The 2009 Nobel Prize in Physics

Honoring Achievements in Optics That Have Changed Modern Life

Vasant Natarajan

The Physics Nobel Prize, 2009 has been awarded jointly: one half to Charles K Kao "for groundbreaking achievements concerning the transmission of light in fibers for optical communication", and the other half to Willard S Boyle and George E Smith "for the invention of an imaging semiconductor circuit – the CCD sensor". In this article, we explain the basic ideas behind these inventions, and why the choice is appropriate in interpreting Alfred Nobel's will in who should get these prizes.

Vasant Natarajan finished his PhD from MIT in 1993 and then worked for 2 years at AT&T Bell Labs, the same place where the CCD camera was invented. He then joined the Indian Institute of Science, Bangalore and has been there ever since. His research interests are in laser cooling of atoms and testing time-reversal symmetry in the fundamental laws of physics.

1. Introduction

The winners of the 2009 Nobel prize in physics, shown in *Figure* 1, have been recognized for two achievements in optics that have revolutionized modern life in the past few decades. The first is the invention of the optical fiber, which makes long-distance communication literally lightning fast. Our modern life is fundamentally dependent on optical communication, from the Internet to the ubiquitous mobile phone. The second invention is the CCD (short form of *charge-coupled device*) camera,

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Physics Nobel Prize 2009, optical fiber, CCD camera.

Charles K Kao Willard S Boyle George E Smith

Figure 1. The winners of the 2009 Nobel Prize in Physics.

the electronic eye that has changed optical imaging and put the traditional photographic film out of use. Today, even the cheapest cell phone has a high-resolution (mega-pixel) CCD camera that allows you to take a picture and email it to a friend halfway across the world. A child growing up in this interconnected world would find it hard to believe that these things were in the realm of science fiction just a short generation ago.

2. The Optical Fiber

All of us learnt in school that light travels in straight lines – the so-called rectilinear propagation of light. Imagine if you could make a pipe for light and make it flow along this pipe like water in a water pipe, whatever be the curves and bends along the path. That is exactly what an *optical fiber* does. It is a thin wire of glass that confines the light and transports it along its length. And this length is not just a short distance of a few meters, but extends over thousands of kilometers.

So, how is the fiber able to do this? It uses the idea of *total internal reflection*, the well-known phenomenon that light, incident on an interface where the refractive index changes from high to low, will undergo reflection if the angle of incidence is larger than a critical angle. The basic idea is shown in *Figure* 2.

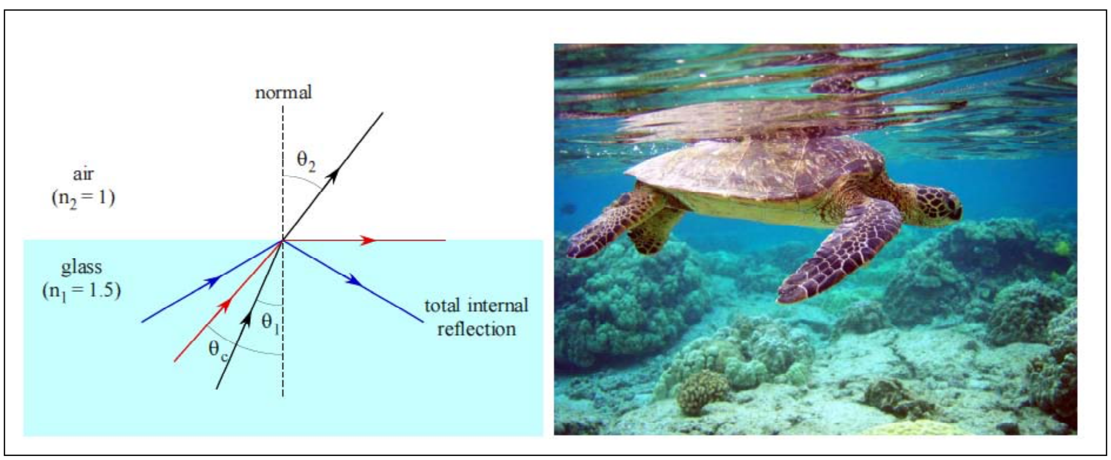

Figure 2. Total internal reflection. The figure on the left shows how the output ray is parallel to the interface when the angle of incidence is θ_c. Total internal reflection occurs at higher angles. The photo on the right shows the reflection of the tortoise at the water surface due to the same phenomenon.

