Lasers in Manufacturing Conference 2017

Inducing scattering centers in medical optical fibers by pulses in the range of ps.

Alexander Wall[a,*], Hans-Jürgen Hoffmann[b], Verena Knappe[a]

[a]*Laser- und Medizin-Technologie GmbH, Fabeckstraße 60-62, 14195 Berlin-Dahlem, Germany*
[b]*Institute of Materials Science and Technology: Vitreous Materials, University of Technology of Berlin, Englische Strasse 20, 10587 Berlin, Germany*

Abstract

Optical fibers are used in dental medicine to treat gingival sulcus with light of 450nm wavelength. About 3mm long diffusers at the end of the fiber increase the irradiation angle by scattering the light inside the core. In order to maximize the stability of the fiber, we investigated a novel approach to induce scattering centers inside the fiber. Limits and possibilities of the front-end induction inside fused silica fibers were studied using laser pulses in the range of 10 ps. Threshold intensities for the generation of scattering centers were determined as well as their growth as a function of intensity, number of pulses and time interval between pulses. The threshold was compared with predictions resulting from a rate-equation. Beside the intended scattering centers other phenomena occurred such as periodical ripples and material alteration inside the fiber that seem to interfere with the creation of the scattering centers.

Keywords: Silica fiber; picosecond pulse; medical optical fibers; fiber processing; scattering center; diffuser; Microstructure

1. Introduction

Developing applications for optical fibers, i.e. in medicine, is strongly related to the ability to process microstructures into these fibers, while maintaining their stability. In particular, focused ultrashort laser pulses allow a fast and confined modification in the target volume around the focal point. Upon relaxation, the irradiated material exhibits structural alterations that can be used to manipulate the propagation of the light inside the fiber. For example for treating liver tumours, scattering centers are inscribed into one end of optical fibers.

* *E-mail address:* wall@campus.tu-berlin.de .

2. Objective

In this paper we investigated the induction of scattering centers into fiber cores through the end face of the fiber by modifying the core with ultrashort laser pulses, as illustrated in Fig. 1. This method can help to prevent the lateral surface (the buffer and jacket of the fiber) from being irradiated, which can help maintaining the stability of fibers.
Systematic studies of the size of the modified areas as a function of the pulse energy E_{Pulse}, the number of pulses N, and the time interval T between consecutive pulses were performed inside the core of the fibers. Furthermore, the determined intensity threshold for inducing a scattering center was compared to the prediction of a rate equation.

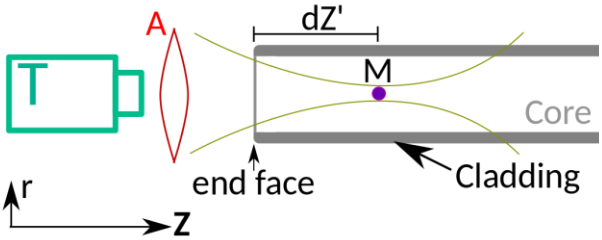

Fig. 1: Modifying the core of a fiber through the end face by the laser T. Laser pulses are focused by the objective A into the fiber. The modified area/scattering center M occurs in the focus of the objective A in a distance to the end face dZ'.

3. Experimental procedure

A Nd:YVO4 laser was used as the source of ultrashort laser pulses with a center wavelength λ = 1064nm and pulse duration t_0 ≈ 9.3ps. Laser pulses with energies up to E_{Pulse} ≈ 150µJ and peak powers up to P_{Peak} ≈ 15.66MW were applied to induce modifications of the fiber core. A multi mode fiber was used throughout the investigation. The fiber core consisted of synthetic fused silica (refractive index n= 1.448, diameter d=400µm) and the cladding of fluorine-doped fused silica (n=1.431, d=440µm). The pulses were focused by an objective (NA = 0.26, working distance WD= 30.5mm) into the fiber core with a distance dZ' to the end face. The laser beam had a minimum beam width w_0 ≈ 7.3µm, Rayleigh length z_0 ≈ 38.4µm and a divergence angle θ ≈ 0.24rad in air.
The buffer and jacket were stripped of the silica fiber to avoid an influence on the focused light beam inside the core, and by cleaving the fiber a plane and orthogonal end face was created (see Fig. 1). Fig. 2 shows a prepared fiber for the processing. The processed fibers were analysed under an optical microscope.

