Perspective

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Plasmonic nanolasers: fundamental properties and applications

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Abstract: Plasmonic nanolasers are a new class of coherent emitters where surface plasmons are amplified by stimulated emission in a plasmonic nanocavity. In contrast to lasers, the physical size and mode volume of plasmonic nanolasers can shrink beyond the optical diffraction limit, and can be operated with faster speed and lower power consumption. It was initially proposed by Bergman and Stockman in 2003, and first experimentally demonstrated in 2009. Here we summarize our studies on the fundamental properties and applications of plasmonic nanolasers in recent years, including dark emission characterization, scaling laws, quantum efficiency, quantum threshold, gain and loss optimization, low loss plasmonic materials, sensing, and eigenmode engineering.

Keywords: nanolasers; plasmonic nanolasers; semiconductor lasers; spasers.

1 Introduction

In 1916, Albert Einstein rederived Planck's law of black-body radiation based on the thermal equilibrium of matter and radiation, and broached the existing of stimulated emission [1]. The discovery of stimulated emission leads to coherent emitters of maser and laser, which are acronyms for “microwave amplification by stimulated emission of

radiation” and “light amplification by stimulated emission of radiation,” respectively. The first maser was reported by Charles H. Townes, James P. Gordon, and Herbert J. Zeiger in 1954 [2]. Due to the large wavelength, the cavity size of a maser is on the order of meters. A laser works by the same principle as a maser, but operates at higher optical frequency. In 1958, Arthur L. Schawlow and Charles H. Townes theoretically extended maser techniques to the infrared and optical region, which is laser, but they call it optical maser at that time [3]. The first laser was reported by Theodore Maiman in 1960 [4].

Soon after the invention, lasers have become a key driver for modern science and technology. Creating smaller lasers has been a research goal since the beginning, aiming at more compact size and lower power consumption. Semiconductor edge-emitting lasers have feature size of $\sim 100\ \mu\text{m}$, and are key drivers for long-haul optical links. Semiconductor surface-emitting lasers have feature size of $\sim 10\ \mu\text{m}$, and are the best solution for short-distance optical interconnects and consumer electronics. Around 2000, the demonstration of microdisk lasers [5], photonic crystal lasers [6] and nanowire lasers [7] has pushed the feature size of a laser down to micrometer or even submicrometer region. However, lasers amplify photons, wherein optical diffraction limit puts a barrier to scaling down its physical size and mode volume. For near infrared and optical region, lasers cannot be smaller than about hundreds of nanometers.

In 2003, Bergman and Stockman proposed the concept of spaser, the acronym for “surface plasmon amplification by stimulated emission of radiation” [8]. Surface plasmons are quasiparticles of coupled photons and electrons excited at the metal surface. Amplifying surface plasmons instead of photons in a plasmonic nanocavity provides a new class of coherent emitters with feature sizes down to tens of nanometers or even smaller, comparable to those of modern transistors. Nowadays, Spaser is also named plasmonic nanolaser. It offers a new powerful tool for a variety of applications ranging from on-chip optical interconnector, sensing and detection, to biological labeling, and tracking.

In 2009, first plasmonic nanolasers were experimentally realized by three teams independently [9–11]. Each

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team demonstrated a plasmonic nanolaser exhibiting subwavelength confinement in a different number of dimensions. After that, a vast number of plasmonic nanolasers have been realized with unique architectures and various gain and plasmonic materials. There are a number of comprehensive review articles on plasmonic nanolasers [12–33]. In this Perspective, we summarize the research of plasmonic nanolasers in our group in recent years, including dark emission characterization, scaling laws, quantum efficiency, quantum threshold, gain and loss optimization, low loss plasmonic materials, sensing, and eigenmode engineering.

1.1 Dark emission of plasmonic nanolasers

In contrast to lasers, plasmonic nanolasers amplify surface plasmons instead of photons, providing amplification of electromagnetic field localized at a scale smaller than the diffraction limit. Normally, plasmonic nanolasers are characterized by the photons scattered to the optical far field, where their intrinsic surface plasmon emission cannot be revealed because of its evanescent nature. In 2017, we reported the imaging of the dark surface plasmon emission of

plasmonic nanolasers using leakage radiation microscopy (Figure 1) [34]. The plasmonic nanolaser consists of a CdSe nanostrip placed on an Ag film with a thin SiO_2 gap layer in between. The thicknesses of Ag and SiO_2 films are 50 and 5 nm, respectively. The substrate is borosilicate glass with a thickness of about 0.15 mm. The thicknesses of the glass substrate and the Ag film are optimized for leakage radiation microscopy. For optical characterization, the device is optically pumped from the top, and the emission is collected by an oil immersion objective underneath with a large numerical aperture (NA) of 1.40.

