Random lasers are intriguing devices with promising applications as light sources for imaging, sensing, super-resolution spectral analysis or complex networks engineering. Random lasers can be obtained from optically pumped dyes, optical fibres and crystals or electrically pumped semiconductor heterostructures. Semiconductor random lasers are usually fabricated by introducing scattering defects into the active layer, adding a degree of complexity to the fabrication process and losing the ease of realization potentially offered by disordered structures. The ready availability of electrically pumped random lasers, avoiding a costly fabrication approach, would boost the use of these devices in research and applications. Here we realize an incoherent semiconductor random laser by simply processing the output mirror of an off-the-shelf Fabry–Pérot laser diode via controlled laser ablation. Optical feedback provided by the intact back mirror and the ablated front mirror results in multimode random lasing with low spatial coherence and disordered angular patterns. This result constitutes a proof of principle for future ground-breaking technology developments in the field of random lasers.

In random lasers (RLs), optical feedback for the lasing action is provided by scattering elements, usually embedded in the active material. Owing to their peculiar characteristics, RLs are promising devices for a range of applications, including laser-based speckle-free imaging, sensors, spectral measurement with super-resolution and networks of coupled resonators.

The first proposal of a non-resonant laser—that is, a laser cavity based on optical feedback from scattered light—consisted of a gain material placed between one mirror and one diffuser. The same authors proposed an alternative implementation of this concept that included a distributed feedback architecture in which the refractive index of the active material varied randomly in space. This approach has been used extensively, leading to the first demonstration of random lasing, and it remains the most widespread fabrication method.

Random lasers with distributed feedback have been achieved in a wide range of materials, essentially by mixing any available scattering element and an active medium. For example, dyes in solid and liquid forms, have been exploited for the realization of RLs, with the stringent requirement of pulsed optical pumping, which strongly limits the ease of operation and applications. Random fibre lasers, in which distributed Rayleigh scattering provides the required feedback, are pumped by laser diodes coupled to the fibres, resulting in high-power continuous-wave output. Electrically pumped semiconductor RLs are suitable devices both for research and applications due to their reliability, ease of operation, small footprint and potentially low fabrication cost in large volumes.

Semiconductor RLs can be fabricated by introducing a matrix of defects inside the active layer, with the size, shape and spatial distribution of the defects designed so that the introduced disorder is controlled and tailored ad hoc. This approach has been used for the realization of quantum cascade RLs, in which holes are etched into the active layer with precise sizes and positions. Alternatively, naturally occurring disordered structures, with casual sizes, shapes and positions, can also be used by depositing a polycrystalline film with grains, by active material growth from randomly distributed seeds on a substrate or by the introduction of random defects into the active layer.

In all the previously mentioned devices, the material growth process must include a specific fabrication step for introducing a random variation of the refractive index into the active layer. This requirement is in contrast with the typical ease of fabrication of RLs, for example, in devices consisting of scattering powders and dyes, which allow manageable processing but require optical pumping. The real simple realization of disordered structure in a semiconductor material that could allow electrically pumped random lasing would be cornerstone for building future applications with RLs.

Our group has previously demonstrated that random lasing can be efficiently achieved in a device in which defects are placed at the edges of the active material, instead of being distributed inside it. In contrast to Fabry–Pérot (FP) lasers, we substituted the mirrors for two differently disordered scattering elements, which provide feedback and output coupling. We observed the same spectral random lasing signature, specific to each device considered, emitted from both laser ends. We thus demonstrated a single optical resonator consisting of the pumped active region and the two passive scattering elements with different disorder. We realized these devices with liquid or solid dye and defects at the edges consisting of scattering nanoparticle aggregates, natural raw materials or ablated polymer surfaces. A review on the architectures based on distributed/non-distributed feedback is provided in Supplementary Section 1.

In this Article, we demonstrate that architectures composed of a resonator with disordered mirrors can be used to achieve a RL diode by simple modification of commercially available, low-cost, FP laser diodes. We use a pulsed, high-energy laser beam for surface ablation of the front mirror of the FP laser diode, which, through roughness, induces defects with random shapes and sizes on the emitting area of the active layer. The back mirror of the laser diode is left unchanged, in a configuration conceptually similar to the first proposal of a non-resonant laser. We characterize the output power...
spectral and spatial emission and spatial coherence of the modified device and compare it to the original FP laser diode, obtaining incoherent random lasing emission that exhibits promising performances for future applications.

