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OPTICAL COMMUNI-CATIONS

Also in this issue: **Lasers**

New technological advances in telecommunications often propose an alternate approach to doing the same thing, only better or more economically. While these new technologies may not totally and immediately replace previous ways of doing things, they often hint at what the telecommunications systems of the future may be like. Today the telecommunications industry stands on the threshold of a new communications concept -- the transmission of information by the use of light. Although the ideal optical communications system is far from a reality, telecommunications companies are busily developing and testing prototypes with that goal in mind.

What is light? What is its nature? Questions like these have stimulated the intense curiosity of the human mind for thousands of years. Ancient scholars had very little concrete knowledge of the nature of light. They surmised that light was composed of many particles emitting from a source; it was even conjectured that perhaps the eye itself emitted particles of light to illuminate objects. Surprisingly, these scholars did establish some theories about light that are still held today, including the idea that light travels in a straight line, that the reflection of light from a mirror is at an angle equal to that at which the light beam meets the mirror's surface, and that a beam of light is bent, or refracted, when it passes from air into a transparent material such as water or glass.

Early Experiments

Experiments conducted in 1666 by Issac Newton made great progress toward determining the nature of light. By noting the results of passing a beam of light through a prism, Newton concluded that white light was really a mixture of light components, each of which was capable of stimulating the eye in such a manner that it produced the sensation of color (see Figure 1).

In a second experiment, Newton demonstrated that white light could be decomposed into its seven spectral colors by passing it through a first prism, then recomposed again by passing the dispersed light through an inverted second prism. Newton's experiments lent support to the popular theory that light was made up of tiny particles traveling at an extremely high speed, which would explain both the straight-line travel of light and refraction, since the particles would slow down when traveling through mediums denser than air. If, however, light indeed consisted of high-speed particles, some questions arose that remained unanswered. Why, for example, was one color of light refracted more than another; or why did the crossing of two beams of light not cause the streams of particles to collide, thereby distorting the individual paths of the beams?

In 1678, a Dutch physicist by the name of Christian Huyghens theorized that light was composed of waves whose varying lengths corresponded to different colors. This theory would explain the variation in refraction of different colors of light, since it was reasonable to assume that waves of different lengths would have varying degrees of refraction. From Huyghens'

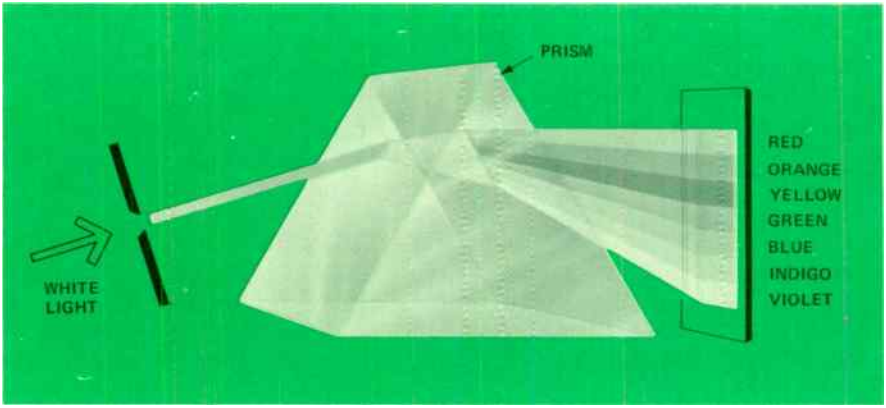

Figure 1. White light is a mixture of various light components. When white light is passed through a prism and projected on a screen, the components are dispersed according to color and wavelength.

theory, it could be explained that two beams of light projected from different directions and crossing each other did not become distorted by virtue of wave action, just as sound waves are able to cross without becoming distorted. In spite of being able to answer questions that could not be explained by the "particle theory," Huyghens' theory did not explain why light waves did not travel around objects as did sound and water waves, or how light waves could travel through a vacuum (the space between the sun and the earth, for example). Furthermore, if light consisted of waves, what was the medium being waved in outer space?

The answers to questions about light came slowly in spite of determined investigations. In 1818, a French physicist by the name of Augustin Jean Fresnel, whose concepts would later be extensively used in microwave communications, fortified the wave theory by showing that if an obstacle within a beam of light is small enough, light waves will definitely bend around it; the obstacle's size, however, must be close to the wavelength of light for this "defraction" to take place. If an object which presents an obstacle to a beam of light is large with respect to the wavelength of light, the light not obstructed by the object will travel straight and cast a sharply-defined shadow: no defraction takes place.

Along with attempts to find out more about the nature of light were studies attempting to determine the speed of light. The Italian astronomer and physicist Galileo Galilei (1564-1642) was the first to attempt light speed measurement, but although his idea of measuring light at increasingly greater distances was correct, he did not have the necessary mechanical devices to make an accurate measurement. More than 300 years later, the German-American physicist Albert Abraham Michelson was able to measure the speed of light in a vacuum and found it to be 186,284 miles per second. Still greater refinements in measurement techniques enabled scientists, in 1963, to determine the speed of light as being 186,281.7 miles per second (2.998×10^8 meters/sec).

Even while an increasing amount of information was gathered on light, some of the old questions still remained, particularly the question of how light, if it indeed consisted of tiny waves, could travel through the vacuum of space. Was there an "ether" beyond the earth's atmosphere that enabled the passage of light from the sun and other stars? Many scientists thought so.

It was the concept of lines of force and strength of magnetic fields proposed by Michael Faraday, and subsequent mathematical derivations of these fields in the 1860's by James Clerk Maxwell, that supplied new insight into the nature of light. The relationships between electricity and magnetism described by Maxwell essentially implied that electric and magnetic fields must coexist: one cannot exist without the other. Further, this coexistence extended to changing fields, where a change in a magnetic field brought about a corresponding change in the electric field, and vice versa. This change phenomenon was what Maxwell termed electromagnetic radiation, an energy field that propagated outward in all directions in direct proportion to the number, or frequency, of the changes. Maxwell calculated that the velocity of an electromagnetic wave was equal to that of the speed of light, and he speculated that not only was visible light an electromagnetic radiation, but that it was only part of a greater spectrum, much of whose wavelengths were not visible to the eye.

