The laser before and after 1960. The laser was born May 16, 1960 at Malibu California

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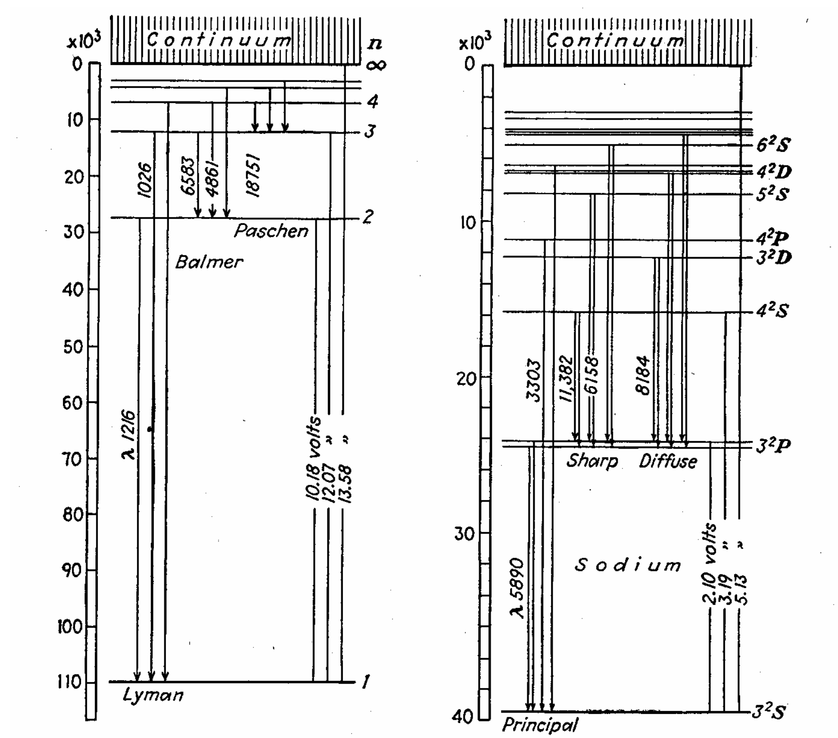
Very Early History

- 1849, N.Fizeau's velocity of light (**c**) measurement
- 1864, J.V.Mawell's E&M theory which predicted **$c=3x10^8 m/s$**
- 1867-1892, H.Hertz's experimental verification of Maxwel'sl theory including **c** measured at 3 and 400 MHz
- 1900, M.Planck's (1858-1947, 1918 Nobel Prize) derivation of the formula for the radiation from blackbodies which introduced **$h=6.624x10^{-34}$Joule sec**
- 1905, A.Einstein (1879-1955, 1921 Nobel Prize) explained the photoelectric effect; **$Ve = hc/\lambda$**
- 1913, N.Bohr's (1895-1962, 1922 Nobel Prize), planetary model of the hydrogen atom, with quantized orbits, derived Balmer's experimental spectral equation:**$\lambda=(365nm)(n^2/n-^2)$,**a=2,3..n. Bohr quantized electron orbit angular momentum in units of **$nh/2\pi$**



Einstein's **A** and **B** coefficients

- 1914-1917, A. Einstein, introduced the concepts of spontaneous (**A**) emission, induced absorption (**B**), and stimulated (**B**) emission of radiation to clarify Plank's derivation of the blackbody law, his own explanation of the photo electric effect, and Bohr's derivation of the spectra of hydrogen. For a two level system with N_2 atoms per unit volume in an upper energy state, N_1 in a lower state, both in a radiation field ρ(ω), Joules per unit volume per second, Einstein assumed that the upper state changed at a rate of

$$dN_2/dt = N_1 B\rho(\omega) - N_2 B\rho(\omega) - N_2 A$$

Blackbody Derivation

- When the atoms are in equillibrian with the radiation field $dN_2/dt=0$ and $B\rho(\omega)[N_1-N_2]=N_2A$ or

