Mathematical model explains how hollow-core fibers guide light with ultra-low data loss

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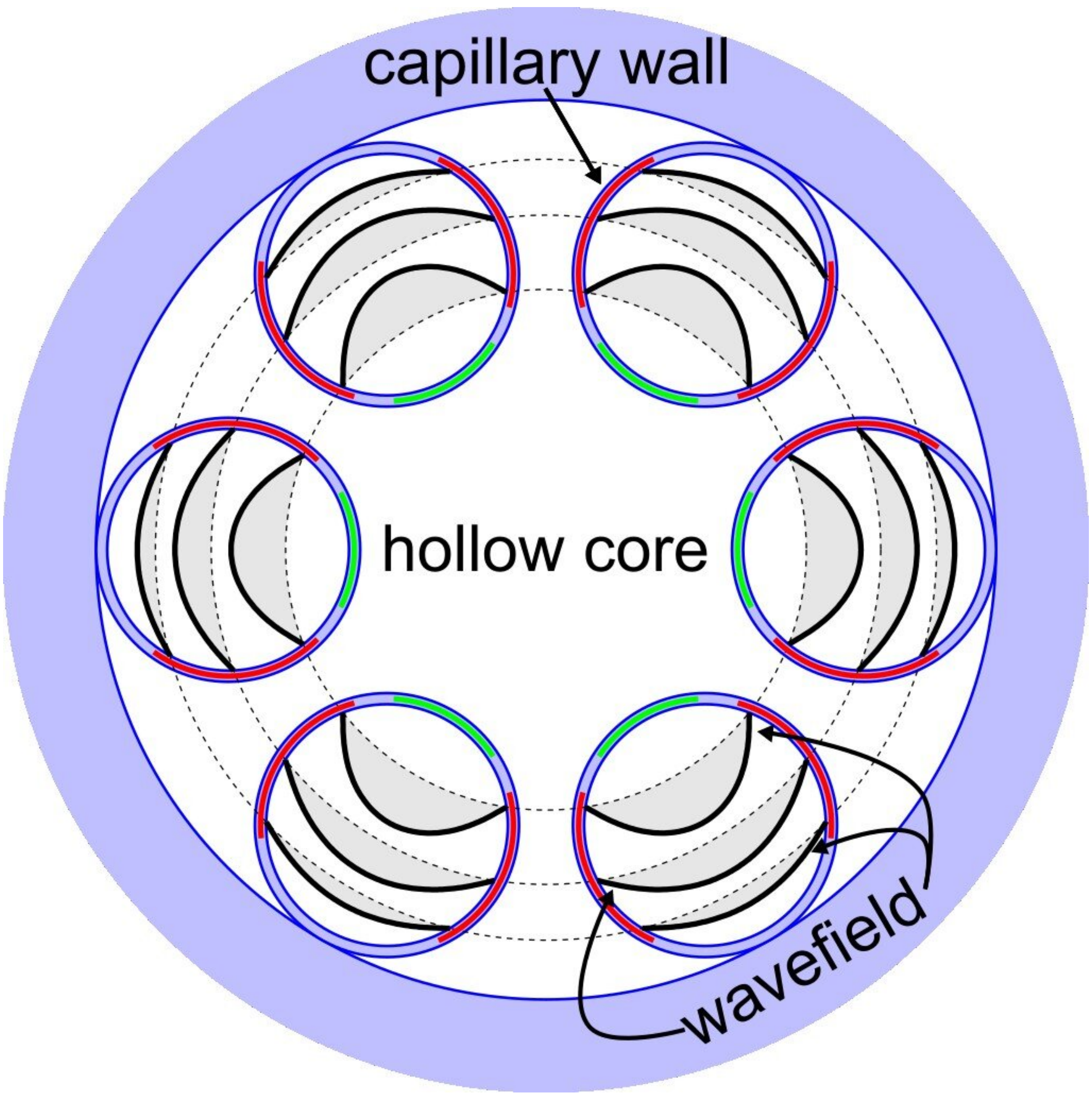

Cross section of a hollow-core fibre fabricated by Leah Murphy. Credit: Leah Murphy. Credit: Leah Murphy

Scientists at the University of Bath have developed a mathematical model to explain how antiresonant hollow-core fibers guide light in a way that keeps data loss ultra-low. Until now, scientists had no complete explanation for this well-observed phenomenon.