**Fabry–Pérot laser diode emission**

The device under study is an AlGaNp laser diode with a multi-quantum-well structure in a transistor outline (TO) can package. A full characterization of the device is provided in Supplementary Section 2.

The lasing threshold was found to be 21 mA, the slope efficiency ~0.27 W A⁻¹ and the spectral width dropped from 16 nm below threshold to 0.3 nm above threshold. The typical emission spectra of FP lasers are observed (Supplementary Fig. 3). Below threshold, spontaneous emission is dominant with respect to stimulated emission, and the gain profile is modulated by the equally spaced longitudinal modes of the FP cavity. Above threshold, modal competition at the gain centre wavelength produces a single-mode spectrum with a dominant peak and few sidebands.

The spatial coherence of the FP laser emission was measured by shining the collimated beam onto a black screen with two parallel slits, 50 µm wide and separated by 500 µm. Radiation from the slits was measured by a charge-coupled device (CCD) camera at different injection currents and the detected intensities were summed in CCD pixel columns parallel to the slits. Fringes appeared due to the interference between the wavefronts exiting each slit, allowing us to estimate the transverse spatial coherence of the laser from the visibility, \( \gamma = (I_{\text{MAX}} - I_{\text{MIN}})/(I_{\text{MAX}} + I_{\text{MIN}}) \), where \( I_{\text{MAX}} \) and \( I_{\text{MIN}} \) are the peak and trough intensities of the interference fringes at the central peak, respectively. Average values of \( \gamma = 0.62 \) and \( \gamma = 0.85 \) were found below and above threshold, respectively.

**Front mirror modification**

The laser source used for surface ablation was a high-energy femtosecond laser emitting at 800 nm (more details on the ablation procedure are provided in the Methods). The results obtained after blasting the front mirror of the laser diode with 200 pulses with an average energy of 100 µJ per pulse are shown in Fig. 1. The beam spot diameter is ~350 µm, overlapping with the emitting area and avoiding the top electrode. The ablation parameters were adjusted to avoid critical damage with no output and below threshold emission in the current range considered, as observed in devices subject to higher and lower amounts of delivered fluence, respectively.

The induced surface roughness is estimated to be in the sub-micrometre range, according to horizontal (0.46 µm) and vertical (0.34 µm) correlation lengths derived from the greyscale sections of scanning electron microscopy (SEM) images of the active region modified by processing (Supplementary Section 3). Laser-induced periodic surface structures are observed on the laser dice, but, remarkably, only above the emitting area, with the ripple direction orthogonal to the polarization of the ablating laser. The modified laser diode shows intense emission when current is injected, characterized by bright and dark spots randomly distributed along the active layer, as shown in Fig. 1c.

We remark that the use of pulsed laser ablation is motivated by considering that other surface modification processes, such as chemical etching or nanopowder depositions, would produce longer autocorrelation lengths or lower index contrast, respectively[41,42].

**Random-laser diode emission.** The output power of the modified laser diode and its emission linewidth are plotted in Fig. 2a as a function of the injected current. The output power increases with current and the lasing threshold is found at ~32 mA. The efficiency slope (1.4 mW A⁻¹) has decreased remarkably with respect to the original FP laser diode (0.27 W A⁻¹). This drastic performance loss is attributed to the ablation process, after which the front mirror average reflectivity has decreased and the local density of states has altered inside the cavity, changed by the new spatial mode distribution. Although detrimental for the device in terms of output power, the induced losses allow for the generation of sufficient scattering feedback for random-lasing action and are key to changing the character of the emission.

The modified device’s emission full-width at half-maximum (FWHM) decreases with current from 16.8 nm at 10 mA to 7.6 nm at 55 mA (Fig. 2a). This spectral narrowing above threshold is the fingerprint of lasing action.

We next study the spectral and spatial properties of the emission of the modified laser diode. The far-field angular emission[43] was characterized with the hyperspectral imaging set-up described in the Methods. Briefly, a multimode optical fibre was scanned across the back-focal plane of the collecting objective, so that the spatial coordinates of the fibre tip corresponded to the azimuthal angles of emission from the edge of the laser diode. In Fig. 2b we show the angular intensity distribution of the modified laser emission integrated over the entire wavelength range of detection, above threshold. A large half angle of emission of ~45° with respect to the axis of the pristine laser was obtained, with most of the radiation falling within 25°. The obtained profile is characterized by an irregular pattern of intensity maxima and minima, typical of RL modes, produced by the particular corrugations formed on the front mirror by the ablation process.

