Effects of Optical Power and Thermal Impacts on Microstructured and Low Index Coated Fibers – A Comparison

Kay Schuster*, Volker Reichel*, Jens Kobelke*, Anka Schwuchow*, Johannes Kirchhof*, Anna B. Wojcik**
* Institute for Physical High Technology Jena
Albert-Einstein-Str. 9, 07745 Jena, Germany
phone: (+49) 3641 206 259, E-Mail: kay.schuster@ipht-jena.de
** Hybrid Glass Technologies, Inc.
Princeton Corporate Plaza, 1 Deer Park Drive, Suite M, Monmouth Junction, NJ 08852, USA
phone: (+1) 732 445 4524, E-Mail: awojcik@hybridglass.com

Abstract

The high power transmission stability is characterized by launching up to 500 W at 940 and 980 nm into the fiber over a period of at least 30 min. The most critical experimental points for comparing the stability results are the reproducible stripping of the coating with a well defined crossover and the strict clean and rectangular preparation of the fiber end faces.

The far field and the numerical aperture are used as an indicator for changes of the optical coating properties. Small changes in the refractive index during the power stability tests have been detected for the low index acrylate and for the hybrid material.

It was tried to correlate the results with the thermochemical investigations of the used coating materials (DTA, TG).

The experimental results show the limits of applicability and the potential of both types of fibers for high power applications.

Keywords: fiber laser, coating, MOF, microstructured optical fiber, high power

1. Introduction

Pure and doped high silica fibers with a large refractive index difference to the outer cladding (high numerical aperture) are widely used for transmission of large optical power for illumination, in medicine or fiber sensor applications. Rare earth doped fibers, mostly with larger cross sections compared to standard telecom fibers are used for high power fiber lasers with specific radiation emission characteristics. In most cases the launched pump power is limited by thermo chemical and/or optical radiation stability of the polymer coating material.

Since the development of fiber lasers for the kW cw-operation [1] it became necessary to turn more attention to the power stability of laser fibers, particularly with regard to absorptions at the fiber-coating interface caused by scattering on microscopic defects and evanescence field effects.

Mainly the double clad fiber structure with high pump light exposure in the pump cladding [2] and with the direct interface to the coating requires high diligence regarding the coating material as well as the preparation technology.

Likewise the use of low index polymer coatings in high temperature evanescence field, Bragg and long period grating fiber sensor applications shows a great importance in temperature stable materials [3 – 6].

2. Experimental

For the investigation of the fiber power stability three different coatings have been selected. So we could examine material as well as numerical aperture influences on the fiber durability.

Fibers of 250 µm diameter has been drawn and coated with a single layer coating of Silicon RT601 (Wacker), a fluorinated Acrylate PC 370 (Luvantix) and double layer coating of the hybrid material HG-Li-3 (Hybrid Glass Technologies). The results have been compared with the testing results of a microstructured optical fiber (MOF) in an air-clad design (Figure 1). The Air-Clad-Fiber was coated with a high index standard single layer coating (DSM 3471-3-14).

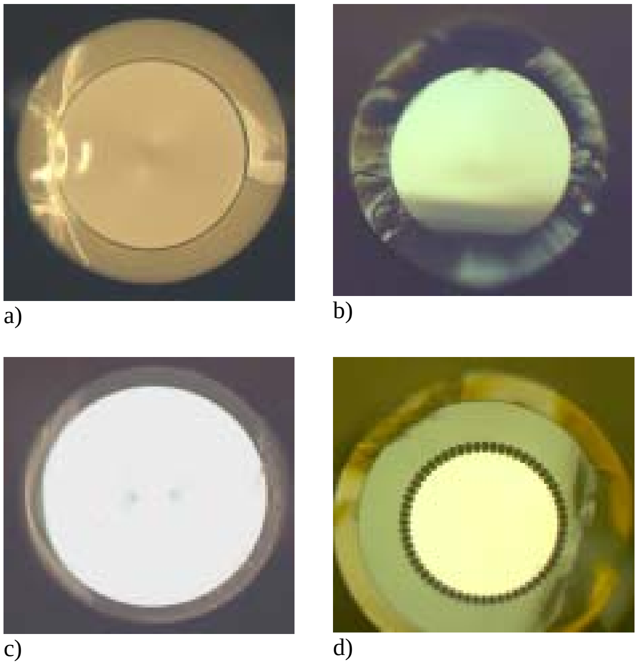

Fig. 1 Investigated fibers: fiber with low index acrylate PC 370 (a), fiber with low index silicon RT 601 (b), fiber with low index hybrid material HG-Li-3 (c), Air-Clad-Fiber with high index acrylate DSM 3471-3-14 (d)