$$\rho(\omega) = \frac{A/B}{\left[\frac{N_1}{N_2} - 1\right]}$$

$$N_1 = k_1 \exp - e\varphi_1 / kT$$

$$N_2 = k_2 \exp - e\varphi_2 / kT$$

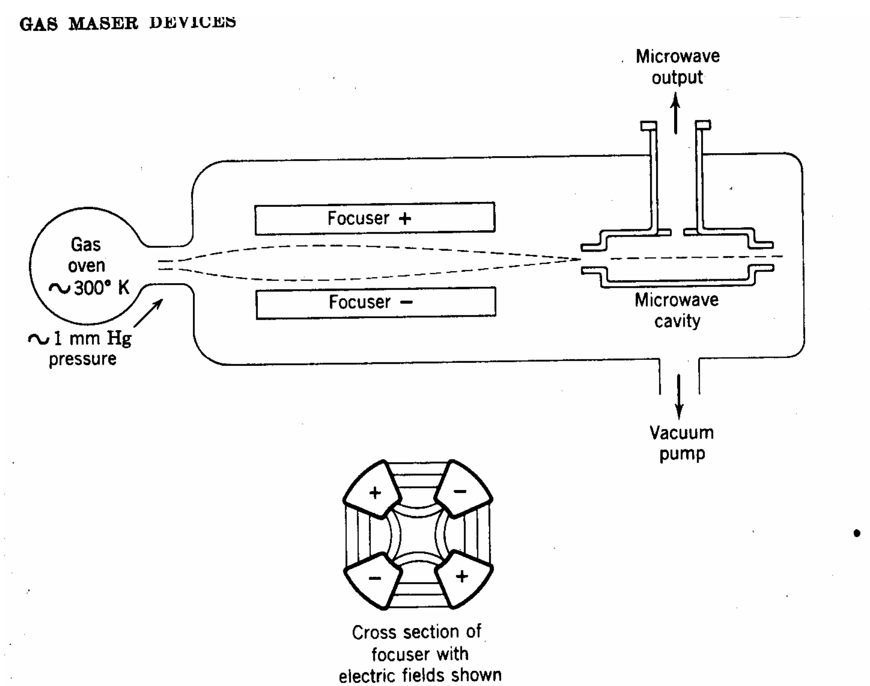
$$e\varphi_2 - e\varphi_1 = h\nu$$

MASERS came before LASERS

- 1930-1945. the development of microwave magnetrons and klystrons saw the invention of cavity resonators; the simplest being two parallel reflectors (the Fabry Perot, also used in optics.
- 1947, D.Gabor (1900-1979, 1971 Nobel Prize) introduced and demonstrated the principal of holography; that a diffraction pattern carries all the information about a scene.
- 1954 Charles Townes' (1915-, 1964 Nobel Prize), invention of the ammonia **MASER**
- 1958, Makhov operated the first magnetically tunable maser which used the ground state of cryogenically cooled pink ruby. The laser was pumped at 24.2 GH (K band) and operated 9.22 GHz (X band)
- 1956-1960 the Hughes Research Laboratories initiated a solid state maser program. T.H.Maiman lead the design and test group. The group achieved maser operation with ruby at 77.4^{o}K
- 1962 D.Devor, C.Asawa, & D'Haenes (Hughes) pumped a ruby maser with a ruby laser
- 1963, A. Pinzias(1933-) and R. Wilson (1936-) discovered and measured the 3.5^{o}K (remeasured 2.735^{o}K) cosmic background temperature with a ruby maser. Both shared the 1978 Nobel Prized with P. Kapitsa

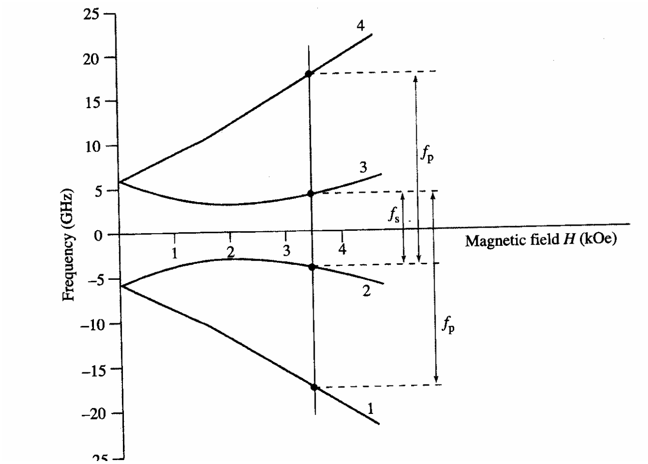
The NH_3 Maser, the first application of stimulated emission

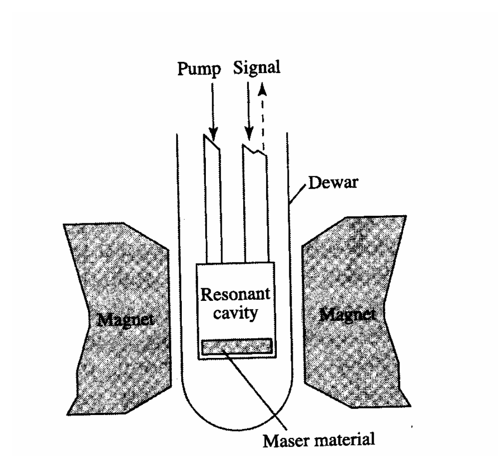
- 1954 Charles Townes (1915-, 1964 Nobel Prize) invention of the ammonia **MASER** (**M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation). An upper state of NH_3 sustained oscillation in a metal tube resonator at 23.870 GHz (λ=1.307 cm and **A**=0) by stimulated emission



The Pink Ruby Maser

- Ground state energy level diagram of pink ruby used as tunable maser along with a schematic of this apparatus