The intensity I of the laser pulse was defined as:

$$E_{Pulse} = \int_{-\infty}^{\infty}\int_{0}^{\infty}\int_{0}^{2\pi} I \cdot r \cdot d\phi dr dt$$

$$I(z,r,t) \approx E_{Pulse} \frac{4\sqrt{ln2}}{\sqrt{\pi}\pi t_0 w^2(z)} exp(-4ln2\, t^2/t_0^2) exp\left(-2\, r^2/w^2(z)\right) \quad (1)$$

with

$$I_{Peak} = E_{Pulse} \frac{4\sqrt{ln2}}{\sqrt{\pi}\pi t_0 w^2(z)}$$

z is the axis parallel to the beam axis, r is the distance to the beam axis, t is the time and $w(z)$ is the beam width as the function of the position z.

4. Results

4.1. Inducing scattering centers through the end face

Fig. 3 and Fig. 4 show an exemplary fiber after it was processed about 700µm behind the end face with single laser pulses focused through the end face. Each pulse, with the pulse energy E_{Pulse} = 135µJ, modified the fiber core. As can be seen in Fig. 4 these modifications also scatter light, as was required.

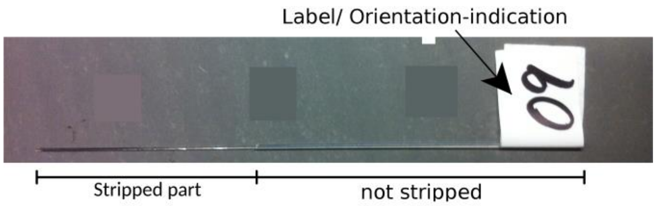

Fig. 2: Prepared optical fiber.

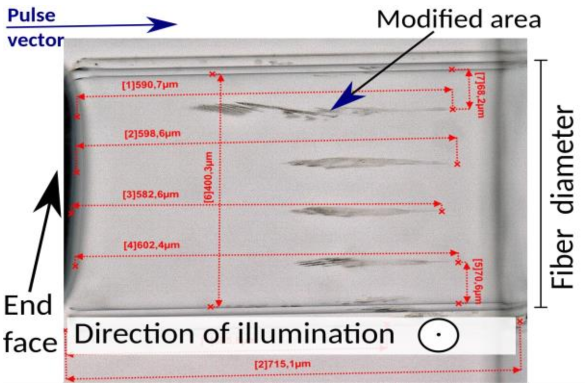

Fig. 3: Processed fiber with single pulses (pulse energy E_{Pulse} = 135µJ). Illuminated from below.

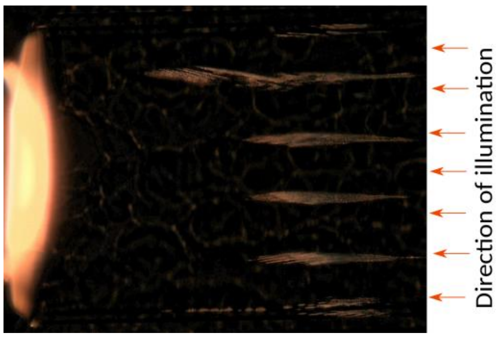

Fig. 4: Similar fiber from Fig. 3. Illuminated from the side to show the capability of the modified areas to scatter the light.

4.2. The length of the scattering centers as a function of the pulse energy, number of pulses and time interval between pulses.

The effect of single and multi pulses on the glass structure of optical fibers has been studied as a function of the parameters:

- Pulse energy $E_{Pulse} \epsilon [4.82\mu J; 135\mu J]$
- Number of pulses $N \epsilon [1; 13000]$
- Time interval between consecutive pulses $T \epsilon [99ns; 100\mu s]$

For the attempts with the multi pulses, on the one hand, the number of pulses N was varied with a constant pulse energy E_{Pulse} = 9.65µJ and time interval between pulses T=100µs. On the other hand, the number of pulses N= 2, and the pulse energy E_{Pulse} = 9.65µJ was kept constant and the time T was varied. The length of the modified areas has been measured and plotted against the pulse energy E_{Pulse}, number of pulses N and the time interval T between pulses. This is presented in Fig. 5.

