ENGINEERING OF SOLID-STATE RANDOM LASING IN NANOPOROUS PHOTONIC CRYSTALS

AIP CONGRESS 2022

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The University of Adelaide

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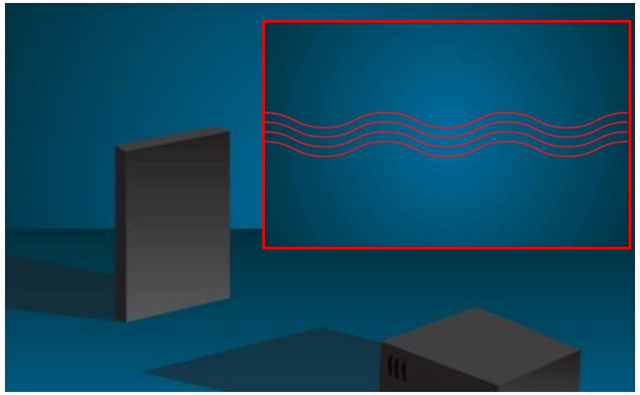
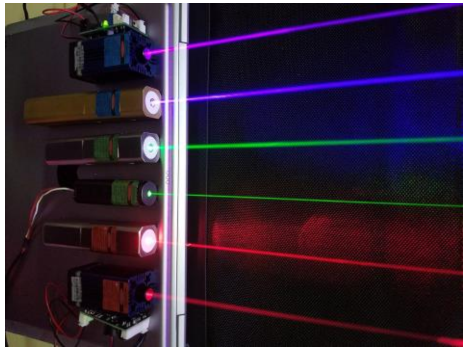
What is a laser?

Definition

A laser is a system that produces a very narrow beam of light of one single wavelength through **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.



The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories.



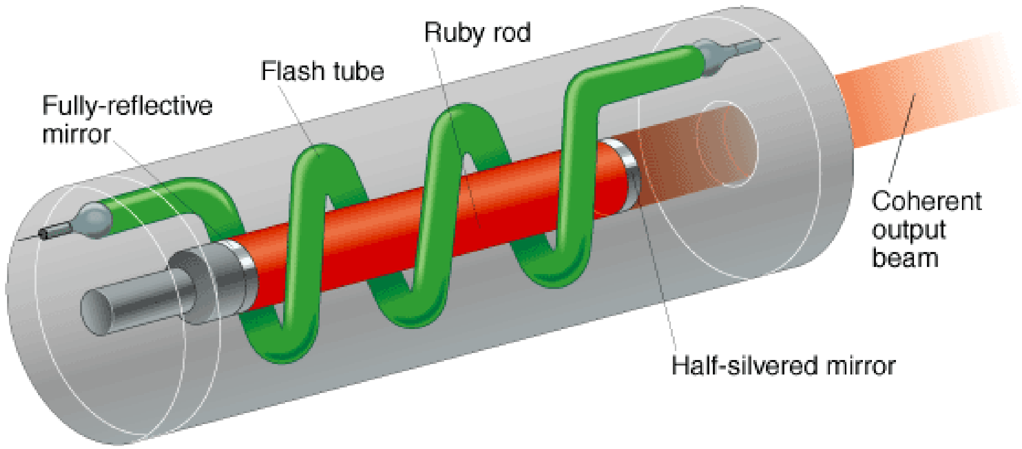
Theodore H. Maiman
(1927–2007)

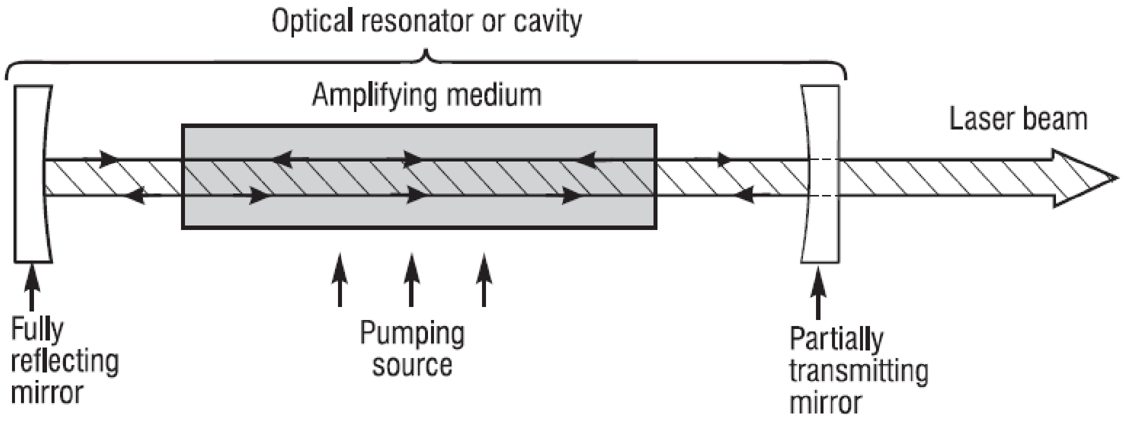
T.H. Maiman, Stimulated optical radiation in ruby, Nature 1960, 187, 493

What is a laser?

Architecture

A typical laser device consists of a **gain medium**, a **pumping source** to input energy into the device, and an **optical cavity** that reflects the beam of light back and forth through the gain medium for further amplification.



