Testing Hollow Core Fibers (HCF)

Introduction

Hollow Core Fibers (HCF) are a specialized type of optical fiber designed to guide light through an air-filled central core, unlike conventional single-mode fibers (SMF) that use a solid glass core. This air-guided structure significantly reduces the interaction between light and the fiber material, resulting in several performance advantages.

Among the key benefits of HCF are:

- **Lower latency:** HCF transmits light at nearly the speed of light in vacuum, resulting in latency of approximately 3.33 μs/km, compared to 4.9 μs/km for SMF
- **Reduced chromatic dispersion (CD):** HCF typically exhibits CD values around <5 ps/nm/km, while SMF shows ~17 ps/nm/km
- **Equivalent polarization mode dispersion (PMD):** HCF can achieve equivalent PMD values below 0.1 ps/√km, compared to 0.1 ps/√km for SMF
- **Reduced nonlinear effects:** Due to minimal light-material interaction, HCF exhibits negligible nonlinearities
- **Lower attenuation at specific wavelengths:** Recent advancements have achieved attenuation as low as 0.07 dB/km, outperforming typical SMF values of ~0.2 dB/km
- **High damage threshold:** The air core allows HCF to handle higher optical powers without thermal damage

However, HCFs also present certain challenges. Their fabrication is complex and requires advanced techniques, which contributes to higher costs. Some designs may have limited bandwidth, and the fibers themselves can be more mechanically fragile than standard glass fibers.

Challenges in Qualifying HCF Installations

Deploying Hollow Core Fiber (HCF) introduces a unique set of challenges that differ significantly from conventional SMF installations. Proper qualification requires adapting both tools and procedures to account for the distinct physical and optical properties of HCF.

1. Attenuation Profile

Attenuation profile testing helps identify non-ideal transmission characteristics such as absorption regions caused by water vapor for example, factors that can impact system reliability and efficiency. During manufacturing presence of gas could generate degassing process creating absorption at certain wavelengths. Field trials have shown that some customers request this data to assess link quality and verify performance claims. In this context, attenuation profiling is not just a technical formality, it is a necessary step to build confidence in HCF deployment and to support informed decision-making in real-world applications.

Unlike conventional glass fibers with well-established and consistent spectral attenuation profiles, HCF are still in the early stages of industrial development. Variations in design, manufacturing processes, and materials across vendors may result in significant differences in attenuation behavior. As a result, post-installation testing of the attenuation profile becomes essential to validate the actual transmission capacity of the link, confirm manufacturer specifications, and ensure compatibility with system requirements. This is especially important in applications where wavelength-specific performance is critical.

2. CD/PMD

HCF are designed to transmit longer distance and higher speed therefore dispersion could have an impact on future upgrade of transmission rate, knowing the real base line is important. Even though dispersion effects are much lower in HCF versus SMF there is a risk of inconsistency as new HCF manufacturing processes are established, validation of CD and PMD parameters ensures nothing unexpected has occurred after splicing all HCF sections together.

3. SMF-to-HCF Adapter Loss

Transitioning from SMF to HCF introduces coupling inefficiencies due to mismatched mode fields and core geometries. Adapter losses can range from 0.2–3 dB, depending on alignment precision and connector quality. These losses must be carefully measured when commissioning a link. The transition from glass to air also generates a high reflection of up to -15 dB when not properly done, this will be a challenge for an Optical Time Domain Reflectometer (OTDR), it will generate tailing on the trace and may mask some events close to this first connection. It is important to control this first adapter and ensure reflection as low as possible: better than -50 dB.

