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First Demonstration of a Double Cladding Optical Fiber Utilizing a Graded Index Multimode Inner Cladding and a Single Mode Core for Enhancing Downhole Distributed Sensing Techniques

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ABSTRACT

A new type of double cladding optical fiber has been demonstrated utilizing a GRIN MM inner cladding and an SM core to allow DTS, DSTS and DAS within a single optical fiber. DAS and DTS results are experimentally proven possible with this novel fiber design.

Keywords: distributed sensing, DTS, DAS, DSTS, optical fiber, acoustic, temperature, dowhole

1. INTRODUCTION

Optical fiber sensor systems have been widely deployed in the oil and gas industry to aid well production through monitoring various processes to help improve extraction efficiency [1]. The most commonly deployed optical fiber sensing technique has been Raman based distributed temperature sensing (DTS) [2] on multimode fiber, which offers a direct and established interpretation of the thermal environment down a well. Over time, other optical technologies have been advancing which offer additional measurands in addition to DTS. These techniques include Brillouin based distributed strain and temperature sensing (DSTS) [3], Rayleigh based distributed acoustic sensing (DAS) [4] and fiber Bragg grating (FBG) based DSTS [5]. Whilst these technologies each present their own unique benefits, they also offer substantial synergies to other measurement techniques. For example, DSTS suffers accuracy drift as spectral attenuation and strain changes along the fiber. DTS techniques can aid drift compensation for DSTS, ultimately increasing the accuracy of DTS whilst also offering additional strain information. Unfortunately the fiber designs for each sensing technique have different requirements, thus requiring multiple fibers to enable multiparameter sensing. DTS typically requires a 50µm core diameter, graded index (GRIN), multimode (MM) fiber whilst Brillouin, Rayleigh and FBG based techniques use single mode (SM) fibers. Therefore, to enable multiparameter sensing, multiple fibers are required to be deployed down well.

Deploying optical fibers within an oil or gas well presents numerous challenges, many of which have necessitated the need to sacrifice optical measurement capabilities in order to reliably deploy the fiber(s). In an ideal world, every well would have a variety of optical fibers within it, including a mixture of SM and MM fibers to enable the maximum possible range of optical sensing capabilities. However, the practicalities of engineering conspire to limit the number of workable design options.

Two of the most commonly used methods of deploying optical fibers within a well are to pump the fiber through a capillary or to deploy the fiber within a pre-assembled cable. Pumping methods are well suited to deploying a single optical fiber and occasionally are capable of pumping two fibers. Multifiber pumping is challenging due to the increase in frictional drag presented by the additional fiber(s) and the subsequent effect on the laminar or turbulent flow of the pumping fluid through the capillary. Figure 1 uses Navier-Stokes equations to illustrate the laminar and turbulent flow that may be experienced as optical fibers are pumped through a tube. The single fiber, Figure 1a), shows drag effects around the outside of the fiber, pulling the fiber along with the pumping fluid and vortices are shown to be shed from the end tip suggesting a drag or suction force on the tip of the fiber. When two fibers are placed inside the same tube but spaced apart, Figure 1b), a similar scenario occurs, there are drag effects pulling each fiber but the chaotic turbulent flow

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created by this geometry will make the tips of the fibers move around, disrupting the pumping efficiency as the localized pressures change. If each fiber undergoes a different force, for example if one fiber strikes the outside of the tube, then the fiber tips can become separated and may lead to one fiber being preferentially pumped. In the scenario where the fibers touch, Figure 1c), the drag force effect between the fibers is lost as the liquid cannot flow past that surface and the system becomes more hydrodynamic, cumulatively reducing the pumping efficiency.