In spite of the new theories and speculations, the question of the ether was not answered. Did it exist or didn't it? In 1900, German physicist Max Planck proposed that radiation consisted of discrete units which he called quanta. Planck theorized that radiation could be absorbed by a body only in multiples of quanta, and that the energy contained per quantum existed in inverse proportion to its wavelength. This latter theory implied that some colors of light would contain a greater degree of energy than others.

A New Concept

German-born Swiss physicist Albert Einstein verified the existence of Planck's quantum units while working out an explanation of the photoelectric effect. Extending the quantum theory, Einstein later proposed that light traveling through space did so in a quantum form which he termed the "photon." Here, then, was a step back to the particle theory of light. However, Einstein proposed that the photon had properties not only of the particle, but of the wave as well, and that depending on the prevailing conditions, either one group of properties or the other was exhibited. This theory now made it unnecessary that an ether exist through which light waves must travel, since they could travel through the vacuum of space due to their properties as particles.

Research into the nature of light has given birth to new terms. In the measurement of the length of light waves, for example, it has been found that the wavelength of red light is around .000075 centimeter. Because numbers such as these are difficult to work with, a more convenient unit called the Angstrom (Å) was adopted. One Angstrom unit equals one hundred-millionth of a centimeter. The previous measurement for the red wavelength (.000075 centimeter) thus corresponds to 7500 Angstrom units. Another unit that is used in connection with the measurement of light waves is the micron. This unit of measurement is equal to one millionth of a meter, or 10^4 Angstrom units. Violet light waves, for example, are in the .38-micron range.

Light Sources

The visible light frequency spectrum appears within the confines of a

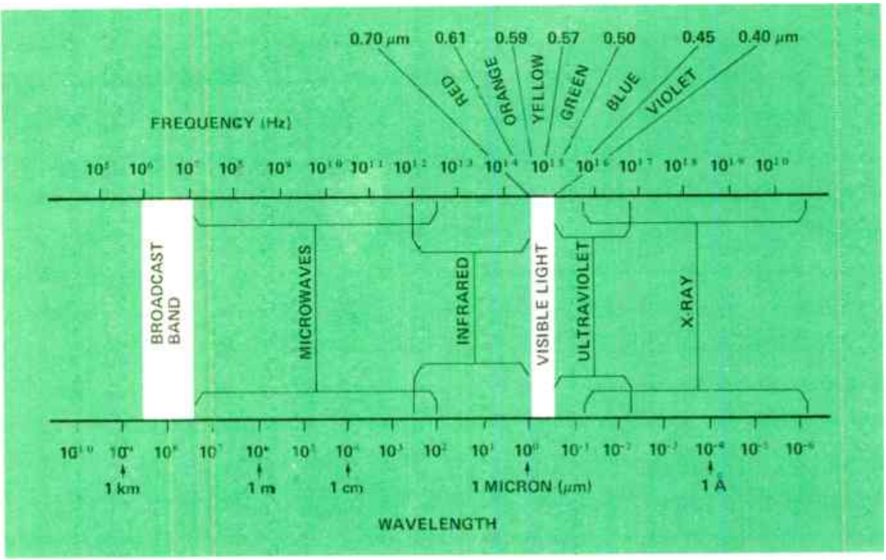

Figure 2. Under the title of light is included not only visible light, but also infrared, ultraviolet, and X-ray frequencies.

larger spectrum as shown in Figure 2. The immensity of the frequency spectrum of what is defined as light – which includes not only visible light but also infrared, ultraviolet and X-ray – has fascinated scientists with the possibility that it might be used to transmit information such as voice, radio, television, and data signals. Recent advances in semiconductor technology have produced two light sources that can be used in the transmission of light signals for communications purposes: the light emitting diode (LED) and the laser. At present, semiconductor lasers that can operate in the visible light spectrum at room temperatures for long periods of time are not yet commercially available. However, recent experimental results involving improvement in the growth of the crystalline material necessary in laser operation promises to bring long-life laser communications systems closer to commercial reality. Unlike the laser, the LED has been developed to the point where it is ready to take its place in experimental optical communications systems, although the ideal optical systems of the future will most likely use laser light sources for wideband communications.

The term "semiconductor" implies a material whose ability to conduct an electric current is limited. Charge carriers exist in semiconductor material, but since most of the electrons strongly adhere to the parent atoms, movement of charge carriers is restricted. To overcome, in a controlled manner, a semiconductor's resistance to electrical conduction, tiny amounts of certain impurities or dopants are added to the material. Dopant material which is composed of atoms having an excess number of electrons produces an "n-type" semiconductor, while one composed of atoms lacking electrons produces a "p-type" semiconductor. If slices of p- and n-type material are joined (a diode junction), the free electrons from the n-type material are combined over a thin portion of the junction (the depletion layer) with the available holes in the p-type material. A voltage applied so that the p material is positive and the n material is negative forward biases the semiconductor, and causes current to flow. Polarity applied in the opposite direction (reverse biasing) causes current to cease flowing. In the case of an LED, current passing through a pn junction causes electrons to be temporarily "pumped" to a higher energy level, but as these electrons return to a more stable state, they release energy in the form of light of a certain color (or wavelength) which is dependent on the atomic structure of the semiconductor material. For example, an LED made of gallium arsenide (GaAs) material will emit light in the infrared portion of the frequency spectrum, while one made of gallium arsenide phosphide (GaAsP) will produce a visible red light. More technically, it can be said that light emission from an LED is caused by recombination of carriers injected across the pn junction.

The electroluminescent emission from an LED is multimode and incoherent light, which means that random relationships exist between the light waves emitted by the different atoms in the source. It is possible to produce a coherent light source, but this requires the use of a laser, which produces an intense light of a certain wavelength

Fiber Optics

Just as it is possible to send Morse code signals to a receiver some distance away by use of a flashlight or some other light source, so is it possible to send signals with an LED, but at a much faster rate and in far greater quantities. The LED typically generates 2.5 milliwatts of wide-angle infrared light in a wavelength band measuring from .87 μm (microns) to .92 μm. Light pulses of short duration suitable for use in T1, T2, and T3 PCM systems can be generated by electrically pulsing an LED.

