expectation, females did not always prefer to approach the speaker producing the most chucks. Instead, female preference strongly depended upon the "chuck ratio" between the two calls: Although females strongly preferred calls with three chucks compared to those with one chuck, they cared little more for three-chuck calls than they did for two-chuck calls. The findings suggest that female discrimination constrains the production of longer calls.

Where does that leave predators—which are often seen as the opposing selective force to female preference—in the evolution of male traits? Although males benefit from bigger or more conspicuous traits that attract more mates, these traits can also make it easier for predators to find and catch males (*8*). Akre *et al*. explored this question by observing the behavior of frog-eating bats. Remarkably, the bats, like female frogs, preferred males that produced calls with more chucks, but their preference also decreased as the chuck ratio became larger. This suggests that male calls may not become more conspicuous to the bats as the calls get longer. Instead, the risk associated with adding an extra chuck declines: A male producing three chucks next to a male producing two exposes himself less to predation than does a male producing two chucks next to a

male producing one. As a result, in the case of male túngara frogs, both the additional benefits of attracting a female and the costs of being eaten decrease as chuck number increases. This adds weight to the idea that female discrimination is acting as a brake on lengthening calls.

These findings raise an intriguing question: Why do some males produce calls with up to seven chucks, despite evidence showing that increasing chuck number by more than two is pointless for attracting unaware females? Males respond to the calls of other males by increasing their chuck number by one (*7*). This suggests that, during competitions with neighboring males, male frogs can distinguish chuck number, even beyond those differences distinguishable to females. Do male túngara frogs differ from females in their discriminatory abilities? Or do they just have more time to listen to their neighbors' calls than do females looking for a mate?

One way to approach these questions is to consider the female's point of view. Females, after all, are caught in a bind: They need to choose a good male before being eaten. The female who chooses a good male quickly is likely to produce offspring, while the female who sits listening to a chorus trying to determine which male is best may become a bat's

dinner. A female in a hurry might discriminate between males only when the chuck ratio is small and detecting a difference is easy. The difference might also mean that the selected male's neighbor can't keep up, so the female really has chosen the best male (at least locally). Although psycho-physics might describe how a choice can become increasingly difficult, it does not explain whether a female is prepared to pay the cost of solving that increasing discrimination problem (*9*). Might this explain why elaboration of male traits varies across species: Female peacocks are prepared to take their time to compare and contrast males, whereas túngara females are not?

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PHYSICS

Spotlight on Plasmon Lasers

A plasmonics-based design approach is enabling coherent light sources to be built at the nanometer scale.

Volker J. Sorger and Xiang Zhang

Lasers are the workhorse of the information age, sending massive amounts of light packets through vast networks of optic fibers. Demands for ever-increasing speed and functionalities call for scaling down of photonic devices, similar to the trend in electronics. However, photonic devices face the fundamental challenge of the diffraction limit of light—a limitation that prevents squeezing light into spaces smaller than half of its wavelength. This barrier limits traditional optical components to sizes that are hundreds of times larger than that of their electronic counterparts. Surface plasmons are collective electronic oscillations on a metal-dielectric interface with a much smaller wavelength

than the excitation or emitted photons, and have emerged as a promising solution to overcome such a barrier (*1*). In 2003, the surface plasmon laser or "spaser" was theoretically proposed. The idea was to tightly confine light in the form of localized plasmons into deep subwavelength dimensions overlapping with a gain medium to achieve stimulated emission and light amplification or lasing, creating a coherent light source at the nanometer scale (*2*). That proposal is now being realized with several plasmonics-based design approaches being used to fabricate nanometer-scale coherent light sources.

The "gold-finger" laser was the first experimental attempt using metals to confine the optical energy to lasing (*3*). A tiny compound semiconductor pillar was used as a gain medium and wrapped in a thin gold layer. This small laser was electrically

pumped though it was diffraction limited because of its nonplasmonic nature. Later, a nanolaser showing plasmonic character with one-dimensional confinement was demonstrated (*4*). The large resistive losses associated with the metal required cryogenic temperatures for laser operation. In a different approach, core-shell colloidal particles suspended in water were optically pumped with localized plasmons bound to the surface of a metal particle (*5*). The 40-nm core-shell particle consisted of a gold core as a plasmonic cavity covered by a shell of silica decorated with dye molecules that provided the gain. Although this nanoparticle approach provides the ultimate scaling down in all three dimensions, its optical mode extends appreciably outside the structure, and electrical connections are difficult to implement.

