

Beam

The Race to Make the Laser

Jeff Hecht



Forty-five years ago this year, physicist Theodore Maiman and his colleagues succeeded in making the first laser work at Hughes Research Laboratories in Malibu, Calif. Maiman performed the experiment on May 16, 1960, using an elegant ruby rod placed in a spring-shaded flash lamp. This article is adapted from Jeff Hecht's new book describing the science, politics and passion surrounding the great laser race; *Beam: The Race to Make the Laser* was published in March 2005 by Oxford University Press.

The new Hughes Research Laboratories building in Malibu seemed “the palace of science” to physicist Bob Hellwarth when he moved in along with Theodore Maiman and other laser pioneers. The hillside Malibu complex had a movie-star’s view of the Pacific. The floors were wood parquet, with long, narrow offices lining the outer walls and windowless labs on the other side.

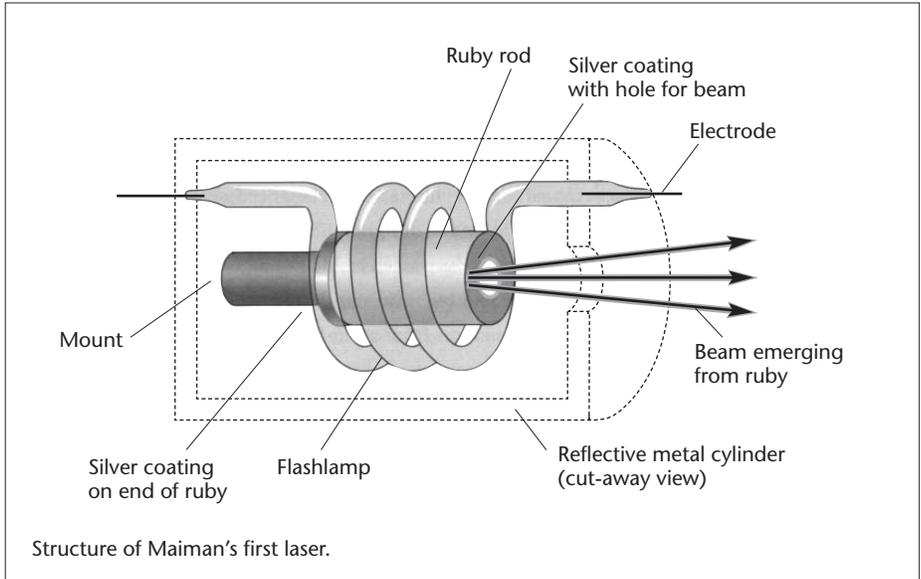
In April, Maiman moved into an office facing the ocean. His colleagues Charles Asawa and Irnee D’Haenens shared the next office. On the other side, Harold Lyons had a larger office that came with his rank of department manager.

Moving his laboratory from Culver City to Malibu stalled Maiman’s progress on laser development by at least three weeks. But as soon as he was able, the intense and competitive Maiman focused as tightly on his quest as a laser beam. He didn’t know that his competitors William Bennett and Ali Javan at Bell Laboratories had measured the first gain in a helium-neon mixture, but he had plenty of other reasons to worry about Bell. Ten times larger than Hughes Research, and with ten times the funds, Bell Labs was the odds-on favorite.

Maiman had made a compelling case for using ruby as a laser material, but he was surrounded by doubters. Arthur Schawlow, who had published the first detailed proposal for building a laser with Charles Townes, had dismissed ruby as an unsuitable material because he thought it could not generate light efficiently or continuously. Outside Hughes, Schawlow’s conventional wisdom that ruby wouldn’t work prevailed. Even within the institution, Maiman felt a lingering air of skepticism from management.

But he forged ahead in the belief that Schawlow had not based his opinion on adequate data, and that ruby could generate pulses that were good enough to demonstrate laser action.

The task before Maiman differed from that which faced Bennett and Javan. Their excited mixture of helium and neon had produced only feeble stimulated emission at an infrared wavelength invisible to the human eye. They needed to tweak the gain upward in every way



Structure of Maiman’s first laser.

they could, and to design optics that could capture every bit of that stimulated emission to produce a detectable beam.

