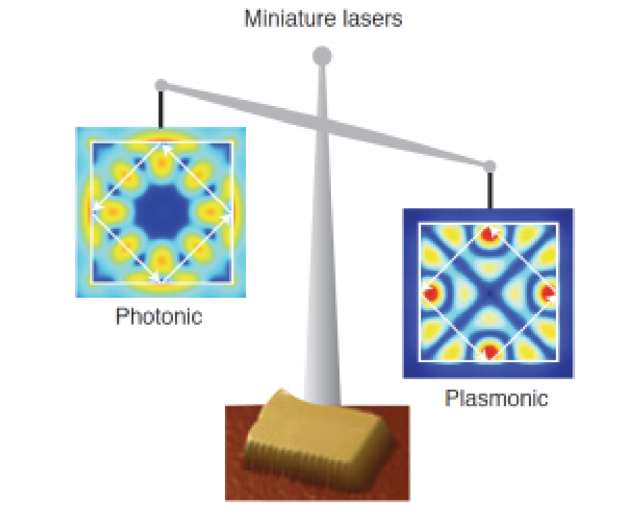
Is metal a friend or foe?



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 $\lambda/2$ – 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 MgF_2/Au and SiO_2 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 spaser[3] is that while the volume of the mode is comparable or less than λ^3, 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 dimensions[7]. 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 coauthors[1] 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 predictions[10].

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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