LARGE AREA, ULTRA-LOW LOSS, TRENCH-ASSISTED FIBER WITH L-BAND EDF ENABLING FUTURE C+L BAND SUBMARINE CABLE SYSTEMS

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Abstract: Fibers with ultra-large effective areas of 153 µm^2, have been successfully qualified in submarine – and terrestrial – cables, with performance suitable for operation in both C and L-bands. To achieve this, a trench-assisted fiber design that minimizes bending losses has been realized in a silica-core material system to achieve ultra-low losses. The fiber design allows for production with draw-speeds that ensure large volume capacity. Some hundreds of megameters have been produced. An L-band EDF optimized for trans-oceanic application has also been realized.

The current thrust in the industry to increase capacity, and reduce cost-per-bit, in a power-efficient way is to increase the fiber pair count in subsea cables (referred to as space division multiplexing, or SDM). It is envisioned that the technologies described in this paper may be a useful adjunct to SDM several years from now, since it would allow one to increase capacity while maintaining the same cabled fiber count and fiber cost, requiring only an increase in the number of amplifiers in the repeater bottle. Whether C+L band with SDM is the lowest cost-per-bit in two to three years will depend on multiple factors not yet quantified. Importantly, the design principles described in this paper apply not only to ~150um2 effective area fibers, but also to lower effective area designs such as 125 and 80 µm^2 that are expected to be deployed as fiber packing density in cables increases.

The optimized design results in very moderate excess loss in the L-band of approximately 0.008 dB/km at 1610 nm, compared to that at 1550 nm. The bending loss at 15mm radius is only 0.005 dB/turn at 1550 nm on average, allowing for tight coiling if needed. The change in loss values from shipping spools to cable is negligible over both bands, including at 1610 nm, in submarine as well as appropriate terrestrial cable designs.

Results on trench-assisted fibers for next-gen SDM cables will also be discussed.

1. INTRODUCTION

The demand for fibers with ultra-large effective areas and extremely low loss has increased in recent years in order to optimize the transmission capacity per fiber of submarine systems over trans-oceanic distances.

In the current work, a method for increasing the capacity is achieved by including the L-band and reducing the nonlinear capacity limit utilizing a fiber with ultra large effective area and low loss in both C- and L-bands. The design of the low loss large-area TeraWave® SCUBA 150 fiber optimized for C- and L-band is presented together with large volume production data that enables excellent performance in both submarine and terrestrial cables, due to the optimized bend performance.

Good understanding of amplifier performance in the L-band will be critical to future deployment. Simulation models have been improved, enabling design of an L-band EDF modified to allow for maximizing the capacity per fiber in a transoceanic C+L band system.

Splicing of ultra large effective area fibers to standard effective area fibers can be done at lower levels than butt-couple predictions, and splice losses down to the 0.1 dB range are achievable by fusion splicing. The fiber has excellent radiation and hydrogen sensitivity and meets the requirements for 25-year lifetime in undersea cables and can even be used in sensors in harsh environment.

2. LARGE AREA ULTRA-LOW LOSS FIBERS FOR C- AND L-BAND

The refractive index profile for TeraWave SCUBA150 has been developed based on previously reported trench designs [1]. Similar trench assisted fiber designs have found widespread use in shorter-reach terrestrial applications where bend-insensitivity is required. Unlike the ITU-T G.657 fibers though, in this work the trench assisted fiber design has been applied to ocean fibers displaying large effective area and low loss achieved utilizing a silica core material. Figure 1 illustrates the schematic index profile applied for the TeraWave SCUBA design.

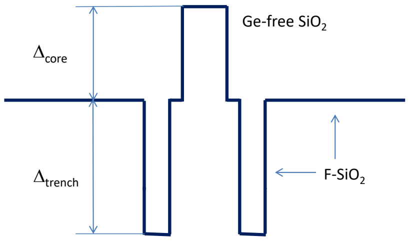

Figure 1: Schematic refractive index profile TeraWave® SCUBA designs.

TeraWave SCUBA 150 has successfully been packaged in submarine cables intended for transoceanic operation. Some hundreds of megameters of TeraWave SCUBA 150 have been shipped, the loss distributions for the shipped fiber at 1550 nm and 1610 nm are shown in Figure 2a and 2b, respectively. It is noted that the average loss value at 1610 nm only is 0.008 dB/km higher than at 1550 nm, indicating that it is suitable for future C+L band transmission.

