Coating of Thin Optical Fibers at High Capillary Number

Pflieger, K.; Schrein, D.; Overmeyer, L.

Abstract

The aim of this work is the construction of a system for the coating of optical single-mode fibers with an optical polymer, which acts as the cladding. These fiber cores are to be processed by means of a dip-coating process. The coating should be as thick as possible. For this purpose, the viscosity is varied via the temperature and the layers thus obtained are examined for their thickness with the aid of a confocal microscope.

1 INTRODUCTION

For the low-loss transmission of optical signals in a waveguide, a defect-free boundary layer between core and cladding is required in addition to a core made of a material with low optical loss.

Defects are, for example, inclusions at the boundary layer or deviations from the radial symmetry. These deviations are often in the form of a cut or a deformation of the core.

In fact, the interface between core and shell is the most important area, but also the most sensitive. The cladding has therefore a double role. It not only fulfils the task of wave guiding, but it also ensures a higher mechanical resistance.

The ITA is currently working on a single-mode waveguide made from a laser-active material as part of the LaPOF project. This laser-active core is manufactured with the help of an extruder.

Single-mode fibers are characterized by a very small core cross-section. The diameter of the fiber core is only a few micrometers. Their small cross-sections make them particularly vulnerable to mechanical damage. Furthermore, the handling of these thin fibers requires special attention.

Therefore, the coating process is particular challenging. Ideally, the ratio of core to shell for a single-mode fiber should be greater than 1:10. This corresponds to a cladding thickness of more than 100 µm.

A coating process has been developed for these thin single-mode fibers. Attention is particularly paid to a thick cladding layer for easier handling.

For the coating, a dip-coating process is used and optimized so that the process can take place right after the extrusion in one process. This means that the pulling speed is not a free variable but is determined by the extrusion parameters. All other parameters must then be adjusted to this value.

In this work, the dip-coating was used to coat a thin fiber with a liquid monomer which is subsequently polymerized with a UV radiation source.

2 CONSTRUCTION

Dip-coating is a process for coating surfaces. For this purpose, the substrate is dipped into the solution and then pulled out quickly. Adhesion forces cause the solution to adhere to the substrate. Subsequently, the cladding must be chemically fixated on the substrate. This can be done for example by solidification of a melt or by polymerization of plastics.

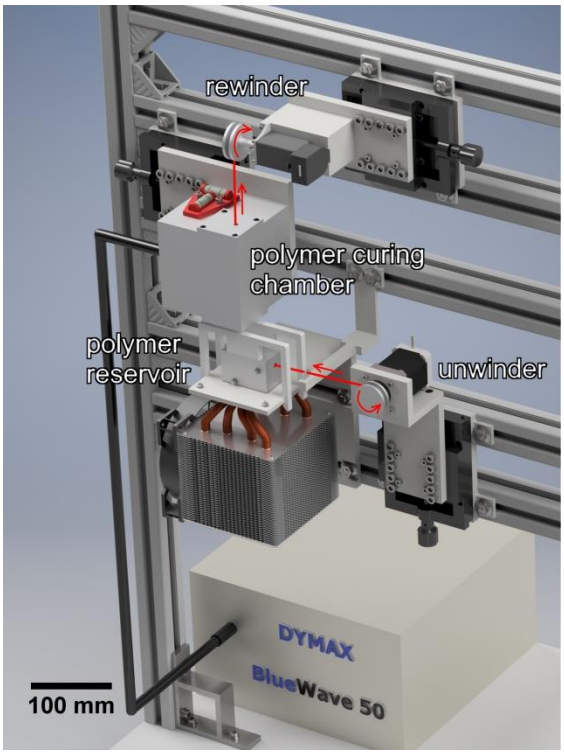

Fig. 1: A rendered image of the construction

To coat the fibers, a test stand was designed, which consists of four assemblies (Fig. 1 and 2). At the beginning and at the end are stepper motors in position 1 and 2 (Fig. 2). These ensure the uniform conveying of the fiber from roll to roll. The motors are each mounted on linear tables, so that the individual components can be

aligned with each other. Assembly 2 consists of the polymer reservoir and a cooling unit.

