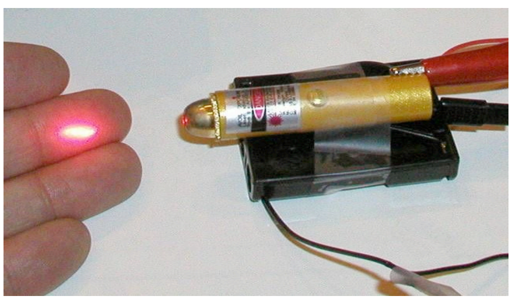
The Presidential Lecture Series was established in the fall of 1987 to recognize the contributions of outstanding members of the Dartmouth faculty. Elsa Garmire, Sydney E. Junkins 1887 Professor of Engineering, delivered the 19th annual lecture on Wednesday, February 15, 2006.

Who Would Have Imagined?

Elsa Garmire

I. Introduction

President Wright is a historian, and that's inspired me to talk about history. I'm going to tell you the story of the laser and how it grew from an idea in a scientist's head to a crucial technology that underlies today's technological world. By the end you should understand what makes a laser extraordinary. At the same time, I'll also tell you something about my own story. As one of the few women in my field, life has been exciting, but also a challenge.

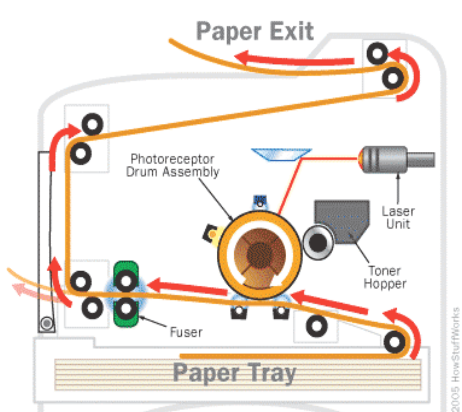


I'll begin with this laser pointer. It took millions of dollars in research and development costs before this laser was made to work. And now it costs $5.00. The laser is a tiny semiconductor diode, about the size of a salt crystal. The light it emits is turned into a beam by lens.

Would anyone spend millions of dollars to develop a laser pointer? No. This technology was actually developed for the laser printer. I don't have time to go into the details, but it is a fascinating story.

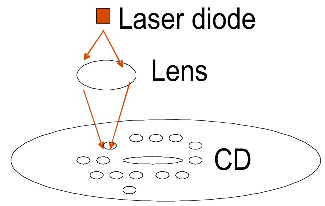
II. Lasers in our lives

Instead of dwelling on one particular technology, let's look at some examples to see how lasers permeate our personal lives.

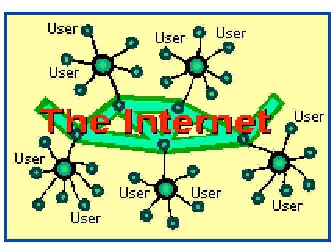


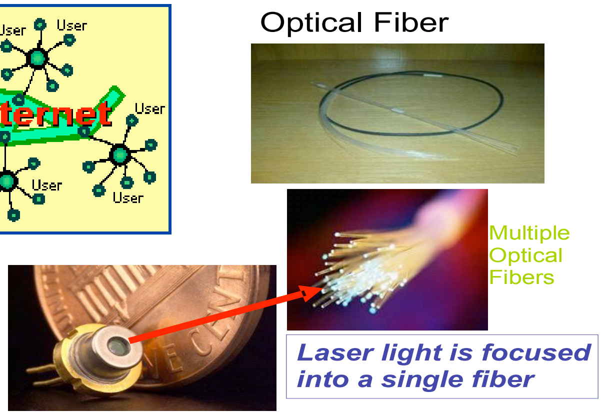
I mentioned laser printers. How many of you have ever used a laser printer? These printers work like photo-copiers, except that light from a laser diode writes the image on the photo-sensitive drum. The light causes charges to build up on the surface, which attract the carbon particles in the toner. Rolling between hot rollers fuses the carbon to the paper, creating the notes that I'm using in this talk.

Most of you have a laser in your house. Do you know what technology I'm talking about? CD and DVD players. These devices have tiny semiconductor laser diodes, just like in the laser pointer, that read holes impressed in the shiny CD's and DVD's that are now ubiquitous. How well I remember the first time I heard a CD player! It was a revolutionary technology compared to cassette tapes – the sound was so perfect. The secret is that it is digital. Laser light is reflected from the shiny side of the CD, except when tiny holes ruin the reflectivity. This gives the "ones" and "zeros" that are read as the digital signal that creates exceptionally high quality sound.



Where else is laser technology crucial? How many of you have used the internet? The back-bone of the internet consists of optical fibers – thin glass wires through which laser light passes. Each glass fiber can transmit light modulated with thousands of phone calls. Thus laser diodes are crucial to the internet.





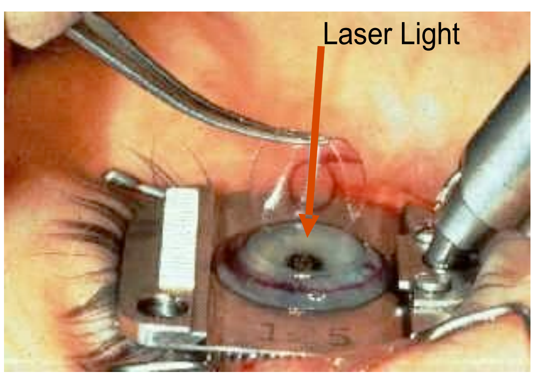
Even if you don't use the internet, when you make a long distance telephone call, the signals go down similar fibers in the form of light that was emitted from similar lasers. The laser light that goes down these glass optical fibers connects us all together throughout the whole world. The glass fibers are imbedded in cables under the oceans, beside railroad tracks, alongside gas and oil pipe lines, and in special lines dedicated to the telephone system. All these fibers send messages in the form of light that was produced by lasers.

How many of you have used cell phones? Mobile phones communicate with cell towers by radio frequency signals, and the cell towers are connected by lasers and fiber optics.

Probably the first laser you personally saw was in supermarket scanners. Lasers scan bar codes and the information is sent to computers that both register the price you will have to pay, and also record the purchase for inventory purposes.

You all have the results of lasers in your pockets: lasers are used to make the holograms on your credit cards to make them hard to counterfeit.

The applications for lasers that I've talked about so far all relate to information technology – communication and storage of information. Another application is lasers and medicine.



How many of you have had LASIK eye surgery? Or know someone who has? The process is keratotomy, the resurfacing of the cornea to correct for astigmatism, as well as near and far sightedness. Lasers have replaced knives, as they are finer, can be computer controlled, and are sterile because they don't touch the eye.

Such precision in surgery was a long time in coming. I remember in the late '70's, when I was at the Center for Laser Studies at University of Southern California. We had a project in collaboration with the USC Medical School. One of our research scientists was giving a seminar when suddenly he received a call from the hospital. A patient with hemophilia had lost a tooth and was bleeding and it would not stop. Treatment with a laser was needed to stop the bleeding, but it took a PhD to run the laser. It was the first time in my life that I felt that my research was actually saving lives. An exciting day! Today such lasers can be automatically computer-operated, making them safe and controllable for use by MD's, not PhD's.

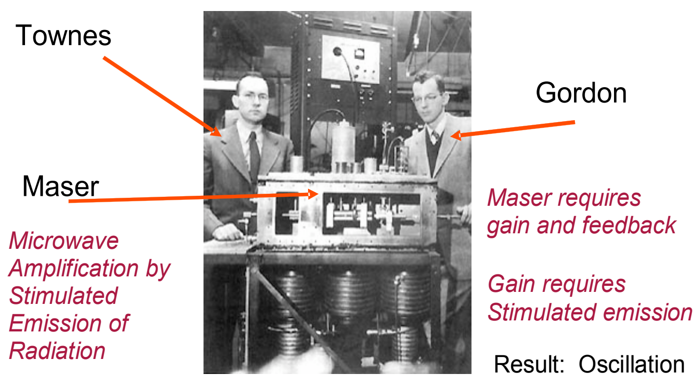
III. The story of lasers.

The history of lasers can tell us a lot about what it takes to get to a practical technology from an original idea. To understand the story of lasers, it is necessary to go back before them to masers, which were an outgrowth of the technology developments of WWII.

The field of masers and lasers is called ***quantum electronics***. This was a brand new field after WWII and came from combining quantum physics and electronics. Before WWII, physics and electrical engineering were very separate fields. However, during WWII, many physicists were drafted into working on practical problems to help the war effort. Radar was one of these efforts. Radar is the use of radio waves to track airplanes. Charles Townes worked on radar during the war, hoping to extend radar to microwaves, rather than radio waves.

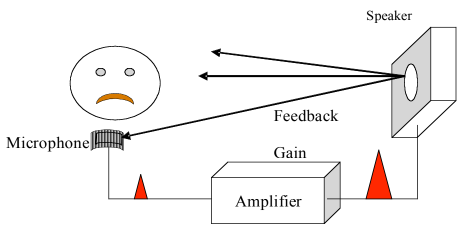
After the war Townes and others with joint experience in both physics and electronics began to see how they could use atoms and molecules to do what electronics had done.

In 1951 Townes had the idea to make a microwave oscillator. This was a device that would use molecules to emit microwaves. From electronics Townes knew that an oscillator requires gain and feedback. From physics he knew that he could achieve gain by the process of stimulated emission and feedback by putting the microwaves in a box. MASER is an acronym for Microwave Amplification by Stimulated Emission of Radiation. The first maser was built with Townes and his graduate student Jim Gordon.



