# Random thoughts

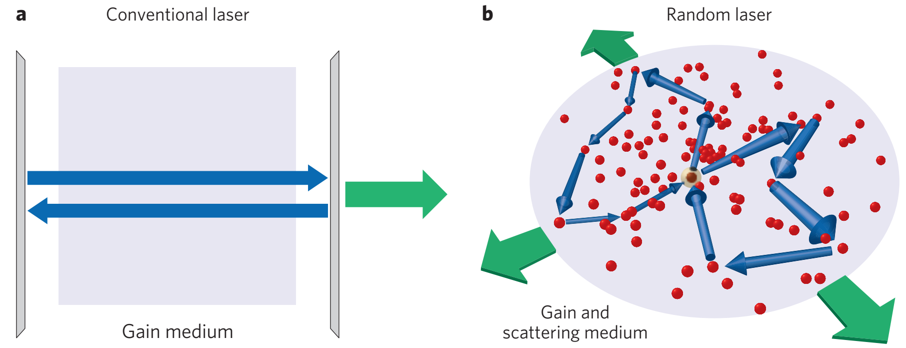
The study of random lasers based on disordered, scattering media has become an active topic of research in recent years. *Nature Photonics* spoke to Hui Cao from Yale University about developments in the area, potential applications and future opportunities.

## What is a random laser and how is it different from a conventional laser?

The first thing to say is that there's not one unique definition; different groups have slightly different opinions. However, as a general statement I think that it's fair to say that a random laser is a laser whose cavity is not formed by reflection from regular mirrors. Instead, the optical feedback comes from light scattering in a disordered media, and the interference of the scattered light gives rise to resonant modes at particular frequencies. Unlike a normal laser, these modes are not regularly structured and the laser doesn't have equally spaced longitudinal modes or an output beam with a well-defined wavefront. Random lasers can occur in both weakly scattering systems and strongly scattering systems. In a weakly scattering system, there are many modes that have similar thresholds, and the lasing dynamics are much more complex than that of a regular laser. Random lasers can be implemented in one-, two- or three-dimensional geometries, depending on whether the scattering media is, for example, an optical fibre, a planar membrane or an aggregate. Just like a conventional laser, a random laser has a threshold at which the gain overcomes the loss. That concept still applies, and stimulated emission is a key ingredient of a random laser. However, random lasers have many unique characteristics that can be very useful. For example, they can exhibit very low spatial and/or temporal coherence; many modes can lase simultaneously with uncorrelated phases over a very broad frequency range.

## How did research into the area start, and what have been the most important developments?

This field began in the 1960s, not long after the first lasers were demonstrated. The Nobel Laureate Basov and co-workers first investigated what happened when they replaced one of the standard mirrors in a Fabry–Pérot cavity with a scattering surface. Then Lektokhov considered incorporating scatterers into gain material, and predicted that there would be a threshold for the self-generation of photons. This was dubbed the 'photonic bomb' as the concept is very much like the generation of neutrons in an atomic bomb. In the 1980s, scientists studied emission from powders of laser crystals. There was some debate about the mechanism behind the emission — whether it was real laser emission or super-radiance — and whether the cavity was formed by internal reflections within individual laser crystal particles or scattering between them. A milestone came in 1994 when Lawandy published a paper in *Nature* showing laser-like behaviour from laser dye solution with particles. A clear pump threshold was observed above which the width of the emission spectrum collapsed to 4–5 nm. This study was important for several reasons. First, the size of particles was very small so it ruled out the possibility of lasing from internal resonances of single particles and proved that the cause of the feedback for lasing was indeed interparticle scattering. Second, the gain was outside the scattering particles, which again showed that it was not a single-particle laser. Lots of experimental and theoretical works followed. In 1998–1999, my group and Vardeny's group at the University of Utah reported the observation of discrete sharp peaks in the lasing spectra, which signified the existence of coherent resonant feedback from wave interference. It showed that we really need to take into account the phase of the light fields.