The fibers have been assembled by selecting of 2 m pieces, carefully end face preparation (cleaving) and cleanly coating remove of 2.5 cm on both fiber ends. Two laser sources with an overall output power of 500 W (940 and 980 nm, NA 0.4) has been used. To prevent damages at the laser beam input it was necessary to cool the fiber ends. Repeated tests show the absolute necessity of a clear coating remove at the fiber ends. Small coating rests led to increased scattering effects, decreased effective NA and to an earlier coating burning off.

The test setup is simplified shown in the scheme of figure 2.

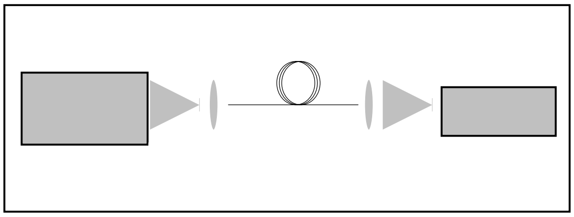

Fig. 2 Setup for the fiber power stability tests

For the evaluation of degradation effects and changing of coating properties the numerical aperture (far field) and the transmission intensity has been measured before and after the experiment. The far field measurements have been carried out with a Hamamatsu FFP Measurement System (white light, 400 – 900 nm). The transmission spectra have been measured with an Instrument Systems spectrometer Spectro 320d.

For the estimation of thermo chemical influences of the coating material on the power stability a TG measurement was carried out using a Perkin Elmer TGA7.

3. Results and discussion

3.1 TG measurements

The thermochemical properties of low index polymer coatings are described elsewhere [7]. It is clearly to be seen, that the thermal stability of acrylate coatings (low index as well as high index) is noticeable lower than that of alternative materials (hybrid material, silicone). The former show onset temperatures of about 250 °C the latter of about 300 °C and 410 °C, respectively.

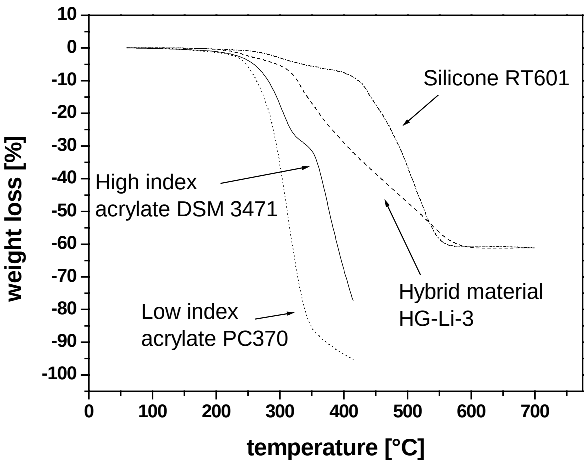

Figure 3 Thermogravimetry of investigated coatings

3.2 Power stability tests and far field measurements

The far field image of non irradiated fibers is shown in figure 4. In a strongly multimode step index fiber as investigated here the far field should have plateau as to be seen for the Air-Clad-Fiber. The Air-Clad-Fiber has a strong index step from silica to air without additional absorptions. The polymer coated fibers have an evanescent part of light in the coating with stronger absorptions for larger angles of propagated light. Note that the penetration depth of the evanescent field decreases with increasing numerical aperture [8]. For that reason the lower intensity of the hybrid material and silicone at angles between 5 and 15 ° is slightly lower because of the higher refractive index and the lower numerical aperture, respectively. For the estimation of the NA the 5 % criterion has been applied (table 1).