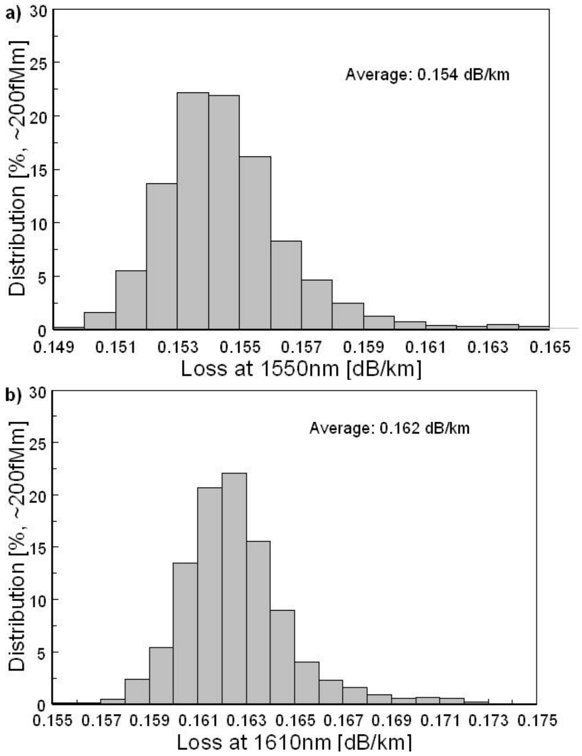

Figure 2: Attenuation distribution for 200.000 km shipped fiber at a) 1550 nm and b) 1610 nm, respectively.

In spite of the conventional wisdom that large effective area results in higher micro-bend sensitivity in the L-band, the attenuation at the long wavelength end of the L-band is only marginally higher than at the center of the C-band. At 1590 nm, the center of the L-band, the loss is on average 0.155 dB/km, i.e., less than a thousandth higher than at the center of the C-band. Also, the minimum loss below 0.153 dB/km is obtained at the long wavelength 1570 nm. Figure 3 shows the typical spectral loss for TeraWave SCUBA 150 across the C & L bands.

Figure 4 shows production data for the effective area at 1550 nm. It is noted that the average value for the distribution is 153 μm^2 and a standard deviation of only 2.6 μm^2. The large effective area together with the low nonlinearity ($2.2 \cdot 10^{-20}$ m^2/W) due to the Ge-free silica core applied reduce the impact of nonlinear effects.

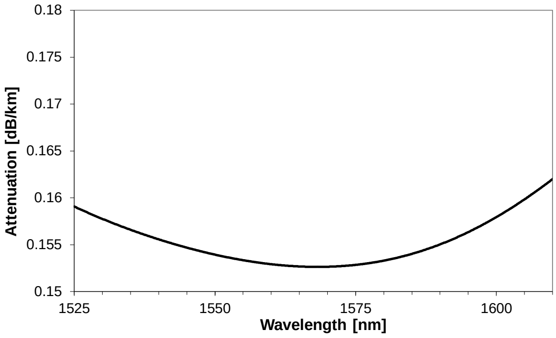

Figure 3: Typical spectral loss curve averaged over large volume fiber.

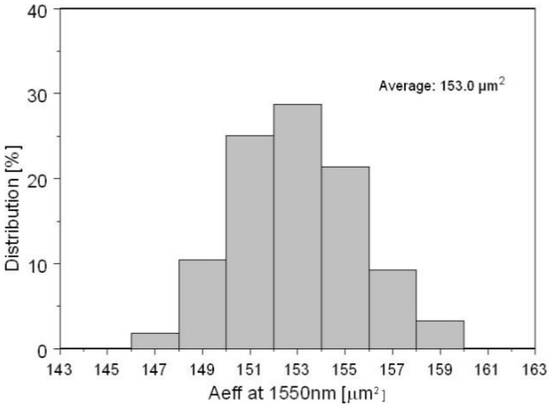

Figure 4: Distribution of A_{eff} at 1550 nm.

The characteristics and typical values for the produced large fiber volume are given in Table 1.

Wavelength [nm]	1550	1610	1625
Fiber loss [dB/km]	0.154	0.162	0.172
A_{eff} [μm^2]	153.0	157.3	158.3
MFD [μm]	13.56	13.73	13.78
Dispersion [ps/nm-km]	22.1	25.8	26.7
n_2[10^{-20} m^2/W]	2.2	2.2	

Table 1: Characteristic values of produced TeraWave SCUBA 150.

