Through a Glass Brightly: Low-Loss Fibers for Optical Communications

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Technological breakthroughs develop through years of scientific collaboration and innovation, each discovery built upon the failures and successes of earlier work. Such was the case with the work on the first low-loss optical fiber. What began with three Corning scientists searching for a communications solution ultimately created what is now known to be a key to the Information Age.

In 1948, Claude E. Shannon [1] proved that optical carrier frequencies provided greater bandwidth than radio or microwave frequencies. But the technology of the day had not yet caught up with the science. Those looking to apply Shannon's work lacked a suitable light source, modulator, and detector technology as well as any kind of transmission conduit.

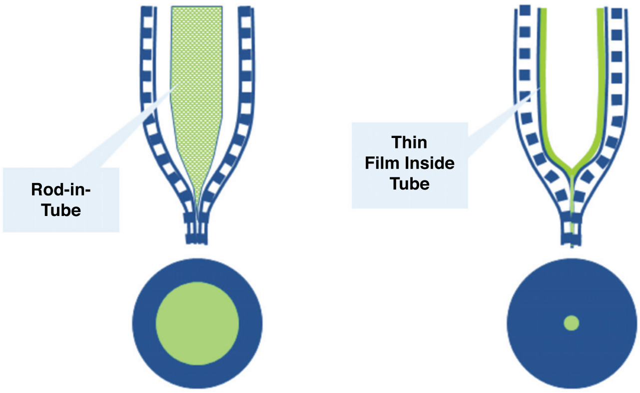
Then in 1960, Ted Maiman [2] demonstrated the first laser. A few laboratories saw it as a source for optical communications with the bandwidth that Shannon described and began to research that application. However, it could not be implemented because at that time, a suitable transmission conduit for light had not yet been invented.

Corning learned of the growing interest in optical communications on 17 June 1966, when one of its scientists, William Shaver, brought back a request from the British military. They wanted a single-mode fiber (100-μm diameter with a 0.75-μm core) with a total attenuation of less than 20 dB/km. This was prior to any publication, such as the Kao and Hockham paper [3], suggesting that optical fibers could be used as a practical communications conduit. The very best bulk optical glasses of the day had attenuation of around 1000 dB/km. The British request required an improvement in transparency of 10^{98} to reach the 20 dB/km goal. Given the science of the time, it was seemingly impossible. But within Corning's culture of scientific innovation—particularly when it came to discovering new applications for glass—"an impossible goal" was merely "a problem yet to be solved."

This particular problem was handed to Robert Maurer, a physicist known for his work on light scattering in glasses. Though Bob did not know it at the time, he actually had begun his fiber work a decade earlier. He published two definitive works in 1956 [4] and 1960 [5], indicating that Corning's flame-hydrolysis fused silica had the lowest Rayleigh scattering of all glasses he had measured.

These studies were built upon the discoveries of two giants within Corning's history, Frank Hyde [6] and Martin Nordberg [7]. In 1930, Hyde demonstrated that when vapors of silicon tetrachloride were passed through a flame in the presence of oxygen, they would hydrolyze to form a fine powder of very pure silicon dioxide that could be fused into very pure silica glass. He noted that the normal glass impurities that give rise to absorptive losses in the glass were low. Nine years later, Nordberg added titanium tetrachloride to Hyde's process and formed a very-low-expansion doped fused silica glass.

While these processes had been used at Corning for years, Bob took them in innovative directions that, ultimately, laid the foundation for the Corning group's invention of low-loss optical fiber. Always the contrarian, and influenced by his earlier work on light scattering, Bob



▲ **Fig. 1.** Illustration of RIT and thin-film processes for making an optical fiber preform. (Courtesy of Corning Incorporated.)

and a summer intern made a rod-in-tube (RIT) fiber (Fig. 1)—the best known processing method at that time—using Corning's fused silica as the cladding. He purposely added an *impurity* to the fused silica to raise the refractive index of the core, Nordberg's titanium doped silica, and obtain light guidance. Losses were still very high, but Bob was encouraged enough to request two additional scientists, Peter Schultz and Donald Keck (the author).