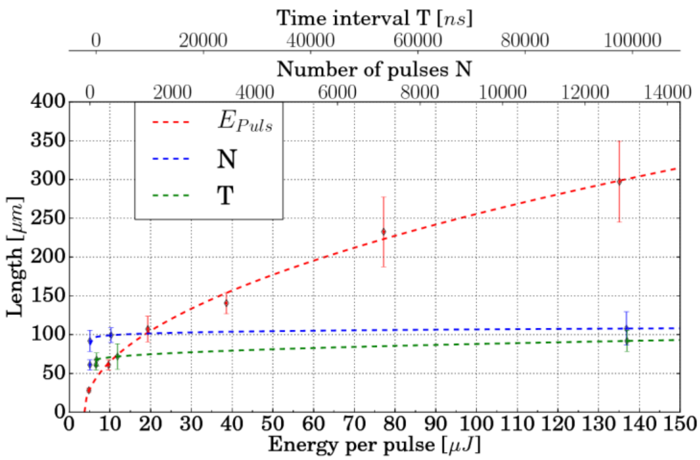

Fig. 5: Length of the scattering centers as a function of the pulse energy E_{Pulse}, number of pulses N, and the time interval T. The points are the measured values and the dashed lines are the fitted curves.

As the results show, the size of the modified area depends mainly on the pulse energy E_{Pulse} and to a lesser extend on the number of the pulses N, and the time interval T between the pulses. To fit the modifications M to a defined size one can take profit by adjusting N and T.

Fitting equation (2) to the data presented in Fig. 5 yielded the threshold energy E_{Pulse} to modify the fused silica.

$$Length = f(E_{Pulse}) = a \cdot \sqrt{E_{Pulse} - b} \tag{2}$$

$$E_{thr,meas} = b = (3.75 \pm 1.21)\mu J$$

The threshold intensity therefore is given as:

$$I_{thr,meas} = E_{thr,meas} \frac{4\sqrt{ln2}}{\sqrt{\pi}\pi t_0 w_0^2} = (0.36 \pm 0.12) \frac{TW}{cm^2}$$

By evaluating the area the peak intensity of the laser pulse (see equation (1)) succeeds the threshold $I_{thr,meas}$, it is possible to make predictions about the size and shape of the modified silica. Fig. 6 illustrates this along the beam axis (the origin of the z-axis corresponds to the focus of the laser beam). As a result the maximum length of a scattering center is $2 \cdot z_{thr}$ and the scattering center lies within the limits (z_{thr}, -z_{thr}).

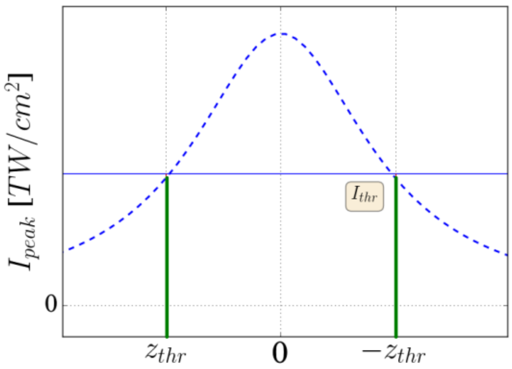

Fig. 6: The blue dashed line is the pulse intensity from equation (1) and the continuous line corresponds to the threshold intensity $I_{thr,meas}$. $\pm z_{thr}$ are the points the intensity I equals the threshold intensity.

Figure 7 to Figure 9 show the modified area of fused silica after the interaction with a laser pulse of a certain pulse energy E_{Pulse}. The blue curve represents the beam width w(z) and the green curve the position the peak intensity of the beam I is equal to the threshold intensity $I_{thr,meas}$.

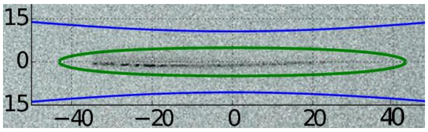

Fig. 7: $E_{Pulse} = 9.65\mu J$

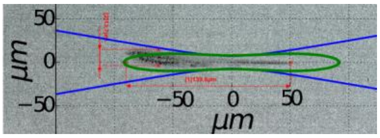

Fig. 8: $E_{Pulse} = 38.6\mu J$

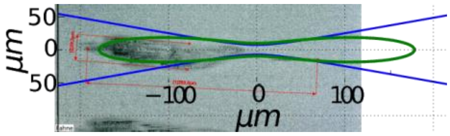

Fig. 9: $E_{Pulse} = 135.1\mu J$

Comparing the real modifications with the predicted contour leads to the conclusion that the predictions are in good agreement with the observation.
One aspect that becomes apparent for the energy value E_{Pulse} closest to the threshold $E_{thr,meas}$ (see Figure 7) is that the modification is more evenly spread within the area between the green curves. With increasing energy E_{Pulse} the formation of modifications becomes more and more dominant in the left part of the green curve. Since the pulses propagated from the left to the right side, this means the formation becomes increasingly dominant in the area where the pulse passes first.
The reason why this behaviour could occur is that, for increasing pulse energies E_{Pulse} on the incoming side, an increasing part of energy is deposited into the fiber material and larger amounts of light is reflected by the induced plasma. As a consequence the laser intensity I declines spatially faster for larger pulse energies E_{Pulse} along the propagation path of the pulse P inside the green area.

