AN OFS **WHITE PAPER**

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A Furukawa Company

AccuCore HCF™ Optical Cable

Low-Latency Hollow-Core Fiber Transmission Primer

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Executive Summary

Optical fiber is key in enabling modern communications and the internet. Moving data, selling data and data-driven machine learning are central to today's global economy. Indeed, five of the six wealthiest companies are businesses selling data[1].

For certain applications, receiving the data as quickly as possible is key. This is what OFS Fitel's AccuCore hollow-core fiber enables: a medium through which light travels about 50 percent faster than through a traditional optical fiber.

Designing a hollow-core fiber is complicated and AccuCore's low-latency today comes at the expense of a higher optical loss and a curtailed transmission window. Cabling hollow-core fiber is also challenging. OFS Fitel has solved these issues to become the first company to sell hollow-core-fiber cables.

AccuCore is already in use for high-frequency trading and is suited for applications such as supercomputing. The fiber has other performance attributes besides low latency that solid-core fiber cannot match, including a lower phase sensitivity with temperature changes and lower non-linear effects.

This White Paper details how OFS' AccuCore hollow-core fiber works, how multi-path interference arises that impairs a working cable and how OFS has resolved the issue. Designing hollow-core fiber telecommunication links is also detailed. The Paper concludes with the customer support services that OFS offers.

Introduction

Optical fiber has two important attributes that make it suited to communications: a huge bandwidth and span. Optical fiber can transmit a vast amount of traffic which is important given that telecommunications network capacity needs to grow at a 50 percent compound annual growth rate.

Optical fiber can also transmit data over a range of distances: from several meters that link data center equipment to sub-ocean links connecting continents over 10,000km apart.

A phrase commonly associated with fiber is its ability to move data at 'light speed'. However, the speed of light is not the same in all media with light travelling much slower in glass than in air (which is close to the speed of light in a vacuum, the fastest speed possible). A traditional optical fiber is all-glass. Hollow-core fiber, as implied by its name, differs from an all-glass fiber in that its core is air. With light traveling faster in the air than in glass, hollow-core fiber has a significant speed advantage when transmitting data. Hollow-core fiber is ideal for applications requiring data in the shortest time possible.

How Fiber Guides Light: Standard Single Mode Compared to the AccuCore Photonic Band Gap Fiber

An optical fiber is designed to deliver light-carrying data to its destination.

Solid-core fiber comprises of a glass core surrounded by a glass cladding. The cladding ensures the travelling light stays guided within the core.

To confine the light, a high-refractive-index glass is used for the core, surrounded by a low-refractive index glass cladding. The difference between the two indices of refraction ensures that the light is confined to the core via the principle of total internal reflection. To efficiently couple light into the core, it must be launched into the core with the correct angle. By 'correct' what is meant is an angle for which the rays of light in the core are no longer refracted (i.e., bent) in the cladding, but totally reflected in the core. See Figure 1.

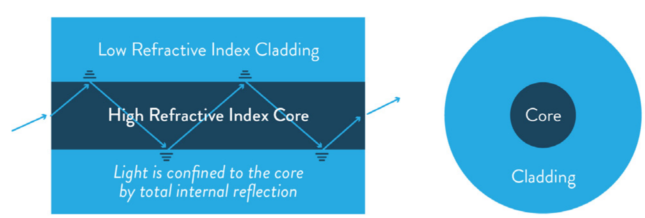

FIGURE 1: Solid-core fiber guiding light.

[1] *An OCF 2020 keynote by Dave Welch celebrating the 50th anniversary of low-loss fiber.*

In contrast, hollow-core fiber has an air core which is surrounded by a microstructured cladding. Air (or more precisely vacuum) is a medium with the lowest refractive index at optical wavelengths, so there is no homogeneous material that can be used to form a cladding to guide light via total internal reflections.