We measured the spectrum as a function of current at a fixed point in the far-field (marked by the crosshairs in the intensity map in Fig. 2b), located in a high-intensity area of emission. The measured spectra are plotted in Fig. 2c. We observe a spectral profile consisting of a large Gaussian background with superimposed narrow peaks, exhibiting subnanometre linewidths and without...
wavelength periodicity. As a function of the injected current, the amplitude of each peak increases while its resonant wavelength remains unaltered. We thus identify these peaks with the lasing modes of the new cavity formed between the disordered front mirror and the flat back mirror.

Spectra acquired at other angles (by changing the collection fibre position in the back-focal plane) presented the same characteristic Gaussian background, with randomly distributed narrow peaks on top that show constant wavelength positions independent of the injected current. The peaks vary in number and position for different detection directions, thus varying the spectral signature (Supplementary Section 4). A map of angular intensity distribution for a given mode can be obtained by extracting the intensity integrated in narrow windows (0.25 nm) around the associated peak from the acquired spectra and plotting this as a function of the corresponding angles. This is equivalent to setting the monochromator to a fixed wavelength and scanning the collection fibre. Spectrally resolved maps of emission present high correlation coefficients, between 0.89 and 0.94, as detailed in Supplementary Section 4. This is at variance with the case of RLs with non-distributed feedback and coherent random lasing emission, which are characterized by fewer peaks that are separated in frequency, exhibiting very different emission pattern for each peak45.

The spectrum shown in Fig. 2d is the total emission obtained by summing, for each wavelength, all the collected spectra in the far-field image in Fig. 2b. A large Gaussian background with FWHM of 7.8 nm is observed, typical of incoherent random lasing emission. In fact, the narrow peaks from all the collected spectra,
which increases with current. This behaviour is quantified by calculating the visibility $\gamma$, shown in Fig. 2g. Below threshold, this varies between 0.02 at 5 mA and 0.19 at 30 mA. Above threshold, $\gamma$ remains almost constant at an average value of 0.22. Compared to the lowest value ($\gamma = 0.60$) below threshold and the highest value ($\gamma = 0.85$) above threshold in the original FP laser, the visibility, and hence the spatial coherence, of the modified device has decreased abruptly.

The number of transverse lasing modes was estimated with speckle statistics by measuring the speckle patterns after passing the output beam through a diffuser (more details are provided in the Methods). Speckle patterns obtained for the original and modified laser diodes, for a bias current corresponding to 1.2$I_{\text{TH}}$ ($I_{\text{TH}}$ is the threshold current for each device), are shown in Fig. 3a and 3b, respectively. The probability density function, $P(I)$, normalized to the average intensity value, is plotted for the original (blue dots) and modified (red dots) laser diode, for 0.5$I_{\text{TH}}$ in Fig. 3c, and for 1.2$I_{\text{TH}}$ in Fig. 3d, and for the white-light source (black dots) in both figures as a comparison.

We estimate the number of transverse modes as $N = C^2$, where $C$ is the speckle contrast, given by $C = \sigma(I)/\langle I \rangle$, with $\sigma(I)$ and $\langle I \rangle$ being the standard deviation and the mean value of the collected pixel intensities, respectively. The results are summarized in Table 1, in which the calculated speckle contrasts for the original ($C_{\text{ORI}}$) and modified ($C_{\text{MOD}}$) laser diode and the numbers of transverse modes for the original ($N_{\text{ORI}}$) and modified ($N_{\text{MOD}}$) laser diodes are shown for different injection currents. The number of transverse modes is approximated to the nearest integer. Above threshold we obtain $N_{\text{ORI}} = 1$ and $N_{\text{MOD}} = 18$: the induced roughness on the output mirror modifies the original device from a single-transverse-mode FP laser to a multi-transverse-mode RL with few transverse modes (Supplementary Section 4 presents additional measurements).

### Theoretical model

The presented experimental results were benchmarked against the theoretical framework of RLs with non-distributed feedback, in which the phase and amplitude of disordered reflectors are assumed to vary randomly with frequency on a subnanometric scale. This assumption shifts the spatial complexity of the device to the spectral domain, where light at each frequency in the gain bandwidth, after being scattered back from the disordered mirrors, re-enters the cavity with random phase and amplitude.

The frequencies for which the phase accumulated along a roundtrip in the cavity (including the random phase contribution of the rough mirror) equal an integer number of $\pi$ (the effective optical path corresponding to an integer number of wavelengths) will survive in the cavity, while the rest will average out to nil upon successive roundtrips. This gives rise to a set of modes with random frequency positions, in contrast to the behaviour of FP lasers, in which the phase acquired upon mirror reflection is the same for all frequencies, leading to equally spaced modes determined purely by the cavity length.