The lasing emission collected by the oil immersion lens contains the information of both parts of scattered photons and surface plasmon emission. The scattered photon emission penetrates the silver substrate with attenuation, whereas the emission coupled to the plasmonic mode leaks into the substrate at a certain polar angle that satisfies the momentum match condition. In the spatial space image, discrete emission beams from the plasmonic nanolaser is observed. In the momentum space image, most of the emission locates on a ring with a radius of $1.04k_0$, where k_0 is the free-space wave number of the emitted 700 nm wave. This thin ring-shaped momentum space image is a signature of the leakage surface plasmon radiation. The

Figure 1: Imaging the surface plasmon dark emission of a plasmonic nanolaser by leakage radiation microscopy.

a Schematic of leakage radiation microscopy for imaging the emission of a plasmonic nanolaser in spatial (top) and momentum (bottom) spaces. **b–c** Spatial (b) and momentum (c) space images of a plasmonic nanolaser emission obtained via leakage radiation microscopy (false color). Figure adapted [34].

directions of discrete emission beams in the spatial space image match well with the azimuthal brightness fluctuation in the momentum space image indicating that these are dominantly surface plasmon emissions of the plasmonic nanolaser propagating in the air/Ag interface.

The precisely determined single-mode lasing emission in spatial, frequency, and momentum spaces provides clear evidence for lasing in plasmonic mode. We further extracted the full properties of the plasmonic lasing mode from the confirmed eigenmode in three-dimensional full wave simulations. In particular, we obtained the surface plasmon generation efficiency (η) of plasmonic nanolasers. Here η is defined as $P_{\text{SPs}}/P_{\text{total}}$, where P_{SPs} and P_{total} are the surface plasmon emission power and the total emission power of a plasmonic nanolaser, respectively. We demonstrated that plasmonic nanolasers can serve as a pure surface plasmon generator with the η approaching 100% in theory and experimentally demonstrate a nanowire plasmonic nanolaser with a η of 74%.

In 2018, we reported the imaging of multimode plasmonic nanolasers using the same technique and characterized their properties of the transition from spontaneous emission to stimulated emission with varied pump powers in spatial, momentum, and frequency spaces [35]. We also demonstrated a method to identify the exact lasing modes in a multimode plasmonic nanolaser. We found that by tuning the spatial position of the pumping spot, the plasmonic nanolaser can be operated at different single modes or multimode. For different modes, their spatial profiles and azimuthal distributions are distinct, which were employed as a fingerprint to identify the lasing cavity modes and analyze multimode devices.

1.2 Unusual scaling laws of plasmonic nanolasers

Plasmonic effect enables strong field confinement. By storing part of electromagnetic energy in the form of free electrons oscillation, the electromagnetic field can be confined in a scale of tens of nanometer. However, the strong field confinement is accompanied by a parasitic metallic absorption loss. Immediately following the first plasmonic laser demonstrations, a debate about whether metals could really enhance the performance of lasers in general began. It is not simple question. In a loss perspective, on one side, there is an additional metallic absorption loss in plasmonic nanolasers. However on the other side, the radiation loss can be significantly lowered. In a dynamic perspective, the Purcell effect increases the

fraction of excited carriers radiating into the desired plasmonic cavity mode, which would lead to a lower laser threshold. However, accelerated spontaneous emission also consumes excited carriers faster, and thereby makes population inversion for gain more difficult.

