Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Characterization of UV optical fibers

Analysis of the effect of hydrogen-loading and
UV-curing on LMA-10-UV photonic crystal fibers

Nathan Torelli

Semester project in the Trapped Ion Quantum Information Group
Supervisors: Christoph Fischer, Dr. Matthew Grau, Prof. Dr.
Jonathan Home

Department of Physics
Institute for Quantum Electronics
ETHZ

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Abstract

In this report the dependence of curing parameters on the transmission of UV light in a photonic crystal fiber is studied. Following the NIST recipe for UV patch chord fibers [1] curing time, intensity and wavelength were varied. Furthermore, the effect of the presence of a protective sleeving and exposure of the fiber to high temperatures has been studied, which have been noticed to influence microbending of the fiber.

Contents

1 Introduction

Solid-core silica optical fibers are an important tool in many laboratories and are ideal for low-loss delivery of single-mode beams from the visible to the infrared. However, in trapped ion experiments beam pointing stability is required and, since transitions are usually in the ultraviolet, special fibers are needed. Unfortunately, optical fibers at shorter wavelengths are not commercially available because they are affected by UV solarization, a collection of UV induced processes that lead to a large drop in light transmission. These include the formation of UV induced color centers and optical damage in the core during the UV irradiation.

For these reasons, the study of processes which induce the formation of color centers and the investigation of possible solutions to the solarization problem have become an important research field. It has been found that hydrogen-loading and subsequent UV-curing of a fiber can influence the way in which solarization happens, in particular conferring some improved solarization resistance [1].

There have already been some efforts in trying to characterize UV optical fibers. In 2009 Yamamoto *et al.* [2] investigated the performance of unloaded LMA-10-UV PCFs for a wavelength of 250 nm. In particular, it was demonstrated that this type of fibers can be used as single-mode patch-cords at that wavelength. However, an induced absorption in the fiber due to the formation of color centers was encountered. It has been noticed that for a power of 0.3 mW at 250 nm, the fiber's transmission dropped to about 65% of its initial value within the first 20 hours of irradiation, but then remains constant for at least another 20 hours. For higher powers, though, no stable transmission had been observed, and for a power of 3 mW at 250 nm the transmission reached zero after only five hours.

In 2010, Gonschior *et al.* [3] demonstrated stable transmission of 405 nm light through LMA-10-UV fiber at output powers of up to 105 mW over a period of weeks. Fused silica is generally very resistant to solarization at longer wavelengths[1] [4].

At the National Institute of Standards and Technology (NIST), hydrogen-loading together with UV-irradiation has been studied [1]. The performance of hydrogen-loaded large mode area photonic crystal fibers under both low and high power UV irradiation have been investigated. In particular, it was demonstrated that after having cured a LMA-10-UV for 16-20 hours at few mW with a 313 nm laser the loss is between 0.4 and 0.2 dB/m at 280 nm and 0.13 and 0.04 dB/m at 313 nm. For higher curing powers (> 100 mW), it was noticed that the transmission saturated to a value independent of the incoming power during the first 30-50 hours. However, after a longer curing time, this effect was not visible anymore, indicating that a prolonged curing time is preferable. In this case, it was also found that the transmission was stable, i.e. both letting the fiber at room temperature for a long time or putting the fiber into an oven at a temperature of 140°C to force out-diffusion of the hydrogen from the silica bulk did not influence the fiber's performance. This suggests that under those UV-curing conditions all color centers were annealed. Last, the sensitivity of optical fibers at macrobending has been studied as well, and it was found that only for bending radii smaller than about 5-6 mm losses become evident[2].

However, there are many knowledges about UV optical fibers that still miss. For this reason, in this report the effect of hydrogen-loading and UV curing of optical fibers has been further investigated. Hydrogen-loaded photonic crystal fibers have been cured under different conditions (in particular different curing time and powers) and their transmission was tested at different wavelengths between 280 nm and 375 nm.

In the next sections an introduction to the formation and the effects of some color centers will be given. Then it will be described which fibers have been tested and how they were prepared. Finally, the results of the experiment will be presented and analyzed.

[1] This is mostly due to the fact that multi-photons absorption has a much lower cross section, i.e. it is less probable that low-energy photons break the chemical bonds in silica to form color centers.

[2] This has also independently been demostrated in [2].

2 Theory of color centers

Here a short introduction on how color centers form and what can be done to (partially) avoid the problem of UV solarization is given.

2.1 Formation of color centers

When SiO_2 optical fibers are irradiated by a UV laser, color centers can be created by the interaction of light with dopants or impurities present in the glass, as well as with strained molecular bonds created during the fiber drawing process [1]. These processes are called solarization and are not only caused by UV light but can occur in the visible and infrared wavelengths as well. However, the threshold intensity required for a noticeable degradation of the fiber decreases with shorter wavelengths, i.e. larger photon energies. The high energy UV photons have enough energy to break chemical bonds, thus, especially in SiO_2, forming the so called E' centers (Si*) and NBOHC (NonBridging-Oxygen Hole Centers; Si-O*)[3], which are responsable for the absorption of a large fraction of the incoming light [6, 7]. The leading reaction is given by:

$$\mathrm{Si-O-Si} + h\nu \longrightarrow \mathrm{Si}^* + \mathrm{Si-O}^*, \tag{1}$$

where the notation X* for a given element X means that it has an unpaired electron which is not in a covalent bond. The photon energy necessary for this reaction to happen is between 8-9 eV and corresponds to the binding energy of the SiO_2 molecule [6]. Therefore, the dominating process for wavelengths roughly between 200 nm and 400 nm is double-photon absorption[4]. On the other hand, for the formation of those types of color centers at longer wavelengths multi-photons absorption is required, which has a much lower probability to happen, i.e. a lower cross section.

