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Optics in the Information Age

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When I tell someone that I am majoring in optical engineering, I usually get one of two reactions: either they ask, "So, what does an optical engineer do?"or they say, "Oh, so you make eyeglasses". Fifty years ago, this would not have been very far from the truth.

Optics is the study of light and how it can be manipulated, and until fifty years ago pretty much the only way to manipulate light was with lenses and mirrors. Inventions and discoveries in the last half-century have improved our ability to control light to the point that optics touches almost every aspect of modern science and technology. An example of this is the dependence of computer and communications technology upon advances in the optics used to make computer chips and optical communications systems.

The Dawn Of The Information Age

The first electronic computers were built using relays and vacuum tubes to perform the logic and amplification functions. The relay was an electromechanical switch that used an electromagnet to bring two pieces of metal into contact so current could flow. It was simple and reliable, but switched relatively slowly - it took approximately 1/1000 second to open or close the switch. In comparison, the switches in modern computers can open and close over a million times faster. The vacuum tube used a small voltage to control the emission of electrons from a hot wire filament, which were then collected at a positively-charged plate. It could switch much faster than a relay, but it used a lot of power and had a short lifetime.

In 1947, John Bardeen, Walter Brittain, and William Shockley of Bell Laboratories demonstrated the first working transistor, a device combining the functionality of the vacuum tube and relay in a much smaller package. Their device consisted of two very closely-spaced, metal contacts on a germanium surface. A small voltage applied across one of the contacts could be used to control a larger voltage across the other contact.

The first transistor proved that it was possible to make such devices, but it was not a very practical design to manufacture. Several advances in technology were necessary to enable the mass production of transistors. In 1955, it was discovered that a chemical reaction of silicon and oxygen could be used to grow a thin layer of silicon dioxide that prevented the introduction of impurities into the bulk silicon. Later, it was shown that when certain chemicals were deposited on this oxide and exposed to light, they made the oxide resistant to acid etching. It followed that by projecting specific patterns of light onto this photosensitive oxide and etching away the unexposed regions, impurities could be introduced into specific regions on the silicon to make transistors. Alternatively, other materials like metals could be deposited on top of the silicon in these unexposed regions to make interconnecting wires.

This light-etching process, called photolithography, is now the standard procedure for manufacturing integrated circuits like microprocessors and computer memory chips. The key to making smaller and faster integrated circuits is to find ways to make the tiny, intricate light patterns projected via photolithography even smaller, which is an increasingly difficult task.

A Solution Looking For A Problem

Light comes as tiny bundles of energy called photons. The exact amount of energy varies from photon to photon, and if it is an amount that our eye can detect, we can observe it as color. This amount of energy can be measured quantitatively and is usually reported as the wavelength of the photon.

In 1917, Albert Einstein demonstrated that there are three different ways that light can interact with matter (Figure 1). The first process, stimulated absorption, begins with an incoming photon and an atom in the ground (lowest-energy) state, resulting in no outgoing photon and the atom in an excited (higher-energy) state. The second, spontaneous emission, is the reverse of this process; it begins with no incoming photon and the atom in an excited state and results in an outgoing photon and the atom in the ground state. Spontaneous emission is the dominant process in generating most natural and artificial light.

An analogy may be helpful in understanding this abstract discussion of energy states. An atom in the ground state is like a boulder at the bottom of a hill: itâs very unlikely that itâs going to do anything unless something interacts very strongly with it. Stimulated absorption is like pushing that boulder up to the top of the hill. It takes energy to get it there, but it makes it more likely that the boulder will do something-most likely, roll downhill. The top of the hill is a rather precarious position, so there is a fair likelihood that the rock will roll down even if we don't push it. This is analogous to spontaneous emission.

Suppose we drop another boulder on the one at the top of the hill. We would expect to see two boulders rolling down the hill. This is the essence of Einsteinâs groundbreaking insight: there must be a third process that begins with an incoming photon and an excited atom and results in two outgoing photons and an atom in the ground state. That process is called stimulated emission. The photon emitted by stimulated emission is identical to the incoming photon in virtually all respects; it has the same wavelength and travels in the same direction.

