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Nanolaser technology with atomic-scale field localization

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Nanolaser research focuses on miniaturizing lasers to enhance performance and broaden their range of applications. Here, we present opportunities and challenges of a new class of singular nanolasers capable of achieving atomic-scale field localization, highlighting their potential applications.

In 1916, Albert Einstein discovered that Planck's law of blackbody radiation implies the existence of stimulated emission – a process in which an incoming photon interacts with an electron in an excited state, causing it to drop to a lower energy state and release a second photon with identical energy, phase and direction to that of the incoming photon[1]. In 1954, James P. Gordon, Herbert J. Zeiger and Charles H. Townes reported on microwave amplification by stimulated emission of radiation, known as maser[2]. The maser can be considered the precursor to the laser, but the laser generates higher frequency coherent radiation, making it smaller, more intense and capable of carrying more information. In 1960, Theodore H. Maiman invented the first laser – light amplification by stimulated emission of radiation[3]. Compared to a normal light source, the emission of masers and lasers is concentrated in a much narrower frequency range. Consequently, the inventions of the maser and laser can be viewed as the localization of electromagnetic waves in frequency space through stimulated emission. Stimulated emission can also be used to localize electromagnetic waves in time, momentum and space. By localizing waves in these dimensions, laser sources can achieve stable frequencies, short pulse durations, high directionality and small mode volumes, enabling us to precisely measure time, observe fast-moving processes, transmit information and energy over great distances, miniaturize devices and resolve small details (Fig. 1). It is precisely these localized characteristics that make lasers powerful tools for understanding and harnessing the natural world.

Extreme field localization

Since the invention of the laser in 1960, the development of high-performance lasers with strong field localization in frequency, time, momentum and space has driven advancements in laser physics and devices. In the frequency dimension, techniques such as high-quality factor cavities, feedback control and environmental isolation enable the laser to maintain exceptionally stable frequency. This extreme field localization in frequency has led to the development of frequency-stable lasers, essential for precise time measurement and interferometry. For example, frequency-stable lasers have been used for gravitational wave detection – a breakthrough awarded the Nobel Prize in Physics in 2017. In the time dimension, techniques such as mode-locking and high-harmonic generation enable the creation of ultrashort laser pulses. Attosecond lasers, which achieve extreme temporal localization, can produce optical pulses lasting around a single optical cycle. This breakthrough, recognized by the 2023 Nobel Prize in Physics, allows the observation of ultrafast movements of fundamental particles, such as inner-shell electrons. Additionally, in the momentum dimension, large-area single-mode lasing enables highly directional laser output, achieving extreme field localization in momentum space. The resulting highly collimated lasers substantially advance interstellar high-speed optical communication. Finally, in the spatial dimension, the introduction of photonic crystals, plasmonics and other field localization mechanisms has led to the development of nanolasers, capable of reducing the laser mode volume to $(\lambda/2)^3$, where λ is free-space wavelength, or even smaller. The emergence of nanolasers opens new avenues for next-generation information technology and research into light–matter interactions under extreme conditions.

Challenges in extreme spatial localization

Lasing modes are eigenmodes of cavities. The mode volume of an eigenmode is fundamentally constrained by the optical diffraction limit determined by the uncertainty principle. Stronger spatial localization of an eigenmode corresponds to a broader momentum distribution. The challenge in achieving extremely small mode volumes is that semiconductors emitting at optical wavelengths usually have dielectric constants below ten[4]. According to the uncertainty principle, these low dielectric constants limit our ability to localize the optical field to scales smaller than hundreds of nanometres in any spatial dimension.

At the turn of the twenty-first century, various semiconductor micro- and nanolasers were developed, including microdisk lasers[5], photonic crystal defect-state lasers[6] and nanowire lasers[7]. All of these have characteristic sizes approaching the order of a vacuum wavelength. The first microdisk laser, realized in 1992, used whispering gallery modes to circulate light in a round-trip path within the microdisk. In 1999, the first photonic crystal defect-state laser was achieved by using point defect modes in a two-dimensional photonic crystal to confine and circulate light within the defect area. The first semiconductor nanowire laser, demonstrated in 2001, was fabricated with the end faces of a nanowire acting as mirrors to form a Fabry–Pérot cavity. However, constrained by the optical diffraction limit, these dielectric cavity-based semiconductor lasers could not be scaled down further.

In 2009, plasmonic nanolasers capable of breaking the optical diffraction limit were experimentally demonstrated[8–10]. The electric field associate with plasmonic modes in the transverse direction, which corresponds to an imaginary momentum, decays exponentially. Consequently, there is an increase in real momentum in the longitudinal direction. This differentiation breaks the optical diffraction limit that is inherently determined by the dielectric constants of materials in both transverse and longitudinal directions. Since 2009, plasmonic nanolasers have been reported to exhibit extremely small mode volumes, ultrafast modulation speeds and low energy consumption. Compared

