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Quantum cascade – a new generation of laser

Scientists at Bell Labs have created a synthetic atom-state analogue which can work as a made-to-measure laser, says S.Ananthanarayanan. It is the quantum cascade laser, a device that generates powerful laser light of colours of choice, rather than of the colours dictated by the materials being used.

An important application of lasers is to detect the minutest traces of gases, if the frequency of the laser happens to be one that the gas would absorb. Now, with the ability to generate laser light at designer frequencies, laser detection of any and every gas becomes possible.

Making waves

Lasers are essentially atomic internals being used as a mechanism for generating electromagnetic waves, or, in other words, light waves. When light was discovered as being a combination of electric and magnetic waves, scientists were quick to take the next step of generating such waves using rapidly alternating electric currents in wires called antennae. As antennae were of metre or larger dimensions, the wave they generated were radio waves, which are a form of light with very large wavelength.

With smaller and smaller components, shorter and shorter waves could be generated but there was soon a physical limit to how small things could get and hence to how high the frequency of the wave emitted could be. This limit applied both to the antennae and transmission media, as well as the oscillator or the electronics to generate the rapidly alternating electric current, which was the heart of the system. This was really the limiting factor - the difficulty of creating an apparatus of the dimensions needed to generate really rapid oscillations, in millions of cycles in a second.

The atomic oscillator

Atoms and molecules keep absorbing and emitting these very short electromagnetic waves, in the ‘microwave’, or shorter waves in the visible regions of the spectrum. If atoms or molecules could be got to play the role of the evasive oscillator, and to act together and ‘in step’, then, very uniform, high frequency radiation could be created.

This is exactly what happens in a laser. Atoms of materials that have just the required structure and internal energy levels are arranged so that they act in concert and can emit a continuous stream of light that is of a single frequency and in a very narrow beam. Methods have been developed to do this using a gas in a tube with reflecting ends or using cylindrical crystals of certain materials, the ends of the cylinders again being ground to act as mirrors.

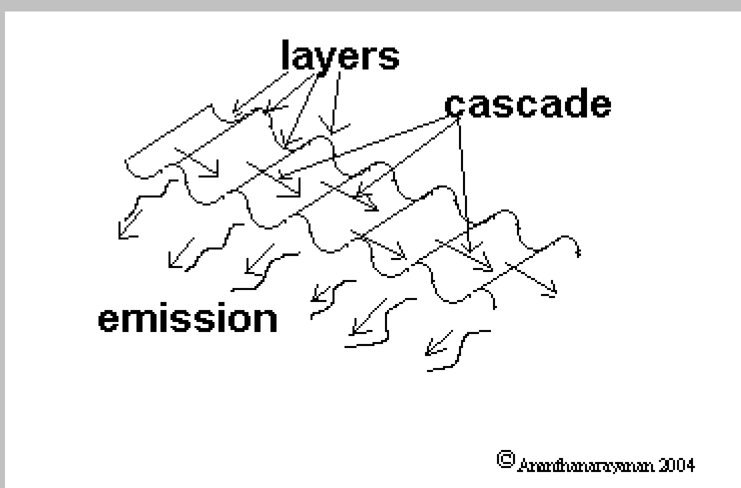
The energy for the beam comes from a low frequency electric oscillator and the laser light is generated when the atoms keep getting ‘pumped’ up to a higher energy level and relaxing to a lower energy state in a well regulated manner.

Limitations

These particular energy states where atoms can be ‘parked’ till there are enough to descend to a lower state ‘together’, and give off laser light are only what the elements in nature come endowed with. Even with advances where more and more materials are used for lasers, the frequencies of the light they emit is limited. The applications of lasers are thus also limited to uses at frequencies available. Among others, this limits the value of lasers in communications.

The quantum cascade

This breakthrough by Fredrico Capasso and Claire Gmachi at Bell Labs is to construct, through crystal growing methods, a staircase of energy levels, using an obstacle-course of atoms of gallium and aluminum compounds. The layers are grown in succession, to nanometer width, which is just the thickness of about 500 atoms.



The junctions of the layers form ‘energy wells’ to trap electrons within ‘high energy wells’ and successive wells can be made to have reducing energies. An electron could then be made to fall from well to well, emitting a photon corresponding to the energy difference each time. “A row of electron waterfalls”, as Gmachi described it.

In the quantum cascade, unlike waterfalls, the electrons do not flow ‘over’ a barrier but can ‘tunnel’ through the separator of one energy level from the next, lower one. This helps one ‘tunneling’ to be controlled by the photon emitted by a previous tunneling and the cascading can work ‘in step’, like a laser.

Advantages

An electron thus takes part in about 75 ‘drops’ and this makes for the QC laser to be capable of high power output. The material is hardy and easily manufactured. This makes for ease of handling and low cost. But the great advantage is that the frequency of the laser light does not depend on the native properties of atoms. It depends on the thickness of the alternate layers used to build the cascade.

With a combination of build specifications and controlling the temperature of the laser, the frequency of light emitted can be sensitively controlled. This flexibility enlarges the fields where lasers can be used, particularly the detection of traces of gases by measuring absorption of laser light of specific frequencies.

Detecting gases

All substances have characteristic frequencies of light which they absorb when light passes through them. The particular frequencies absorbed by a gas is then its ‘fingerprint’ and even exceedingly minute trace presence gives itself away if a search is made at those frequencies. This is what the Bell Labs development makes possible.

Hardy, inexpensive QC lasers are ‘tuned’ to specific frequencies corresponding to particular gas traces to watch out for. When light from these lasers is passed through the ambient gases, even in remote locations, changes in the gas composition can be easily monitored by automated systems.

Early Warning

One application proposed is to use the method to predict possible activity of volcanoes. It is found that the magma in volcanoes has a lightly different ratio of the occurrence of C^{12} and C^{14}, two isotopes of carbon, compared to naturally occurring carbon. Now, gases that contain different isotopes of carbon have different absorption fingerprints and the ratio of the two forms of carbon present can be measured. If magma starts collecting, to suggest that the volcano may erupt, there would be a change in the C^{12}/C^{14} ratio and steps could be taken to evacuate the area, etc. With the use of QC lasers, this monitoring of the gas in volcanoes becomes possible continuously, with the results of analysis being available early enough to be useful.