4.3. Theoretical threshold intensity to modify fused silica

The minimum intensity $I_{thr,meas}$ to modify fused silica will be determined in this section with the calculations proposed by Stuart et al, 1996. The assumptions made by Stuart are:

- Modifications occur in fused silica for electron densities larger than $\rho_{thr} = 10^{21}\ {}^{1}/_{cm^3}$.
- The multi photon and avalanche ionization are considered the dominant ionization processes. Thermal effects can be neglected for pulse durations $t_0 < 20\text{ps}$.

In this approximation the total change of electron density ρ can be determined by the following rate equation:

$$\frac{d\rho(t)}{dt} = \frac{d\rho_{MP}[I(t)]}{dt} + \frac{d\rho_{AI}[I(t)]}{dt} = P[I(t)] + \alpha\rho I(t)$$

The first addend denotes the change of the electron density induced by multi photon ionization and the second, the change due to avalanche ionization. $\alpha = (6.5\ to\ 13)\, cm^2/(ps\ \cdot TW)$ is the avalanche ionization rate for fused silica and P[I(t)] is the multi photon ionization rate, in our case for the wavelength λ = 1053nm and the eight photon process, which is given by:

$$P[I(t)] = 9.52 \cdot 10^{10} \cdot I^8(t) \frac{1}{cm^2\,ps} \qquad (3)$$

The units of the intensity $I(t)$ in equation (3) is TW/cm^2.

Because we evaluate the change in electron density for a fixed position we just have to consider the temporal change of the intensity:

$$I(t) = I_{Peak} \cdot exp(-4\ln(2)\, t^2/t_0^2)$$

Setting $\rho = \rho_{thr}$ and solving equation (4) for the peak intensity I_{Peak} yields the threshold intensity I_{thr} required to modify SiO2.

$$\rho(I_{Peak}) = \int_{-\infty}^{\infty} \frac{d\rho(t)}{dt} dt \qquad (4)$$

$$I_{thr,calc} = I_{Peak} = (0.45 - 0.77)\frac{TW}{cm^2}$$

The measured threshold intensity $I_{thr,meas} = (0.36 \pm 0.12)\, TW/cm^2$ and the calculated interval $I_{thr,calc} = (0.45\ to\ 0.77)\, TW/cm^2$ are consistent within their errors.

Figure 10 shows the damage fluence F for a series of measurements as a function of the pulse duration $t_0 = \tau$ by Stuart et al, 1996. The measured damage fluence F of the present investigation is

$$F_{thr,meas} = \frac{I_{thr,meas} * t_0\sqrt{\pi}}{2\sqrt{ln2}} = (3.5 \pm 1.19)\, J/cm^2$$

$F_{thr,meas}$ is inserted into the Figure 10 as a red dot.

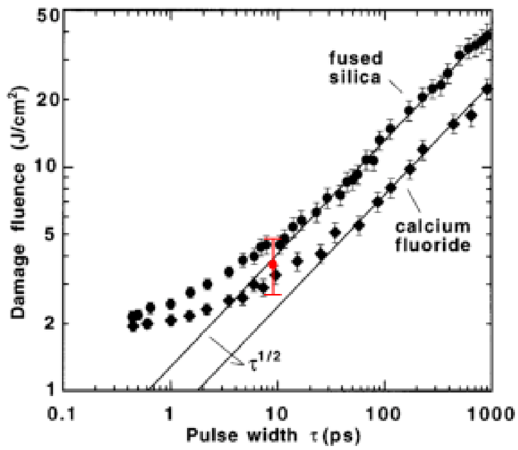

Fig. 10: Measured values of damage threshold for the wavelength λ = 1053nm and fused silica as well as calcium fluoride. This figure has been taken from an article written by Stuart et al, 1996. The measured value from the present investigation is added as a red dot.