The cooling consists of a thermoelectric cooler in conjunction with an air-cooled heat sink. The reservoir is fixed on the Peltier device. The temperature in the polymer is measured with a Pt100 measuring resistor. An external control unit allows the polymer to be cooled to a given temperature.

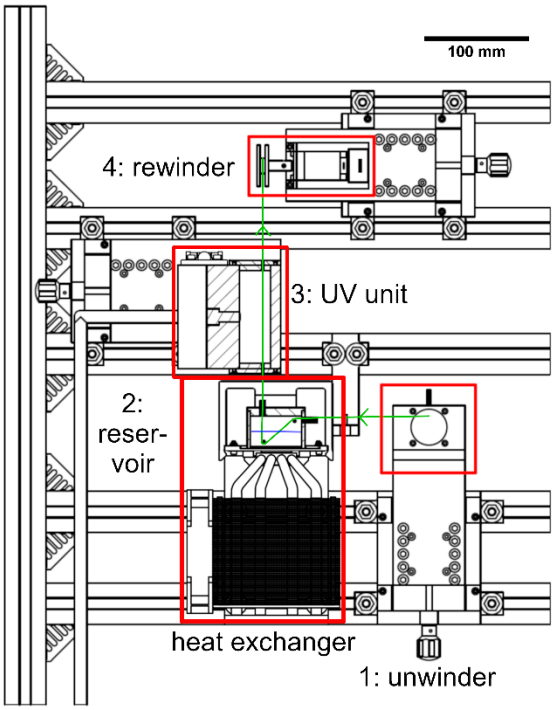

Fig. 2: A schematic representation of the construction

The coating works as follows. The fiber enters the polymer container from the right motor through a little hole and is then redirected twice inside so that the fiber dips into the polymer bath and comes out of the container upwards. Directly above the bath is a chamber with an UV lamp inside (assembly 3) for curing the UV-active polymer. The fiber is then guided through this chamber. Finally, the coated fiber is wound up with the second motor on top of the assembly.

Since the viscosity of the polymer affects the coating ability and the temperature effects directly the viscosity via the Andrade equation, the temperature has direct impact on the coating. Therefore, the temperature of the polymer must be adjustable. For that reason, a controlled system was designed (Fig. 3), which consists of the Peltier device, the fan, an amplifier circuit and a digital PID controller (LC100).

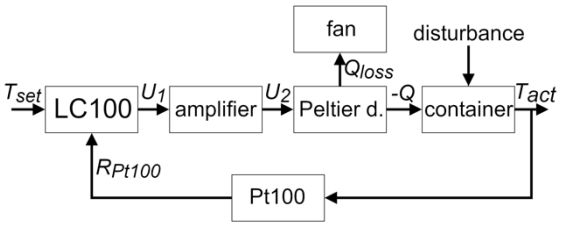

Fig. 3: A sketch of the control system

The Andrade equation is given as:

$$\eta = A \exp\left(\frac{b}{T}\right). \qquad (1)$$

In this equation is η the viscosity and T the temperature in Kelvin. To get the material constants A and b, the viscosity was determined at different temperatures and the collected data was used for fitting these parameters.

3 DETERMINATION OF THE FIBER DIAMETER

To determine the diameter of the coated fiber, a confocal microscope was used. With this measuring device it is only possible to determine the topography of the surfaces facing the lens. Therefore, only the topography of circle segments, but not an entire circle, can be determined. Consequently, the diameter of the fiber can be determined only indirectly via a function adaptation of the circle segments to the circle equation.

First, a piece of fiber is aligned along an axis of the measuring plane and then measured. This leads to a cylinder segment (Fig. 4).

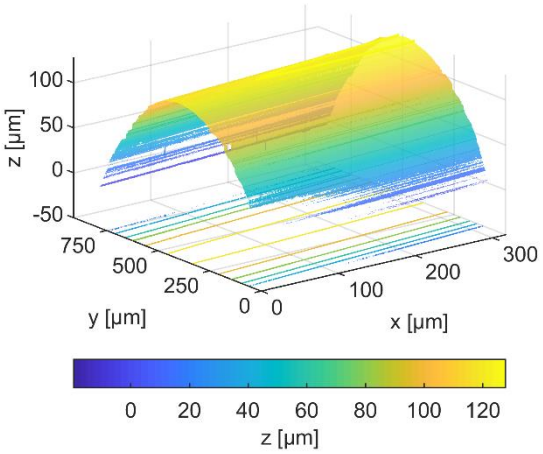

Fig. 4: A surface plot of a measured cylinder segment

Then the image is rotated so that the fiber is exactly parallel to the x-axis. In the next step, profile cuts are made orthogonal to the fiber through the measurement plane (fig. 5).

