Great Experiments in Physics

5. Birth of Quantum Electronics – Lasers

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Previous articles in this series 1. Discovery of Transistor Effect that changed the Communication World, *Resonance*, Vol.3, No. 9, 1998.
2. Tunnelling in Superconductors: The Josephson Effect. *Resonance*, Vol.3, No.11, 1998.
3. Measuring Diameters of Stars: The Hanbury Brown–Twiss Effect, *Resonance*, Vol.4, No.5, 1999.
4. Birth of Quantum Electronics – Masers, *Resonance*, Vol.4, No.9, 1999.

In Part 1 of this article, we described masers. In this part, we describe lasers, their optical counterpart.

Once the validity of the principle of the maser had been proven, it was natural to try to extend it to optical frequencies and realise the laser. This step, however, was far from trivial. Some of the problems were discussed and solutions to them proposed in a paper entitled 'Infrared and Optical Masers' by Townes and his brother-in-law Arthur Schawlow in 1958. These are,

(1) The use of a resonant cavity could not be extended even to the infrared, let alone to the visible range. This is because, to maintain a single isolated mode in a cavity the linear dimensions of the cavity would need to be of the order of one wavelength and thus too small at these higher frequencies. The cavity dimension had to be made much larger than the wavelength resulting in a multimode operation.

(2) A problem of using multimode operation is the possibility of oscillations being set-up in one mode jumping over to another mode causing sudden jumps in the frequency of the operation of the amplifier.

(3) Spontaneous emission probability increases with the cube of frequency, so the minimum power required to sustain oscillations may be rather large.

Schawlow and Townes got over the main difficulty of selecting a single oscillatory mode by using a cavity formed by two partially silvered mirrors which are strictly parallel and separated by a distance large compared to their diameter. This arrangement is a variant of the Fabry–Perot interferometer and A M Prokhorov in Moscow and R H Dicke at Princeton also independently

Box 1. Mode Selection

In case of optical range, the wavelengths are small compared to the dimensions of the cavity and many modes would be supported in the cavity. Consider a rectangular cavity of length L and two square end walls of dimension $D(L >> D)$ which are semi-transparent and other surfaces perfectly reflecting. Transparency of the end walls provides coupling to external space by a continuously distributed excitation, which corresponds to the distribution of field strengths at these walls. The resulting radiation produces a diffraction pattern, which can be easily calculated at a large distance from the cavity. The field distribution along the end walls is proportional to $\sin(\pi n_1 x/D).\ \cos(\pi n_2 y/D)$ and the resonant wavelengths for waves travelling in near axial directions are given by,

$$\lambda = 2 / [(m/L)^2 + (n_1/D)^2 + (n_2/D)^2]^{1/2},$$

where m is the number of half wavelengths along the axial direction and n_1 and n_2 are integers with $m >> n_1, n_2$. For strictly axial direction, $n_1 = n_2 = 0$. We can write approximately,

$$\lambda = (2L/m) [1 - (Ln_1/Dm)^2 / 2 - (Ln_2/Dm)^2 / 2].$$

The Fraunhofer diffraction pattern of the radiation emerging from the end wall has an intensity variation in the x direction given by,

$$I \propto (2\pi n_1)^2 \sin^2(\pi D \sin\theta / \lambda + \pi n_1/2) / [(\pi n_1 + 2\pi D \sin\theta/\lambda)^2 (\pi n_1 - 2\pi D \sin\theta/\lambda)^2]$$

where θ is the angle between the direction of observation and the axial direction. For a given value of n_1 the diffraction maxima occur at $\sin\theta = \pm n_1\lambda / 2D$ and the 1st minima on either side occur at $\sin\theta = \pm n_1\lambda/2D \pm \lambda/D$

Thus the maximum of the radiation from a mode designated by $n_1 + 1$ falls approximately at the half intensity point of the diffraction pattern from the mode designated by n_1, so that they can be resolved. There may be more than one mode, which has similar values of n_1 and n_2 but different values of m, and radiate in essentially identical directions. However, the frequencies of such modes are appreciably different and may be sufficiently separated from each other by an appropriate choice of the distance L between the end plates. The frequency separation between modes for small n_1 and n_2 is given by the Fabry–Perot condition, $\delta\nu = c / 2L$. If this value is greater than the atomic line width, then only one axial mode can oscillate at a time. The axial mode has an angular width due to diffraction of about λ/D and if this is comparable to D/L, then all off-axis modes are appreciably more suppressed than the axial mode.

