Singular dielectric nanolaser: breaking diffraction limits to atomic scale

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Lasers have been a cornerstone of modern physics, playing a crucial role in advancing fields[1–4] such as photonics, atomic physics, and quantum mechanics, while also revolutionizing applications in optical communication, manufacturing, and medical treatment. Since their invention in 1960,[5] miniaturizing lasers has been one of the primary goals for physicists. However, the diffraction limit, which restricts optical field compression to no smaller than half the wavelength of light in a given medium, presents a significant challenge due to inherent constraints on available photon momentum.[6,7] One promising approach to overcome this limit involves plasmonic effects, which can realize superior field confinement by coupling light fields with oscillations of free electrons in metals.[8,9] In 2009, plasmonic nanolasers that compress light fields to a scale of around 10 nanometers were achieved, breaking the diffraction limit.[10,11] However, plasmonic effects face inherent ohmic losses, causing heat, higher power consumption, and reduced coherence times.[12]

In dielectric systems, recent simulations[13–16] have shown that integrating a dielectric bowtie nanoantenna into a photonic crystal can achieve sub-diffraction-limited mode volumes. However, the fundamental mechanism for breaking the diffraction limit in such structures remained unclear, and experimental studies were limited to passive dielectric cavities. In a groundbreaking study published in *Nature*, researchers from Peking University, led by Dr. Ren-Min Ma, introduced a singular dielectric nanolaser capable of localizing light to atomic scales, surpassing the diffraction limit.[17] This study thoroughly and comprehensively elucidates the principles underlying how dielectric systems can overcome the diffraction limit. Their device combines a dielectric bowtie nanoantenna with a twisted lattice nanocavity to achieve sub-diffraction-limited mode volumes.

The diffraction limit originates from the uncertainty relationship between momentum and position. Optical-band semiconductor materials typically possess low dielectric constants, which thus restricts field localization to scales of hundreds of nanometers. In plasmonic oscillations, the momentum along the propagation direction is real, while the vertical momentum is imaginary, allowing large propagation momentum while maintaining a finite total momentum governed by the dielectric constant. Similarly, in this work,[17] Ouyang et al. found that near the apices of the dielectric bowtie nanoantenna, the angular momentum component is real, while the radial component is imaginary, both diverging in magnitude near the apices. Notably, the total momentum remains finite and small, determined by the dielectric constant, in a mechanism reminiscent of plasmonic modes but without ohmic losses.

The dielectric bowtie nanoantenna used here consists of two adjacent triangular dielectric nanoparticles, with their apices pointing toward each other (Fig. 1), significantly enhancing the confinement of the light field to a diffraction-limited spot in the center of the nanocavity. The nanoantenna effectively localizes the intensity of the light at its apices. Detailed theoretical analysis, based on Maxwell's equations, indicates that the dielectric nanoantennas exhibit an electromagnetic eigenmode characterized by an infinite singularity in the electric field at the apices. This singularity arises from substantial radial and angular wave vector components (ik_ρ and k_φ, where both k_ρ and k_φ are real numbers, as illustrated in Fig. 1) within the eigenmode, despite the overall small magnitude of the wave vector, determined by the material's dielectric constant, which resemble similar mechanism to plasmonic modes while distinctly lacking its inherent ohmic loss. To further enhance the confinement of the cavity mode, the nanoantennas were integrated into a twisted lattice nanocavity. This integration not

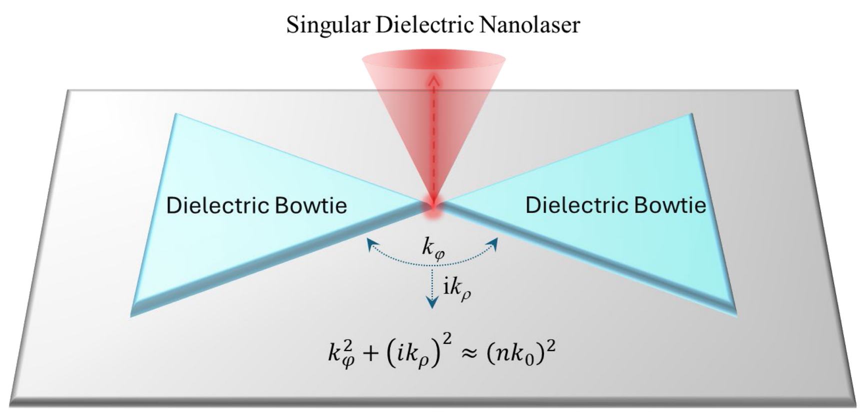

Fig. 1 Schematic of a singular dielectric nanolaser featuring a dielectric bowtie nanoantenna integrated at the center of a twisted lattice nanocavity.

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only allows for feature sizes significantly below the diffraction limit but also capitalizes on the high quality factor of the twisted lattice structure, thus boosting the overall performance of the device.

By precisely controlling the nanoantenna's gap size through a two-step fabrication process involving etching and atomic layer deposition (ALD), the researchers created a dielectric bowtie nanoantenna with a single-nanometer gap embedded in a twisted lattice nanocavity. The process begins with e-beam lithography to transfer patterns onto e-beam resist, followed by etching. ALD is then used to deposit a conformal thin film of titanium dioxide (TiO_2) on the structures, enabling precise control over the gap size. Simulations indicated that reducing the gap size with the TiO_2 layer decreases the mode volume. Leveraging ALD's atomic-level precision, the team achieved a bowtie gap size as small as (1.7 ± 1.0) nm.

The singular dielectric nanolasers were optically pumped at room temperature, where the lasing threshold is of 26 $\mathrm{kW/cm^2}$. Significant narrowing of the cavity mode's linewidth was observed around the threshold, confirming single-mode lasing behavior. Additionally, an S-shaped light-curve on a logarithmic scale was observed, signifying a transition from spontaneous to stimulated emission. The nanolaser exhibited strong field localization at the center of the nanoantenna, along with an ultrasmall mode volume, measured as low as $0.0005\,\lambda^3$. This mode volume is less than one-sixth of the optical diffraction limit. A possible highly directional emission can be realized when integrated with an array of nanolasers. Furthermore, an accelerated emission rate resulted in a Purcell factor of up to 58, highlighting the enhanced light–matter interaction inside the device.

The development of this groundbreaking dielectric nanolaser marks a pivotal milestone in the field of integrated photonics and quantum photonics, showcasing a substantial technical achievement. It underscores the immense potential of optical sciences to revolutionize technology and applications. This technology promises transformative advancements across various fields, including not only integrated photonic chips, quantum sources, and optical communication, but also nanosensors, super-resolution imaging, and optical storage. Moreover, the mechanisms employed by this singular dielectric nanolaser can be broadly adapted to enhance other photonic devices and components, paving the way for further innovations in the field.

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