Unusual scaling laws for plasmonic nanolasers beyond the diffraction limit

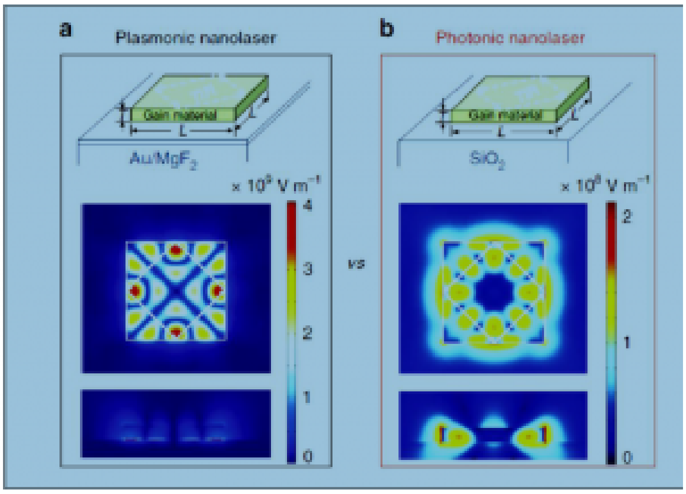

Fig. Schematic of plasmonic and photonic lasers and their cavity modes. a Top: schematic of the plasmonic nanolaser devices consisting of a nanosquare gain material on top of metal separated by a few nanometers of dielectric. Bottom: top and side views of electric field (|E|) profiles of a cavity mode in a 700 × 700 × 100 nm plasmonic cavity. b Top: schematic of the photonic nanolaser devices consisting of a nanosquare gain material on top of dielectric. Bottom: top and side views of electric field (|E|) profiles of a cavity mode in a 700 × 700 × 100 nm photonic cavity. In both panels, L and T are the length and thickness of the nanosquare, respectively, and TIR represents total internal reflection.

Plasmonic nanolasers are a new class of amplifiers that generate coherent light well below the diffraction barrier bringing fundamentally new capabilities to biochemical sensing, superresolution imaging, and on-chip optical communication. However, a debate about whether metals can enhance the performance of lasers has persisted due to the unavoidable fact that metallic absorption intrinsically scales with field confinement. Here, we report plasmonic nanolasers with extremely low thresholds on the order of 10 kW cm−2 at room temperature, which are comparable to those found in modern laser diodes. More importantly, we find unusual scaling laws allowing plasmonic lasers to be more compact and faster with lower threshold and power consumption than photonic lasers when the cavity size approaches or surpasses the diffraction limit. This clarifies the long-standing debate over the viability of metal confinement and feedback strategies in laser technology and identifies situations where plasmonic lasers can have clear practical advantage.

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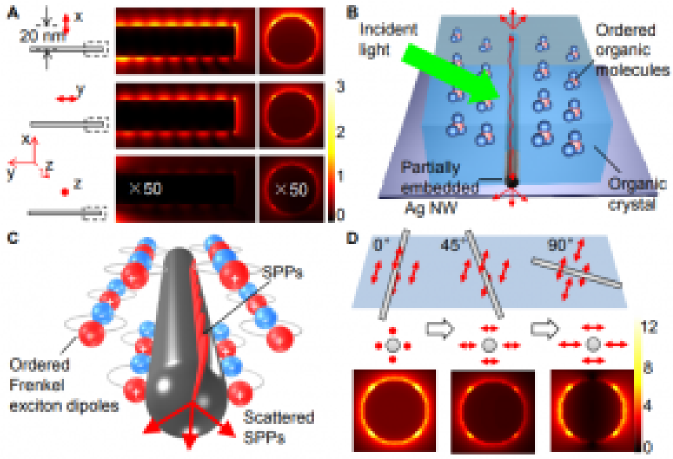
thesis defense

congratulations to Ms. Asgari , Ms. Mahboubi, Ms. Gachilou and Mr. kouhestanian, for defending your dissertation at approved times.