Photo Courtesy: wikimedia.org

From Snell's law of refraction

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}, \tag{1}$$

where θ_1 is the angle of incidence in medium 1, θ_2 is the angle of refraction in medium 2, and n_1 and n_2 are the refractive indices of the two media. Both angles are measured with respect to the normal at the boundary. If $n_1 > n_2$, there is a critical angle θ_c above which there is no real value of θ_2 that can satisfy the equation. The light then undergoes total internal reflection, the phenomenon that gives a well-cut diamond its sparkle. It is called *total* because at smaller angles of incidence there is partial reflection and partial refraction, and the reflection becomes total beyond θ_c. For the glass–air interface shown in the figure, the refractive index changes from 1.5 to 1 and the critical angle is 41.8°.

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Guiding of light using a region of high refractive index is an old idea. It was first demonstrated in a stream of water by Daniel Colladon and Jacques Babinet in Paris in the early 1840s (see *Box* 1). The modern optical fiber,

Box 1. An Optical Waveguide in Water

You can set up a simple experiment to demonstrate guiding of a light beam. The experimental set-up is shown in *Figure* A. Make a container of cross-section 150 × 150 mm^2 and height 300 mm by gluing sheets of 4 mm thick plexiglas. The joints should be water tight (use the glue used by aquarium makers). Make a hole of diameter 8 mm in one side at a height of 70 mm from the bottom. Fill the tank with water to a height of about 200 mm. There should be a steady stream of water, which can be collected in a bucket and resupplied to the container. Now if you direct a laser beam (from a low-cost laser pointer) at the stream, you will find that it gets guided along the parabolic path of the water due to total internal reflection. Voila! You have just made an optical water waveguide.

Figure A. Optical waveguide in water. The stream of water emanating from the container guides the red laser beam along its parabolic trajectory. The angle of incidence inside the water is always greater than the critical angle of 48.8°, so that the beam remains confined by total internal reflection. (Courtesy: Prof K S Sangunni, Department of Physics, IISc, Bangalore.)

made entirely of glass and consisting of a high-index core surrounded by a low-index cladding, was invented in the 1950s. Experiments conducted by the Indian-born American physicist, Narinder Singh Kapany, played an important role in this development[1]. Indeed, Kapany, rightly acknowledged as the father of the optical fiber, coined the term *fiber-optic*. But these early fibers suffered from severe attenuation of the light signal as it propagated through the fiber, making it impractical for long-distance communication.

[1]In November 1999, Fortune magazine featured Kapany as one of seven people who have greatly influenced life in the twentieth century but are its unsung heroes.

This is where the breakthrough contribution of Kao comes in. In 1966, when he was working for the British company Standard Telephones and Cables, he published a seminal paper along with his colleague G A Hockam. In the paper, titled 'Dielectric-fibre surface waveguides for optical frequencies', they proposed that the attenuation in fibers available at the time was caused by impurities, which could be eliminated, rather than fundamental physical effects such as scattering. They correctly pointed out that fibers with low loss could be manufactured by using high-purity glass. The benchmark at the time was an attenuation level of 20 decibel per kilometer (dB/km)[2]. Indeed, just 4 years later, researchers at the American company Corning (the well-known company that makes glass dinnerware) demonstrated a fiber with an attenuation of only 17 dB/km by doping silica glass with titanium. A few years later they produced a fiber with only 4 dB/km attenuation using germanium dioxide as the core dopant. Such low attenuations made optical fiber telecommunications a practical reality.

[2]The decibel unit, defined as 10 log(P_2/P_1), is a logarithmic scale. Thus, a 20 dB attenuation would correspond to a reduction in power by a factor of 10^{-2}, or that 1% of the input power survives.