One of the major challenges confronting

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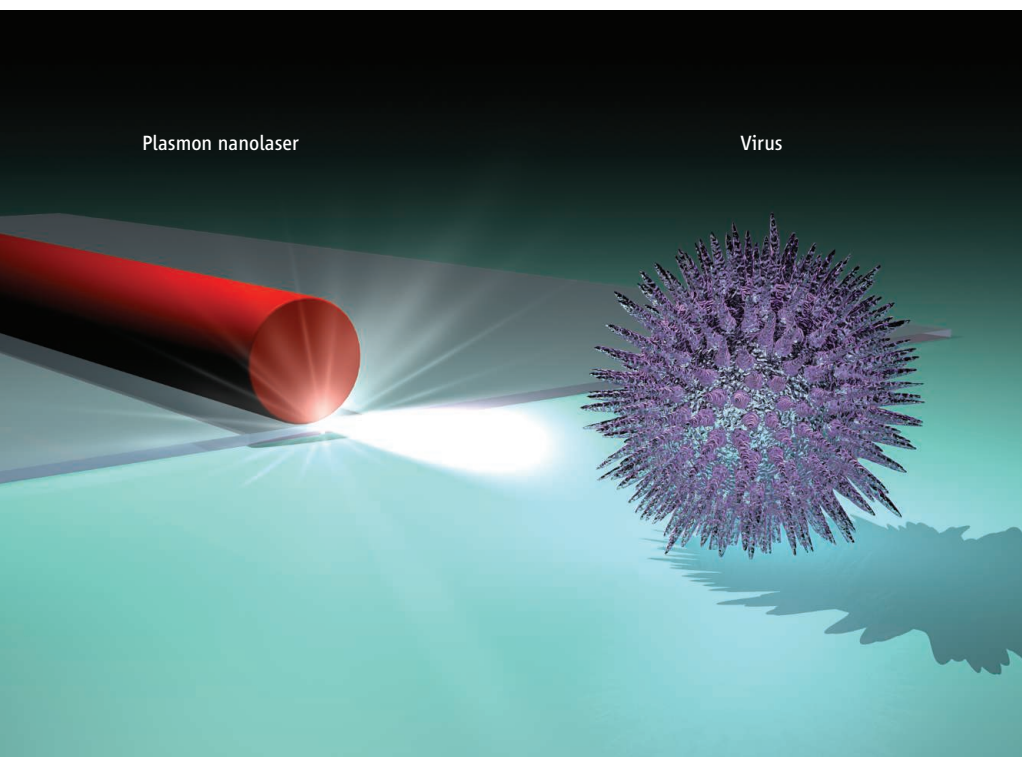
In the spotlight. The tiny coherent light spot from a plasmon laser is comparable in size to a single virus (around 20 nm in diameter), opening new possibilities such as ultrafast data communication and biomedical diagnostics at the single-molecule level.

plasmon devices is the high resistive losses in the metal at optical frequencies. A hybrid approach was developed to overcome such a limitation (6–8). A high-index semiconductor cadmium sulfide nanowire atop a silver surface separated by a thin low-index insulator concentrates a hybrid plasmon mode in the insulator gap of 5 to 10 nm with its tail overlapping with the semiconductor gain (6). In this approach, the electromagnetic field is lifted from the metal into the dielectric gap, resulting in low loss operation, yet maintaining the plasmonic nature of high confinement. Plasmon lasers of extremely small mode area at cryogenic and room temperatures have been demonstrated (6, 9). The mode size of these plasmon nanolasers is comparable to that of a virus or state-of-the-art electronic transistor (see the figure). In addition, various other nanolaser designs have been pursued. For instance, by increasing the diameter of the semiconductor gain core, the optical mode is pushed away from the metal surface, reducing the resistive loss (10, 11). Although these efforts have shrunk the device footprint, the fundamental diffraction limit remains because their modes are photonic rather than plasmonic.

With these exciting preliminary successes, we may ask whether plasmon lasers are simply a scaled-down version of a con-

ventional laser. The physical mechanisms of a plasmon laser are indeed unique. First, the strong confinement in plasmonic systems is key to enhancing the spontaneous emission, known as the Purcell effect, which depends on the ratio of quality factor to mode volume (12–14). Unlike simple miniaturization of conventional lasers, where the quality factor must be high owing to the diffraction limit of the mode volume, plasmon lasers can operate at a much lower quality factor because the mode volume can be squeezed far below the diffraction limit. In particular, the anomalous scaling in low-dimensional plasmonic systems suggests ultrahigh Purcell enhancements away from the plasmon resonance, promising high-performance laser devices (13). In addition, such a strong Purcell enhancement leads to the preferential emission into a particular plasmonic lasing mode, thereby enhancing the efficiency of using the stimulated emission for lasing. This potentially enables low-threshold or even thresholdless lasers (6, 15). Lastly, lossy plasmons make the Purcell enhancement broadband in nature, which could lead to ultrafast lasers with the modulation frequency up to terahertz, far exceeding the limit due to nonlinear gain saturation in conventional semiconductor lasers (13, 14).

Key challenges must be overcome to achieve practical nanometer-scale plasmon lasers. Electrically pumped plasmon lasers must be developed that require innovative designs of device structures and electrical contacts without perturbation of the optical mode. Materials must be chosen carefully, because scaling down of the laser not only reduces the amount of available gain, but also produces intense heat due to extremely concentrated optical fields. Fortunately, the metal offers three notable advantages: as a plasmon carrier, an electrical contact, and an effective heat sink. A further challenge is to achieve directional emission, which is difficult owing to the large momentum mismatch of light inside and outside the nanometer-sized cavity. The integration of nanolasers into photonic circuits demands new and creative approaches of efficient coupling of coherent nanoscopic light into a waveguide that routes the light signals to various other devices such as detectors and modulators, as well as to the outside world.

Such tiny and fast plasmon lasers offer the prospect of exciting applications. Coherent nanometer-scale light sources could enable the seamless on-chip integration of ultrafast photonics with electronics. This will dramatically increase the speed and functionalities of our communication networks. Further, as the extremely small mode size of plasmon lasers approaches the single-molecule scale, it allows for ultra-high-resolution biomedical diagnostics. In addition, these tiny lasers can be used to store our optical and magnetic data with unprecedented capacity for consumer electronics.

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