Influence of core diameter and coating material on nanosecond laser-induced damage threshold of optical multimode fibers

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Single and multi pulse laser-induced damage thresholds (LIDT) of core, cladding, and coating materials of high-power optical multimode fibers were determined in accordance with ISO 11254 for 532 nm and 1064 nm wavelength in the 10-ns pulse duration regime with spatial Gaussian beam shape. For all-silica fibers, LIDT increases with rising core diameter in a range between 100-600 μm for a constant cladding-core ratio of 1.2. The damage resistance of the low refracting cladding (0.3 % fluorine doped fused silica) is comparable to the undoped SiO_2 core. Coating materials show significantly lower LIDT than light-guiding parts of the fibers.

1. Introduction

Optical multimode fibers are applied in different fields like automotive, defense, aviation, medicine, and biotechnology. Often they are parts of high-power laser tools. Normally, constituent parts of optical multimode fibers are core, cladding, coating, and jacket. Fig. 1 depicts a schematic representation of a typical fiber.
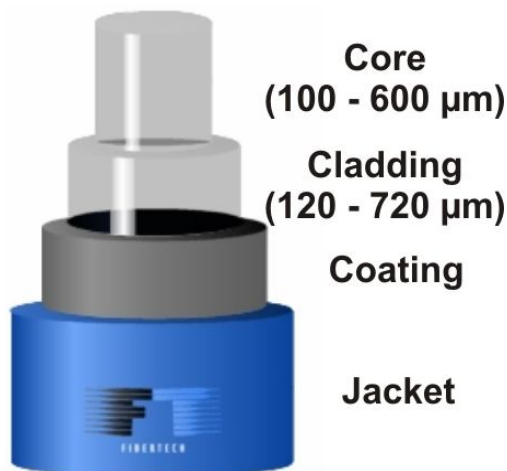

Fig. 1. Scheme of an optical multimode fiber consisting of all-silica core, fluorine doped SiO_2 cladding, polymeric coating, and jacket. Range of core and cladding diameters used for the experiments are indicated.

For high-power operation, damage of optical multimode fibers at the end faces or within the core is a limiting factor. Therefore, the determination of laser-induced damage thresholds (LIDT) of fibers is more or less congruent with the LIDT determination at the end face or within the bulk of the core of the fiber. Taking into account e.g. a significant bending of the fibers, i.e. a deviation from a standardized use of the fibers, light energy can penetrate into cladding and coating of the fiber and destroy these parts. Hence, the evaluation of damage thresholds of cladding and even coating materials of fibers is also of interest.

The most important material of high-power optical multimode fibers is undoped (core, e.g. F300, Heraeus) and doped (cladding, e.g. F320, Heraeus) fused silica. The influence of wavelength λ and pulse duration τ on laser-induced front side damage of fused silica samples was evaluated in the past [1-7]. Generally, LIDT in terms of energy density (or laser fluence) drops with decreasing wavelength and shorter pulse duration. Additionally, a varying surface quality, e.g. roughness [2,6], and heat treatment [6,7] of fused silica specimens changes LIDT significantly. LIDT values of $F_{th} = 20$ J/cm^2 (308 nm, 22 ns [2]), $F_{th} = 110$ J/cm^2 (532 nm, 8.5 ns [7]), and $F_{th} = 350$ J/cm^2 (1064 nm, 15 ns [7]) were measured for nanosecond pulse illumination. In the nanosecond pulse regime, F_{th} scales with $τ^{0.5}$ [8].

A drawing process of SiO_2 preform material is used for the production of optical fibers. Drawing rates of the order of meters per minute are applied. A higher drawing rate results in fibers with smaller diameters. For fibers with core diameters between 180 μm and 600 μm, a decreasing LIDT with increasing drawing rate was found for ns-laser impact at 532 nm wavelength [9].