Defense time		
Mr. Kouhestanian	96/10/23	10:00
Ms. Gachilou	96/10/23	13:30
Ms. Mahboubi	96/10/23	15:00
Ms. Asghari	96/10/25	8:30

Orientation-Dependent Exciton-Plasmon Coupling in Embedded Organic/Metal Nanowire Heterostructures



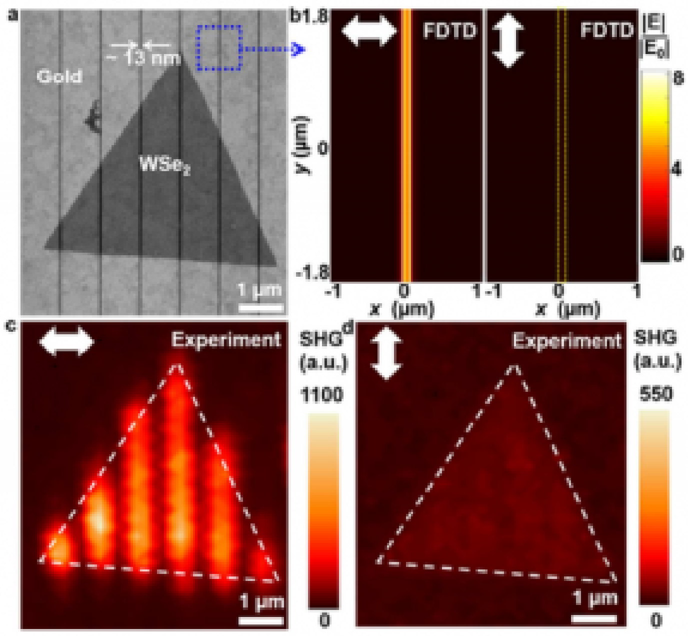
Organic/metal nanowire heterostructures for the study of orientation dependent exciton-plasmon coupling. (A) Numerically simulated $|E|^2$ distribution of SPPs at the end of a 200-nm-diameter and 6 μm-long AgNW, where SPPs are launched by a dipole oriented along three coordinate axes x, y, and z, respectively. The dipole is positioned at the middle of the wire with a distance of 20 nm. (B) Schematic illustration for the proposed heterostructure with orderly arranged molecules around a partially embedded AgNW. (C) Oriented Frenkel typeexciton dipoles created around the AgNW by irradiation of an incident light at the junction. SPPs can be efficiently launched by the exciton dipoles, which will subsequently propagate along the AgNW and scatter into free space at the distal ends. (D) SPPs coupling by multiple exciton dipoles. The cross angle between the AgNW and the polarization of dipoles are 0°, 45° and 90°.

The excitation of surface plasmons by optical emitters based on exciton-plasmon coupling is important for plasmonic devices with active optical properties. It has been theoretically demonstrated that the orientation of exciton dipole can significantly influence the coupling strength, yet systematic study of the coupling process in nanostructures is still hindered by the lack of proper material systems. In this work, researchers have experimentally investigated the orientation-dependent exciton-plasmon coupling in a rationally designed organic/metal nanowire heterostructure system. The heterostructures were prepared by inserting silver nanowires into crystalline organic waveguides during the self-assembly of dye molecules. Structures with different exciton orientations exhibited varying coupling efficiencies. The near-field exciton-plasmon coupling facilitates the design of nanophotonic devices based on the directional surface plasmon polariton propagations.

this research has published as a paper.

more information:https://www.ncbi.nlm.nih.gov/pubmed/28930431

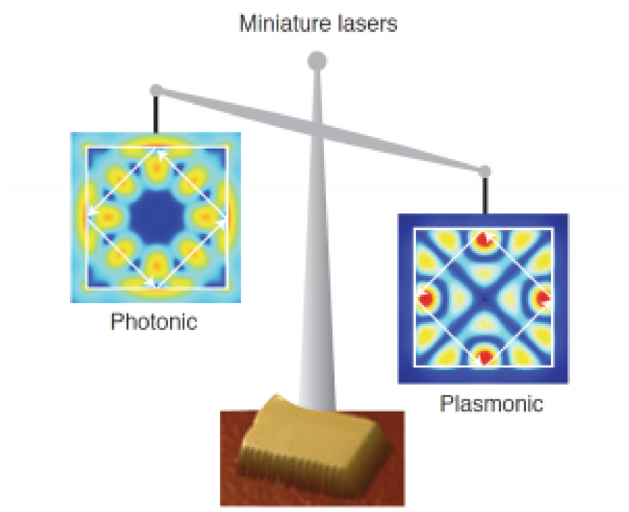
Selectively Plasmon-Enhanced Second-Harmonic Generation from Monolayer Tungsten Diselenide on Flexible Substrates