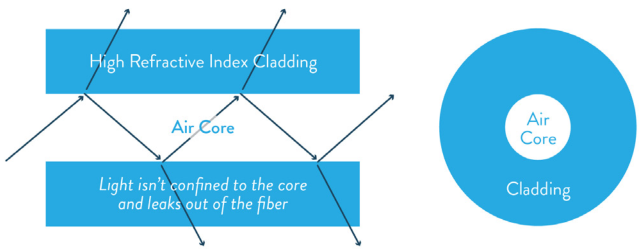

FIGURE 2: A leaky fiber resulting from surrounding an air-based core with homogeneous (glass) cladding.

A hollow core surrounded by a glass cladding can be used but it results in a leaky waveguide, making it practical for extremely short spans only. See Figure 2. If a hollow-core fiber is to be used for lengths of several kilometers or more, a different waveguide design is needed.

Figure 3 shows the cross-section of OFS's AccuCore photonic band gap fiber; photonic band gap being a particular class of hollow-core fiber. The fiber uses a relatively large air-core encapsulated by an array of smaller hexagonal cells that run along the length of the fiber. The cladding also has six large holes surrounding the core that form the 'shunts', whose role is explained in the next section.

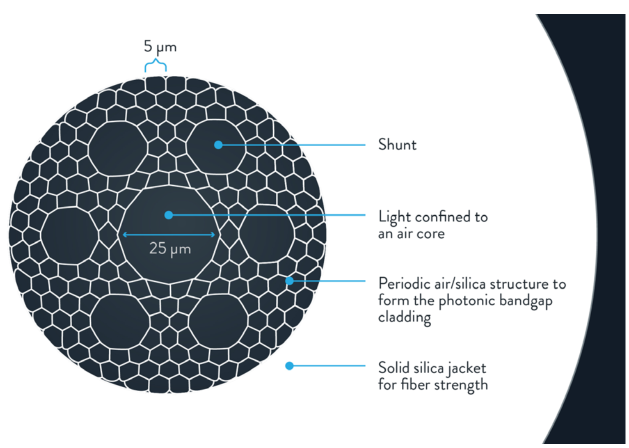

FIGURE 3: The cross-section of a hollow-core fiber showing the core, lattice structure, the shunts, and the solid silica jacket.

The cladding confines the light to the air-core along the length of the fiber, as with a solid-core fiber. The periodic air-glass cladding prohibits light from penetrating into the cladding due to the photonic band gap effect. In principle this mechanism is similar to total internal reflection in that the light cannot leak out of the fiber at a continuous range of angles. Hence the light stays confined to the core.

At some discrete wavelengths, though, such light that is confined to the fiber can be guided not only within the core, but also in the many glass features around the core and in the cladding. Due to the inevitable microscopic roughness of the air-glass interfaces in the fiber, a small fraction of this light keeps being reflected at random angles while it propagates along the fiber creating narrow spectral regions of high optical loss. So, the transmission spectra of the hollow core fiber are characterized by windows of low loss separated by high loss at certain wavelengths, see Fig. 4. This contrasts to traditional optical fibers that enable transmission over a wide continuous range of wavelengths.

Modes, Cores, and Shunts

To understand light's transmission in fiber requires an introduction to the concept of modes. A mode is a distribution of light in the cross section of the fiber that doesn't change as it propagates along the length of the fiber.

There are two dominant fiber types based on how the light travels in the core: single-mode and multi-mode. The core can be designed such that only the fundamental mode of light transits, known as single-mode transmission. By increasing the core diameter and/or the refractive index, multiple modes of light can co-exist: the fundamental mode and higher-order modes.

AccuCore photonic band gap fiber has a relatively large core - 25 microns in diameter (Figure 3) - that provides freedom in how light is distributed so that multiple modes can guide. As mentioned above, the dominant loss mechanism in a hollow-core fiber is scattering at the air-glass interfaces. The fiber loss can be reduced by increasing the core diameter which has the effect of limiting the amount of light at these interfaces.

