Laser miniaturization using metallic cavities

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The minimum dimensions of lasers are no longer limited by their operational wavelength, opening up a new field of nanolaser research and applications.

In the last few years, a number of groups worldwide have achieved significant laser-size reductions by employing different approaches involving metallic structures. We have encapsulated shaped type III–V semiconductor heterostructure pillars in an inner, thin dielectric and an outer, thick noble-metal layer. The higher-index material in the heterostructure core and the metal create an optical mode that is centered on the high-index gain material (see Figure 1). Such structures can be pumped electrically by creating one electrical contact on the top of the pillar structure, and a second on the substrate supporting it. This arrangement has the advantage that the electrical contacts are well separated from the region where the optical mode is located. The separation allows use of metals that have poor optical properties but can form electrical contacts. In addition, a thin dielectric layer can be placed between the semiconductor gain medium and the metal to prevent diffusion of free electrons from the metal into the semiconductor.

Based on such encapsulated heterostructures, we have demonstrated the smallest electrically pumped lasers, operating close to the diffraction limit. We have also demonstrated waveguide lasers where the waveguides squeeze light into plasmon modes that have dimensions below the diffraction limit. These devices work at cryogenic temperatures, where the semiconductor gain is increased and metallic losses reduced. However, slightly larger electrically pumped devices have been shown to work in pulsed mode at room temperature or in continuous mode close to room temperature. Other researchers have also made changes to such structures to obtain optically pumped lasing at room temperature with devices that are smaller than the free-space wavelength of light in all three dimensions.

One of the benefits of using metals for construction of resonant laser cavities is that many different configurations are possible, characterized by different sizes, shapes, and light/metal-interaction strengths. Some optically pumped devices exhibit extremely localized plasmon-mode fields. Excitingly, these have also been shown to work at room temperature. In theory, therefore, electrically pumped nanolasers may eventually be reduced to sizes of just a few tens of nanometers.

Such devices could have many interesting and useful properties. Larger devices could become efficient emitters of light because of the moderate quality factor that can be achieved in such cavities, particularly at longer wavelengths. For smaller devices that rely on plasmonic modes, attaining lasing at room temperature typically pushes the semiconductor gain material to its limits. Development of very efficient, coherent light emitters on scales of a few tens of nanometers will be difficult. However, for many applications, the main aspect of interest may be the inherently high speed that can possibly be achieved with such small devices, along with their low threshold power. It is

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predicted that these extremely small laser devices could have terahertz intrinsic modulation bandwidths with operating powers in the microwatt range. These properties will be of interest for processing of either high-speed optical signals or high-speed communications systems that could operate over short distances, for example between or inside integrated circuits. Even for LEDs, metallic or plasmonic cavities may provide significant advantages compared to dielectric cavities.

In summary, the rapid progress in development of metallic and plasmonic nanolasers witnessed over the past few years will likely continue. In theory, these devices have many interesting and exciting properties. As the technology improves, we should see the minimum size limit of lasers become ever smaller. Hopefully, useful devices for various applications will also appear. We continue to pursue both of these aims.

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References