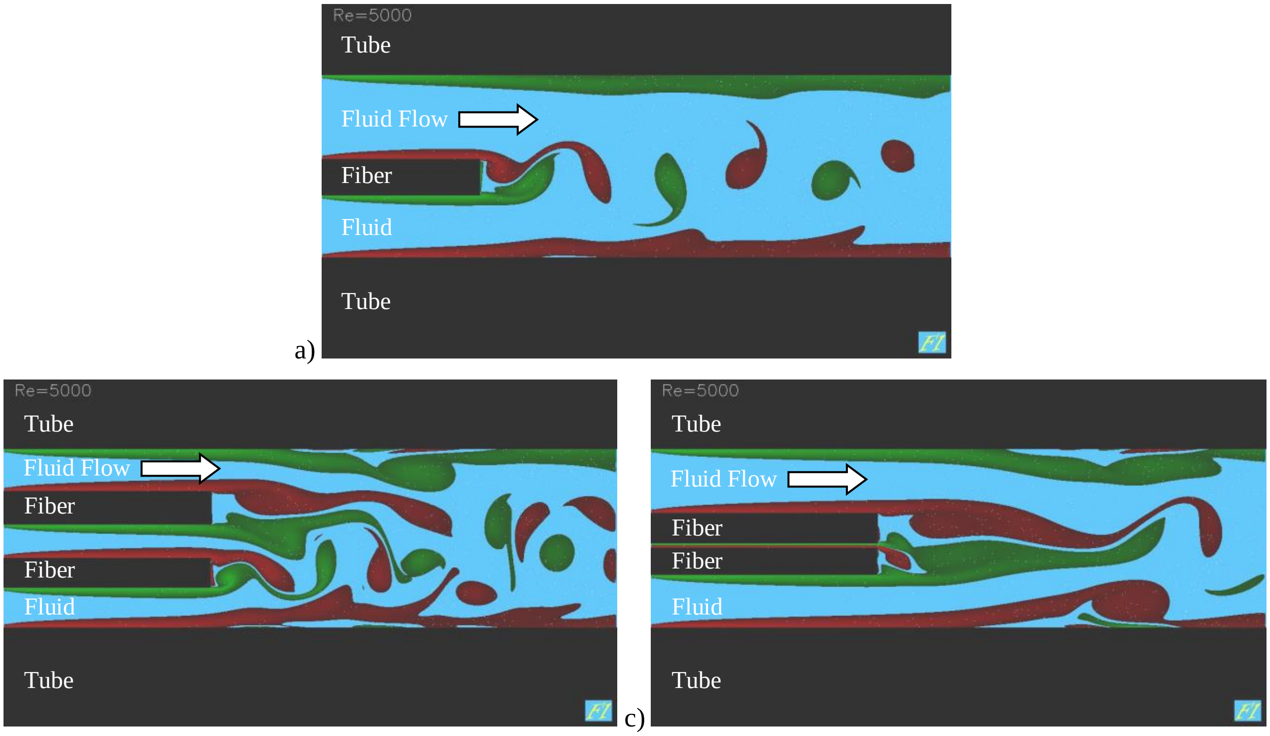

Figure 1. Illustrative representation of optical fiber pumping through a tube, based on fast solution of Navier-Stokes equations [6]. a) Single fiber, b) two fibers with a space between the two and c) two fibers in close proximity. Red colors indicate regions of high positive vorticity (rotating fluid particles) and green areas indicate large negative vorticity regions.

Due to these challenges, not all wells with fiber pumping capabilities are able to have multiple fibers deployed, limiting their sensing capability typically to a single measurand. Cables are the alternative approach where cable designs can easily integrate multiple fiber types, however, the additional cabling and fiber cost and reduction in reliability associated with a cable installation adds notable risks, costs and lead times to any cable-based fiber optic sensing deployment. Unlike pumping methods, the cable cannot be replaced easily so the associated risks with installation and increased corrosion through cable related work-hardening and handling issues drives the need for a solution to combine the benefits of a multifiber sensing design into a pumping-capable single fiber design.

Historic methods of combining multiple fibers have been attempted by fusing the glass cladding of multiple optical fibers together during the draw, creating what is known as a Gemini fiber [7]. Multicore fibers with SM cores are able to be manufactured without sacrificing the cladding diameter [8], but do not benefit from having SM and MM cores. To enable both core types, larger cladding diameters are required. Such fibers benefit from being able to mix-and-match any core glass at the preform stage but they suffer from a larger than normal diameters, increasing frictional forces during pumping and require specialized handling to break out or address each core.