The polarization mode dispersion is extremely low both when measured on shipping spools (0.019ps/√km) and in low mode coupling [LMC] configuration. The LMC data mimics PMD in the final cable, and data from volume production are shown in Figure 5. The average value is 0.011 ps/√km, and for long submarine links the average is the relevant value.

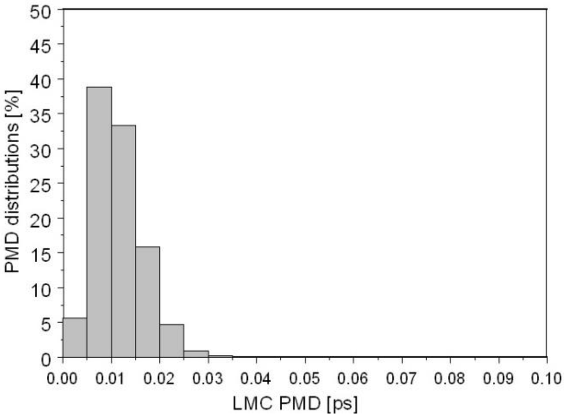

Figure 5: LMC PMD values, average 0.011 ps.

3. BENDING PROPERTIES

The performance of a fiber in cable is dependent on the bending properties both micro- and macro-bending. If carefully designed using accurate electromagnetic models, ultra large effective area fibers can be made to possess both excellent bending properties and ultra-low loss. Here we will show how the silica core trench design of TeraWave SCUBA 150 promotes not only ultra-low loss but also excellent bending performance enabling to transfer the low loss from fiber to fiber-in-cable.

The cut-off shifted trench-assisted fiber designs are known to have micro-bending induced losses which are almost wavelength independent over the C- and L-band [1,2,3]. By applying the design methodology outlined previously [2], we have minimized the micro- (and macro-) bend sensitivity by optimizing the index profiles with trench and down doped cladding. A typical added loss spectrum due to micro-bending from a wire mesh on a drum is shown in Figure 6. This illustrates that the L-band does not suffer more from micro-bending as compared to the C-band. This is different from the behaviour in step index fiber designs. The micro-bend sensitivity of TeraWave SCUBA 150 is approximately 3 times lower than the level obtained for a large area NZDF submarine fiber [2]. Part of the micro-bending sensitivity has been alleviated by use of a soft primary coating with low Youngs's modulus. However, excessively low modulus may give rise to mechanical issues, so there are limits to this approach.

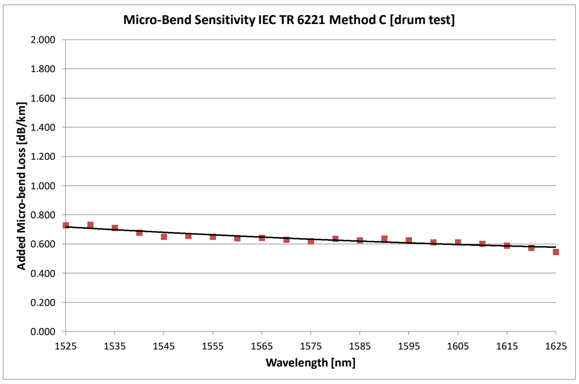

Figure 6: Example of measured added loss due to micro-bending sensitivity following the IEC TR 6221 Method C (drum test).

Even though the nominal effective area is 153 μm^2 the macro-bending at small bending radii is outstanding due to the trench design which often also is applied in bending-loss insensitive single-mode fiber designs complying to ITU-T G.657. Figures 7a and 7b show the distributions for macro-bending induced loss for 15mm bending radius at 1550 nm and 1625 nm, with typical values of 0.005 dB/turn and 0.011 dB/turn, respectively. It is noted that these values are significantly below the corresponding requirements in the ITU-T G.657.A1 of maximum 0.025 dB/turn and 0.1 dB/turn.