Most of you know about oscillators, although you may not realize it. How many of you have heard a sound system emit a loud shriek? This is an

Oscillation from gain and feedback
Example: sound systems



Result: a shriek!!

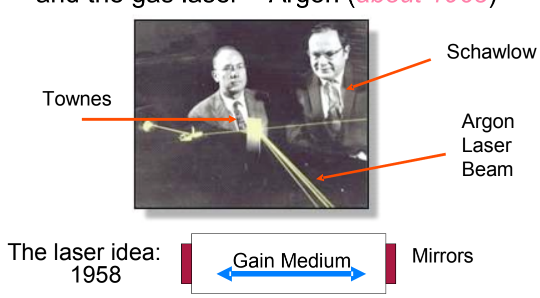
example of oscillation. If a microphone is placed to pick up some of the signal from a loudspeaker, this is called *feedback*. That feedback signal will get gain from the amplifier and become much stronger. Then it is emitted as a much louder signal. Some of this louder signal is again picked up by the microphone, and amplified even further. This is a run-away effect, limited only by the characteristics of the amplifier. The sound system gives out a shriek whose pitch depends on the amplifier and not the original sound. This combination of feedback and amplification is just the oscillation process that occurs in masers and lasers.

No one but Townes was working on creating an oscillator for microwaves and most people didn't think it would work. Even if it did, what would people do with this weak source of microwaves? Much better sources had been developed during the war. But Townes had the basic curiosity of a scientist. He, along with his graduate student and post-doc, made it work.

Eventually the technology was improved enough to operate as a very high quality microwave amplifier and was used to measure the 3 degree black body radiation from space, proving to astronomers the existence of the big bang and providing a Nobel prize for Townes' student Arno Penzias.

The idea for the laser took several years after the invention of the maser, because how to extend the ideas into the visible was not obvious.

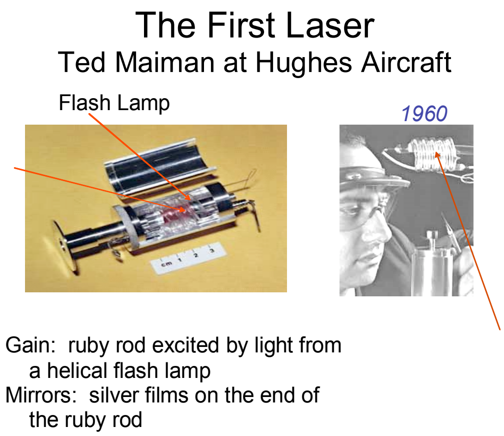
Charles Townes and Art Schawlow
and the gas laser – Argon (*about 1963*)

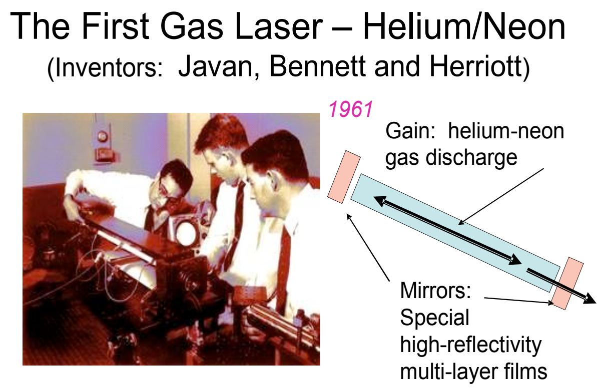


In 1958 Townes and his brother-in-law wrote a paper describing how to make a laser. They proposed to use mirrors to provide the required feedback. This photograph shows them with an argon laser that was invented about five years later.

After the 1958 theoretical paper, the race to make a laser was on. Who would be the first to demonstrate success? The race was won in 1960 by

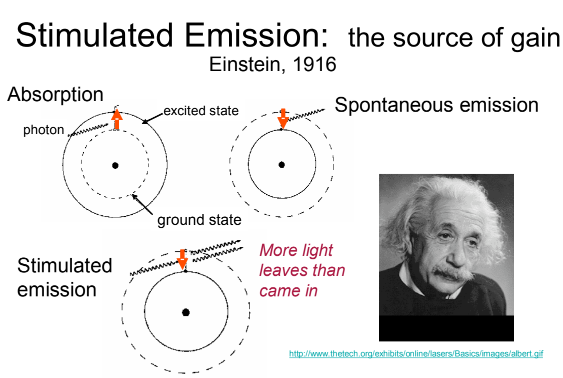
Ted Maiman, at Hughes Aircraft. He made a ruby laser: a ruby rod about 3 cm long and 1 cm in diameter was mirrored on each end. This was inserted into a helical flash lamp as shown.





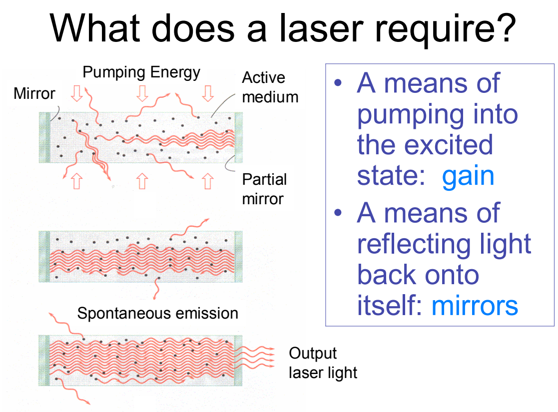
The ruby laser was followed soon after by the gas laser, a mixture of helium and neon. This is an interesting laser because it was the only one that was fully predicted theoretically, and yet in order to work it required the development of a new kind of mirror with high enough reflectivity.

Stimulated emission is how gain (amplification) is produced. The concept was introduced by Einstein in 1916. Consider how light interacts with atoms and molecules. You know about absorption: pavement gets hot in sunlight because its atoms and molecules absorb the sun's energy. When an atom absorbs light, the electron goes from a ground state to an excited state.



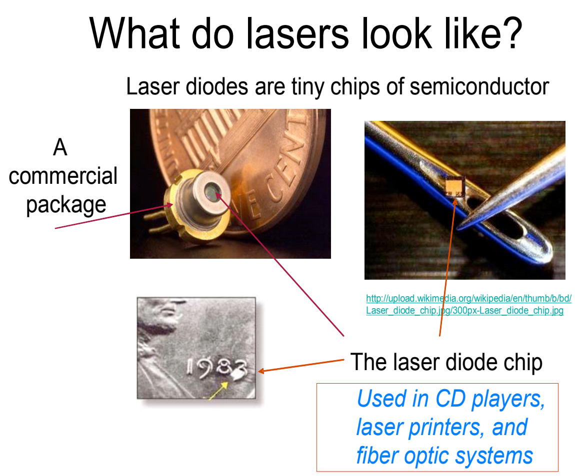
Emission is a process you also know. Fluorescent bulbs give off light because atoms in the coating on the glass emit light when excited by the gaseous discharge inside the bulb. The process of emission that you are familiar with is called "spontaneous emission." If atoms or molecules are excited by the discharge, at some time later they will give up their excitation, at a time of its own choosing. In the atomic picture, the atom goes back down to its ground state.

But Einstein realized that to explain how atoms and light interact, it was necessary to add a third process: ***stimulated emission.*** This occurs when light enters atoms that are already in their excited state. They are stimulated to emit their energy as a new photon that is identical and adds to the old photon. This means that stimulated emission creates the gain that a laser needs.

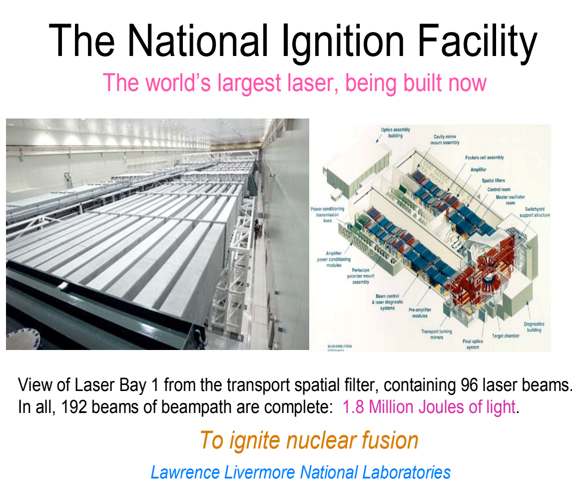


A laser requires gain and feedback. Gain, or stimulated emission, requires a means of pumping the atoms into an excited state. When everything is done right, bright light comes out of the laser, which has become an oscillator for light.

While all lasers work on the same principle of stimulated emission and feedback, their characteristics differ dramatically. What do lasers look like? You've seen the ruby laser. The rod was surrounded by a flashlamp to provide the pumping. You've seen the gas laser, with a gas discharge tube providing the gain. The first gas laser was HeNe, used in supermarket scanners. Later on, argon and krypton lasers were developed, the lasers used in laser light shows.



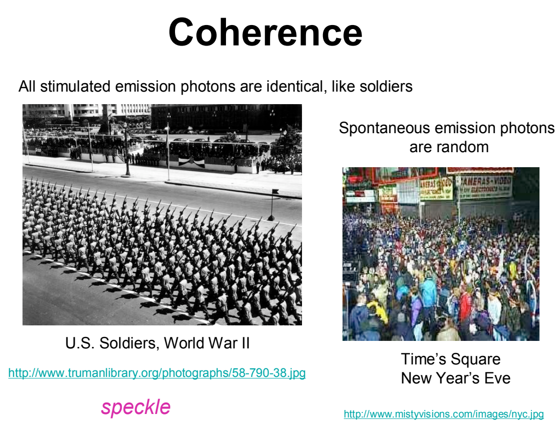
The world's smallest commercial lasers are semiconductor diodes, tiny chips like the one in the laser pointer, about the size of a grain of salt. The pointer needs also a lens and a battery. These laser diodes are also used in CD players and fiber optic communication systems.



