

those of minor mutations; small changes in the inputs used to trigger patterning mimic the natural variation in development seen from embryo to embryo. On both of these counts, the network is satisfactorily robust. Most small changes in parameter values have little effect — only at rare thresholds does the behaviour of the model switch from one stable state to another.

Initial conditions can also be varied more widely, to explore how this gene network might behave in different developmental contexts. For example, the model was designed with a precise periodic input to trigger activity of the segment-polarity genes throughout the whole length of the body. This mimics what happens in *Drosophila* (Box 1). In many other insects, however, segmentation spreads through a field of cells from head to tail (much as it does during early patterning in vertebrate embryos). In these cases, the segment-polarity system seems to be conserved<sup>4</sup>, but the upstream triggers may not be<sup>5,6</sup>. Von Dassow *et al.* are quite happy with this: their model will generate the same segment pattern with a variety of different inputs, and the inputs can be much less precise than those known from *Drosophila*.

Our understanding of gene networks is at an early stage. We perceive their complexity only after it has been filtered by the limitations of the techniques used to study them. Genome databases and DNA-chip technology, which enables huge numbers of genes to be screened for activity, will undoubtedly provide more, and much more complicated, data than anything produced by *Drosophila* genetics. If a relatively simple gene network such as the segment-polarity system is hard to understand intuitively, we can be certain that modelling will be essential to make sense of the flood of new data.

But this will not be elegant theoretical modelling; rather, it will be rooted in the arbitrary complexity of evolved organisms. The task will require a breed of biologist-mathematician as familiar with handling differential equations as with the limitations of messy experimental data. There will be plenty of vacancies, and, on present showing, not many qualified applicants.

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Laser physics

# The smallest random laser

Diederik Wiersma

**H**ow small can you make a light source? A common light bulb is a few centimetres in diameter. You can make light bulbs several millimetres across, but for a light-emitting device much smaller than this, we should turn to lasers. Lasers are nowadays widely used in industry, in hospitals and in many devices that we have at home. A compact disc player, for instance, makes use of a miniature laser diode only a few millimetres big. In two papers in *Applied Physics Letters*<sup>1</sup> and *Physical Review Letters*<sup>2</sup>, Cao *et al.* describe a laser that is a thousand times smaller still: their laser is a small grain, 1.7 micrometres in diameter — about one-tenth of the diameter of a human hair.

The microlaser created by Cao *et al.* is not the smallest ever laser source, but it is a special type of microlaser. It uses a highly disordered structure to obtain laser action. The behaviour of light waves in disordered structures is highly complex, yet disordered materials are familiar to us all. Every substance that looks white falls into this category, including paper, white paint, fog, marble and a glass of milk. The study of the behaviour of light in such disordered materials is an active field of research<sup>3,4</sup>.

A light wave that passes through a white object like a glass of milk will undergo a process called multiple scattering. Milk is a suspension of many small fat droplets, each with a strong tendency to scatter light: when a light wave hits a fat droplet its direction of travel will be changed in an arbitrary way. A light wave passing through a glass of milk will be scattered thousands of times by

thousands of fat droplets. This is what gives milk and all other disordered substances their opaque white appearance.

It is this mechanism of multiple scattering that Cao *et al.* use to make a tiny random laser. However, multiple scattering alone is not enough to make a laser. A laser requires two ingredients: a material that amplifies light, and some feedback mechanism that (temporarily) traps the light in order for the amplification to be efficient. In normal lasers the trapping element is a cavity — two mirrors facing each other with the amplifying material in between. The light passes back and forth between the mirrors, thereby passing several times through the amplifier, until it leaves through one of the mirrors that is partially transmitting (Fig. 1a).

In the case of a random laser the cavity is replaced by multiple scattering. In 1967, Letokhov<sup>5</sup> predicted that the combination of multiple scattering and light amplification would lead to a form of laser action. Nonetheless, it was 25 years before random laser action was observed experimentally<sup>6</sup>. It became clear that the multiple scattering of light that takes place in a disordered material does not really provide a feedback mechanism, but it makes the light stay inside the material long enough for the amplification to become efficient. Instead of bouncing from one mirror to another, the light waves bounce from one particle to another thousands of times before they leave the disordered material (Fig. 1b). Because the multiple scattering is completely random, the term 'random laser' is used. The emission charac-

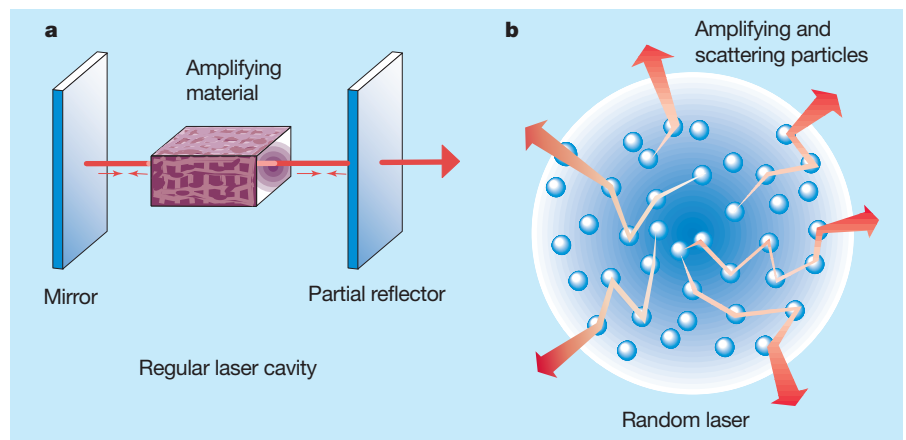


Figure 1 Comparison between a regular laser and a 'random laser'. a, In a regular laser the light bounces back and forth between two mirrors that form a cavity. After several passes through the amplifying material in the cavity, the gain amplification can be large enough to produce laser light. b, In a random laser the cavity is absent but multiple scattering between particles in the disordered material keeps the light trapped long enough for the amplification to become efficient, and for laser light to emerge in random directions.

teristics of a random laser are similar to those of a normal laser: the emission spectrum can be extremely narrow, which means that the colour of the emission is well defined, and the output can be pulsed<sup>7-9</sup>. But unlike a regular laser, a random laser will emit randomly in all directions, just like the emission from a common light bulb.