2.2 Factors influencing the formation of color centers and possible solutions to the solarization problem

It has been found that trapped excitons which will dissociate to form color centers are already present before the irradiation [8, 9, 10]. For that reason, a first step towards a solution of the solarization problem is to try to reduce the color centers formation during the fiber drawing process.

It has, for example, been noticed that high hydroxyl or germanium concentrations reduces the LIDT (Laser-Induced Bulk Damage Threshold) and therefore it is better to decrease those concentrations. For this reason, modern optical fibers are often composed of an undoped core with a fluorine-doped cladding [4]. Moreover, some E' and NBOH centers are already created during the drawing process of the fibers. E' centers form through the evaporation of oxygen atoms from the SiO_2 network and NBOHC are produced through the mechanical break of Si-O bonds when SiO_2 rods are deformed into fibers. Therefore, through an optimal control of the O_2 flow in the glass sintering process, the drawing temperature and the drawing speed, it is possible to reduce solarization already in the fiber drawing process [9].

Another process that could be done in order to solve the solarization problem is to hydrogen-load optical fibers in a high-pressure molecular hydrogen environment and cure them by successive exposition to UV light [11]. This is the process that was studied in this report. The effect of the presence of molecular hydrogen in the fiber has been investigated in [5, 7], by looking at the reaction kinetics of the various color centers. It was found that E' centers and NBOHC react with the hydrogen to form either optically inactive products, or other products that interact at other (usually lower) wavelengths (see Figure 1).

[3] These are the two most important colour centers which play a role in induced absorption in fibers. However, for some configuration, e.g. in fibers with a low-OH core, also other forms can be created, like peroxy-bridges ($\mathrm{Si-O-O-Si}$) and oxygen vacancy ($\mathrm{Si-Si}$), often referred to with the common name of Oxygen Deficient Centers (ODC) [5].

[4] The photon energy at a given wavelength λ is approximately given by: $E[\mathrm{eV}] = 1240/\lambda[\mathrm{nm}]$.

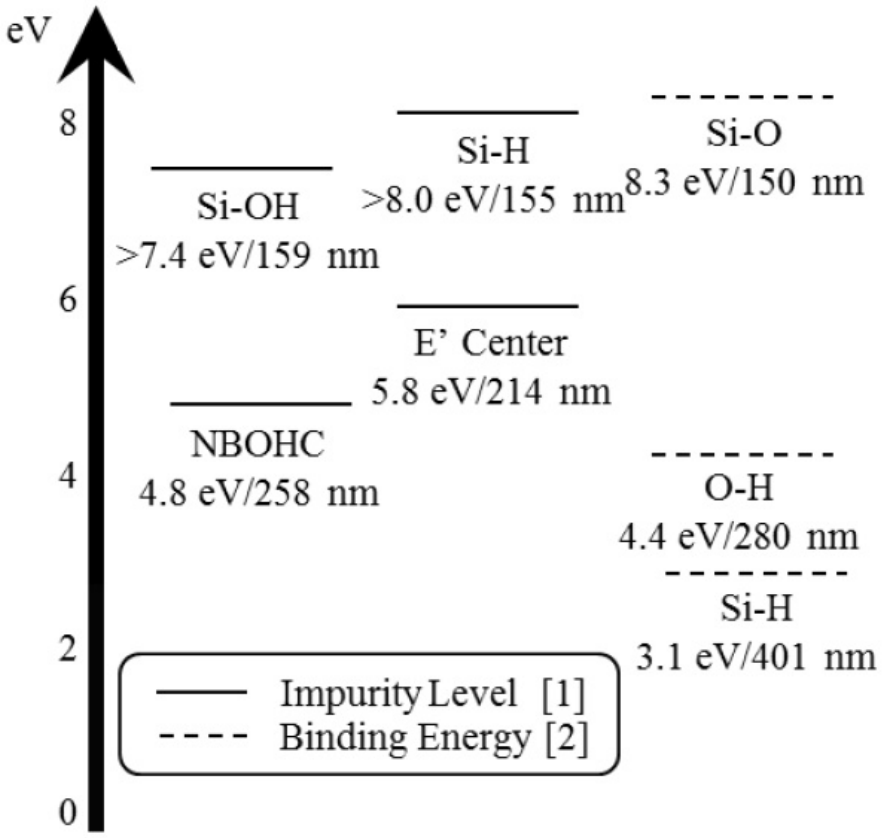

Figure 1: This diagram shows the impurity levels and binding energies of certain of E' and NBOH centers and their products after reacting with the hydrogen (Si-H and Si-O-H) [4].

E' centers have been found to be more stable and often to only react with atomic hydrogen. On the other hand, NBOHC are less stable and can decay after some recovering time once the irradiation has been turned off. However, under a prolonged UV-irradiation and with a high concentration of molecular hydrogen, color centers tend to anneal to stable products that do not interact any more with the wavelength that has been used to cure the fibers. The involved reactions are the following:

$$\mathrm{Si-O^{*}+H_2 \longrightarrow Si-O-H+H_1}, \tag{2}$$

$$\mathrm{Si-O-H}+h\nu \longrightarrow \mathrm{Si-O^{*}+H_1}, \tag{3}$$

$$\mathrm{Si^{*}+H_1 \longrightarrow Si-H}. \tag{4}$$

According to the present knowledges of the author, no accurate quantitative experiments have been performed with the intent to investigate which wavelengths are affected by the products of these reactions. It has for now only been found that solarization resistance is imparted for wavelengths other than that employed in the curing process. For instance, it was demonstrated that curing at 375 nm with 50 mW imparted solarization resistance for 200 mW at 313 nm, and curing at 313 nm with 200 mW imparted solarization resistance for 10 mW at 235 nm [12].