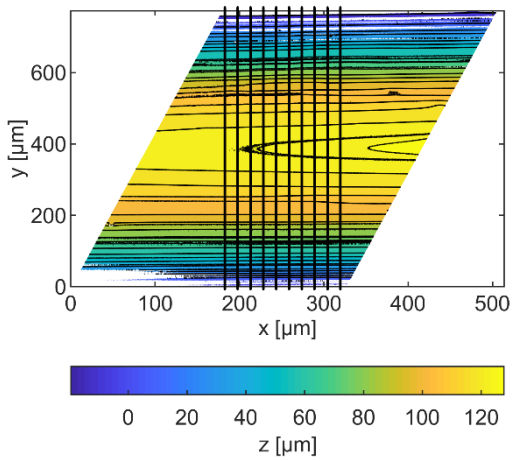

Fig 5: A contour plot of the aligned segment. The profile cuts are illustrated by lines.

As a result, a plurality of circle segments is obtained. To obtain the diameter of the coated fiber, a circle is fitted to the segments (fig. 6). The method of Coope [1] was used for that.

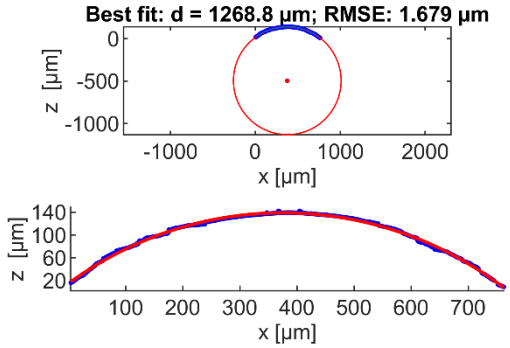

Fig. 6: a diagram of one profile cut with a fitted circle

With this method one gets not only the diameter of the fiber, but also information about possible deviations from the ideal circle or from the spatial distribution of the diameter on the examined piece.

4 THE LLD-THEORY

Due to the viscosity of the polymer, the liquid directly at the fiber surface must move with the same speed as the fiber. This means, there must be a flow of material from the reservoir. At the same time the surfaces get enlarged by the flow. This leads to an energetic unfavorable condition. Therefore, the surface tension tries to create a volume with less surface area. This force counteracts the coating. Therefore, the quotient of these two forces plays an important role. It is called Capillary number, Ca:

$$Ca = \frac{\eta V}{\gamma}. \qquad (2)$$

In this equation, η is the viscosity, γ is the surface tension and V is the drawing speed.

For small Ca Levich, Levi and Derjaguin first found a relationship between Ca and the layer thickness [2]. It is called the LLD-Theory. Small means, Ca is much smaller than 1. The exact LLD law is written as:

$$h = 1.34\, r\, Ca^{\frac{2}{3}}. \qquad (3)$$

The film thickness is given by h and r is the radius of the used fiber.

4.1 WHITE-&-TALLMADGE-CORRECTION

The LLD law can only be applied if Ca ≪ 1 and this means h ≪ r. In the case of a single-mode fiber with a radius of less than 10 µm, that corresponds to a layer thickness of less than 1 µm. This is too small for coating optical fibers.

To achieve thicker layers, the White-&-Tallmadge-Correction must be used [2]. This new law is

$$h = \frac{1.34 r Ca^{\frac{2}{3}}}{1 - 1.34 Ca^{\frac{2}{3}}}. \qquad (4)$$

This equation has a divergence point for Ca = 0.64. Here, the pressure gradient disappears between layer and reservoir. The entire fluid in the basin would be entrained under zero gravity and the achievable film thicknesses increase drastically.

Above the point of divergence (Ca > 0.64), the equation loses its validity. This becomes clear as the calculated layer thickness becomes negative.

4.2 THE CASE OF HIGH VELOCITY

In the case of high speeds, the momentum transfer from the fiber to the liquid must be considered. One speaks of high speeds already at a Weber number We of more than 0.1.

