We develop an analytical theory, supported by full-wave simulations, for nanolasers based on optical nanopatch antennas tightly coupled to a metal film. The gap region between the metal nanopatch and underlying metal film forms a resonant cavity, where the local fields can be strongly enhanced, thus enhancing the coupling factor to emitters as well as other parameters relevant to lasing. The theoretical approach makes use of a coupled-mode theory [1] to predict the scattering and field enhancement associated with the nanopatch structures. To better capture the radiative and resistive losses in the nanopatch system, the cavity modes are expanded in quasi-normal modes (QNMs). Once the effective polarizability of the nanoparticle has been found from coupled mode theory, the radiative losses and coupling to surface plasmons are then determined and used to modify the effective polarizability [2].

With the electromagnetic problem solved, the enhanced field distribution is then found everywhere throughout the gap region where emitters are to be placed. For this analysis, a common dye molecule—Rhodamine 800—is assumed, for which the essential parameters can be easily referenced. Modeling the Rhodamine 800 as a four-level system, the rate equations describing the population density dynamics are then solved [3], leading to closed-form expressions for the minimum population density for lasing, the minimum number of pump photons, and finally the critical lasing intensity threshold.

The analytical theory can be used to perform rapid and efficient optimization of the key lasing parameters. Here, we consider three types of nanolaser geometries: The nanostripe, nanocube, and nanocylinder. We find that all three can exhibit considerably low thresholds at room temperature, with the nanocylinder and nanocube vastly outperforming the nanostripe. In all cases, we compare the predictions of the analytical theory to full-wave simulations and find excellent agreement, indicating the accuracy of the coupled-mode theory based on QNMs. We conclude that nanolaser sources based on the nanopatch geometry can be created based on these results.

References