The choice of ruby gave Maiman some big advantages. He could buy the coiled flashlamp needed to excite the chromium atoms from a standard catalog. General Electric made three models that he calculated could produce enough energy, and he bought a few of each to be on the safe side. His early experiments also indicated that ruby converted that excitation energy efficiently into red fluorescence. Thus, he wouldn’t need to struggle for months to measure a small amount of amplification, as Bennett and Javan had done. Nor would he require a resident optical wizard like Don Herriott at Bell to make the ideal set of optics, which, even when perfectly adjusted, would extract a weak and invisible beam. Maiman fully expected to see the red ruby beam from his laser.

What Maiman needed, however, was a way to concentrate the lamp’s intense flashes of white light onto the laser rod, and to make sure the red light from the rod was stimulated emission rather than ordinary fluorescence.

When he first thought about exciting ruby with a bright continuous lamp, Maiman had planned to put the lamp at one focus of an elliptical cylinder and a ruby rod at the other. That approach didn’t look promising for the coiled flashlamps, so he looked for another focusing arrangement. Inspiration came from a

salesman who said the biggest of the three coiled lamps was so intense that it could ignite a piece of steel wool placed next to it. Maiman realized he didn’t need special optics to focus the light. He could simply slip the ruby crystal inside the spring-shaped lamp, where the coils would surround the rod with a bright surface.

After making that decision, Maiman designed a simple experimental apparatus. His calculations showed that the smallest of the three lamps should suffice to drive a ruby laser, so he started with the FT-506, which could fit in the palm of his hand. He needed a small ruby rod to fit inside, so he picked one 3/8 in. in diameter and 3/4 in. long—a cylinder roughly the size of a fingertip.

He had the Hughes shop polish the ends of the ruby rod flat, perpendicular to the length of the rod and parallel to each other. Then he had both ends coated with silver, the most reflective metal available. He scraped the silver off the center of one end, leaving a transparent opening so the beam could escape from the reflective cavity.

Maiman had an aluminum cylinder machined and polished to slip around the spring-shaped flashlamp. The shiny inside of the cylinder reflected light emerging from the outside of the lamp coils back toward the ruby rod. The lamp coil absorbed some of the light, but some passed between the widely spaced coils, delivering more pump light to the rod.

BEAM: THE RACE TO MAKE THE LASER

Hughes Research Laboratory, courtesy AIP Emilio Segrè Visual Archives



Theodore Maiman and Irnee D'Haenens display the first laser a quarter century after they made it.

Plugs that slipped into the ends of the aluminum cylinder held the ends of the lamp in place, and served as mounting points for the ruby rod and the electrode that triggered the lamp to fire. One plug had an opening for the beam to emerge.

The whole package was the size and shape of a small water glass. Some light from the flashlamp leaked out through the beam opening, but the cylinder confined most of the lamp's blindingly bright flash, so it wouldn't completely dazzle the experimenters' eyes. A power supply fired electrical pulses, which electrical cables delivered to the lamp.

The ruby laser design was remarkably simple compared to the helium-neon gas laser being developing at Bell. Maiman's calculations indicated that he had a generous margin for error. He didn't need the best mirrors; simply silvering the ends of the ruby cylinder would suffice for a first trial. Nor did he need the best crystal—which was fortunate because the optical quality of his ruby rod was not very good.

The aluminum cylinder wouldn't reflect all the light back onto the rod, but he calculated that it should reflect enough. The Hughes machine shop

made the parts that he couldn't buy. Starting with the smallest of the lamps, Maiman hoped to avoid the need for cryogenic cooling to remove excess energy. If it didn't work the first time, he could try better mirrors, bigger lamps or both.

In contrast, Bell Labs knew they were working at the margins of possibility. They needed the best mirrors to push the helium-neon laser over the threshold of operation. They didn't see any reason to seal their experimental laser tube in a case. They didn't expect a blinding glare from the tube, and leaving it open to the air would help dissipate the heat.

A critical part of the experiment was collecting conclusive results. Nobody had made a laser before, so Maiman needed to devise his own set of tests. It wasn't enough to look for light; ruby glowed red with fluorescence when illuminated by violet, blue or green wavelengths. He needed a way to distinguish clearly between ruby's ordinary red fluorescence and the coherent beam generated by the amplification of stimulated emission in a resonant cavity. Fortunately, theory predicted some important differences.

The most obvious was that laser light should be concentrated in a narrow beam—the idea that had excited Gordon Gould and others. Simple fluorescence is spontaneous emission, so it should emerge from a sample of ruby in all directions. Stimulated emission that amplified light bouncing back and forth between a pair of mirrors should be directed along a line between the mirrors.