4.3. Periodical structures

Some of the modified areas induced in the fiber exhibited rippled structures, as can be seen in Fig. . The appearance of these ripples was neither uniformly distributed over a single modification nor similarly shared by other modifications. Further it can be stated that the likelihood of occurrence of the periodical structures is higher at the edge of the fiber.

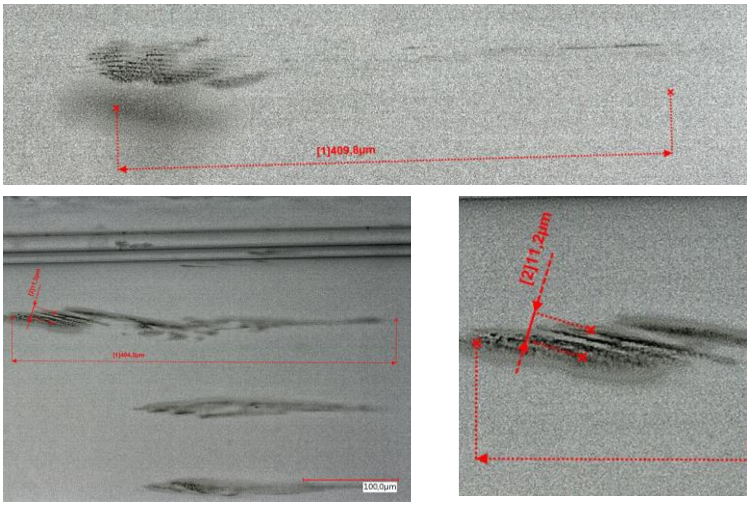

Fig. 11: Modifications with periodical structures.

4.4. Unintended alterations of the fiber core

Beside the intended modification around the focal point in a depth of dZ'=4mm inside the fiber, further material alterations (referred to as Lines and Tails) occurred closer to the end face during the laser processing. Such alterations can be seen in Fig. .
They are about 900µm to 1500µm long and extend up to a depth of dZ' = 2864µm, which coincides approximately with the position of the focus in air. The analysis of the processed fibers showed that very often modifications just were successfully induced in areas free of tails in the beam path of the processing pulses.

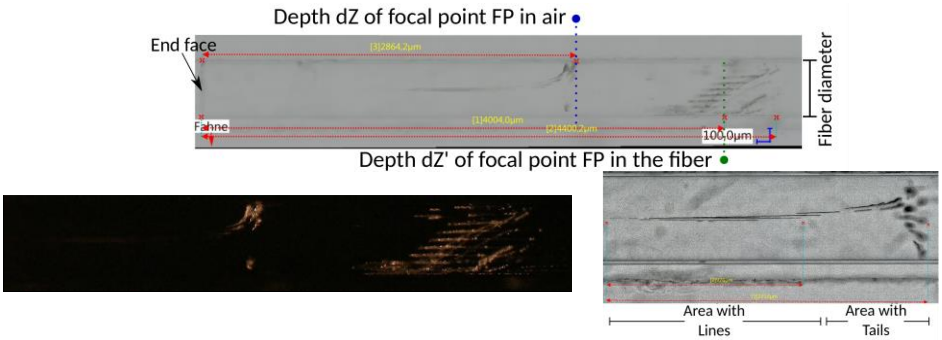

Fig. 12: Unintended material alterations referred to as Lines and Tails.

5. Conclusion

All in all we were able to induce scattering centers into the core of silica fibers through the end face. Further, we studied their length as a function of the pulse energy, number of pulses and pulse repetition rate and were able to determine the intensity threshold to induce a material modification in fused silica.

$$I_{thr,calc} = I_{Peak} = (0.45 - 0.77)\frac{TW}{cm^2}$$

By evaluating the intensity distribution of the pulse we estimated the size of the modifications as a function of the pulse energy. A comparison (see Figure 13) showed that the prediction was in a good agreement with the experimental results.

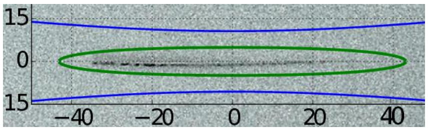

Figure 13: $E_{Pulse} = 9.65\mu J$

Bibliography

B. C. Stuart, M. D. Feit, S. Herman, A. M. Rubenchik, B. W. Shore, and M. D. Perry, 1996, Nanosecond-to-femtosecond laser-induced breakdown in dielectrics, Phys. Rev. B **53**, no.4, 1749-1761