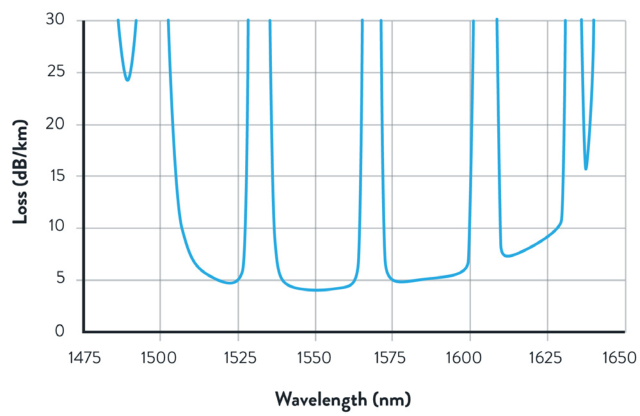

FIGURE 4: AccuCore HCF transmission windows

The disadvantage of multi-mode transmission is that each mode of light travels at a different speed. The digital information carried by the light doesn't arrive all at once but is spread over time, making data recovery harder at the optical receiver.

Higher-order modes have another undesirable effect in that small imperfections in the fiber and disturbances – such as pressure on the fiber due to compression or bending - can cause the modes to couple and exchange energy with each other. This coupling creates an echo of the original signal. Such interactions are known as multi-path interference and complicate the data recovery as the echoes are effectively noise added to the signal. More significantly, multi-path interference hinders the working of the fiber cable, as explained below.

OFS Fitel has solved the issue of multi-path interference by embedding shunts in the cladding[2]. The shunts deliberately perturb the cladding's periodic structure to increase significantly the loss experienced by the higher-order modes. The shunts act as an optical filter, stripping out the light in higher-order modes so that AccuCore is effectively a single-mode fiber. This happens at the beginning of the light's transmission; a few centimeters into the fiber, the cladding has already stripped away the higher-order modes without affecting the fundamental mode.

AccuCore's Key Characteristics

AccuCore hollow-core fiber's main characteristics are its latency, optical loss and transmission bandwidth.

Lowest Latency

AccuCore has a significant advantage in terms of speed of transmission compared to a solid-core fiber.

An electromagnetic wave, be it an electrical signal sent across a copper wire or light traveling along a solid-core fiber, is delayed when travelling through a solid medium compared to travelling in free space. Accordingly, light travels faster in the air than it does through glass resulting in hollow-core fiber having a lower latency. Latency is defined as the time it takes a signal, once sent, to begin arriving at the destination.

The relative speeds of light in hollow-core and glass-core fiber is determined by the ratio of their respective refractive indexes. The refractive index of AccuCore isn't quite the 1.0 of air because a small portion of the light travels through the cladding's glass. The difference, however, is tiny; the effective refractive index of hollow-core fiber is marginally greater than 1.0. Light travels about 50 percent faster in hollow-core fiber than it does in traditional glass fiber, as shown in Figure 5.

FIGURE 5: The speed advantage of light through a hollow-core fiber compared to glass fiber is **1.5 microseconds per km**

AccuCore fiber has a 31 percent latency advantage compared to glass fiber. However, it comes at the expense of a higher optical loss and a limited transmission bandwidth.

[2] *J.M. Fini et al., "Low-loss hollow-core fibers with improved single-modedness", Opt. Exp., 21, 6233 (2013).*

Optical Loss

The AccuCore fiber has an optical loss specified conservatively at under 7dB-per-kilometer (dB/km), notably higher than the 0.2dB/km of solid-core fiber. The solid-core fiber loss figures come after 30 years of production; the AccuCore fiber's loss figures will also improve over time as production volumes increase.

Solid-core fiber's loss is caused by the scattering of light in the core. Density fluctuations in the glass cause small changes in the refractive index which act to scatter the light. In hollow-core fiber, the loss is caused by surface roughness at the air-glass (core-cladding) interface as mentioned above.

Transmission Bandwidth

Solid-core fiber transmits light across a much broader range of wavelengths compared to photonic bandgap hollow-core fiber. The transmission bandwidth of traditional single-mode fiber is from 1,250 to 1,750nm although only certain 'windows' across the spectrum are used. For telecom, the C-band (1,532-1,565nm) is used although some telecom operators also use the L-band (1,565-1,625nm) to more than double transmission capacity. For datacom, such as linking equipment in the data center, the O-band (1,260nm to 1360nm) is used.