The modified laser diode considered here consisted of a disordered front mirror and a flat back mirror, which are modelled with random spectral responses $R_{\text{ORI}}(\nu) \times \exp[\phi_{\text{ORI}}(\nu)]$ and $R_{\text{MOD}}(\nu) \times \exp[\phi_{\text{MOD}}(\nu)]$, where $\nu$ is the frequency and $R_{\text{ORI}}(\nu)$ and $\phi_{\text{ORI}}(\nu)$ are the reflection amplitude and phase of mirror 1 (front) and 2 (back), respectively.

| Table 1 | Speckle contrasts and number of transverse modes |
| --- | --- | --- | --- | --- |
| $I/I_{\text{TH}}$ | $C_{\text{ORI}}$ | $N_{\text{ORI}}$ | $C_{\text{MOD}}$ | $N_{\text{MOD}}$ |
| 0.2 | 0.17 | 36 | 0.04 | 798 |
| 0.5 | 0.21 | 22 | 0.11 | 80 |
| 1.0 | 0.44 | 5 | 0.17 | 33 |
| 1.2 | 0.81 | 1 | 0.24 | 18 |

Measured speckle contrasts for the original ($C_{\text{ORI}}$) and modified ($C_{\text{MOD}}$) laser diodes and the numbers of transverse modes for the original ($N_{\text{ORI}}$) and modified ($N_{\text{MOD}}$) laser diodes for different injection currents, expressed as a function of the threshold currents of the devices ($I_{\text{TH}}$).
The frequency-dependent phase profile expresses the concept that modes of different frequencies are scattered back from the ablated mirror into the active region with different phase values. No spatial information is included in the model.

By introducing the mirrors’ spectral response into the well-known roundtrip condition, we obtain the lasing condition in amplitude and phase

\[ g_{\text{TH}}(\nu) = \alpha + \frac{1}{2L} \ln \left( \frac{1}{R_1(\nu)R_2(\nu)} \right) \]

\[ \frac{2nUL}{\nu} + \frac{\phi_1(\nu) + \phi_2(\nu)}{2\pi} = m \]

where \( g_{\text{TH}}(\nu) \) is the frequency-dependent gain at threshold, \( \alpha \) represents the internal losses, \( L \) is the cavity length, \( n \) is the refractive index and \( m \) is an integer number.

We numerically construct a frequency vector spanning 80 nm centred at 630 nm, with resolution of 1.5 pm, and consider \( L = 365 \mu \text{m}, n = 3.5 \) and \( \alpha = 113 \text{ cm}^{-1} \), estimated from the measured slope efficiency of the original laser diode\(^6\). Gain is modelled with a Gaussian profile centred at 630 nm and linewidth at FWHM of 16.5 nm. Further details about the simulation parameters are provided in Supplementary Section 5.

We numerically solve equations (1) and (2) for the original and modified laser diodes. In both cases we consider the back mirror modelled with \( R_1(\nu) = 0.9 \) and \( \phi_1(\nu) = 0 \), for all frequencies. For the original laser diode, the front mirror is modelled with \( R_2(\nu) = 0.3 \) and \( \phi_2(\nu) = 0 \), for all frequencies. For the modified laser diode, we model \( R_2(\nu) \) and \( \phi_2(\nu) \) with both uniform and Gaussian statistical distributions of values between 0.1 and 0.3 and between \(-\pi \) and \( +\pi \), respectively. The uniform distribution aims at reproducing a modified mirror with perfect randomness, while the Gaussian distribution describes an intermediate case in which the modified mirror disorder is not totally random, but exhibits preferred values for \( R_2(\nu) \) and \( \phi_2(\nu) \).

Losses vary randomly with frequency, due to the contribution of \( R_1(\nu) \) in equation (1), and the allowed modes are found at frequencies for which equation (2) is verified, as shown in Fig. 4a. Solution for the original laser diode gives constant losses with frequency and modes evenly spaced with a free spectral range equal to \( 2nUL/c \) and corresponding to 0.155 nm at 630 nm (Supplementary Section 5).

The calculated emission spectrum of the modified laser diode with random disorder is shown in Fig. 4b, corresponding to the net gain profile available at allowed frequency modes. For practical reasons we limit our simulations to linear non-interacting modes; consequently, no spectral narrowing is observed. A full set of equations in the framework of coupled mode theory\(^6\) would require a time differential equation for each mode.

