Fibers With Flare

Heat triggers damaging, fuse-like behavior in certain types of optical fibers

By IVARS PETERSON

A length of optical fiber, coiled to form the words "Southampton University," glows with an eerie blue-green light in the darkened room. A technician touches the fiber with a flaming match, and the heated spot suddenly flares. A patch of brilliant light begins to creep along the fiber, letter by letter snuffing out the glowing words.

Philip St. J. Russell of the University of Southampton, England, uses this dramatic demonstration to illustrate how heat combined with low-power laser light at visible wavelengths can damage the kinds of glass filaments often used for carrying optical signals from place to place. Once initiated, this "fiber fuse" can travel long distances, leaving in its wake a trail of tiny, evenly spaced bubbles that disrupt light transmission along the fiber.

Such behavior can have alarming consequences when light-transmitting optical fibers are used in hostile environments where the temperature can suddenly increase to the levels needed for triggering the fuse effect. For certain kinds of optical fibers, heat-initiated damage can occur when the visible-light laser power transmitted along the fiber is as low as 4 milliwatts, less than the power of a small flashlight.

"With all these optical fibers [coming into use] these days, the idea of hundreds of kilometers of fiber being destroyed just like that is frightening," Russell says. Communications cables, such as optical-fiber telephone lines, are *unlikely* to suffer the same kind of damage because they generally carry signals at much longer, infrared wavelengths.

In the latest twist on this unusual phenomenon, researchers at Brown University in Providence, R.I., have discovered that a sharp temperature gradient, ranging from 700°C to 1,000°C, by itself can produce a characteristic damage pattern in the core of a heated optical fiber — even when no laser light passes through the fiber. This finding, reported in the July 1 OPTICS LETTERS, complicates attempts to explain how the fiber fuse works, and adds to concerns about the conditions under which optical fibers can be used safely.

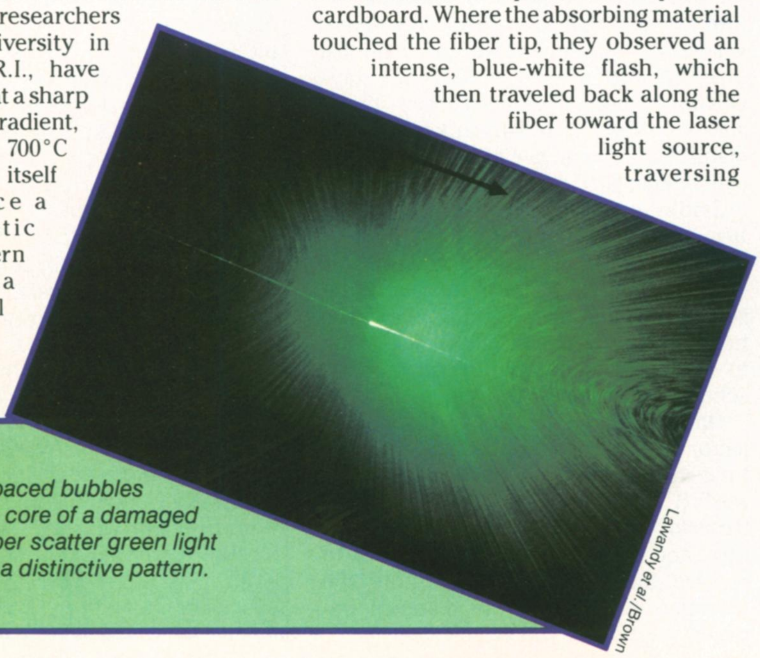
"Fibers are a great way to send signals around," says physicist Nabil M. Lawandy, who coauthored the report on the heat-induced fiber fuse. "We're concerned about people using [optical fibers] in places where there are high temperature gradients. This kind of damage could happen to a fiber, for example, in a nuclear power plant's sensor network."

Researchers have known for more than a decade that high-power lasers can damage optical fibers. But the fuse effect — which produces a different, distinctive pattern of destruction — apparently first showed up in 1983, when investigators at the IBM Thomas J. Watson Research Center in Yorktown Heights, N.Y., discovered that fibers sometimes catastrophically destroyed themselves when carrying pulsed light from a powerful neodymium-YAG laser.