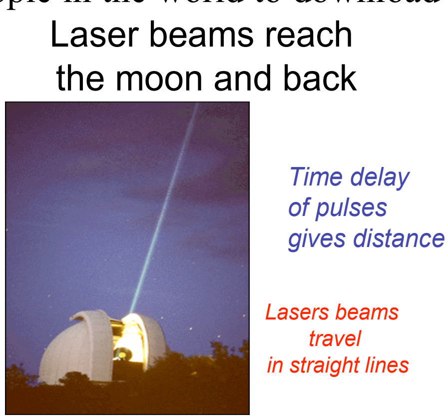
The largest laser, at least in this country, is the National Ignition Facility in Livermore, CA. In the

NIF, 192 laser beamlines direct 1.8 MJ of laser energy onto targets. The purpose is to simulate nuclear fusion, since weapons testing is no longer allowed. Do you see the tiny man in the picture? That is a big laser!

The laser has a wide range of capabilities. The special property of laser light is that it is "coherent," which we'll describe in a minute. Another capability is that it has enabled researchers to reach new realms of stable frequency. In fact, lasers now provide the stable reference for frequency standards, one part in 10^{15}, which corresponds to 15 minutes in the life of the universe, or a millionth of a second in your lifetime, or one second in the time since proto-humans first appeared on earth. Lasers can also emit ultra-short pulses, enabling ultra-high-speed communications, with the potential for all people in the world to download movies simultaneously over one glass wire.

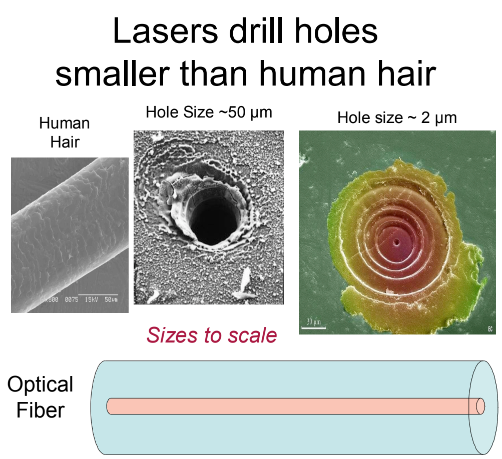


Long distance communications include signals traveling around the earth without stopping as well as to the moon and back. Pulses of light are so short (attoseconds) that they can resolve the time it takes the electron to move across a molecule. Lasers can be so powerful that they can initiate nuclear explosions, or be so small that they can be cubes only a half-wavelength on a side.



What makes the laser so exceptionally useful? The light coming from a laser has very different characteristics compared to ordinary light. The property of *coherence* describes light in which all photons behave in an identical manner, because stimulated emission makes all the light travel in the same direction with the same phase. This property leads to a number of important applications. We can understand how powerful coherence can be if we compare the identical marching of soldiers to people milling around Times Square. When soldiers march in unison, the rhythmic beat of their feet can become impressive, and they can be controlled with a single order from their commander, while a disorganized crowd, like ordinary light, can be hard to control.

Coherent light can be made directional, such as this laser pointer. The directionality of lasers is much better than the best search-light. The very first moon landing placed a reflecting mirror on the moon, and a laser beam was shone to the moon, reflected, and the signal picked up back at earth. This is directional! The time delay between when the pulse was sent out and when it was received allowed the distance to the moon to be measured to incredible accuracy, the kind of accuracy was needed to calibrate what would become the GPS system that many of us now use for navigation. This directionality of lasers is regularly used by surveyors.



Coherent light can be focused down to very small spots. We know that focusing sunlight can start a fire. When I was a graduate student we focused ruby laser beams to blast holes in razor blades. This was a way of measuring how much intensity you had: how many razor blades could your laser blast through? The holes were smaller than the diameter of a human hair. With careful control, the hole can have a diameter smaller than the core of a single mode fiber. Focused laser beams are used for a variety of manufacturing applications, and that very large building-sized laser what I showed, the National Ignition Facility, relies on the fact that all the light generated by the huge laser can be focused to a tiny spot that enables nuclear fusion to be initiated. Focused laser beams can be used for laser surgery. And microscopes can be made with lasers. Recent research efforts have enabled light to be focused down to spots much smaller than a wavelength.

Coherent light also demonstrates the phenomenon of interference. The best explanation of interference is to think of the spreading ripples on a pond caused by throwing in a pebble. When the ripples hit the edge of the pond, they are reflected back, and the pattern becomes altered by the interference between the original wave and the reflected wave. The two waves interfere. The interference pattern between a laser beam and its reflection can be measured, and from this engineers can learn details about the reflecting surface, or the medium through which the light has passed. This has a wide variety of applications in non-contact measurement, or non-destructive testing. Distance and/or motion can be measured. One of the most subtle interferometers measures motion in the earth's crust, in order to predict earthquakes (we hope). The most sensitive interferometer is a current effort to measure gravitational waves to understand the general theory of relativity, an effort called LIGO. (laser interferometric gravitational observatory) This is the world's largest interferometer.

LIGO Interferometer
for measuring gravity waves

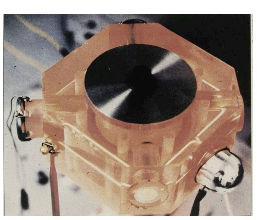
near Baton-Rouge Louisana

Monochromatic light

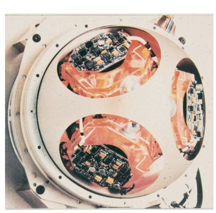
Interferometric measurements usually require the laser light to be a single color, which we call monochromatic. Light can be so monochromatic that it is accurate to one part in one thousandth of a billion billion, which call 10^{-15}. A thousand billion billion light waves go by before the light loses its coherence. An important use of this highly monochromatic property is the laser gyro. Every time you fly on a Boeing 767 or more modern plane, you are relying on lasers to tell the pilot the path of the airplane. A commercial laser gyro has three ring laser gyros. These are lasers whose light travels in a ring. The clockwise light and counterclockwise light will have slightly different colors, or frequencies, if the airplane is rotating. This is called the Sagnac effect. The measurement of these two different colors tells the pilot the trajectory of the airplane. The laser gyro replaced mechanical gyros because because the laser has no moving parts. It is more reliable and does not require waiting to spin up.

Ring Laser Gyro: *Sagnac Effect*

Honeywell



One gyro

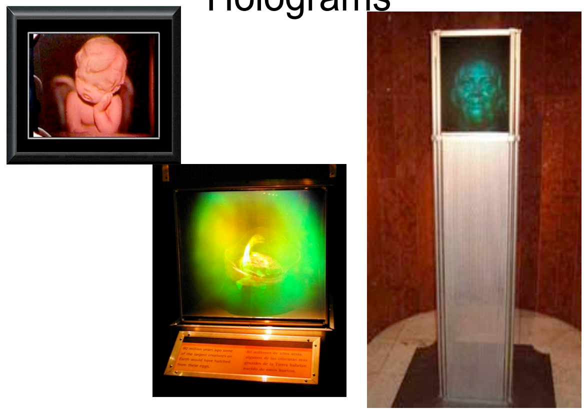


The 3-gyro system

Monochromatic laser light
Different frequencies determine rotation

Interference of laser light also creates holograms, some examples of which are shown here. It is especially eerie to see a hologram of a person. The three-dimensional property of the hologram makes it appear as if the person were really there.

Holograms



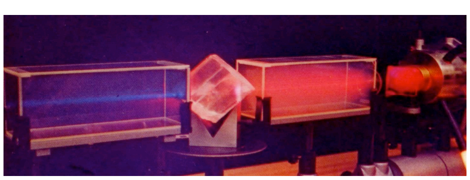
IV. Return to History

Getting back to history: The years between 1962 and 1966 were incredibly exciting for the field of lasers. When Townes moved to MIT from Columbia in 1961, there were only two lasers: the pulsed ruby and the monochromatic, continuous HeNe (which wasn't yet operating on visible wavelengths). I began graduate school at MIT in fall of 1961, while Townes was Provost. I experimented with the second commercially sold ruby laser, originally alone, and then with another graduate student, Raymond Chiao. Because Townes was busy with administration, the two of us were his only graduate students, but we saw him often, as long as it was after 5 PM!

It was an exciting time. New lasers were being invented almost monthly. Important new lasers were: diodes (miniature), argon (visible), carbon dioxide (very high power), excimer (ultra-violet), dye lasers (tunable), pulsed (Q-switching and mode-locking).

