Great Experiments in Physics

4. Birth of Quantum Electronics – Masers

Amit Roy

Amit Roy is at the Nuclear Science Centre, New Delhi, building a superconducting linac booster for the pelletron accelerator. He spent over two decades at the Tata Institute of Fundamental Research, Mumbai investigating nuclei using accelerators and probing symmetries in physics. His hobbies are books and music.

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.

There are few devices that have seen applications in so many diverse fields as the *laser*. In basic research it has triggered a renaissance in optics, opening up a new field called nonlinear optics. The use of lasers is so vast, in different branches of physics, chemistry and biology, that no modern research laboratory is complete without it. Lasers have entered almost every domain of our lives as well. It has found applications in medicine for 'bloodless surgery', for welding of metals in industry, for bar-code readers in supermarkets and as hand-held pointers to aid lecturers. The compact disk systems for storing data in computers and also for recording music employ tiny lasers. Laser interferometry provides hitherto unachievably accurate determination of large distances, a striking example of which was the accurate determination of the distance from the earth to moon.

Laser is an acronym for 'lightwave amplification by stimulated emission of radiation'. But before we take up the story of the laser, we must look at the development of its precursor in the longer wavelength, the *maser*, which is an acronym for 'microwave amplification by stimulated emission of radiation'.

Whenever we look at a light source, say a candle or a light bulb or the sun, the light that reaches our eyes has mostly been generated by the spontaneous emission from the atoms excited in the source. If thermal energy excites an atom, the excited state is generally unstable and the atom returns to the ground state by emitting radiation whose wavelength is determined by the energy of transition. This is true not only for visible light but also for radiations of shorter or longer wavelengths. The intensity of such emissions depends on the temperature of the source and follows Planck's law. Normally, incandescent sources can have

temperatures of a few thousand degrees and this sets an upper limit on the radiation intensity. However, if we take an atom in an excited state and bathe it with radiation having the same frequency that the atom would have normally emitted, another mode of emission of light would occur. This was recognised by Einstein in 1916 when he tried to account for the equilibrium distribution of energy states of atoms in interaction with radiation. He named this process as induced or stimulated emission of radiation.

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For over 35 years after Einstein's discovery, the subject of stimulated emission had little or no practical usage. During World War II, the development of microwave technology gave rise to a new field known as microwave spectroscopy. In Columbia University, USA, the group headed by Charles H Townes and in Russia, N Basov and A M Prokhorov recognised that stimulated emission could be used as a basis for a very high-resolution detector, oscillator or amplifier.

The basic problem with an electronic amplifier or oscillator is that usually the vital part of the circuit is of the same size as the wavelength generated. This fact limits the use of electronic amplifiers to wavelengths of $\sim$1 mm or larger. The spectroscopists asked themselves, why not use the atomic or molecular oscillators built by nature? A single atom, however, radiates very little power and that too intermittently. So the need was to find a way to synchronise a large number of atoms to produce a coherent wave. Normally this process would violate the second law of thermodynamics since the interaction of radiation with atoms at any finite positive temperature cannot produce amplification. Let us take an atomic species, which has two energy levels. At a given temperature the number of atoms in the lower level would be larger than that in the higher level and thus there would be a net absorption of radiation by the atom and no amplification. However, suppose the number of atoms in the higher level is made larger than that in the lower level (population inversion or negative temperature, *Box* 1). Then we have more stimulated emission than absorption and hence a net amplification of the radiation with frequency corresponding to that of the transition. This was

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Box 1. Population Inversion

Suppose an atom or a molecule has two states a and b with energies E_a and E_b, E_a being lower than E_b. In the presence of an electromagnetic field, atoms in state a (numbering N_a) can absorb energy to go to state b. Those in state b (numbering N_b) can come to state a by either spontaneous or stimulated emission. If we denote, following Einstein, the absorption probability for $a \rightarrow b$ by B_{ab} and the spontaneous emission probability for $b \rightarrow a$ by A_{ba} and the stimulated emission probability for $b \rightarrow a$ by B_{ba}, then the rate of change of electromagnetic energy, I, is given by,

$$dI/dt = A_{ba} N_b - B_{ab} I N_a + B_{ba} I N_b$$

At equilibrium, $dI/dt = 0$, and this gives us an expression for

$$I = A_{ba} N_b / (B_{ab} N_a - B_{ba} N_b) = A_{ba} / [B_{ab} (N_a / N_b - B_{ba} / B_{ab})]$$

At a given temperature T, considering Boltzman distribution of the atoms,

$$N_a / N_b = \exp [(E_a - E_b) / kT]$$

Comparing this to the Planck's radiation formula Einstein came to the conclusion that

