

Towards the low limits of 1383 nm loss in PCVD enabled single mode fibre production

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Abstract: Based on a pilot development series it is shown that careful prevention of OH⁻ contamination in all PCVD process steps enables industrial production of SM fibres with a 1383 nm loss reaching below 0.30 dB/km.

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1. Introduction

Optimal usage of the enormous intrinsic transmission capacity of single mode fibre asks for a significant reduction of the OH⁻ excess loss (the so-called water-peak). This enables future use of DWDM systems in the E-band and also supports full exploitation of CWDM systems. In various papers [1], it has been shown that the technology to produce low or even zero water-peak SM fibres (LWP) on a large scale is available for some time already. As a result of this, standards like ITU-T: G.652.C and IEC: B1.3 have been approved and such fibres have been offered, including those being manufactured by PCVD core production technology. In this paper we will show for the first time that applying the PCVD based process allows for excess OH⁻ loss levels far below the levels required for practical use and approaching the theoretical limits of state-of-the-art fibres. The presented results are based on a joint R&D effort of the companies listed above.

2. Excess loss caused by hydroxyl contamination and its sources

The main objective of the LWP SM fibre is opening up the 1360 - 1460 nm E-band. Applying the Walker fibre loss model [2], it can easily be derived that for an OH⁻ excess below 0.02 dB/km, the maximum attenuation in the E-band is predominantly determined by intrinsic Rayleigh scattering loss at the 1360 nm edge and is at a level below 0.285 dB/km. Therefore our main goal is to achieve an excess OH⁻ loss ≤ 0.02 dB/km as a tolerable level in LWP SM fibre. As a restrictive second goal the cost-effectiveness of our current 500 km preform standard production process should not be affected.

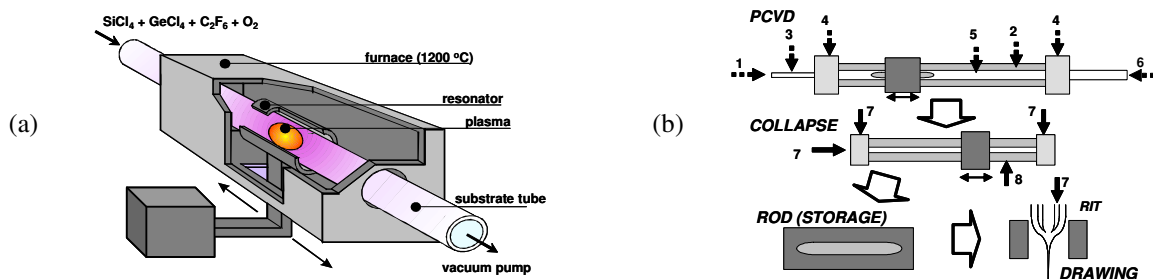


Fig. 1 Setup of a PCVD core production machine (a) and total process flow (b) with arrows showing potential sources of contamination

In the PCVD-based core rod production process (Fig. 1a) the gaseous reactants are directly vitrified into dense glass layers on the inside of a fused silica substrate tube, hence making this process step extremely sensitive to the incorporation of hydroxyl groups. Any subsequent purification of the deposited layers, e.g. drying by chlorine, is hardly effective. In Fig. 1b the various sources for OH⁻ contamination in the complete production cycle are indicated. A distinction can be made between a) basic material, i.e. chlorides, oxygen and the fused silica substrate tube (1, 2), b) non-ideal machine components like gas supply seals and connections (3), low pressure feed throughs (4) and c) process-cycle related surface contamination originating from tube mounting (5,6), collapsing (7,8), core rod storage

and rod-in-tube (RIT) mounting. Note that all contaminations in the PCVD process are directly incorporated in the core area. Surface contamination is important at three critical interfaces: i) the core rod centre-line that is exposed during the collapsing process, ii) the interface between deposited PCVD material and substrate tube and iii) the interface between core rod and jacket tube.

The contribution of the hydroxyl in the jacket tube and in the coating process may be neglected due to the large distance to the fibre core.

3. Reducing the hydroxyl contaminations

In view of the fact that later purification of plasma deposited material will be extremely difficult, the most straightforward solution is: *Prevention!* For the basic materials, gases and tubes, this involved intensive discussions with our supply partners resulting in the required quality of starting materials. In this discussion also the quality of auxiliary quartz in e.g. tube handles was taken into account. However, it is not sufficient to consider material quality alone. To get the pure materials uncontaminated into the process equipment asked for many improvements. Important examples are the chloride vessel (re)filling procedures, leak-tightness check procedures of the gas supply system, as well as proper and careful tube cleaning and handling. Redesign of machine parts sensitive to surface contamination during tube (de)mounting resulted in a decrease of surface area and "dead volumes". A very challenging task was the further optimization of the PCVD feed through construction to reach the required high leak-tightness of the PCVD low vacuum system. As for the *collapsing heat sources*, it appeared that the use of both electrical furnace and hydrogen-oxygen burners leads to similar results. Apparently, the formation of OH⁻ groups due to the flame of an H₂-O₂ burner can be reduced by a surface treatment (see below).

Quite another approach is to reduce the hydroxyl content in the environment surrounding delicate machine parts. In Fig 2 an example is given of the positive effect of reducing the relative humidity in the immediate vicinity of the feed throughs showing the extreme conditions for the low pressure process.