In this paper, nanosecond LIDT measurements on the end faces of fused silica fibers (FiberTech) with core diameters between 100 µm and 600 µm at 532 nm and 1064 nm wavelength are reported. Damage threshold investigations were extended to cladding and coating materials. The fluorine doped cladding of the optical multimode fibers was modeled by means of a fluorine doped preform (F320 HQ, Heraeus) while the different coating materials were deposited on fused silica substrates in a thickness range between 100 µm to 1 mm. LIDT values were calculated according to the standards ISO 11254-1 [10] and ISO 11254-2 [11].

2. Experimental

The experiments were performed with three types of specimens. Firstly, all-silica fiber samples (FiberTech) with core diameters between 100 µm and 600 µm, a constant cladding-core ratio of 1.2 and a length of 50 mm were investigated (Table 1). Prior to the laser damage experiments, the samples were polished with Al_2O_3 and diamond suspension down to grain diameters of 0.2 µm and afterwards cleaned using a steam jet. Secondly, a polished cylindrical specimen (F320 HQ, Heraeus, 9 mm diameter, 23 mm thickness) was studied with respect to its damage resistance. That preform material consists of about 0.3 % fluorine doped SiO_2 and serves as model for the cladding of the fibers. Thirdly, eight different polymer films (Table 3) were deposited on fused silica substrates representing the coating of the fibers.

Single and multi pulse LIDT of the bulk samples were determined according to the relevant standards [10,11] or with a stepwise increase of the laser fluence on a single spot in the case of the fibers. Recently, it was demonstrated that both methods yield identical LIDT values within the experimental uncertainty for fused silica preform materials [9]. For all laser experiments, a purging of the sample surfaces with nitrogen was done.

In principle, the experimental setup was described in [7]. The Nd:YAG laser system (SL 852, Spectron Laser Systems) emitted laser pulses with a duration of $\tau = 12$ ns at 1064 nm wavelength with a beam quality parameter of $M^2 \approx 1.4$. Applying a KD*P crystal, 8.5-ns pulses at 532 nm wavelength ($M^2 \approx 1.3$) were generated. The beams were linearly polarized. Laser focus diameters (second moment) in the interaction region of $2w = 49\pm2$ µm (1064 nm) and $2w = 30\pm1$ µm (532 nm) were determined using a CCD camera (Grasshopper, pixel size 3.45 µm, Point Grey) and a beam-analyzing software (BeamAnalyzer, TU Berlin).

On the preform material and on the different coatings, ten test sites were illuminated. Damage on the samples was detected in-situ with a CCD camera (Scorpion, pixel size 4.4 µm, Point Grey). Subsequently, the specimens were inspected by means of a light-optical microscope (Eclipse L200, Nikon). For a given laser fluence, the number of damaged spots was counted and a damage probability P was calculated. LIDT was obtained using a plot of P vs. maximum laser fluence F_0. The fibers were illuminated on one spot stepwise with increasing energy density using single pulses until breakdown was monitored in-situ. A total of eleven or twelve fibers of each type (core diameter) were used for each wavelength.

An overall error of the F_{th} determination of about 30 % has to be taken into account resulting from the accuracy of the energy measurement of 5 %, the beam diameter determination of 4 %, the statistical behavior of the damage process (error of the fit of 10 %), and an influence of a τ variation (5 %).

3. Results and discussion

Fig. 2 depicts an example of a damage curve P vs. F_0 for 12-ns pulse laser illumination of an all-silica fiber with a core diameter of 100 µm. A damage threshold of $F_{th} = 145$ J/cm² was found for the application of infrared pulses.