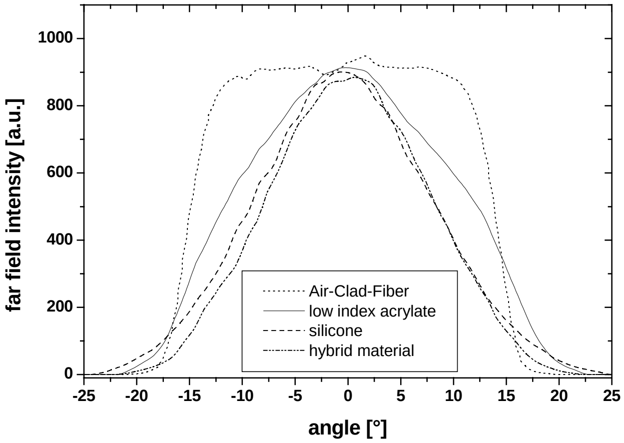

Figure 4 Far field image of non irradiated fibers (polymer coated fibers in comparison to an Air-Clad-Fiber)

Table 1 Numerical apertures of investigated fibers before and after high power irradiation (accuracy ± 0.02)

	Air-Clad-Fiber	Silicone RT601	Hybrid material HG-Li-3	Acrylate PC370
NA (before)	0.29	0.34	0.30	0.35
NA (after)	0.29	0.34	0.32	0.36

As shown in table 1 and figure 5 the small change in numerical aperture of the thermal curable hybrid material and low index acrylate during high power irradiation is negligible.

However, we have to note that the numerical aperture of the hybrid material and the low index acrylate coated fibers are much lower than expected. Calculations from the measured refractive indexes of the bulk materials should give NA values of at least 0.48 for both materials. For the power stability tests as well as for the NA investigations 2 m fiber samples have been used as described above. The preparation conditions have apparently a strong influence on the measured NA caused by coating absorption effects of high order modes. The exact influence of the silica/air interface (length and surface quality, here 2.5 cm coating has been removed) is critically and will be a topic of further investigations.

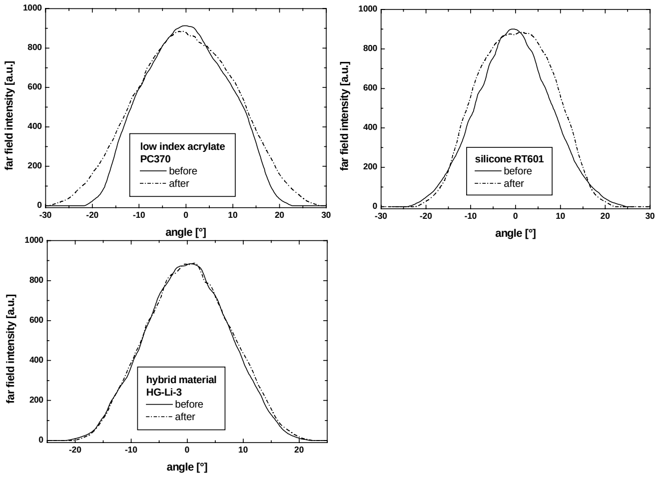

Figure 5 Far field intensity of different coated fibers before and after the high power irradiation

With the exception of the Air-Clad-Fiber all other polymer coated fibers have been stable against the high power irradiation. In the course of exposure test the output power has been detected (figure 6). It can be seen that the output power of the fibers is slightly enhanced as a result of the output power shift of the pump diodes. The repeated tests for low index acrylate and silicone show the good reproducibility.

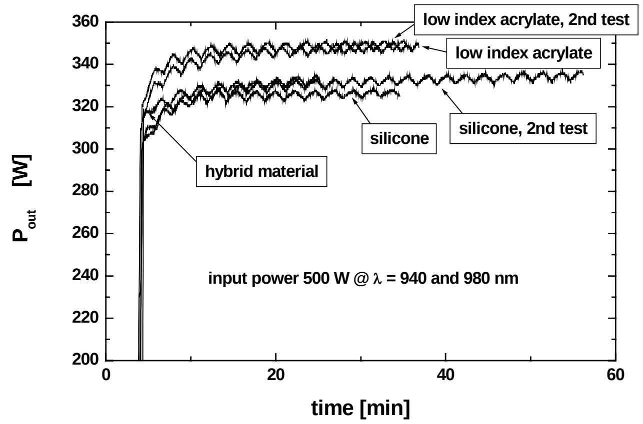

Figure 6 Time elapsed of the power stability test. The low index acrylate coated fiber shows a decreasing power transmission.

During the irradiation the fibers with the low index coating showed a homogeneous "glow" along the whole fiber length whereas the Air-Clad-Fiber showed distributed bright and hot spots. As a result the coating burned off while the input power has been increased. The spots are an outcome of a partially leaking light through the bridges. Because of the high refractive index of the standard single layer acrylate (1.51 @ 1300 nm) the leaked light is absorbed and transferred into thermal energy at the coating / fiber interface. Caused by the low heat conductivity and the low thermal stability of the acrylate coating the fiber is damaged (see 3.3 Simulation of thermo-optical capability).