The technology was so new that few experiments had been done. It was not difficult to make revolutionary discoveries. The field of our research was called "nonlinear optics." Normally, when light goes through matter is can be absorbed, but is otherwise unchanged. That's why you can see the outside through a window. The process of nonlinear optics was a new one, made possible only by the high power of the new ruby laser. When we pointed the laser through materials, strange and wonderful things happened. First, new colors came out. Colored glass does not change the color of light – it merely

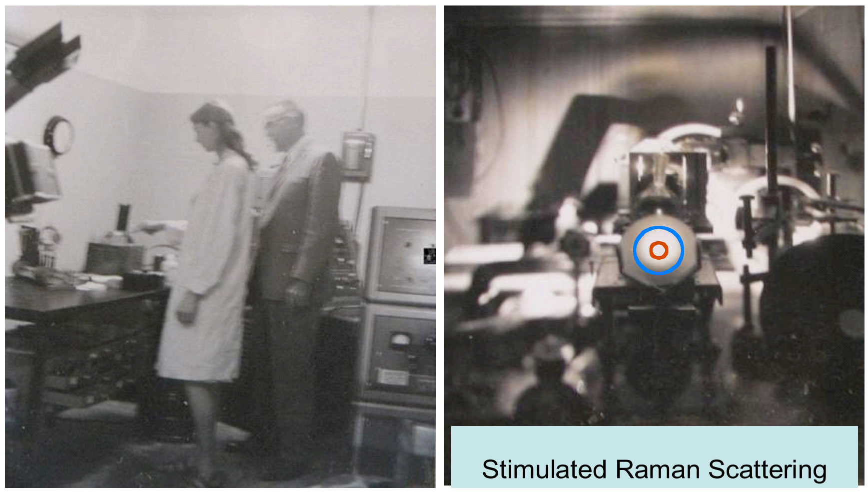
Nonlinear optics
Second Harmonic Generation



Laser beam enters a crystal of ADP as red light and emerges as blue

fy.chalmers.se/.../Photonic/information.html absorbs some colors of sunlight, allowing other colors through. But with nonlinear optics we obtained new colors. The first such process was called Second Harmonic Generation, in which special crystals known as ADP could turn high power red light into blue light. This phenomenon was reasonably well understood when I began graduate research.

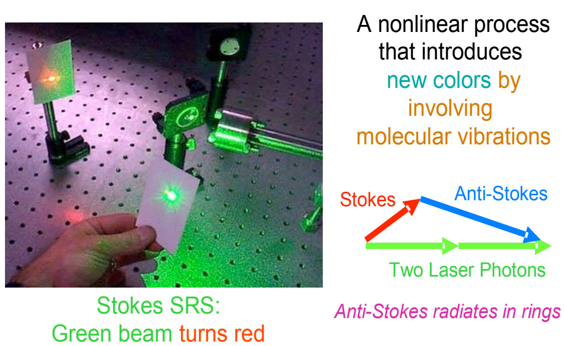
MIT Laser Laboratory, 1964



There were, however, other nonlinear optical processes that were not fully understood and I chose to work on them. Intense light from a ruby laser, sent through a cell of liquid, was converted into new wavelengths by a process known as "stimulated Raman scattering."

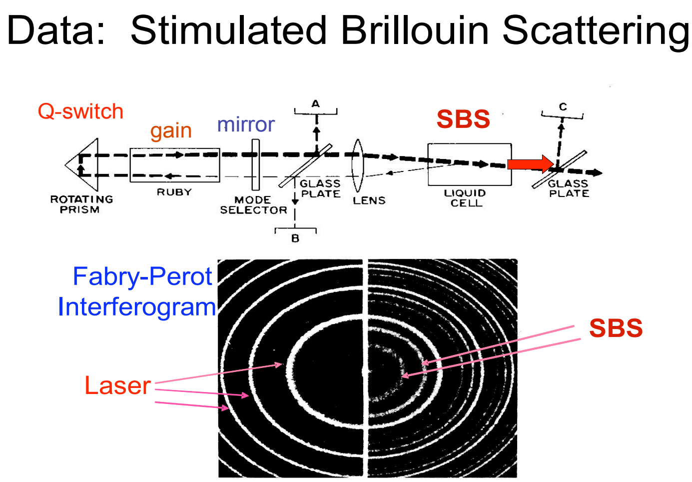
The weak effect of Raman scattering was well known in spectroscopy and had led to a Nobel Prize by this famous Indian. But it was a very weak effect. The laser caused an intense nonlinear process in these liquids, comparable to the stimulated emission of lasers. Intense incident light set up molecular vibrations within molecules of a liquid such as benzene, and the process caused the light to change color, both to longer (called Stokes) wavelengths, and to shorter (called anti-Stokes) wavelengths. This process was not well understood – the anti-Stokes light came out in angles that did not agree with theory. My thesis involved discovering that these angles did not agree, and coming up with a new theory that explained them.

My PhD research: Nonlinear Optics
Stimulated Raman Scattering



A similar effect, stimulated Brillouin scattering, was predicted and later observed in the same liquids. This was another part of my thesis research.

A story from graduate school will tell something about how research is done.



Soon after I got my first ruby laser, I put a cell of benzene in the way of the beam and measured an output that I didn't expect at port A (in the diagram). It appeared as if light was coming from the benzene back into the laser, experiencing gain there, and being re-emitted into the beam at A. Naturally I went to tell Dr. Townes, but it was completely unexpected. I was a new student and not very confident about my results. He couldn't explain it and decided that it must be my experimental technique. I knew that it wasn't, but didn't have the slightest idea what to do. So after a week I let it drop.

Two years passed. Townes had the idea for Stimulated Brillouin Scattering, which was observed by my fellow graduate student in a crystal. But I was still working on benzene. One day Townes came into my laboratory, noticed some anomaly in my data, and asked what it was. I said I didn't know, I thought it wasn't important, but said I'd look more closely at it. It turned out to be Stimulated Brillouin Scattering in benzene. And once I'd investigated it closely, it explained exactly the data I'd observed two years earlier! The diagram is from the paper I ultimately published.

What's the lesson? You can't understand new phenomena until the time is right. We hadn't understood enough (and I was too new a graduate student) two years early. Ideas need time to come to fruition. The second lesson is that I should have looked more carefully at the anomaly I had two years later.

A third phenomenon that we observed and explained was self-focusing, in which an intense beam will focus itself as it travels along in a nonlinear liquid. This leads to a second story about my research. After we predicted the effect, I was eager to measure it. I suggested to Dr. Townes that my laser output was not very uniform and that I should introduce a pinhole so that the collapse of the beam would be easier to observe. Dr. Townes was convinced that the effect would be so large that a pinhole wasn't needed. It turns out that he was wrong. As a result, the first observation of self-focusing was at Harvard, where a smooth beam was used. After I introduced a pinhole, I observed the dramatic results shown here. I wish that I'd originally had the confidence to perform the experiment that my gut told me I should and not wait for approval from my professor.

The message of these stories: the professor is right sometimes, but not always. Graduate students, particularly women graduate students, need to have more confidence.

Now I'll tell a little side-note. People ask me how I got to work with a Nobel prizewinner. When I began at MIT I was working for someone else. I was miserable and went home crying every night. I almost dropped out of graduate school. Why did I stay? Even though I was a Radcliffe graduate (Harvard) the only job open to me after graduation in 1961 would have been as a secretary. However, a graduate student made as much money as a secretary, and it was more fun! So I hung in there. I looked for a new advisor and there was this guy called Townes who was new to MIT and looking for a student and I was available. Two years later he won the Nobel prize and I knew that I'd chosen well. My problems with graduate school were apparently not me, but my first advisor. The message, particularly to women students, is: don't always blame yourself if you're having a tough time. And look for opportunities to change your circumstances if they're not going well.

Townes was very supportive. I should also add that I was married, to Gordon Garmire, who was also a graduate student in physics, and he was very supportive. When I thought about quitting, he encouraged me to hang in there.

Like many graduate students, my project had a rough time for a while. I had given myself the task of explaining why SRS did not come out at the proper angles. It was only by good luck that I discovered the answer. However, while I was discouraged I got pregnant. So it was a race between baby and thesis: it was essentially a tie. I proof-read my thesis in the hospital and defended two weeks after Lisa was born. I then went home to raise my child, like a good mother of the sixties. But I lasted only a month. Somehow new babies weren't as exciting to me as working on lasers with a Nobel-prize winner. I begged Townes to take me back as a post-doc, which he did.

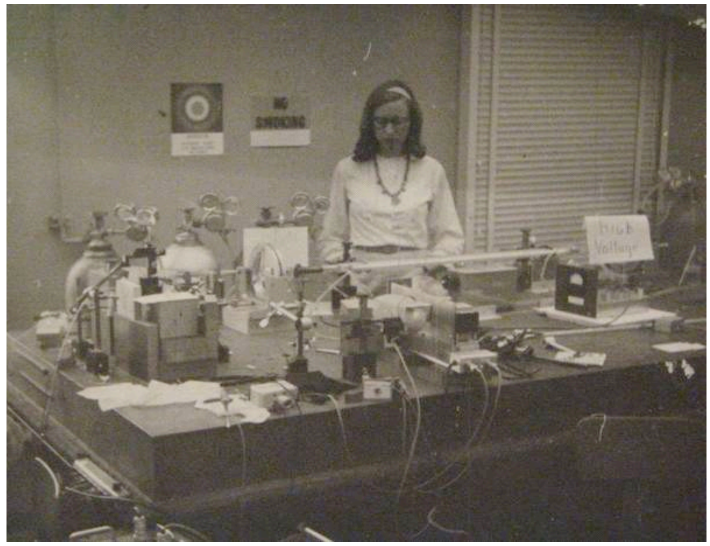
Let's get back to the story of the laser:

Very soon after the ruby laser was developed, researchers at Bell Laboratories produced a gas laser. And three different laboratories produced the laser diode, made out of semiconductor material. Each of these lasers had very different properties and they were eventually put to very different uses. This was followed by a whole variety of other lasers.