Peter took a fresh look at Hyde's flame hydrolysis process. He built a small boule furnace and began making various doped fused silicas and measuring their properties. Based on Bob's earlier results, the group of three focused their efforts exclusively on fused silica fibers made by flame hydrolysis. They continued the counterintuitive approach, adding an impurity to the pure fused silica to raise the refractive index and create the fiber core.

So began a time of trial and error. No human endeavor progresses more rapidly than can be measured. The group began to systematically measure and identify the sources of their optical losses. They knew absorptive losses were one source, and they struggled to examine the impurities introduced in the flame hydrolysis glasses that could cause absorption. The best analytic equipment of the day could measure impurity levels only to the parts-per-million level, and parts-per-billion were needed. An attempt was also made to evaluate losses in a few centimeters of bulk glass, but this still could not produce the losses in an actual fiber that had gone through all the processing steps. Making their own fibers was the only way to get a thorough understanding of optical losses.

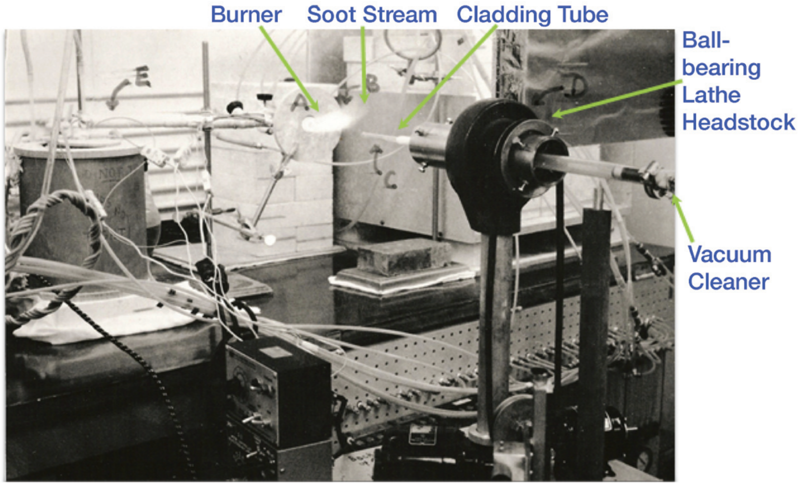
Optical absorption from formation of reduced-titanium (Ti^{3+}) color centers during the high-temperature fiber drawing step accounted for about half of the fiber loss. At first the losses were annealed away by heat-treating the fibers at 800°C to 1200°C. Unfortunately this treatment drastically weakened the fibers as a result of surface crystallization. The other half of the loss originated from light-scattering defects at the core–cladding interface. No publication of the day ever mentioned this most significant source of loss. The Corning group believed that this loss originated during the RIT process from dirt in the lab environment.

With each failure a little more was learned until an idea was hit upon that proved to be the key: the traditional RIT method was abandoned and a new approach was invented. Rather than inserting a core rod, the group decided to directly deposit a thin layer of core glass inside a carefully flame-polished cladding tube (Fig. 1). This produced intimate contact between core and clad materials and, it was hoped, would get rid of the scattering defects observed in the RIT fiber.

For those who believe that excellent work can be done only with the very latest equipment, take note of the Corning lab pictured in Fig. 2. The equipment was crude but effective. A portable lathe headstock held the rotating cladding tube in front of the flame hydrolysis burner. The burner produced a soot stream containing titania-doped silica. Initially the soot would not go into the 5–6-mm hole in our cladding tube. One of the group spotted the lab vacuum cleaner. Putting this at the end of the cladding tube beautifully sucked soot from the flame and deposited a uniformly thin layer onto the inside tube surface. This coated tube was then placed in the fiber draw furnace where the soot sintered into a clear glass layer, the hole collapsed to form a solid rod containing the doped core, and the entire structure was drawn down into fiber.