3.3 Simulation of thermo-optical capability of polymer coated solid fibers and Air-Clad-Fibers

The thermochemical capability of the fiber polymer coating is often a limit for high power applications [9]. The question of propagation behavior relating to geometrical fiber parameters of Air-Clad-Fibers has been intensively discussed by Issa [10].

We approximated numerical the radial temperature profile by using a finite element method. Thermal load of the core was assumed corresponding to a temperature of 300 °C. The surface of the fiber coating is cooled to room temperature (20 °C). The heat transfer is modeled by convective heat flow in the silica, the air chambers of PCFs and coating polymer. The material coefficients are listed in table 2. The comparison between solid and air-clad polymer coated fibers shows, that the air clad region with typical bridge width of 1 µm has only a moderate influence on the radial temperature distribution (< 20 % of total temperature slope, figure 7). It is mostly influenced by the polymer coating. This effect is particularly caused by the about one order of magnitude lower thermal conductivity λ of the polymer related to silica (whereas density ρ and heat capacity c_p are similarly)

Table 2 Material parameters for thermal distribution simulation

	SiO_2	coating polymer (acrylate)	air
c_p [J/kg/K]	1255	1500	1000
λ [W/m/K]	1.36	0.18	0.024
ρ [kg/m³]	2200	1200	1.29

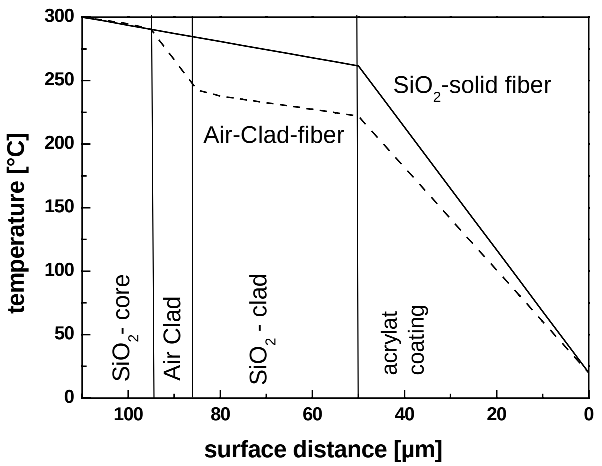

Figure 7 Simulated radial temperature profiles of solid fiber and Air-Clad-Fiber (bridge width: 1 µm, bridge length: 10 µm)

Bridge widths of a few micrometers have an almost negligible effect on the radial temperature slope. The fiber as investigated here has an average bridge width of about 1.3 µm. With this bridge width we got a temperature drop of merely 40 °C. An effective thermal insulation of the fiber core requires bridge width well below micrometer dimensions (figure 8).

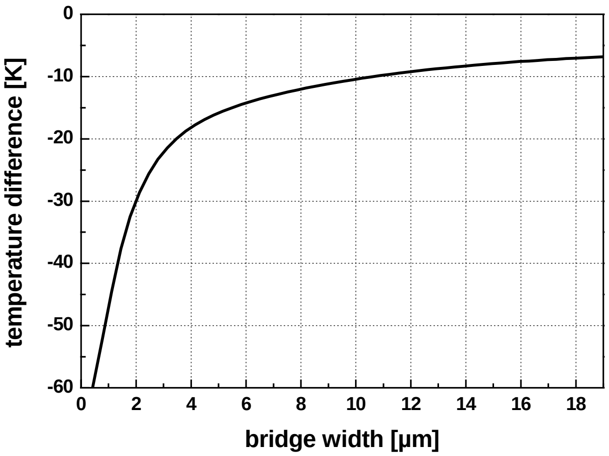

Figure 8 Influence of the bridge width on the temperature difference over the air clad region (bridge length: 10 µm)

4. Conclusions

We have shown that coating materials with high (silicone, hybrid material) as well as lower thermal stability (low index acrylate) offer a high potential for the use in high power fiber lasers. Air clad fibers in combination with a high index coating exhibit the risk of leaking light via the silica bridges and a subsequent absorption in the coating material. An effective optical decoupling of the coating and a strongly decreased thermal conductivity could be achieved with a bridge thickness < 1 µm.

5. References

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