In 1987, scientists at British Telecom Research Laboratories in Ipswich found they could generate the effect by letting visible laser light emerging from the end of an optical fiber strike a light-absorbing material, such as a paint fleck or piece of cardboard. Where the absorbing material touched the fiber tip, they observed an intense, blue-white flash, which then traveled back along the fiber toward the laser light source, traversing 1 meter in about 1 second.

In examining the fiber under a microscope, the researchers discovered that the entire length of its core was pitted with a string of evenly spaced, bullet-shaped hollows, each about a micron in length. This damage effectively ruined the fiber as a medium for transmitting light. One test showed that a single flare could damage 1.5 kilometers or more of fiber.

All of these fuse effects occurred in single-mode optical fibers. Such fibers — made from silica, the basic component of sand — contain small amounts of dopants, such as germanium, in their cores to modify the degree to which silica bends light. Doping permits optical fibers to guide light more effectively.



Lawandy et al./Brown

Evenly spaced bubbles along the core of a damaged optical fiber scatter green light to create a distinctive pattern.

Researchers at Southampton's Optoelectronics Research Centre became interested in this phenomenon when they started looking into the possibility of using lasers to splice single-mode fibers automatically. Because light absorption in an optical-fiber core rises very sharply at temperatures beyond 1,000°C, they hoped to connect two fibers by sending laser light through while heating the splice. The increased light absorption, they thought, would add enough heat to melt the glass, spontaneously fusing the two pieces.

"Unfortunately, this set off the fiber fuse, and that destroyed the whole core," Russell says.

Russell and graduate student Duncan P. Hand found they could initiate the fuse in many different types of optical fibers. The ease of initiation depended on the fiber's germanium concentration. "The [fuse] effect is stronger if you've got a high germanium concentration," Russell notes. "If it's too low, it won't work."

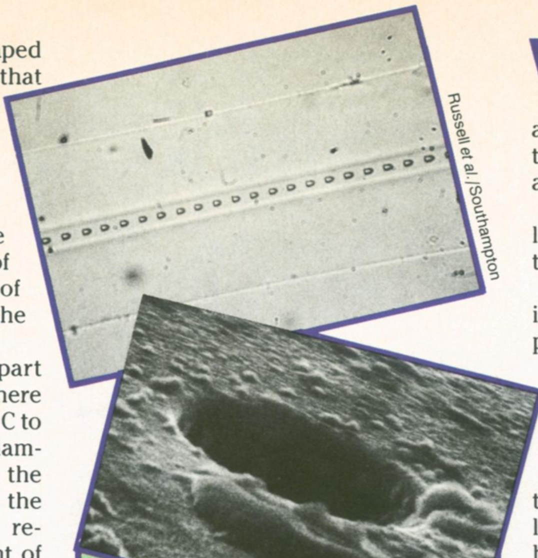
In many instances, he adds, "there's enough energy in 5 milliwatts of green light from an argon laser to set this thing off if you heat the fiber. That's a startling result because 5 milliwatts is not much power, and the heat source may be a match or a cigarette lighter."

The experiment conducted by Lawandy's group at Brown involved heating a germanium-doped, single-mode optical fiber threaded through a tube-shaped furnace. The researchers discovered that the fiber suffered damage — strings of tiny, elongated bubbles — at the spots where the fiber emerged from the furnace's two ends.

"The furnace is just a hot tube," Lawandy explains. "We found the bubbles in regions maybe a couple of centimeters long, where the product of the temperature and the gradient of the temperature is the highest."

Nothing happened in the hottest part of the furnace. Only at the edges, where the temperature dropped from 1,000°C to 700°C, did damage occur, and that damage didn't spread any farther down the fiber. Moreover, even at its highest, the temperature of the furnace itself remained well below the melting point of silica glass.

"The amount of damage varies from fiber to fiber, and we don't quite know why," Lawandy says. "It probably depends on the type and density of germanium-related defects in the glass."



Russell et al./Southampton

The fiber-fuse effect damages an optical fiber by producing a sequence of bullet-shaped cavities (bottom) along the fiber's core (top).

The Brown results complicate the search for a full explanation of the fiber fuse.

British Telecom researchers initially suggested that the fiber core had to be heated above its melting point of approximately 1,700°C to start the process. According to their scenario, the heated core absorbs light strongly, raising the local temperature enormously and prompting the formation of a plasma of electrons and ions in a confined space. Diffusion of the heat generated in the process, combined with an effect known as self-focusing, would shift the hot spot to a new location, and the process would repeat itself.