Remark: A similar process of hydrogen loading and gamma ray exposure has been used to harden fibers against degradation caused by ionizing radiation [1].

3 Fibers description

Here a description of the optical fibers that have been studied and, in particular, of how they were connectorized and cured will be given.

3.1 Employed fibers

In this semester project, hydrogen-loaded solid-core photonic crystal fibers (PCFs) with a large-mode-area (LMA-10-UV, NKT Photonics) have been investigated. These have a core size of 10.1 $\pm$ 0.5 μm and a cladding diameter of 125 $\pm$ 2 μm, with a hexagonal lattice of air holes surrounding a low-OH solid core [1, 13].

The reason why large-mode area photonic crystal fibers were analyzed is that those have an increased mode field diameter compared to normal single-mode fibers. This has the effect to reduce the intensity passing through the bulk of the fiber, thus increasing the solarization resistance for a given input power. The presence of the air holes into LMA photonic crystal fibers, in fact, permits the fiber to propagate a single-mode also with a larger mode field diameter. The criterion in order for a fiber to propagate single-mode is that the V-number has to be lower than a certain value. A PCF has a smaller V-number than a conventional fiber because the guided mode is larger and hence the NA smaller. For a conventional single-mode fiber this is given by:

$$\mathrm{V} = \frac{2\pi\rho}{\lambda}\mathrm{NA} < 2.405, \tag{5}$$

where $\rho \simeq 8$ μm is the core size and the numerical aperture is of the order NA ~ 0.1. For a LMA-10 PCF the V-number reads instead:

$$\mathrm{V} = \frac{2\pi\Lambda}{\lambda}\mathrm{NA} < \pi, \tag{6}$$

where $\Lambda = 6.3$ μm is the dimension of the hexagonal hole pattern (i.e. the distance between two opposite corners of that hexagon) and the numerical aperture at 285 nm is $\mathrm{NA}_{285nm} = 0.02$ [12].

3.2 Fibers connectorization and curing step

The fibers were held in a freezer at -18°C to avoid out-diffusion of the hydrogen, but they were allowed to reach room temperature at the moment of the connectorization. To connectorize a fiber the NIST UV fiber patch-cord recipe [14] was followed, i.e. the photonic-crystal holes were first collapsed in a 400- to 700-μm-long section near the end of the fiber[5] using a fusion splicer arc. Because the holes represent a relatively small fraction of the total cross-sectional area, the outer diameter of the fiber changes negligibly upon collapsing the holes inside. Then the fiber was cleaved in the collapsed region, leaving a collapsed section of approximately 200-300 μm. After that, the end of the fiber was glued in a FC/PC connector with a zirconia ferrule, supported and protected by stainless steel and polyimide tubing, which was then polished in order to have a 8° facet angle[6]. Researcher at NIST found that fibers without a sufficiently angle cleave at the output showed some back-reflection and tended to form narrowband reflective gratings after several days of UV exposure [1].

Furthermore, hydrogen loading[7] of pre-connectorized fibers was tested for two handmade (i.e. connectorized as reported above) and one commercial patch cord fiber[8].

[5] This step is crucial to avoid the hydrogen escaping from the core of the fiber, since diffusivity of H_2 in air is 10^8 times larger than in silica [12]. Moreover, it has been found that a collapsed fiber show a smaller number of low-intensity features surrounding the main output peak [1].

[6] In most of the fibers that were prepared and studied, a FC/PC connector was mounted only at one of the ends of the fiber, whereas on the other side the fiber was only collapsed and cleaved. When curing, respectively testing, the fiber, the well-connected side was coupled to the collimator and on the other end was mounted a movable connector in order to make it easy to record the power using a powermeter.

[7] iXblue SAS

[8] Newport F-SM10-PM-C 2FCA

Once the fibers were ready, they were coupled to different UV-lasers. They were then cured at different wavelengths (mainly at 313 nm and 280 nm) under different conditions varying both the curing time and the curing power, and tested to observe their transmission (mostly at 280 nm and 375 nm).

4 Experiment and results

In this section the results of the experiment, and in particular how the transmission of the fibers changed under different curing conditions, will be presented.

4.1 Effect of curing time on the fibers' transmission

Three different fibers have been cured with a 313 nm laser at an input power of 250 mW for 4, 12 and 24 hours. The fibers were all about 90 cm long. The output powers were around 130 mW, corresponding to a total transmission of 52%[9]. It has also to be remarked that a sort of saturation of the output power for high input powers has been observed, as reported in [1]. For an input power of 150 μW, a transmission of 66% has been observed.

These cured fibers were then tested both at 280 nm (for an incoming power of 40 mW) and at 375 nm (for an incoming power of 700 μW). The results are shown in Figure 2.