$B_{ba} = B_{ab}$ and then

$$I = (A_{ba} / B_{ab}) / (\exp [(E_a - E_b) / kT - 1])$$

Then we have

$$dI/dt = A N_b - B I (N_a - N_b)$$

Since $E_a < E_b$, it follows that at normal temperatures $N_b < N_a$ and dI/dt is negative. Only if we can make $N_b > N_a$, dI/dt would be positive and radiation energy would be amplified. This is called population inversion. We can see that the situation when more atoms are in state b than in state a is mathematically equivalent to the temperature, T, being negative. The first experimental evidence of population inversion was obtained as early as 1928 by H Kopfermann and R Ladenburg working in the Kaiser Wilhelm Institute in Berlin (see [6]). They achieved it by controlling the excitation current in a discharge tube filled with neon. However, the idea of using it for maser/laser process didn't occur to anyone till the historic work of C Townes.

the birth of quantum electronics.

Population inversion in two level systems was first discussed by Lamb and Retherford in connection with their measurement of fine structure of hydrogen and the first demonstration was done by Purcell and Pound in their nuclear magnetic resonance experiment (see *Box* 1).

Townes and his co-workers, Gordon and Zeiger achieved this situation working with ammonia molecules. This molecule has two states corresponding to the superposition of two equivalent positions of the N atom on either side of the plane containing the three H-atoms as shown in *Figure* 1. One of these states is symme-

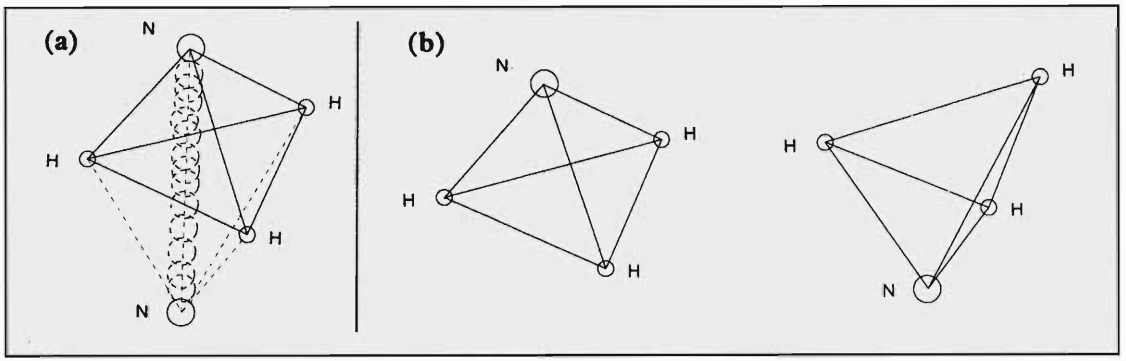

Figure 1. The ammonia molecule. (a) Classical representation. (b) Quantum mechanical states are superpositions of these two representations.

tric to the interchange of the position of the N-atom while the other is antisymmetric. The symmetric one has lower energy and the energy difference of 10^{-4} eV corresponds to frequencies in the microwave range, 23.87 GHz and a wavelength of 1.25 cm for the transition. If somehow we could drive away the molecules in the lower energy state, then we would be left with an ensemble of molecules only in the upper state achieving population inversion. This is what they proceeded to do using another important property of the ammonia molecule, its electric dipole moment. Although the ammonia molecule does not have a permanent electric dipole moment, an applied electric field will induce one and its sign is opposite for the two states mentioned above. If the electric field is inhomogenous, there will be a force on the molecule, which also has opposite signs for the two states. The lower energy state is attracted by a strong field whereas the upper energy state is repelled by it. An electrostatic quadrupole lens provided the required electric fields.

They needed a directional beam of molecular ammonia, which was achieved by stacking fine tubular channels of size 0.05 mm $\times$ 0.15 mm and length 6 mm together forming a circular array of radius 5 mm. Gas from a tank of anhydrous ammonia was maintained behind this array at a pressure of few mm of Hg to produce a strong directed beam of ammonia molecules flowing in the direction of the tubular channels. The four electrodes of the focusser were arranged as shown in the *Figure* 2 to form a strong quadrupole field. As the molecules passed through the focusser, the molecules in the upper state would preferentially go towards

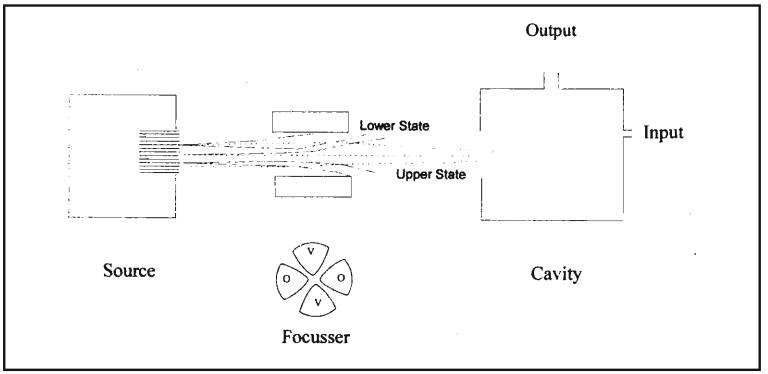

Figure 2. The experimental arrangement used in the observation of maser action.