Since both field confinement and Purcell effect have arguably positive and negative influences on laser performance, fundamental questions emerge concerning the viability of metal confinement and feedback strategies in laser technology: Are plasmonic nanolasers intrinsically with high threshold due to the metallic loss? And, are there defendable benefits of constructing plasmonic nanolasers when compared to photonic nanolasers? To try to answer these questions, we have measured 170 plasmonic and photonic nanolasers in total. To make a fair enough comparison, all these devices are with the same gain material and the same cavity feedback mechanism [36]. We systematically studied their key parameters, including physical size, mode volume, threshold, power consumption, and lifetime, based on which, we obtained a set of laws that show how these parameters scale against each other (Figure 2). These scaling laws reveal that plasmonic nanolasers can be more compact, faster and with lower power consumption than photonic lasers when the cavity size approaches or surpasses the diffraction limit, which helps to clarify the long-standing debate over the viability of plasmonics in laser technology and identified situations in which plasmonic lasers have clear practical advantages [37]. To date, there are many experimental demonstrations on plasmonic nanolasers with high performance and theoretical analysis on the fundamental advantages of plasmonic nanolasers with well-defined figure-of-merits. These works indicate that there are situations where plasmonic nanolasers have superior performance for practical applications. We kindly ask readers to refer to review articles of refs. [12–33] and the literatures cited therein for more details.

1.3 Quantum threshold of plasmonic nanolasers

Conventionally, lasing threshold is defined at the intersection of two linear region of very high and very low pump intensity. This conventional threshold definition is a good approximation for large lasers with a small spontaneous emission coupling factor, β where the threshold appears as a sharp kink in the output power versus pump intensity curve in the linear scale. However, for small lasers with a larger β the transition from below to above threshold becomes “fuzzy” with a less sharp kink [38–41]. For small lasers, we can use an unambiguous definition of threshold

Figure 2: Scaling laws of plasmonic and photonic nanolasers.

a In total, 170 plasmonic nanolasers (left) and photonic nanolasers (right) were measured for performance comparison. **b–e** Comparisons of cavity size (b), spontaneous emission lifetime (c), threshold (d), and power consumption (e). These comparisons suggest that plasmonic nanolasers can be more compact and faster with lower power consumption than photonic nanolasers when the cavity size approaches or surpasses the diffraction limit. Figure adapted [36].

that is the condition in which the rates of spontaneous and stimulated emission into the laser mode are equal. According to relation between Einstein's A and B Coefficient, this condition is equivalent to saying that a lasing mode should contain one photon to reach the threshold, which can be called as quantum threshold of a laser [42, 43].

According to the quantum threshold, one can simply calculate the power consumption of a laser without specifying any particular configuration parameters [43]. For a given cavity loss, the minimum power to maintain a photon in the laser mode requires a power (P_{cavity}) of $\gamma_C \cdot h\nu \cdot \frac{1}{\beta}$, where γ_C is the cavity photon loss rate, $h\nu$ is the energy of the one photon, and β is the spontaneous emission factor, the fraction of spontaneous emission directed into the laser mode. For a plasmonic laser cavity, the photon loss rate usually reaches 10^{13} – 10^{14} s⁻¹ due to the parasitic metallic loss. Assuming an emitted photon energy $h\nu$ of ~ 1 eV and a β factor of 1, we can obtain a minimum threshold power of plasmonic nanolasers around 1–10 μ W. This low threshold power of 1–10 μ W is equivalent to 0.1–1 fJ per bit at a data rate of 10 Gb s⁻¹, which ensures plasmonic nanolasers with low enough power consumption for integrated optical interconnects [27]. As plasmonic nanolasers can have very small foot print down to a few tens of nanometers in diameter, the threshold power density could reach the order of MW cm⁻², which is about two orders of magnitude higher than the commercialized semiconductor laser diode. However, a larger physical foot print will naturally give a lower threshold power density. Therefore, it is not necessarily advantageous in certain practical applications for a laser with smallest physical size.

The total threshold power should also include the power needed to pump and maintain the carriers at an upper energy level for population inversion. The minimum power to maintain population inversion requires a power (P_{Gain}) of $\gamma_{\text{SP}} \cdot E_{21} \cdot V \cdot n_{\text{tr}}$, where γ_{SP} is the spontaneous emission rate, E_{21} is the energy required to pump carriers onto excited energy level ($\sim h\nu$), V , and n_{tr} are the physical volume and the transparency carrier density of the gain material. For normal semiconductor gain materials, γ_{SP} and n_{tr} are on the order of $\sim 10^9$ s⁻¹ and $\sim 10^{17}$ – 10^{18} cm⁻³, respectively. γ_{SP} can be accelerated to $\sim 10^{10}$ – 10^{11} s⁻¹ by Purcell effect in a plasmonic nanolaser cavity. Assuming a γ_{SP} of 10^{10} s⁻¹, E_{21} of ~ 1 eV, V of 500 nm (length) $\times$ 500 nm (width) $\times$ 200 nm (height), and n_{tr} of 10^{18} cm⁻³, we can obtain a threshold power of 80 μ W, a threshold power density of 32 kW cm⁻². 80 μ W is equivalent to 8 fJ per bit at a data rate of 10 Gb s⁻¹.

