Dielectric singular nanolaser with atomic-scale field localization

Yun-Hao Ouyang[1ǂ], Hong-Yi Luan[1ǂ], Zi-Wei Zhao[1ǂ], Wen-Zhi Mao[1], Ren-Min Ma[1,2,3*],

[1] State Key Laboratory for Mesoscopic Physics and Frontiers Science Center for Nano-optoelectronics, School of Physics, Peking University, China
[2] Peking University Yangtze Delta Institute of Optoelectronics, Nantong, Jiangsu, China
[3] National Biomedical Imaging Center, Peking University, China
ǂ These authors contributed equally to this work.
* Correspondence to: renminma@pku.edu.cn

Compressing the optical field to the atomic scale opens up possibilities for directly observing individual molecules, offering innovative imaging and research tools for both physical and life sciences. However, the diffraction limit imposes a fundamental constraint on how much the optical field can be compressed, based on the achievable photon momentum [1,2]. In contrast to dielectric structures, plasmonics offer superior field confinement by coupling the light field with the oscillations of free electrons in metals [3–6]. Nevertheless, plasmonics suffer from inherent ohmic loss, leading to heat generation, increased power consumption and limitations on the coherence time of plasmonic devices [7,8]. Here we propose and demonstrate singular dielectric nanolasers showing a mode volume that breaks the optical diffraction limit. Derived from Maxwell's equations, we discover that the electric-field singularity sustained in a dielectric bowtie nanoantenna originates from divergence of momentum. The singular dielectric nanolaser is constructed by integrating a dielectric bowtie nanoantenna into the centre of a twisted lattice nanocavity. The synergistic integration surpasses the diffraction limit, enabling the singular dielectric nanolaser to achieve an ultrasmall mode volume of about $0.0005\lambda^3$ (λ, free-space wavelength), along with an exceptionally small feature size at the 1-nanometre scale. To fabricate the required dielectric bowtie nanoantenna with a single-nanometre gap, we develop a two-step process involving etching and atomic deposition. Our research showcases the ability to achieve atomic-scale field localization in laser devices, paving the way for ultra-precise measurements, super-resolution imaging, ultra-efficient computing and communication, and the exploration of light–matter interactions within the realm of extreme optical field localization.

References

1. Shim, H., Monticone, F. & Miller, O. D. Fundamental limits to the refractive index of transparent optical materials. *Adv. Mater.* **33**, 2103946 (2021).
2. Khurgin, J. B. Expanding the photonic palette: exploring high index materials. *ACS Photon.* **9**, 743–751 (2022).
3. Schuller, J. A. et al. Plasmonics for extreme light concentration and manipulation. *Nat. Mater.* **9**, 193–204 (2010).
4. Gramotnev, D. K. & Bozhevolnyi, S. I. Plasmonics beyond the diffraction limit. *Nat. Photon.* **4**, 83–91 (2010).
5. Kauranen, M. & Zayats, A. V. Nonlinear plasmonics. *Nat. Photon.* **6**, 737–748 (2012).
6. Tame, M. S. et al. Quantum plasmonics. *Nat. Phys.* **9**, 329–340 (2013).
7. Khurgin, J. B. Ultimate limit of field confinement by surface plasmon polaritons. *Faraday Discuss.* **178**, 109–122 (2015).
8. Khurgin, J. B. How to deal with the loss in plasmonics and metamaterials. *Nat. Nanotechnol.* **10**, 2–6 (2015).