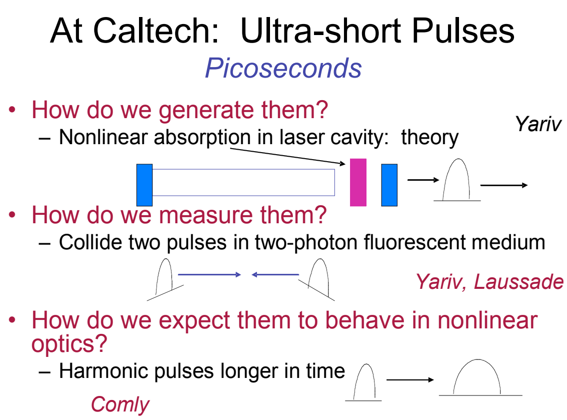
Was the race for new lasers science or engineering? The maser had begun with the thought that perhaps an amplifier could be practical, but with no specific amplification goal in mind. There did not seem to be a need for light amplifiers. What would one do with a light oscillator? The one application that was clearly in the minds of a number of people was the theoretical understanding that communications at optical wavelengths would be able to send many more telephone calls than communications at microwave wavelengths.

V. My life at Caltech

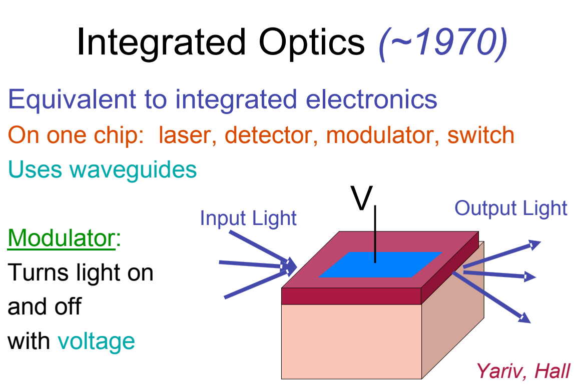
On this philosophic note, I left MIT where I was one of only two women in graduate school in Physics at the time and moved to Caltech where women students were not allowed, nor women faculty, and I was one of a very few women post-docs in all of Caltech. At Caltech my husband was an assistant professor and I was a part-time post-doc while raising my daughter. After two years I had a second daughter. I was able to split my life between raising my children and doing research. All the money that I earned went to pay for the housekeeper who took care of my children while I worked from 10 to 3 every day.



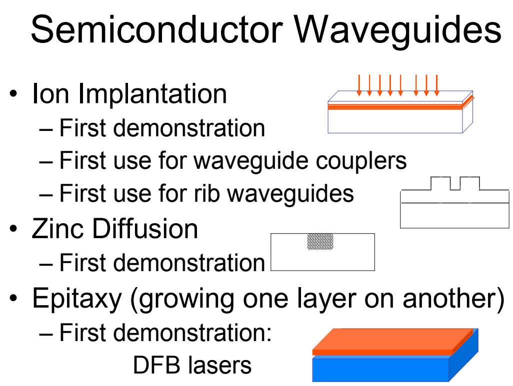
Lasers don't have to be monochromatic, or single frequency, operating continuously. The first ruby laser, of course, was pulsed. The Heisenberg uncertainty principle tells us that if light is pulsed it cannot be monochromatic and vice versa. Our research involved creating very short pulses from continuously pumped lasers. If a laser has the potential to operate over a range of frequencies, these can be locked together to make ultra-short pulses. This was discovered while I was still a graduate student. At Caltech I worked on new ways to generate these ultra-short pulses, working out the first theory on how a nonlinear absorber within a laser cavity produces short pulses. Then I worked on ways to measure them. Two pulses can be collided and a process of two-photon fluorescence will occur brightest where they overlap. The length of the pulse in space determines its length in time, by the velocity of light. We measured pulses about 7 psec long, or about 1 mm in space.



About 1970 the concept of integrated optics was introduced. The idea was to integrate onto one chip all the functions that one wanted to include in a light circuit: lasers detectors, modulators, switches. The concept could be thought of as analogous to integrated electronics, where many transistors, diodes, resistors and capacitors can be integrated onto



one chip. For integrated optics the light will travel around the chip in waveguides. We were among the first to modulate light in a semiconductor waveguide. By changing a voltage across the waveguide, the light was modulated from off to on.

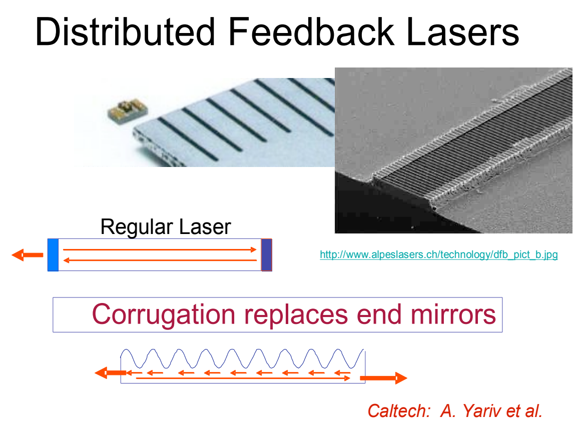


The challenge at that time was how to make semiconductor waveguides. I became very interested in this effort. I had been a post-doc for several years and Yariv asked me to find my own funding. I wrote a proposal to the NSF, based on the novel idea of using ion implantation to make waveguides, and as a result obtained the first program funded in integrated optics. However, Yariv was the PI and not me, because of Caltech's rules. At that time Caltech would not allow women to become faculty members nor allow anyone who was not a faculty member to submit proposals in their own name.

Nonetheless, the idea worked. We were the first to use ion implantation to make a waveguide, then to use this technology for waveguide couplers and channel waveguides, by introducing ribs on the surface through ion milling.

Another approach that I introduced was to diffuse an impurity into semiconductor substrate to create a waveguide. The most practical technique, however, turned out to be to grow a crystalline waveguide layer on the semiconductor substate. This process is called epitaxy, and at that time it was "liquid phase epitaxy," in which a liquid melt was drawn onto the top of the substrate, at high heat, and then the heat was reduced so that the waveguide layer grew out onto the gallium arsenide substrate.

Several companies were working on this process and Yariv wanted to introduce this technology to a university laboratory. I made a grand tour of Bell Laboratories, Lincoln Laboratory, IBM and RCA laboratories in order to learn as much as I could. When I visited RCA laboratories, they were not intending to give me any real information, because of industrial security. They had no idea who this post-doc from Caltech was and did not intend to spend much time with me. However, I was well-prepared technically. And the date was the early '70's, a time of mini-skirts! Apparently I wowed them because they kept me all afternoon and showed me everything they were doing. In later years they teased me that it was only because of my miniskirt that they were so helpful! So it isn't always a bad thing to be a woman scientist or engineer!



Once we were up and running at Caltech with our liquid phase epitaxial system we were able to do some exciting research. Most important was the first demonstration of distributed feedback lasers in semiconductors. These lasers have become incredibly important for telecommunications. Instead of mirrors on the end, as in a regular laser, corrugation is placed along the path of the light, causing mini-reflections at each depression. These mini-reflections build up to a large reflection only for one particular color. Thus these DFB lasers control the color of the light coming out of the laser. In fact, they are the only useful way to do that in semiconductor lasers.

I've made it sound like my research life was straight-forward, both at MIT and at Caltech. Just be there first and do good work. However, things weren't that easy for me. I was lacking in self-confidence. This isn't unique to women scientists, but much more common in women. I was a post-doc while my husband was rapidly rising through the ranks in the Caltech Physics department. There were no women on the faculty. In fact, there were no women students when I arrived. The first woman to get tenure had to sue to achieve it – and it was in the English department. In fact, there were no women in the physics department before 1990 and there still are no women in the Applied Physics Department, which is where I was a post-doc.

So it was hard to keep my self-confidence. I tried teaching, an advanced mathematics course where they really needed someone. But it was really hard! I had a new baby and was worried what I would do if my housekeeper got sick. (It was unheard of in those days that a father would stay home with the children.) Besides, I was no whiz at math and there were some real Caltech geniuses in my class. This just lowered my self-confidence further. And during this time our research at Caltech had pretty much reached a stand-still. We had not yet ventured into integrated optics. Yariv was spending his time writing several textbooks that would make him doubly famous.

I had had some new ideas about short pulses, but I was still insecure. I'd just had my second baby and was working part time. Money for research was plentiful and individuals in the government begged me to take money because Yariv said he couldn't use any more. But Caltech's rules were that as a post-doc I had no rights to my own research funding, and Yariv was not interested in pursuing research in ultra-short pulses. So I was unable to continue working in this area.

So after a couple of years at Caltech I got side-tracked from research into spending time on laser art. Another characteristic of lasers is that they are pretty!

Laser Art

Laserium: laser light show

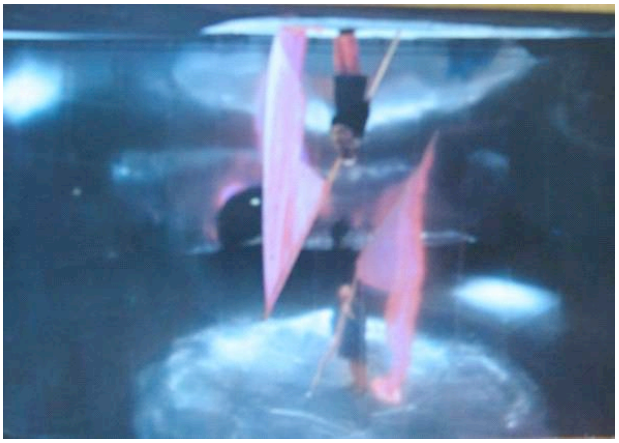
Laser Light Wall

Laser Beacon

Caltech Moon Landing Celebration

On TV at art opening, 1970

This inspired several of us in the early days to make beautiful patterns with laser light. I was experimenting with these patterns in the laboratory at Caltech and met several artists who were also interested. We made a short film, and developed a laser light show. I incorporated a company that developed Laserium. In 1969, when men landed on the moon, I arranged an art event called the "Moon Landing Celebration" at Caltech. We built a laser light wall as one of the pieces. I also experimented with laser beam displays up into the sky. Today such events are illegal because they can temporarily blind pilots.