suggested similar arrangements for masers at short wavelengths. A beam of light travelling along the axis joining the two mirrors would travel back and forth many times. During these journeys stimulated emission from the pumped atoms in the enclosed space would reinforce the beam. If the build-up were enough to compensate for the losses at the mirrors a steady wave would result. Part of the wave can escape through the partially silvered mirror giving the output of the optical maser. The different modes would be separated by the strict directionality of the reflected beam and a single mode could be selected. Schawlow and Townes gave an example of a possible optical maser using potassium vapour and a potassium lamp as the excitor. Potassium atom has a set of energy levels suitable for pumping a metastable state and the required population inversion. They also considered the use of crystals of rare earth salts in which metastable states were known to exist. However, they were somewhat less optimistic about optical maser action using solids as the active material because of two reasons. First, the spectral lines are generally broader in solids making mode selection difficult and second, pumping radiation at the appropriate frequencies required for the solids were not readily available.

After Schawlow and Townes published their paper on the possibility of laser action in the infrared and visible spectrum, it wasn't long before many researchers began seriously considering practical devices. The work towards the realisation of the laser proceeded in two directions, one through optical pumping in solids and the other through collisional excitations in gas mixtures. Most experts were speculating that gases would be the first to lase in the optical and infrared. It came as a surprise that ruby was the first substance to produce laser action in the visible spectrum (Maiman, 1960). The work on gas mixtures at Bell Labs eventually led to an important class of lasers, the continuous wave (CW) helium-neon laser.

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Ruby is a crystal of Al_2O_3 with a fraction of percent of Cr_2O_3 as impurity and in addition to being a gemstone, is a useful substance for a physicist. It can be synthesised fairly easily. Moreover, the crystal structure is simple enough to be tractable but not trivial. The Cr ions have magnetic and optical properties that can be utilised readily. In fact, ruby was a widely used medium for solid state masers. T H Maiman at the Hughes Research Laboratories in USA was working with ruby in this connection and was thus concerned with the behaviour of Cr ions. He noted that when a

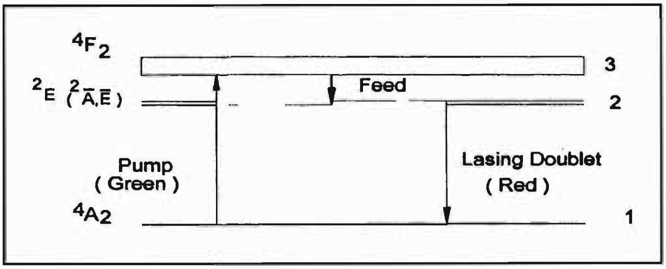

Figure 1. The energy levels of ruby used for the laser action.

ruby crystal is excited with green light, often the return to the ground state takes place with the emission of red fluorescence near 6900Å. He proceeded to demonstrate that significant depletion of ground state could be produced. This he reported in a paper to the *Physical Review Letters* in 1960. He took a crystal of ruby and mounted it between parallel silvered plates to form a microwave cavity resonant at the ground state zero-field splitting frequency (11.3 GHz). The reflection coefficient of the cavity was monitored on an oscilloscope while a short pulse (200 msec) of light from a flash tube irradiated the crystal. The magnitude of the microwave magnetic absorption was observed to decrease abruptly and then return to equilibrium with a time constant of about 5 msec. This delay could be attributed to a temporary depletion of the ground state population with subsequent decay back from the fluorescent level.

The next step was to produce an actual population inversion and stimulated emission. In mid-May of 1960, Maiman and his assistant Irnee J D'Haenens got their first signs of lasing.

They needed a high intensity pumping source. For a uniform illumination with isotropic (uniform in all directions) radiation the required power level was > 555 Watts/cm^2. To take care of the heat dissipation problems, the experiments were performed using a pulsed source. For the case in which the exciting light pulses are short compared to the fluorescence life-time, the requirement on the flashtube is that the energy per unit area is ~ 1.67 J/cm^2. The source used was a Xenon filled quartz flashtube, having a spectral efficiency of 0.064 (ratio of required light output to electrical input energy) and a radiation area of 25 cm^2. A crystal of dark ruby was used in the form of a cylinder 3/8″