An optical communications system requires, besides the light source, a medium over which the light signals are transmitted and a sensor, generally a semiconductor diode, which converts the light signals back to electrical signals. The medium by which light signals will be transmitted to a receiver in optical communications systems is most certain to be one of several types of hair-thin glass fibers, some of which are presently available for use and some of which are still in the development stage. An optical fiber is actually a tiny waveguide which supports optical frequency waves using the principles of total internal reflection at the boundaries of the fiber.

Transmission over optical fiber promises advantages over copper wire in the form of larger bandwidths, freedom from crosstalk and other types of interference, low cost, and light weight. In addition, much more information can be carried at optical frequencies than at the lower microwave frequencies. Bundles of optical fibers, each capable of carrying thousands of telephone conversations, could eventually replace miles of copper wire now being used for the same purpose.

Fiber Optic Modes

Fibers are usually categorized as one of three types: single-mode and multimode step-index fiber, and multimode graded-index fiber (see Figure 3). A single-mode fiber can function efficiently only by working in conjunction with the coherent light from a laser, since it has been determined that if the fiber's core is small enough, only the fundamental mode is guided along the fiber. A multimode fiber, on the other hand, may be used with incoherent light sources such as LED's. Figure 4 shows how incoherent light

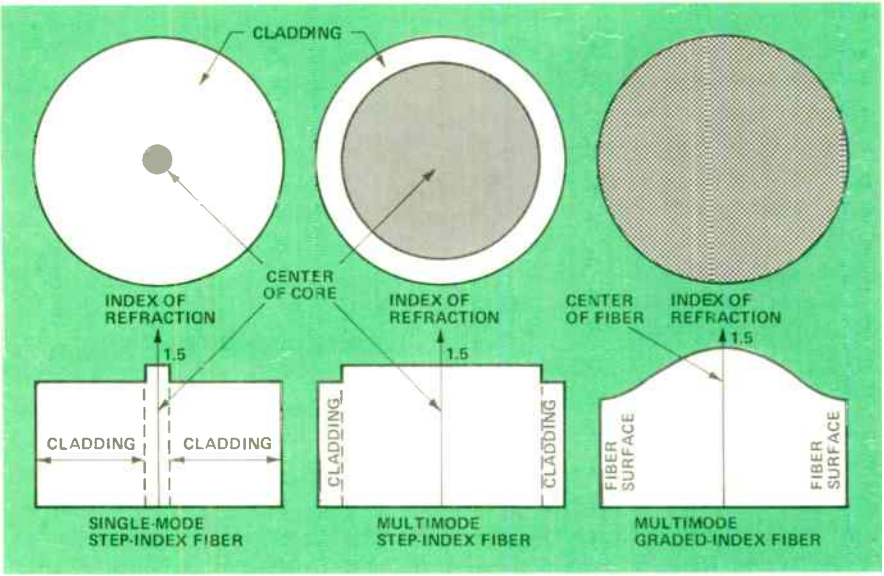

Figure 3. The three optical fibers most likely to be used for telecommunications are single-mode and multimode step-index, and graded-index multimode fiber.

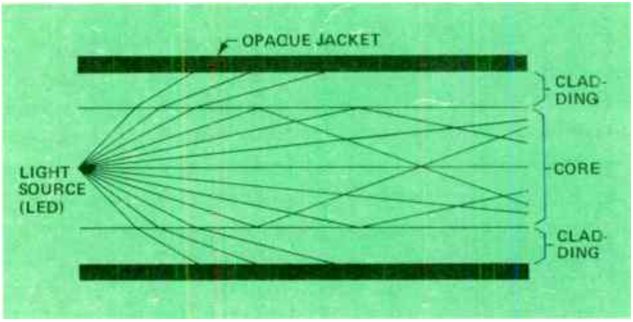

Figure 4. Incoherent light waves emitted from an LED are confined to the core of a multimode step-index fiber due to reflection from the cladding material. The light waves travel a zig-zag path along the fiber to the distant end.

waves from an LED travel along a multimode step-index fiber. Light rays are emitted uniformly by the LED from many points. Those rays not captured within the core of the fiber become totally absorbed by the jacket, while the others strike the interface area between the core and the cladding at angles which, by the process of total internal reflection, are forced to propagate within the boundaries of the core.

Because the core and cladding of an optical fiber are composed of materials differing slightly in index of refraction, the light from the LED travels through them at different speeds. The index of refraction of the core, being slightly higher than that of the cladding, causes light rays striking the interface at grazing angles to be reflected back into the core material: only a small amount of the total light propagates within the cladding region.

As in any communications system, the transmited signals in an optical fiber must span the distance to the receiver and arrive there in an acceptable enough condition so that they can be detected with a certain degree of reliability. To this extent, the maximum range of a system largely depends on the type of light sources and light detectors used, and on the purity of the optical fiber and the nature of its construction.

Signal Degradation

Assuming that digital signals such as those produced by a PCM terminal were to be used in a hypothetical system, they would appear as bursts or flashes of light occurring within a uniform array of time slots. To be able to decipher the message that is represented by the signals, it is necessary that the receiving end be able to distinguish the bursts of light not only in intensity but also in time. Signal degradation in a fiber mainly occurs in the form of attenuation (dimming of light intensity) and differential delay (the broadening of the signal in time).