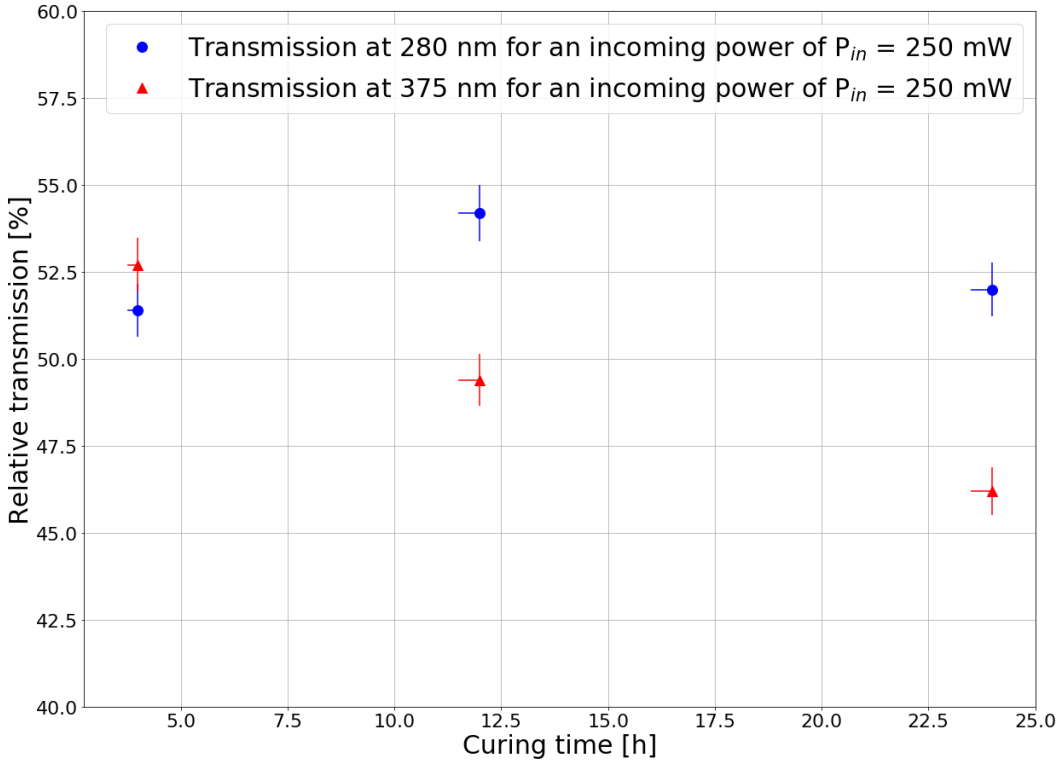

Figure 2: Transmission at 280 nm and 375 nm after being cured at 250 mW with a 313 nm laser. The plot shows the results for 3 different fibers that have been cured for 4 hours, 12 hours and, respectively, 24 hours (the uncertainty in the curing time is due to the fact that the high power laser is very sensitive to movements in the lab and sometimes it was found unlocked during the curing process). Note: these measurements do not take into account the incoupling efficiency. Remark: The uncertainty in the measured transmission has been estimated through three repeated independent measurements within a relative small time interval and was found to be about 1.5% of the measured value.

First of all, it can be noticed that at 280 nm the transmission is better than at 375 nm. However, this is only due to the fact that the incoupling efficiency at 375 nm was lower than the one at 280 nm. In fact, as reported in [1], the UV-induced absorption should be expected to be much less pronounced at the longer wavelength.

[9] All the transmission values that are reported in this thesis refer to the ratio between incoming and outcoming powers, without taking into account the (non perfect) incoupling efficiency. For similar fibers and experimental setup, researchers at NIST calculated the incoupling efficiency to be about 70% [1].

From Figure 2 it can also be seen that the transmission for the three fibers is more or less the same for short wavelengths (i.e. 280 nm in our case), but differs considerably for higher ones (375 nm). Moreover, at 375 nm the fiber cured for the shortest time (i.e. 4 hours) is the one with the lowest induced absorption, whereas the one cured for the longest time (24 hours) is the one which absorbs more of the incoming light. These results are quite surprising. In fact, according to the theory about the formation and annealing of color centers, two possible behaviours would have been expected. In the case that all the color centers had already annealed, both at 280 nm and at 375 nm the relative transmission should have saturated more or less to the same value for all three fibers. Alternatively, if 4 hours of curing under the above conditions were not enough to set all color centers, a difference in the transmission depending on the curing time should have been noticed, where the fiber cured for longer time would have had a better transmission. The fact that at 280 nm the values for the relative transmission are more or less the same suggests that after 4 hours of exposure to 250 mW of incoming power at 313 nm, most of the color centers annealed to inactive products due to the presence of the hydrogen. The better transmission of the fiber which have been cured for 12 hours should then be related to some effect independent on the curing process, i.e. for example to a difference in the connectorization step. However, the differences at 375 nm, and the fact that the relative transmission at this longer wavelength depends somehow on the curing time, indicate that there must still be some difference in the transmissions of fibers cured for different time and that neither 4 nor 12 hours are sufficient to completely cure the fiber. On the other hand, the fact that at 375 nm for higher curing time the fiber's transmission results worser is strange. This is the opposite from what it would be expected if the induced absorption were caused by resilient (i.e. non-annealed) color centers and no explanation has been found for that.

Independent of the reasons for the differences in the transmissions, the fact that those are present is an indicator that the curing time was too short and not all color centers annealed. When all the color centers are annealed, the fibers' performance would be expected to become independent of the curing time, at least up to other (unknown) effects.

4.2 Effect of curing power and wavelength on the fibers' transmission

In the same manner as was done for the three fibers in Figure 2, some fibers were also cured at lower powers both at 313 nm and at 280 nm. In particular, a fiber ($\sim$ 90 cm long, connectorized only by one side) was cured for 17 hours at 280 nm, with an incoming power of 39 mW and a relative transmission of 48.6 $\pm$ 1.5 %. After the curing, the fiber was allowed to rest over a night and tested the day after, when it has been measured a transmission of 47.2 $\pm$ 1.5 % at 280 nm (with an incoming power of $\sim$ 42 mW) and 48.1 $\pm$ 1.5 % at 375 nm (with an incoming power of 130 μW). What can be noticed from this test is that these values are lower than the ones that were obtained curing fibers at 313 nm ($\sim$ 52.5 %) and that after recovering from the curing process the transmission was slightly lower than the one that the fiber had at the beginning. The latter suggests that under those curing conditions there are still some resilient color centers (in particular NBOHC[10]) that have not annealed [7]. The low measured transmission is again an indicator that the curing time, respectively the curing power, are not enough for all color centers to anneal. In fact, for low-OH fibers (as LMA-10-UV PCFs are) there should be a slight increase in the transmission compared to the initial one. This is because the curing step should also fix the oxygen deficient centers that are already present after the drawing process.