The Southampton group agrees that a heat gradient probably sets off the fuse. But their model suggests a much more complicated interplay between heat and laser light within the fiber. It predicts that parts of the core may reach temperatures as high as 5,000°C or 6,000°C.

"The equations are pretty complicated, and it was a very difficult model to put together," Russell says. "But we were able to get a model which fitted pretty well to what we measured in practice."

Lawandy, however, rejects these explanations. He suggests that the fiber core itself supplies the additional energy to generate the extremely high local temperatures needed for damage to occur. Heating the fiber may initiate a heat-generating chemical reaction, he argues.

"A convenient model for this scenario would be to view the propagating fuse as a set of match tips lined up in a row, spaced such that if one match is ignited, its nearest neighbors barely escape ignition," Lawandy and his collaborators write in OPTICS LETTERS. "The addition of laser energy, however, brings the nearest neighbor match above ignition when another is lit, thereby setting the fuse into motion."

A furnace heated to a temperature higher than the reaction's ignition temperature would also initiate damage. "You don't need light," Lawandy says. "A temperature gradient anywhere along the fiber will do it."

Determining exactly which chemical reactions may be responsible remains difficult, however. Lawandy suspects that the process may involve molecular oxygen and defects formed by the introduction of germanium atoms into silica glass.

"What [Lawandy and his co-workers] haven't done is to make some sort of estimate of how many defects and how much molecular oxygen there is in the material," says Cornelius T. Moynihan, a materials scientist at Rensselaer Polytechnic Institute in Troy, N.Y. "What surprises me is that there would be enough defects and molecular oxygen in there to give you a reaction that would push the temperature up to a point where you can melt glass."

"There's a big puzzle here," he adds. "You can't accept the chemical reaction explanation without some further evidence, and the fact that [the fiber fuse] is touched off thermally seems to discount somewhat the other theories."

Russell, too, disagrees with Lawandy's conclusions. "I find Lawandy's results intriguing, and they are certainly novel," he says. "However, they do not agree with our own careful measurements."

In particular, Russell points to evidence that under the right conditions, the fuse effect is reversible, leaving no permanent damage, and that under some circumstances, no damage occurs at all.

Whatever the explanation, the fiber fuse does exist, and it afflicts the types of commercially available, germanium-doped optical fibers often used for transmitting optical signals at visible wavelengths.

"People need to be aware of the problem," Lawandy says. "It can creep up in things like sensor systems."

When G.W. Bibby of National Power PLC in Leatherhead, England, saw the Brown paper, he wrote immediately to the researchers to obtain further information.

"I'm interested in temperature sensing using optical fibers," Bibby told SCIENCE NEWS. The Brown results revealed "an unexpected, new degradation mechanism" that prompted him to look beyond his initial concerns about how well a fiber and its coating would survive moderately high temperatures.

Mike Krainak, a laser communications specialist at NASA's Goddard Space Flight Center in Greenbelt, Md., went so far as to visit Lawandy's laboratory to see a demonstration of the fuse effect. "It's a lot more catastrophic than just cutting a line," Krainak says. "You basically destroy the fiber."

The fuse phenomenon may have implications for the design of optical-fiber cables needed for communication and data transfer among spacecraft instruments. "Now you're going to have to look at the thermal environment [in which optical fibers operate]," Krainak says.

"For applications where you need to deliver a lot of power to a remote point using an optical fiber," says Russell, "there is a very significant worry that the fuse could damage your whole system. If you're delivering a lot of blue or green light to a sensor point in maybe an atomic reactor, it's just possible that [the fiber] might get heated and destroy itself."

Researchers are already considering possible solutions to such problems. "What we'd like to do is figure out how to make fibers with a low defect concentration," Lawandy says. "There may also be a way of processing the fiber to control its oxygen content."

Another possibility is to use germanium-free optical fibers. "We've seen the effect in several types of fibers, but not in pure-silica-core fibers," Lawandy says.

The Southampton group has discovered that tapering a section of the fiber to make it thinner limits how far the fuse travels. "By heating and pulling it, you reduce the fiber's diameter and the diameter of its core," says Russell. That causes any light traveling along the fiber to spread out into a beam wider than the core. This constricted section stops the fuse from propagating further.

"It's a safety feature," he explains. "If the fuse goes off, it won't destroy your whole system." □