During those years of being involved in the art world, I worked with the organization *Experiments in Art and Technology* to design the world's largest hemispherical mirror. This was for the PepsiCola Pavilion at Expo '70 in Japan. This photo is turned upside down to show the upside-down real image of a woman holding a flag. To see what the mirror dome actually looked like, turn this photo upside down.

VI. My Sojourn in Great Brittain

The rest of my personal saga involves my husband and I and two children taking a year's sabbatical in 1975, going around the world with two children, and ending up in England where I worked at Standard Telecommunications Laboratory and undertook one of the first integrated optical experiments in Brittain. It was there that my experiment was sabotaged. I was the first woman and the first American to work in the laboratory and it was apparently too much for one of the old-time technicians. While I was out of the lab, he purposely misaligned my laser, thinking that I'd play dumb, come to him, and he could be the hero by re-aligning it. However, I'd worked on lasers since beginning my PhD and so I didn't ask for help. I tried to re-align it. But not knowing what he'd done, I was unable to do it. By then I'd fooled around with it so much that he couldn't align it either. No one, it seems, could get it to work. Finally he gave it back to me and said that I'd need to buy a new one. But I was undaunted. I took off both mirrors, got a second laser, and carefully aligned the mirrors one at a time. When I was done I announced "when I turn it on, it will work." And when I turned it on, it did work. He was so impressed that he admitted to our boss what he'd done. I found the reality of sabotage very hard to take. While it meant only the loss of a week's work to me, I can imagine what it meant to others who were more harassed than I was.

Coming back to California from our trip, my husband left me for the wife of another physics professor. I was now alone with my two children and I'd had enough of Caltech! I was invited to University of Southern California by Jack Marburger. You've probably heard of him. He's the science advisor to President Bush.

VII. My life at USC

It was at USC that I became an independent researcher. I now had an opportunity to raise my own research dollars and develop my own research program. This was a crash course in fighting for money, research space and graduate students. It wasn't easy, because it was all new to me. Fortunately, since I was on soft money, I did not also have to learn to teach at the same time. I only taught one semester, when a physics professor unexpectedly passed away.

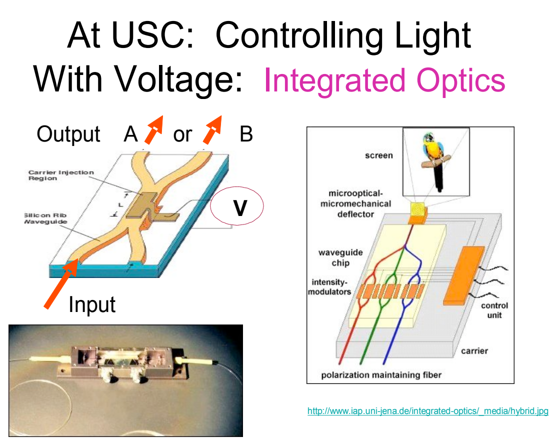
I received an NSF grant to work on infrared waveguides. It helped that I was a friend of the NSF program director, but I think the technical approach was interesting anyway. We got lots of interesting results, but didn't solve the problem of infrared waveguides. It still hasn't really been solved. People continue to use handpieces with small mirrors to guide CO_2 laser light for surgery and machining applications, rather than waveguides. The Dean at USC introduced me to a visitor from the Air Force Research Laboratory saying "This is one of our brightest young faculty members." I told him about some of my interests and it turned out that we had a mutual interest in integrated optics gyros. He offered to fund my research in this area. However, I was really more interested in non-linear optics. I was young and perhaps arrogant: I told him that I would work on his gyro problem if he'd first find me funding for my interests in nonlinear optics. He actually did this, and his last act before he retired was to provide me with half a million dollars of research funding. The message of this story is that it is really important to have powerful people behind you. Both the Dean and this research leader in the Air Force were behind me. Without them, I would still be begging for research dollars.

While I did, indeed, obtain enough funding to carry on my research, I became disenchanted with raising all my own salary through "soft money." So I applied for a regular faculty position. Fortunately, because of working in stellar laboratories, I had over 40 publications. I had also been careful to keep a few research projects in my name only. And I had been successful in raising research funding. Thus in 1979 I became a full professor with tenure, without having to climb the tenure-track ladder. My youngest child was now 11 years old and I could throw my heart into my career.

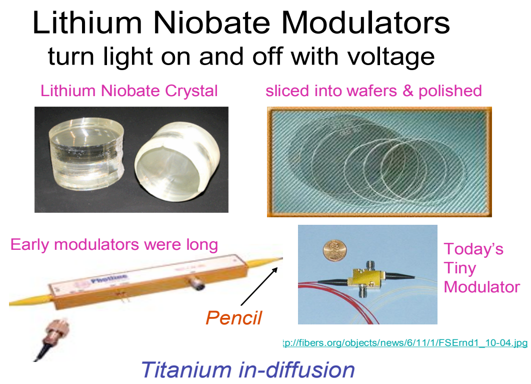
I should also say that in 1979 I married Bob Russell, the man to whom I have been happily married ever since and who has been incredibly supportive of my career. The picture shows us, along with daughters Lisa and Marla, at our wedding in Palos Verdes, CA. How do you like my '70's hair style?

My research interests at this point were in how to obtain more functionality with light. It is challenging to switch laser light. Laser light is transmitted very well – for example, it goes around the world in fiber optics – but switching it from one place to another and/or turning it on and off is very difficult.

Integrated optics can be used to switch light from one output to another. Alternatively, integrated optics may be used to turn light on and off. That is to modulate the light. Today commercial packages with such modulators, connected to optical fibers are readily available. People are even suggesting ways to use these modulators to make miniature displays for high definition TV and movies.

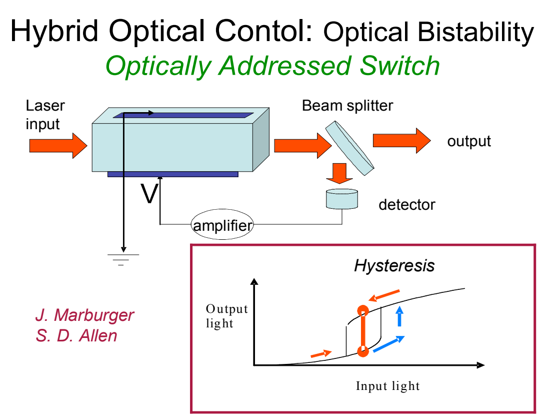


I joined the search along with others to investigate switches in the most promising crystal: lithium niobate. But much of my research was involved in identifying problems with materials and devices that needed to be solved before they could become practical. In this case, we demonstrated that light could cause charges to be created inside the modulator, causing the output signal to become unstable. This is called the photo-refractive effect and we were one of the teams who pointed out that the lithium niobate switch design at that time would not work. It took improvements in the material and in the switch design before the technology was perfected. Eventually it was, and now they are readily commercially available. One of my post-docs contributed in a major way to this technology, which became important in fiber optics. These devices have had a large market providing modulated



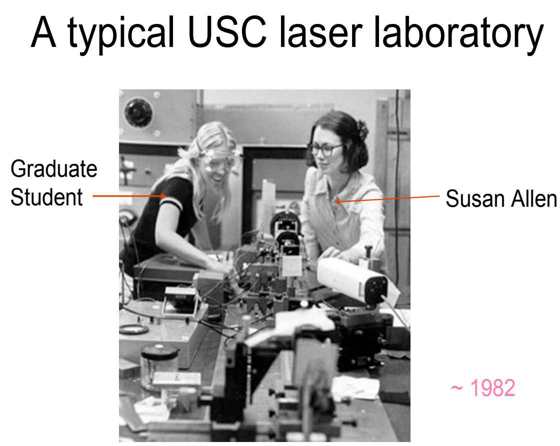
lasers for fiber optics cable TV. In fact, major research continues in this area: new designs and fabrication techniques have enabled them to be much smaller.

In the fiber systems used around the world, optical signals coming out of fibers are detected, turned into electrical signals, routed and used in turn to modulate another laser. The dream of many researchers was to find a way in which the signals could remain optical, even while they were being routed around through the internet. A characteristic of the internet is that information is sent in individual packets that carry with them the address to where they are going. You can think of each packet as envelopes in the US postal system. The dream was to have an optical system that would route each packet individually. The ultimate way to do this is to use nonlinear optics, but researchers weren't making much progress in this direction.



The approach that we introduced was a hybrid system, in which some of the light exiting an ordinary lithium niobate modulator is detected, and the signal is fed back to alter the voltage across the modulator. This simple hybrid device emulated the nonlinear optics devices, but was much easier to make. We demonstrated the self-switch concepts, and studied its transient properties. When extra light is added, as demonstrated by the blue arrows in the diagram, the modulator switches from its low state to its high state. The fact that there exist two stable output states for a single input state is the concept called BISTABLITY. This was a field of great interest for a while. Interestingly, this work was done with Jack Marburger, who is now Science Advisor to the President, and with Susan Allen who is now VP at Arkansas State.