The extent to which a multimode fiber can accept and transmit light energy depends upon the angle at which the light rays enter the fiber. Relative to the axis of the fiber, this angle must be less than the critical acceptance angle (Θ_C) of the particular fiber being used (see Figure 5). In general, only about 4% of the total wide-angle light initially emitted by the LED is transmitted in the optical fiber. The attenuation of light energy traveling in a fiber is mainly due to absorption and scattering. Absorption loss is caused by the presence in the fiber of impurities such as iron, copper, nickel and cobalt. These materials usually are found trapped in the glass from which the optical fiber is made. For a good-quality fiber, the total amount of metallic-ion impurities should not be more than one part per million. To meet these requirements, intensive research by fiber manufacturers has produced fabrication

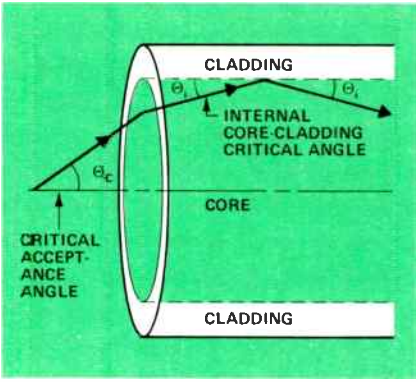

Figure 5. Light rays entering a step-index multimode fiber at greater than the critical angle (a higher order mode) will be absorbed by the opaque jacket.

methods that provide glass of such great purity that absorption loss is minimized in the manufacture of the latest experimental fibers.

Power loss due to scattering is caused by imperfections in the core material and by flaws in the region where the core interfaces with the cladding. Rayleigh scattering, another type of scattering which causes attenuation in optical transmission, is caused by the existence of tiny dielectric inconsistensies in the glass. Because these material inconsistencies are small with respect to the particular wavelength propagating in the fiber, scattering of light energy takes place in all directions, almost uniformly.

The transparency of optical fiber to be used for communications must be extremely high for a system to operate efficiently over an acceptable distance. For example, for a given intensity of light of a certain wavelength, a particular optical fiber might convey the energy a distance of 1000 meters, whereas in high quality optical glass and ordinary window glass or water, the energy would be conveyed only about 5 meters and 1 meter, respectively, for an equal amount of loss.

Differential Delay

The degradation of light by differential delay (pulse broadening or spreading) in modern optical fibers has more significant effects on transmission than does scattering. The cause of pulse broadening begins with the angle at which a ray from a light source enters the fiber. Those rays entering a multimode step-index fiber parallel to the fiber axis travel the shortest distance to the receiver, while those entering at various angles must be reflected by the cladding, and thereby travel a longer distance to the receiver. The difference in time of arrival at the receiver of the various rays causes a spreading of individual pulses. If the difference in arrival time between the fast and slow rays exceeds the time interval allowed between pulses, a pulse overlap occurs. Because pulse spreading increases with fiber length, it is important that light rays travel as close to the core as possible. For this to occur, the difference in refractive indexes of the core and cladding must be kept small, thus also keeping the critical acceptance angle small. Pulse broadening must be especially limited in systems processing higher bit rates, since higher data speeds mean a shorter time interval between pulses and, consequently, less tolerance for errors due to pulse spreading.

New Developments

Developments in fiber optic technology have come at a rapid pace. In 1970, Corning Glass Works developed a fiber with a loss component of 20 dB per kilometer; four years later, experimental fibers had been tested that yielded losses of only about 2 dB per km. How soon such fibers will be available commercially is difficult to predict, but such advances show that the concept of light transmission for communications will not fall short due to lack of the necessary technology.

A departure from the step-index method of confining light energy to the core is a graded-index optical fiber developed by the Nippon Sheet Glass Co. of Japan. Called Selfoc (abbreviation for "self-focusing"), this graded-index fiber consists of one material interspersed with a second material in such a way that the index of refraction decreases at a faster and faster rate with distance from the axis of the fiber. By this means, the light rays travel back and forth across the axis of the fiber in a sinusoidal manner, with the refractive index reaching a maximum value at the fiber's center and a minimum value at the surface (see Figure 6). Because the speed of a light ray varies inversely with the refractive index of the material through which it propagates, it will travel slower in areas close to the center and faster in regions farthest away from the center. The effect of this action is that all rays traveling in the Selfoc fiber will reach the receiver at nearly the same time.

One additional method of eliminating differential delay is by constructing a step-index fiber with a core so small that only a single electromagnetic mode is allowed to propagate. This single-mode technique eliminates the interference that is created when light rays of different wavelengths propagate along the fiber. However, this type of fiber construction requires use of the monochromatic light that only a laser can produce (see Figure 7). Also, the single-mode fiber is not only difficult to manufacture, but difficult to handle in practical applications, although fibers of such construction have the potential for carrying much more information than fibers of other design. Semiconductor lasers are currently being developed which may be used with single-mode fibers. This kind of compatibility between available components and those yet to be developed may some day revolutionize

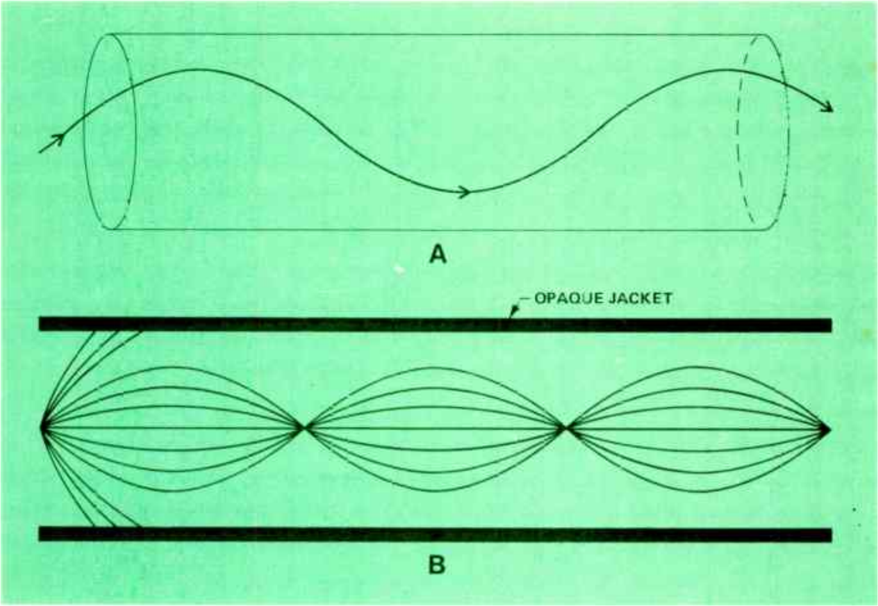

Figure 6A. A single ray travels a sinusoidal path along a graded-index fiber. The effect of the self-focusing property of graded-index fiber on incoherent light waves is shown in Figure 6B.

the field of wideband communications.

