Rayleigh scattering reveals light propagation in optical nanfibers

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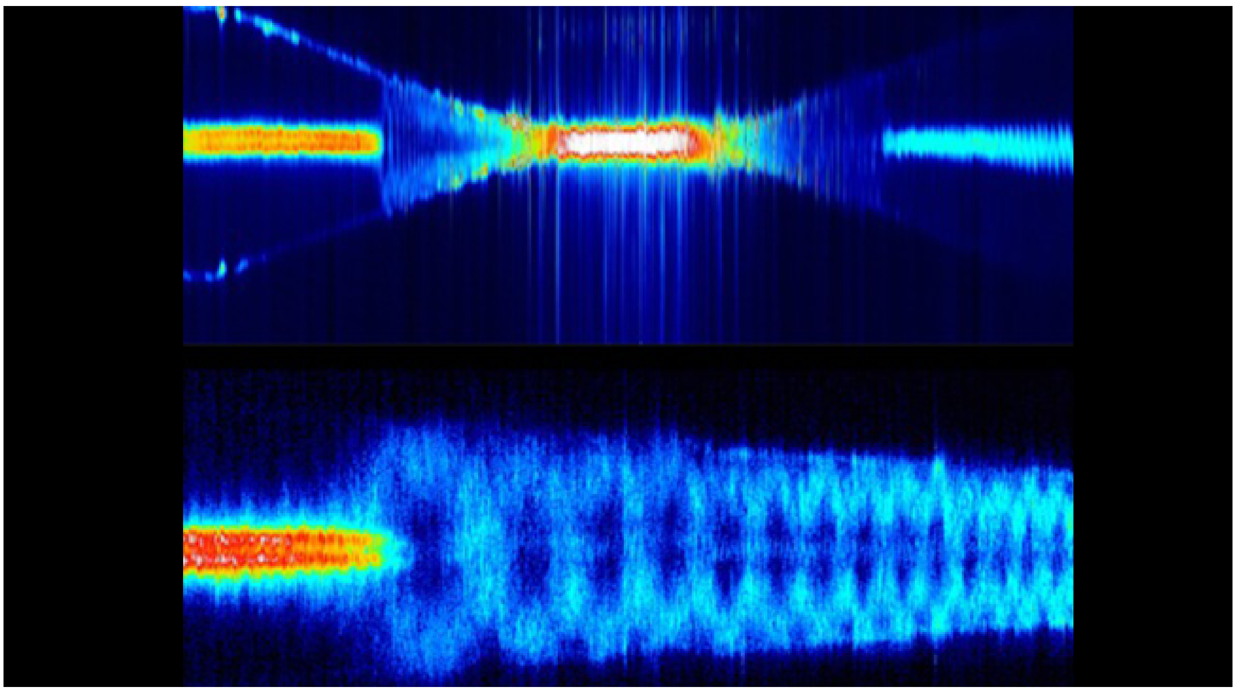

This technique directly images the propagation of light through an optical nanofiber, seen here as blue waves. The upper image is a zoomed out compilation of the Rayleigh scattering along the nanofiber. The saturated white section is the narrow neck of the nanofiber.

Optical fibers are hair-like threads of glass used to guide light. Fibers of exceptional purity have proved an excellent way of sending information over long distances and are the foundation of modern telecommunication systems. Transmission relies on what's called total internal reflection, wherein the light propagates by effectively bouncing back and forth off of the fiber's internal surface. Though the word "total" implies light remains entirely trapped in the fiber, the laws of physics dictate that some of the light, in the form of what's called an evanescent field, also exists outside of the fiber. In telecommunications, the fiber core is more than ten times larger than the wavelength of light passing through. In this case, the evanescent fields are weak and vanish rapidly away from the fiber. Nanofibers have a diameter smaller than the wavelength of the guided light. Here, all of the light field cannot fit inside of the nanofiber, yielding a significant enhancement in the evanescent fields outside of the core. This allows the light to trap atoms (or other particles) near the surface of a nanofiber.

JQI researchers in collaboration with scientists from the Naval Research Laboratory have developed a new technique for visualizing light propagation through an optical nanofiber, detailed in a recent Optica paper. The result is a non-invasive measurement of the fiber size and shape and a real-time view of how light fields evolve along the nanofiber. Direct measurement of the fields in and around an optical nanofiber offers insight into how light propagates in these systems and paves the way for engineering customized evanescent atom traps.

In this work, researchers use a sensitive camera to collect light from what's known as Rayleigh scattering, demonstrating the first in-situ measurements of light moving through an optical nanofiber. Rayleigh scattering happens when light bounces, or scatters, off of particles much smaller than the wavelength of the light. In fibers, these particles can be impurities or density fluctuations in the glass, and the light scattered from them is ejected from the fiber. This allows one to view the propagating light from the side, in much the same way as one can see a beam of sunlight through fog. Importantly, the amount of light ejected depends on the polarization, or the orientation of oscillation of the light, and intensity of the field at each point, which means that capturing this light is a way to view the field.

The researchers here are interested in understanding the propagation of the field when the light waves are comprised from what are known as higher-order modes. Instead of having a uniform spatial profile, like that of a laser pointer, these modes can look like a doughnut, cloverleaf, or another more complicated pattern. Higher-order modes offer some advantages over the lowest order or "fundamental" mode. Due to their complexity, the evanescent field can have comparatively more light intensity in the region of interest—locally just outside the fiber. These higher order modes can also be used to make different types of optical patterns. Nanofibers aren't yet standardized and thus careful and complete characterization of both the fiber and the light passing through them is a necessary step towards making them a more practical and adaptable tool for research applications.

This research team had previously developed techniques for controlling the fiber manufacture process in order to support extremely pure higher-order modes. Mode quality depends on things like the width of the fiber core and how this width changes over the length of the fiber. Small deviations in the fiber diameter and other imperfections can cause undesirable combinations and the potential loss of certain modes. By analyzing how the transmitted light changes as the fiber is stretched into a nanofiber, they could infer how the modes change while propagating through the fiber. However, until now there was no way to directly measure the intensity of the field along the fiber, which would offer far more insight and control over how the evanescent fields are shaped at the location of the trapped atoms. This could be useful for analyzing fibers where the propagation conditions change multiple times, or in the case where a fiber undergoes strain or bending during use.

By collecting images of the Rayleigh scattering, the scientists can directly see how the field changes throughout a nanofiber and also the effects of changing the pattern of light injected into the fiber. In addition, the team was able to use the imaging information to feedback to the system and create desired combinations of modes in the nanofiber—demonstrating a high level of control. The same technique can be used to measure the profile and width of the fiber itself. In this case, they were able to estimate a fiber radius of 370 nanometers and variations in the waist down to 3 nm. Notably, this type of visualization is done in-situ with relatively standard optics and does not require destroying the fiber integrity with the special coatings that are necessary when using a scanning electron microscope. This also means these characterizing measurements can be used to optimize the fields that interact with atoms during experiments. "An advantage of this technique is that it can be applied to fibers that are already installed in an apparatus," explains Fredrik Fatemi, a research physicist at the Naval Research Laboratory and author on the paper: "One could even probe fibers or other nanophotonic structures designed for fundamental modes by using shorter optical wavelengths."

To further refine this approach, the researchers plan to modify the optics in order to capture the entire length of the nanofiber in a single image. Currently, the images are made by stitching several high-resolution images together, as in the image seen above.

More information: "Rayleigh scattering in an optical nanofiber as a probe of higher-order mode propagation," *Optica*, 2, 416 (2015). dx.doi.org/10.1364/OPTICA.2.000416

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