

Light emission

A temperature-tunable random laser

Random lasers have fascinating emission properties that lie somewhere between those of a conventional laser and a common light-bulb. We have created a random laser that can be brought above and below its threshold for laser emission by small changes in its temperature, thereby creating a light source with a temperature-tunable colour spectrum. As a single random laser can be made as small as a grain of tens of micrometres in diameter, we expect our device to find application in photonics, temperature-sensitive displays and screens, and in remote temperature sensing.

Lasers are now commonplace — for example, they are used in industry and in hospitals, in bar-code scanners and compact-disc players. Conventional lasers are based on an optically active material and some sort of laser cavity that traps light for long enough for laser action to occur. A new type of laser source, known as a random laser¹, has been discovered that does not require a regular cavity but instead depends on a diffusive material such as a fine powder^{2–4}. In a random laser, light waves are trapped by multiple light scattering (that is, light diffusion⁵), which takes over the role of the cavity in a regular laser (Fig. 1). The emission of a random-laser source has a well defined colour spectrum and can be pulsed, just like a regular laser^{6–11}, although its emission is in several directions because of the intrinsic randomness of the system.

To create a random laser, light diffusion must be combined with light amplification, for instance by grinding a laser crystal into a fine powder or by adding diffusely scattering particles such as glass powder to a laser-dye solution. For our random-laser material, we infiltrated sintered glass with laser dye dissolved in a liquid crystal (see Fig. 1 legend). Random-laser action was evident as a strong narrowing of the emission spectrum (by up to a factor of 5) and an abrupt increase of the emitted intensity above an excitation energy of about 1 millijoule per pulse, as is commonly seen for random lasers based on laser dye.

The threshold at which a random laser starts to manifest is determined by the careful balance between gain and loss, as for a common laser. The losses for a random laser are due to light that escapes through the sample surface; the overall gain depends on the excitation energy and on how strongly the material scatters light (expressed in terms of a photon-diffusion constant). The more the material scatters light (the smaller the diffusion constant),

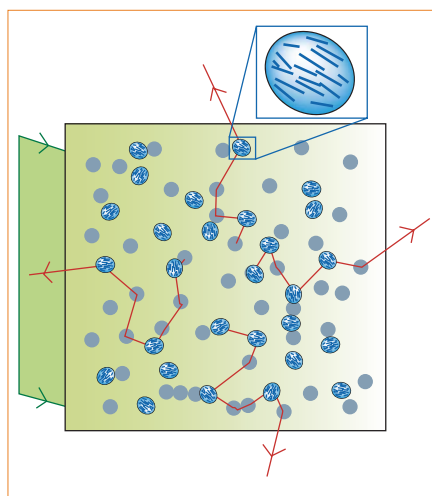


Figure 1 A temperature-tunable random laser. Light waves are multiply scattered by the sintered glass and liquid crystal and are amplified by the laser dye, which is excited by an external laser (green). The multiple scattering keeps the light inside the system for long enough for the amplification to become effective; when gain becomes larger than loss, the system will exhibit random-laser action. Our samples were made from SK11 glass (Schott) powders (pressed into discs of diameter 1 cm and thickness 1.3 mm). The resulting percolating porous structure was infiltrated at room temperature with the laser dye DCM (Lambdachrome 6500) dissolved in liquid crystal 4-cyano-4'-n-heptylbiphenyl (7CB) at various concentrations.

the longer the light is kept inside and the larger the overall gain can grow.

By using a liquid crystal inside our disordered material, we can have external control over the diffusion constant¹². Liquid crystals go through partially ordered phases when heated — each liquid-crystal phase has a different refractive index and therefore different scattering properties. When a random sample is infiltrated with a liquid crystal, its diffusion constant becomes strongly temperature-dependent, in much the same way that a polymer-dispersed liquid-crystal display changes its opacity with temperature¹³. For our samples, we observe a diffusion constant that increases gradually with temperature, with a more abrupt increase around the nematic–isotropic phase-transition temperature of the liquid crystal (in the nematic phase, the liquid-crystal molecules are aligned along a common axis, causing this phase to be birefringent; at higher temperatures, in the isotropic phase, the liquid crystal behaves as a normal isotropic liquid). This enables us to bring the random laser above and below its threshold by temperature-tuning of the diffusion constant.