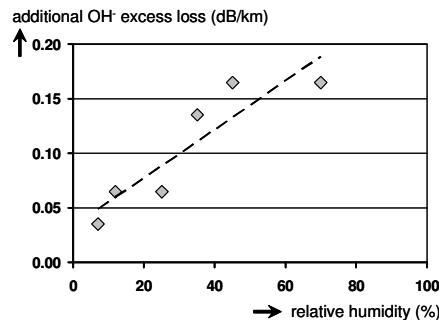


Fig. 2 Effect of reduction of relative humidity on OH⁻ excess loss compared with an arbitrary reference level.

4. Reducing the effect of residual hydroxyl contaminations

Although prevention can lead to a very low OH⁻ contamination, a small residue will always remain. The effect of this residue can be reduced by various means. The positive effect of *fluorine doping* has been recognized from its inception [3]. Optimization of the doping level showed a further excess loss reduction. Additional purification of the fluorine source itself appeared very essential.

Every open air exposure of a fused silica surface immediately leads to adsorption of a thin layer of water, which can lead to further in-diffusion during subsequent hot processes. A *surface etching treatment* is essential and effective in removing these surface contaminations. In the PCVD process this is done by O₂/C₂F₆ plasma etching. In the collapse stage C₂F₆ etching is applied to remove the centre-line contamination while after collapsing, a room temperature HF wet-chemical etch removes any possible surface contamination of the preform.

Careful modeling of the OH⁻ diffusion during core rod collapsing and fibre drawing revealed that the diffusion effect is very much dependent upon the precise chemical reactions underlying the OH⁻ transport. In the glass matrix both stable and meta-stable hydroxyl groups can be distinguished [4]. The stable OH⁻ species diffuse only very slowly due to the covalent bond to the silica glass matrix. This is the case in state-of-the-art synthetic fused silica produced by soot deposition (like the substrate tube) as it is free of molecular hydrogen and water. Hydroxyl groups incorporated in the glass surface during hot processes tend to have a meta-stable character. The rapid diffusion of this type of hydroxyl might be dominated by diffusion of either molecular hydrogen and/or molecular H₂O [5, 6].

Diffusion of residual OH⁻ groups into the core region during collapsing and fibre drawing is also determined by the *distance* from the substrate and from the surface of the preform to the core area. In the standard SM fibre

production process these interfaces are major factors in process productivity [7], and hence the fibre cost price. Increasing these distances could be prevented up to now by surface etching. Another development will be a high quality substrate tube with a significantly reduced hydroxyl content of the bulk glass (less than 100 ppb).

5. The result of the combined measures

Even though the total effect will be less than the sum of the individual effects, the combination of all the measures mentioned above, yield a layered defense against hydroxyl based on redundancy. The total effect is also determined by statistical factors during process execution. Careful process control, improved operational procedures and feedback based on fibre results usually shows a learning curve effect leading to the ultimate yield of the required product characteristics after some time. For this reason it was very encouraging that even in the first pilot run on a line fully equipped with the combination of all measures the first <0.30 dB/km fibre was produced already (Fig. 3c). For reference, the set target (a) and a loss limit as standardized by ITU-T and IEC (b) are also indicated in figure 3

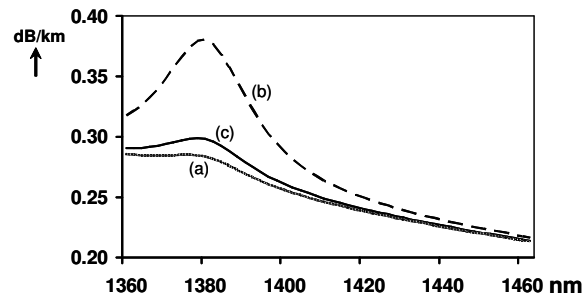


Fig. 3 E-band loss curves: (a) target with 0.285 dB/km loss at 1383nm, (b): example of G.652-c limit loss of 0.38 dB/km at 1383 nm for a fibre specified as 0.38 dB/km @ 1310 nm and (c) current best result from pilot PCVD series

At low levels of the OH⁻ excess loss, *aging* due to the reaction of free hydrogen with defects in the core silica structure may become significant [8]. Again, countermeasures are in curing (e.g. deuterium fibre treatment [9]) and in prevention by careful choice of material composition and heat-treatment during drawing. Applying this latter method resulted in negligible aging effects without affecting the operational PCVD and drawing processes significantly.

As none of the above measures is restrictive with respect to *scalability* we will apply the developed improvements also in the next generation 2000 km preforms. With PCVD core rod technology and very large synthetic fused silica cylinders (RIC: Rod-In-Cylinder technology) we are able to produce preforms with a diameter of 150 mm and larger, yielding high quality fibres. Applying the developed improvements to these concepts allows for even more cost-effective LWP fiber production.

6. Conclusions

Careful and precise quantification of all the hydroxyl contamination sources combined with skillful engineering and supply of high purity raw materials revealed that the production of enhanced LWP fibre with the PCVD based SM fibre production process is feasible. A sub-ppb residual OH⁻ concentration in the fibre core region has been achieved corresponding with a total loss level below 0.30 dB/km, i.e. far beyond the limits as set in the international standards for LWP fibres. As none of the measures is restrictive with respect to product type and process scale the result is sustainable for future process steps. These may be in applying the developed improvements also in other fibre types where applications in the E-band are relevant and in further scaling-up steps.

7. References

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