A Laser Casts a Shadow

Through its interactions with a crystal, light becomes an opaque object—an effect that could be harnessed in applications.

By **Rachel Berkowitz**

For millennia, humans have understood that material objects block light to cast shadows on surfaces. Researchers have now shown a counterintuitive phenomenon in which it is light itself that casts a shadow. Raphael Abrahao, formerly at the University of Ottawa, Canada, and now at Brookhaven National Laboratory, New York, and his colleagues have demonstrated how a laser beam can act like an object that blocks light from another source [**1**]. The resulting shadow's contrast was similar to that of a tree on a sunny day.

Light has no mass or substance and, therefore, should not cast any shadow. As physics and flashlight beams confirm, photons pass through other photons unimpeded. But over a lunchtime discussion, one of Abrahao's junior colleagues pointed out that many peer-reviewed optics publications include diagrams in which a laser beam casts a shadow. "We chuckled," says Jeff Lundeen, group leader at the University of Ottawa, where the work was carried out. "But this put the question in my head about whether we could make light cast a shadow."

A laser beam can sometimes act like a solid object and cast a shadow that is visible to the naked eye. Here, the shadow appears as the horizontal line traversing the blue background.
Credit: R. A. Abrahao *et al.* [1]

The researchers suspected that they could achieve such a feat using special optical materials. To find out, the researchers used a green (532-nm) laser beam as the object that would create the shadow. This "object" beam traveled through a cube of standard ruby crystal, 1.2 cm on a side, chosen for its nonlinear optical properties. From the crystal's other side—perpendicular to the object beam's direction of travel—a second, blue (450-nm) laser beam, enlarged with lenses to engulf the cube, provided the illumination. A camera placed in the illumination beam's path, across from the crystal, captured the blue light that passed through and landed on a screen, unobstructed except for a thin streak of darkness where the object beam passed in front. Abrahao says, "My thought when I first saw the shadow was kind of 'whoa, it works!"'

What they observed ticked all the boxes of a bona fide shadow. It was a large-scale effect, visible by the naked eye on an ordinary surface, apparently coming from the object beam blocking the illumination light. It took the shape of the object beam and followed the object as the researchers changed its position. And it followed the contours of the object, giving the sense of three-dimensionality.

The shadow comes from the ruby crystal's atomic makeup. A photon from the green laser (the object beam) boosts the ruby's minority chromium ions from their ground state into an excited state, which then decays rapidly via phonons to an intermediate energy level. At this energy level, the Cr^{3+} ions can absorb photons from the blue laser (the illumination beam) and transition to another excited state—thus blocking part of the blue light. "The effect only takes place if the absorption cross section of the second transition is larger than that of the first transition," Abrahao explains. For ruby, the green light locally changes the material's optical properties and increases the crystal's optical absorption of blue light, creating the observed shadow effect. Specifically, the effect happens because ruby presents a nonlinear optical effect called reverse saturation of absorption. Whereas most materials become more transparent in the presence of a powerful laser, this is not the case for ruby for certain wavelengths. "In other words, ruby becomes more absorptive," he says.

The researchers varied the optical power (5–18 W) of the green light object and measured what percent of the blue light was transmitted through the ruby. This transmittance corresponds to the contrast of the shadow of the green laser and had a peak value of 22%. Using an analytical model, the researchers found they could predict the contrast between the shadow and its surrounding illumination from the optical power and spatial intensity of the object beam—further evidence that the mechanism for the shadow was indeed blockage of the illuminating light.

Abrahao explains, "Strictly speaking, it is not massless light that is creating the shadow." Rather, the object beam is composed of strongly coupled photons and atomic excitations: a polariton. The shadow is technically that of this polariton, which has a matter component that has mass.

"This is the sort of report that captures the imagination," says Andrew Forbes, a photonics specialist at the University of the Witwatersrand in South Africa. "In the past, the focus of nonlinear optics was 'changing light's color,' but the modern trend is to move beyond this to full control." Using one laser to control another one's intensity opens possibilities for exploiting light–matter interactions—perhaps for optical switches or to pattern light for imaging or lithography, he says.

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REFERENCES

1. R. A. Abrahao *et al.*, "Shadow of a laser beam," **Optica 11, 1549 (2024).**