4. Bend Sensitivity

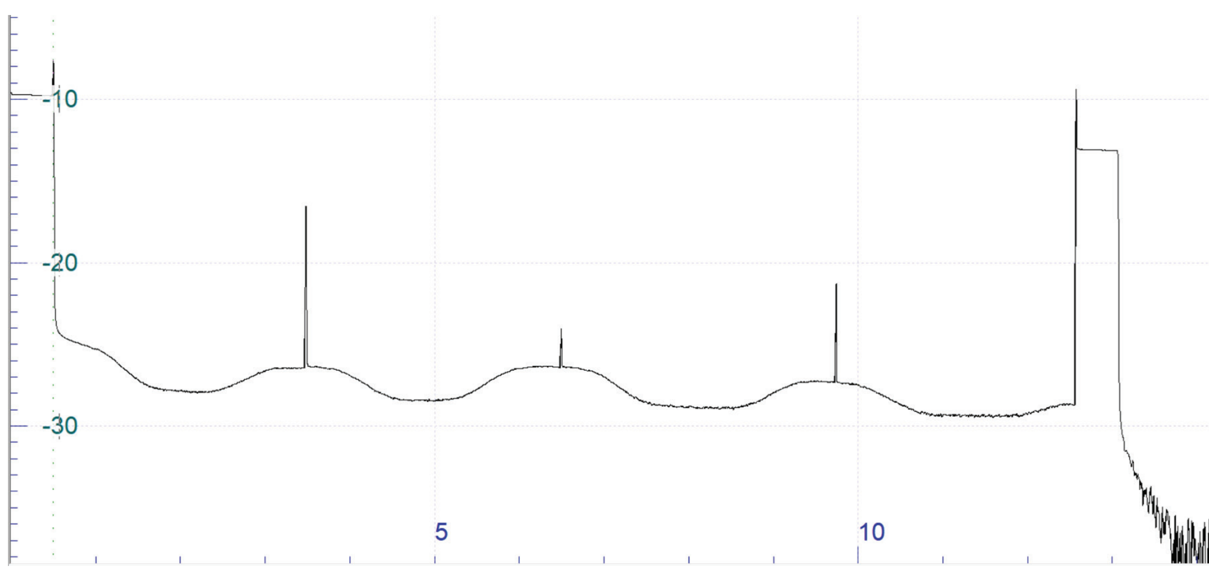
HCFs are 10× more sensitive to bending than SMFs due to their complex micro structured design and air-core geometry. While SMFs can tolerate bend radius as low as 7.5 mm, HCFs often require minimum bend radii of several centimeters to avoid excessive attenuation or structural damage. This makes HCF less suitable for tight routing environments unless specifically engineered for bend tolerance. Installers must ensure proper routing and strain relief to maintain performance.

5. Rayleigh Backscattering (RBS)

HCF exhibits RBS levels approximately 14 to 20 dB lower than SMF. This significantly affects OTDR trace visibility, making it harder to detect events and measure distances with standard OTDR settings.

6. Variable Backscattering Coefficient

Unlike SMF, where backscattering is relatively uniform, HCF may show non-uniform backscattering along the fiber length due to microstructural variations. This complicates OTDR trace interpretation and requires different test settings than for SMF (K factor). Variable backscatter coefficient also means that bidirectional OTDR test and analysis is the only method suitable for characterizing fiber and splice losses.



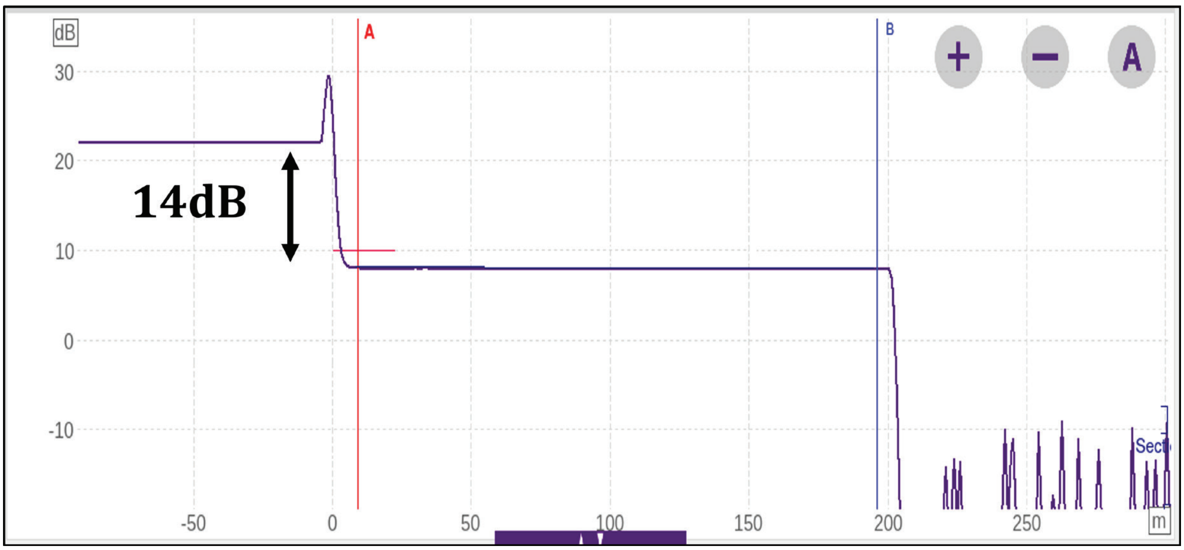
OTDR trace showing the variation of RBS coefficient and the reflective splices