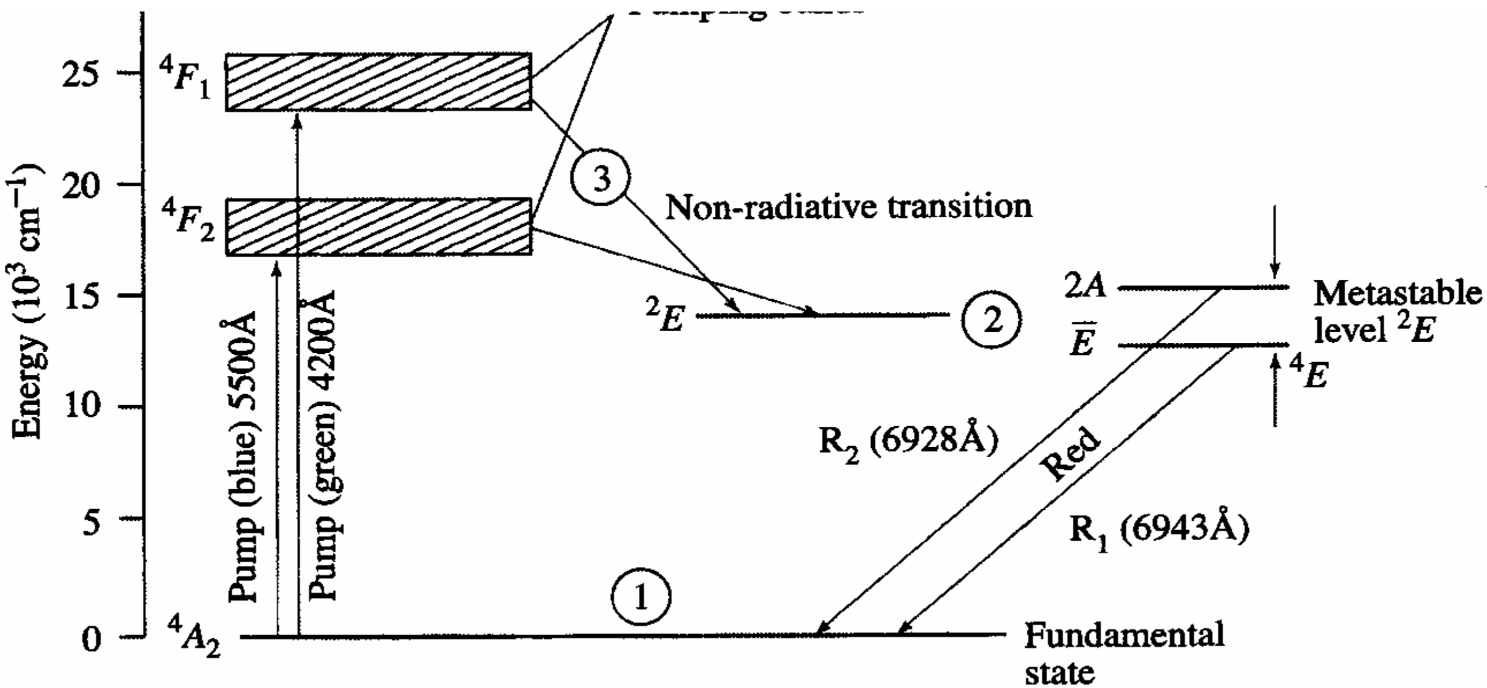


The Spontaneous Emission Barrier

- 1955-1960 attempts to generate visible light by stimulated emission were considered. The large value of **A** in the visible (15 ns for Na resonant radiation at 589 nm) led many to conclude that a "visible light maser" could be impossible.
- During this period, Bell Telephone were investigating CW gas discharges in He-Ne, resonant pumping, and fluorescent solids. An aerospace company (TRG) hired Gordan Gould who had already claimed the concept a laser with two end mirrors.. His initial choice for a lasing media was a CW discharge in thallium vapor.

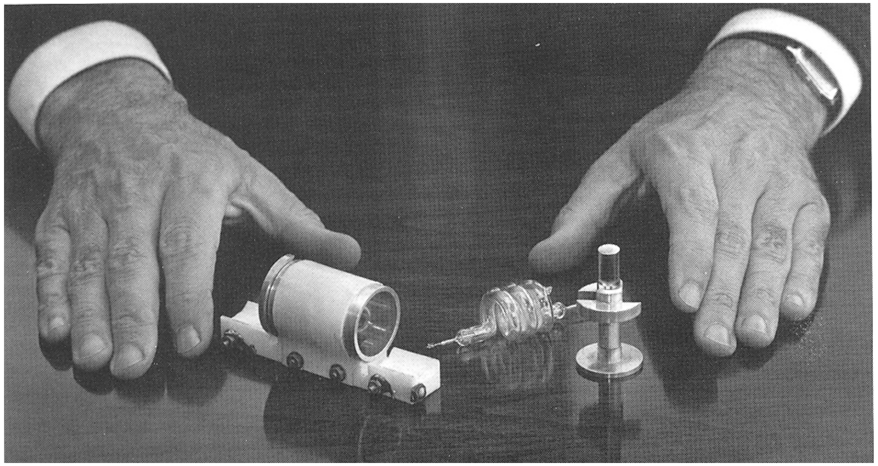
$$\frac{1}{\tau_{spon}} = A = \frac{64\pi^4 e^2 \nu^3}{3hc^3}\left[x^2\right]$$