Yet it wasn't that simple for a ruby rod. If the entire volume of the rod glowed uniformly and none of that fluorescence was absorbed inside the ruby, the light would look brightest when you looked at the thickest parts of the ruby. Thus, more light would emerge from the ends of the rod than from the sides.

Maiman's rod was short and stubby, but the package he had designed let him observe only the light coming from the end. He hoped to see the light narrow into a beam, but he didn't expect it to be tightly focused. He also knew that merely projecting a red spot onto a wall wouldn't convince skeptics. He needed to make additional quantitative measurements that other physicists could replicate. Reproducibility would be the acid test.

A subtler way to distinguish laser light from spontaneous emission was to measure the speed at which the red ruby emission dropped after the pulse from the flashlamp ended.

Chromium atoms quickly released some of the energy they absorbed from the flashlamp, dropping into a metastable state. If left alone, they spontaneously emitted the rest of the energy as red fluorescence in about 3 ms.

However, if other photons with the right energy came along during the milliseconds that the chromium atoms retained that extra energy, they could stimulate the atoms to emit their extra energy before they dropped to the lower laser level on their own.

As long as the ruby produced only spontaneous emission—ordinary fluorescence—the intensity of the red light should drop by a factor of two every 3 ms. If laser action switched on, stimulated emission would drain the light energy faster, producing a shorter, more intense spike of light than ordinary fluorescence. The human eye couldn't respond fast enough to sense that

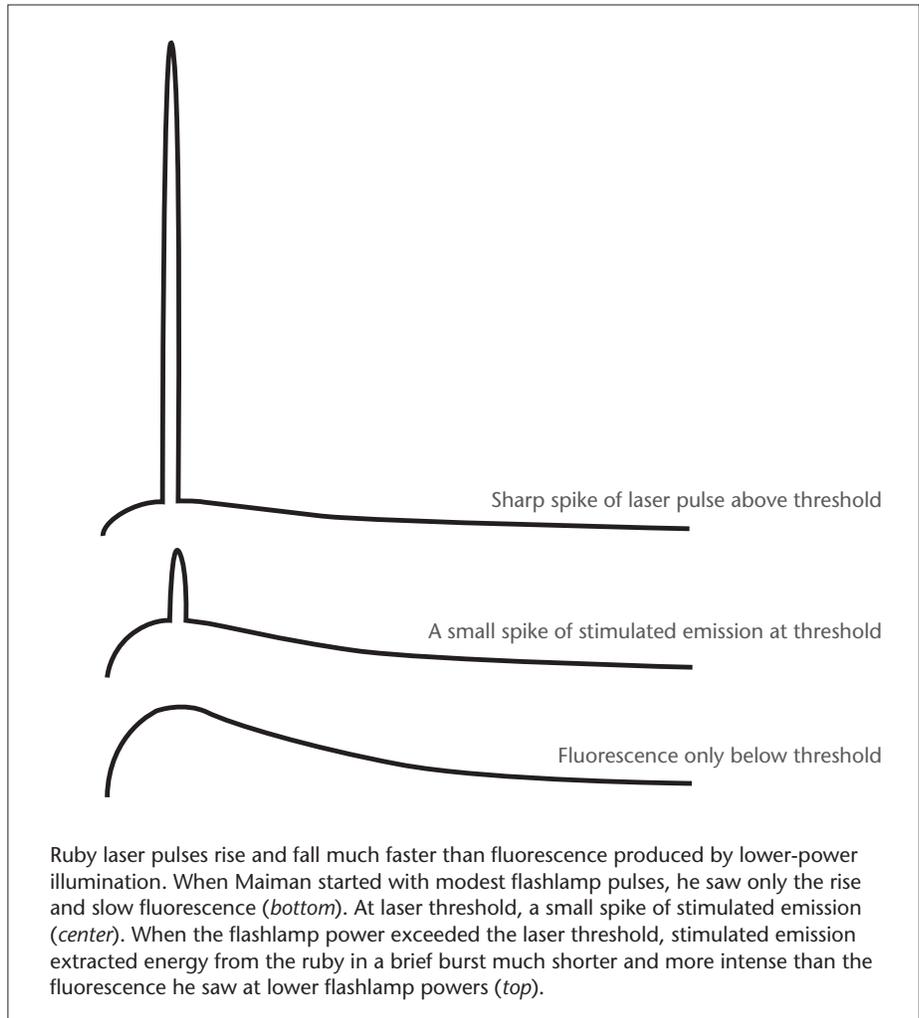
difference, but sensitive light detectors and electronic instruments could measure it on an oscilloscope screen. When laser action began and stimulated emission overwhelmed spontaneous emission, Maiman expected the peak of the pulse on the oscilloscope screen to become shorter and sharper, followed by a rapid decline. That was one test for a working laser.