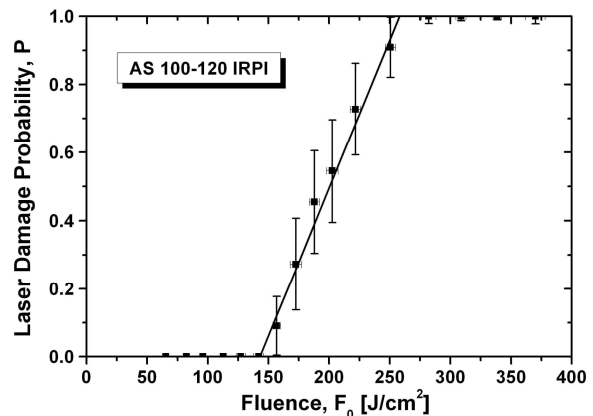*Fig. 2. Damage probability P vs. maximum laser fluence F_0 for the illumination of the core of an all-silica multimode fiber AS 100-120 IRPI (FiberTech). $\lambda = 1064$ nm, $\tau = 12$ ns. The straight line represents the fit of all data points P different from 0 and 1. The interception point of the line of best fit with the F_0 axis is named 0 % damage fluence F_{th}.*

Using the approach according to Fig. 2 for fibers with different core diameter and for an identical end face preparation, a matrix of LIDT values was obtained for the green and the infrared laser radiation (Table 1). For the same core diameter, the damage resistance is higher for the longer wavelength. The LIDT for the different wavelengths vary between a factor of three (for 600 µm core diameter) and only 10 % (100 µm core diameter). For both wavelengths, a trend of a drop of F_{th} with decreasing core diameter is evident. The glass structure of the core material is influenced by the drawing conditions of the fiber production process. For smaller core diameters, a faster cooling process takes place and the glass structure contains more defects and residual mechanical stress corresponding to a higher fictive temperature [12]. Hence, LIDT vs. core diameter behavior might be a result of the drawing rate of the fiber production process.

Table 1. Single pulse damage threshold F_{th} in dependence on fiber core diameter for a constant cladding-core ratio of 1.2. Wavelengths of 532 nm (8.5 ns) and 1064 nm (12 ns) were used.

Fiber Type	Core Ø [μm]	F_{th} [J/cm²] 532 nm	F_{th} [J/cm²] 1064 nm
AS 100-120 IRPI	100	135	145
AS 200-240 IRPI	200	180	265
AS 400-480 IRSN	400	210	340
AS 600-720 IRSN	600	200	570

The F_{th} values for a wavelength of 1064 nm are in excellent agreement with recently published data [9]. The end faces of the fibers displayed in Table 1 were polished with Al_2O_3 and diamond suspension down to grain diameters of 0.2 μm (polish "B") while previously examined fibers were prepared with Al_2O_3 and diamond suspension down to grain diameters of 0.5 μm (polish "A" [9]). The RMS surface roughness of the "B"-fibers was smaller (3–8 nm) than the roughness of the "A"-fibers (3–22 nm).

For a fiber end face preparation according to procedure "B", 532-nm-LIDT can be reproduced within the experimental uncertainty (compare values in Table 1 and [9]). In contrast to the findings for the infrared light, LIDT changes with different surface polishing ("A" vs. "B") by a factor of about two. Obviously, LIDT for 1064 nm impact depends weaker on surface polishing quality in comparison to the green radiation.

As a matter of fact, nanosecond LIDT values depend strongly on the drawing process (influencing the core diameter) for 1064 nm wavelength and significantly on the end face preparation for 532 nm wavelength.

The damage resistance of cladding material of high-power optical multimode fibers was simulated with a fluorine doped preform sample (F320 HQ, Heraeus). The cylindrical specimen consists of about 0.3 % fluorine doping in fused silica and shows a lower refractive index than the pure silica core material.
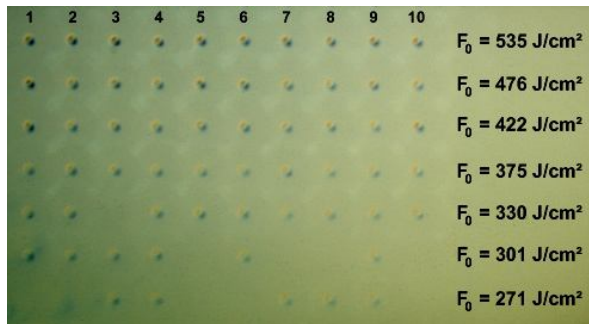

Fig. 3. Light microscopic picture of a part of an array of laser induced damage sites on fluorine doped SiO_2 preform material (F320 HQ, Heraeus). At the top, the consecutive number of test sites is given. On the right, maximum laser fluences are indicated. Distances between the test sites are 0.18 mm.