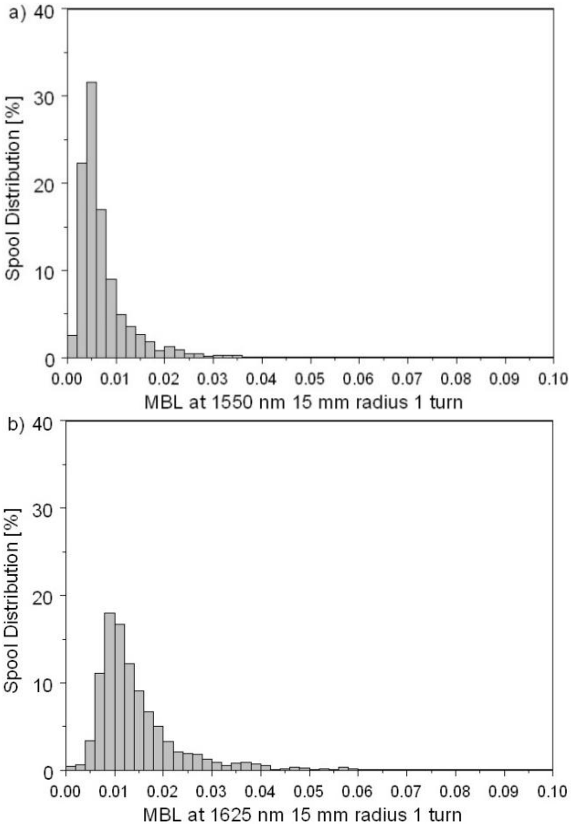

Figure 7: Distributions for macro-bending induced loss for 15 mm radius 1 turn at a) 1550 nm and b) 1625 nm, respectively.

In Table 2, the typical macro-bend induced losses at small bend radii of 10mm, 15mm, 20mm and 30mm, are given.

Bend radius [mm]	10 [1 turn]	15 [1 turn]	20 [1 turn]	30 [100 turns]
1550 nm [dB]	0.06	0.005	<0.001	0.01
1625 nm [dB]	0.09	0.011	0.003	0.04

Table 2: Typical macro-bending induced losses at various small radius bends for TeraWave SCUBA 150.

This verifies that the TeraWave SCUBA 150 is very bend-insensitive, also even for the 10 mm radius and meets the ITU-T G.657.A1 with respect to macro-bending performance.

The value at 30mm radius should be below 2 dB/100 turns according to ITU-T G.654.D which is the standard for cut-off-shifted submarine fibers. However, the typical values are well within even the ITU-T

G.654.E requirement of 0.1 dB/100 turns at 1625 nm.

The environmental reliability of the fiber is also excellent, and the loss changes, e.g. with temperature, are well within the requirements of the IEC60793-2-50 as illustrated in Figure 8. Both the loss changes under a temperature cycle from -60°C to 85°C is an order of magnitude lower than the ±0.05dB/km at both the 1550 nm and 1625 nm wavelengths. From the loss change under temperature cycle the coefficient of the loss change with temperature is approximately $5 \cdot 10^{-5}$ dB/km-°C and $9 \cdot 10^{-5}$ dB/km-°C at 1550 nm and 1625 nm, respectively. The larger coefficient at 1625 nm compared to 1550 nm indicates that the origin is not exclusively due to micro-bending.

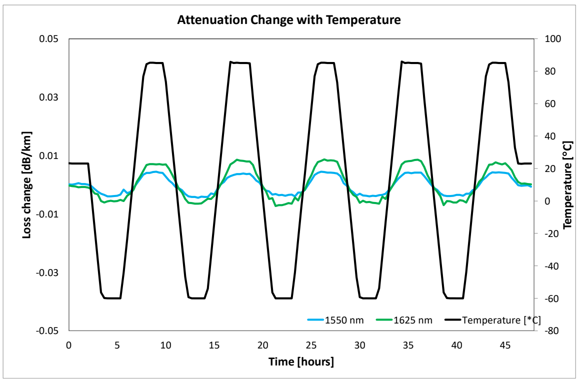

Figure 8: Typical attenuation change with varying environmental temperature. IEC60793-2-50 requirement loss changes with ±0.05 dB/km.

The results show that the TeraWave SCUBA 150 indeed is very bend-insensitive and typically performs according to ITU-T G.657.A1 and G.654.E with respect to bending.

4. CABLES

The submarine network design evolves into not only to terminate at the cable landing station, but also include terrestrial optical sections to inland point of presence or data-center (DC), or sometimes going over islands rather than going around. This introduces the need of fiber cable designs that are suitable for terrestrial use. I.e. the TeraWave SCUBA family is a G.654.D fiber but even with the large effective area the bending performance, as indicated in the previous section, is adequate for appropriate, existing terrestrial cable designs.