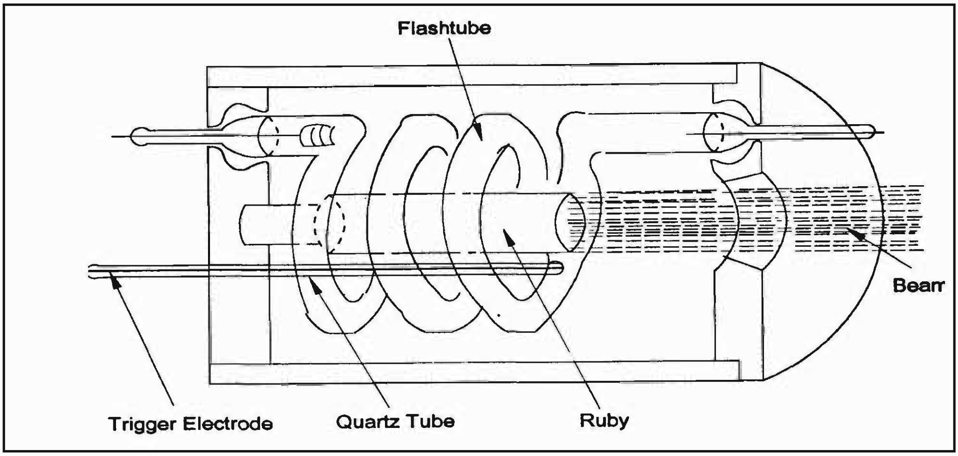

Figure 2. The schematic of apparatus used by Maiman and co-workers for the ruby laser.

diameter and 3/4″ long with the ends flat to within l/3 at 6943Å. The ruby crystal was supported inside the helix of the flashtube which in turn was enclosed in a polished aluminium cylinder as shown in *Figure* 2. Provision was made for forced air cooling to take care of the heat dissipation. One flat end of the crystal was made opaque by deposition of a thick layer of silver and the other end was made semi-transparent with a thinner layer of silver with a small opening at the centre. The energy to the flashtube was obtained by discharging a 1350 mF capacitor bank and the input energy varied by changing the charging potential. The output radiation was monitored with a photomultiplier tube which was calibrated at 6943Å by comparison with a thermopile to radiation at this wavelength with a band 200Å wide. Since the intensity of emitted light was high once lasing took place, attenuation of the light was necessary to ensure linear response of the photomultiplier. This was achieved by use of calibrated neutral density gelatine filters. Peak output power and details of the output pulse were obtained from the phototube output across a 1000 W resistor on an oscilloscope, the system having a response time of 0.1 msec.

The first ruby crystal had poor optical properties and thus they did not observe an abrupt onset of laser action but exhibited the line narrowing by a factor of only 4 or 5, a faster (0.6 msec) but smooth time of decay compared with that for fluorescence. The

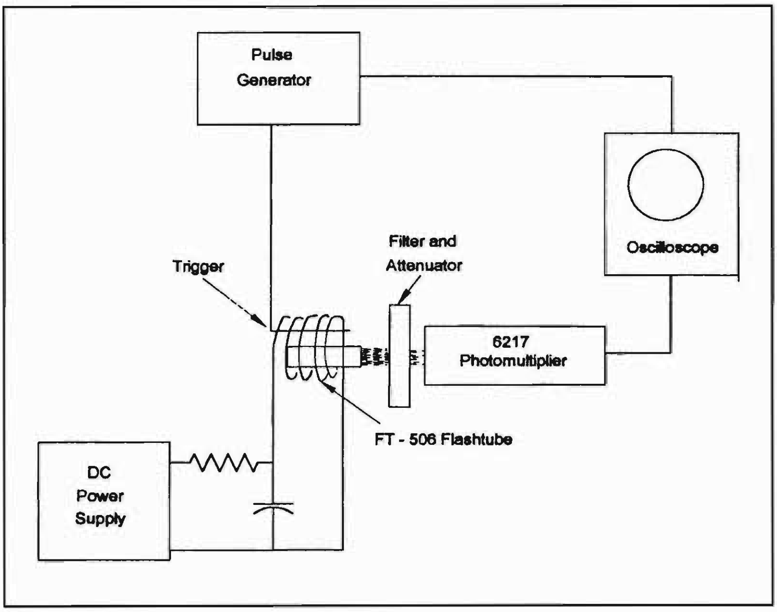

Figure 3. Schematic diagram of the electronics for ruby laser.

output beam angle was ~ 1rad. Maiman reported this in a paper in *Nature*. Better quality crystals exhibited pronounced line narrowing of nearly four orders of magnitude, an oscillating behaviour of the output pulse and a beam angle of 10^{-2} rad and a very clear-cut threshold for the input energy where pronounced laser action occurred. Their apparatus is schematically shown in *Figures* 2 and 3.