Measuring that first low-loss fiber was an unforgettable experience. It was late afternoon, and, after heat-treating a piece of the group's latest fiber, the author positioned it in the attenuation measurement apparatus. With a viewing telescope he could observe and position the focused He-Ne laser beam on the fiber end. When the laser beam hit the fiber core, a blindingly bright returning laser beam was produced. It took a moment to realize that the laser was being retro-reflected off the far end of the fiber and coming back through the optical system.

Fig. 2. Photograph of apparatus for making the first low-loss optical fiber. (Courtesy of Corning Incorporated.)



The brilliant laser beam emanating from the end of the fiber was so dramatically different from anything previously seen that it was apparent something special had occurred. With considerable anticipation, the author measured the fiber loss, and to his delight and surprise it was ~17 dB/km. With little sense of history, Donald Keck's excitement was registered in his now fairly well-known lab-book entry: "Whoopee!" (Fig. 3).

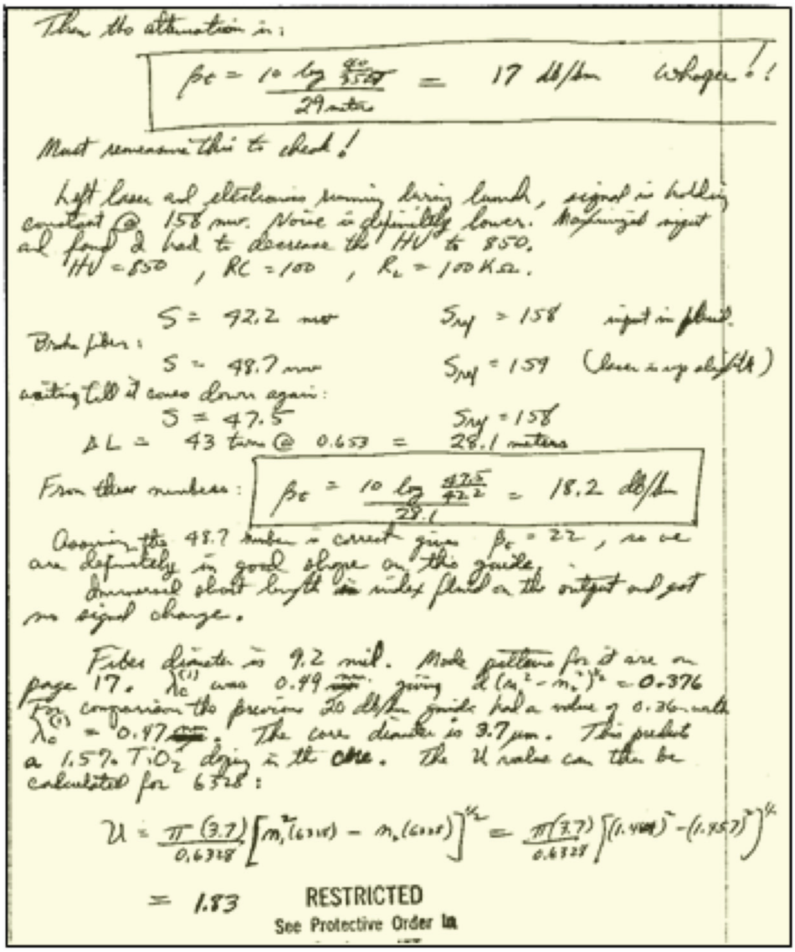
In 1970 the result was announced to the world when Bob presented the Corning group's paper "Bending losses in single-mode fibers" at an Institution of Electrical Engineers Conference in London on analog microwave technology [8]. In that paper, he mentioned that the fiber had a total attenuation of only 17 dB/km, prompting scientists at the conference to remark that at least their 2-in. helical microwave guides could be filled with lots of optical fibers. We also submitted our paper to *Applied Physics Letters*, and it was initially rejected! The reviewer commented, "It is rather difficult to visualize an amorphous solid with scattering losses below 20 decibels per kilometer, much less the total attenuation." Eventually, however, the paper was published [9]. (See Fig. 4.)