Also, the splice loss is important in order to reduce the span loss, if spliced spans are applied, as often is the case for matched sets. A consistent low loss splice from SCUBA to SCUBA is thus required, and in standard production environment a typical splice loss of 0.037 dB ± 0.022 dB is achieved at both 1550 nm and 1610 nm. Low loss for a splice between the large area 153 µm^2 and a standard area 83 µm^2 fiber down to order of 0.1 dB can be achieved [2,4].

Figure 9 shows the loss distribution at 1550 nm for spliced fiber sets. The distribution is narrower than that of the individual fibers and the average is only 0.153 dB/km.

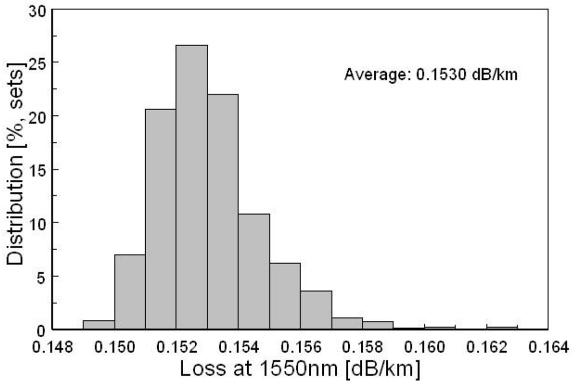

Figure 9: Distributions of loss for spliced fiber sets at 1550 nm.

The performance in submarine cables is illustrated by the limited added loss (0.0003 dB/km) at 1610 nm, as shown in Figure 10.

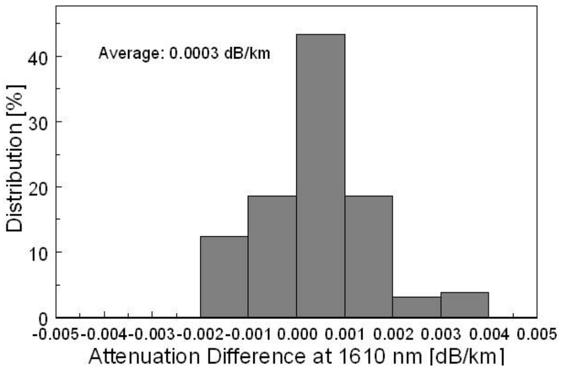

Figure 10: Distributions of added loss for cabled fiber sets at 1610 nm.

The terrestrial cable design selected for this study was a 5-position, single jacket/single armor loose tube design with gel-filled PBT tubes. A trial cable of this construction with TeraWave SCUBA 150 fiber had low as-manufactured attenuation, and met all optical, mechanical and environmental requirements of Telcordia GR-20 Issue 4 standard for terrestrial cable. Figure 11 compares the attenuation of as-drawn, uncolored fiber to that of as-cabled fiber for the wavelengths of 1550nm, 1570nm, 1590nm, and 1610 nm. The results confirm that this large effective area fiber can be cabled with low loss in this terrestrial construction. The change in median attenuation observed at the 1610 nm wavelength is only 0.003 dB/km.

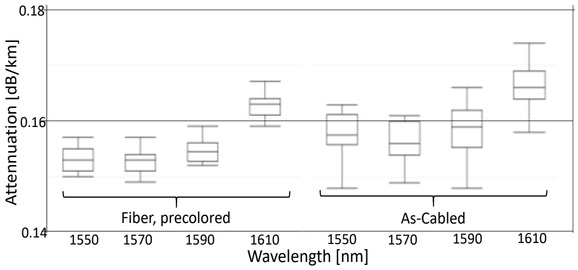

Figure 11: Box-plots of attenuation for precolored fiber and as-cabled fiber in a terrestrial cable design at 1550nm, 1570nm, 1590nm and 1610 nm.