Thereafter, very soon, lasers with several other types of active materials were produced. Sorokin and Stevens at IBM got the Uranium doped CaF_2 crystal to lase as also the samarium laser. Schawlow and Devlin at Bell labs and independently Wieder and Sarles at Varian Associates demonstrated lasing action in dark Ruby. Ali Javan and co-workers got the He-Ne system to lase in Dec 1960. This was the first continuous laser. So in the span of six months, lasers were available in five different varieties. In 1962 Basov and Oraevskii proposed that rapid cooling could produce population inversions in molecular systems. A few years later others suggested that this could be accomplished by expansion of a hot gas through a supersonic nozzle. This creates a highly non-equilibrium region where a strong population inversion takes place. Very high laser output power can be achieved. And in 1966, the first gas dynamic laser was successfully operated at the Avco Everett Research Lab.

Another very important class of lasers came through the discovery that a *p-n* junction of GaAs through which a current is passed can emit near infrared light from recombination processes with very high efficiency. Hall and co-workers at the General Electric Laboratory got the first semiconductor laser using crystals of GaAs. With this development it was possible to construct lasers of the size of a transistor, and equally important, at about the same cost. All the early lasers had more or less fixed wavelengths. With the introduction of pumped dye lasers the frequency or the wavelength of the lasing light could be varied over a wide range. This was a great boon to the spectroscopists and other researchers worldwide. Search for new lasing media with higher efficiency, power, and tunability continues even today. Free electron lasers where high energy electron beams are passed through periodically varying magnetic fields are expected to provide these features.

Due to its enormous commercial potential, there was a bitter legal battle over who invented the laser, that lasted for about 30 years. However, as it often happens in science, Mother Nature has pre-empted the maser/laser action a long time ago. Not long after the discovery of laboratory masers and lasers, the first natural masers were discovered in interstellar and circumstellar gas clouds. Javan in 1958 predicted that negative absorption might eventually be discovered in radioastronomy. Seven years later the Radio Astronomy Group led by H Weaver at Berkeley California discovered radio emissions at 1670 MHz coming from OH molecules near stars, which can excite a population inversion by radiation or other energy mechanisms. Today hundreds of maser transitions are known in more than 36 molecules. Astrophysical masers, due to their extremely high intensity and spectral purity, are valuable tools in studies of the birth and death of their associated stars. They can be observed from the ground with special instruments, but the major part of the infrared spectrum where potential lasers might be seen is hidden from the ground observer by earth's absorbing atmos-

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phere. Townes, a frequent investigator onboard the flying Kuiper Astronomical Observatory (KAO), was among the discoverers of the first strong astrophysical water masers. The long awaited discovery of a natural laser was made on the last scheduled flight of the KAO instrument – the Ames Cryo-genic Grating Spectrometer that permitted sensitive detection of emission from atoms and molecules throughout the mid- and far-infrared spectral domain. Astronomers have discovered a powerful ultraviolet laser beam, several times brighter than our sun, shooting towards earth from a super-hot 'death star.' The observations, made with NASA's Hubble Space Telescope have identified a gas cloud that acts as a natural ultraviolet laser, near the huge, unstable star called Eta Carinae – one of the most massive and energetic stars in our Milky Way Galaxy.

Lasers are now available in almost all wavelengths from infrared to ultraviolet with the possibility of X-ray lasers very promising. The frequency or the wavelength of the lasers can be tuned *at will* making it an extremely powerful tool for spectroscopists as well as in many other applications like isotope separation. The power available for current lasers is truly awesome (in the range of terrawatts), the largest of them being used for fusion research and welding of materials. They can be operated in the pulsed mode or in the continuous wave mode depending on the need. At the other end of the scale we have tiny diode lasers having an output of a milliwatt.

The technological applications of the laser follow from the property of high intensities, extremely narrow bandwidth and coherence, which allow the light to be focused to an extremely narrow spot. The use of lasers in welding and microsurgery are due to these properties. Already lasers are playing an ever-increasing role in communications via fibre-optics. What started as a search for a spectroscopic tool for basic research is now poised to enter our everyday lives as a ubiquitous technology

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Suggested Reading

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