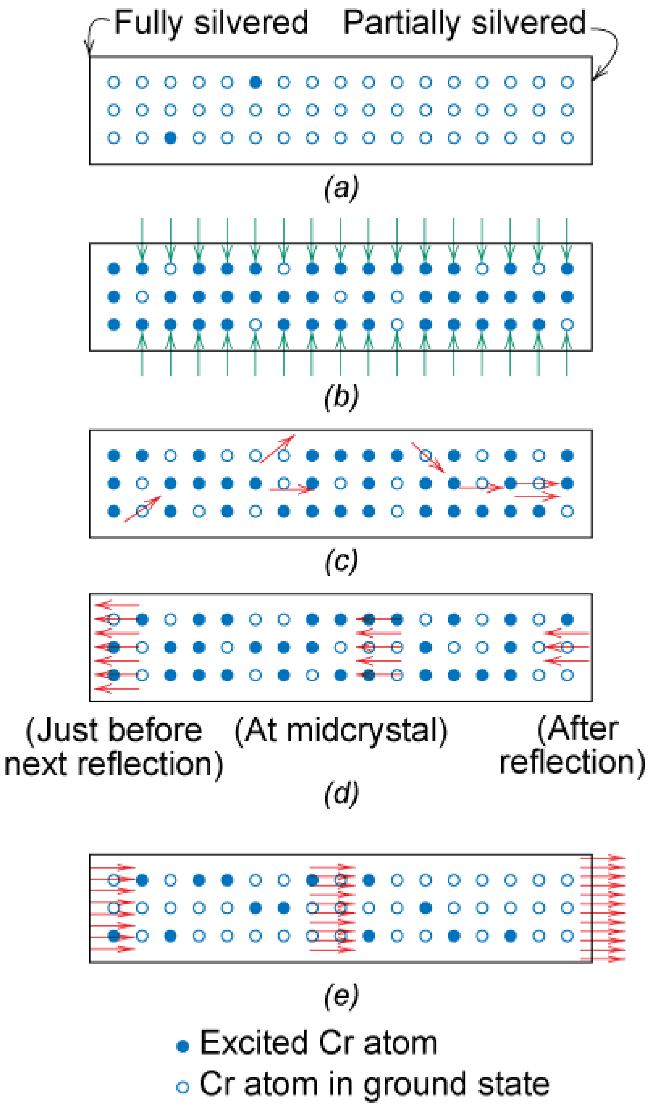


T.H. Maiman, Stimulated optical radiation in ruby, Nature 1960, 187, 493

What is a laser?

Mechanism

Simulated emission: Results when an electron in a higher-lying level of an atom and a photon collision. The photon stimulates the atom to radiate a second photon having the same energy as that of the incident photon and traveling in the same direction in order to satisfy the laws of conservation of energy and momentum.

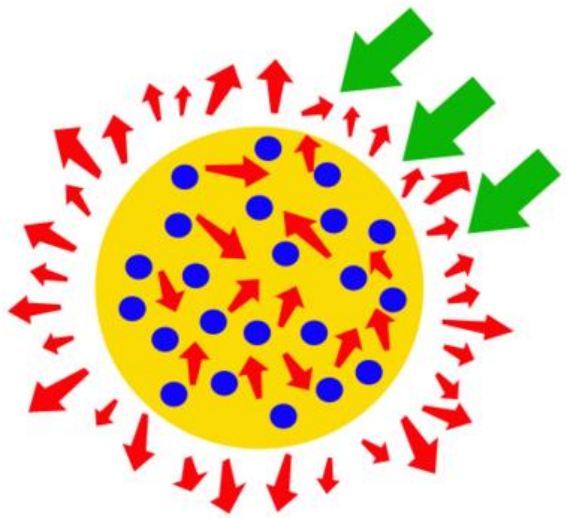


T.H. Maiman, Stimulated optical radiation in ruby, Nature 1960, 187, 493

Other types of lasers

Cavity-free lasers

Random laser (RL): Lasing feedback and amplification mechanisms in RLs are determined by multiple light scattering events in randomly distributed diffusive elements (scatters) embedded in an active gain medium.



Type of Scatters

- Colloidal solutions of particles and organic dyes
- Living tissue
- Semiconductor powders
- Doped optical fibers
- **Composite porous materials**
- Liquid crystals
- Etched semiconductors
- Polymers

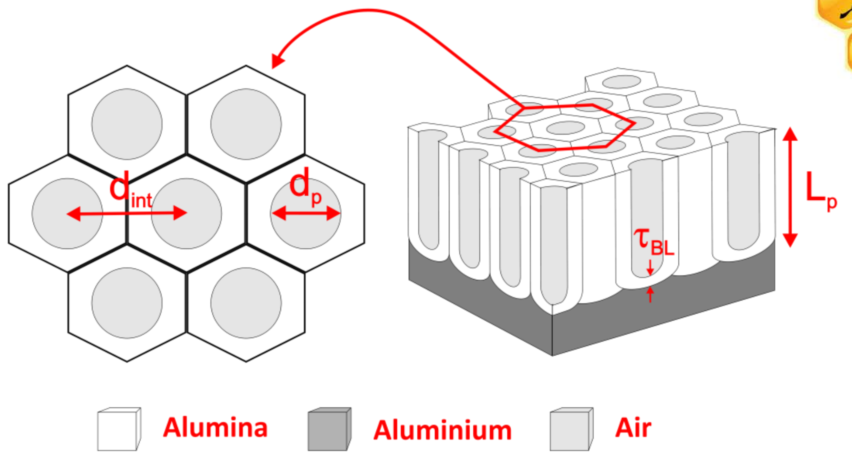
R.V. Ambartsumyan, IEEE J. Quantum Electron. 1966, 2, 442
R.V. Ambartsumyan Prog. Quantum Electron. 1970, 1, 107