AccuCore cable has a much smaller transmission window and is designed to operate within the C-band, resulting in a transmission window approximately 20nm wide (See Fig. 4).

OFS Fitel can design photonic band gap hollow-core fiber with other transmission windows.

Optical Fiber Cabling

OFS is the first company to provide a cabled, hollow-core fiber from tens of meters to several kilometers long. An optical cable packages the fiber for deployment, with each fiber covered with an opaque plastic sheath. Cabling hollow-core fiber is as complicated as designing the fiber. That is because cabling changes the fiber's behavior to a degree that the fiber may not even work.

To understand why this occurs, it is important to realize that hollow-core fiber behaves differently when wrapped on a spool than when it is cabled.

Fiber on a spool is wrapped repeatedly over itself. Such layering compresses, bends, and stretches the fiber, causing a significant disturbance. Optical fiber cable, on the other hand, is designed to protect the fiber from such external disturbances, so the amount of compression, bending and stretching can be greatly reduced.

To recap, multi-path interference arises when a portion of the signal couples back and forth between modes of light. Disturbing the fiber causes refractive index changes and induces coupling when the effective indices of two modes match. Although not all modes couple with each other, when the fundamental mode couples to a higher-order mode, part of its light propagates in the higher-order mode before coupling back or reaching the detector. The result is that part of the signal is delayed while travelling along the higher-mode path because the modes have different speeds. When the delayed light couples back to the fundamental mode or reaches the detector, the signal is indistinguishable from noise.

Spooled fiber experiences such a strong disturbance that the higher-order modes are actually stripped out of the fiber before they have a chance to accumulate a significant time delay. As a consequence, modal interference is not significant in a spooled fiber as it is in a cabled fiber, where the reduced disturbances lower the loss of the higher-order modes and thus increase the impact of their more significantly delayed contributions. In essence, hollow-core fiber is highly sensitive to disturbances making practical cabling a challenge.

The ideal approach is to avoid modal interference altogether. But that isn't possible in practice, so the next best thing is to increase the loss experienced by the higher-order modes to stop coupling arising. This is what OFS's fiber does: the shunts visible in Figure 3 provide a pathway for the higher order modes to leak out of the fiber even when protected in a cable. AccuCore fiber attenuates the higher-order modes such that multiple-path interference is mitigated, making OFS the first company to sell long lengths of cabled hollow-core fiber.

Hollow-Core Fiber Applications

AccuCore fiber is ideal for applications where minimizing the data's transmission time is paramount. High-frequency trading, where computer algorithms execute stock transactions in fractions of a second, is one such application.

High-frequency traders have long sought ways to trim the time it takes to complete a transaction to gain an edge on fellow traders. They have cut the time required to execute the trading algorithm by using specialist hardware such as field-programmable gate arrays (FPGAs), and by writing algorithms in assembly language code. Assembly code is the unique low-level language of a processor; it runs faster on the processor but requires specialist skills to code.

High-frequency traders employ microwave radio links to streamline the network connection to a trading exchange's computers. Microwave links are simpler to deploy than laying optical fiber across a city and also have a lower latency. Radio links span up to 100km and can deliver a gigabit of data, sufficient capacity for the trading data.

In his book, *Flash Boys: A Wall Street Revolt*, Michael Lewis mentions how a straight-line optical cable link was planned to connect Chicago to New York to reduce latency for high-frequency trading. Since then, numerous microwave links have been built to lower delay.

One remaining part of the network where high-frequency traders can trim latency is the last-mile connection between the microwave tower and the data center hosting the trades. It is here that low-latency hollow-core fiber trounces glass fiber.

The fiber has also been considered for high-frequency trading by spanning lakes and for short subsea links such as crossing the English Channel. But such deployments are costly and are a challenge to achieve a return on investment.