2. FIBER DESIGN

To overcome the challenge of having separate SM and MM fibers, an optical fiber has been developed and manufactured that combines a telecoms style SM core within the graded index structure of a 50µm core diameter, multimode region. These cores are combined within a standard 125µm diameter glass cladding to enable simplistic stripping, cleaving and splicing. The SM core is based on a germanosilicate structure so is photosensitive to UV light, allowing FBG inscription into the core for DSTS techniques.

This combination of multiple guiding structures takes inspiration from the all-silica double cladding fiber design, SMM900, pioneered by Fibercore Limited [9], which incorporates an MM inner cladding region with an SM core but uniquely, unlike most double cladding fibers, does not rely on a low index polymer-based coating to create the MM guiding region but instead uses a lower refractive index fluorosilicate outer cladding.

As the end-use is defined as a downhole oil and gas application, where temperatures regularly exceed 180C, the most appropriate coating package is a carbon and polyimide mix. The carbon coating provides hermetic sealing [10] against both hydrogen and water ingress and the polyimide coating is the only cost effective and proven reliable optical fiber coating for prolonged use above 180C. Two different coating packages have been demonstrated, acrylate for temperatures up to 85C and carbon-polyimide for temperatures up to 300C.

This new fiber has been defined as a double cladding fiber with a ~10µm mode field diameter SM core, graded index 50µm MM inner cladding diameter, 125µm cladding diameter fiber with either an acrylate coating or a carbon and polyimide coating and given the product numbers: DCGI(10.4/50/125) and DCGI(10.4/50/125)CP, respectively. A conceptual visualization of the fiber is given in Figure 2 and the measured refractive index profile shown in Figure 3.

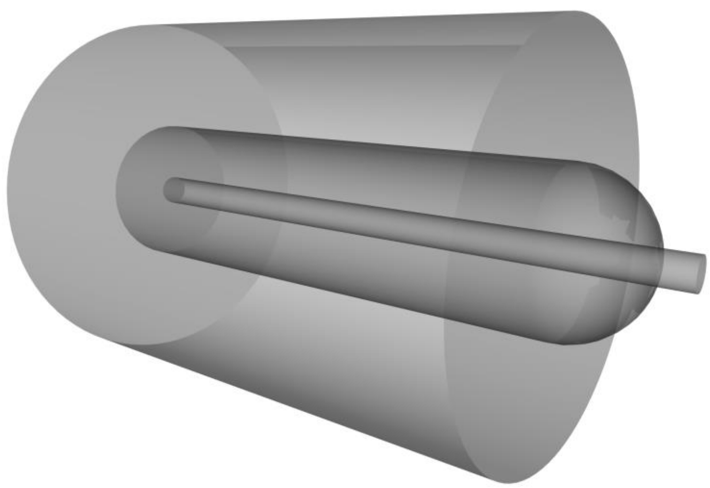

Figure 2. 3D CAD representation of the DCGI(10.4/50/125), showing the SM core, MM GRIN inner cladding and silica outer cladding. The coatings are not displayed.

The DCGI(10.4/50/125) fiber had the following measured properties:

Table 1. Optical and geometric properties of DCGI(10.4/50/125) as measured on Photon Kinetics geometry and attenuation test benches.

Parameter	Value
Attenuation – SM Core @ 1550nm	0.54 dB/km
Attenuation – MM Core @ 850nm	3.44 dB/km
Attenuation – MM Core @ 1300nm	1.59 dB/km
Cladding Diameter	125 µm
Coating Diameter - Acrylate	245 µm
SM MFD	9.6 µm
SM NA	0.12
MM Inner Cladding Diameter	51.5 µm
MM Inner Cladding NA	0.23
Proof Test	1 %

The fiber has also been demonstrated with a larger GRIN region at 62.5µm inner cladding diameter and given the product number DCGI(10.4/62.5/125).