Schematic of the design of (**a**) a conventional laser resonator cavity with its two discrete end mirrors and (**b**) a random laser based on scattering. Due to their different geometries the lasers exhibit very different characteristics. Green arrows indicate the output laser beam from the devices; red spheres are scattering particles and blue arrows show optical paths. Image courtesy of A. Douglas Stone research group, Yale University.

## What kinds of systems have been used to make random lasers?

Random lasers have been realized across many different systems. For example, we have used semiconductor nanorods or nanoparticles because we can precisely control their size and shape. Other people used a variety of organic and inorganic materials such as polymers, colloids, optical fibres and even biological tissues. The key is to bring together a gain material and a scattering structure. Random lasing is a very general phenomenon that applies to many systems. One intriguing aspect is that it can be demonstrated over a wide range of length scales — from the micrometre scale of a cluster of tiny zinc oxide nanoparticles to the kilometre scale of long optical fibres. It is just a question of the required strength of scattering and amplification.

## What are the potential applications of random lasers?

Because the modes of a random laser are sensitive to the scatterers, one may use the random laser as a sensor for anything that modifies the scattering characteristics of the medium. So sensing is certainly one potential application. The lasing frequency

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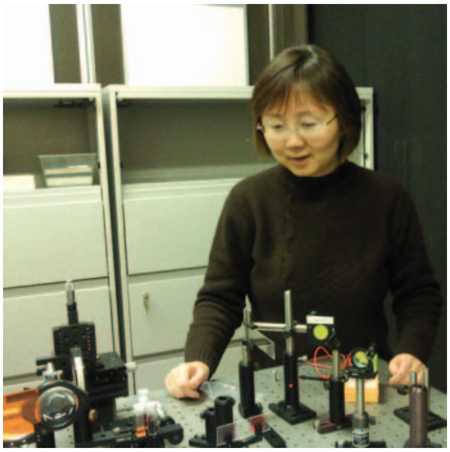
acts as a fingerprint of the random system. For example, Vardeny's group has looked at using random lasers to detect cancer. Random lasers can also have very low spatial coherence owing to the existence of many independent lasing modes with different wavefronts, and we can actually tune the spatial coherence of the laser by modifying the scattering strength or pump geometry. This could be useful for parallel imaging, in which we wish to avoid the cross-talk and speckle associated with highly coherent illuminated light. The combination of high intensity and low spatial coherence are useful not only for full-field imaging and microscopy, but also for laser projection schemes such as pico projectors. Typically people try to reduce the speckle by employing additional devices such as rotating diffusers; random lasers do not generate this speckle and so avoid the problem altogether. I have been working with colleagues at Yale Medical School on applying random lasers to full-field optical coherence tomography, where it's important to have a light source with low spatial coherence to avoid artefacts. Using thermal light sources or LEDs isn't an option because we require high intensities to probe deeper into the tissue, so this provides random lasers with a unique opportunity.

### What are the future opportunities and outlook for the field?

From a fundamental point of view, the random laser is a fascinating system that combines optical amplification, scattering, nonlinearity and/or localization. The laser dynamics are much more complex than that of a conventional laser, and there is still much to understand. For example, scientists recently explored the mode-locking of random lasers and investigated how to control their operation. People have tried two approaches so far. One is to design and engineer the characteristics of the random material. The other is to control the pump, for example by varying the spatial profile of the pump beam. Another interesting area is pseudo-random lasers that exploit deterministic aperiodic systems with a variable degree of order. These structures provide a diversity of modes that can lase. From an application point of view, random lasers are also exciting because of the unique characteristics that allow them to be used when conventional lasers aren't suitable, for example in cases where low coherence and high intensity are important.

**INTERVIEW BY OLIVER GRAYDON**


H. CAO

Hui Cao in her lab at Yale University in the USA. Over the years, Cao's findings have helped to unravel the intriguing operational characteristics of random lasers.

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