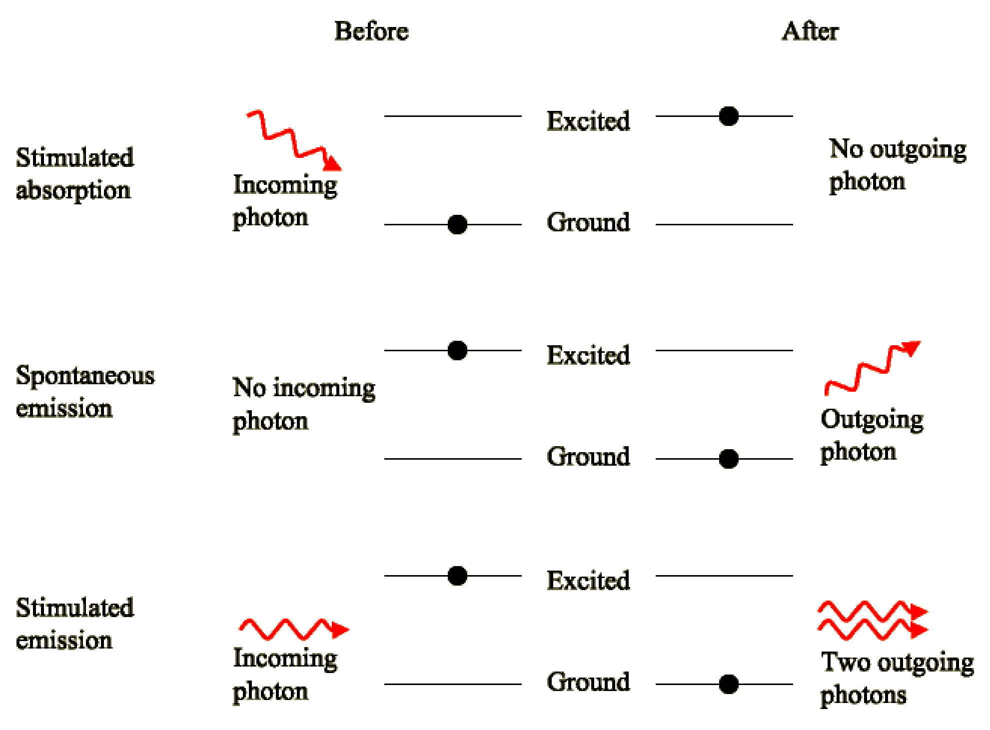

Figure 1: Light-matter interaction

For a long time, this idea lay dormant. It was revived in the mid-1950s when a group at Columbia University headed by Charles Townes demonstrated a device that amplified microwave radiation (radio waves) by the stimulated emission process. The device was christened the ãmaser ä , an acronym for Microwave Amplication by Stimulated Emission of Radiation. In 1958, Townes and Arthur Schalow published a paper extending maser principles to the optical region of the electromagnetic spectrum. After the publication of this paper, a number of groups worked to construct a working optical maser, or laser, which is the acronym for Light Amplification by Stimulated Emission of Radiation. The first working laser was demonstrated by Theodore Maiman of Hughes Research Laboratories in 1960. The components of Maimanâs first laser are illustrated below (Figure 2).

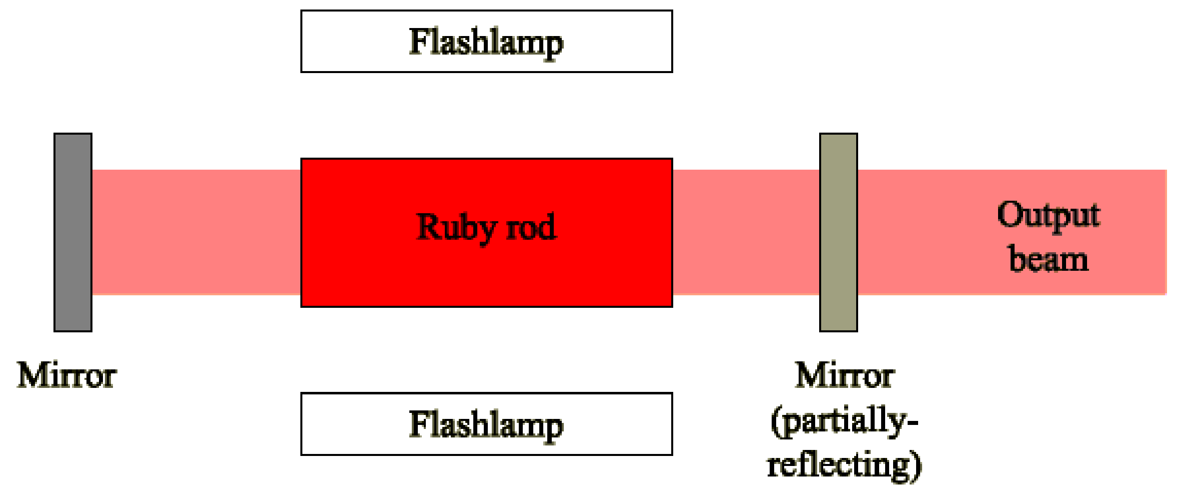

Figure 2: Maiman's ruby laser

A laser consists of three components. The first is the laser medium, the material in which the laser light is generated. In Maiman's laser, this was a polished ruby rod. The second is a mechanism - either optical, electrical or chemical in nature - for getting the atoms in the laser medium into the excited state; Maiman used a flashlamp coil. Finally, the light needs to be confined with a resonator so that the laser light can be amplified by the laser medium sufficiently to produce a useful output. A resonator consists of one fully-reflecting mirror and one partially-reflecting mirror surrounding the laser medium. The laser beam begins as spontaneous emission of a single photon from an excited atom in the laser medium. This photon generates more and more photons by stimulated emission as it passes back and forth through the resonator. A specific fraction of these photons are allowed to escape the cavity each round-trip through the partially reflecting mirror. This is the output beam.