The tiny random laser built by Cao *et al.*<sup>1,2</sup> consists of disordered clusters of zinc oxide (ZnO) nanocrystals. After excitation by an external light source, these ZnO nanocrystals provide both the amplification and the random scattering needed for random laser action. They are also easy to make and extremely cheap: one ZnO cluster costs much less than 1 cent. In addition, the laser characteristics can be easily tuned by varying the geometry of the clusters. Each cluster will operate at its own specific wavelength, depending on its shape and size.

One might question how laser action occurs in a disordered material, given that it lacks a real cavity (Fig. 2). The answer is simple. The condition for lasing comes from a careful balance between gain and loss. The gain depends on how much time the light spends inside the amplifying material; the loss depends on how easily the light can escape. Lasing simply occurs when the gain becomes larger than the loss. For example, within a sphere of disordered amplifying material of radius  $a$ , the gain is proportional to its volume ( $4\pi a^3/3$ ) and the loss is proportional to its surface area ( $4\pi a^2$ ). This means that, upon increasing the volume, it is possible to reach a situation where the gain becomes larger than loss and the system starts to lase. The threshold volume does not necessarily have to be very big: in the case of random ZnO clusters it is only a few cubic micrometres.

Although random laser action in ZnO clusters can be explained by multiple scattering, the details are still vague. Apart from the trapping of light by multiple scattering, other processes can play a role. If the scattering is very strong, light waves can start to bounce randomly in closed loops and get trapped. This is the mechanism behind localization of light in a disordered medium<sup>3,4</sup>, a peculiar phenomenon in which light transport comes to a complete stop. But the conditions for obtaining localization are very strict, and not likely to exist in ZnO clusters. More common is additional feedback from the surface of the sample. The outer surface of a cluster will reflect light back inside, which enhances the entrapment. Especially for micro-size systems, such as small clusters or films, feedback from the boundaries is expected to be an important factor. More theoretical and experimental work is needed to understand these random microlasers in detail.

Reducing the size of a laser source to a few micrometres opens up many possibilities. It



Figure 2 Model of an amplifying disordered material used to build a 'random laser'. Green light is multiply scattered by the spheres and charges the system, thereby enabling the amplification process. The red light is both multiply scattered and amplified. The combination of multiple scattering and amplification leads to random laser action. Miniature random lasers can be used as sources in optical devices, such as wave-guides or all-optical switches. Their tiny size also makes them suitable for marking documents or materials in a hidden way.

allows, for instance, the integration of a laser within tiny optical devices. There is a growing effort to develop materials, called photonic crystals, that can guide and switch light waves in the way that electronic devices control electric currents. A random microlaser would play the crucial role of the active element or miniature light source in such crystals. But this is just one of many possible applications. On a different note, random microlasers can be used to monitor the flow of liquids by adding a small amount of ZnO clusters to the liquid and detecting the laser emission over large flow distances. Furthermore, its specific wavelength of operation, depending on shape and size, makes the miniature random laser suitable for encoded marking of documents or materials. The presence of a specific ZnO cluster could be detected by monitoring its particular laser emission, but would be invisible to the human eye. ■

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#### 100 YEARS AGO

Mr. E. G. Green, Government entomologist at the Botanic Gardens at Peradeniya, Ceylon, has recently been able to confirm by personal observation the web-spinning habits of the red ant (*Ecophila smaragdina*). He has seen ants actually holding larvæ in their mouths and utilising them as spinning machines. To find what would be done, some leaves which had been newly fastened together by ants were purposely separated by Mr. Green. The edges of the leaves were quickly drawn together by the ants, and, about an hour later, small white grubs were seen being passed backwards and forwards across the gaps made in the walls of the shelter. Each grub... was held in the jaws of one of the worker ants, and its movements directed as required. A continuous thread of silk proceeded from the mouth of the larva, and was used to repair the damage. There were no larvæ amongst the occupants of the disturbed inclosures, and the grubs used for spinning were apparently obtained from a nest a short distance away, which probably accounts for the considerable time that elapsed before the rent was repaired. From *Nature* 12 July 1900.

#### 50 YEARS AGO

The Royal Canadian Air Force, Engineering Division, has carried out investigations upon aircraft de-icing for some time past, and now considers that thermal de-icing, or actually anti-icing, appears to hold more promise than either the heated surface, mechanical pulsation, or chemical treatment hitherto employed. It has equipped a large four-engined Rolls-Royce Merlin-powered 'North Star' aircraft with the necessary apparatus for flying tests and observation, and intends to collect meteorological data upon cloud conditions... as well as to experiment upon the dispersal or prevention of ice accretions. The principal feature of the 'Ice Wagon' is a large 'shark's fin' on the top of the body. This will be fitted with the electro-thermal de-icing devices, and has blister-type observation domes on either side from which an operator can study and control the ice-shedding process during flight. The propellers are also fitted with similar electric blade heating... The general principle of the new technique is one of intermittent flow of current along wires installed at places where the ice that is forming is most readily dislodged. This is considered to be more efficient than continuous heating of a surface. From *Nature* 15 July 1950.