The marked effect of different temperatures on the emission spectrum is shown in Fig. 2a. At low temperatures, there is random laser action (narrow spectrum), whereas at higher temperatures the random laser is below threshold (broad emission spectrum). By varying the temperature, the spectral width of this random laser

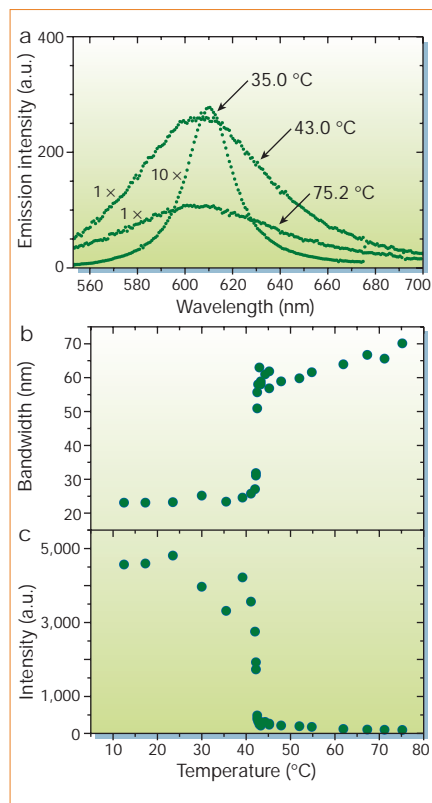


Figure 2 Action of a temperature-tunable random laser. The random-laser emission is characterized by exciting the sample with a frequency-double Nd:YAG laser and recording the spectrum of the diffuse emission (beam diameter, 1.9 mm; pulse duration, 14 ns; repetition rate, 10 Hz). **a**, Temperature dependence of the emission spectrum. At the highest temperature, the liquid crystal is in the isotropic phase and the laser is below its threshold (height at 35 °C is scaled by a factor of 10). **b**, Temperature dependence of the emission bandwidth. The bandwidth drops abruptly below 42.5 °C owing to the onset of laser action. **c**, Change in maximal emission intensity (arbitrary units, a.u.), showing an abrupt increase below the threshold temperature. By choosing different liquid-crystal/glass combinations the random laser can be designed with different tuning curves.

can be controlled (Fig. 2b); the abrupt reduction in bandwidth below 42.5 °C is due to the onset of laser action. The transition temperature corresponds, within experimental error, to the nematic–isotropic phase-transition temperature (42.8 °C) of the liquid crystal 7CB used here.

The onset of laser emission is nicely illustrated if we plot the observed intensity at the wavelength at which the emission spectrum is maximal (Fig. 2c). There is an abrupt increase in intensity below 42.5 °C; intensity then saturates at lower temperatures. This strong increase is possible due to repumping of the laser dye above threshold⁷. By choosing different tuning curves for the diffusion constant through selection of the sintered glass/liquid-crystal combination, the tunable random laser can be designed to show different spectral behaviour — for example, the temperature at which laser action occurs can be chosen and the abruptness or smoothness of the tuning

curves varied. This laser may find application as a source in active displays and temperature-sensitive screens and — because the threshold behaviour of tunable random lasers can be set to specific temperatures — in remote temperature sensing, for example in investigations of biological processes.