. Pump-laser-polarization dependent SHG mapping. (a) SEM image of single-crystalline monolayer WSe2 flake on trenches with a pitch of 910 nm. (b) Simulated electric field distribution at a plane 1 nm above the surface of gold substrate with pump laser polarized perpendicular (left panel) and parallel (right panel) to the trench. The dotted line outlines the geometry of the trench. (c,d) Corresponding experimental SHG mappings of the exact WSe2 flake on trenches as shown in the SEM image in (a) under resonant and non-resonant excitations, respectively. White dashed lines outline the WSe2 flake. The white arrows show the polarization directions of the pump laser.

Monolayer two-dimensional transition metal dichalcogenides (2D TMDCs) exhibit promising characteristics in miniaturized nonlinear optical frequency converters, due to their inversion asymmetry and large second-order nonlinear susceptibility. However, these materials usually have a very short light interaction lengths with the pump laser because they are atomically thin, such that second-harmonic generation (SHG) is generally inefficient. In this research, Joel.K.W.Yangs group fabricated a judiciously structured 150-nm-thick planar surface consisting of monolayer tungsten diselenide and sub-20-nm-wide gold trenches on flexible substrates, reporting ~7000-fold SHG enhancement without peak broadening or background in the spectra as compared to WSe2 on as-grown sapphire substrates. their proof-of-concept experiment yields effective second-order nonlinear susceptibility of 2.1 × 104 pm/V. Three orders of magnitude enhancement is maintained with pump wavelength ranging from 800 nm to 900 nm, breaking the limitation of narrow pump wavelength range for cavity-enhanced SHG. In addition, SHG amplitude can be dynamically controlled via selective excitation of the lateral gap plasmon by rotating the laser polarization. Such fully open, flat and ultrathin profile enables a great variety of functional samples with high SHG from one patterned silicon substrate, favoring scalable production of nonlinear converters. The surface accessibility also enables integration with other optical components for information processing in an ultrathin and flexible form.

[Is metal a friend or foe?]



A long-standing question debated among the nanophotonics community is whether size matters and helps to reduce the

threshold ofmicrometre- and submicrometre-sized lasers, and whether the presence of metal interfacing the gain medium harms or improves the laser performance. In a work published in Nature Communications, Ren- Min Ma and colleagues1 address this issue through a thorough experimental study, and conclude that when the device dimensions approach the diffraction limit, plasmonic (metal-based) lasers have superior performance over traditional photonic lasers as they are faster and have lower threshold and lower power consumption (Fig. 1). A laser has two major components: (i) a gain medium providing for stimulated emission and light amplification, and (ii) a resonator facilitating stimulated emission feedback (loosely speaking, reflecting generated photons to the place of their origin and, in many cases, enabling a coherence of laser radiation). The most basic laser cavity supporting standing-wave oscillation modes consists of two parallel mirrors, the distance between which is equal to an integer number of 'half-wavelengths' (λ/2) of laser radiation. Therefore, the minimum distance between the mirrors is equal to λ/2, which is equivalent to ~250 nm in the visible part of the spectrum – an order of magnitude larger than the typical size of a modern transistor. This hinders the dream of keeping up with the Moore's law by replacing electronic circuits with much faster optical circuits2, which would require laser-based sources and amplifiers of
coherent light. A novel solution to the size problem was put forward in 2003 by Bergman and Stockman3, who proposed to change the feedback mechanism and replace a set of large (by the nanoworld standards) mirrors with a nanoscopic metallic structures
that support resonant oscillations of free electrons (weakly) coupled to modes of electromagnetic radiation – the phenomenon known as a localized surface plasmon. The proposed device, termed spaser, which can be as small as a few nanometres, was primarily intended to generate surface plasmons (rather than photons) and be directly integrated into optical frequency circuits4. The first experimental demonstration, in 2009, of