7. HCF-to-HCF Splice Loss

Fusion splicing between HCF to HCF segments is more complex and can result in splice losses of 0.1–1.5 dB, depending on fiber alignment and cleanliness. Also compared to splices between SMF to SMF, HCF to HCF splices generate high reflectance which creates dead zones. In the field splices could be 2 to 4 km apart which reinforces the importance of having an OTDR with high dynamic range at short pulse widths to be able to measure each of them and not end up with merged results.

8. Non-Standard OTDR Traces

HCF produces different OTDR signatures compared to SMF. The lower backscatter (-14 to -20 dB) and unique modal behavior result in different traces: reflective splices and infiltration of ambient air components around the splice point. Standard OTDR settings to test SMF may fail to detect key features, requiring different testing parameters such as pulse width and averaging time.



Trace from a coherent OTDR measuring 14 dB difference of RBS from SMF to HCF

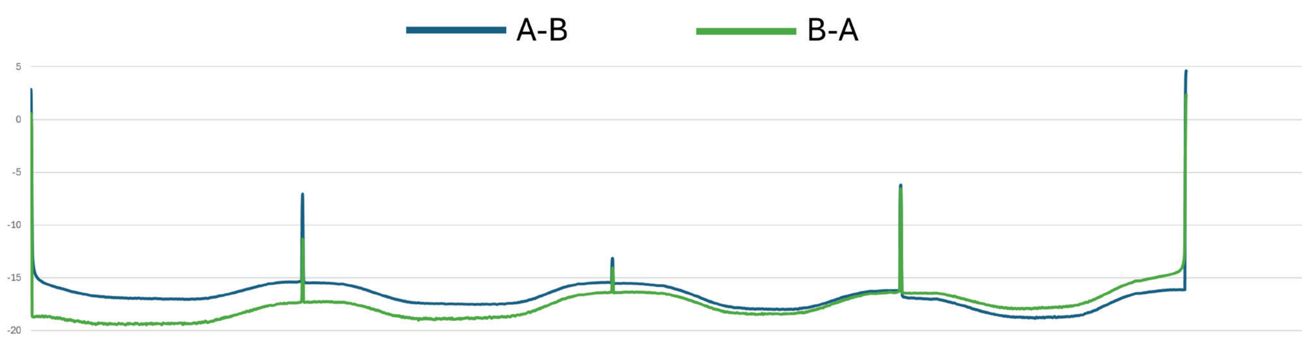
9. OTDR Test Wavelength

As of now, most HCFs are optimized for operation in the S-band (starting around 1450 nm) and above, OTDR testing at 1310 nm, as typically done with standard SMF, will not produce relevant or useful results so testing at 1550 nm is required. As with SMF testing using additional wavelengths allows for better fiber and splice loss characterization and bend detection. Therefore, at present HCF will require measurements at 1550 and 1625 nm for field acceptance testing.