Furthermore, a similar fiber was cured for 18 hours at low power at 313 nm ($\sim$ 3 mW outcoming power[11]) as well. This fiber has then been tested at 280 nm with an incoming power of $\sim$ 42 mW and a relative transmission of 43.7 $\pm$ 1.5 %. It can again be noticed that the transmission of that fiber is lower than the ones for fibers which have been cured at higher powers, indicating the presence of a large number of non-annealed color centers.

[10] As was already remarked, those color centers are unstable and can decay after a short recovering time.

[11] This fiber was connected in series with another fiber using a "FC/APC Mating Sleeve" (ADAFC3) from Thorlabs. The power coming out from the first fiber was of 80 mW, but due to the bad incoupling of the two fibers only a very low power coming out the second fiber has been observed.

From these studies, it can be understood that both high curing times and, in particular, high curing powers[12] are preferable. From the measurements that have been done in this thesis, the author is not able to exactly give an estimate for a curing condition (i.e. curing time and power for a given wavelength) which would permit annealing all color centers which form in the bulk of the fiber. It can, however, be stated that a LMA-10-UV PCF has very probably to be cured at a incoming power of 250 mW at 313 nm for more than 20 hours, and according to the observations made at NIST even more than 50 hours [1].

4.3 Solarization resistance

Although it has been seen that less than 20 hours of curing at 250 mW at 313 nm are probably not enough for all the color centers to anneal, it can be shown that this does not cause the fibers to solarize afterwards, i.e. that the color centers that have annealed do not decay according to reaction (3) also when the residual hydrogen present in the silica core flows out. To do this the fibers were put into an oven at 140°C in order to accelerate the diffusion of the hydrogen out of the bulk. For a LMA-8-UV fiber the hydrogen loss within one hour at 140°C is equivalent to 8.4 days at room temperature [1]. Since this estimate is based on the diffusion rate of hydrogen in fused silica it can be assumed a similar value for a LMA-10-UV, which only has a larger core size.

The fibers were then tested again at the same wavelengths. The results are shown in Figure 3, from which many interesting features can be noticed.

4.3.1 Relative transmission at 280 nm

As it can be seen from Figure 3, after the fibers spent some hours at high temperatures, their relative transmission at 280 nm has the dependency on the curing time that was expected, i.e. the fiber which have been cured for longer shows lower induced absorption, thus less color centers. This effect strengthens the observations that a longer curing time has to be preferred, and that both 4 and 12 hours of curing at 250 mW at 313 nm are not enough for all the color centers to anneal.

4.3.2 Microbending sensitivity

Besides macrobending sensitivity (which has been studied both in [1, 2]), also microbending is an important factor that could cause losses in the transmitted light. By comparing the transmission before putting the fibers into the oven and after 17.5 hours at 140°C, an increase in transmission can be observed. A possible explanation for this effect is that at high temperatures there could have been a relaxation of the fiber, which caused a decrease of microbending losses. This observation is supported by the fact that this effect is much more pronounced at 280 nm than at 375 nm, since losses due to microbending are expected to be larger at shorter wavelengths [15].

4.3.3 Effects on the fiber due to the exposition to high temperatures: solarization resistance and unexpected loss effects

From Figure 3 it can also be noticed that, at least up to 62 hours spent at 140°C (which corresponds to about one and a half year of hydrogen out-diffusion at room temperature), there is no relevant change in transmission. The transmitted power of the fibers which had a larger induced absorption at 280 nm was monitored and no change within the first ten hours was observed. This observations suggest both that the already annealed color centers remain optically inactive and that without enough hydrogen in the fiber's bulk there is no more the possibility for other resilient color centers to anneal. Otherwise an increase in transmission would probably have been observed.

[12] The fact that the formation of color centers (and thus their annealing) depends more on the curing power instead of the curing time, has already been (indirectly) demostrated in [2] for unloaded fibers.