Today, optical fibers are used everywhere from scientific laboratories to the cable that brings TV and Internet to your home. In my laboratory, we use *single-mode* fibers to transport laser light from one point to another. A typical fiber used for green laser light is shown in *Figure* 3. This is called a fiber patch cable and is terminated terminated with a simple connector that allows us

Figure 3. Single-mode fiber cable used for transporting green laser light. The cable is terminated with a fiber connector (green strain relief and silver nut) that allows us to connect the beam to the experimental apparatus. The actual fiber is covered with a yellow furcation tubing seen on the left. Note the perfect modal quality of the output beam falling on the white card.

to screw it on to our system. The fiber itself has a core of 5 μm diameter surrounded by a cladding of 125 μm diameter. This is surrounded by a protective coating of 250 μm, and finally a furcation tubing of 3 mm (seen in yellow in the figure). Apart from allowing light to be transported without the use of steering mirrors, the main advantage of using the single-mode fiber is that the mode coming out of the fiber is pure Gaussian. The light coming out of a laser is Gaussian to start with, but gets distorted due to optical elements and even dust particles along the way; the use of a single mode fiber is a great way to clean it up. We can see this in the figure where the output beam is allowed to fall on a white card.

One of the most important uses of optical fibers is in *endoscopy*, the minimally invasive technique used in medicine to image internal parts of the human body. The endoscope usually consists of a flexible fiber bundle and a small camera lens at the end. The fibers deliver light to illuminate the object and also bring the scattered light back to form the image. Endoscopy can help a surgeon visualize hard-to-reach areas of, for example, the gastrointestinal tract, and even deliver the medication with the same endoscope if needed.

No discussion of optical fibers would be complete without a mention of *solitons*[3], solitary waves that propagate without changing shape. In 1973, Akira Hasegawa, working at the famous Bell Labs of the American telephone giant AT&T, was the first to suggest that solitons

[3] V C Kuriakose and K Porsezian, Elements of Optical Solitons, *Resonance*, Vol.15, No.7, pp.643–666, 2010.

In 1988, Linn Mollenauer and his team, again at AT&T Bell Labs, transmitted soliton pulses over 4000 kilometers using the Raman effect.

could exist in nonlinear optical fibers, due to a balance between self-phase modulation and anomalous dispersion. In 1988, Linn Mollenauer and his team, again at AT&T Bell Labs, transmitted soliton pulses over 4000 kilometers using the Raman effect. Overnight, AT&T decided to invest billions of dollars laying trans-Atlantic fiber-optic cables instead of the conventional copper cables, because they were convinced that the future of communication was optical. Time has proved this hunch right. While solitons are not in common use now, their use in the near future may increase the bandwidth of existing optical cables many fold.

Fiber-optic cables are at the heart of today's communication-intensive world. As I sit typing on my computer, such cables are transmitting trillions of bits of information every second, bits of information carrying voice, data, and still and video images. Since the time of Edison, we know how to convert audio into electrical signals, but converting an image to electronic form is a different matter altogether. This brings us to the second part of the Nobel Prize – the CCD sensor.

3. The CCD Camera

A conventional camera consists of an optical system that forms an image on the image or focal plane, and a film at the image plane where some photosensitive material changes its properties depending on the amount of light incident at any point. Upon developing, the film is transformed into a photograph that represents the object which was imaged. The CCD camera is an electronic version of the same idea, with the photographic film replaced by a CCD array at the image plane.

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Since we want an electronic image, we have to first convert the photons into electrons. This is done by making use of the photoelectric effect, first explained by Albert Einstein in 1905 and for which he got the Nobel Prize in 1921. Einstein correctly pointed out that the number of electrons produced in this process is proportional to the intensity of the light. Therefore, if we could design a sensor that could collect and read out the number of electrons at a given point (or small region), we would have an electronic camera. Each image point is called a *pixel*, and the larger the number of pixels in a given area, the better the resolution. So the challenge was to read a large number of pixels in a short time.