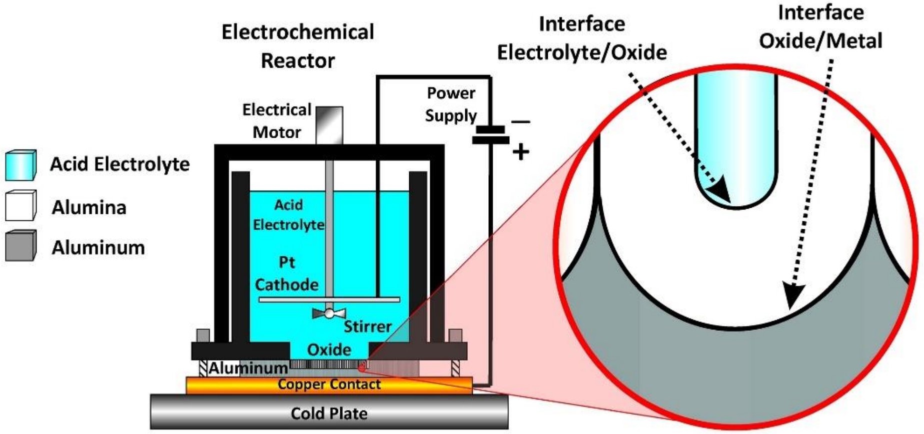
Structural engineering of porous random lasers

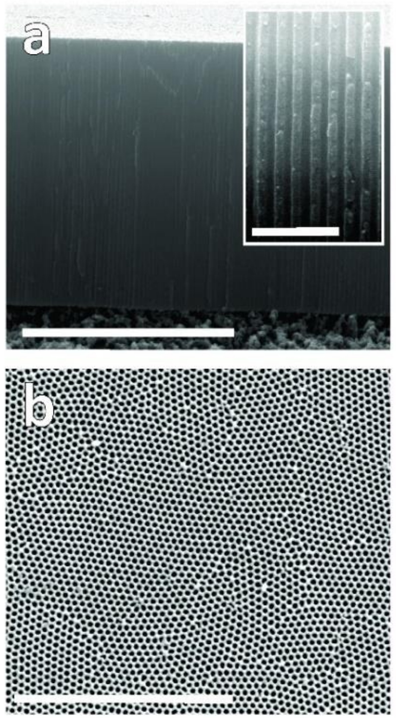
Nanoporous photonic crystals

Nanoporous anodic alumina (NAA): Produced by electrochemical oxidation (anodisation) of aluminium in acid electrolytes.

d_{int} → Interpore distance (50–500 nm)
d_p → Pore diameter (5–400 nm)
L_p → Pore length (from nm to mm)
τ_{BL} → Barrier layer thickness







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A. Santos, Journal of Materials Chemistry C 2017, 5, 5581

Structural engineering of porous random lasers

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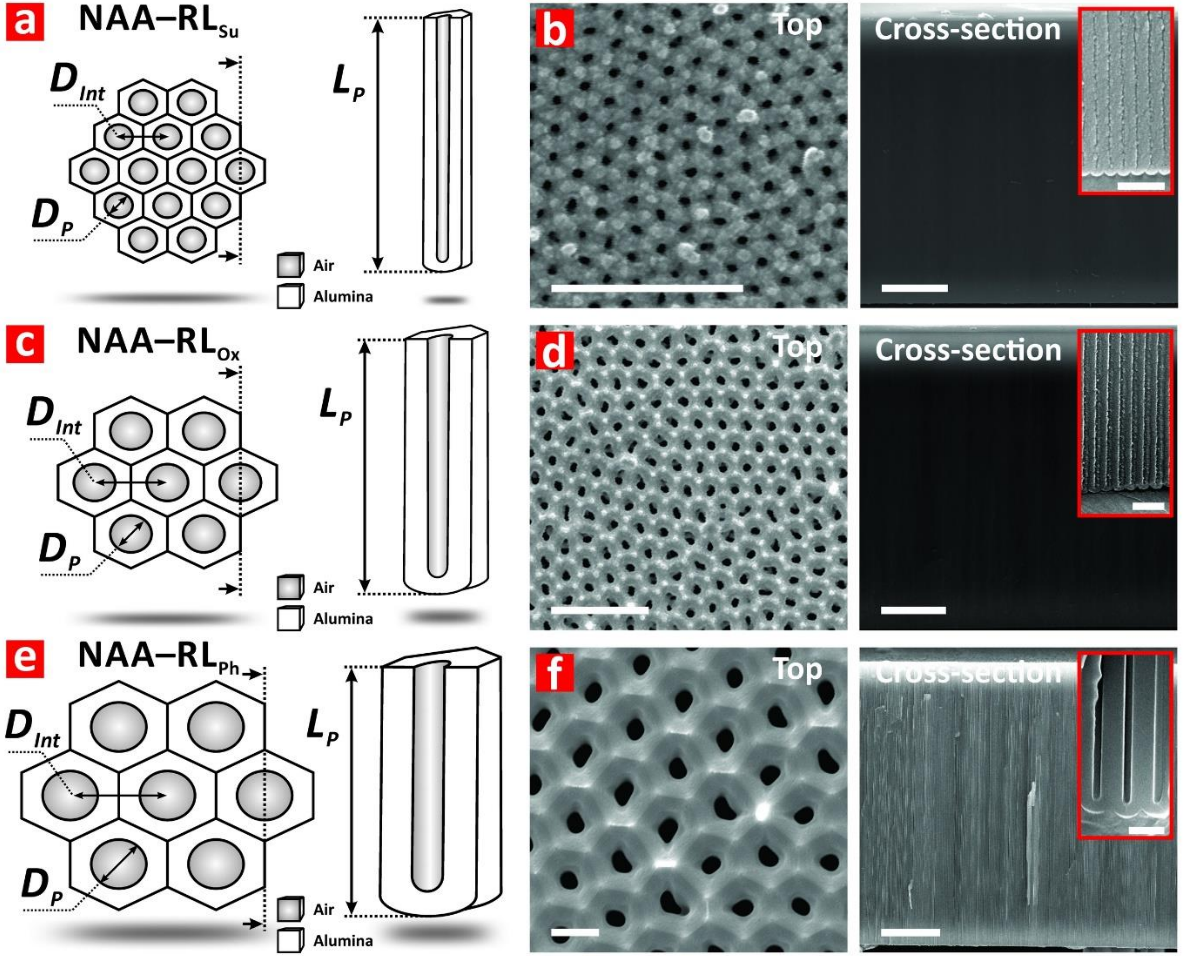
Nanoporous photonic crystals

Model random lasing platform: Using nanopores as model scatters to understand random lasing mechanisms.