Here's a photo of one of our laboratories at USC. This photo shows, by the way, how dangerous it is to take information off the web unless it is corroborated by other information. I found this photo when I did a google

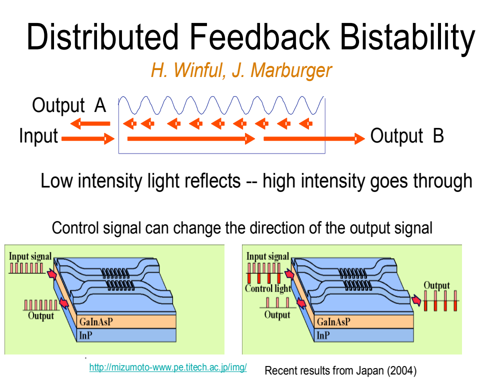


search for images of Elsa Garmire. USC put this image in a historical brochure, but attributed Susan Allen to Professor Garmire. Now it's on the web, wrong, for all time!

I made a point of hiring women and minority students and post-docs as well as the usual complement of males. I can't say the same for USC engineering school. I was the first woman on the faculty, out of about 200. While there for 20 years, I remained the only woman in my department, and only three other women were hired during the entire time. Since I left ten years ago, they have hired no women faculty to replace me in my department. It was not easy for women at that time. I published a paper with Susan Allen and this female graduate student. Faculty members teased me about three women on a paper – they wouldn't have thought a bit about three men on a paper!

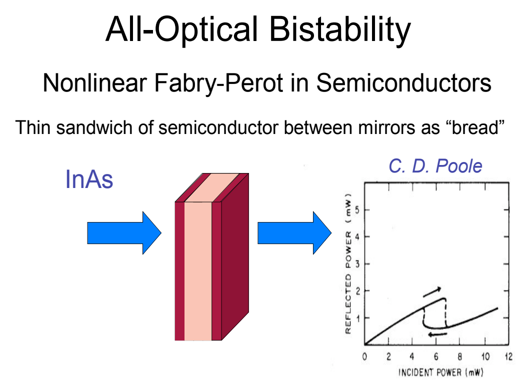
The 1970's were a time of great interest in the role of women in society, and people were beginning to wake up to the possibility that we might be able to contribute to science. I was very excited about our work and talked about it whenever I could. Typical of what life was like in the late 1970's, I received a phone call from the head of the Southern California Optical Society. He said "we've never had a woman give a talk to our group and we'd like to hear from you." He didn't say "we've never had a talk on optical bistability and we'd like to hear from you." I believe I gave a good talk, finished with a flourish, and asked for questions. The first was "I believe that I speak for all of us here when I tell you how threatened I feel to hear a woman who knows more than I do." What a shock! I'd thought they were listening to what I had to say. Instead they were thinking "woman, woman, woman!"

VIII. Back to science

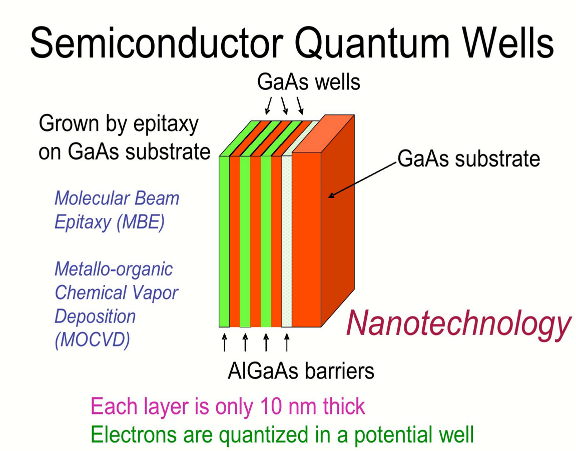


Perhaps the most important contribution we made during this time, however, was to develop the theory for nonlinear distributed feedback optical devices. This work was carried out by graduate student Herbert Winful in collaboration with Jack

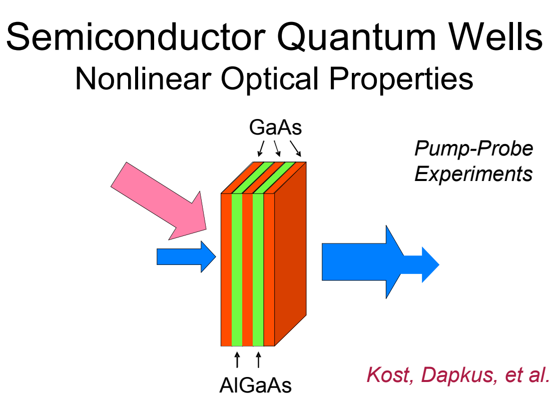
Marburger. Considerable work has been done since on these devices. Some very recent work from Japan is shown. The packets of light normally come out the left. When red control pulses are added to designated packets, those packets come out the end of the device to the right.



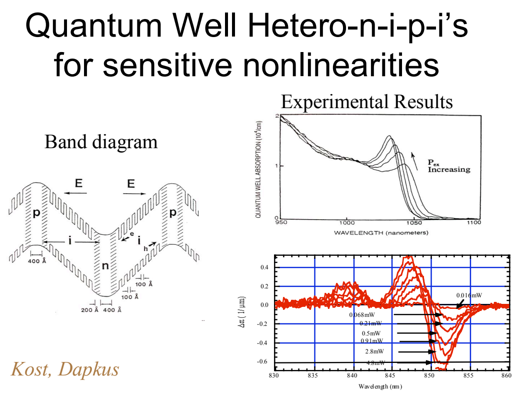
In an all-optical experiment, optical bistability could be observed by using thin plates of semiconductor that were coated with mirrors on either side. We were the first to do this at high contrast, using a reflective geometry.

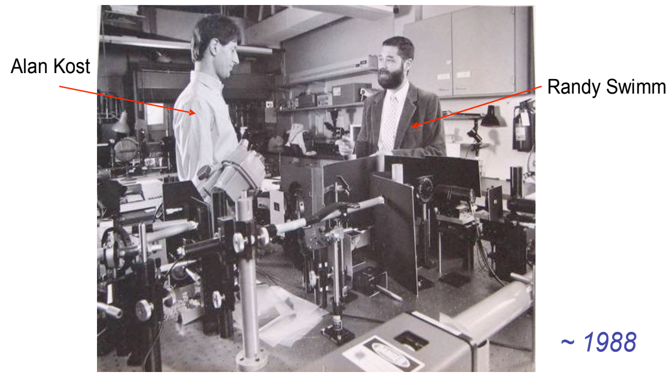


The use of thin films in semiconductors got us interested in semiconductor quantum wells. These are very thin layers of one semiconductor, here GaAs, sandwiched between barriers of another semiconductor, here AlGaAs. The GaAs layers form wells that quantize the electrons, giving them unique nonlinear properties that are much larger than would normally be observed.



Post-doc Alan Kost and my students and I measured these properties with experiments in which we introduced a weak probe beam and then an intense pulse of pump light. The signal from the probe increases after the pump pulse has caused a reduction of the absorption. We were the first to make such measurements in quantum wells grown by MOCVD (metallo-organic chemical vapor deposition) provided by Professor Dapkus at USC. We also introduced a new semiconductor structure – the quantum well hetero-n-i-p-i – that enabled nonlinear transmission with extremely small pump powers, the order of a few milliwatts – as obtained from this laser pointer. This gets a bit technical, however, so I'll only just mention it here. The structure and experimental data are shown in the Figure.





IX. The Legacy

I'm going to deviate from science into discussing what has happened to my former students. The purpose is to show how government and university investment in research pays off in the long-term economic well-being of our country. Nine of my students and post-docs have become faculty members. Susan Allen has become VP at Arkansas State, Herb Winful and Nan Jokerst have both become named professors at prestigious universities. Two more in the US and 4 abroad makes a total of 9 faculty members. I'm particularly proud that my two students have both won best teaching awards and have become fellows of several professional societies, as shown in the slides:

Where are my students/post-docs now?

- Universities:

Herbert Winful, University of Michigan, Arthur Thurnau Professor
Professor of the Year, EECS (twice)
State of Michigan Teaching Excellence
Fellow: OSA, IEEE, APS

Nan Marie Jokerst, Duke University.
J.A. Jones Distinguished Professor
Best Teacher in EECS
Fellow: OSA, IEEE

- •SongSil Univ. Korea
- •Chaio Tung Univ. Taiwan
- •Japanese Defense Academy
- •Frederick Institute of Technology,Cyprus

Post-Docs:
Susan D. Allen, VP for Research & Academic Affairs, Arkansas State
Ping Tong Ho, University of Maryland, Professor
Alan Kost, University of Arizona, Associate Professor

Six students have started successful companies and five others have influential positions in other's companies. Eigenlight's detector is used in almost every fiber optic telecom system, and I note that Millerd's products have won awards for creativity. Over the years the government has invested about \$5 M per year in my research, paying for my students, and the return on investment I estimate to be about \$15 M per year. A pretty good investment!

- Started companies
  - C. Poole, Eigenlight, CTO (10,000 Sq. ft. manufacturing) OSA Fellow

  - R. Pillai, Nuphoton, President, \$3.4 M annual sales (14th largest Indian-American manufacturer)
  - R. Logan, Phasebridge, President (\$2 M annual sales)
  - E. Park, LuxN, CTO (36 employees, bought out)
  - D. Magharefteh, Azna Inc. Chief Technology Officer
  - J. Millerd, 4D Technology Corp., CTO (R&D 100, NASA awards)

- Key positions in companies
  - T. Hasenberg, JDS Uniphase, Director of Wafer Fabrication.
  - K. Tatah, Cray Inc. Lead Optical Engineer
  - R. Kuroda, XCOM Wireless, Vice President of Engineering
  - S. Koehler, Phasebridge, VP of Strategic & Product Marketing

  - M. Jupina (MBA), Checkpoint Technologies, Sales & Marketing Manager

- Small start-ups and sole proprietorships
  - W. Richardson, Qusemde, CTO. (3 employees) (after research scientist at Stanford)
  - K. Liu, All-optronics, President (3 employees)
  - G. Hauser. Sole proprietor, microscopes
  - J. Menders, IPITEK, Principal Investigator
  - D. Tsou, consultant
- Government Service
  - A. Partovi (MBA), The Science Foundation of Ireland, Research Advisor
  - C. Mueller, Aerospace Corporation, 20-yr award; NASA awardee, 2003
  - M. Chang, Aerospace Corporation
  - K. Wilson, Jet Propulsion Laboratories
- Other
  - T. Papaiannou, Cedars Sinai Hospital
  - Erich Ippen, Industrial Light and Magic
  - M. Yang, retired (raising two children)

My other students are in a wide variety of positions. I note that Afshin Partovi is a research advisor to the NSF of Ireland, and Craig Mueller has won an important NASA award. Students have such diverse jobs as running laser research in hospitals and one student went to work in Hollywood. One of my students is retired and raising two children, but I imagine that she'll go back to work eventually.