Data Center Deployments

In a regulated stock exchange, the data center must ensure equal transit time for all high-frequency traders; a slightly shorter latency would benefit a trader. Exchanges deliberately add delay to those customers that are closer to the trading

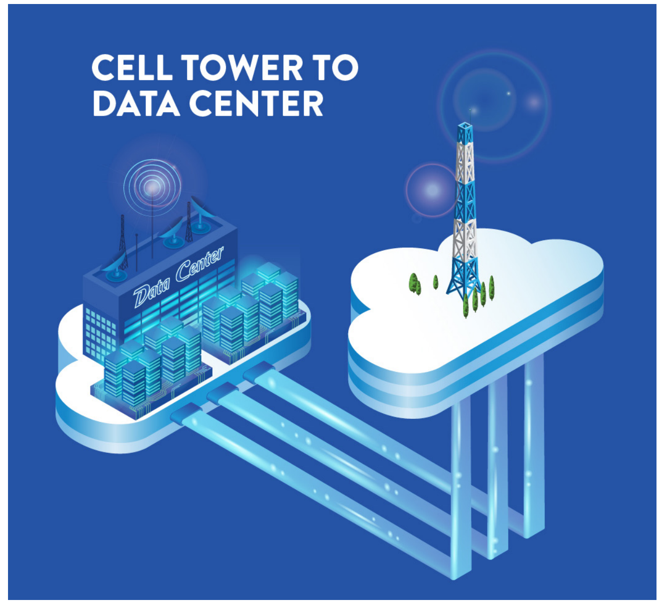

FIGURE 6: AccuCore for tower to datacenter connectivity, an application hollow-core fiber trounces glass fiber.

hardware to ensure that competing traders further away are not disadvantaged. Stock exchanges also guarantee a maximum latency for all. By deploying hollow-core fiber, the data center's floor size can be doubled while still meeting the exchange's latency limit.

Hollow-core fiber can be used for other applications in a datacenter. The largest datacenters deploy up to 100,000 servers and 50,000 switches. The servers account for half of the data center's capital expenditure and half its operational costs. Server hardware is not fully utilized since workloads never map onto the servers with maximum efficiency. The servers are also input-output constrained, meaning part of the time the CPUs are idle awaiting data to process. Hollow-core fiber with its lower latency improves the data feed to the servers.

That said, hollow-core fiber is much more expensive than solid-core fiber and data center operators dislike managing a mix of fibers. But for niche applications, such as specialist high-performance computers as used by government agencies, hollow-core fiber is justifiable. Improving the computational performance of costly supercomputing platforms using low-latency fiber makes economic sense.

Other Photonic Band Gap Hollow-Core Fiber Attributes

Hollow-core fiber has two other performance attributes that distinguish it from glass fiber: it is much less susceptible to non-linear effects and it has a lower phase sensitivity. Such characteristics are useful and exploitable.

Non-linear effects occur when high intensity light is put into a fiber. Sufficient intensity affects the fiber's properties, changing the core's refractive index and causing scattering effects. This limits the light power that can be carried by a solid-core fiber. Non-linear effects in hollow-core fiber are much lower due to the core being of air. Accordingly, much higher power levels can be put into the fiber. This can be used to boost the signal-to-noise ratio of a signal and the fiber can be used as a power lead. For example, if the location of an optical amplifier is such that electrical power can't reach it, hollow-core fiber can act as an optical power conduit to the amplifier. Note a hollow-core fiber with a low-loss transmission band for the pump laser is required. Also, care is needed when using high power with cables: in terms of the importance of cleaning the fiber and connectors and the health-and-safety aspects of working with powerful electromagnetic radiation.

The latency of a hollow-core fiber has a lower sensitivity to temperature changes than a glass fiber and this suits applications where latency (or phase) change is critical. Light is an electromagnetic wave and is comprised of frequency and amplitude. Each frequency component has a phase between 0 and 360 degrees. The phase of an optical wave is the relative position of two or more optical waves of the same frequency.

With environmental changes such as a rise in temperature, the fiber will lengthen and slightly increase its cross-sectional area due to the volumetric expansion of the fiber and cable. These increases are extremely small, but the wavelength of the light used is also very small.