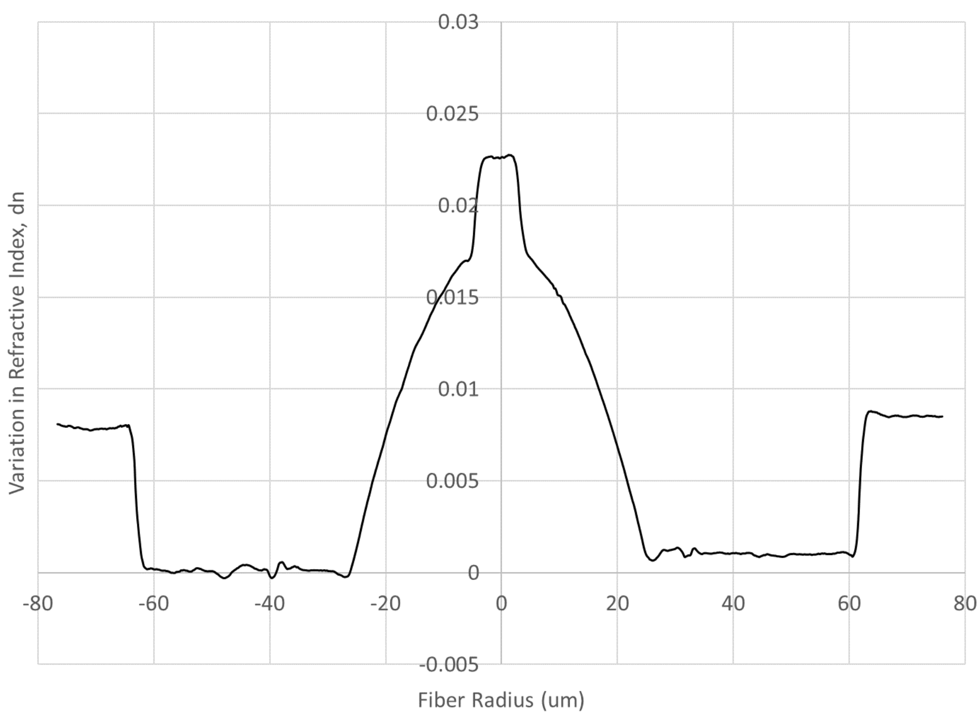

Figure 3. Refractive index of the DCGI(10.4/50/125) measured on an S14 refractometer.

3. DISTRIBUTED TEMPERATURE AND ACOUSTIC MEASUREMENTS

Utilizing an AP Sensing N4586A Raman DTS system and an AP Sensing N5226A Rayleigh DAS system, the fiber was tested for suitability to allow both DTS and DAS measurement techniques.

Due to the novel double cladding structure, there currently is no optimized component for coupling in the SM and MM light from one direction. Subsequently, a 2+1x1 pump combiner from Lightcomm was used to attempt single-ended measurements, Figure 4b). Due to high insertion losses and high Fresnel reflections associated with the non-optimized designed of the pump combiner, DTS measurements were not possible in this configuration so measurements were also made from each end of the fiber, Figure 4a).

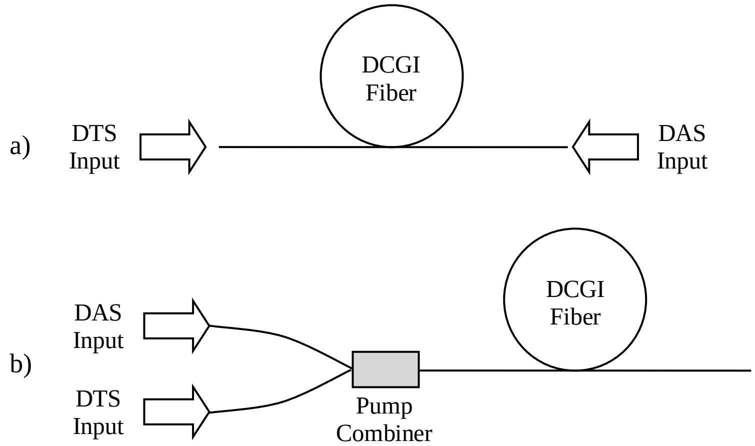

Figure 4. Experimental layouts for a) dual-ended measurements and b) single-ended measurements.

