**1895** Guglielmo Marconi (Italy) invents the wireless telegraph (radiotelegraph) and receives a patent for it in London, his patent request in Italy having been turned down.

**1897** Sir Joseph John Thomson, an English physicist, concludes from his experiments that all matter contains tiny electrified particles called electrons (originally, he calls them corpuscles). He also  the charge-to-mass ratio of electrons.

**1899** Lord Rayleigh (England). Explained the blue colour of the sky and red sunsets as being due to the preferential scattering of blue light by molecules in the earth's atmosphere.

**1899** Marie P A C Fabry and Jean B G G A Perot (France). Described the Fabry-Perot interferometer which enabled high resolution observation of spectral features

**1900** Max Karl Planck (Germany). In his successful explanation of the spectrum of radiation emitted from a hot black body, Planck found it necessary to introduce a universal constant described as the quantum of action, now known as Planck's constant. A consequence is that the energy of an oscillator is the sum of small discrete units, each of which has a value that is proportional to the frequency of oscillation

**1905** Albert Einstein analyzes the phenomena of the photoelectric effect and theorizes that light may be taken to be made up of vast amounts of packets of electromagnetic radiation in discrete units. the quanta subsequently becoming known as photons

Einstein publishes his paper, "On the Electrodynamics of Moving Bodies," drawing out the symmetries of Lorentz's electromagnetic theory, underlying connection in measurement theory and the status of the electromagnetic aether.

**1907** Hermann Minkowski, through considerations of the group properties of the equations of electrodynamics, reinterprets Einstein's relativity theory as a kind of geometry of spacetime, considered as a single medium.

**1908** Gustav Mie (Germany). Presented a description of light scattering from particles that are not small compared to the wavelength of light, taking account of particle shape and the difference in refractive index between the particles and the supporting medium

**1913** Neils Henrik David Bohr (Denmark). Bohr advanced a theory of the atom in which the electrons were presumed to occupy stable orbits with well-defined energy. According to this theory, the absorption and emission of light by an atom occurs in discrete amounts, or quanta, equal to the energy gained or lost by the electrons when moving from one orbit to another of different energy. This allowed an explanation of the observation that atoms absorb and emit light at particular frequencies that are characteristic of the atom

**1916** Albert Einstein (Germany). Proposed that the stimulated emission of light is a process that should occur in addition to absorption and spontaneous emission

In the 1920's, J.L. Baird and C.W. Hansell patented the idea of using arrays of transparent rods to transmit images for television and facsimiles respectively.

Clarence W. Hansell outlined in 1928 the principles of the fibre-optic imaging bundle at the RCA Rocky Point Laboratory on Long Island.

**1924** Louis de Broglie (France) develops a revolutionary theory of electron waves, proposing that particles of matter may behave like waves under certain conditions.

**1924** Indian physicist Satyendra Nath Bose publishes a paper clarifying the relationship between waves and particles. This will lead to a collaboration with Albert Einstein and a theory called Bose-Einstein statistics.

**1927** Paul Adrien Maurice Dirac (England). Presented a method of representing the electromagnetic radiation field in quantized form

**1928** Indian physicist Chandrasekhara Raman observes that when light passes through a transparent substance, some of the light is deflected and changes in wavelength. This effect arises from the scattering of light by vibrating molecules This will eventually be called Raman scattering, a result of the Raman effect.

In **1930** Heinrich Lamm was the first person to assemble a bundle of optical fibers to carry an image.

**1930** While studying flaws in diffraction gratings, Fritz Zernike (Holland) discovers the phase contrast principle that allow him to view the internal structure of transparent objects. The different materials making up the object have different refractive indices, which makes it possible to illuminate them in a way that they are visible.

**1934** Pavel A. Cherenkov (Russia) discovers that electrons emit light (Cherenkov radiation) as they pass through a transparent medium, if they are moving faster than the speed of light for that medium.

The first coaxial-cable system, put into service in **1940**, it was a 3-MHz system capable of transmitting 3000 voice channels or a single television channel, considerably increasing the system capacity as compared to wire pairs. However, the bandwidth of such systems is limited by the frequency-dependent cable losses. For frequencies beyond 10MHz, the cable losses increased rapidly. Because of this limitation, microwave communication systems were developed to overcome such limitation.