The result is that the temperature increase changes the latency (or phase) of the light at the end of the fiber in two ways. Once via the increase in length and once via the increase in diameter. In the case of photonic bandgap hollow core fibers, unlike solid core fibers, both phase changes can compensate each other, leading to a near-perfect insensitivity of the latency with respect to temperature changes at certain discrete wavelengths.

Phased-array radars use an array of emitters. The phase of each emitter is changed to steer the radar's beam. For such radar technology, the control electronics can be hundreds of meters from the mesh of radio emitters, with each one connected with a fiber. Since the radar's accuracy is dependent on phase, using hollow core fiber minimizes the environmentally induced phase changes each emitter experiences.

Hollow-Core Fiber Transmission Link Design Considerations

Several design issues must be considered when deploying AccuCore fiber. The scenarios include the optical wavelength count sent over the hollow-core fiber and whether optical amplification is required.

Typical data transmissions rates using hollow-core fiber are 1 or 10 gigabits-per-second (Gbps). Higher data rates are possible but for high-frequency trading, one-gigabit capacity is sufficient. In turn, transmission distances are up to 2km although longer spans of hollow-core fiber can be deployed.

Optical loss defines the transmission distance possible using a fiber. The optical receiver has a certain sensitivity and if the received signal is weak enough that it is below the sensitivity threshold, it is not recoverable. Noise is another channel impediment impacting the channel's performance.

Single-Wavelength Links

The important parameters for an unamplified optical link are the optical transceiver's transmitter power and the receiver's sensitivity. The required transmitter power can be determined by summing the losses (in decibels) of the elements in the link and adding the total to the receiver's sensitivity. The goal is to ensure that the signal received exceeds the receiver's sensitivity so that it is recoverable. A typical optical link design is used as an example.

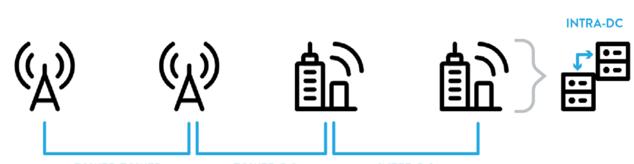

FIGURE 7: AccuCore is applicable for tower to tower, tower to datacenter, intra-datacenter, and inter datacenter today.

AccuCore cable, as mentioned, has a specified loss of under 7dB-per-km. This is a conservative figure since the loss of the fiber in practice is 5dB/km. The two end-connectors of the fiber introduce more loss, each adding 2.5dB. The standard connectors have a small length of solid-core fiber and are designed to be spliced to the hollow-core fiber while achieving a low-loss connection. OFS's fiber design and splicer machine programs ensure robust (mechanically sound) low-loss splices. OFS offers splicing technology and fiber design technology as discussed in the bottom section, OFS's specialty-fiber support services

A 1km cable thus has an assumed loss of 10dB (5dB/km of the fiber and 5dB for the connectors), while a 2km link has a 15dB loss (10dB for 2km of fiber and 5dB for the connectors). A safety margin is also added for environmental changes the cable may experience such as temperature and stress as well as an end-of-life margin to account for any aging the cable may experience. A transceiver with an output power of 0dBm and a power budget of 20dB means the receiver's sensitivity should accommodate 15dB of cable and connector loss while providing an ample safety margin of 5dB for changes the fiber may experience.

Wavelength-Division Multiplexing Links

Sending two or more wavelengths, the considerations are similar to the single-wavelength case: the transmitter power is determined by summing up the losses along the link and adding the safety window on top so that the received signal exceeds the receiver's sensitivity. The difference when sending two or more wavelengths from the single-wavelength example is that an optical multiplexer and demultiplexer are needed to combine and separate the wavelengths at the fiber's ends. The multiplexer and demultiplexer each add a loss of between 2 and 5dB such that the overall link budget is increased by between 4dB and 10dB overall. The multiplexer and demultiplexer technology can be chosen to reduce the loss if needed. The receiver sensitivity should be at least -24dB assuming a 2km cable, connectors and optical multiplexing and demultiplexing, and a 0dBm transmitter power.