the spaser-based nanolaser5, in which the 14-nm Au plasmonic nanoparticle, providing for a stimulated emission feedback, was surrounded by the 44-nm dye-doped silica shell, providing for gain, was followed by a rapid development of a variety of micrometre- and submicrometre-sized plasmonic lasers (or spasers)6, bringing the dream of nanocircuitry operating at optical frequency closer to reality. Besides the very possibility of having a laser whose size is not limited by λ/2 – which, not coincidentally, is close to the diffraction limit for light (the minimum area into which the light can be focused) – the heuristic expectation that a smaller volume laser can have a lower power consumption is one of the prime motivations for laser miniaturization1. This poses the following dilemma: on one hand, surface plasmons, supported by metallic particles and structures, allow lasers to be small, giving the hope of a low power consumption and high speed. On the other hand, metals are known to have large optical loss, which tends to increase the threshold pumping power (the laser threshold) and the overall power consumption. Therefore, do metals and surface plasmons help or harm miniature lasers and does the answer to this
question depend on the laser size? Ma and co-authors fabricated and characterized an impressive sum of 170 optically pumped plasmonic and photonic lasers based on rectangular CdSe slabs placed on top of MgF2/Au and SiO2 substrates, respectively (with the thickness of the slabs varied between 50 nm and 1,000 nm, and their length varied between 0.8 μm and 6 μm). The key difference between the metal-assisted lasers in this work and the spaser3 is that while the volume of the mode is comparable or less than λ3, the demonstrated lasers are subwavelength only in one vertical dimension, while in-plane they are larger than λ and exhibit standard multiple resonances due to reflections from the cavity edges. As a result, only a small fraction of light energy penetrates into the metal and the losses are substantially reduced in comparison to the metallic structures that are sub-wavelength in all three dimensions7. The

stimulated emission threshold power density P_{th}/S (kW cm−2), the power consumption at the threshold P_{th} (mW) and the emission lifetime τ (ns) have been studied as the function of the CdSe slab's volume V (measured in units of λ^3). Furthermore, the emission lifetime τ was studied and correlated with the threshold power density P_{th}/S for multiple slab thicknesses T. It has been shown that although P_{th} and P_{th}/S in large ($V \geq 5\lambda^3$) photonic lasers are comparable or even superior to those in plasmonic counterparts, these quantities increase dramatically at smaller laser volumes (particularly if the CdSe slab's thickness approaches the diffraction limit). At the same time, in small plasmonic lasers (T ≤ diffraction limit), the growth of P_{th}/S with the reduction of V is much less dramatic and the power consumption P_{th} decreases with the reduction of V, justifying the quest for laser miniaturization. This allowed Ma and co-workers to demonstrate a low lasing threshold of ~10 kW cm−2 in a plasmonic laser operating below the diffraction limit ($V \sim \lambda^3$ and T ~ 100 nm). According to Purcell[8], spontaneous emission lifetime in a cavity (in the absence of non-radiative decay) is roughly proportional to the mode volume V_m and, since the emitter is broadband, inversely proportional to the quality factor Q, defined as $Q = \omega/\Delta\omega_{sp}$, where ω is the frequency and $\Delta\omega_{sp}$ is the spontaneous emission bandwidth. Hence, the lifetime is predicted to decrease with the reduction of the physical volume of the CdSe slabs, in both photonic and plasmonic lasers[1]. This prediction was in good agreement with the experimental emission lifetimes measured in lasers of different sizes. Furthermore, the threshold was experimentally demonstrated to grow with the reduction of the spontaneous emission lifetime, in good agreement with 'old school' laser science[9]. Importantly, it has been experimentally shown that sub-diffraction plasmonic lasers can have shorter lifetimes than photonic lasers, for the same threshold value. Therefore, plasmonic lasers can be faster and, at the same time, have lower threshold than photonic lasers when the cavity volume approaches or becomes smaller than the diffraction limit cubed. The results reported by Ma and coauthors1 are of high importance, as they demonstrate the advantage of plasmonic lasers over photonic lasers (of the same sub-diffraction size) and pave the road to their further miniaturization. The next critical step in this direction would be an experimental study of the size dependence of plasmonic lasers, which are sub-diffraction in all three dimensions, and a comparison of the results with the theoretical predictions10.

In the long term, however, achieving electrically pumped plasmonic nanolaser operation will truly open the doors for practical applications of these devices.

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