IFT plots obtained from the spectra of the simulated original and modified laser diodes are shown in Fig. 4c. A peak corresponding to a cavity length of 365 μm is observed for the original laser diode (blue line). Uniformly distributed random \( R_1(\nu) \) and \( \phi_1(\nu) \) correspond to pure, ideal disorder, leading to the absence of a peak in the IFT (black line). When \( R_2(\nu) \) and \( \phi_2(\nu) \) are modelled with Gaussian distributions, with mean values \( \mu_R = 0.2 \) and \( \mu_\phi = 0 \) and standard deviations \( \sigma_R = 0.03 \) and \( \sigma_\phi = 0.1 \), respectively, we still observe the peak at a cavity length equal to 365 μm (red line); however, this demonstrates an intensity decrease of more than 100 dB with respect to the FP case. Therefore, the small residual periodicity observed experimentally in Fig. 2d and Fig. 2e (red line) is numerically reproduced by employing a non-uniform distribution for \( R_1(\nu) \) and \( \phi_1(\nu) \).

Discussion

By analysing the emission properties of the modified laser diode, we identify the following five clues to multimode random lasing action:\(^6\): (1) lasing threshold and spectral narrowing with increasing driving current, (2) a Gaussian profile of emission with 7.8 nm FWHM above threshold exhibiting (3) subnanometre linewidth peaks at spatially varying random frequencies, with increasing amplitude as a function of injected current, (4) speckled intensity angular distribution and (5) low spatial coherence at any driving current with multi-transverse mode emission above threshold.

The increase of lasing threshold (from 21 mA to 32 mA) and decrease of slope efficiency (from 0.27 W A\(^{-1}\) to 1.4 mA W\(^{-1}\)) are attributed to the roughness added to the front mirror via three major mechanisms: lower reflectance (which lowers the energy inside the cavity), altered density of states (which lowers the recombination rate) and surface states in the new mirror (which lowers radiative recombination). Such detrimental effects are intrinsic to the modified device, as scattering feedback is more lossy compared to the flat mirror specular reflection.

The FWHM width of the spectrum is similar in both devices below threshold (~16 nm) but differs greatly above threshold. In the original FP laser diode, a single longitudinal mode is dominant above threshold due to mode competition sustained by the modes’ long lifetime due to the high-quality cavity. In the modified laser
Articles

Periodic modes in the spectrum, as the mean values are more recurrent than others (Supplementary Section 5). The amplitude of the IFT peak can be decreased by 100 dB, which is attributed to the contribution of the RL spectral output being obtained from a set of FP lasers, with random cavity lengths, with a Gaussian profile with FWHM width of 7.8 nm and multiple subnanometre spikes observed. The occurrence of many simultaneous modes is attributed to multimode emission from modes randomly distributed in frequency, experiencing a lessened interaction due to the reduced lifetimes, which does not allow any dominant peak to emerge.

The angular emission is characterized by an irregular speckle-like distribution of intensity maxima and minima, in contrast to the elliptical shape expected from the FP laser diode. This results from the contribution of the transverse profiles of all emitting modes due to the corrugated scattering surface.

The increase in the number of transverse lasing modes after the ablation process reduces the spatial coherence of the modified device, as previously observed in multi-transverse-mode laser sources.

These results are in agreement with the theoretical framework of RLs with non-distributed feedback, in which unpredictable phase contributions from disordered mirrors produce a random distribution of frequency modes. In the experimentally modified laser diode, the ablation process changes the front mirror phase profile, resulting in multimode random lasing emission.

In our vision, the evidence of random lasing is supported by the following rationale: if the modified mirror acted only as an external diffuser for the original laser diode, the speckled emission pattern would still be observed, but the emission spectrum would be the same as that of the original laser diode. The occurrence of a completely different spectrum, with narrow randomly distributed peaks at constant wavelengths for different bias currents, is proof that the processing not only adds optical elements outside the cavity that will filter or redirect the emission, but also gives rise to the RL device rather than a FP laser.

An alternative interpretation of the results could be defended: the RL spectral output can be obtained from a set of FP lasers, with random cavity lengths, formed between the flat back mirror and the set of narrow reflective sections on the ablated mirror. However, we exclude this hypothesis on consideration that such narrow sections (with subwavelength lateral dimension) would strongly diffract and mix the modes. As shown in Supplementary Section 3, the ablated mirror is characterized by an irregular surface with sub-wavelength autocorrelation lengths (0.3–0.5 μm), which diffracts and mixes modes from the active region beyond those of independent FP lasers.