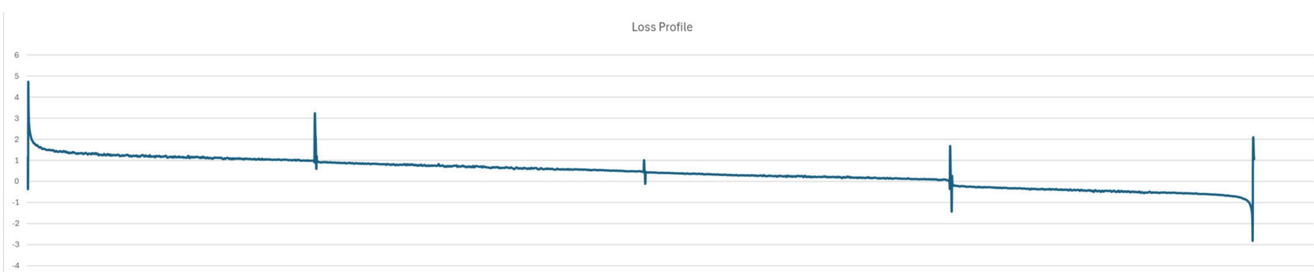
10. Post-Processing Analysis

Due to the unique trace characteristics (RBS varying along the fiber), bidirectional analysis is required but standard bidirectional OTDR post-processing analysis algorithms do not apply. Custom software or manual interpretation is often needed to create the loss profile, assess splice quality, connector loss, and fiber integrity. It is necessary to match each point/event from each direction, align the two traces and make a bidirectional analysis, (AB-BA)/2, to obtain the actual loss profile.

Loss profile trace obtained by bidirectional analysis will then allow measurement of attenuation for each HCF section and the loss of each event on a link.



OTDR traces acquired from testing HCF in both directions (A-B and B-A)



Loss profile trace obtained by performing bidirectional analysis

11. No Method of Procedure (MoP)

HCF deployments lack standardized MoPs, making each installation a bespoke process.
This increases the risk of inconsistency and requires detailed planning, documentation, and validation protocols.

12. Limited Technician Experience

Most fiber technicians are trained on SMF systems and may be unfamiliar with HCF specific handling, testing, and troubleshooting. Training programs and manufacturer support are essential to ensure successful deployment.

Selecting the Right OTDR Equipment

It is necessary to select an OTDR with highest possible dynamic range while using the lowest pulse width in order to cope with the variation of back scattering coefficient as describe above. All OTDR are specified using the maximum pulse width (20 μs with 3 minutes averaging time). A pulse of 20 μs in a standard single mode fiber will generate a minimum of 2 km tail of light (no reflection, no splices). In HCF, since the index of refraction is close to 1 for the same pulse width, it will travel 1.46 time faster so the tail of light is now close to 3 km. As an example (refer to the table below), a 40 km HCF with loss of 0.1 dB/km means a fiber loss of 4 dB. 4 splices, each with a loss of 0.2 dB, adds 0.8 dB loss. The first and last connectors, each with a loss of 0.3 dB, adds 0.6 dB totaling 5.4 dB. To make accurate measurements and reliably detect events, 5 to 7 dB of usable dynamic range is needed above the noise. Next, take into account the 14 to 20 dB difference in RBS mentioned earlier, that range now becomes 24.4 to 32.4 dB and the limit of what can be achieved with this pulse width is being approached. This means a dynamic range of between 24.4 to 32.4 dB is needed at short pulse width to characterize all events accurately.

Total fiber loss (0.1 dB/km)	4 dB
Total splice loss (4 splices)	0.8 dB
Total loss SMF to HCF adaptor (x2)	0.6 dB
Signal to noise	5 to 7 dB
RBS	14 to 20 dB
Pulse width dynamic range required	24.4 to 32.4 dB

Accurately means linear attenuation with no tailing and shortest dead zone. If an OTDR doesn't have enough dynamic range, then a longer pulse width needs to be used which means longer dead zones. If the link is longer and has more loss the maximum dynamic range may have to be used which can result in splices being merged together, preventing correct characterization.

Also, the adaptor from SMF to HCF is very challenging for the OTDR hardware and response of the photodiode (drop of RBS from 14 to 20 dB). The OTDR should have a sharp recovery after the adaptor with minimum tailing, otherwise some events could be lost in the tailing (merged in the tailing).

This is why for HCF measurement we recommend an OTDR with a minimum 45 dB dynamic range, such as the VIAVI 4100 series C module. A higher dynamic range, such as 50dB with the 8100 series D module, is preferable as using an OTDR with higher dynamic range at lower pulse width will produce better measurement results.

OTDR Testing Procedure

As with SMF it is very important to begin by inspecting all connectors: on the OTDR port and on the fiber interface. This has always been the first cause of failure in any network topology.