OFS detailed a multiple-wavelength transmission demonstration using AccuCore cable in a post-deadline paper at OFC 2020[3]. Ten-gigabit dense wavelength-division multiplexing (DWDM) direct-detect signals were sent over 3.1km of hollow-core fiber cable. The 3.1km link was made by combining several cascaded hollow-core strips. The demonstration showed a successful, error-free transmission of 33 wavelengths each modulated at 10-gigabit per second.

For applications such as high-frequency trading, a single wavelength is sufficient for the typical data rates. But hollow-core fiber has significant capacity for future growth with DWDM technology.

Other Link Design Considerations

Using light to transmit data, there is always a probability of a bit error occurring at the optical receiver. For data rates of 1 and 10 gigabits-per-second sent over short distances such as 2km, the bit error rate is negligible (1 in 10^{15}). The probability of error increases, however, when higher transmission rates and optical amplification, a source of noise, are used. For such links forward-error correction (FEC) techniques are needed.

Appending additional bits to the transmitted data and using FEC techniques, bit errors occurring during transmission can be corrected at the receiver. A block of data thousands of bits long needs to be received first before the error correction algorithm can be applied. This adds delay and eats into the latency advantage of hollow-core fiber. For short fiber spans, FEC algorithms introduce a sufficiently long delay that it mitigates the latency advantage of hollow-core fiber. For a span of cable 0.5-2.0km, the FEC delay introduced is 2.5-10 microseconds.

Amplification[4] is needed when the optical losses are higher than the link budget. But adding amplifier stages along the link introduces latency, system noise and increases the bit-error rate. With traditional glass fiber, terrestrial amplification stages are added every 80-100km. Given the much higher loss of hollow-core fiber, amplification is needed for much shorter spans, making deployments more complicated and costly in terms of installing and powering the amplifiers and operating them.

[3] *B. Zhu et al., "First Demonstration of Hollow-Core-Fiber Cable for Low Latency Data Transmission", OFC 2020, paper, PDF Th4B.3, 2020*

[4] *OFS has demonstrated low-latency amplifiers for such applications.*

Adding amplification boosts the signal but adds noise and increases the bit error rate. A 10-gigabit link would need amplification after every few kilometers, but the relatively low data rate means that four or more amplification stages are possible without using FEC. For longer links, FEC is needed because of the noise.

However, the latency delay FEC introduces over such links would be excessive. Accordingly, FEC only makes sense for longer links, greater than 40km, since then the delay it introduces is a fraction of the latency savings hollow-core fiber brings i.e. hollow-core fiber with FEC will still have a notable latency advantage compared to solid-core fiber.

At 100 gigabit, dispersion effects become a factor at reaches of several tens of kilometers which increases the probability of bit errors. For the same reaches, 100-gigabit coherent technology can be used and coherent technology is a must for 200-gigabit and 400-gigabit wavelengths. Coherent technology recovers the amplitude and phase information of the transmitted signal, and since dispersion effects are linear, the information can be used to compensate for the dispersion at the receiver. Like FEC, the dispersion-compensation algorithm requires time and hence adds latency. But the latency is relatively small, 20 percent of the delay that the FEC introduces.

OFS's Specialty-Fiber Support Services

OFS Fitel offers two hollow-core fiber cables: one cable uses four hollow-core fibers while the second cable type is a mix of two hollow-core and two solid-core ones. OFS can make a cable with different fiber-pair numbers for custom requirements, but its current offerings serve market needs.

OFS provides ready-made connectors, a standard connector that is spliced onto the hollow-core fiber. The company says standard connectors from other suppliers can be used but its connectors guarantee the low losses specified. OFS recommends and even sells a fusion-splicing machine to splice two fibers or to add the connector to the hollow-core fiber. OFS has devised a program that optimizes the fusion-splicing of the Fitel machine but stresses other manufacturers' machines can be used.

OFS works with clients to define the solution they need for a given link. OFS divides orders into two: a standard order such as a 10-gigabit single channel over a 1km link and what it calls engineered solutions that are custom designs. OFS will review the design requirements for a custom request and recommend the components needed.