Energy level diagram of pink ruby



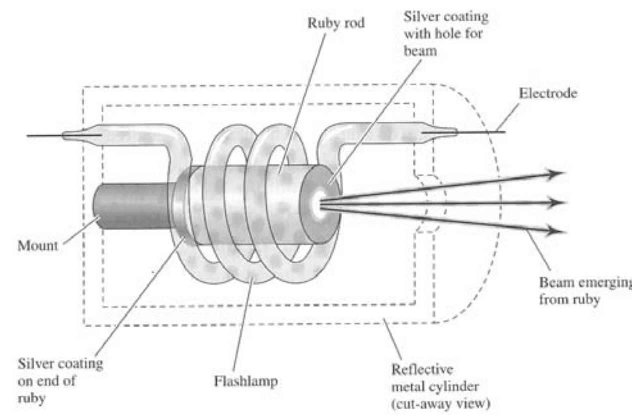
The first visible laser

- 1960, T.H.Maiman (1927-2007) put a 1x2 cm piece of pink ruby, with parallel silvered ends, inside a small helical xenon gas pulsed electronic photographic flash lamp (≥5,000°K), both were mounted inside a reflecting aluminum housing. A hole scratched in the center of one of the silver end coatings sampled the emitted light..



May 16,1960 the first laser

- At low energy flashes he observed the expected 3ms decaying 694.3 nm spontaneous emission, As the flashlamp's discharge energy increased abrupt high amplitude stmulated emission pulses were seen. The first visble light laser was born at the new Highes Research Laboratory Malibu California, overlooking the Pacific Ocean.



Early improvements and discoveries

- Maiman's experiment was duplicated throughout the world. Other fluorescentt solids were found to **LASE** (**L**ight **A**mplification by **S**timulated **E**missin of **R**adiation) when subjected to pulsed flashlamp irradiation: neodymium in glass (1060 nm), neodymium in calcium tungstate (1800 nm), uranium in calcium flouride (2050 nm), etc. Maiman's success introduced optical pulsing as a new method for generating visible and infra red laser radiation.
- The silver coatings, on the ends of the ruby, were replaced by dielectric coatings. The semi reflecting output mirror was optimized to extract the most energy from longer and larger ruby rods. A single coated ruby rod produced a jumble of kilowatt pulses. Focused by a lens these outputs could drill a microscopic hole through a steel razor blade. Early ruby lasers were judged by the number of Gillette blades thar could be drilled
- A second uncoated ruby functioned as an amplifier (Gain of ~3 for a 10 cm long rod).
- The end mirrors could be separated from the oscillator's ruby
- 1961, R.W. Helliwarth (see Advances in Quantum Electronics, pp 334); a single "giant" pulse was generated by a shutter between the 100% end mirror and the oscillator ruby. The shutter could be a rotating disk with a hole, a rotating end reflector, an electronic Kerr cell, or a solid state Pockles cell. When the shutter was opened, during the flashlamp pulse, the "giant" pulse was typically 50 ns duration. A ruby 1 cm in diameter and 10 cm length could be timed to emit a Joule in 50 ns or a pulse of 20 MW. When the beam was focused with lens, a spark formed in air with a bang!

More Important Discoveries

- 1961 P.Frankin (1928-1999) focused a gaint ruby laser pulse into quartz and observed the generation of ultra violet light at half the wavelength of the ruby laser ($\lambda = 694.3/2 = 346.1$nm) Later more efficient means for 2nd harmonic generation or "doubling" were discovered when the two frequencies travel through the crystal at the same speed. KDP and ADP crystals can be so aligned and can convert 50% of the input light into doubled radiation.