NAA–RL	D_P (nm)	D_{Int} (nm)	L_P (mm)
NAA–RL_{Su}	19 ± 3	64 ± 5	42.7 ± 0.2
NAA–RL_{Ox}	46 ± 5	110 ± 3	42.6 ± 0.4
NAA–RL_{Ph}	108 ± 13	490 ± 12	45.1 ± 0.4

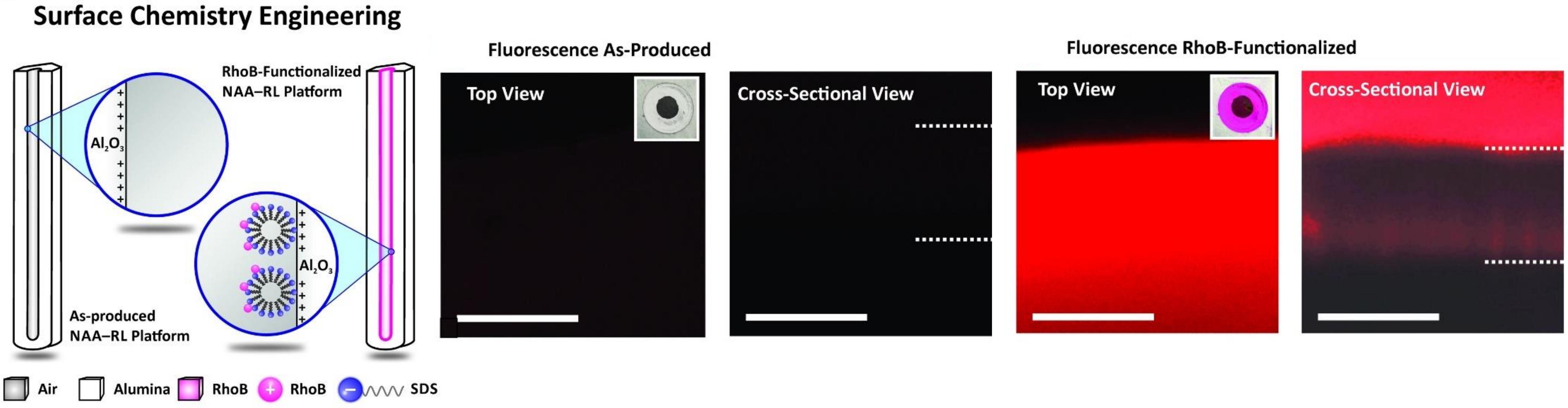


S. Gunenthiran et. al., ACS Applied Nano Materials. DOI: 10.1021/acsanm.2c02574

Chemical modification of porous random lasers

Solid-state organic random laser

Encapsulation of rhodamine B (RhoB): RhoB functionalisation of NAA-based RLs (NAA–RLs) via micellar solubilisation of sodium dodecyl sulphate (SDS) surfactant.



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Random lasing in photonic crystals

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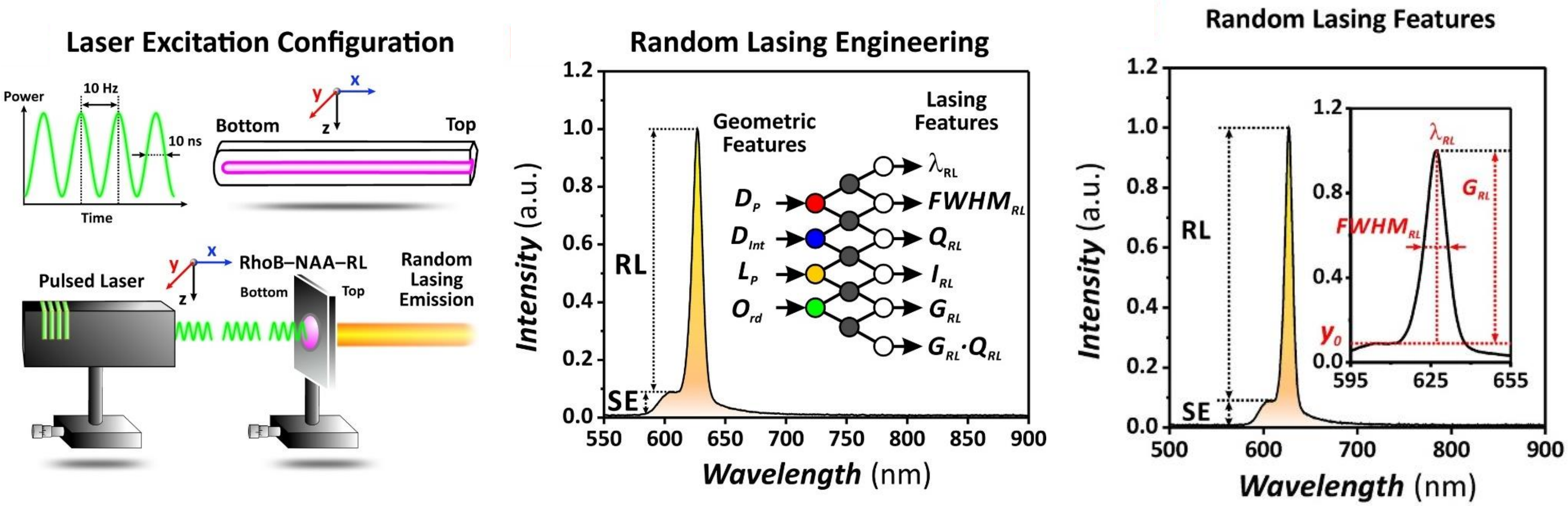
Solid-state organic random laser

Lasing characterisation: Generation of lasing emissions from RhoB-functionalised NAA–RLs under pulsed optical pumping (i.e., 532 nm, 10 ns, and 10 Hz).