The Corning group had done it, but they were far from done. Though revolutionary, their breakthrough fiber solution was not exactly robust. Only small preforms could be made, and the heat treatment required to achieve low attenuation made the fibers brittle. Also, the preferred fiber design had shifted to multi- rather than single-mode. The larger core diameter was believed necessary to more easily couple light into the fiber from the relatively crude semiconductor lasers of the day.

To make such fibers, Peter, our colleague Frank Zimar, and the author invented another flame hydrolysis approach later dubbed "outside vapor deposition." In this method, first core and then cladding soot were deposited onto a removable rotating rod to build up a porous soot preform. Because of the lower temperature in this process, Peter found he could incorporate new dopants that had vaporized in the higher-temperature boule process. One of these dopants was germania, a glass former like silica.

In June 1972, the first fiber incorporating germania was drawn in the core. The group was obviously on the right track, as the bright light of the draw furnace was still visible through the end of a kilometer of fiber on the wind-up drum. The loss measured was only 4 dB/km, no heat treatment was needed, and fiber strength was excellent. This was the first truly practical low low-loss fiber.

This writing marks the 42nd anniversary of the Corning group's invention of low-loss optical fiber. With more than 1.6 *billion* kilometers of it wrapped around the globe, a world has been created that is dependent upon reliable, speed-of-light access to people and information anywhere, anytime, through almost any device of their choosing. The dramatic increase in users has brought with it unprecedented demand for bandwidth. Several sources, including a University of Minnesota Internet Traffic Study and Cisco, have estimated that the average Internet traffic today worldwide is ~150 Tb/s and growing at about 50% per year.


Then the attenuation is:

$$\beta_c = \frac{10 \log \frac{?}{?}}{29 \text{ meters}} = 17 \text{ dB/km} \quad \text{Whoopee!!}$$

Must remeasure this to check!

Left laser and electronics running during lunch, signal is holding constant @ 158 mv. Noise is definitely lower. Maximized signal and found I had to decrease the HV to 850.
HV = 850, RC = 100, R_L = 100 KΩ.

S = 92.2 mv S_{ref} = 158 input in fluid.
Broke fiber: S = 48.7 mv S_{ref} = 159 (laser is very stable)
waiting till it comes down again:
S = 47.5 S_{ref} = 158
ΔL = 43 turns @ 0.653 = 28.1 meters

From these numbers: $$\beta_c = \frac{10 \log \frac{47.5}{92.2}}{28.1} = 18.2 \text{ dB/km}$$

Assuming the 48.7 number is correct gives $\beta_c = 22$, so we are definitely in good shape on this guide.
Immersed short length in index fluid on the output and got no signal change.

Fiber diameter is 9.2 mil. Mode patterns for it are on page 17. $\lambda_c^{(1)}$ was 0.49, giving $a(n_1^2 - n_2^2)^{1/2} = 0.376$. For comparison the previous 20 dB/km guide had a value of 0.36 with $\lambda_c^{(1)} = 0.47$. The core diameter is 3.7 μm. This predicts a 1.5% TiO_2 doping in the core. The U value can then be calculated for 6328:

$$U = \frac{\pi(3.7)}{0.6328}\left[n_1^2(6328) - n_2(6328)\right]^{1/2} = \frac{\pi(3.7)}{0.6328}\left[(1.4??)^2 - (1.457)^2\right]^{1/2}$$