the axis where the field was zero. The molecules in the lower state were attracted by the electrodes and were lost from the beam direction. A diffusion pump was used to evacuate the system, but it proved inadequate to pump the large amount of ammonia gas from the source. They made the focusser electrodes hollow and filled them with liquid nitrogen to provide cryopumping. At the boiling point of nitrogen ~ 77 K, the vapour pressure of ammonia is $< 10^{-6}$ mm of Hg and so the cold electrode surfaces provide a large trapping area which helped maintain pressures $< 10^{-5}$ mm of Hg. However, this gave rise to a complication as the build up of solidified ammonia on the electrodes distorted the focussing fields and eventually the flow of ammonia was impeded. So they had to run the system intermittently for small periods, warming up the system in between.

The molecules emerging from the focusser were predominantly in the upper state. They were then made to enter a cylindrical cavity resonator of 1.5 cm diameter and 11.4 cm length made of copper whose natural frequency matched the transition frequency of 23.87 GHz. Microwave power could be fed in through an input hole at one end of the cavity and could be taken out of the cavity through a hole on the side wall. Amplification of the input signal was obtained with extremely low levels of noise. The power output of the first maser was about 10^{-9} W. The reason for the low level of noise is that the molecules are neutral objects carrying no charge. Their motions in contrast to that of electrons in electronic circuits produce no unwanted random electromagnetic signals. Only source of noise in it is the thermal noise in the cavity from the

walls. In fact if we cool the cavity to near 0 K the limiting noise fluctuation is equivalent to only one quantum of energy in the cavity which makes a maser yield the most perfect amplification allowed by the uncertainty principle. The maser also had extremely narrow bandwidth of a few KHz governed by the time required for the molecules to travel the length of the cavity (see *Box* 2).

In electronics any system that amplifies can be modified to oscillate by introducing feedback coupling. Maser has not been an exception to this. It only required enough ammonia molecules in the *upper energy state* to enter the cavity so that the number of photons emitted by stimulated emission more than compensates those lost to the walls of the cavity. The oscillations in the maser were extremely stable and due to its narrow bandwidth, produced very nearly perfect sine waves. A clock regulated by a maser would gain or lose no more than one second in a few hundred years, and masers found immediate application in providing an accurate measure of the second in conjunction with an atomic transition in the cesium atom.

However, as an amplifier the use of the ammonia maser was very limited, as the frequency of the transition can not be easily changed. A practical amplifier needs to be tuneable. Also the ammonia maser cannot work continuously, but in bursts. The maser action stops once all the molecules in the upper state make a transition to the lower state. This shortcoming was removed a couple of years later in the idea of the three-level paramagnetic maser introduced by Nicolaas Bloembergen of Harvard University. Basov and Prokhorov had already proposed a rather similar three-level pumping scheme for application to molecular beam system. They utilised the fact that the separation between the $(2S+1)$ energy levels of a paramagnetic atom with spin S when placed in a magnetic field depends on the value of the magnetic field. In the case when spin is 1/2, the two levels would be split and the frequency corresponding to the separation is given by $\nu = 2.8$ (H) MHz where H is the magnetic field in gauss. In case of spin 3/2 there would be four levels as happens to be the case with Cr^{2+} ions in ruby crystals placed in a magnetic field of 3900 gauss as shown in

Box 2. Resonant Cavity and Linewidth

A resonant cavity is an enclosure where standing waves of electromagnetic radiation are sustained and it does not radiate. The dimensions of the cavity and its geometric shape naturally determine the wavelengths of the waves for which standing waves can be sustained. In the microwave range the frequency of a cavity can be tuned over a small range by either deforming the walls or by introducing a small piece of metal which changes either the effective capacitance or the inductance of the cavity. For visible light, the frequency can be tuned by either using a dielectric material or changing the cavity length by moving one end mirror over a desired amount. The frequency of a laser cavity can also be changed by rotating a grating fixed on a fine motion control stage at one end so that the wavelength for which feedback occurs changes.

The transition probability for any molecule at low field strengths is given by,

$$P_{ab} = 1/(2\pi h)^2 \, |\mu_{ab}|^2 \, | \int \varepsilon(t) \exp(-i\,\omega_0 t)\, dt \, |^2$$

where μ_{ab} is the dipole matrix element for the transition, and $\varepsilon(t)$ is the rf electric field at the position of the molecule. The total power emitted by the beam is given by,

$$P = N h \nu P_{ab},$$

where P_{ab} is an average over the trajectories, velocities and matrix elements for all the molecules of the beam.

