Plasmon lasers: light from the nanoworld

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A novel solid-state, subwavelength laser characterized by efficient, enhanced spontaneous emission and thresholdless operation represents significant progress toward nanoscale coherent light sources.

Since its first demonstration in the middle of the last century, laser technology has made tremendous progress toward higher-power, faster, and smaller light sources. However, the diffraction limit of light imposed a fundamental limit on the minimum device dimensions. This physical constraint seemed beatable when Bergmann and Stockman proposed a laser setup using surface-plasmon polaritons (SPPs), in essence a light surface wave ‘surfing’ along a metal-dielectric interface. While plasmonics offers optical confinement below the diffraction limit, it comes with a tradeoff: the plasmonic signal dies out over a distance of a few micrometers at visible frequencies because of high ohmic losses. Thus, it is not surprising that it took six years since Bergman and Stockman’s concept was published before we succeeded in realizing a plasmonic nanoscale laser.

The first experiments that amplified surface plasmons (corresponding to the first step toward lasing) did not overcome the large plasmonic losses, even for low optical-mode confinement. This is likely even more challenging for high mode confinement, i.e., for nanoscale laser-light sources. Eventually, the hybrid-plasmon-mode concept that we developed previously enabled realization of a plasmon laser with deep subwavelength (nanoscale) optical confinement. In brief, a high-dielectric-gain material (e.g., a semiconductor nanowire) separated from a metal interface by a nanometer-thin oxide layer forms an optical capacitor based on polarization charges. This design allows for mode confinements of up to 1/20 of the operating wavelength while maintaining significant modal overlap with the gain material to provide optical amplification, thus leading to lasing action. We realized our plasmon laser based on the hybrid-plasmon-mode concept by placing a cadmium sulfide nanowire, bridged by a 5nm-thin magnesium fluoride layer, on top of a silver film oxide. We then optically pumped the laser device: see Figure 1(a). The associated subwavelength optical confinement can be seen clearly in the electric-field distribution: see Figure 1(b).

Figure 1. (a) Deep subwavelength plasmonic laser, consisting of a cadmium sulfide (CdS) semiconductor nanowire (d: Diameter) atop a silver (Ag) substrate, separated by a nanometer-scale magnesium fluoride (MgF$_2$) layer (h: Thickness). (Inset) Scanning-electron-microscope image of a typical plasmonic laser. (b) Subwavelength mode distribution of the plasmon laser. |E(x, y)|: Electric field.

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Upon increasing the pump intensity, we observed the onset of amplified spontaneous-emission peaks. These correspond to longitudinal cavity modes that form when propagation losses are compensated by gain amplification. They allow plasmonic modes to resonate between the reflective nanowire end facets: see Figure 2(a). Increasing the pump intensity even further produces sharp (full width at half maximum <0.5nm) lasing peaks. The behavior of the plasmon laser-light output power as a function of pump intensity yields a characteristic superlinear curve: see Figure 2(b). The lasing light exiting from the nanowire’s end facets can be clearly seen in a far-field microscope image: see Figure 2(c). The internal processes of this plasmon laser (exciton generation and annihilation⁴) result in a 10% efficient laser, which is strong enough to observe with the naked eye in ambient-light conditions: see Figure 2(d).

Proving subwavelength confinement of this plasmon laser can be achieved in a number of ways,⁴ e.g., by monitoring the characteristic polarization of the hybrid SPP mode or by employing gain clamping upon reaching the laser threshold. We checked this through the frequency-pulling effect, a characteristic of strong gain dispersion and mode confinement. As an alternative method, one can measure the emission rate, which is inversely proportional to the optical mode volume (Purcell

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The up-to-sixfold increased emission rate (compared to emission into free space) has its origin in the squeezed light inside the plasmon laser: see Figure 3(a). Finally, the power output as a function of pump intensity shows the signature of thresholdless lasing. With increasing mode confinement (i.e., decreasing laser diameter), the spontaneous-emission factor ($\beta$) increases, showing a nearly ‘flat’ curve for the smallest lasers.

This first demonstration of a semiconductor plasmon laser with subwavelength confinement is an important milestone toward true nanoscale photonic circuits, single-molecule detection, and other applications in optical computing and nonlinear optics. While our plasmonic nanolasers had to be kept at cryogenic temperatures, we recently demonstrated a similar plasmonic, subwavelength laser operating at room temperature, featuring an even smaller mode volume and showing stronger Purcell enhancement. We are currently investigating how to drive such a small laser device electrically toward light-on-chip applications.

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References