An Optical System

With the degree of technology presently existing in the field of electronics, it is theoretically possible to assemble available components into a working optical communications system. Indeed, this is one type of development that is being done in advanced telecommunications laboratories such as Bell Labs and GTE Labs. A simple experimental optical communications system might appear as shown in Figure 8. Signals from a D2-type channel bank such as the GTE Lenkurt 9002B are amplified and fed directly to an LED, which transforms the electrical signals to light and transmits them down the glass fiber at a T1 rate of 1.544 megabits per second. After the light energy in the fiber has undergone an attenuation of about 45 dB,

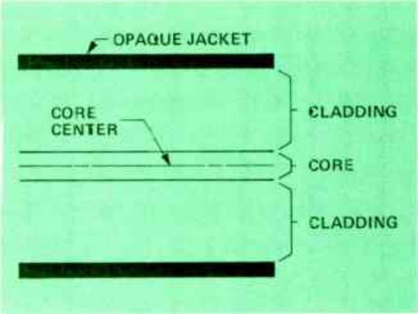

Figure 7. The step-index single-mode optical fiber must be used with the coherent light from a laser.

or when pulse distortion due to differential delay exceeds one-half of a time slot, it becomes necessary to regenerate the light pulses in a repeater so that they may be properly detected at the distant end. At the repeater, the degenerated light pulses first encounter a photodiode, which is a semi-

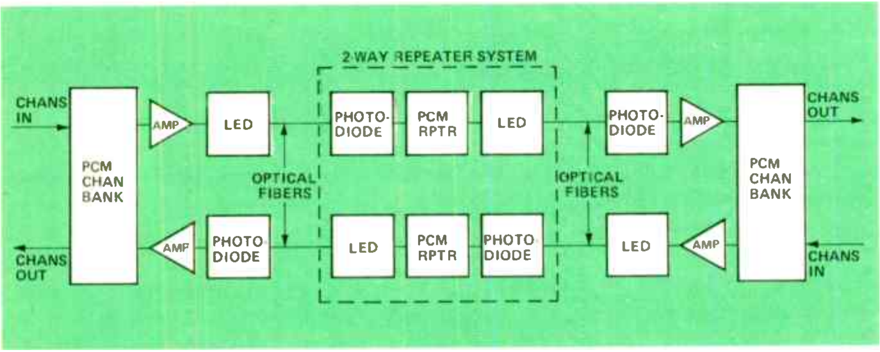

Figure 8. A simple, hypothetical optical communications system using currently available PCM equipment.

conductor device whose function is to convert light impulses into electrical energy. This electrical energy in the form of pulses is amplified, detected, timed, regenerated, and conveyed to an LED. The LED converts the electrical energy back to light pulses which are then sent into the following section of optical fiber. At the distant end of the line, the light pulses are again transformed into electrical pulses which are amplified and processed as usual in the PCM terminal. For signals transmitted in the other direction, the opposite action takes place.

The prospect of optical communications systems is truly attractive, since they not only promise to replace tons of expensive copper wire with hair-thin strands of silica, one of the most abundant materials on earth, but they also offer such potential advantages in future systems as bandwidth capacities of 50,000 voice channels or 30 TV channels per single fiber, using an LED light source.

Coupled with the advantages are, of course, technological problems yet to be overcome before these systems become a practical reality. Some of these include developing cables that will carry not only light signals, but also the electric power necessary for repeater operation. Adequate alignment and splicing techniques must be developed so that optical fibers may be serviced in the field, and still maintain their continuity, with a minimum of loss. Development of an all-optical repeater will also do much to maximize system length.

If technology progresses at its current pace, the not-too-distant future may hold such innovations as optical systems that use integrated optical circuitry (IOC) in the same way that today's electronic equipment uses integrated circuits, except that IOC components will consist of microscopic lasers, optical switches, and laser modulators.

To be sure, widespread use of commercial optical communications systems will depend on whether they are economically feasible. However the speculation on feasibility runs, research labs such as GTE Laboratories are planning to test prototype systems in the field this coming year. These tests will not only help determine the economics of optical systems, but also give some insight on additional developments that may be required for commercial system applications.

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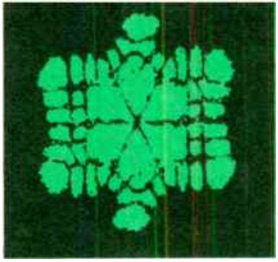

Lasers

The laser has evolved from a science fiction concept into a working device which has found widespread use, from delicate eye operations and the treatment of skin cancer to a cutting source for intricate integrated circuits. In the telecommunications field, intensive investigation is being conducted in an effort to harness the enormous bandwidth of the laser beam for the transmission of information.

The laser (acronym for light amplification by stimulated emission of radiation) comes in a myriad of varieties, each specifically developed for a certain function. Laser types include: ruby, gas, chemical, liquid, metal-vapor, and semiconductor lasers.

The principle of the laser is based on atomic physics, and dates back to 1917 when Albert Einstein theorized that controlled radiation could be obtained from an atom (or molecule) under certain conditions. All matter consists of atoms made up of a "heavy" nucleus surrounded by electrons. Atoms in their natural state are usually in a relatively undisturbed, or "ground," condition because, normally, enough electrons surround the nucleus to neutralize its charge. That is, the energy of orbiting electrons is balanced by the energy in the atom's nucleus. In an atom's ground condition, electrons revolving around the positively charged nucleus are confined to a number of shells, usually designated K, L, M, etc. The maximum number of electrons allowable in the K shell is 2; 8 are allowed in the L shell, 18 in the M shell and 32 in the N shell. The electrons occupy specific orbits determined by their own energy levels. The distance of each orbit from the nucleus represents the specific amount of energy possessed by the electrons in that orbit. The closer the electron orbit is to the nucleus, the lower the electron energy level (see Figure 1).