1.4 Quantum efficiency of plasmonic nanolasers

Direct characterization of quantum efficiency of plasmonic nanolasers is a challenge due to its near-field surface plasmon emissions, divergent emission profile, and the limited emission power. In 2018, we reported quantitative characterization of external quantum efficiency of plasmonic nanolasers by synergizing experimental measurement and theoretical calculation (Figure 3) [44]. In contrast to conventional lasers, the radiation field of plasmonic nanolasers consists of two parts, the photons scattered to the

Figure 3: Quantum efficiency of plasmonic nanolasers.

a The radiation field of a plasmonic nanolaser consists two parts, the photons scattered to the optical far field and the dark emission of surface plasmons propagating evanescently in the near field. **b** Full lasing properties can be reconstructed by three dimensional full wave simulation when the lasing eigenmode is identified. And thereby, full emission power can be extrapolated by only measuring a certain part of it. Figure adapted [44].

optical far field and the dark emission of surface plasmons propagating evanescently in the near field. Consequently the external quantum efficiency (EQE) of plasmonic nanolasers should contain both of these emission powers, and thereby can be defined as, $\eta_{\text{EQE}} = \frac{(P_{\text{photon}} + P_{\text{SPP}})/h\nu}{P_{\text{IN}}/h\nu_{\text{IN}}}$, where P_{IN} and $h\nu_{\text{IN}}$ are the pump power and pump photon energy, respectively, P_{photon} , P_{SPP} are the emitted powers of photons and surface plasmons, respectively, and $h\nu$ are the energy of the emitted photons and surface plasmons.

We developed a method to determine pump power via measuring the reflected power of the pump laser beam. We first measured the absolute reflected power of the pump laser beam at the Au/air interface, and then move the pump beam onto a CdSe nanosquare, the gain material of a plasmonic nanolaser, to get the absolute reflected power of the pump laser beam with the device being excited. Due to the absorption of the CdSe nanosquare, the power of the reflected pump laser beam will decrease. Such a contrast P_{con} between the absolute power reflected at the Au/air interface and device interface approximately equals to the input power absorbed by gain material. To obtain a more precise value, we further considered the reflectivity of each material interface and the absorptions of both Au and CdSe. After these calibrations, the absolute absorption power of the device can be determined.

For the output power, we utilized a fundamental feature of the laser emission field of that, any lasing mode must be an eigenmode of the laser cavity. For a nanoscale laser, there are only limited number of eigenmodes exist in the cavity with spectral overlap with gain spectrum, which gives the feasibility to identify the lasing eigenmodes. Especially for a single mode laser, we can reveal the full

lasing properties providing the lasing eigenmode is identified and reconstructed by three dimensional full wave simulation. Thereby we can extrapolate the full emission power by only measure a certain part of it.

The experimentally obtained external differential quantum efficiency is about 13.4% for a typical plasmonic nanolaser. To further increase the EQE of plasmonic nanolasers, a smaller cavity with lower radiation quality factor can be used, where cavity configuration engineering, metal quality improvements are crucial for loss compensation by gain materials. In particular, the waveguide embedded plasmonic nanolaser configuration can be used [45], where not only the radiation efficiency can be enhanced, but also the emission directionality can be recovered.

1.5 Loss and gain of plasmonic nanolasers

In 2020, we reported the quantitative study of the loss and gain in a plasmonic nanolaser (Figure 4) [46]. In a laser device, the loss mainly consists of gain material loss due to stimulated absorption and radiation loss. In a plasmonic nanolaser, there is an additional metallic loss. To achieve plasmonic lasing state, carriers need to be pumped in the excited energy level to a certain density to provide gain to compensate all the losses of gain material loss, metallic loss, and radiation loss. We first obtained excited carrier concentrations at varied pump intensity from spontaneous emission spectra and lasing emission wavelength shift, which are used to calculate Fermi inversion factors and consequently gain coefficients at each pump intensity. We

Figure 4: Loss and gain of plasmonic nanolasers.

a The loss of a plasmonic nanolaser consists of three parts, radiation loss, gain material loss, and metallic loss. **b** To achieve plasmonic lasing state, carriers need to be pumped in the excited energy level to a certain density to provide gain to compensate all the losses of gain material loss, metallic loss, and radiation loss. **c** Gain spectrum at full lasing state. The maximum gain in the gain spectrum approximately equals to the sum of the metallic loss and radiation loss. Figure adapted [46].

further determined the gain material loss, metallic loss, and radiation loss of the plasmonic nanolaser.