Within the OTDR setup first make sure the IOR is set at one (1) and the backscattering coefficient is set at the value specified by the fiber manufacturer.

Always use launch and receive fiber of the same type (and same batch when possible). The length of the receive and launch fibers always depends on the fiber length under test, in most cases 500 m should be enough, if in doubt use 1 km or more. Using the same type of launch/receive fibers ensures the same backscattering level and allows measurement of an end-to-end loss very accurately. It does not matter that there is HCF in the middle, the end-to-end loss of HCF will be accurate because the points of reference are at the same backscatter level. The difference is the loss of fiber under test, just like a power meter and light source measurement.

Connect the HCF under test to the launch and receive fibers and verify that the OTDR pulse width and acquisition time are configured to provide accurate results. The first measurement made is to correctly set up and fine tune the test parameters when there is no specific requirement in the MoP. When the right configuration has been found, it must be used consistently for all measurements in both directions (A to B and B to A). Make sure to name test result files in a suitable way to ensure they can be easily identified and matched (paired) for both directions of the same fiber.

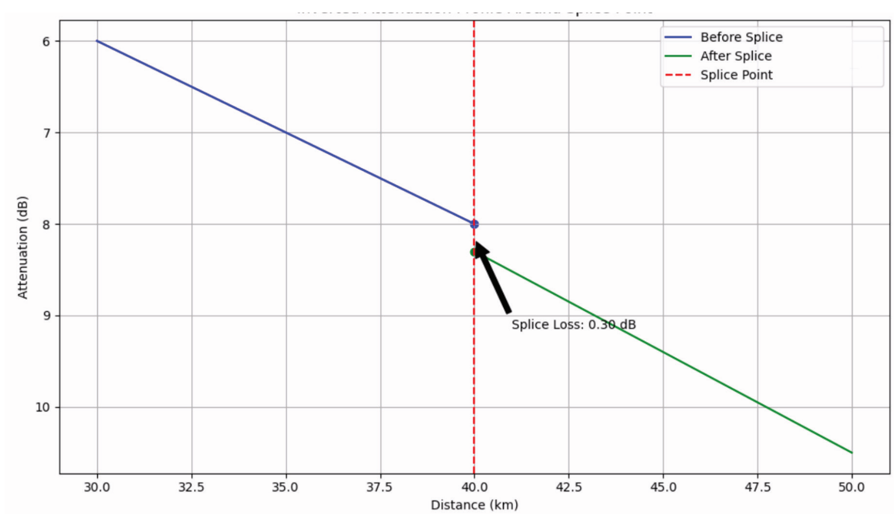
Once both acquisitions are complete, inspect each OTDR trace to verify that the end-to-end loss appears to be within acceptable limits and roughly the same for both directions, use the launch and receive fibers as reference points. If there is a significant difference between end-to-end loss this may indicate there is an issue with the fiber under test or the test setup.

Post-Processing and Analysis

At the beginning of the HCF (transition from SMF to HCF), a peak reflectance is typically observed, followed by a 14 to 20 dB drop in backscatter, this marks the start of the HCF. Similarly, at the end of the HCF (transition from HCF to SMF), backscatter returns to a higher level (14 to 20 dB), with a peak reflectance indicating the end of the HCF under test.

Event alignment is crucial for accurate analysis. Each wavelength used will produce two traces, one for each direction (A to B and B to A). Begin by reversing the B to A trace. Use the start and end points of the HCF to align the traces. If there are no splices within the HCF, this method is the only way to align the traces. If splices are present, use each splice point to refine the alignment.

To generate a loss profile, calculate the difference between the aligned traces at each point using the formula: (Trace_AB - Trace_BA) / 2. This calculation produces a new trace representing the loss profile of the HCF link. For each splice, determine the slope before and after the splice using markers. Then, calculate the loss of each segment in the form: y = mx + b. Evaluate the value of y at the splice point x for both segments. The difference between these values represents splice loss. Repeat this process for all splice points in the fiber.



