicians but essentially useless to physical scientists. It was real proof—demonstrated proof, actual proof, hard evidence—that visible coherent light could be generated. Not only did Maiman realize the first laser, in one great jump he moved the frequency of stimulated emission and coherent oscillation ~10^4 times, an astounding amount—beyond the microwave domain, way beyond that of ordinary microwave equipment and experiments. Equally striking, he demonstrated a power level of watts, not the microwatts of masers. This has to be one of the great moments in science and technology, at last a coherent oscillator in the spectrum where humans see.

To be sure, Maiman did not show how to realize all the forms of lasers that eventually emerged, in particular the important case of the now-dominant semiconductor laser—the bipolar, plus-minus, electron and hole (e–h) conductive substance supplying spectrally smeary recombination radiation. The vital substance that for many good reasons intrigued many of us in electronics. He did not "teach" us how to proceed in this case, which required substantially more knowledge and two more years of work. Nevertheless, those of us who built the first semiconductor lasers knew from Maiman, and not from masers, that coherent light could exist, could indeed be generated and be visible.

It appeared, however, that we were left out, that we were dealing with the wrong kind of substance as a light source. But the semiconductor was unique in being a source of light fed directly, not indirectly, by e-h current. The misunderstood complication of the broad recombination-radiation linewidth and the problem of how to deal with it baffled many people. And it led to bizarre and lame notions (1962) to seed the crystal with foreign-atom discrete light-generating centers, a notoriously poor idea. This could only compromise and steal from the band-to-band light-generation process.

To be more specific, the reason I wanted to build a visible-red gallium arsenide phosphide (GaAsP) laser—a "red" bandgap III–V alloy diode laser, assuming it was possible—was because down the hall in Building 3 in Syracuse (GE) I had already seen the unique red light of a ruby laser, a Maiman laser, and I knew, based on my own work on III–V semiconductor alloys (beginning in 1959–1960), that I could make and use the alloy crystal GaAsP to generate red light. I had already devised a vapor-phase epitaxial way to grow GaAsP (U. S. Patent 3, 249, 473). Why not generate coherent red light? Was it possible? Knowing about oscillators, I knew a cavity was needed, but what else? Maybe nothing, in spite of the smeary band-to-band electron-hole recombination-radiation linewidth. I wanted to see from a semiconductor the kind of light Maiman could see from ruby. I knew that I had to use the band-to-band e-h recombination-radiation light source—a gift of the semiconductor and its energy gap—and try to make it coherent. Anything else in a semiconductor would be a compromise. I knew from Maiman what to look for in coherent red light, how it should appear. Above all, I wanted to work with visible light, light humans could see, not infrared radiation or microwaves. What I needed to know was that light could be coherent, and this I learned from Maiman's ruby laser.

How did others know that light could be coherent? What demonstration? What proof? Whose proof? This information was vital. If visible light—say, red—could not be coherent, why should I struggle with the stranger and more complicated light emission of a semiconductor? Would anything work if nothing yet had been demonstrated to work? I needed to know light could be coherent, that something did work, and, maybe more important, I needed to know that a p-n junction, and its injection current e-h recombination, could be an efficient source of light, which for me came from R. Rediker's Lincoln Lab group at the 1962 New Hampshire IRE Device Research Conference.

After DRC I set out (at GE, Syracuse) to make a red diode laser, thinking the advantage for success was mine in working with visible light. After all, I knew how to make visible-spectrum (red) direct-gap ($k_e = k_h$) GaAsP (U. S. Patent 3, 249, 473). We would have to learn whatever else was required, again not knowing what was possible. Would just adding a cavity suffice, say, the external cavity I had in mind after DRC? Simpler and better, my Schenectady GE colleague R. N. Hall later suggested (Aug 1962) that the semiconductor crystal itself, with suitable mirror facets normal to the junction plane, could serve as the cavity. And here I thought, working in the visible, I was ahead of everybody! The external cavity idea, particularly with grating tuning, proved to be valuable later in various analytical measurements and experiments.

When the diode laser arrived (fall 1962)—Hall's GaAs laser (infrared) with polished mirrors and then my GaAsP with a different polishing "recipe" (an attempt to cleave cavity mirrors delaying me)—my laser, a higher-gap III–V alloy, was the first III–V alloy device and was visible red like Maiman's ruby laser. Maiman's laser sparkled in the red in 1960 and mine sparkled red in 1962, the first visible semiconductor laser and LED. My crystal was homemade and the beginning—the prototype for all the direct-gap ($k_e = k_h$) III–V alloys now used in LEDs and diode lasers. It was the beginning of, as Egon Loebner (H-P) called it (not an easy admission for Egon), the "alloy road" to LEDs. It was the III–V alloy that made possible heterojunctions and today's devices. We had landed in our struggle to build a semiconductor laser on the path to an "ultimate lamp,"[2] both in principle and in fact, both as diode laser and as LED.

At this point the simplest way to explain my thoughts is to tell a story. Not too many years before his death (January 1991), John Bardeen, the two-time physics Nobelist, my Ph. D. advisor who introduced me to semiconductor research (1952–54) and invited me back to Urbana, was talking to me in my laboratory office (EERL, Urbana) and told

2 Holonyak, Jr., N. 2000. Is the light-emitting diode (LED) an ultimate lamp? *Am. J. Phys.* 68(9):864–866.

me about some comments in a recent annual-review volume written by a well-known European scientist. The comments dealt with how this scientist's thoughts and work on superconductivity had anticipated the famous BCS (Bardeen-Cooper-Schrieffer) theory of superconductivity. Bardeen laughed through clenched teeth in a peculiar manner, with obvious disdain at this totally absurd comment, and then remarked, with his teeth only slightly parted, that this was just like when various individuals lay claim to the laser, or the laser notion, and Maiman reaches into his pocket, pulls out his historic laser ruby rod, and then says, "Here's the first laser."

Just as before Bardeen there was no transistor, and after Bardeen there was a transistor, as well as later BCS theory—before Maiman there was no laser, and after Maiman there was a laser. I think it is clear that John was revealing to me something about pretenders to BCS superconductivity theory, and similarly pretenders to Maiman's laser. Typical of Bardeen, he did not discuss or say much; but, by use of comparison and the simple fact that he raised the issue, he revealed his thoughts. To him, theft of the BCS idea looked the same as theft of the laser. After the fact, after a great accomplishment, here come the pretenders! Bardeen knew and obviously admired what Ted Maiman had done. He knew nothing preceded the transistor, nor BCS theory, nor Maiman's ruby laser. He knew whose early work mattered. It of course pleases me that now, more than 50 years after the transistor, my colleague M. Feng and I, with our grad student and postdoc colleagues, have reinvented the transistor (2004) in the form of a three-terminal laser, into a true transistor laser. Obviously we owe something to the past, in my case, and now my colleagues,' to Bardeen and the transistor and Maiman and the laser.

What is there to say further? It is clear what Bardeen thought, and what many of us think. No one beat Maiman to the laser. How important is the laser? How important are all lasers? That is how important we have to regard Maiman's contribution. I am happy to say I received the Japan Prize in 1995, which is eight years after Maiman received the Japan Prize. My prize is worth something to me because someone like Maiman received it before me. Ted Maiman deserved every prize he ever received, and more. He and the laser changed all of our lives, everyone's!

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