Immense progress has been made in recent years to increase the efficiency of optical fibers through the design of cables that allow data to be transmitted both faster and at broader bandwidths. The greatest improvements have been made in the area of hollow-core fibers—a type of fiber that is notoriously "leaky" yet also essential for many applications.

Now, for the first time, scientists have figured out why some air-filled fiber designs work so much more efficiently than others. The puzzle has been solved by recent Ph.D. graduate Dr. Leah Murphy and Emeritus Professor David Bird from the Center for Photonics and Photonic Materials at the University of Bath.

The researchers' theoretical and computational analysis gives a clear explanation for a phenomenon that other physicists have observed in practice: that a hollow-centered optical fiber incorporating glass filaments into its design causes ultra-low loss of light as it travels from source to destination.

Dr. Murphy said, "The work is exciting because it adds a new perspective to a 20-year-long conversation about how antiresonant, hollow-core fibers guide light. I'm really optimistic that this will encourage researchers to try out interesting new hollow-core fiber designs where light loss is kept ultra-low."

The communication revolution

Optical fibers have transformed communications in recent years, playing a vital role in enabling the enormous growth of fast data transmission. Specially designed fibers have also become key in the fields of imaging, lasers and sensing (as seen, for instance, in pressure and temperature sensors used in harsh environments).

The best fibers have some astounding properties—for example, a pulse of light can travel over 50km along a standard silica glass fiber and still retain more than 10% of its original intensity (an equivalent would be the ability to see through 50km of water).

But the fact that light is guided through a solid material means current fibers have some drawbacks. Silica glass becomes opaque when the light it is attempting to transmit falls within the mid-infrared and ultraviolet ends of the electromagnetic spectrum. This means applications that need light at these wavelengths (such as spectrometry and instruments used by astrophysicists) cannot use standard fibers.

In addition, high-intensity light pulses are distorted in standard fibers and they can even destroy the fiber itself.

Researchers have been working hard to find solutions to these drawbacks, putting their efforts into developing optical fibers that guide light through air rather than glass.

This, however, brings its own set of problems: a fundamental property of light is that it doesn't like to be confined in a low-density region like air.

Optical fibers that use air rather than glass are intrinsically leaky (the way a hosepipe would be if water could seep through the sides).

The confinement loss (or leakage loss) is a measure of how much light intensity is lost as it moves through the fibers, and a key research goal is to improve the design of the fiber's structure to minimize this loss.

Hollow cores

The most promising designs involve a central hollow core surrounded and confined by a specially designed cladding. Slotted within the cladding are hollow, ultra-thin-walled glass capillaries attached to an outer glass jacket.

Using this set-up, the loss performance of the hollow-core fiber is close to that of a conventional fiber.

An intriguing feature of these hollow-core fibers is that a theoretical understanding of how and why they guide light so well has not kept up with experimental progress.

For around two decades, scientists have had a good physical understanding of how the thin glass capillary walls that face the hollow core (green in the diagram) act to reflect light back into the core and thus prevent leakage. But a theoretical model that includes only this mechanism greatly overestimates the confinement loss, and the question of why real fibers guide light far more effectively than the simple theoretical model would predict has, until now, remained unanswered.

Dr. Murphy and Professor Bird describe their model in a paper published this week in the journal *Optica*.

The theoretical and computational analysis focuses on the role played by sections of the glass capillary walls (red in the diagram) that face neither the inner core nor the outer wall of the fiber structure.

As well as supporting the core-facing elements of the cladding, the Bath researchers show that these elements play a crucial role in guiding light, by imposing a structure on the wave fields of the propagating light (gray curved lines in the diagram). The authors have named the effect of these structures "azimuthal confinement."

Although the basic idea of how azimuthal confinement works is simple, the concept is shown to be remarkably powerful in explaining the relationship between the geometry of the cladding structure and the confinement loss of the fiber.

Dr. Murphy, first author of the paper, said, "We expect the concept of azimuthal confinement to be important to other researchers who are studying the effect of light leakage from hollow-core fibers, as well as those who are involved in developing and fabricating new designs."

Professor Bird, who led the project, added, "This was a really rewarding project that needed the time and space to think about things in a different way and then work through all the details.

"We started working on the problem in the first lockdown and it has now been keeping me busy through the first year of my retirement. The paper provides a new way for researchers to think about leakage of light in hollow-core fibers, and I'm confident it will lead to new designs being tried out."

More information: Leah R. Murphy et al, Azimuthal confinement: the missing ingredient in understanding confinement loss in antiresonant, hollow-core fibers, *Optica* (2023). DOI: 10.1364/OPTICA.492058

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