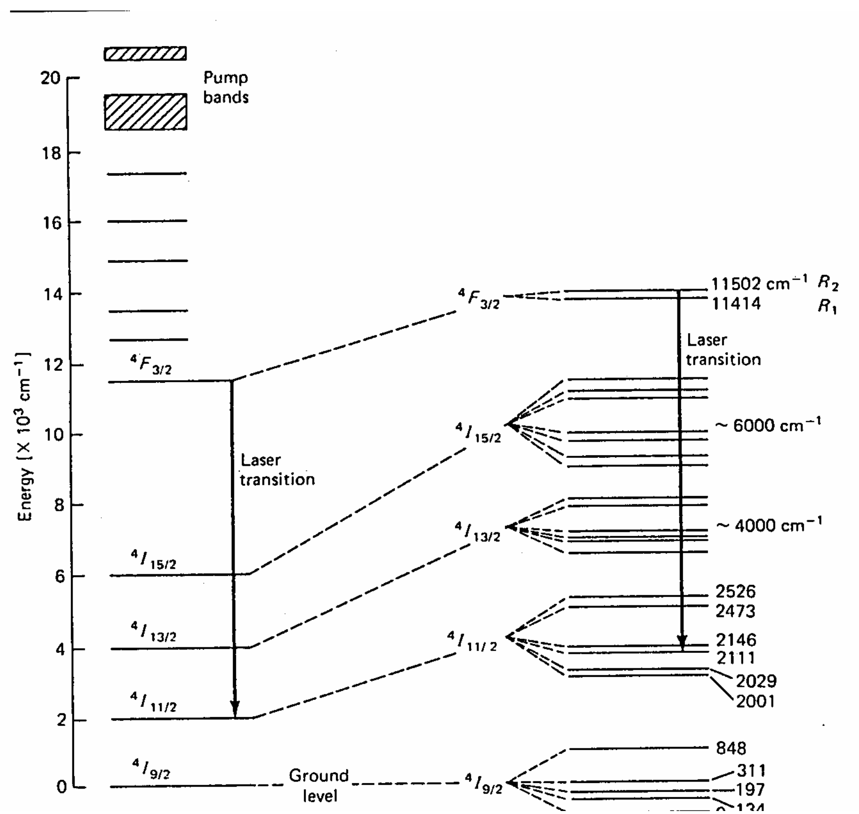
- 1961A.Javan (Bell Labs) operated the first continuous gas dischare HeNe laser which emmted at 1150 nm.

- 1962, J Geusic and E. Scovil demonstrated lasing from flash lamp pumped neodymium in a yttrium aluminum garnet crystal (YAG, $Y_3Al_5O_{12.}$). Nd in either YAG or glass is a four level laser mrdia. The terminating quantuim state is above the ground state with the result that the threshold for lasing is much lower than ruby. Nd YAG have been pumped with CW lamps. The YAG laser has replaced the ruby laser in most of the applications that required Q switched pulse generation, etc.

- 1962, E.Leith and J.Upatnieks, first off axis holograms that produced true three dimensional positive imagery with continuous changing parallax.

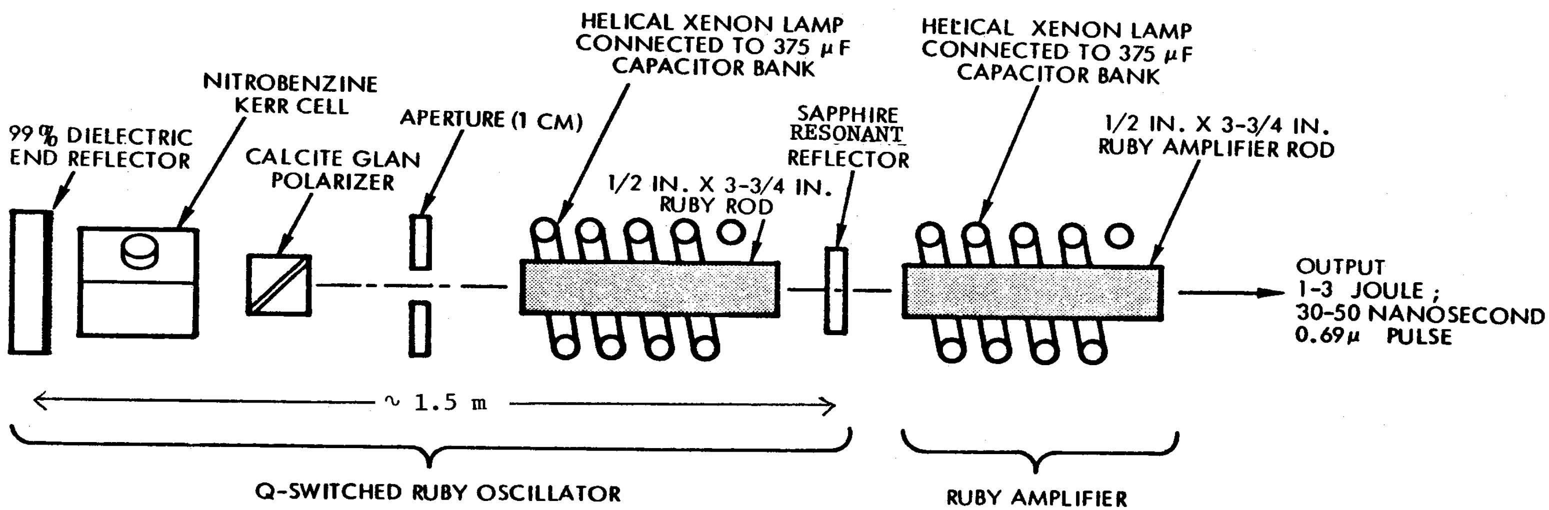
- 1963 B.Soffer, saturable filters function as Q switch and mode control element. Saturable dyes for ruby include include cryptocanine dissolved in acetone or ethyl alcohol, DDI in methyl alcohol, Vandylphthalocyanine in nitrobenzene, and chlorphyll-d in mineral oil..