The effect of momentum transfer enhances the delivery of fluid from the reservoir. This ensures that a higher layer is built up than the LLD theory predicts. In addition, the point of divergence shifts to lower Ca.

Beyond the point of divergence, a plateau appears in which Ca has only a minor role on the layer thickness. Here the fiber diameter and the distance the fiber travels in the basin play a much more important role [2].

Much has already been written in the literature on the case of low viscosity and speed. Since the expected film thicknesses are small in this regime, the work will be focused on Ca ≈ 1, beyond the divergence point.

5 PLATEAU–RAYLEIGH INSTABILITY

A fiber enclosed by a liquid cladding is not a stable system. This metastable state breaks down after a certain time t_0 into a periodic chain of single droplets. The driving force is the minimization of the surface energy.

These droplets grow exponentially from an initial disturbance. Therefore, there is a period t_0 in which the effect is negligible. But if the time t_0 passes, these modulations will grow explosively. t_0 is highly dependent on the viscosity of the used polymer and high viscosity leads to long times t_0 [4]. In this setup was t_0 between 1 and 30 seconds.

Thus, the cladding must be fixated within t_0. Consequently, t_0 is the time, during which the fiber must be delivered from the reservoir to the UV lamp.

6 RESULTS

The coating was done with two different fibers. First, a copper fiber with a diameter of 100 µm was used. Second, a fiber was coated, which consists of 14 twisted nylon fibers. This cord has a diameter of 37 microns. The speed at which the fiber was drawn is 2.5 cm/s. The fiber was then coated at different viscosities, which was adjusted through the temperature.

Figure 6 shows the fiber diameters after coating at different viscosities for the two different fibers.

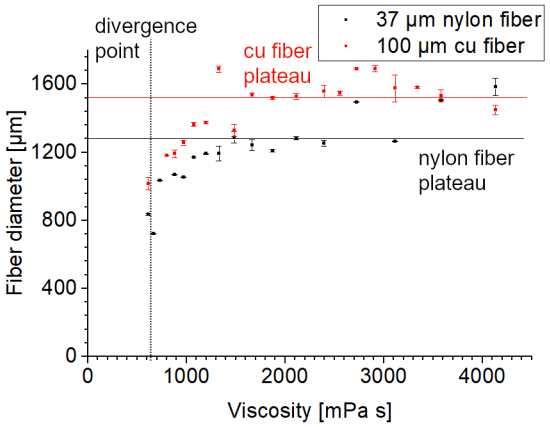

Fig. 6: Fiber diameter after coating with UV curing polymer at different viscosities

The diagram can be divided into two sections. There is the divergence point and the plateau area. The divergence point is around 650 mPa s. At viscosities of over 650 mPa s, a plateau of the layer thicknesses forms. For the copper fiber the plateau has a maximum value of 1700 µm. But it is typically around 1520 µm. This plateau is for the thinner nylon fiber around 1240 µm. The maximum diameter for this nylon fiber was 1600 µm. The thickness exceeds the correspondent value for the copper fiber. Although the copper fiber has a radius that is more than three times thicker, the influence of the radius is small in the examined interval.

7 CONCLUSION

The highest achieved diameter ratio between the fiber core and the coated fiber for the copper fiber was 1:17. And the nylon fiber has a maximum ratio of 1:43. This is more than needed to use the process for coating optical fibers. The thinnest possible cladding must have the thickness of a couple of light wavelengths. That corresponds to a fiber to cladding ration of 1:3. Furthermore, was a requirement to create a fiber, which is robust and easy to handle. The setup also meets this requirement, since most standard optical fiber have a smaller diameter than 200 µm. In this work a diameter of 1700 µm was measured.

The layer thickness is monotonically dependent on the viscosity in the divergence regime. This could be used to control the thickness of the cladding directly by temperature. For this, however, further investigations need to be made.

It must be said that low viscosities, which lead to thinner layers, are more difficult to handle, since Plateau–Rayleigh instability quickly occurs. Therefore, this method is more suitable for coating with a high viscosity to create thick layers.

8 REFERENCES

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Author:	Pflieger, Keno Schrein, Daniel Overmeyer, Ludger
University:	Leibniz University Hannover
Department:	*Institute of Transport and Automation Technology*