**1941** W C Anderson. Measured the speed of light using a Kerr cell to modulate a light beam that passed through a Michelson interferometer. Obtained a value of 299,776 km.s-1

**1948** Dennis Gabor (Hungary/England) performs his first experiments in "wavefront reconstruction" a technique designed to improve electron microscopes. In the 1960s, after the invention of the laser, his technique is renamed "holography" and is used to produce three dimensional photographs, or holograms.

**1948** The first microwave system operating at the carrier frequency of 4GHz was put into service.

**1954** C H Townes, J P Gordon and H J Zieger (USA). In a paper entitled "Molecular microwave oscillator and new hyperfine structures in the microwave spectrum of NH3", they described a maser built at Columbia University which used ammonia to produce coherent microwave radiation.

**1954** Dutch scientist Abraham Van Heel and British scientist Harold. H. Hopkins independently publish papers on imaging bundles, which leads to the development of modern fiber optics.

In **1954**, A. Van Heel and H.H. Hopkins separately wrote papers on imaging bundles. Hopkins reported on imaging bundles of unclad fibers while Van Heel reported on simple bundles of clad fibers. He covered a bare fiber with a transparent cladding of a lower refractive index. This protected the fiber reflection surface from outside distortion and greatly reduced interference between fibers. At the time, the greatest obstacle to a viable use of fiber optics was in achieving the lowest signal (light) loss.

In **1956** N.S. Kapany invented the glass-coated glass rod which was used for non-telecommunications applications. The glass-coated glass rod helped eliminate the biggest problem that hindered Alexander Gram Bells photophone by providing a means of protecting the beam of light from environmental obstacles. Kapany is also known for coining the very familiar phrase, fiber optics [AMP,82,p.11]. In 1956 Kapany used a rod of glass coated with a further layer of glass. This was not used for communication purposes, but was nonetheless the first appearance of the structure we now use as an optical fiber.

**1956** melting a tube onto a rod of higher-index glass for making glass clad fibers first suggested then applied by Curtiss.

**1958** Arthur L Schawlow and Charles H Townes (USA). Published a paper entitled "Infrared and Optical Masers" in which it was proposed that the maser principle could be extended to the visible region of the spectrum to give rise to what later became known as a 'laser'

**1959** American Optical in collaboration with Hicks draws fibers so fine they transmit only a single mode of light. Elias Snitzer is the first to recognize them as single-mode waveguides.

**1960** Theodore H Maiman (USA). Described the first ruby laser (fig. 8). The laser was built at the Hughes Research Laboratories and used a rod of synthetic ruby as the lasing medium Important groundwork for optical communications was clearly being laid so far. Bending light, containing it in "tubes" and making glass fibers all would prove critical to creating practical optical communications systems; but the time was not yet right for these early experiments to come together. The combination of these advances in knowledge needed a catalyst. After the Mainman's invention, the possibility of optical communications became a reality. Light waves have an important advantage over radio waves: a much higher frequency. The higher the frequency of a signal, the more information it can carry. The enormous bandwidth meant substantially increased potential to transmit video signals, which require about 6Mhz. However, the vast potential of the laser could not be realized unless the light it emitted could be transmitted through some medium..

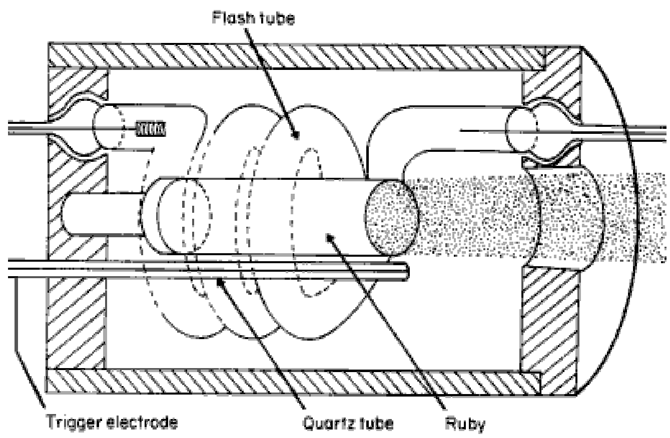


**Fig. 8:** Schematic view of the Maiman's first ruby laser, after **[8]**

In **1961**, Elias Snitzer of American Optical published a theoretical description of single mode fibers, a fiber with a core so small it could carry light with only one waveguide mode. Snitzer's idea was appropriate for a medical instrument looking inside the human, but the fiber had a light loss of 1dB/m. Communications devices needed to operate over much longer distances and required a light loss of no more than 10-20dB/Km.