By benchmarking the experimental results against numerical simulations, we infer that the residual periodicity observed in the experiments (the IFT peak decrease by 100 dB) is attributed to the modified mirror disorder degree. Only a complete uncorrelated random disorder would allow elimination of the IFT peak. On the other hand, the Gaussian distributions of $R(s)$ and $\phi(s)$ promote periodic modes in the spectrum, as the mean values are more recurrent than others (Supplementary Section 5). The amplitude of the IFT peak can therefore be tuned by inducing a different degree of disorder in the modified mirror, possibly by varying the processing parameters. We envision that it is possible to adjust the ablation parameters, such as the fluence, number of pulses, wavelength and polarization direction, to purposefully vary the RL properties (threshold, efficiency, spectral and spatial characteristics). This would require a statistical analysis on many processed devices and a more detailed model including spatial mode information for relating the emission properties to the induced disorder.

Conclusions

We have demonstrated the realization of an incoherent semiconductor RL from a commercially available FP laser diode by pulsed laser ablation of its output mirror. Our simple method requires a high-energy pulsed source and a commercial laser diode, elements often found in photonics laboratories, in contrast with the more complex processes required for semiconductor device fabrication, such as molecular beam epitaxy or nanoscale lithography.

We obtain a continuous-wave electrically pumped source with random multimode emission and low spatial coherence. Such a device is a practical choice for multiple applications in which optically pumped RLs are usually employed, such as imaging, sensing and optical information processing.

Additionally, fine tuning of the pulse duration and energy provides a practical means for varying the scattering properties of the modified mirror and thus adjusting the emission characteristics, for example, the number of lasing modes, as observed in devices based on ablated dye-doped polymers, and different degrees of spatial coherence. If the emission of the modified laser diode were proven to be stable over time, it could be suitable for exploring the behaviour of chaotic emission. In fact, we believe that, with greater output power in future devices, such a system could be driven to the chaotic regime by means of synchronous external cavity feedback.

With the reported results we also demonstrate the implementation of a hybrid RL device with one flat and one disordered mirror. This can open the way to the realization of more types of RL based on non-distributed feedback and ordered/disordered structures (some examples are described in Supplementary Section 1). Finally, the proposed work provides an efficient way to tailor electrically driven random lasing that will strongly promote its application in innovative light sources.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41566-021-00946-0.