Considering the cavity to be only one half wavelength in the axial direction, the emitted power has a maximum at the natural transition frequency ν_m and a total width at half maximum of $\sim v/L$ as given by the inverse of the time of flight of the molecules in the cavity. For transitions off resonance,

$$P_{ab} = 1/(2\pi h)^2 \, |\mu_{ab}|^2 \, | \varepsilon_0 \int [\exp(i(\omega-\omega_0)t) + \exp(-i(\omega+\omega_0)t)]\, dt \, |^2$$

The second term oscillates too rapidly and averages to zero. The first term on integration gives a value

$$= 1/(2\pi h)^2 \, | \, \mu_{ab} \, |^2 \, \varepsilon_0^2 \, (L/v)^2 \, \sin^2[(\omega-\omega_0) L/v] \, / \, [(\omega-\omega_0) L/v]^2$$

Here L is the length of the cavity and v is the velocity of the molecule. The line width given by this function is shown in *Figure* a.

Figure a. Line width of a maser transition.

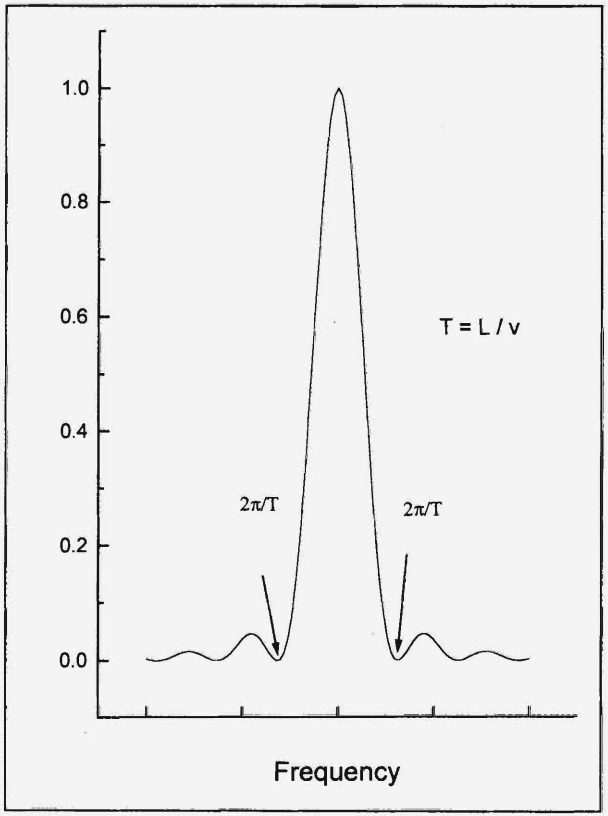

Figure 3. The populations of levels 1 and 3 tend to become equal if enough power is provided for the pump transition. This would then establish a population inversion between levels 3 and 2. If the decay or relaxation rate of level 2 to 1 is more rapid than the decay from level 3 to 2 then continuous operation is possible. Since the transition frequency between these levels depends on the strength of the magnetic field, varying the magnetic field we can easily tune the frequency.

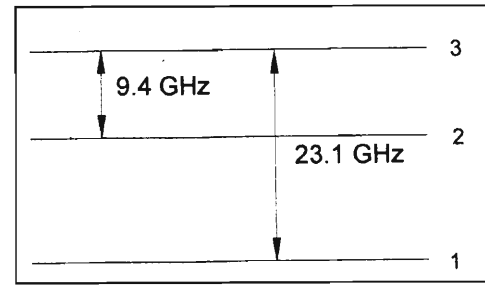

Figure 3. The three level maser system using the excited levels of ruby.

A short time later G Fehler, H E D Scovill and H Seidel at Bell Labs built a solid state maser based on this principle using the levels of the rare-earth Gadolinium ion (Gd^{3+}) in a crystal of Lanthanum ethyl sulphate. An explosion of activity on solid-state masers followed soon. It was soon realised that ruby crystal provided a more suitable choice and was used for the three level masers. As the energy separations of the maser transitions is small, it was necessary to cool the crystal to low temperatures to reduce the thermal contributions to the excited states, especially the lower maser level, thus allowing for rapid radiative depopulation of the middle level 2. Low temperatures are also required in order to reduce non-radiative processes such as phonon collisions (lattice vibrations) which compete with the radiative processes and can reduce the lifetime of the upper laser level 3 (it must have a longer lifetime than that of the lower laser level). Such a ruby maser was used as a low noise amplifier by Arno Penzias and Robert Wilson at Bell Labs for their discovery of 3 K cosmic microwave background radiation.

Suggested Reading

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Address for Correspondence
Amit Roy
Nuclear Science Centre
Aruna Asaf Ali Marg
P.O. Box 10502
New Delhi 110 067, India.
Email: roy@nsc.ernet.in