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Fruit photonics and the shape of water

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To microwaves, grapes are resonant, spherical blobs of water.

Cut a grape in half, leaving the hemispheres attached by an isthmus of skin. Then irradiate the pair in a household microwave oven. Those are the directions for a deceptively simple experiment Patrick Michaud published online in 1994. Within a few seconds, sparks emanate from the skin bridge and ignite a plasma. For decades the popular parlor trick has delighted and surprised millions of YouTube viewers, science-fair participants, and others, including readers of this magazine (see Back Scatter, PHYSICS TODAY, October 2017, page 96). In my lab at Trent University the oddity has blossomed into a research project involving several undergraduates, many pounds of charred fruit, and a dozen broken microwave ovens.

This past year we published our own account of the phenomenon. To some people the surprise comes from seeing biological tissue spark in ways they have come to expect only from metallic objects. But to us and other physicists, the surprise comes from the deeply subwavelength nature of electromagnetic-energy concentration. Microwave ovens operate at a frequency of 2.5 GHz, which corresponds to a free-space wavelength of 12 cm. With diameters ranging from 1 to 2 cm, grapes are much smaller than microwave wavelengths. Charred markings on the grapes are smaller still, on the order of millimeters. That size, mysteriously, is about one-hundredth of the 12 cm wavelength.

Two related photonic mechanisms can create intense, highly localized electromagnetic-field "hot spots:" surface plasmon resonances (SPRs) in metals, and morphology-dependent resonances (MDRs) in nonmetals. The SPRs are resonant surface-charge oscillations induced at the nanoscale (see the article by Mark Stockman, PHYSICS TODAY, February 2011, page 39). By analogy to atomic resonances that combine, or hybridize, to form new molecular resonances, SPR resonances can hybridize to produce super-intense hot spots at the nexus of dimers and larger clusters. Such hot spots are driving applications across a range of fields, such as chemical sensing, single-molecule spectroscopy, and photodynamic therapy.

The MDRs in transparent dielectric particles can likewise display optical resonances that yield electromagnetic hot spots. Recent research shows that when the nonmetal particles have a sufficiently large index of refraction, they can mimic the near-field hot spots of metallic SPRs. But unlike metals, transparent dielectrics admit electric fields into their interior, which makes internal light modes an important characteristic of MDRs.

A central question in our sparking-grape research is which of the two mechanisms is responsible for creating microwave-field concentrations intense enough to ignite a plasma. At first glance, the ion-laden cut grapes appear sufficiently conductive to make a plasmonic explanation plausible. And I initially wondered whether the hemispheres were acting like short metallic antennas. Further investigations, however, found that the answer lies in the grapes' behavior as dielectric spheres, not metallic ones. In this Quick Study, I describe why treating grapes as simple balls of water is the key to explaining why they spark in the microwave oven and why MDRs are the source of the phenomenon.

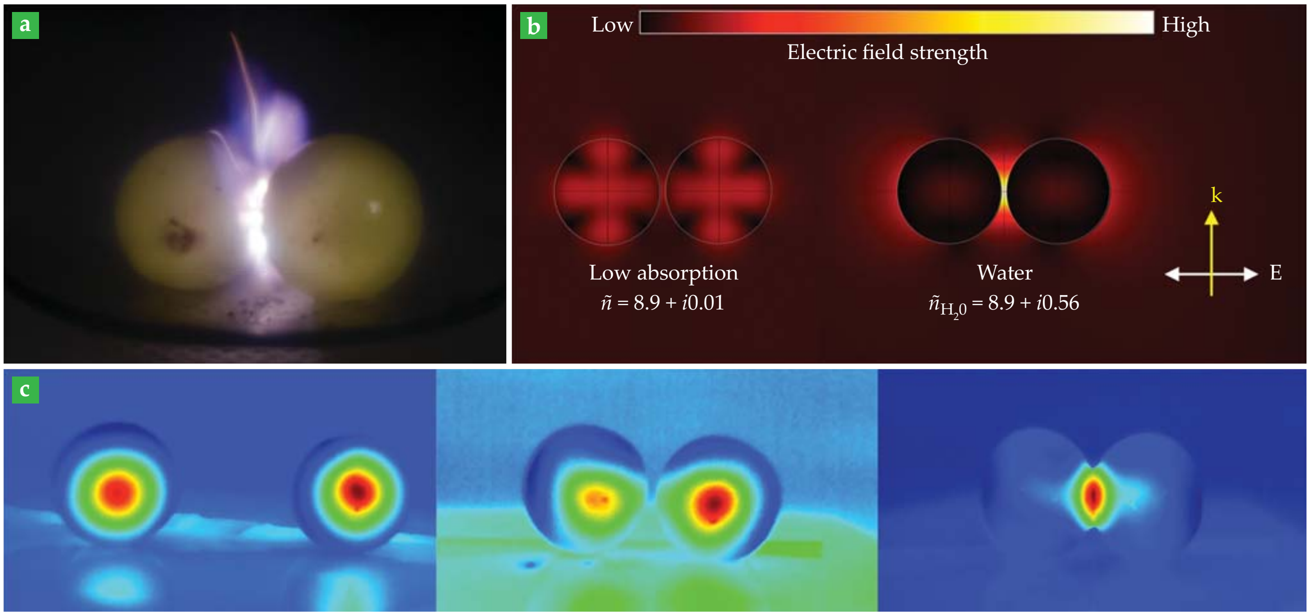
Spheres of water

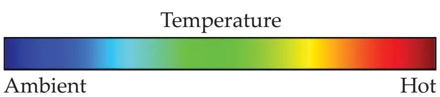
The first hint that something was amiss in the plasmonic explanation was our discovery that grapes do not need to be cut in half to generate plasma. As long as they are at least near contact, a pair of whole grapes will spark, as shown in the figure's panel a. The skin bridge is merely a convenient way to keep the objects close together. That finding led us to a breakthrough hypothesis—that the biology is irrelevant, and that grapes simply act like blobs of water in air. To confirm the hypothesis, my group made hydrogel balls, small sodium polyacrylate beads that hydrate to form skinless grape-sized (or larger) balls containing more than 99.6% pure water. Much like grapes, the beads never sparked when they were alone, but routinely created a microwave plasma when they were dimers in contact.