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This is what the CCD sensor invented by Boyle and Smith in 1969 achieved. Think of each pixel as a bucket that can hold a certain number of electrons. The number of electrons or charge accumulated in each bucket is proportional to the intensity of light incident on the pixel (by the photoelectric effect). The pattern is read out as a shift register: (i) the last bucket is read out first, (ii) each bucket then transfers its charge to the next neighboring bucket and the last one is read out again, (iii) and so on, until all the buckets are empty. The key to the design is the ability of the charge to be transferred from one bucket to the next, hence the name *charge-coupled device*. In reality, each bucket is a silicon capacitor. Since the charge Q in a capacitor C is linearly related to the voltage V, $Q = CV$, the charge can be transferred between neighbouring capacitors by suitably changing the two voltages. Similarly, the charge in the last capacitor is transferred to a charge amplifier and read out as a voltage. If the array is 2-dimensional, we have our electronic image.

Boyle and Smith were then working at AT&T Bell labs, the same place mentioned earlier in connection with the soliton work. Until the 90's, Bell Labs provided an unparalleled intellectual environment for doing basic research. It is a shame that such industrial research labs are becoming extinct now. Boyle and Smith reminisce fondly about the freedom they had in their work and the lack of any "directives" from upper management. This

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was partly because the head of the lab was not a money-minded bureaucrat but a scientist like them. There was an open management style with no hierarchy, and senior scientists would stop by for casual chats. It is no wonder that Bell Labs has produced about 10 Nobel Laureates in physics, starting with C J Davisson in 1937 for the famous Davisson–Germer experiment which confirmed the de Broglie hypothesis on the wave nature of matter. According to Boyle, he and Smith came up with the idea of the CCD in just an hour of brainstorming during an afternoon in 1969. If only our brainstorming sessions were so productive!

The CCD camera has made photography accessible to everyone. Each pixel in a CCD array is only about 10 μm in size, therefore a chip of few square cm can hold several million (mega-) pixels. Small cameras and cell phones boast of 10 mega-pixels, which gives a resolution unheard of a decade ago. In fact, it is hard to imagine that only a few years ago, everyone was carrying a bulky film camera that could take at most 36 images (remember the Kodak 35-mm film!). You would not know if the photo was taken with a shake, or was out of focus, or if it was properly exposed, until you got the film developed and printed. Today, the digital CCD camera takes high-resolution images that you can instantly review, and zoom into any part without a significant loss in resolution. And you can take poster-size prints of any photo that you like. A small flash memory card will hold thousands of such images.

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But the use of the CCD camera is not limited to the lay public. It plays an equally important role in science and technology. In fact, at the front end of most endoscopes mentioned earlier is a CCD camera that allows the surgeon to see the images in real time. In my laboratory, we use CCD cameras to image trapped particles, as shown in *Figure* 4. In *Figure* 4(a), we show an image of a cloud of laser-cooled atoms held in a *magneto-optic trap*