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Random lasing in photonic crystals

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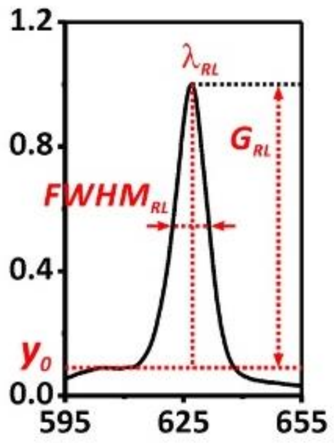
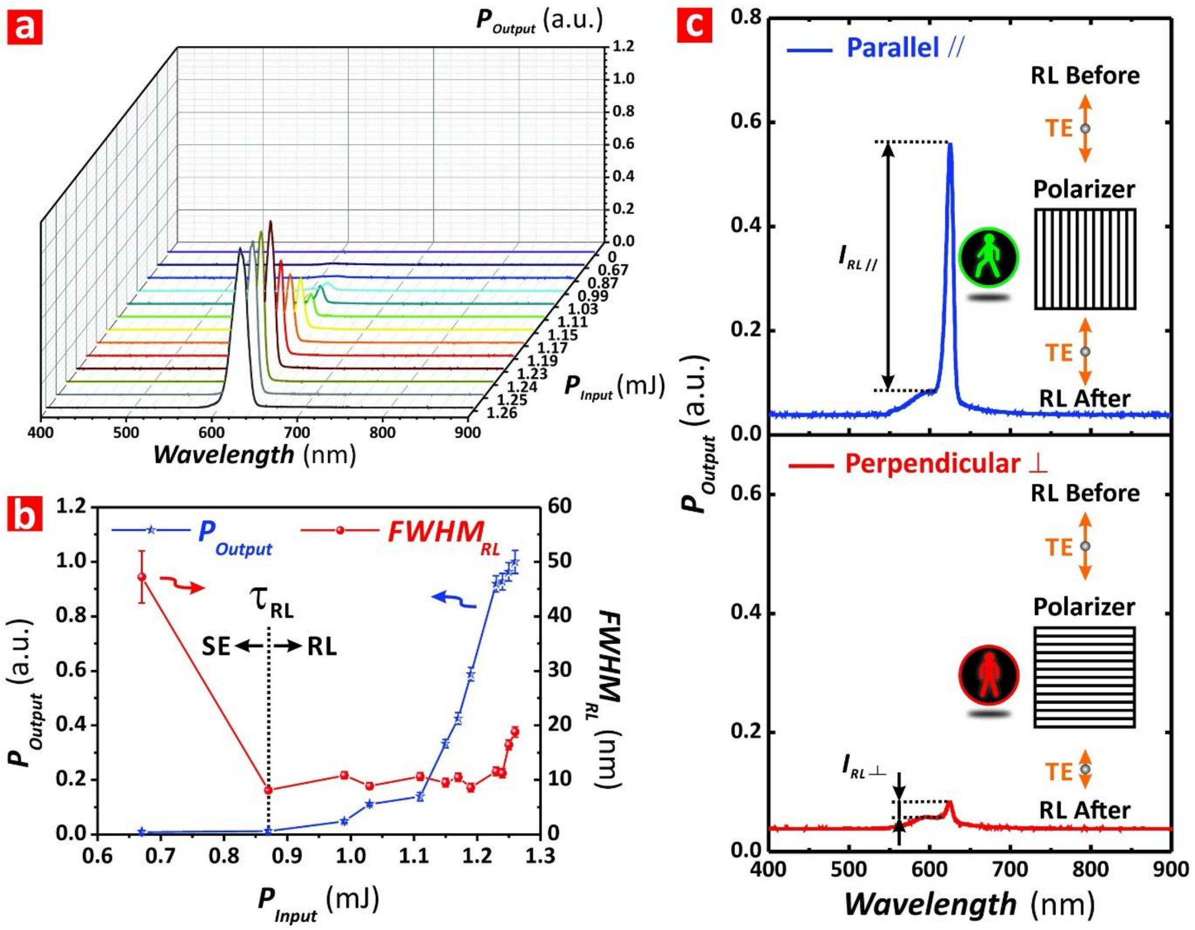