**1961** P A Franken, A E Hill, C W Peters and G Weinreich. Demonstrated harmonic generation from light by passing the pulse from a ruby laser through a quartz crystal

**1961** Ali Javan, W R Bennett and Donald R Harriott (USA). Described the first gas laser (helium-neon). Built at the Bell Laboratories, the lasing medium was a mixture of helium and neon and emitted at wavelengths in the near infrared, the most intense beam being at a wavelength of 1.153 um

**1962** Robert N. Hall's team at General Electric makes first semiconductor diode lasers, but they operate only at liquid-nitrogen temperature.

**1962** Four groups in the United States described the observation of stimulated emission from homojunction gallium arsenide semiconductor diodes: M I Nathan et al, (IBM); R N Hall et al, (GEC); T M Quist et al, (MIT); N Holonyak and S F Bevacqua, (GEC).

In **1964**, a critical (and theoretical) specification was identified by Dr. C.K. Kao for long-range communication devices, the 10 or 20 decibels of light loss per kilometer standard. Kao also illustrated the need for a purer form of glass to help reduce light loss.

**1964** William B Bridges (USA). Built the first ion lasers at Hughes Research Laboratories

**1964** Jerome V V Kasper and George C Pimentel (USA). Described the photodissociation Iodine laser, built at the University of California, Berkeley, in which a population inversion in atomic iodine was produced by the photodissociation of either CF3I or CH3I. The laser output was in the near infrared at a wavelength of 1.315 um

**1964** Chandra K. N. Patel (USA) builds the first carbon dioxide laser at Bell Laboratories.

**1964** Emmett Leith and Juris Upatnieks of the University of Michigan produce the first hologram.

**1966** Sorokin and J R Lankard. Built the first organic dye laser

In **1966** K.C. Kao and G.A. Hockham suggested to the Institution of Electrical Engineers in London that glass fiber could be used as waveguides for light transmission. In order to make glass fiber a viable media for transmission of light, losses per kilometer, which were around 1000 dB/km in the late 1960s, had to be reduced. Kao and Hockham theorized that by controlling the purity of the glass, the loss per kilometer could be reduced to 20 dB/km, making them suitable for communications. At the same time, GaAs semiconductor lasers, operating continuously at room temperature, were demonstrated. The simultaneous availability of a compact optical source and a low-loss optical fiber led to a worldwide effort for developing fiber-optic communication systems. On the same year, R. Maurer at Corning Glass Works (now Corning, Inc.), starts a research project on fused-silica fibres.

**1967** Shojiro Kawakami proposes graded-index optical fibres. They show a better tolerance to microbendings as compared to step-index fiber optics

**1967/69** S L McCall and E L Hahn (USA). Described studies of the propagation of very short optical pulses through a medium consisting of resonant two level atoms, developing in the process the criteria to be satisfied by the shape of the pulse so that it would propagate as an optical soliton (the area theorem) and describing the propagation mechanism of self-induced transparency (SIT)

**1969** The first computer network and predecessor of the Internet, ARPANET (Advanced Research Project Association Network), is established. This allows scientists at four universities to access each other's computers in order to share information.

Since the **late 60's** guided wave optical communication systems become a reality. One of the problems associated with fiber optics communication was related to signal repeaters able to recondition and reamplify the optical signal. The solution offered by conventional optics, through a system of bulk mirrors and lenses separated by distances of 10 to 100 meters, was clearly unsatisfactory. A reseacher at Bell Laboraties, S.E. Miller, borrowing the concept of the integrated electronic circuit, proposed an optical integrated circuit (OIC) in which various components could be combined and interconnected with optical waveguides on a single, small, substrate. The concept of integrated optics was born.

In **1970**, one team of researchers began experimenting with fused silica, a material capable of extreme purity with a high melting point and a low refractive index. Corning Glass researchers Robert Maurer, Donald Keck and Peter Schultz invented fiber optic wire or "Optical Waveguide Fibers" capable of carrying 65,000 times more information than copper wire, through which information carried by a pattern of light waves could be decoded at a destination even a thousand miles away. The team had solved the problems presented by Dr. Kao.

**1970** First continuous-wave room-temperature semiconductor lasers made by Zhores Alferov's team at the Ioffe Physical Institute in Leningrad.