Another test was even subtler. Maiman expected stimulated emission from ruby to span a much narrower range of wavelengths than spontaneous emission. Ruby fluoresces across a range of wavelengths that all look red to the eye, but they are not the same. The fluorescence is most likely to be at the center of the range, with the probability dropping off at the sides, so the light intensity varies in the same way.

Stimulated emission spans the same range of wavelengths as the fluorescence, but it amplifies the initial fluorescence. That amplification process concentrates stimulated emission in a much narrower range of wavelengths, as if the emission curve was multiplied by itself many times. The gain is highest in the middle of the curve, so that wavelength is amplified more than wavelengths to the side.

If the fluorescence intensity varies by a factor of two, the difference will double at each round of stimulated emission. Laser emission should span a much narrower range of wavelengths than fluorescence, with the exact variation depending on the nature of the laser material and the resonant cavity. Maiman expected a good spectrometer to show this line-narrowing effect, shrinking the band of red fluorescence narrow to a laser line, as shown in the figure at the top right of the page.

Both pulse-shortening and line-narrowing are closely related to the existence of a distinct threshold for laser action. When input power is low, nothing happens beyond the emission of a little fluorescence, which increases slightly as power rises. When the input power escalates above a threshold value, stimulated emission takes over and the laser turns on, with power increasing much more rapidly. The effect is like pushing an object along an increasing downhill slope until it finally starts moving on its own.



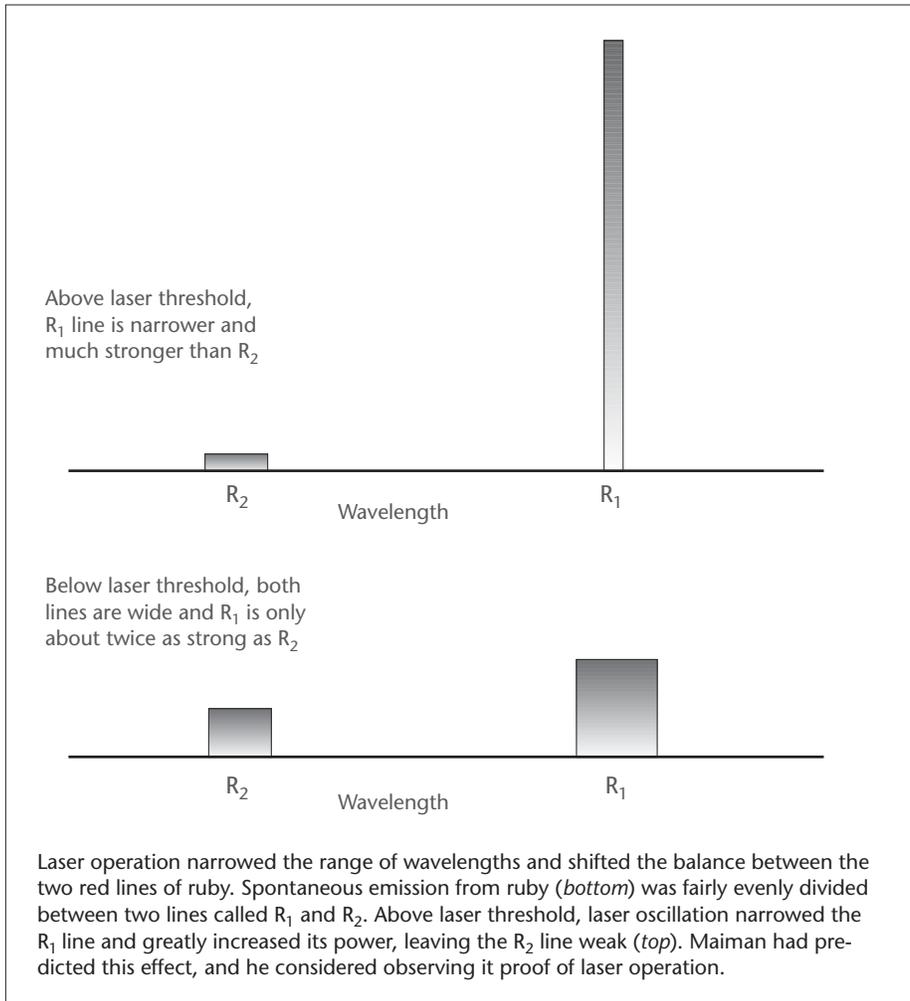
Stimulated emission becomes significant once the pump energy produces a population inversion. However, such an inversion is not enough to reach laser threshold. Only when the gain from stimulated emission equals the internal losses does the laser reach threshold. For example, if one percent of the light is lost on each round trip of the laser cavity, and another percent emerges as the beam, the gain on a round trip of the laser cavity must be two percent in order to reach laser threshold.