$$Q_{LE} = \lambda_{LE}/FWHM_{LE}$$

$$G_{LE} = I_{LE}/I_{SE}$$



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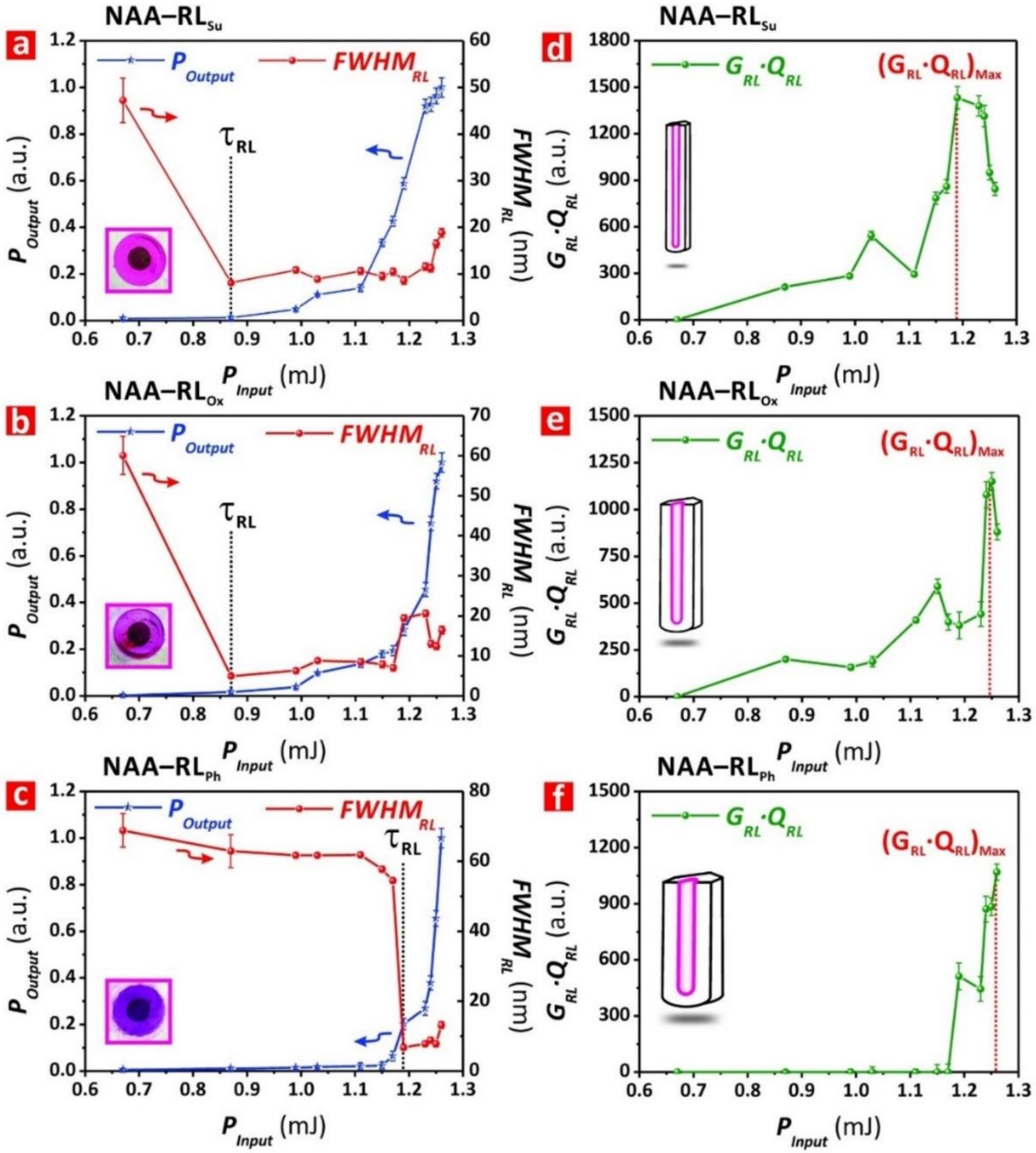
Random lasing in photonic crystals

Solid-state organic random laser

Combined effect of D_{Int} and D_P on lasing:

- D_{Int} = transport mean free path or distance that a wave travels before its direction of propagation is randomised by a scatter (L_{Free})
- D_P = scatter size ($L_{Scatter}$)
- Since $L_{Scatter} = D_P << L_{Free} = D_{Int}$, random lasing in all NAA–RL platforms is within the ballistic regime
- The estimated $(G_{RL} \cdot Q_{RL})_{Max}$ follows the order RhoB–NAA–RL_{Ph} < RhoB–NAA–RL_{Ox} < RhoB–NAA–RL_{Su}