Energy level diagram of Nd-YAG



A 1960-1980 era Q Switched laboratory ruby laser

- Most of the unique properties of laser light were discovered with Q switched ruby lasers like the one shown schematically below



Important Early Discoveries Continued

1964, K.Patel (1932-) invented the 100600 nm CO_2 laser

1965, J.M.Dawson (1930-2001) (UCLA) and O.N.Krokhin (1927-, Russia) independently proposed pulsed laser interaction with fusion pellets as a new thermo nuclear scheme. Later neutrons were generated at LLNL with a 50 J Q switch ruby oscillator-amplifier system. The achievement launched a world wide effort in laser fusion research.

- 1966,P Sorkin, made dye solutions lase by including them in the cavity of a Q switched ruby laser. The Q switch radiation pumped the inter cavity dyes..
- 1966, L.O.Heflinger, R.Wuerker, and R.Brooks, first holographic interferograms which showed that holograms reconstruct amplitude and phase of a complex wave front.
- 1967, B.H. Soffer and B.B.McFarlane assembled the first Q-switched doubled ruby pumped tunable dye laser, illustrating that short spontaneous life time media can be pumped with enough power. A popular laser dye is Rhodamine B dissolved in alcohol which absorbs in the ultra violet (doubled ruby) and more strongly in the green (doubled YAG). The solution fluoresces between 500 -700 nm and can be tuned to the 586 resonant lines of the sodium atom. Such lasers can probe the ionospheric Na layer at 100-120 kmaltitude. The dye laser and collecting telescope is known as a LIDAR.
- 1967, L.D.Siebert. First large format holograms of a human subject with dye cell Q switched ruby oscillator-amplifier system
- 1978, A.Yariv, optical phase conjugation in liquids