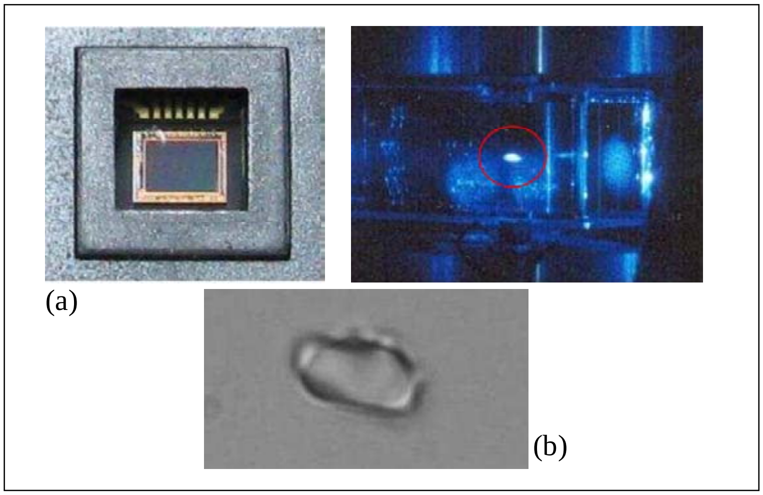


Figure 4. (a) Image of laser-cooled Yb atoms taken with a CCD camera. The camera is shown on the left with the 4 x 6 mm² silicon array visible in the center. The Yb atoms are laser cooled and held in a magneto-optic trap. The blue image in the center is from the resonance fluorescence emitted by the atomic cloud. The cloud of size 3 mm has about 50 million atoms at a temperature of just three-thousandths of a degree above absolute zero (3 mK). (b) A CCD image of a single malaria-infected red blood cell held in an optical-tweezers trap. The cell is about 8 μm in size.

(MOT). In *Figure* 4(b), we show an image of malaria-infected red blood cells trapped by a laser beam in *optical tweezers*. Both traps were invented at Bell Labs. The MOT was invented jointly by Dave Pritchard of MIT (my thesis advisor) and Steve Chu (who went on to share the Nobel Prize for laser cooling in 1997[4] and is currently Energy Secretary in the Obama administration), and the optical tweezers by Art Ashkin.

[4]Vasant Natarajan, and N Srinivasan, Nobel Prize in Physics – 1997: Laser Cooling and Trapping, *Resonance*, Vol.3, No.2, pp.16–27, 1998.

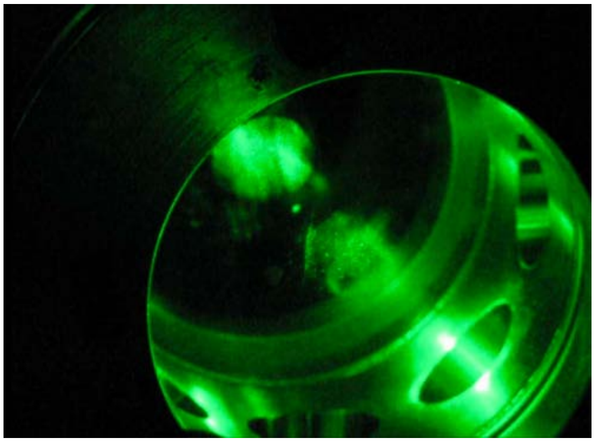
CCD cameras also find widespread use in astronomical telescopes due to their high quantum efficiency and linearity (i.e., signal proportional to the light intensity). Compared to photographic plates, the photoactive part of the CCD array can easily be made sensitive to different regions of the electromagnetic spectrum, ranging from X-rays to UV to visible to infrared. Each one gives us a different eye into the Universe!

4. Conclusion

Alfred Nobel wrote in his will that

> "The whole of my remaining realizable estate shall be dealt with in the following way: the capital, invested in safe securities by my executors, shall constitute a fund, the interest

Cover-Page Image Description: *Laser-cooled ytterbium atoms held in a magneto-optic trap. This is a real-colour image of the fluorescence from the atomic cloud. The cloud has 1 million atoms at a temperature of 50 millionths of a degree above absolute zero. The atoms are inside a vacuum chamber, so that the vacuum acts as a great insulator between the cold atoms and the hot room. The green laser beams for cooling are transported using an optical fiber and the image is taken with a CCD camera, both of which are part of the 2009 Nobel Prize in Physics.*



on which shall be annually distributed in the form of *prizes to those who, during the preceding year, shall have conferred the greatest benefit on mankind*. The said interest shall be divided into five equal parts, which shall be apportioned as follows: *one part to the person who shall have made the most important discovery or invention within the field of physics*; . . . ".

The reader will agree that the inventions of Kao, Boyle, and Smith, have indeed conferred one of the greatest benefits on mankind. Though they may not have been made in the preceding year, they satisfy Nobel's wish that the inventions be *most important*, as their importance has stood the test of time.

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Suggested Reading

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[2] http://blogs.physicstoday.org/newspicks/2009/10/nobel-prize-in-physics-awarded.html
[3] http://en.wikipedia.org/wiki/Nobel_Prize_in_Physics