For the measured plasmonic nanolaser, the gain coefficient saturates at $\sim 15,100 \text{ cm}^{-1}$ at the full lasing state, which approximately equals to the summation of metallic loss and radiation loss. The wavelength of the lasing peak is at 707.0 nm. The gain material loss at this wavelength is $\sim 29,400 \text{ cm}^{-1}$. Around the lasing threshold where the cavity resonance just starts to supply feedback, the gain from CdSe approximately just compensates the metallic loss. This condition can be recognized as the resonant peak emerging in the spontaneous emission background, which corresponding to a gain coefficient of $12,600 \text{ cm}^{-1}$. Thereby we obtained the metallic loss and radiation loss to be 12,600 and 2500 cm^{-1} , respectively, which are consistent with our full wave simulation result.

We also provided relationships between quality factor, loss, gain, carrier density, and lasing emission wavelength of a plasmonic nanolaser. To improve the performance of plasmonic nanolasers, better gain materials with higher gain coefficient, and better cavity design with lower radiation loss are crucial. Because the gain material loss is always larger than the summation of radiation loss and metallic loss, the lasing resonance wavelength of a plasmonic cavity should be also carefully designed to lower the total cavity loss.

For semiconductor gain materials, gain material loss is the dominant loss in general. Without pumping, electrons follow Fermi–Dirac distribution and reside in the valance band dominantly. Therefore, a gain material needs to be pumped to a transparent population level at a given lasing wavelength to begin to provide gain to compensate cavity loss. The power consumed on transparent population is the origin of gain material loss. Beyond the transparent population, extra excited carriers on conduction band provide

gain to compensate cavity loss. The highest gain coefficient a gain material can provide is under the condition that the population is fully inversed on the corresponding energy levels at a given lasing wavelength at $T = 0$, and this highest gain coefficient equals to the gain material loss coefficient where the valance band is fully occupied and the conduction band is completely empty. However, at finite temperature (e.g. room temperature), the gain coefficient is always smaller than the gain material loss coefficient at a given wavelength, and therefore, gain material loss dominates lasing threshold. The main implications of gain material loss dominated threshold are two folds for lasing threshold power minimization. First, cavity loss needs to be minimized, which is not only for a lower cavity loss power consumption, but also for a lower material gain required for lasing. Second, the lasing resonance wavelength of the cavity should be carefully tuned, because the gain material loss is strongly wavelength dependent. For a given cavity loss, the resonance wavelength of the cavity should be tuned to where the gain material can provide enough gain with the least population inversion.

1.6 Low loss sodium plasmonic material for plasmonic nanolasing

Noble metals, particularly silver and gold are the most often used in plasmonic nanolasers due to their relatively low loss. Alkali metals, such as sodium, have long been regarded as ideal plasmonic materials primarily because of their low intraband damping rate. In 2020, we reported room temperature sodium-based plasmonic nanolaser with a low threshold of 140 kW cm^{-2} (Figure 5) [47]. The device consists of an InGaAsP multi-quantum-wells (MQWs) nanodisk on top of sodium film with a 7-nm-thick Al_2O_3 layer in between.

Figure 5: Room-temperature sodium-based plasmonic nanolaser.

a–b, Schematics of a sodium-based plasmonic nanolaser in three dimensions (**a**) and two dimensions (**b**). **c,** SEM image of an InGaAsP MQWs nanodisk without sodium coating. **d–e,** Top (**d**) and side (**e**) views of the electric-field intensity distribution of the calculated lasing mode. **f,** Normalized electric-field intensity profile along the white dashed line in (**e**). **g,** Spectra of spontaneous emission (black), amplified spontaneous emission (red), and single-mode laser emission (green) of the sodium-based plasmonic nanolaser. Figure adapted [47].