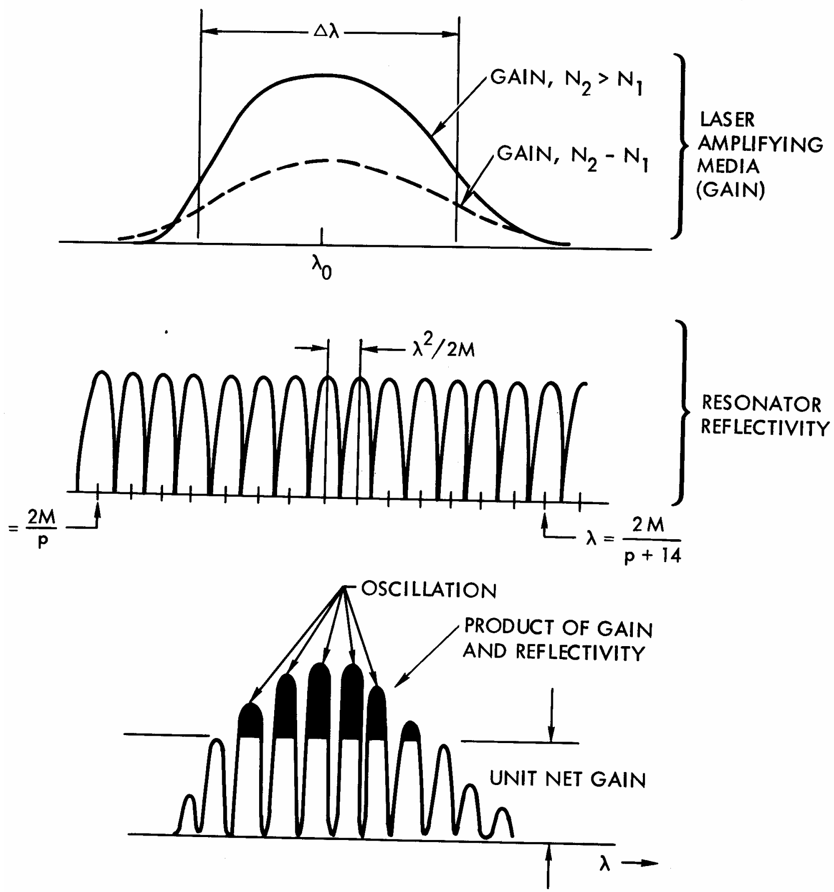
The Nature of Laser Light

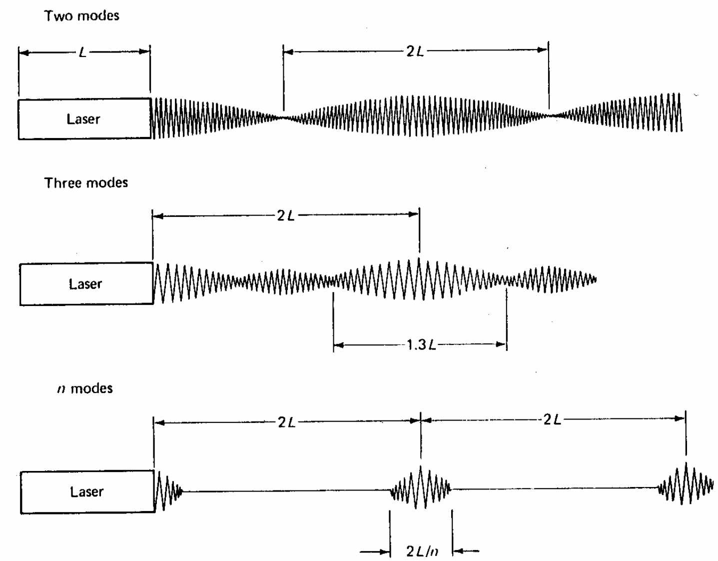
- Laser light can be coherent both spatiallyand temporally. Ideally the beam is a plane wavefront parallel to the direction of propagation and of a single frequency. In actuality the radiation is determined by the resonator and the gain of the rod.

- Two parallel mirrors separated by a distance L have resonances at mλ=2L. If two modes oscillate there is a beat pattern that repeats itself every 2L/**c** seconds. If many modes oscillate the laser emits a series of pulses every 2L/**c** seconds. This phenomena has been used to generate extremely short pulses in broadband materials such as Ti Saphire. The temporal coherence length of the radiation (C_{temp}= τ**c**) where τ is the duration of the laser pulse..

- A laser beam of wave length λ and diameter D will focus to a spot (S) of ~(λ/D)f where f is the focal length of the lens. For a ruby laser beam of 1 cm diamter focused by a 2 cm focal length lens, the spot will be ~ 6 microns in diameter or $4x10^{-7}$ cm^2 area. For a 2 J pulse of 20 ns duration (100MW peak) the peak flux would ~$3x10^{12}$ W/cm^2. The input flux is only limited by the size of the laser. Incoherent sources, in comparison, cannot concentrate light to temperatures greater than the temperature of the source.

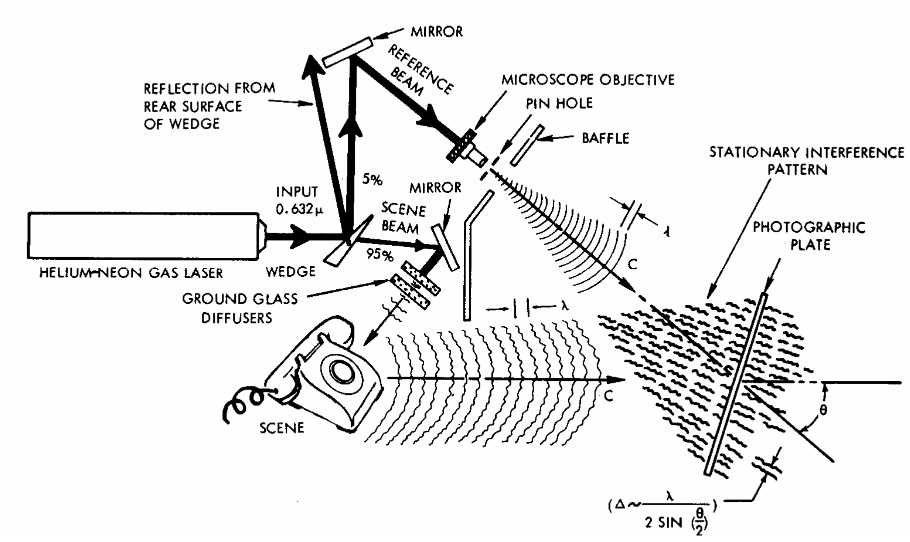
The number ofoscillating cavity modes determines the coherence of the laser beam





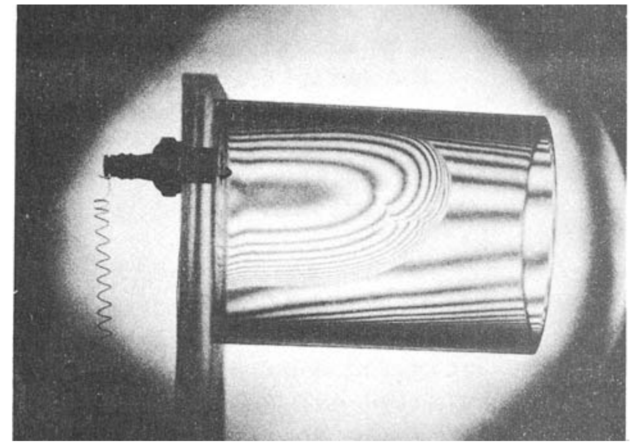
Laser Holography

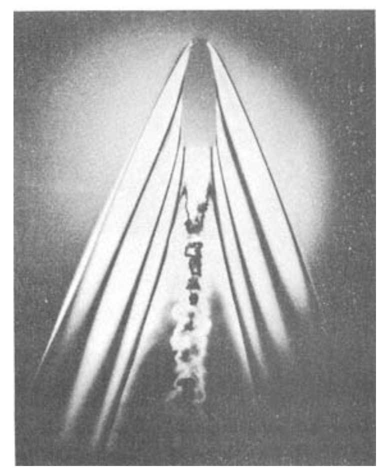
- Holography was in first enunciated (1947)by D.Gabor but it was E.Leith and J.Upatnieks(1962) that moved the reference beam off axis and made the first true three dimensional positive imagery with continuous changing paralalx. The discovery of Holographic Interferometry showed that a hologram reconstructs the original wavefront both in amplitude and phase. When the reference beam is reversed the hologram reconstructs the conjugate image