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1. Letokhov, V. S. *Zh. Eksp. Teor. Fiz.* **53**, 1442–1452 (1967) [*Sov. Phys. J. Exp. Theoret. Phys.* **26**, 835–840 (1968)].
2. Gouedard, C., Husson, D., Sauteret, C., Auzel, F. & Migus, A. *J. Opt. Soc. Am. B* **10**, 2358–2363 (1993).
3. Lawandy, N. M., Balachandran, R. M., Gomes, A. S. L. & Sauvin, E. *Nature* **368**, 436–438 (1994).
4. Wiersma, D. S. & Lagendijk, A. *Phys. Rev. E* **54**, 4256–4265 (1996).
5. Sheng, P. *Introduction to Wave Scattering, Localization, and Mesoscopic Phenomena* (Academic, San Diego, 1995).
6. Zyuzin, A. *Phys. Rev. E* **51**, 5274–5278 (1995).
7. John, S. & Pang, G. *Phys. Rev. A* **54**, 3642–3652 (1996).
8. Berger, G. A., Kempe, M. & Genack, A. Z. *Phys. Rev. E* **56**, 6118–6122 (1997).
9. Beenakker, C. W. J. *Phys. Rev. Lett.* **81**, 1829–1832 (1998).
10. Cao, H. *et al.* *Phys. Rev. Lett.* **82**, 2278–2281 (1999).
11. Xunyu, J. & Soukoulis, C. M. *Phys. Rev. Lett.* **85**, 70–73 (2000).
12. Wiersma, D. S., Colocci, M., Righini, R. & Aliev, F. *Phys. Rev. B* **64**, 144208-1–144208-6 (2001).
13. Drzagic, P. S. *Liquid Crystal Dispersions* (World Scientific, Singapore, 1995).

By contrast, uniparental gene activity can be monitored as transgene expression in embryos from crosses^{3,5}. Whereas paternal contribution implies post-fertilization expression, zygotic activity of the maternal allele can only be inferred when there is no evidence for pre-fertilization expression.

The *AtRPS5A::GUS* transgene strongly expresses β -glucuronidase (GUS) from the promoter of the gene encoding the small-ribosomal-subunit protein 5A in early embryogenesis. Fertilization of wild-type egg cells with transgenic pollen results in detectable GUS expression in most embryos as early as the two-cell stage (Fig. 1a), indicating that there is early activity of a paternally derived transgene.

Mutations in several *Arabidopsis* genes affect early embryogenesis, indicating that these genes function at the early stages of embryo development^{6–8}. Vielle-Calzada *et al.*³ propose that early embryogenesis depends on the maternal genome and that early defects due to a non-functional maternal allele cannot be complemented by a functional paternal allele. As subtle early-embryo phenotypes are difficult to classify unambiguously as either wild-type or mutant, we used a double-mutant genotype, *knolle keule*, in which cytokinesis is blocked from fertilization onwards, resulting in single-celled embryos with multiple nuclei⁷ (Fig. 1b). We found that

selfing of *knolle keule* heterozygous plants gave the expected one-quarter of single-celled embryos, whereas almost all embryos from wild-type pollination were normal (Fig. 1c). We conclude that functional paternal alleles are sufficient for normal embryogenesis from the earliest stage.

By using a two-component expression system⁹ in *Arabidopsis*, we found additional evidence for early expression of paternally inherited transgenes (results not shown). However, expression from the maternal genome was consistently stronger than from the paternal genome, as shown here by reciprocal crossing between a driver line with an epidermis-specific gene promoter¹⁰ fused to a chimaeric transcription factor, and a line with the corresponding artificial response element controlling the GUS reporter gene (Fig. 1d). These differences in expression between maternal and paternal alleles may occur in early (data not shown) as well as in later embryogenesis.