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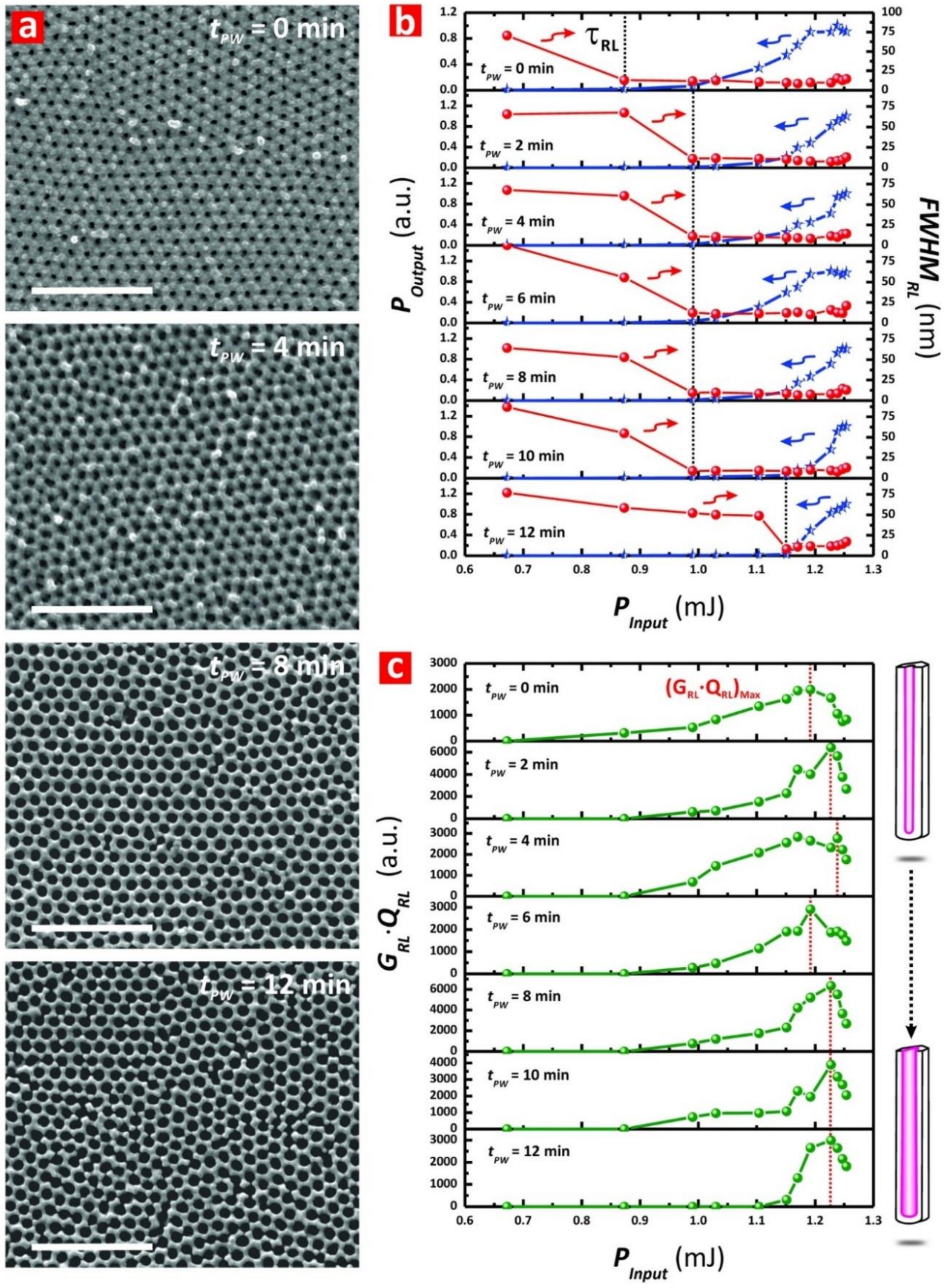
Random lasing in photonic crystals

Solid-state organic random laser

Effect of small variation of D_P on lasing:

- D_P = scatter size ($L_{Scatter}$)
- Finely tuned from ~20 to ~40 nm via pore widening through wet chemical etching
- Lasing threshold—value of P_{Input} at which the transition from SE to RL occurs—is found to increase with increasing nanopore diameter
- The estimated $(G_{RL}\cdot Q_{RL})_{Max}$ indicates that a small variation of scatter size is not statistically affected by small variation of scatter size



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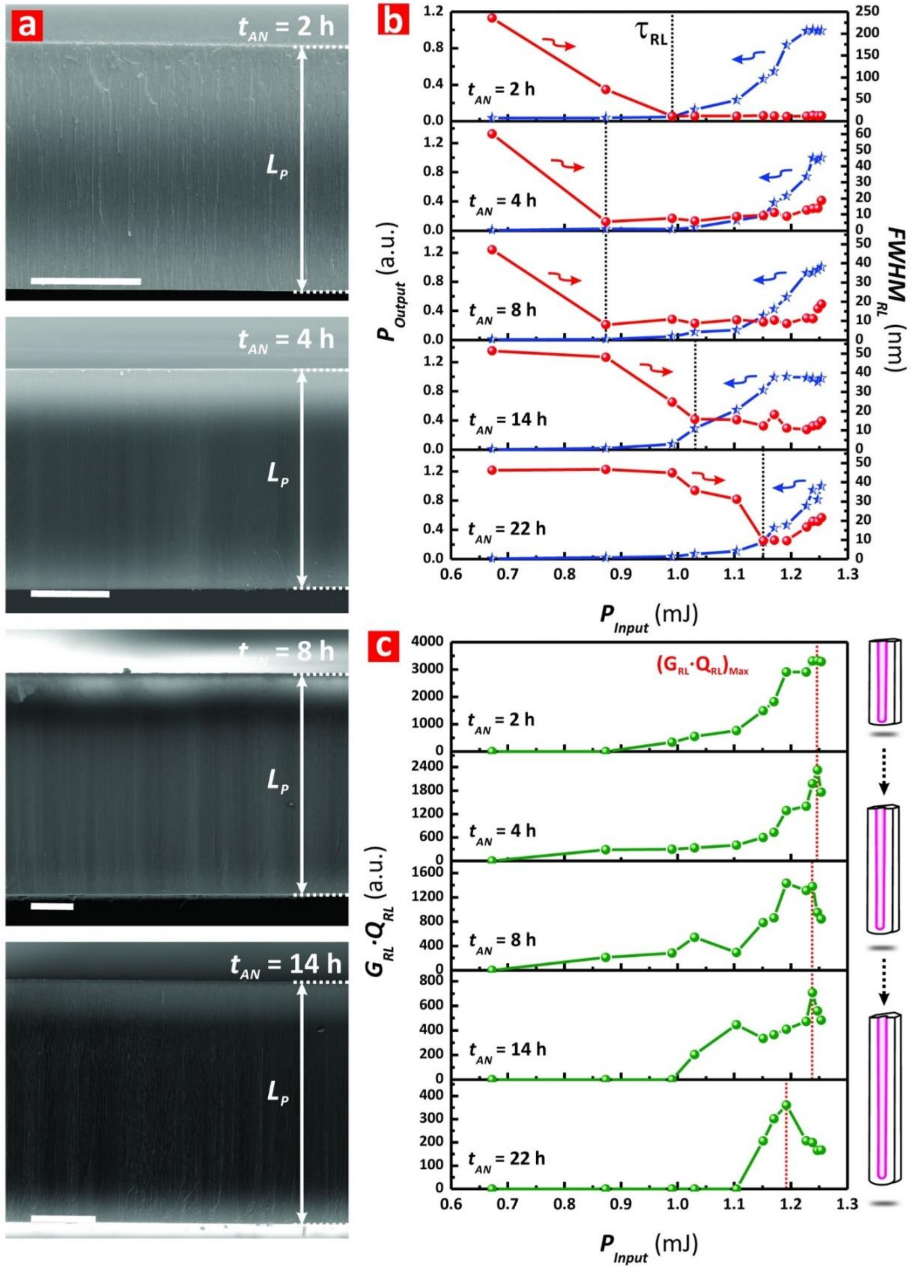
Random lasing in photonic crystals