Double exposed hologram examples

- Both were recorded with a Q switched ruby laser. The upper example recorded the burning of acetylene inside a transparent plastic cylinder. The lower picture is an interferogram of a 22 caliber bullet in flight





Laser Saves Italian Art! Photograph of the holographic reconstruction of Donattello's John the Baptist

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I PRIMI ESPERIMENTI A VENEZIA

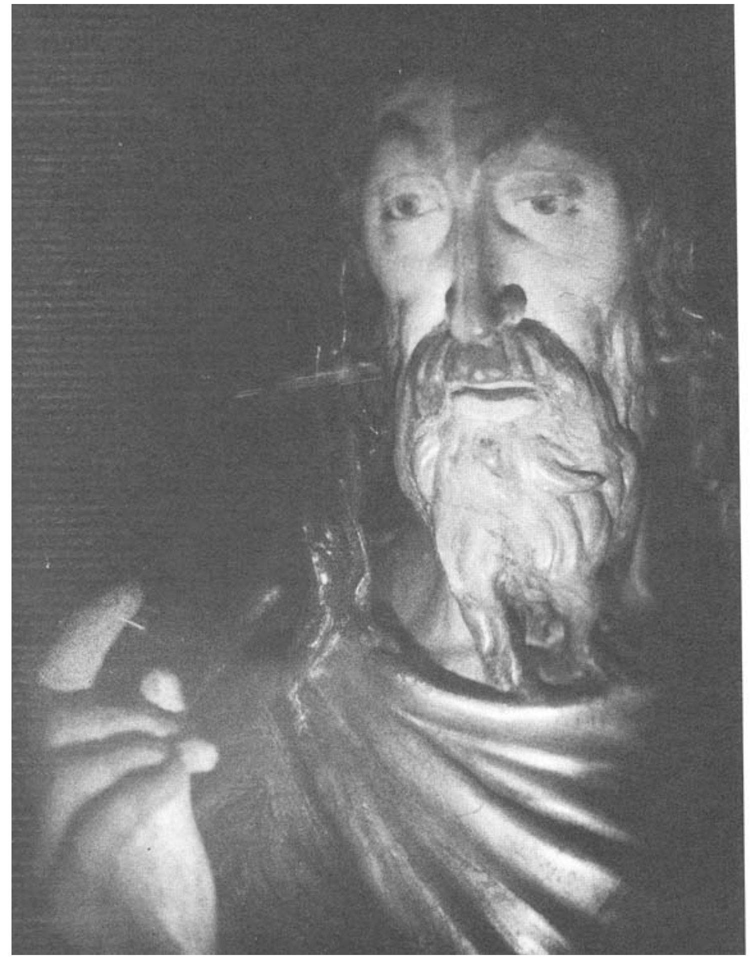
Restauri d'arte col laser

Il prodigioso raggio è in grado di rivelare ogni possibile segno di deterioramento, anche microscopico, sui materiali: tele, legno o marmo - Sarà possibile riprodurre copie esatte dei capolavori

Roma, 13 marzo.
Col «laser» si riprende l'immagine tridimensionale, olografica, fedelissima in ogni

Nell'istituto operano dieci restauratori, dieci operatori tecnici, due microbiologhe, tre chimici, un fisico e due

«know how». Probabilmente i ricercatori di Roma e dell'Aquila avrebbero potuto portare avanti il loro lavoro an-



Who invented the laser?

- A. Einstein for the concept of stimulated emission of radiation?
- C.Townes for achieving microwave oscillation in a resonator by stimulated emission?
- T. Maiman for the first stimulated emission in the visible from pink ruby with reflecting ends under flash lamp excitation?
- G.Gould for patenting tubes with end mirrors?.
- Many others were involved and contributed. The invention of the laser will be considered one of the important discoveries of the 20th century!
- Suggested reading:

  - M.Bertolotti, The History of the Laser, Institute of Physics Publishing,1999
  - C.H.Townes, How the Laser Happened: Adventures of a Scientist, Oxford University Press, 1999
  - N.Taylor,The Inventor, the Noble Laurate and the thirty year patent war, Simon & Shuster, 2000
  - T.Maiman, The Laser Odyssey, Metropolitan Printers, Canada 2000
  - J.Hecht, BEAM, The Race to Make the First Laser, Oxford University Press, 2005

“From little acorns great oaks do grow!” Ted Maiman at LLNL (1980) with a portion of the NOVA fusion laser in the background