**1970** Corning Glass (USA) researchers Robert Maurer, Donald Keck, and Peter Schultz produce high quality optical fiber for use in telecommunications.

By **1972**, Corning Glass Works was producing laboratory test fibers with losses of 4 dB/km. The loss per kilometer of present day fiber is between 0.25 and 0.4 dB/km depending on the wavelength of the light propagating through the fiber.



The most advanced coaxial system, was put into service in **1975**, operated at a bit rate of 274Mbps. However, a high-speed coaxial system requires the small repeaters spacing (appox. 1km) that makes the system relatively expensive to operate. Microwave communication systems generally allow larger repeater spaces, but their bit rate is also limited by the carrier frequency of such waves.

**1976** Masaharu Horiguchi and Hiroshi Osanai make first fibres with low loss at long wavelengths, 0.47 dB/Km at 1.2μm.

**1976** John M J Madey (USA). A group at Stanford University demonstrated the first free electron laser (FEL)

**1977** General Telephone and Electronics (GTE) establish the first fiber optic network for phone services, in Long Beach, California.

The commercial deployment of lightwave systems followed the research and development closely. After many field trials, the first generation lightwave systems operating near 0.8 micrometer began to deployed in **1978**. They operated at a bit rate in the range 50-100Mbps range and allowed a repeater spacing of about 10km. The larger repeater spacing compared with coaxial system was an important motivation for the system designers as it decreased the installation and maintenance costs associated with each repeater. During the 70s, the repeater spacing was increased considerably by operating the lightwave system in wavelength region near 1.3 μm, where fiber loss is generally below 1dB/km. Furthermore, optical fibers exhibit minimum dispersion in this wavelength region. In 1977, InGaAsP semiconductor lasers and detectors were developed. Such lasers operate near 1.3μm.

As early as 1979, a loss of 0.2dB/km in 1.55 μm was realized (fig.9). However, its introduction was considerably delayed due to large fiber dispersion near 1.55μm. The dispersion problem can be overcome either by using dispersion-shifted fibers designed to have minimum dispersion near 1.55μm or by limiting the laser spectrum to a single longitudinal mode.

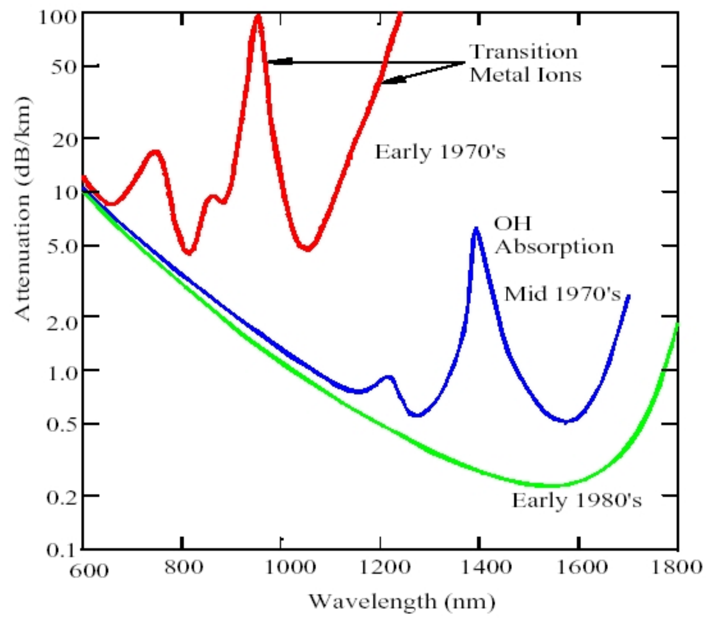


**Fig. 9:** Wavelength Vs. Attenuation evolution in the period 70s-80s. After **[9]**

In early **1980s**, the second generation of fiber-optic communication systems became available and allowed a repeater spacing in excess of 20km. However, the bit rate of early systems was limited to below 100Mbps because of modal dispersion in multi-mode fibers. This limitation was overcome by the use of single-mode fibers. A laboratory experiment in 1981 demonstrated 2-Gbps transmission over 44km of single-mode fiber. The introduction of commercial systems soon followed.

**1981** Gerd Binnig (Germany) and Heinrich Rohrer (Switzerland) develop the scanning tunneling microscope, providing the first images of individual atoms on the surfaces of materials

**1982** British Telecom abandons graded-index in favour of single-mode after performing field trial of single-mode fiber

**1985** D L Matthews et al (USA). Described x-ray laser experiments at the Lawrence Livermore National Laboratory in which amplified spontaneous emission was observed at wavelengths around 20nm. Fiber optic networks for long distance phone service spread across the United States, carrying signals at 400 million bits per second and up.