Once you exceed the threshold, the light power increases sharply. If the rise in power—the gain—is only one percent per pass, the power increases 64.4 percent after 50 round trips and cascades upward from there. After 100 round trips, the power is 170 percent (a factor of 2.7) higher; after 500 round trips, it increases by a factor of 145. Since the round trips

are at the speed of light, a nearly instantaneous jump in power can be observed as the laser exceeds threshold and turns on. The power doesn't grow infinitely because only a limited number of atoms can be excited at any instant, and the amplification process saturates.

Maiman's plan was to slowly crank up the power applied to the flashlamp and watch what happened. He expected to see ordinary red fluorescence at lower power, increasing gradually until he reached threshold. Above threshold, the laser would turn on, emitting a much brighter red beam. Crossing laser threshold was important, but he knew that accomplishing that alone would not convince skeptical physicists. He wanted to record both pulse shortening and line narrowing on his instruments.

Maiman and D'Haenens conducted their first test of the ruby laser on the



afternoon of May 16, 1960. Electrical cables connected a power supply to the two ends of their flashlamp. Another cable linked the trigger electrode to a source of high voltage pulses synchronized with an oscilloscope. The heart of the power supply was a big capacitor, which slowly accumulated a charge and held it until the trigger voltage ionized the xenon in the lamp and allowed the capacitor to discharge its energy through the lamp.

Linking the trigger voltage to the oscilloscope synchronized the firing of the lamp with the trace drawn across the oscilloscope screen, so Maiman and D’Haenens could compare the sequence of events for many different pulses as they changed the voltage across the lamp. The trace measured the amount of red light registered by their sensor. It swept across the screen at a constant rate, with horizontal markings measuring the

passage of time, and vertical markings gauging voltage from the detector. The researchers set the trigger voltage to fire at a certain point in the cycle. A memory inside the oscilloscope recorded the traces from successive pulses.

They aligned the laser package to focus the ruby output into their monochromator, which spread the light into a spectrum. Then they directed a thin slice of that spectrum to a sensitive photomultiplier tube, where the photons triggered a cascade of electrons that drove the oscilloscope. The oscilloscope trace rose and fell with the strength of the signal, measuring how much light reached the tube.

Each sweep showed how emission from the ruby varied as the pulse of light from the flashlamp hit it. Maiman had bigger flashlamps in reserve, just in case the little one didn’t have enough power to push ruby above the laser threshold.

They started firing the flashlamp with pulses of 500 V, a modest level for their lamp, and well below the threshold for laser action. When they fired the lamp, it flashed, and the oscilloscope showed a trace of light rising in power, then dropping in about 3 ms—just what they expected from ruby fluorescence. They adjusted the knobs and started turning up the voltage step by step, expecting the power in the ruby pulse to increase incrementally.

The experiment was simple and repetitive: Turn up the voltage, fire the pulse, and look at the oscilloscope trace. Today it would be computer controlled, but in 1960 Maiman and D’Haenens did it by hand, firing a single pulse that triggered both the flashlamp and the oscilloscope scan. Gradually the power level increased, but the more powerful pulses dropped with the same 3 ms decay time. The aluminum cylinder contained most of the light from the flashlamp, but bright flashes of ruby fluorescence scattered red light through the room.

Maiman and D’Haenens kept their eyes on their instruments, but the red flashes inevitably reached their eyes. The brightness of the ruby pulses increased steadily as they turned up the voltage. Their instruments showed that the increase was proportional to the extra energy delivered to the lamp—a sign that everything was working properly. They continued to increase the voltage, and watch their instruments each time they fired the flashlamp. The oscilloscope trace was a heartbeat on the screen. The flash brightness increased in small steps until they turned the power supply above 950 V. Maiman saw the oscilloscope trace surge.

“The output trace started to shoot up in peak intensity and the initial decay time rapidly decreased,” Maiman wrote. “Voilà. This was it! The laser was born!”