Solid-state organic random laser

Effect of thickness of gain medium on lasing:

- Finely tuned from ~10 to ~116 μm via anodisation time (t_{AN})
- Lasing threshold undergoes an initial decrease but, as the gain medium becomes thicker than ~43 μm, the required energy to activate the random lasing mechanism in these model platforms increases
- It is found that $(G_{RL}\cdot Q_{RL})_{Max}$ decreases with the film thickness due to excessive scattering of excitation photons within the amplifying region



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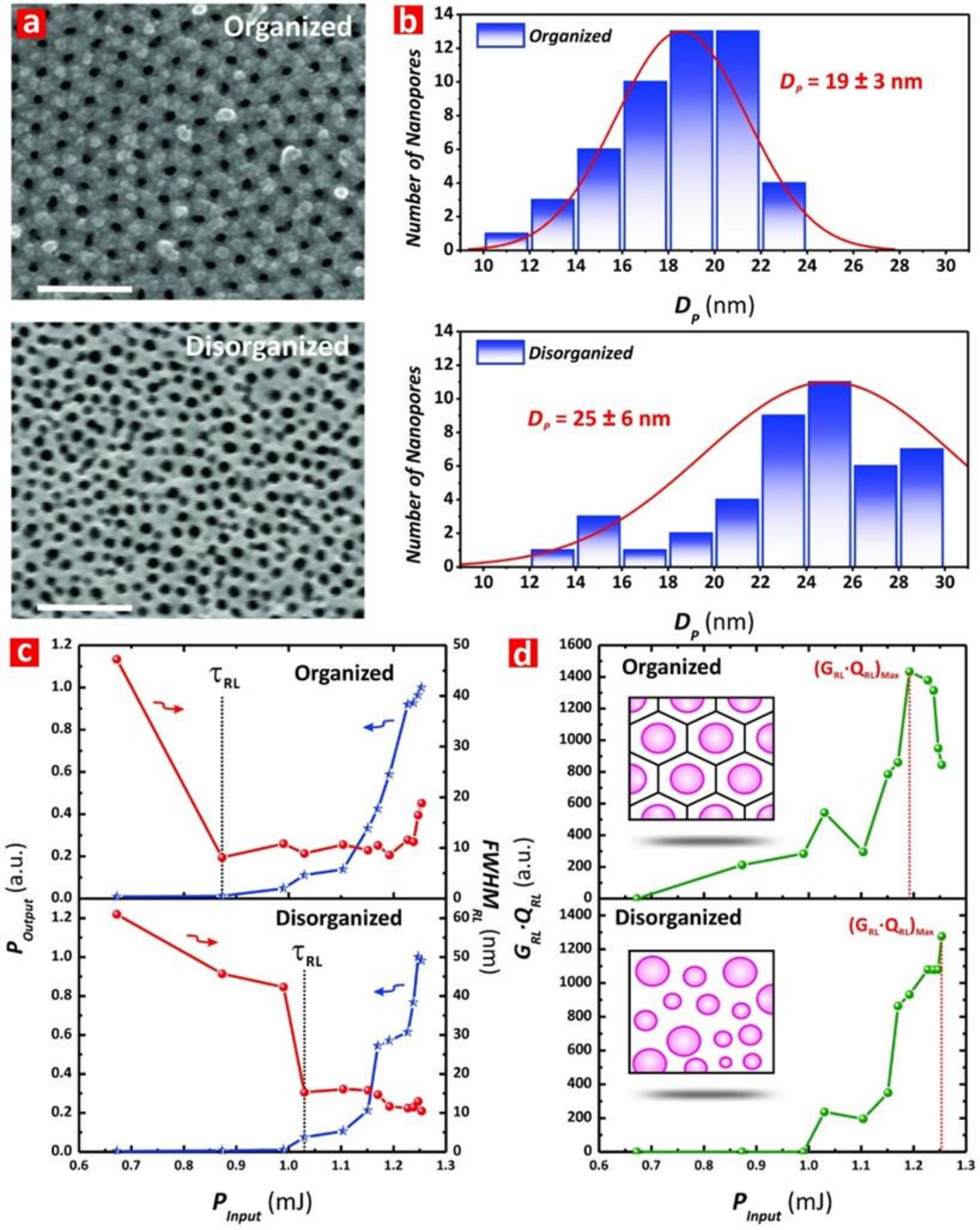
Random lasing in photonic crystals

Solid-state organic random laser

Effect of scatter organisation:

- Tuned between organised and disorganised states through anodisation
- Average scatter size and its dispersion decrease with the level of organisation
- Lasing threshold increases with disorganisation of scatters
- It is found that $(G_{RL} \cdot Q_{RL})_{Max}$ decreases with the level of disorganisation for a given input power



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Thank you for listening!

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