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References

1. Cao, H. Random lasers: development, features and applications. Opt. Photon. News 16, 24–29 (2005).
2. Redding, B., Choma, M. A. & Cao, H. Speckle-free laser imaging using random laser illumination. Nat. Photon. 6, 355–359 (2012).
3. Ignesti, E. et al. A new class of optical sensors: a random laser based device. Sci. Rep. 6, 55225 (2016).
4. Boscheti, A. et al. Spectral super-resolution spectroscopy using a random laser. Nat. Photon. 14, 177–182 (2020).
5. Caselli, N., Consoli, A., Mateos Sánchez, A. & López, C. Networks of mutually coupled random lasers. Optica 8, 193–201 (2021).
6. Ambartsymyan, R. V., Basov, N. G., Kryukov, P. G. & Letokhov, V. S. A laser with a nonresonant feedback. IEEE J. Quantum Electron. 2, 442–446 (1966).
7. Ambartsymyan, R. V., Basov, N. G., Kryukov, P. G. & Letokhov, V. S. Non-resonant feedback in lasers. Prog. Quantum Electron. 1, 107–185 (1970).
8. Gouedard, C., Auzel, E., Mugas, A., Husson, D. & Sauteret, C. Generation of spatially incoherent short pulses in laser-pumped neodymium stoichiometric crystals and powders. J. Opt. Soc. Am. B 10, 2358–2363 (1993).
9. Lawandy, N. M., Balachandran, R. M., Gomes, A. S. L. & Sauvain, E. Laser action in strongly scattering media. Nature 368, 436–438 (1994).
10. Cao, H. et al. Ultraviolet lasing in resonators formed by scattering in semiconductor polycrystalline films. Appl. Phys. Lett. 73, 3656–3658 (1998).
11. Caixeiro, S., Gaio, M., Marelli, B., Omenetto, F. G. & Sapienza, R. Silk-based biocompatible random lasing. Nat. Photon. 6, 357–360 (2013).
12. Azkargorta, J. et al. Random laser properties of Ni5+ crystal powders. Opt. Express 26, 11787–11803 (2018).
13. Song, Q. et al. Random lasing in bone tissue. Adv. Opt. Mater. 4, 998–1003 (2016).
14. Wang, C.-S., Chang, T.-Y., Lin, T.-Y. & Chen, Y.-F. Biologically inspired flexible quasi-single-mode random laser: an integration of Pieris canidia butterfly wing and semiconductors. Sci. Rep. 4, 6736 (2014).
15. Viola, I. et al. Random laser emission from a paper-based device. J. Mater. Chem. C 1, 8128–8133 (2013).
16. Baudouin, Q., Mercadier, N., Guerrera, V., Guerin, W. & Kaiser, R. A cold-atom random laser. Nat. Phys. 9, 357–360 (2013).
17. Vasileva, E. et al. Lasing from organic dye molecules embedded in transparent wood. *Adv. Opt. Mater.* 5, 1700057 (2017).
18. Sznitzko, L., Mysliwiec, J. & Miniewicz, A. The role of polymers in random lasing. *J. Polym. Sci. B* 53, 951–974 (2015).
19. Ma, R., Rao, Y. J., Zhang, W. L. & Hu, B. Multimode random fiber laser for speckle-free imaging. *IEEE J. Sel. Top. Quantum Electron.* 25, 1–6 (2019).
20. Yu, S. F. Electrically pumped random lasers. *J. Phys. D* 48, 483001 (2015).
21. Schönhuber, S. et al. Random lasers for broadband directional emission. *Optica* 3, 1035–1038 (2016).
22. Liang, H. K. et al. Electrically pumped mid-infrared random lasers. *Adv. Mater.* 25, 6859–6863 (2013).
23. Zeng, Y. et al. Designer multimode localized random lasing in amorphous lattices at terahertz frequencies. *ACS Photon.* 3, 2453–2460 (2016).
24. Biasco, S. et al. Frequency-tunable continuous-wave random lasers at terahertz frequencies. *Light Sci. Appl.* 8, 43 (2019).
25. Yu, S. F., Yuen, C., Lau, S. P. & Lee, H. W. Zinc oxide thin-film random lasers. *Opt. Express* 18, 843–846 (2010).
26. Ma, X. et al. Room temperature electrically pumped ultraviolet random lasing on silicon substrate. *Appl. Phys. Lett.* 84, 3244–3246 (2004).
27. Ma, X., Chen, P., Li, D., Zhang, Y. & Yang, D. Electrically pumped ZnO film ultraviolet random lasers on silicon substrate. *Appl. Phys. Lett.* 91, 251109 (2007).
28. Qiao, Q. et al. Surface plasmon enhanced electrically pumped random lasers. *Nanoscale* 5, 513–517 (2013).
29. Chu, S., Olmedo, M., Yang, Z., Kong, J. & Liu, J. Electrically pumped ultraviolet ZnO diode lasers on Si. *Appl. Phys. Lett.* 93, 181106 (2008).
30. Wang, C. S., Nieh, C. H., Lin, T. Y. & Chen, Y. F. Electrically driven random laser memory. *Adv. Funct. Mater.* 25, 4058–4063 (2015).
31. Ma, X. et al. Room temperature electrically pumped ultraviolet random lasing from ZnO nanorod arrays on Si. *Opt. Express* 17, 14426–14433 (2009).
32. Gao, F. et al. Electrically pumped random lasing based on an Au-ZnO nanowire Schottky junction. *Nanoscale* 7, 9505–9509 (2015).
33. Liu, X. Y., Shan, C. X., Wang, S. P., Zhang, Z. Z. & Shen, D. Z. Electrically pumped random lasers fabricated from ZnO nanowire arrays. *Nanoscale* 4, 2843–2846 (2012).
34. Huang, J. et al. ZnO p-n homojunction random laser diode based on nitrogen-doped p-type nanowires. *Adv. Opt. Mater.* 1, 179–185 (2013).
35. Leong, E. S. P., Yu, S. F. & Lau, S. P. Directional edge-emitting UV random laser diodes. *Appl. Phys. Lett.* 89, 221109 (2006).
36. Leong, E. S. P. & Yu, S. F. UV random lasing action in p-SiC(4H)/i-ZnO-SiO2 nanocomposite/n-ZnO:Al heterojunction diodes. *Adv. Mater.* 18, 1685–1688 (2006).
37. Liang, H. K., Yu, S. F. & Yang, H. Y. Directional and controllable edge-emitting ZnO ultraviolet random laser diodes. *Appl. Phys. Lett.* 96, 101116 (2010).