As the laser surged to life, its brilliant red glow permeated the room. The two men had aimed the cylinder at a piece of white poster board, and Maiman’s red-dazzled eyes were focused on his instruments. The beam formed a red horseshoe-shaped spot a few degrees wide on the poster board. D’Haenens jumped with joy. Maiman felt numb,

relieved that his gamble had paid off. They basked in the red light of glory.

Others in the atomic physics department came to take a look. Bob Hellwarth, who had brainstormed with Maiman on how to recognize laser action, congratulated him. Harold Lyons was delighted: His department had beaten Bell Labs to a prize that Bell had spent far more time and money seeking.

The next morning, Lyons showed up bright and early at Maiman's office, with plans to put out a press release. But Maiman was not ready to go public. He was proud of his achievement, but he also insisted on precision. His first experiment had left some doubt in his mind. He had not seen as sharp a jump in laser power as he had expected at laser threshold. He wanted to track down the cause of the anomaly. He suspected the problem stemmed from imperfections in the ruby crystal.

Maiman immediately ordered three new ruby crystals, and asked the supplier to cut them into rods and polish their ends, because he wasn't sure the Hughes shop could handle the hard ruby crystals properly. Indeed, Asawa soon found that the first ruby rod had internal flaws that caused light scattering. In addition, the end faces had not been made precisely parallel, so the light did not bounce back and forth properly between them. Unfortunately, only a single company, a division of Union Carbide, could supply the ruby crystals, and Maiman would have to wait weeks for delivery. For the moment he had to do the best he could with the original.

In the first experiment, Maiman and D'Haenens had concentrated on the easiest measurement—the change in how fast the red emission dropped. The decrease they saw was consistent with laser action, but Maiman sought more evidence. He wanted to show that the range of wavelengths in the ruby output narrowed when stimulated emission dominated above laser threshold.

He also wanted to verify the presence of a line narrowing specific to laser light. Pink ruby fluoresces at two closely spaced red lines, R_1 and R_2 , at wavelengths of 694.3 and 692.9 nm, respectively, at room temperature. This happens because the metastable upper laser level is actually a



When it came time to announce Maiman's laser, Hughes's public relations firm hired a top photographer to take pictures. The photographer liked to get shots of people behind their inventions, but Maiman's first laser was too small, so he insisted on using a larger flashlamp and ruby rod. This photo was widely published as the "first" laser, and when other researchers tried to duplicate Maiman's work, they used this larger flashlamp to pump their ruby rods. Although they had the wrong lamp, their experiments worked within a few weeks.

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pair of closely spaced energy states. When the chromium atom is in the lower state, it emits on the R_1 line; when it is in the upper one, it emits at the shorter-wavelength R_2 line. When ruby fluoresces, it emits about twice as much light at the longer R_1 wavelength; Maiman expected stimulated emission to increase the dominance of the R_1 line.

Maiman's modest monochromator couldn't make the required measurements. He needed an expensive high-resolution spectrograph. Another Hughes physicist, Ken Wickersheim, had just received exactly the instrument that Maiman needed, but he had a backlog of experiments to perform because he had been waiting for it for six months. At Maiman's request, Lyons pulled rank and commandeered the new instrument so that Maiman and Asawa could perform additional tests. The furious Wickersheim, an old classmate of Asawa's, took an extended camping vacation in the Sierra Nevadas to cool off.

Maiman and Asawa got results quickly. When Asawa ran the ruby output through the new spectrograph, he recorded the line narrowing that Maiman had predicted. The light was so bright that it

initially blackened the photographic plates that they had used to record the spectrum. Asawa had to insert high-density filters or spread the light in order to record the spectrum properly. The spectrograph also clearly separated the two closely spaced red lines. Asawa found that the R_1 line was at least 50 times brighter than the R_2 line, confirming another of Maiman's predictions. Maiman and Lyons were delighted; they had results good enough to publish, and a big success to report.

After this second experiment, which finally convinced Maiman that the laser was working properly, word spread around the lab in a matter of hours. But Maiman still had to persuade the outside world that his laser worked, and that would pose a new round of challenges . . .

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Sources

Primary sources: Theodore Maiman, *The Laser Odyssey* (Laser Press, 2000); interviews with Charles Asawa and Irnee D'Haenens.

Secondary sources: Telephone interviews with George Birnbaum, Richard Hellwarth and Bela Lengyel; documents collected by Laser History Project.