Einstein suggested that "pumping" energy into atoms by means of external excitation would cause electrons to leave their natural orbits and rise to the second, third or higher level, depending on the quantity of energy applied. If enough energy is applied to the electron to raise it from one level to another, it will absorb only that amount of energy required for the jump. This pumping of energy places an atom in an "excited" state, and its natural reaction is to return to its ground state. When this takes place, a

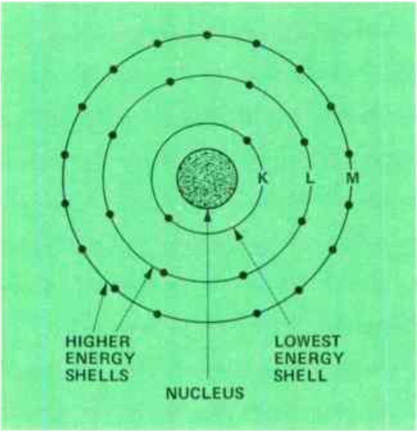

Figure 1. In an atom's natural state, electrons orbiting the nucleus are confined to a number of shells.

photon of radiation is emitted. (A photon is a discrete packet of electromagnetic waves.) The energy of the photon is exactly proportional to its frequency – the higher the energy, the higher the frequency and the shorter the wavelength. For example, high-energy photons may appear as X-rays or ultraviolet radiation, while those of lower energy may give off visible light of any color, radiant heat, or radio waves. Also, the exact amount of energy absorbed or emitted by an electron in jumping from one energy level to another differs with each type of material and for each combination of electron shells. This means that an electron will emit radiation of one wavelength in dropping from the second to the first shell (the shell closest to the nucleus) in a substance, and a second wavelength when dropping from the third to the second shell. This can be observed in such familiar examples as neon light, where the atoms in molecules of gas are excited to upper energy levels by the presence of a high voltage. As the excited and ionized gas molecules drop back to their ground state, they emit light of a characteristic white color. This also accounts for the yellow-orange light of sodium vapor lamps, and the bluish-green from mercury vapor.

Optical Pumping

Pumping is a term generally used to mean the raising of matter from one energy level to a higher one. Light is a particular type of matter, and in optical pumping light energy is the power source used to raise individual atoms to higher internal energy states. A simplified explanation of the pumping process can be made with the help of Figure 2. The atoms in Figure 2 can be made to achieve any one of three energy levels, designated A, B, and C. Levels B and C are of low energy and are spaced very close together. The differences between the energy levels correspond to photons vibrating at certain frequencies. Before pumping, the atoms are distributed evenly between levels B and C (2-1). If this group of atoms is bombarded with a beam of light from which the spectral line AB has been removed by filtering, that light beam contains photons capable of exciting atoms at level C but not at level B. The atoms excited at level C absorb energy and rise to level A (2-2), where they will remain for a very short time (as short as one ten-millionth of a second), then return to either level B or C, emitting energy as they do so (2-3). Once an atom drops to level B, it can no longer be excited by the incident light. Given enough transitions between levels C and A, each atom will eventually arrive at the B level, which means the material has been totally pumped (2-4 and 2-5). Atoms can be returned to energy level C by irradiation at a frequency which corresponds to the transition energy between the C and B levels (2-6).

The Ammonia Molecule

The road to the development of the laser began with studies of the ammonia molecule (NH_3), which contains three hydrogen atoms and one nitrogen atom arranged in a pyramidal structure, and can be displayed in the manner shown in Figure 3. One hydrogen atom is positioned at each corner of the base of the pyramid, with the nitrogen atom occupying a position at the apex. The ammonia molecule can be made to vibrate by irradiating it with microwave energy, which means that the nitrogen atom is repeatedly caused to travel a path through the plane of the triangle to a corresponding position on the other side, and back again. This vibration is extremely consistent at 24 billion times a second (2.4×10^{10} Hz). In 1949, using this property of the ammonia molecule,

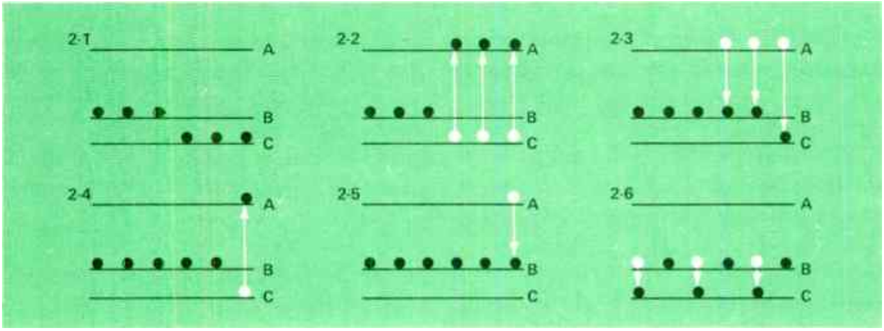

Figure 2. Optical pumping involves the transferring of atoms to a higher energy level by external excitation of the laser medium.

American physicist Harold Lyons constructed an extremely accurate atomic clock. By 1964, atomic clocks capable of such chronologic accuracy as one second of variation in 100,000 years were being produced.

A vibrating ammonia molecule emits electromagnetic radiation at 24 GHz, which corresponds to a microwave wavelength of 1.26 centimeters. The ammonia molecule may be seen as being able to occupy two discrete energy levels. The difference in energy between these two levels is equivalent to that of a photon providing a radiation of electromagnetic energy with a wavelength of 1.26 centimeter. A photon with these characteristics is emitted when an ammonia molecule falls from the higher energy level to the lower level. Similarly, when an ammonia molecule located in the lower energy level absorbs a photon with the appropriate characteristics, it ascends to the higher level.