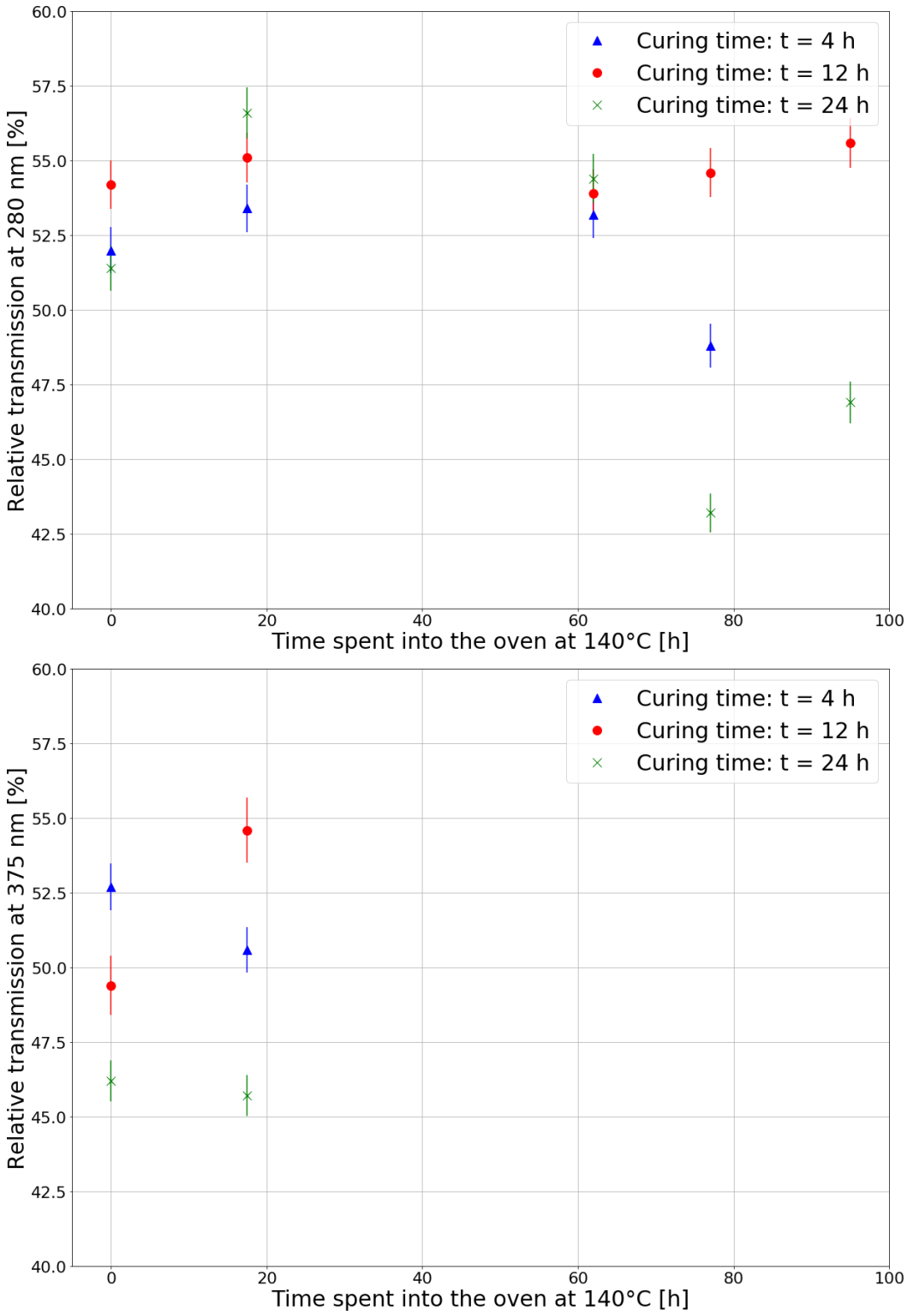

Figure 3: Transmission at 280 nm (*upper panel*) and 375 nm (*lower panel*) for three fibers cured at 250 mW with a 313 nm laser for different time spent into the oven.

However, for longer time spent in the oven a drop of up to 10% in transmission at 280 nm for the fibers that have been cured for 4 and 24 hours can be seen. This has been checked and confirmed also at 313 nm. It cannot be explained why the fiber cured for 12 hours was not affected by that change, nor the reason of the effect itself. However, that change in transmission was accompanied by a worsening of the output mode (which was not due to a ruined fiber facet, as it was checked by

looking at the fiber facet on a microscope).

A comparison of the output mode before and after 77 hours at 140°C is shown in Figure 4.

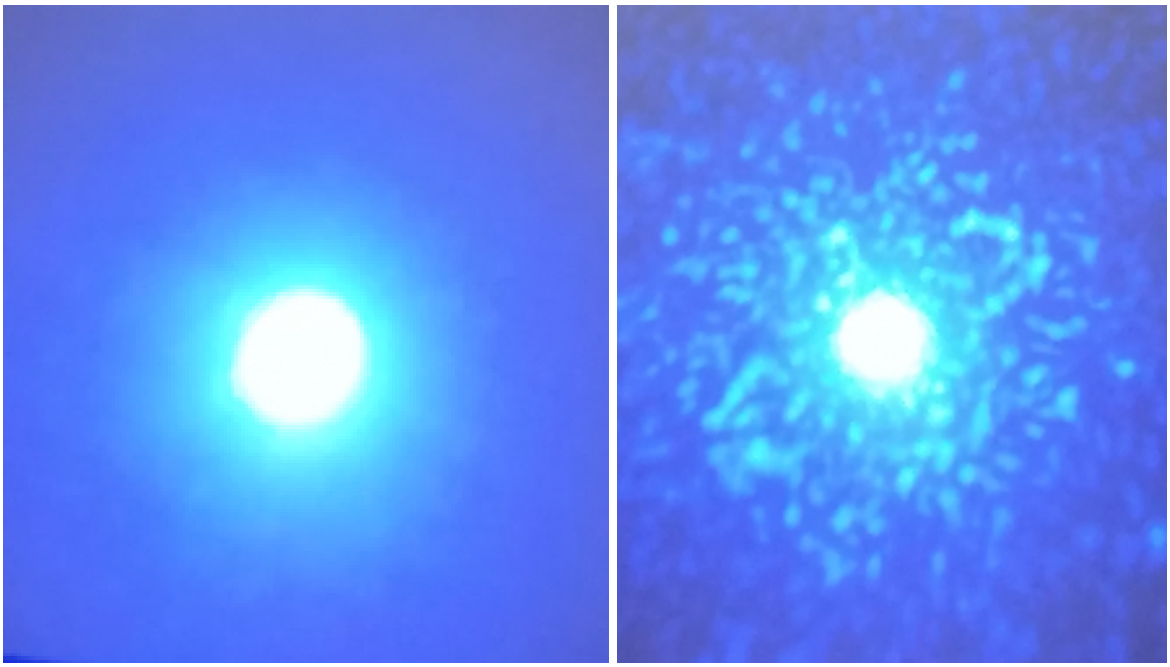

Figure 4: This figure shows both the output beam of the fiber that has been cured for 24 hours before the transmission drop (*left panel*) and after 77 hours at 140°C (*right panel*).