Figures 5 and 6 show the attenuation and DTS plots from the DCGI fiber, tested within a laboratory environment with the dual-ended setup, shown in Figure 4a), whilst the fiber was mounted on a large diameter spool. Before the DCGI fiber, a 1km spool of standard MM fiber is used as a comparison. The DTS plot displays normal room temperature results and appears well calibrated with the generic MM fiber result at the splice point. This shows that the fiber does not cause a notable impact on calibration and can be used as a drop-in replacement.

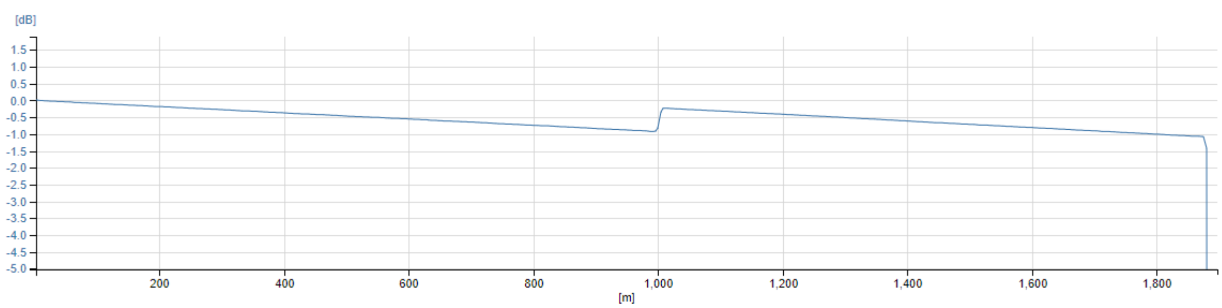

Figure 5. Attenuation plot at 1064nm from the AP Sensing N4586A DTS system showing 872m of the DCGI fiber after the 1,000m point.

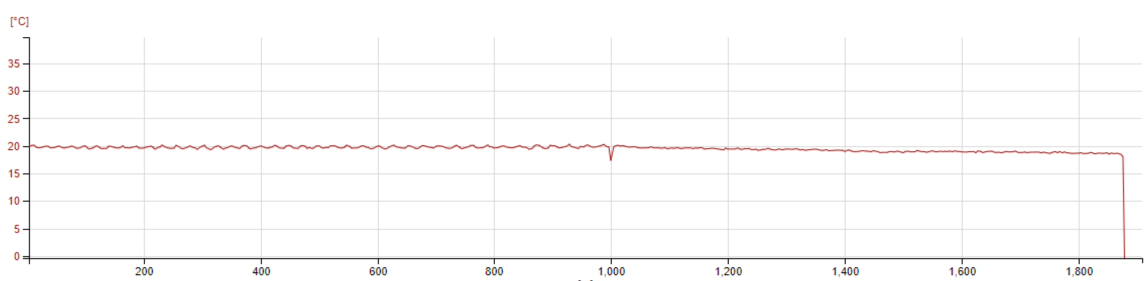

Figure 6. DTS plot at 1064nm from the AP Sensing N4586A DTS system showing 872m of the DCGI fiber after the 1,000m point.

DAS results from the SM core were obtained using the AP Sensing N5226A Rayleigh DAS system operating at 1550nm, shown in Figures 7 and 8. Preceding the DCGI fiber was a 1.1km length of SM fiber. A low frequency acoustic signal was supplied by tapping the spool 10 times whilst the location, optical DAS signal and time was logged, as shown in Figure 7. The central location of the acoustic signal is measured around 400m into the DCGI spool.