When an ammonia molecule which is already located in the higher energy level is exposed to additional photons corresponding to a wavelength of 1.26 centimeter, the molecule will be forced back to the lower level, but will emit a photon of the exact size and traveling in the same direction as the entering photon. Essentially, this means that two identical photons exist where only one existed before. Molecules of ammonia bombarded by microwave frequency radiation can be pumped from a lower energy level to a higher level and vice versa. It occurred to scientists that if all the available ammonia molecules could be conveyed to the upper energy level, bombardment by a beam of radiation at a microwave frequency should have a

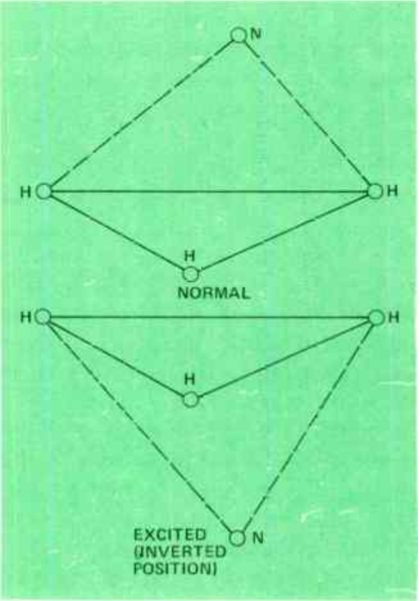

Figure 3. The ammonia molecule can be caused to vibrate by irradiating it with microwave energy.

cascading effect as far as release of energy was concerned. The microwave radiation would provide a photon which would strike an ammonia atom, thus forcing it to a lower energy level, but causing it to emit a second photon in the process. These two photons would then be capable of striking two more molecules, thus releasing two more photons, etc. In this way, the initial action of a single photon would create a deluge of new photons of equal frequency and direction.

The First Maser

By 1953, an American physicist by the name of Charles Townes had succeeded in isolating ammonia molecules occupying the high energy level. He then bombarded these molecules with photons of the proper wavelength, causing a stimulation which created the appearance of a great number of photons. In effect, this process signified a form of amplification, since the ratio between the number of input photons and the number at the output was very high. This was the first example of a gaseous "maser" (acronym for microwave amplification by stimulated emission of radiation). Masers were soon developed which used solid material rather than ammonia gas.

The first masers required pumping to the higher energy level before stimulation. This came to be called an intermittent maser, since after delivering a burst of radiation of very short duration, the pumping process had to be repeated before stimulation could occur again. The delay caused by having to pump and stimulate at discrete intervals led to the development of the 3-level system of operation.

In devising the 3-level system, Dutch-American physicist Nicolaas Bloembergen theorized that by selecting for the maser core material a substance containing electrons in each of three discrete energy levels, pumping and emission could take place at the same time. The eventual incorporation of this process led to the development of the continuous maser.

The basic principle of maser operation can be applied to electromagnetic waves of any length. When such principles are applied to electromagnetic waves in the visible light spectrum, the device may be called a laser.

The First Laser

In 1960, an American physicist by the name of Theodore Maiman succeeded in constructing the first laser. In Maiman's device, a bar of synthetic ruby (which is mainly aluminum oxide with traces of chromium oxide) was exposed to high-intensity light. This caused the electrons of the chromium atoms to be momentarily pumped to higher levels. As the electrons retreated back to the lower levels, the first photons which were produced collided with other atoms which in turn produced additional photons.

The essential elements of Maiman's ruby laser appear as shown in Figure 4. The laser ruby is polished to optical flatness and silver coated at each end. One end of the crystal, however, is heavily silvered so that it reflects all light, while the other end is more thinly coated, and reflects only about 92 percent of the light incident on it. Around the crystal is a helical xenon flash tube which provides the intense light necessary for optical pumping. When photons from the flash tube irradiate the ruby crystal rod, the energy of some of the chromium atoms rises from the ground state to higher energy levels. As the elevated chromium atoms drop back toward the ground state, some come to rest temporarily at an intermediate or metastable (only slightly stable) state. Because the flash tube continues to irradiate additional chromium atoms,

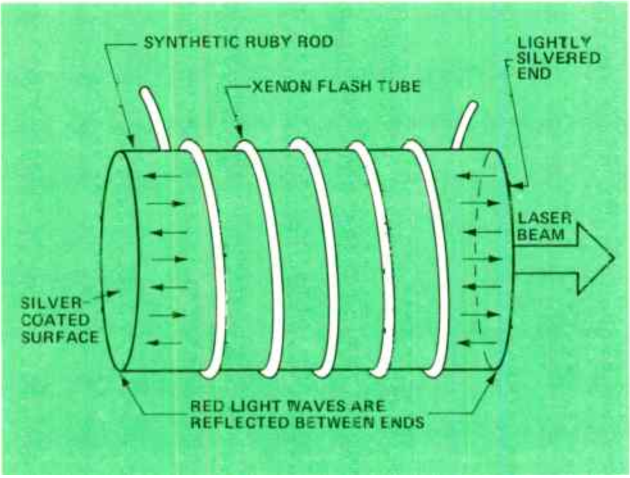

Figure 4. Theodore Maiman's first laser had silver coatings on the ends of the ruby rod; later adaptations of the device utilized external silver mirrors at the ends of the rods.

more of these atoms collect at the intermediate level than at the ground level. This is a condition called "population inversion," which is indicative of a state of great potential energy. This energy is released when a random chromium atom drops from the intermediate level to ground level, causing a photon to be emitted. This photon collides with nearby metastable atoms, causing the emission of more photons which in turn collide with other metastable atoms. Some of these photons strike the silvered ends of the ruby crystal and are reflected along the rod to the opposite end. In a short time, a whole stream of photons is bouncing back and forth between the ends of the rod. As they do so, they trigger additional metastable atoms and eventually generate an intense beam of light which, when of sufficient magnitude, bursts through the lightly silvered end of the rod as a pulse of monochromatic (one color or frequency), spatially coherent light. Because the photons in this beam of light are almost exactly parallel, they remain in this state for great distances, whereas incoherent beams of light, such as emitted from an incandescent lamp, are quickly dispersed in all directions. The basic operation of the ruby laser is similar to that of other types of lasers, even though the material that is irradiated differs.