What's so special about water? Transparent over the broad, visible spectrum, and with an index of refraction of 1.3 at visible wavelengths, water is a mundane optical material; it absorbs little radiation and has a refractive index lower than that of glass. However, in the microwave regime, water is an exciting material whose index of refraction is of order 10. That's high enough for water blobs to behave like resonant cavities that strongly confine the microwaves.

The lowest-order MDRs, namely the electric and magnetic dipolar modes, form when the wavelength of incident light inside a dielectric is about the size of the particle's diameter. At 2.5 GHz one would expect to see fundamental optical scattering modes that mimic SPRs in spheres of water 1.3 cm in diameter—the size of grapes. Computer simulations, shown in the figure's panel b, reveal those field-concentration patterns in such spheres. When the absorption of water is included in the simulations, the resonance modes are more uniform and localized near the center. As two grapes are brought together, the modes overlap, merging into the tight space between the grapes, where the electric field grows enormous.

Although impressive, the plasma itself is of little scientific interest. Its presence simply indicates the formation of an intense electromagnetic hot spot. The concentration of microwaves is what prompts our interest. As described above, a





SUBWAVELENGTH ELECTRIC-FIELD CONCENTRATIONS in dielectric dimers. A pair of grapes **(a)** spark in a household microwave oven because of an optical hot spot at their point of contact. **(b)** Electromagnetic simulations in nonabsorbing grape-sized dimers show concentration patterns (left) inside and near their point of contact. The complex refractive index $\tilde{n}$ includes the refractive index and the absorption of radiation. When water's absorption of microwaves is included in the simulation (right), the internal mode structure is far more uniform and the evanescent hot spot outside the absorbing particles dominates. That hot spot creates the grape plasma. **(c)** A thermal-imaging sequence in microwave-irradiated grape hemispheres reveals the mixing of isolated optical resonances as two grapes are brought together. (Images adapted from H. K. Khattak, P. Bianucci, A. D. Slepkov, *Proc. Natl. Acad. Sci. USA* **116**, 4000, 2019.)

key difference between plasmonic resonances and MDRs is the internal optical modes of dielectrics. A measurement of electric-field distributions both inside the dielectric spheres and near their surfaces would thus be strong evidence tying MDRs to the creation of a dimer hot spot.

But measuring such fields directly is difficult, mainly because the hot spots are so small—about one-hundredth the microwaves' wavelength—and easily perturbed by contact probes. Instead, we exploited the fact that aqueous objects absorb at microwave frequencies. We used thermal imaging as an indirect way to measure time-integrated field intensities. Guided by additional three-dimensional finite-element method simulations, thermal imaging provides key evidence of the microwave MDRs in water spheres and of the mixing of their modes, shown in the figure's panel c.

Thermal imaging of irradiated hydrogel and grape hemispheres of various sizes reveals the increasing complexity of those internal resonances. Particles larger than grapes accommodate higher-order modes. Even so, the presence of internal modes does not by itself preclude a surface-conductivity effect. Our best evidence against surface conductivity comes from a fun experiment with quail eggs: Using thermally activated paper, which turns black above 90 °C, we confirmed that a pair of unmodified eggs (about 24 mm in diameter) develops a literal hot spot at the point of contact. When eggs are emptied of their contents, the hot spot disappears. And when they are refilled with water, it reappears.

Grape Expectations

Beyond the pyrotechnics, our studies have opened the door to other interesting avenues of research. Early on, we noticed that the dimer tends to vibrate rapidly when irradiated, often just before a plasma ignites. We recently tied that motion to the vaporization of water from the superheated hydrogel surface. Analogous to the Leidenfrost effect in liquid–solid interfaces (see PHYSICS TODAY, November 2018, page 14), a volatile elastic solid can convert thermal energy to mechanical motion. The microwave optical resonance creates a dynamic hot spot that explosively vaporizes the objects at their point of contact and allows them to push off each other.

Such remote activation may find applications in soft robotics. Other, more fanciful applications, such as omnidirectional antennas or MDR-based analogues of surface plasmon lasers, are also possible. In broader terms, the work demonstrates how microwave-water photonic research can be a powerful experimental sandbox for scaled-up investigations of resonant-scattering phenomena that cannot be elucidated at the nanoscale.

Additional resources

▶ H. K. Khattak, P. Bianucci, A. D. Slepkov, "Linking plasma formation in grapes to microwave resonances of aqueous dimers," *Proc. Natl. Acad. Sci. USA* **116**, 4000 (2019); for a video, see https://www.youtube.com/watch?v=wA4uZGRENas.

▶ A. I. Kuznetsov et al., "Optically resonant dielectric nanostructures," *Science* **354**, aag2472 (2016).

▶ H. K. Khattak, S. R. Waitukaitis, A. D. Slepkov, "Microwave induced mechanical activation of hydrogel dimers," *Soft Matter* **15**, 5804 (2019). PT