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Methods

Ablation. The main elements of the ablation set-up are the pulse laser source and the focusing optics (also used for imaging the ablated surface). Pulse energy from the laser source (Coherent Libra, 100-fs-long pulses at 800 nm with 1 kHz repetition rate) is controlled by a J/4 waveplate and a linear polarizer. A fraction (10%) of the beam is sent via a beamsplitter to a power meter connected to a PC to monitor the pulse energy. The number of delivered pulses is controlled by the PC and a numerical routine. Pulses are delivered by means of a ×40 microscope objective (NA = 0.45).

The can of the laser diode (Thorlabs L635P5) is removed to grant access to the chip and the laser output mirror. The laser dice is mounted on a silicon substrate placed on the heat sink and cathode terminal. The active layer is located at the bottom of the dice, close to the silicon substrate, as verified by imaging the emission while injecting a small amount of current (Supplementary Fig. 4). The front mirror of the laser diode is positioned out of the focusing plane of the objective so as to shine on a large area of the laser mirror.

The external mirror surface is simultaneously imaged in reflection using the same objective, a beamsplitter and a white-light source. The image of the illuminated mirror is projected onto a CCD camera (Pixelink PL-B776F) with a 50:50 beamsplitter and an imaging lens (focal length of 5 cm). A short-pass filter is used in front of the CCD camera to block the high-energy 800 nm radiation scattered from the mirror surface.

As pulses are sent to the laser diode mirror, the ablated area is observed on the CCD camera. By moving the laser diode by means of micrometric translational stages, we are able to place the ablation pulses at the desired position.

Optical emission characterization. The original (Thorlabs L635P5) and modified laser diodes are fed with a current driver (Thorlabs LDC 205 C) and are temperature-controlled with a thermo-electric cooler (Thorlabs TED 200C). Continuous-wave currents and a temperature of 15 °C are used in all experiments.

The output beam is collimated with a ×100 microscope objective (0.9 NA) and sent to a 50:50 beamsplitter. The transmitted beam is sent to a calibrated photodiode (Thorlabs S130C), connected to a PC, for power measurements. The reflected beam is sent to an imaging lens (focal length of 5 cm), and a fibre tip (diameter of 100 μm) is placed on the image plane and mounted on two computer-controlled, motorized translation stages (Thorlabs ZB12). The fibre is coupled to a spectrometer (Andor Shamrock 303), and hyperspectral measurements of the far-field angular distribution emission are obtained by scanning the fibre probe on the x–y plane over a grid of 80 × 80 equally spaced (100 μm) collection points.

In the set-up for measurement of the spatial coherence of the emitted radiation, the collimated output beam shines on a black screen with two parallel slits (width of 50 μm), separated by 500 μm. The slits were obtained from a 50-μm-thick aluminium foil by pulsed laser perforation. A cylindrical lens (focal length of 7.5 cm) is located after the slits and before the CCD camera, where the interference fringes are detected. In the measurements performed with the modified laser diode, the collimated beam diameter is ~8 mm and both slits are placed where the beam intensity is at a maximum.

Speckle contrast measurements are performed by placing an opaque adhesive tape on the propagation path of the collimated output beam. Diffused light from the adhesive tape is imaged on an 8-bit CCD camera with a 5-cm-focal-length lens. The object plane is located 3.8 cm from the tape, and lens and CCD camera distances were adjusted to achieve a magnification of 1.25. Three sources are considered: (1) white light, (2) the original laser diode and (3) the modified laser diode. Additional measurements, shown in Supplementary Section 4, were performed by placing a resolution test target (Thorlabs R2L2S1P) on the object plane.

Statistics and reproducibility. SEM and optical microscope images of the original and modified laser diodes, such as those in Fig. 1 and Supplementary Figs. 4 and 5, were repeated several times and obtained the same qualitative results. Speckle measurements, as shown in Fig. 3 and Supplementary Fig. 9, were repeated ten times, obtaining the same qualitative results.

Data availability
The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

Code availability
The MATLAB codes developed to execute the calculations presented in this paper are available from the corresponding authors upon reasonable request.

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Author contributions
A.C. conceived the device and designed the experiments. A.C. and N.C. performed the experiments. Additional measurements, shown in Supplementary Section 4, were performed by placing a resolution test target (Thorlabs R2L2S1P) on the object plane.

Competing interests
The authors declare no competing interests.

Additional information
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