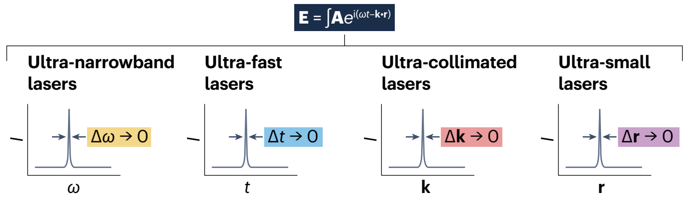

Fig. 1 | Advancing lasers with extreme field localization. A lasing mode is an eigenmode of the corresponding laser cavity. Generally, it can be expressed as $\mathbf{E} = \int \mathbf{A}e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})}$, where $\mathbf{A}$ is the complex amplitude, and ω, t, $\mathbf{k}$ and $\mathbf{r}$ represent the angular frequency, time, wavevector and position, respectively. The integral is taken over the variable that corresponds to the specific laser type. Lasers can achieve extreme localization in the dimensions of ω, t, $\mathbf{k}$ or $\mathbf{r}$, meaning that $\Delta\omega$, Δt, $\Delta\mathbf{k}$ or $\Delta\mathbf{r}$ of the lasing mode approach zero. By achieving stronger localization of light fields in these dimensions, laser sources can attain more stable frequencies, shorter pulse durations, higher directionality and smaller mode volumes, thus providing us with more powerful tools for exploring and utilizing the natural world. Singular nanolaser research is pushing the boundaries of spatial field localization and its applications.

to dielectrics, plasmonics provide superior field confinement, where the light field is coupled to the oscillations of free electrons in metals. However, the inherent ohmic losses in plasmonics, caused by electron oscillations, lead to heat generation, increased power consumption and limitations on the coherence time of plasmonic devices.

Mechanisms of singular nanolasers

In 2024, singular nanolasers with atomic-scale field localization were realized in pure dielectric systems[11]. To break the diffraction limit within a dielectric structure, a dielectric bowtie nanoantenna is embedded in a twisted lattice nanocavity. The nanoantenna comprises a pair of triangular dielectric nanoparticles positioned adjacent to each other, with their apices directed towards one another. The twisted lattice nanocavity effectively confines the light field[12], restricting it to a diffraction-limited spot in the central region of the nanocavity where the bowtie nanoantenna is positioned. The bowtie nanoantenna further confines the intensity of the light field at its apices, where the singularity of the electric field has an essential role.

The singularity of the electric field results from the divergence of the momentum. Near the tip, the angular momentum component of the singularity is a real number, whereas the radial component is an imaginary number. The absolute values of these momenta diverge near the tip, but the total momentum, determined by the dielectric constant of the material, remains a finite small value. This mechanism is similar to the field confinement observed in plasmonic modes, but it operates without the associated ohmic losses. The singularities of the electric field in dielectric systems enable extreme compression of the light field, with a full width at half maximum of about 1 nm, and a mode volume much smaller than the optical diffraction limit of $(\lambda/2n)^3$, where λ is the free-space wavelength and n is the refractive index. Inherited from twisted lattice nanocavity, the quality factor (the ratio of the stored energy to the energy lost per cycle) of singular nanolaser cavities can exceed one million.

Applications of singular nanolasers

Owing to their high quality factor, extremely small mode volume and nanometre-scale optical field, singular nanolasers can provide a platform for developing high-performance coherent light sources and innovative imaging tools with atomic-scale resolution for both physical and life sciences.

Miniaturizing lasers can lower the threshold power and enhance the modulation speed. The threshold power of a laser generally comprises two key elements: one ensures that the gain medium becomes transparent, while the other compensates cavity losses. In the case of a singular nanolaser, both of the elements are less required, since the extremely small mode volume reduces the demand on the gain medium, and the high cavity quality factor lowers cavity losses. Additionally, lasers achieve high modulation speeds when both the cavity lifetime and the spontaneous emission lifetime are short. These short lifetimes typically necessitate a moderate quality factor alongside a high ratio of quality factor to mode volume. Singular nanolasers, with their extremely small mode volumes, naturally meet this requirement.

Additionally, electron-based imaging technologies such as scanning electron microscopy and transmission electron microscopy achieve higher resolution compared to photon-based methods such as optical microscopy, primarily owing to the markedly shorter wavelength of electrons compared to visible light. Although techniques that focus light from the far field to a small near-field scale can enhance the resolution of optical imaging, they encounter limitations associated with diffraction and focusing efficiency. Singular nanolasers, however, can directly generate atomic-scale light spots in the near field, making it possible to develop imaging techniques with atomic-scale resolution.

Light–matter interaction, which involves the exchange of energy between photons and electrons, is fundamental to the generation, control and absorption of light by matter, as well as the modification of material properties by light. However, this interaction is typically weak, owing to the mismatch between the wavelengths of photons and electrons. The singular nanolaser cavity can confine the light field to the atomic scale, substantially enhancing the local electric field intensity and thus strengthening the interaction between light and matter. The singular nanolaser cavity with a high quality factor can serve as an ideal platform for studying cavity quantum electrodynamics. Additionally, it holds promise for achieving single-photon nonlinearity. Realizing single-photon nonlinearity can transform a system of non-interacting photons into one with interactions, which is a crucial step in advancing optical computing and simulation.

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Competing interests

The author declares no competing interests.