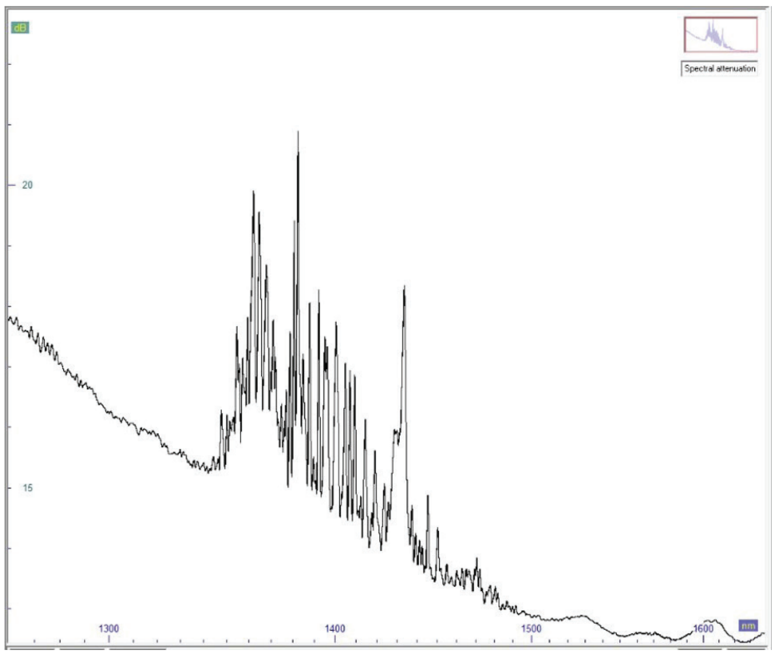
Splice Loss Calculation

Generating the loss profile is usually carried out as a post processing activity once test measurements have been completed and techs have left the installation site. It can be a very manual, time-consuming and cumbersome process. Therefore, it is preferable to get the results while the technical team is in the field so that any issues can be fixed without additional site visits. In this case the manual post processing approach described above is not practical.

To address this VIAVI have added HCF loss profile generation to the post processing software called 'ReportPRO'. By simply selecting the A to B and B to A traces the loss profile will be automatically generated. This eliminates the majority of processing time and off-site result analysis, meaning if there are any issues they can be fixed while a tech is still on site, improving workflow and efficiency.

Attenuation Profile

Various methods exist but users should opt for a solution that covers the whole spectrum range (from 1250 to 1640 nm), such that the characterization validates not only the performance of the fiber in the transmission bands but also provides the loss characteristics in the water absorption window.



Hollow core fiber attenuation profile measurement

Dispersion Tests

In addition to the OTDR tests described above, CD and PMD parameters are key attributes that will provide the complete picture (characterization) of the installed link. However, dispersion measurements based on OTDR tests will be subject to the same 14-20 dB drop in RBS and the same limitation/trade off between dynamic range and pulse width setting. As such it will significantly limit the length of fiber that can be assessed making it only suitable for short links at best.

Utilizing a dispersion test method based on an optical source and receiver, such as the VIAVI OBS-500 optical broadband light source and Optical Dispersion Measurement (ODM) module, overcomes the issue of RBS drop and enables more accurate testing over longer distances as it is not dependent on the dynamic range of the test unit and in-line reflectance like in a single ended method OTDR-based. Various methods exist, such as phase shift for chromatic dispersion or fixed analyzer for PMD that will provide accurate readings with significant dynamic range margin.

Post Deployment

The intent is that a HCF fiber will carry significantly more traffic than a SMF, as such it is even more important to know if a HCF is degraded, damaged or cut accidentally. This is best achieved by using a fiber monitoring system, such as the VIAVI ONMSi Optical Network Management System, to maintain service. There is also the possibility of protecting fiber cables from external threats by monitoring with a system based on distributed acoustic sensing (DAS) technology.

Conclusion

HCF is substantially more expensive than SMF and represents a large investment in terms of cost and deployment complexity, as such it is even more important to ensure the maximum return on investment (ROI). Therefore, in order to confirm HCF is installed properly it should be characterized completely (OTDR, CD, PMD, AP) to avoid any compromise in initial or future performance. As with deployment of any new technology it is important to make sure that it performs as expected in order to deliver the operational and business benefits.

Contact Us: +1 844 GO VIAVI | (+1 844 468 4284). To reach the VIAVI office nearest you, visit viavisolutions.com/contact

testinghcf-an-fop-nse-ae
30194611 900 1025