When the device is pumped above lasing threshold, a single lasing mode becomes dominant at 1257 nm. We have identified this lasing cavity mode as the gap plasmonic whispering-gallery mode with an azimuthal order of $l = 15$ and a cold cavity quality factor of about 340 using full-wave simulation. One natural concern on sodium based plasmonic devices is their stability. We passivated the sodium based plasmonic nanolasers by quartz and epoxy, after which these devices remain functional at a low threshold even after six months.

1.7 Lasing enhanced surface plasmon resonance sensing

In the past decades, surface plasmon resonance (SPR) sensors have become a prominent tool for characterizing and quantifying biomolecular interactions and are perhaps the most extensively utilized optical biosensors. A fundamental limitation to all kind of surface plasmon sensors is

the strong radiative and nonradiative dampings, which natively accompanies and weakens the plasmon resonance. As a consequence of the strong dampings, plasmon resonances in the visible and near infrared region have a linewidth of typically tens to hundreds of nanometers, which results in a very low quality factor and limits the sensing performance fundamentally.

In 2016, we reported lasing enhanced surface plasmon resonance (LESPR) sensing where plasmonic nanolasers are used for refractive index sensing (Figure 6) [48]. In a plasmonic nanolaser, the excited carriers radiate dominantly to surface plasmon modes due to Purcell factor. This excitation-relaxation generation process of surface plasmons avoids the sophisticated setup required for conventional SPR sensors where surface plasmons are indirectly generated by an external laser via phase match process. Furthermore, these directly generated surface plasmons are localized in the small foot print of a plasmonic nanocavity. The refractive index change of the analyte modifies the cavity resonance wavelength and thus the lasing

Figure 6: Lasing enhanced surface plasmon resonance (LESPR) sensor.

a Measurement scheme. A plasmonic nanolaser is surrounded by the liquid analyte. The refractive index change of the analyte modifies the cavity resonance condition and thus the lasing wavelength. Due to the coherence nature of the lasing emission the signal from a LESP sensor has a much narrower linewidth comparing to the SPR sensor. **b** A schematic showing that, for a given resonance peak shift, a resonance with narrower linewidth will have larger intensity change. Figure adapted [48].

wavelength. Due to the coherence nature of the lasing emission by amplification of the stimulated emission, the signal from such a LESP sensor has a much narrower linewidth comparing to conventional SPR sensors. And thereby, for a given resonance peak shift, the intensity change at a certain wavelength of a LESP sensor will be much more dramatic compared to that of a SPR sensor. In the experiment, we obtained a figure of merit of intensity sensing of $\sim 84,000$ for a LESP sensor, which is about 400 times higher than state-of-the-art SPR sensor.

In 2017, we further studied the stability and yield of plasmonic nanolasers for sensing [49]. We show that the as-fabricated plasmonic nanolasers based on CdS and CdSe gain materials can barely survived in aqueous solution due to photochemical reactions, although they can be stably operated in an ambient environment. To improve the stability of plasmonic nanolasers, we used a step of surface passivation, where a layer of ALD grown Al_2O_3 is employed to passivate the device from photochemical reactions. After surface passivation, plasmonic nanolasers can be stably operated in aqueous solution with high yield. We further showed that these passivated plasmonic nanolasers can serve as high-performance refractive index sensors, where the intensity detection figure of merit of our device is ~ 8000 .

1.8 Eigenmode engineering of nanolasers

A lasing mode should be one of the eigenmode of its laser cavity. The number of eigenmodes (N) allowed in a laser

cavity can be estimated by, $N = \rho V_{\text{PHY}} \Delta\nu_E$, where ρ is the density states of the cavity, V_{PHY} is the physical size of the cavity, and $\Delta\nu_E$ is the gain spectrum bandwidth. For typical organic dyes and semiconductor materials, $\Delta\nu_E$ is about a few tens of THz generally, which only allows a few eigenmodes coinciding spectrally with the gain spectrum when the laser cavity size is subwavelength scale in all three dimensions. The very limited number of allowed nanolaser eigenmode makes it much easier to engineer them in a controllable manner for novel inner laser cavity fields and/or emission beam synthesis [27].