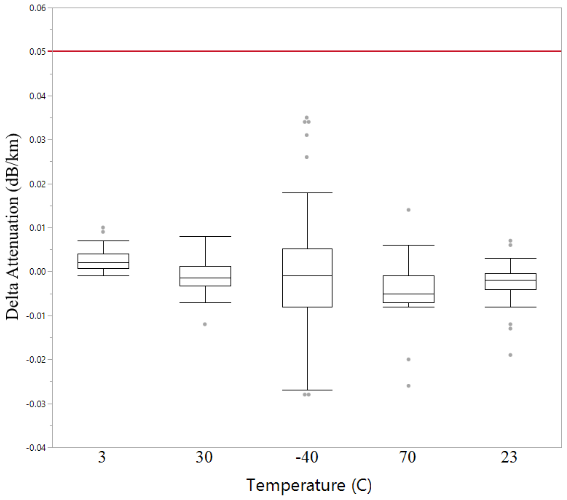

Figure 12: TeraWave SCUBA 150 GR-20 Environmental Test Results

Figure 12 displays the cable's transmission performance at 1550nm when exposed to extreme temperature conditions during environmental testing. The results displayed are for the second exposure of the cable to each temperature, as required by GR-20 Issue 4. Temperatures 3 °C and 30 °C are the anticipated operating temperature and -40°C and 70°C are the extreme temperatures required by GR-20 Issue 4. Added attenuation at the GR-20 extremes are well below the maximum allowed average change in fibers attenuation coefficient criteria of 0.05 dB/km defined in the specification.

The bend insensitivity of the SCUBA trench-assisted fiber design also makes higher count fiber cables possible and an average loss difference from fiber sets to cable within 0.001 dB/km has been achieved on a 48-fiber count terrestrial cable.

5. L-BAND AMPLIFICATION

The performance of amplifiers in the L-band also needs to be addressed and optimized.

Simulating performance in the L-band needs to be brought up to a similar level of accuracy as simulations in the C-band. Once the EDF fiber design is optimized to reduce non-linearities in C-band, the NF is limited by excited state absorption (ESA) in the signal band at long wavelengths. This is difficult to measure directly, and indirect methods have been developed to estimate ESA and allow more accurate estimate of NF at the longest wavelengths. The improved L-band simulation NF is shown in Figure 13. A number of high performances EDFs for L-band applications have been developed recently in order to support future submarine applications as an adjunct to SDM.

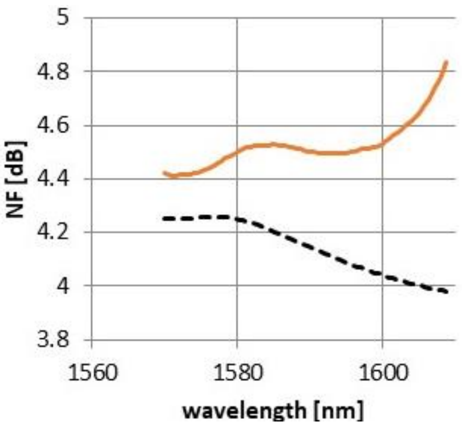

Figure 13: The black curve shows previous simulation results on NF, the red curve simulations using better estimate of ESA, resulting in more precise NF.

6. HYDROGEN AND RADIATION SENSITIVITY

The Hydrogen sensitivity is tested under standard conditions [IEC60793-2-50], and the added loss is within the sensitivity of the measurement. However, the SCUBA fiber has also been tested at extreme conditions e.g. 170°C and 1500psi. These tests showed that the OH sensitivity is very limited and much superior to Ge containing fibers and no short wavelength edge is observed.

The exposure of radiation from natural radioactivity must be considered for very long fiber cables. In submarine the dose rate is expected to be $4.6\cdot10^{-5}$ rad/hour during the 25 years life integrating to a total dose of 10 rad. Radiation induced loss are very dependent on fiber manufacturing process, the various doping elements, and the applied dose rate. Testing at the natural dose rates are very impractical and we have applied the dose rate transformation method [5]. A test dose rate of 5 rad/hour and a total dose of 25 rad was obtained from a Co-60 radiation source. From the 0.01 dB/km added loss observed at both 1550 nm and 1625 nm, the expected added loss due to radiation over 25 years will be only $2\cdot10^{-4}$ dB/km. The Ge-free silica core surely aids the insensitivity towards radiation.

These results show that hydrogen and radiation insensitivity of TeraWave SCUBA is excellent and that it that respect could be applied in very harsh environments and may be applicable for sensing [6].

7. SUMMARY

The TeraWave SCUBA family of ultra-low-loss fibers have excellent loss transferable to both submarine and terrestrial cable designs. This has been demonstrated by large volume data for the largest nominal effective area fiber, SCUBA 150 subsea fiber, including performance in a 48f terrestrial cable construction suitable for island crossings or inland datacenter termination. Owing to the bend insensitive trench-assisted design the fiber is optimized for use in the C-band as well as future L-band applications. The transmission reach in un-repeatered links can also be extended by use of large effective area ultra-low loss fiber cables [7]

The TeraWave ultra large area fiber family have now been shipped in volumes of half a million kilometers.

8. REFERENCES

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