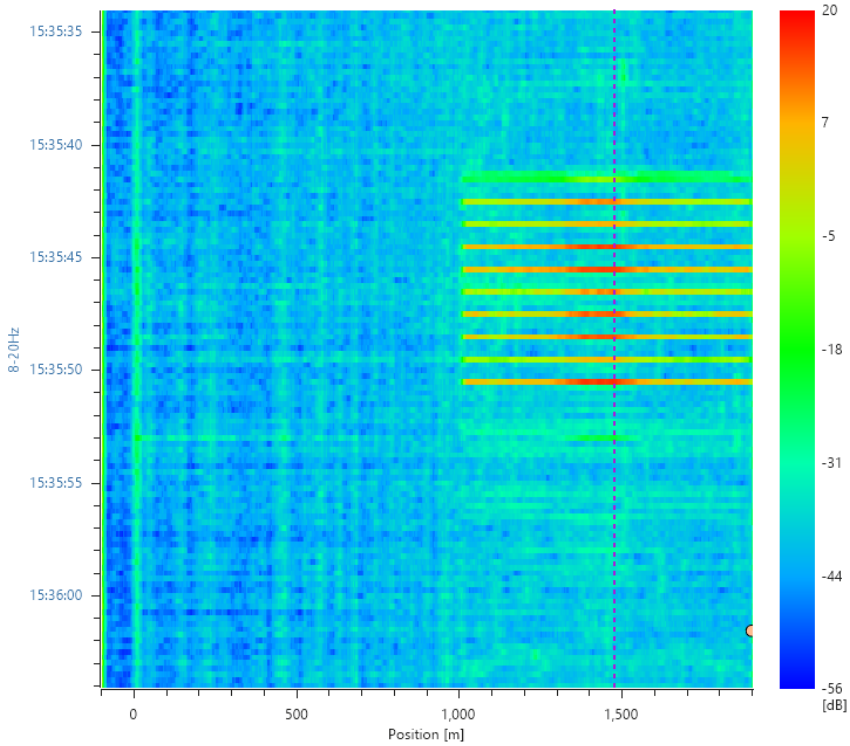

Figure 7. Waterfall plot of the generic MM fiber’s (first 1,000m) and DCGI fiber’s (>1,000m) DAS response within the frequency range of 8-20Hz over a duration of 30 seconds.

High frequency measurements were achieved by placing the spool on a vibration plate vibrating at 172Hz, as shown in Figure 8. A clear strong DAS signal was achieved, far above the noise floor and correctly registering the 172Hz acoustic impulse. The DAS experiment demonstrates the DCGI fiber’s ability to be used within fiber optic DAS systems.