In 2018, we reported a chiral plasmonic nanocavity (CPN) that can be used to construct plasmonic vortex nanolasers [50]. The CPN is constructed in a metal-insulator-metal coaxial ring resonator with parity-time (PT) symmetric refractive index modulation. When operated at exceptional point, a pair of degenerate chiral modes traveling in opposite directions becomes identical, forming a single chiral eigenmode inside the CPN. The CPN provides a strong local chiral vacuum field with a mode volume of $0.24 \times \left(\frac{\lambda}{2n_{\text{eff}}}\right)^3$ and quality factor of 480, which can lead to plasmonic vortex nanolasers with high spontaneous emission coupling factor and low threshold.

When a single dipole emitter interacts with such a CPN, we found a counterintuitive phenomenon that the dipole can display the opposite handedness to the coalesced eigenstate of the system at an exceptional point, which violates the conventional wisdom that an emitter radiates into and interacts with eigenstates of the photonic environment (Figure 7) [51]. The radiation field in the ring cavity

Figure 7: Chirality-reversal radiation at an exceptional point.

a A normal ring cavity supports two counter-propagating eigenstates (left). A single emitter at the resonant frequency will excite a standing wave consisting both eigenstates (right). **b** With parity-time symmetric refractive index modulation, the two eigenstates become identical in a ring cavity at an exceptional point (left). A single emitter can become fully decoupled from the only eigenstate and radiates to the missing dimension with the opposite handedness (right). **c** Evolution of the directions of the two eigenstates of a parity-time symmetric ring cavity as a function of refractive index modulation. Figure adapted [51].

reveals the missing dimension of the Hilbert space, known as the Jordan vector in mathematics. The phenomenon revealed a striking fact that the radiation field of an emitter can become fully decoupled from the eigenstates of its environment. We have experimentally confirmed this phenomenon in both electromagnetic and mechanical systems.

A single nanolaser can be used as a building block to form a nanolaser array that can produce a macroscopic response that would not be possible in conventional lasers. In 2019, we reported a topological bulk laser based on band-inversion induced reflection (Figure 8a and b) [52]. We used semiconductor nanodisks as building block and carefully engineered their dipole and quadrupole mode bands. We patterned these nanodisk arrays to form a photonic crystal cavity showing topological band inversion between its interior and cladding area. In-plane light waves are reflected at topological edges forming an effective cavity feedback for lasing. This band-inversion-induced reflection mechanism induces single-mode lasing with directional vertical emission.

In 2020, we used semiconductor nanodisk arrays to construct topological photonic crystals with band structures distinct in topology and demonstrated a high performance topological vortex laser boosted by spin momentum locking (Figure 8c and d) [53]. We found that

spin-momentum locking not only protects in-plane unidirectional wave propagation for effective resonance, but also decouples the radiation direction from the resonant plane for directionally surface emitting. We verified the immune of backscattering by the identical lasing emission wavelength of the two topological edge modes with opposite spin. We found that the gain saturation effect enables individual lasing from a single topological edge mode resulting in a flow of pure photonic spin. The near-field spin and orbital angular momentum of the topological edge mode are probed via the circularly polarized vortex beam of far-field lasing radiation. Both of topological bulk lasers and topological vortex lasers have surface emission feature, because the lasing modes of these two kinds of lasers have dominant out-of-plane momentum around Γ point. Highly directional plasmonic nanolasers can be realized when these topological feedback mechanisms are introduced into plasmonic systems.

2 Conclusion and outlook

From maser to laser, the operation frequency is greatly shifted. From laser to spaser, the amplified particles become surface plasmons but not photons any more. The proposal of spasers by Bergman and Stockman in 2003 has

Figure 8: Topological bulk laser and topological vortex laser.

a SEM image of a topological bulk laser based on band-inversion-induced reflection. **b** Schematic of a topological bulk laser with vertical emission. **c** SEM image of a topological vortex laser based on spin-momentum locked edge modes. **d** Schematic of a topological vortex laser with vortex emission. Figure adapted [52, 53].

inspired great interesting in exploring nanolasers with ever smaller physical size, faster operation speed and lower power consumption. These nanolasers own intrinsic merits stemming from their capability to localize electromagnetic fields at optical frequencies simultaneously in frequency, time and space, which promises their great potential in various applications, including optical interconnects, near-field spectroscopy and sensing, optical probing for biological systems and far-field beam synthesis through near-field eigenmode engineering [27].

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