4.4 Effect of the jacketing on a fiber

Most of the fibers that have been tested did not have a protective jacketing. However, also few fibers with a sleeving have been investigated. These were prepared in the same way as the other ones, but this time they were surrounded with a protective jacketing which has then been glued to the connectors. Since it makes it easier to put the sleeving on the fibers and in order to avoid the fiber to be stretched, respectively crushed (thus avoiding as much as possible macro- and microbending), a 10-20 cm gap was led in the sleeving near one end of the fibers.

The first fiber that has been analyzed was about 350 cm long and was cured for 14 hours at 313 nm with an input power of 190 mW and a relative transmission of about 53%. This fiber was then tested at both 280 nm (incoming power of 40 mW, relative transmission of 24%) and 375 nm (incoming power of 126 μW, relative transmission of 43%). Although the relative transmission at 313 nm during the curing process is comparable to the one of the fibers without any jacketing, this is not valid anymore at 280 nm and 375 nm. Especially at 280 nm the performance of the fiber was very bad and the effect could not be mitigated by moving the fiber inside the jacketing or removing it completely. This effect, and mostly the fact that this is much more evident at 280 nm, suggests that the jacketing probably induces some microbending.

In another experiment two 2 m-long fibers were tested (one with the sleeving and the other without it). These were prepared in the same way as described above, but this time connectorized on both sides and hydrogen-loaded after they have been connectorized. Both fibers have been cured at 280 nm with an incoming power of 42 mW and a relative transmission about 48%. After a recovering time of a few days they were tested at 280 nm, again with an incoming power of 42 mW. The results confirm the effect of the sleeving on the fibers' transmission. For the fiber without jacketing it was measured a relative transmission of 47.5 $\pm$ 1.5 %, whereas for the fiber with the jacketing this was only of 36.7 $\pm$ 1.5 %. Moreover, the fact that a decreased transmission of the fibers due to the jacketing has been observed only after they have been cured, indicates that this effect is not only caused by the presence

of the sleeving, but instead by a combination of the sleeving and the UV irradiation.

It can additionally be remarked that the transmission of the fiber without the jacketing seemed to be slightly better than for similar fibers cured under the same conditions. However, this effect is not so remarkable, suggesting that the hydrogen concentration is high enough also after conserving the fibers in a freezer for some time. Moreover, it can be deduced that the already connectorized fibers do not suffer any major damage during the hydrogen-loading process[13].

The influence of jacketing on the fiber's performance has been observed also by others [12]. They also proposed a solution to this problem, which consists of stretching a fiber that has been bounded on both ends with a rotating wheel to eliminate the elastic memory in the fiber.

4.5 Hydrogen loaded fibers after connectorization

Fibers that have been connectorized first and hydrogen loaded afterwards have also been studied.

Two of these 2 m-long fibers were prepared in the same way as the other ones (LMA-10-UV PCFs with FC/APC connectors on both ends), one with and one without a protective jacketing. The results are presented in the previous subsection (4.4).

Moreover, also a commercial fiber ("Newport, patch fiber, single-mode, F-SM10-PM-C-2FCA, connector type FC/APC") has been tested. This fiber has been bought unloaded, and, as the other two, hydrogen-loaded afterwards. It was cured for 24 hours with an incoming power of 250 mW at 313 nm and observed to have a relatively low transmission (32.7 ± 1.5 %). This fiber was then tested at 375 nm (with an incoming power of 12 mW), at which wavelength a stable relative transmission of 44.4 ± 1.5 % was measured. At 280 nm many problems have been encountered, because the transmission oscillated a lot by slightly touching or stretching of the fiber. It was also observed that the mode of the fiber was distorted, i.e. a low intensity ensemble of many small dots (much smaller than the one showed in Figure 4) when the connector was screwed tightly into a holder was noticed. By loosening the connector a Gaussian mode was recovered. This effect was only observed at 280 nm and not at 375 nm.

A knife edge measurement was also performed to determine the mode field diameter of the commercial fiber. This method consists of measuring the power of a laser beam as a function of the position of the knife edge transverse to the beam. The measured data was fit to the function:

$$\mathrm{P_{measured}(z)} = \frac{\mathrm{P_{tot}}}{2}\left[1 - \mathrm{erf}\left(\frac{\sqrt{2}(z - z_0)}{w_z}\right)\right], \tag{7}$$

where z refers to the knife edge position, z_0 corresponds to the position of the center of the beam, w_z describes the $1/e^2$ radius of the beam in the vertical direction and erf(x) is the error function[14]. Performing measurements at different distances from the fiber and making a linear fit of the different values for $w_z(d)$, the MFD of the commercial fiber could be found, which is given by:

$$\mathrm{MFD} = 2w_0 = 2\frac{\lambda}{\pi\theta}, \tag{8}$$

where w_0 is the beam waist, λ is the wavelength and θ is the beam divergence. An accurate description of the knife edge method to measure the mode field diameter of a fiber at a given wavelength can be found in [16].

The results of those measurements are showed in Figure 5, where w_z was computed at different distances from the fiber's end at regular intervals of 2 mm. We have to remark that the measurement might not be saturated, i.e. it is possible that the photodiode only covered a small section of the beam and the flattening of the measured voltage did not coincide with the end of the beam.

[13] Unless for the fact that their facets were found to be slightly worse. Those fibers were therefore polished again before being tested.

[14] Actually not the beam power but the voltage measured on a photodiode was fit. However, to get the value of w_z the ratio between the measured and the total powers is needed, which corresponds to the ratio between the measured and total voltage, since they are linearly related by the Gauge constant of the setup that was used for that measurement.