A laser beam, with its coherent light waves, is capable of some astounding feats. It can, for example, be focused with enough intensity to heat a pail of water at a distance of one thousand miles. In 1962, laser beams projected toward the moon's surface arrived with a spread of only two miles after having traveled some 240,000 miles through space. In medicine, the laser can prevent the eventual blindness caused by a detached retina: a laser beam focused through the lens of the eye welds the retina back in place. Eye tumors can also be disintegrated by a laser beam, and lasers can be used to cauterize wounds and to take the place of the dentist's drill.

Communications

One possible application that has resulted in intensive research is the use of lasers in the transmission of information. The tremendous bandwidth available at coherent light frequencies is many times that presently available in the microwave spectrum. Utilization of the light spectrum for communications brings closer to the realm of reality the possibility that each person on earth can someday have his own personal wavelength.

To use light frequencies for carrier communications, it is necessary to modulate the carrier frequency. Optical modulators for communications are still under investigation. Optical waveguides capable of conveying light from point to point offer great possibilities for the transmission of information by laser. At present, a point-to-point laser communications system over open space similar to a microwave system seems unlikely, since light waves are much more subject to interference by fog, clouds, and dust than are microwaves. There is, however, a possibility that the carbon-dioxide laser, which produces continuous high power laser beams in the infrared region, may make atmospheric communications possible.

Semiconductor Lasers

Many lasers are inefficient in the conversion of pumping energy into laser light. Consequently, they tend to require great amounts of power for operation, which usually means a very heavy and unwieldly power supply. The semiconductor laser (also called injection, junction, and diode laser) is a step toward the solution of this problem, since it is extremely efficient and lightweight. The injection laser is simply a semiconductor diode, usually composed of gallium arsenide (GaAs), or of gallium arsenide-phosphide (GaAsP). The semiconductor gallium phosphide fascinated scientists for years because it emitted flashes of bright red light when current passed through it. It was later discovered that other semiconductor materials composed of compounds of gallium and arsenic radiated infrared light when a current was passed through them. And, while this infrared light consisted of incoherent waves, it still was possible to use it in an experimental transmission system to send messages through the atmosphere to a receiver 30 miles away. The fact that semiconductors were capable of converting electrical energy into photons of electromagnetic radiation led scientists to believe that with a large enough current, lasing action might be achieved. In 1962, laser action in a semiconductor was achieved, although a current density of 10,000 amperes per square centimeter was necessary for proper operation. This required that the laser be cooled down to temperatures close to absolute zero (–273°C).

An injection laser might appear as shown in Figure 5. Electrons injected into the diode junction produce the initial photons which go on to strike neighboring atoms, causing them to emit additional photons. Just as in the ruby laser, the end surfaces of the semiconductor junction are polished so that they may reflect the photon bombardment; when the reflections build up to sufficient energy, a beam of coherent light is emitted from the semiconductor junction. One definite advantage of the injection laser is that there is no requirement for a separate pump mechanism since the direct injection of electrons performs this function (for almost each electron injected, a corresponding photon is produced). Also, the output frequency of the injection laser can be controlled by varying the operating temperature and by altering the chemical composition of the semiconductor material. The output power varies in proportion with the magnitude of the current through the device.

In spite of the development of ruby, gas, and semiconductor lasers, and their subsequent use in industry, medicine, astronomy and as laboratory tools, the role of the laser as a signal carrier has as yet to be truly realized.

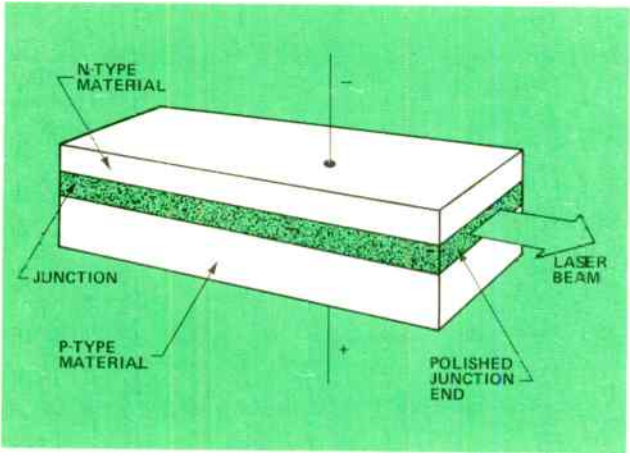

Figure 5. Principal elements of the injection laser.

The large lasers are too expensive for a large-scale communications system, and even the injection lasers have, until recently, had such a high current requirement that continuous operation could not be sustained (due to overheating) except at cryogenic (very low) temperatures. At room temperature, injection lasers could operate properly only in a pulsed mode, a limitation that is not compatible with the modern transmission of information.

Continuing developments in laser technology have produced semiconductor lasers capable of operating continuously at room temperature, and with a significantly smaller current requirement than the previous injection lasers. The types of lasers which can perform these functions are called double heterostructure (DH) injection lasers. In fact, the most promising injection laser for telecommunications is presently the double heterostructure laser composed of layerings of $Al_xGa_{1-x}As$ (with varying values of x). This type of laser is well suited for use with optical fiber communications systems. It has such desirable characteristics as small size, ruggedness, good efficiency, and can be pumped and modulated by means of the injected current. DH lasers are tinier than a grain of sand, can be powered by ordinary dry cell batteries, and together with other necessary advancements in optoelectronics will very likely play a part in the first experimental optical transmission systems.

The coupling of laser energy into multimode optical fibers can be accomplished easily and efficiently simply by positioning the fiber at the laser output end. However, there are still problems to be solved. For example, when coupling a DH laser to single-mode optical fiber, some type of mode transformation device is necessary because the mode of the laser output has an elliptical cross section, while that of the optical fiber is circular.

The future of laser communications is still very much in the making. And, at this point, it is difficult to say just where, and how far, scientific development will take the field of optical communications. But in a world where modern technological miracles seem to be occurring in great abundance, it is perhaps unwise to set limitations on possibilities by calling them science fiction.

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