By **1985** the laboratory transmission experiments showed the possibility of communicating information at bit rates up to 4Gbps over distances in excess of 100km.

**1986** The term "Internet" is used for the first time to describe the loose collection of networks that make up the ARPANET.

**1986** AT&T transmit 1.7 billion bits per second through single-mode fibers intended to carry 400 million bits per second.

By **1987**, second-generation 1.3 micro-meter lightwave systems operating at bit rates up to 1.7Gbps with a large initial installation cost, such systems were cheaper to operate in the long run compared with coaxial systems, which generally operate at lower bit rates about 100Mbps with smaller repeater spacing less than 10km.

**1988**: First transatlantic fiber-optic cable, TAT-8, begins service, using single-mode fiber.

The third-generation 1.55 µm systems operating at 2.4Gbps became available commercially in **1990**. Such systems are capable of operating at bit rates in excess of 10Gbps with careful design of semiconductor lasers and optical receivers. The development of 10Gbps lightwave systems is under way in several laboratories. The limiting factors are frequency chirping and the occasional transient turn-on of a secondary laser mode; both lead to errors in the presence of fiber dispersion. The best performance is achieved by using dispersion-shifted fibers together with single-longitudinal-mode lasers.

The fourth generation of lightwave systems is concerned with an increase in the bit rate through frequency-division multiplexing and an increase in the repeater spacing through optical amplification. Such systems sometimes make use of homodyne or heterodyne detection schemes; they are then referred to as coherent optical communication systems. Coherent systems have been under development worldwide during 1980s, and their potential advantage has been demonstrated in many system experiments. In one experiment 100 channels of 622Mbps were multiplexed by using a star coupler and transmitted over 50km of fiber length with negligible inter-channel crosstalk. In another experiment a single coherent channel operating at 2.5 Gbps was transmitted over a fiber length of 2223km without signal regeneration: Fiber loss was compensated by using erbium-doped fiber amplifiers spaced every 80km. The use of coherent detection is not a prerequisite for



lightwave systems employing optical amplifiers. Data transmission over 4500km at 2.5Gbps and over 1500km at 10Gbps has been demonstrated in the laboratory experiments by using the conventional (no-coherent) techniques. Another experiment showed the possibility of transmission over 21,000 km at 2.4Gbps and over 14,300km at 5Gbps by using a recirculating-loop configuration.

Beginning in **1990**, optical amplifiers appear to have begun revolutionizing the field of optical fiber communications.

The fifth generation of fiber-optic communication systems is already at the stage of research and development. It is based on the novel concept of fiber solitons, optical pulses that preserve their shape during propagation in a lossless fiber by counteracting the effect of dispersion through the fiber nonlinearity. In 1988, a laboratory experiment showed the possibility of transmission over 4000 km by compensating the fiber loss through stimulated Raman scattering. In 1989, Erbium-doped fiber amplifiers were used for solitons amplification starting. Since then, several system experiments have demonstrated the eventual potential of solitons communication systems. In two system experiments solitons were transmitted over 1000 km at 10Gbps and over 350km at 20Gbps. In another recirculating-loop experiment, solitons at 2.4Gbps could be maintained over 12,000 Km

**1991** Soliton signals through a million kilometers of fiber reported by Masataka Nakazawa of NTT.

**1991** The World Wide Web is born. After two years of developing his concept for the Web, Tim Berners-Lee (England) establishes the first web server at CERN in Geneva, Switzerland.

**1993** using a simpler soliton system Linn Mollenauer of Bell Labs sends 10 billion bits through 20,000 kilometers of fibres.

**1998** The Federal Communications Commission (FCC) issues its specifications for the conversion of television signals from analog to digital, beginning in 1999 and culminating in 2006 with the abolition of all analog TV broadcasts.

Today more than 80 percent of the world's long-distance traffic is carried over optical fiber cables, 25 million kilometers of the cable Maurer, Keck and Schultz designed has been installed worldwide. Even though the field of optical fiber communications is barely two decades old, it has progressed rapidly and has reached a certain stage of maturity. This is apparent from the publication of a large number of books on this field during the 1980s. Most of these books have become outdated because of the rapid pace of progress.

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