I hope that you see how government investment in research produces human capital, as well as good technical ideas.

I mentioned earlier my dedication to making opportunities available for women and underrepresented minorities: here's a list of 13 – almost one-third of the total number of graduate students and post-docs I've had over the years.

My women/minority students & post-docs

- Katherine Liu
- Nan Marie Jokerst
- Mei Yang
- Jean Yang
- Grace Huang
- Susan Allen
- Kate Zachrewska
- Cao Mingcui
- Patricia Berghold

Herbert Winful
Keith Wilson
Wayne Richardson
Antonio Mendez

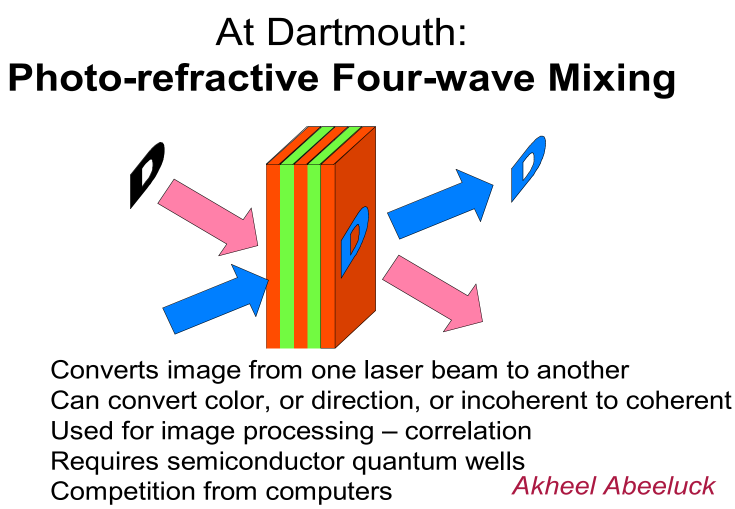
13 out of 45: ~1/3

My USC research group in 1990 is shown:

~ 1990

X. My Life at Dartmouth

What have I been doing at Dartmouth? When I came, I transferred a project from California that investigated the use of lasers to remove graffiti. A Nd:YAG laser has enough power to "zap" the paint off highway signs and concrete walls. We built a portable, practical system, but graffiti doesn't seem to be the problem in NH than it was in California, so we did not pursue this any further.



My first PhD research at Dartmouth was in the area of photo-refractive four-wave mixing. This is a process by which an image can be transferred from one laser beam to another. The new beam may be in a different color, or direction. One can even transfer an ordinary incoherent image to a coherent image. This enables image processing, such as correlation. That enables recognizing images such as handwriting.

The best devices use semiconductor quantum wells, as I described earlier. Akheel finished his thesis in this area, working in collaboration with a company called Coretek, but few practical applications have arisen yet, because computers get better and better for image processing. Akheel got a job working in fiber optics, and when the bottom fell out of that field in early 2000, he went to work for a company researching new kinds of lasers. This demonstrates that the actual details of one's PhD thesis don't matter very much. If you've learned a variety of skills, lots of jobs are available. In my area the skills you learn are the ability to do experiments, to carry out simple analytic models, and to do computer simulation. Akheel could do all three, increasing his usefulness to a company.

Philip Heinz carried out his thesis research on ways to detect surface vibrations optically. The usual way is to use an interferometer, as I talked about earlier. However, he came up with a much simpler method that does not require an interferometer, which must be carefully aligned. His unique detector uses a four-point probe on photoconductive material. If you're interested in the details, you can contact him. Our research in this area now is to develop a detector that can measure faster vibrations, up into Megahertz.

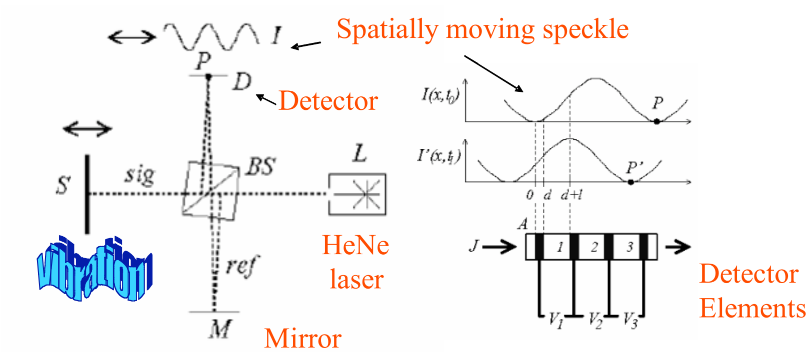
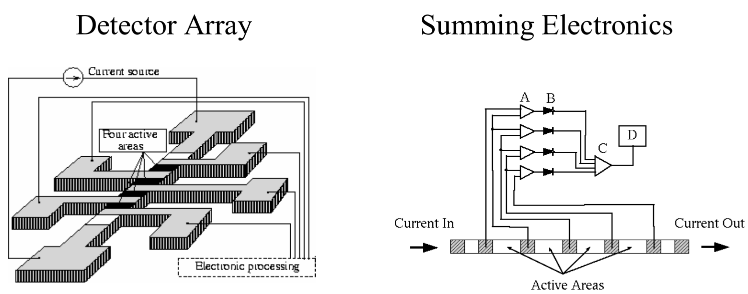


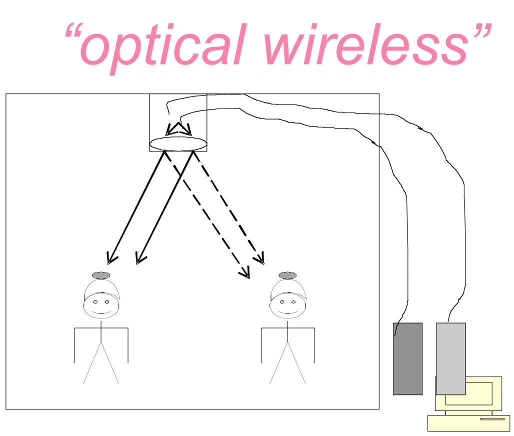
Diagram of experimental setup is shown. Detector D has a linear array of four elements, as shown, that monitor different spatial parts of the speckle.



Researching ways to measure faster vibrations

Details of the detector array geometry and the electronics used to sum the signal are shown. Research is under way with two new graduate students to increase the detector's speed.

The latest research we are working on is optical wireless communications. There are times that the bandwidth must be much larger than the usual rf wireless can accommodate. An example is in simulation environments, such as the military require, or might be used in amusement parks. Our research in this area is the pointing and tracking system.



High bandwidth needed for simulated environment
Military training, amusement parks

Where are my Dartmouth graduates now?

Ergun Canoglu, who set up my laboratory at Dartmouth, but received his PhD from USC is at **LuxN** in California, as Principal Engineer. Akheel Abeeluck, my first Dartmouth PhD student, is now a Principal Investigator at **Directed Energy Solutions** in Colorado. Philip Heinz, my second Dartmouth PhD is at **Prismark Partners**, in New York. I've had two MS students. Brian West received his PhD from University of Arizona and is now at post-doc at University of Toronto. Jacob Halbrooks is an engineer at MathSoft.

Impact of Lasers Today

Lasers have led to considerable scientific advances. Unfortunately this would be a talk in itself. Some examples are: high resolution spectroscopy, femtosecond chemistry, confocal microscopy and fluorescence tags for biology, Bose Einstein Condensation, combustion analysis, Aerodynamics, the Atomic Force Microscopy (AFM), the Michelson-Morley experiment, which proved that there is no ether, high resolution interferometry for earthquake analysis. Science enabled by lasers has been the subject of Nobel prizes 11 times, including 24 individuals. More are announced each year.

There is also no time to talk more about specific applications. It is sufficient to point out that most applications can be divided into three areas: processing, information and measurement. Some examples of processing applications are in medicine (LASIK, surgery, coagulation), manufacturing (cutting, welding, heat treating), and materials processing (chemically selective reactions). We talked about some examples of lasers and information: CD players, laser printers, the internet and cell phones. Lasers and measurement would include surveying, measurements of distance, producing a level line (a device now advertised on TV), specialty tools.

What have we learned?

- Lasers are ubiquitous
- They differ in type, capabilities, and size
- They are a fundamentally new technology, operating on a different principle from anything before.
- Who could have imagined the science and the applications?
- Government's investment in my research pays off annually in the business output of my former students.

• I would never have imagined where it would lead me – it's been an exciting ride.

I end with a couple of pictures. The first shows me (along with my spouse) in China in 1982. Opportunities for travel have been an important advantage to me in pursuing a career in research. The second was taken just recently.

One of the Advantages of being a Researcher

1982

My family in October, 2005
at Charles Townes' 90th Birthday Party