The OFS installation team can visit the customers premises worldwide and install the AccuCore cable. OFS' expertise in characterizing hollow-core-fiber cable means it will guarantee the installed cable meets the specification agreed.

Summary

- Hollow-core fiber has a 31 percent lower latency that traditional solid-core fiber.
- Applications for the specialty fiber include high-frequency trading, datacenter connectivity, and military applications such as radar.
- The fiber supports data rates of 1 and 10Gbps without FEC. If FEC is needed, for example if amplification or higher data rates or both are used, it can only be used for longer fiber spans, 40km and greater.
- OFS Fitel provides support services for its cable including connectors, splicing machines, link design verification and installation.

About OFS

OFS Fitel was formed in 2001 after its parent company, Furukawa Electric Company, bought the optical fiber division of Lucent Technologies, including Bell Labs, the renowned research and development lab of AT&T. Bell Labs was part of Lucent Technologies at the time after AT&T's monopoly of the U.S. telephony business was broken up.

OFS started work on hollow-core fiber in 2008 as part of a U.S. government-backed project. But the company started researching the fiber earlier. OFS is the first company to sell longer spans of cabled hollow-core fiber.

DAVID J. DIGIOVANNI is CTO of OFS Fitel and President of its central research arm, OFS Laboratories. Dr. DiGiovanni received his Ph.D in 1987 and began his professional career at AT&T Bell Labs in 1987 working on design and fabrication of erbium-doped optical fiber. He has worked on and managed many areas of optical fiber technology, including design, fabrication and application of fibers for telecommunications, high power lasers and sensors. These activities have resulted in a wide array of technical publications, patents and new products.

DARYL INNISS is Director, New Business Development at OFS Fitel, LLC. He was formerly Components Practice Leader (i.e., Director) at market research firm Ovum and RHK and recently co-authored Silicon Photonics (Morgan Kaufmann, 2016). Daryl has been in the telecom industry for over 30 years. He was Technical Manager at JDSU and Lucent Technologies, Bell Laboratories. Daryl started his career as a Member of the Technical Staff, AT&T Bell Labs and holds a PhD in Chemistry from UCLA and an AB from Princeton University.

TRISTAN KREMP received Dipl.-Ing.(M.S.) and Dr.-Ing. (Ph.D.) degrees in electrical engineering from the Karlsruhe Institute of Technology, a Dr.rer.nat. (Ph.D.) degree in mathematics from RWTH Aachen University, Germany, and multiple awards for his work on efficient numerical algorithms for high frequency and fiber-optical simulations. Since he joined OFS Laboratories in 2008, Dr. Kremp has worked on the analysis and design of fiber-optical technologies such as hollow core fibers, Bragg gratings, distributed sensing and fiber amplifiers.

VITALY MIKHAILOV received the M. Sc. degree in optics and physics from Electrical Engineering Institute and A. F. Ioffe Institute, Saint Petersburg, Russia, in 1996. He then joined the Optical Networks Group, University College London, London, U. K., where he received the Ph.D. degree in telecommunications in 2003. He studied various aspects of high-speed fiber optic transmission systems, including advanced modulation formats, fiber nonlinearities, signal demultiplexing and routing, digital signal processing. In 2008, he joined OFS Laboratories, Somerset, NJ, USA, as a Research Scientist. He is currently working on fiber optic transmission systems, optical fiber sensors, and development of novel fiber devices.

BENYUAN ZHU is a Distinguished Member of Technical Staff (DMTS) at OFS Labs, where he currently focuses on DWDM transmission system, new fibers and advanced amplifier technologies development. He joined Bell Laboratories, Lucent Technologies in Holmdel, NJ USA as an MTS in 1999. He has authored/coauthored +200 journal/conference papers, one book chapter, and held 25+ US patents, He has served as technical program committee (TPC) members or TPC chairs for the conferences of OFC, IPC, ACP. He also served as Associate Editors of the IET *Electronics Letters*, OSA *Optics Express* and IEEE *Journal of Quantum Electronics*. Benyuan Zhu received Ph.D. degree in Physics from Bath University, UK in 1996.