At the time it was invented, the laser was described as "a solution looking for a problem."Now, lasers are everywhere: in bar code scanners, in CD players, and in laser printers, just to name a few modern-day applications. You can even buy your very own laser pointer for less than ten dollars.

Optics and the Internet

One of the less visible yet more pervasive applications of lasers is in telecommunications. Nowadays, long-distance phone calls and Internet data are primarily sent as pulses of laser light travelling inside a glass fiber thinner than a human hair. As a result, advances in optics and laser technology are at the heart of the ongoing Internet revolution.

The idea of communicating with light is nothing new. People have communicated with light by fire, then lanterns, and eventually electric lights. Messages can be encoded by the presence or absence of light, the number of lights ("one if by land, or two if by sea"), or by a blinking light pattern.

Laser communication takes the third approach: information is coded as a sequence of light pulses. However, lasers have advantages over other light sources like fires or light bulbs. First, laser light is highly directional, so most of the light goes in the direction the laser is pointed. This, combined with the use of flexible light pipes called optical fiber, makes laser communication more confidential than a blinking light bulb. In addition, lasers can be switched on more rapidly than a thermal source like a light bulb, which takes a perceptible amount of time to turn on and off. In fact, lasers can be switched more rapidly than transistors, so an optical fiber link can carry information faster than computers can supply it.

What does this have to do with the Internet? Well, the Internet is essentially a lot of computers connected by a web of wires and optical fiber connections. When a web page is viewed, the viewer's computer sends a message to its nearest neighbors requesting that page from the web server. That computer, in turn, requests that page from its nearest neighbors. Eventually, the web server receives this request and sends the web page back down this chain to the viewer's computer. This type of communications architecture requires a backbone of very fast computers and very fast connections in order to be efficient because many computers may be trying to send data between the same two points. With more and more computers accessing the Internet, older optical connections are being pushed to the limits of their information-carrying capacity and are being replaced or augmented with faster ones. Breakthroughs in laser and fiber technology will be necessary to meet the ever-increasing demand for data on the Internet.

Conclusions

I have only covered two of the ways in which optics affect information technology. There are many more, but many of these are much less mature. Optical data storage is just entering its second generation with the advent of the Digital Versatile Disc (DVD) but it may be replaced by holographic storage in special crystals or plastics. Display technology is also at the brink of a revolution as researchers are developing organic light-emitting diodes that could bring about bright computer screens that you can fold (or roll or crumple) into your pocket. The future of the information age depends on future developments and advances in optics.

Further reading

The interested reader may wish to explore any combination of these topics in the following sources:

Born, M., E. Wolf. *Principles of Optics*, 7th ed. New York: Cambridge UP, 1999.

> Sometimes called the Bible of optics, it derives classical optics from Maxwellâs equations. A graduate-level text.

Feynman, R. *QED: The Strange Theory of Light and Matter*. Princeton: Princeton UP, 1985.

> Using a simple and elegant graphical approach, the late Caltech physicist Richard

Feynman presents the most accurate theory of light and matter to date, quantum electrodynamics, for which he received the Nobel prize in physics.

Hecht, E. *Optics*. Reading, MA: Addison-Wesley, 1998.

A standard undergraduate optics text. Describes many experiments that demonstrate unusual optical phenomena with fairly common materials.

O'Shea, D.C., W.R. Callen, W.T. Rhodes. *Introduction to Lasers and Their Applications*. Reading, MA: Addison-Wesley, 1977.

A very-accessible introduction to the theory and applications of lasers.

Ross, I.M. (1998) The Invention of the Transistor. *Proc. IEEE*. 86: 7-28.

A history of the invention of the transistor by a Bell Labs researchers who worked alongside Bardeen, Brittain, and Shockley.

Sedra, A., K. Smith. *Microelectronic Circuits*, 4th ed. New York: Oxford UP, 1998.

A comprehensive text describing the terminal characteristics and device physics of transistors and how they can be used to construct both analog and digital microelectronic circuits. Assumes an introductory course in circuit analysis.

Townes, C.H. *How the Laser Happened: Adventures of a Scientist*. New York: Oxford UP, 1999.

A firsthand account of the invention of the laser.

Those interested in pursuing further study in optics may wish to browse the following websites:

Optical Society of America
Society of Photo-optical Instrumentation Engineers
University of Arizona Optical Sciences Center
University of Central Florida School of Optics
University of Rochester Institute of Optics

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