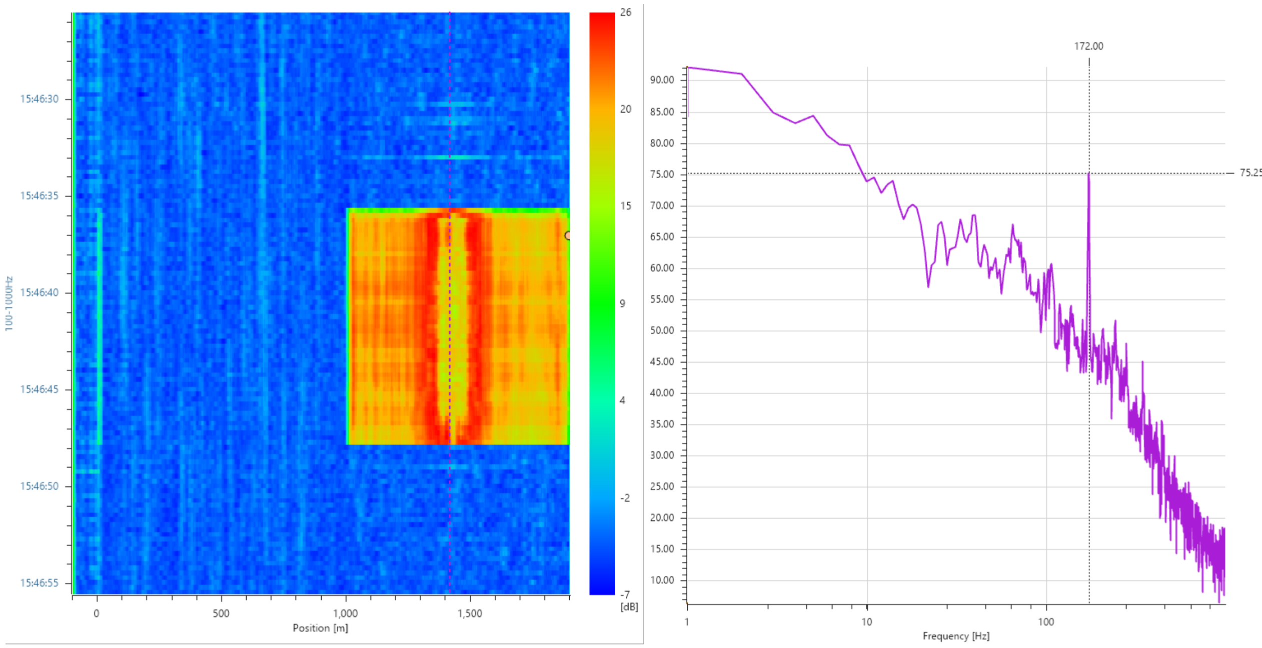

Figure 8. High frequency DAS test using a 172Hz vibration plate, showing the spatial and time response (left) and frequency response (right).

Due to the inability to gain single ended DTS results through the pump combiner, an Exfo MM OTDR was used to investigate the losses in the configuration shown in Figure 4b). The distributed Rayleigh scattering of the MM core was measured at 850nm and 1300nm, Figure 9. The results display non-linear attenuation, likely due to mode stripping of the higher order modes which are loosely guided within the outer regions of the graded index MM core. This additional attenuation is to be expected as the pump combiner has multimode fiber with a 105µm step index core diameter which does not match the OTDR's 50µm step index pigtail or the DCGI's 50µm graded index MM core. To create an ideal experiment, an optimized pump combiner would have 50µm GRIN MM fiber in the pump arm and the launch conditions would be more accurately controlled. Despite the non-ideal setup, distributed Rayleigh scatter is measured, suggesting that with component development, single ended DAS and DTS measurements should be possible, raising the possibility of simultaneous DAS and DTS acquisition.

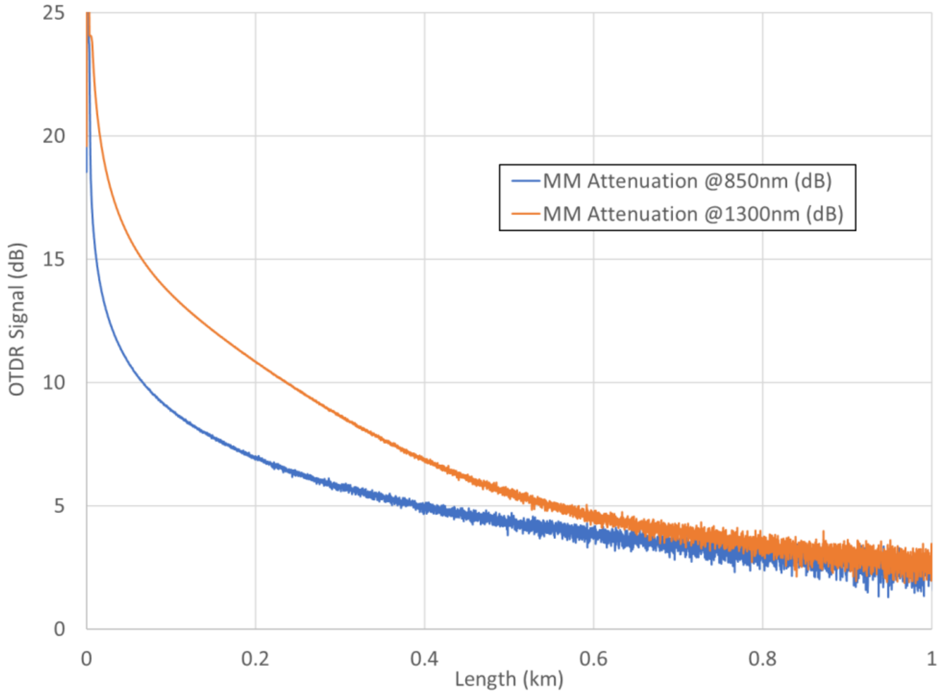

Figure 9. Distributed Rayleigh scattering of the MM core measured using an Exfo OTDR launched into the pump combiner.

4. CONCLUSION

An optical fiber has been designed, developed and manufactured which meets the needs of the oil and gas industry for a multifunctional fiber that combines the glass structures of an SM core and GRIN MM region to enable multiparameter sensing measurements of DTS and DAS techniques within a single monolithic design, without necessitating the requirement for a larger fiber cladding diameter.

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