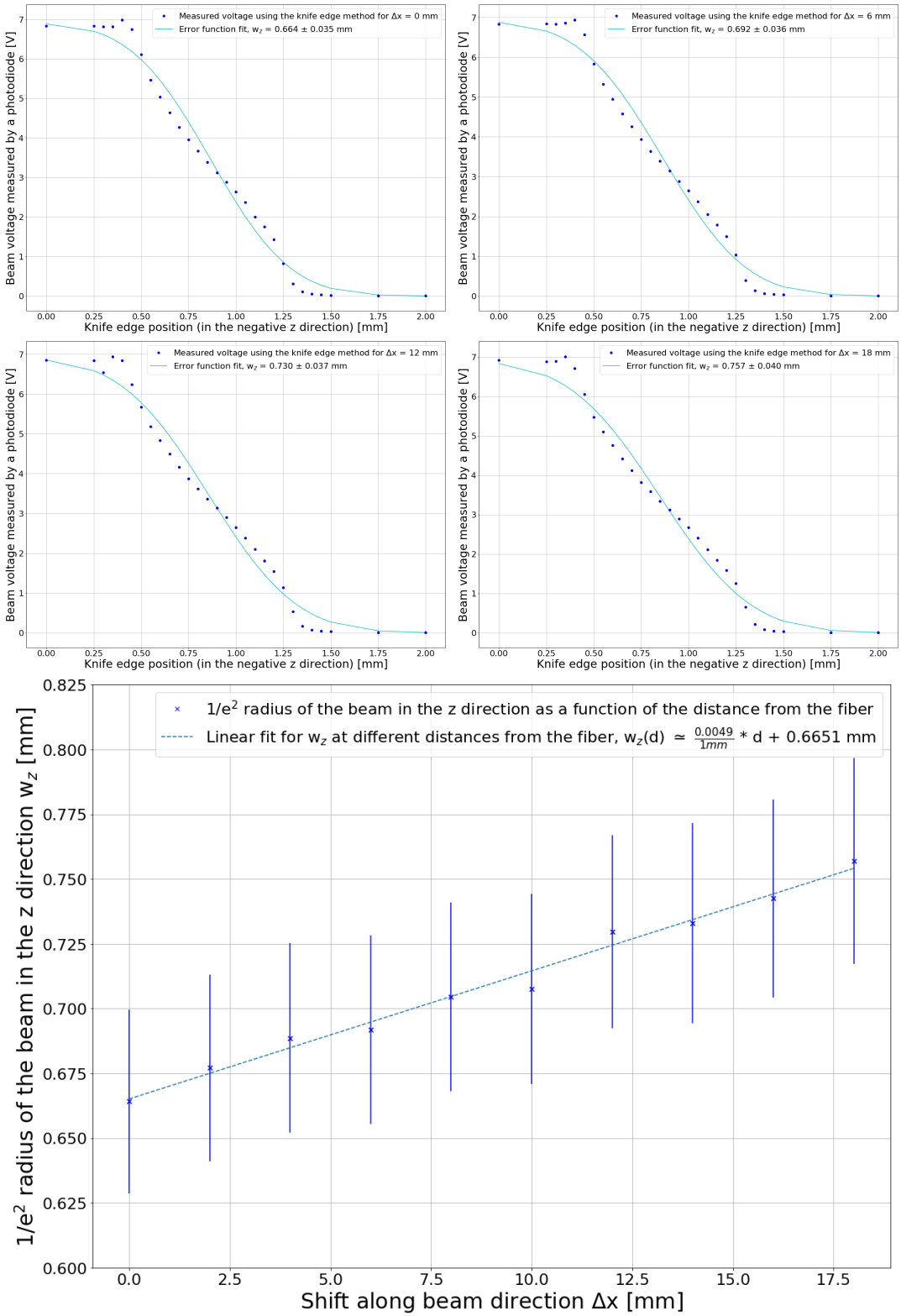

Figure 5: Knife edge measurement of the $1/e^2$ radius of the beam for different distances from the fiber's end (here only the plots of $\Delta x = 0$ mm, 6 mm, 12 mm and 18 mm are shown). Notice that these distances do not refer to the real distances from the fiber's end, but to the relative distance from a given point about 20 cm distant from the fiber's end. The linear fit of those different values is also shown and can be used to find the beam divergence (*lowest panel*). Remark: The error bars in the lowest plot refer to the standard deviation of w_z and have been estimated directly by the function "curve_fit" of the "scipy"-package of Python.

From these measurements the beam divergence was determined, $\theta = 0.00494 \pm 0.00024$ rad, and therefore also the mode field diameter of the commercial fiber at 280 nm, which is $\mathrm{MFD}_{280\mathrm{nm}} = 36.08 \pm 0.88$ μm.

This value of the mode field diameter is considerably different from one of a LMA-10-UV PCF which is around 8 μm for wavelengths roughly between 200 nm and 400 nm [13]. This could explain why such a bad behaviour was observed when trying to study the commercial fiber.

5 Conclusion

The effects of hydrogen-loading and UV curing optical fibers have been studied. In particular, it was found that in order to have a stable transmission which is not significantly affected by color centers, the fibers need to be cured with the highest available curing power of 250 mW. Additionally, long curing times ($>$ 24 hours) and high hydrogen concentration are preferable.

Moreover, it was also shown that when working below 313 nm, jacketing the fiber has more negative than positive effects, and therefore it is preferable not to use it.

There are, however, several aspects that have been noticed but still miss a clear explanation, as, for example, what caused the decrease of transmission accompanied by a distortion of the transmitted mode when keeping the fiber at 140°C for 77 hours.

Finally, it is important to note that the method of hydrogen-loading and UV curing that was studied here is not the only possibility to get solarization-resistant optical fibers. In 2014, a related work on hollow-core Kagomé lattice single-mode PCFs for UV applications at 280 nm has been reported [17].

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