Our findings seem to contradict the idea of overall maternal control of early embryogenesis³, but may be reconciled with those of Vielle-Calzada *et al.*³ if paternal gene expression is attenuated rather than silenced, or if it is affected by locus-specific rather than genome-wide imprinting. Whether or not the activity of a specific paternal gene is sufficient during early plant embryogenesis might depend on

COMMUNICATIONS ARISING

Seed development

Early paternal gene activity in *Arabidopsis*

Both parental genomes are expressed during embryogenesis, although the time of activation of the paternally inherited genes varies between organisms^{1,2}. Results reported by Vielle-Calzada *et al.*³ have suggested that delayed activation of the paternal genome seems to be the rule in plant development. We find, however, that during early embryogenesis in *Arabidopsis*, paternal genes are expressed and are sufficient for normal development. Our findings indicate that there is no overall maternal control of early embryogenesis, and that the contribution of the parental alleles needs to be assessed for each gene individually.

Arabidopsis embryos develop from a small egg cell within an ovule that consists largely of maternal tissue, making it difficult to determine the parental origin of embryonic transcripts by polymerase chain reaction with reverse transcription. *In situ* hybridization detects differential gene expression between the two daughter cells of the zygote⁴ without revealing the parental origin of the endogenous messenger RNA.

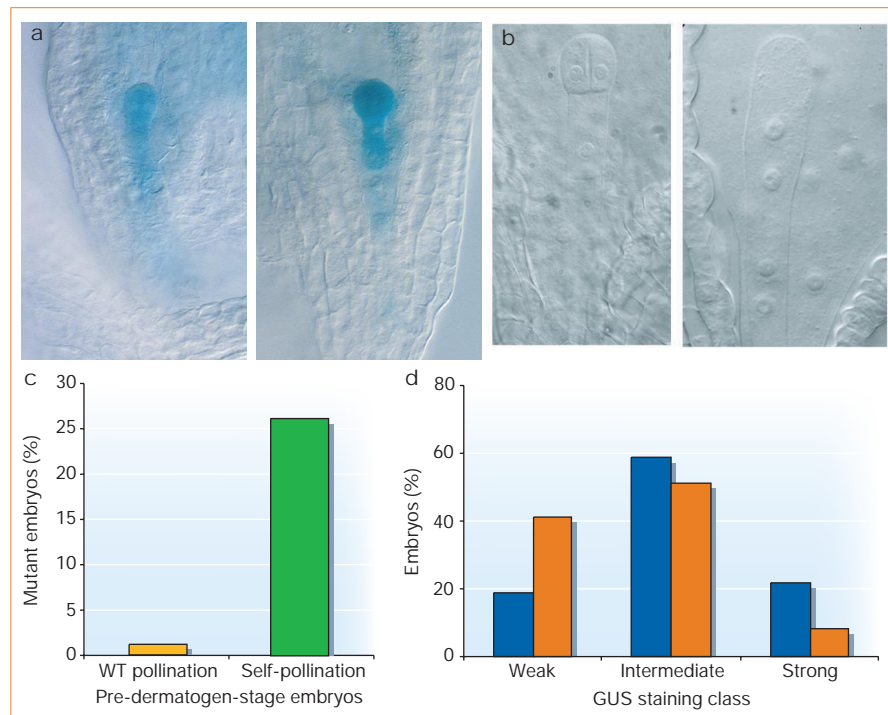


Figure 1 Paternal gene activity during early embryogenesis. **a**, β -Glucuronidase (GUS) activity in embryos from a cross between an *AtRPS5A::GUS* male and a wild-type female. **b**, Wild-type two-cell-stage embryo (left) and *knolle keule* double mutant (right). **c**, Selfing of a heterozygous *knolle keule* double mutant *cis*-line leads to 26.2% mutant embryos ($n = 172$) versus 1.2% mutant embryos ($n = 173$) from wild-type (WT) pollination. Embryos from one-cell to eight-cell stages were counted. **d**, GUS activity in protoderm cells of heart to torpedo-stage embryos from reciprocal crosses between a *pLTP1::GAL4-VP16* line and a *pUAS::GUS* reporter line. Blue bars ($n = 144$), maternally expressed, and orange bars ($n = 132$), paternally expressed *pLTP1::GAL4-VP16*, indicating the proportion of embryos classified as weak, intermediate or strong expressors.