$$= 1.83$$

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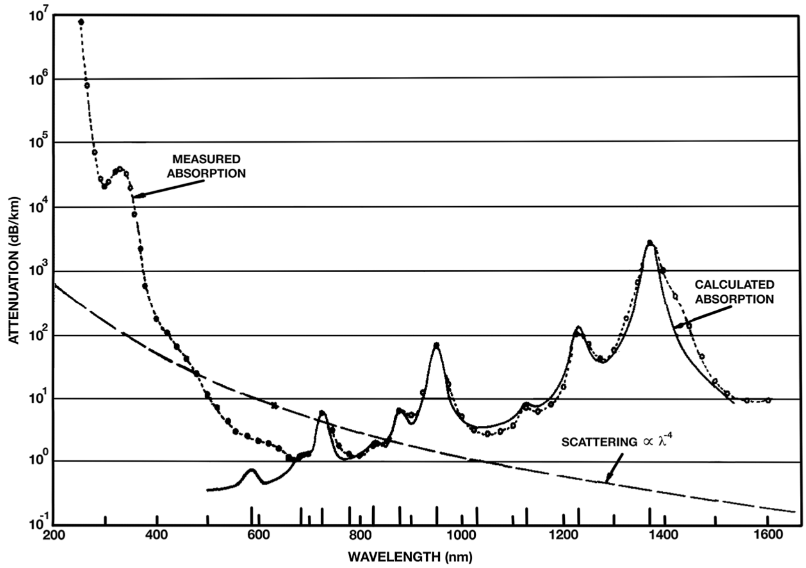
Fig. 3. Laboratory notebook with the first sub-20-dB/km fiber measurement. (Courtesy of Corning Incorporated.)

This growth rate is not surprising. Collectively we have moved from simple audio to increasing video content in our communications. Estimates are that two-thirds of the mobile data traffic will be video by 2015 as social networking continues to explode. People sending data is one thing, but machines-talking-to-machines (M2M) as is happening increasingly is yet another. The latter will overtake the former in just two or three years—all this without even considering potential new data-generating applications. We are already seeing the deployment of fiber-enabled remote sensors to monitor our environment. Power lines and highway and civil structure monitors provide an optical fiber safety net supporting the infrastructure we rely upon every day. Emerging biomedicine and biotechnology applications ranging from transmission of x-ray data to real-time high-definition video for remote surgeries to the potential petabytes involved in DNA data transmission and analysis are still in the future. It is now well established that creative people will invent new ways to use the "bits" if technology can provide improved "cost of transmitting the bit."

The amount of information that can be transmitted over a single fiber today is staggering. Commercial core networks today operate at 50 Tb/s on a single fiber, and as reported at OFC 2012, scientists are achieving in their labs record data rates of more than 305 Tb/s.

While this capacity is enormous, fiber bandwidth is finite—perhaps only 10 times higher than today's core network traffic level. Our current demand for bandwidth will most likely exceed our capacity before 2030. This would require a beginning over-build of the core networks even as we finish the build-out of the local loop! We should not be surprised if the 1.6-billion-kilometer fiber network of today will be but a fraction of that which will exist in just a couple of decades.

Fig. 4. *Applied Physics Letters* paper [10] on the ultimate fiber losses and predicting that a 0.2 dB/km loss would be possible near 1550 nm. (Reproduced with permission from D. Keck, R. Maurer, and P. Schultz, Appl. Phys. Lett. **22**, 307 (1973). © 1973, AIP Publishing LLC.)



But beyond all the bits and bytes, the most important story of the communications revolution brought about by optical fiber may well be the one about improving human lives. All of us who have worked and continue to work in optical fiber communications technology have truly made the world a better place—and for that we should be proud.

When asked about glass, most people *still* picture something breakable that shatters when dropped. But low-loss optical fiber has shown us that hair-thin strands of glass filled with light are strong enough to help people all over the world shatter long-held assumptions and break down centuries-old political and cultural walls.

In 2000, the United Nations created the Millennium Project, aimed at lifting millions of people in the developing world from impoverishment, illness, and death. One of the primary methods for achieving that objective was to deploy the benefits of optical fiber technology for their education and economic betterment.

The International Telecommunications Union continues to track progress toward that end. In 2011 they reported that today, thanks to optical fiber, more than two billion people around the world are instantaneously and simultaneously accessing the Internet, virtually 75% of the world's rural population has cell phone coverage, and more than 60% of the world's countries have a National Research and Education network.

We have come a long way since we first stood on the shoulders of those giants of early optical communications. Today the optical fiber network has become the lifeblood of our society, providing the medium through which commerce and culture are being simultaneously created and communicated on a personal and global scale. We can never be sure just what the future of optical communications holds, but given the remarkable history of low-loss fiber, it is fairly certain to be a future full of light.

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