Fig. 3 depicts the results of a LIDT measurement according to standard ISO 11254-2:1999 at 1064 nm

wavelength for 10-on-1 conditions. It can be seen that the number of damaged sites increases with rising laser fluence. Calculating damage probabilities P and plotting P vs. F_0 (compare Fig. 2), the LIDT value of F_{th} = 205 J/cm² was obtained. Single and multi pulse LIDT for 532 nm (8.5 ns) and 1064 nm (12 ns) wavelengths are given in Table 2.

Table 2. Single and multi pulse damage thresholds F_{th} for a laser treatment of the cylindrical fluorine doped SiO_2 preform.

	F_{th} [J/cm²] 1-on-1	F_{th} [J/cm²] 10-on-1
532 nm	160	130
1064 nm	440	205

Taking into account slightly different surface preparation conditions, the single pulse LIDT of fluorine doped SiO_2 preforms of 440 J/cm² (1064 nm, F320) and 160 J/cm² (532 nm, F320) are in reasonable agreement with maximum F_{th} values of 350 J/cm² (1064 nm, F300 [6]) and 110 J/cm² (532 nm, F300 [7]) published recently for undoped SiO_2 samples. Therefore, the doping of the fused silica with 0.3 % fluorine does not influence the LIDT considerably. Assuming that the fiber drawing process does not change the damage behavior, the cladding of an all-silica fiber is not the crucial part for the damage resistance of optical multimode fibers.

Table 3. Single and multi pulse damage thresholds F_{th} for various coating materials on fused silica substrates employing 8.5-ns laser pulses at 532 nm wavelength. Labeling of coating materials according to FiberTech GmbH.

Sample	F_{th} [J/cm²] 1-on-1	F_{th} [J/cm²] 10-on-1
Silicone	25	17
Polyimide	8	<4
Single Layer-Acrylate	33	28
Fluorine doped Acrylate I	29	24
Fluorine doped Acrylate I	40	38
Primary Coating I	44	34
Primary Coating II	53	49
Secondary Coating	30	10

The coating is an important component of a commercial optical fiber. LIDT of different coating materials were investigated for a wavelength of 532 nm. The F_{th} values for single pulse impact covering a range between 8 J/cm² and 53 J/cm² (Table 3). This means that the LIDT of the coating is about one order of magnitude lower than the LIDT values of the fiber (core and

cladding). Hence, the coating is a sensitive part of a multimode fiber in the case of an undesired leakage of energy out of the cladding e.g. due to intense bending of a fiber. Furthermore, the different polymeric materials show differently pronounced incubation effects. LIDT of the "secondary coating" decreases by a factor of three for a multi pulse impact in comparison to single pulse illumination while F_{th} of "fluorine doped acrylate I" does not change in dependence on pulse number per spot significantly. Polyimide as a common coating material shows the lowest LIDT value amongst the materials and a distinct accumulation effect.

4. Conclusions

Nanosecond laser-induced damage thresholds were determined for all-silica fibers with varying core diameter, a fluorine doped sample as a model for cladding of such fibers and different coating materials. For the fibers with core diameters of 100-600 μm, an improvement of the surface damage resistance with an increasing core diameter was found for 532 nm and 1064 nm wavelengths. LIDT values critically depend either on the drawing process (1064 nm) or on the fiber end face preparation (532 nm). LIDT were significantly lower for an impact of green laser pulses (135-210 J/cm^2) in comparison to the infrared radiation (145-570 J/cm^2). The fluorine doped fused silica sample showed LIDT comparable to an undoped SiO_2 specimen. The cladding of an all-silica fiber is a noncritical part regarding damage behavior while coating materials show significantly lower LIDT compared to the light-guiding components.

Acknowledgements

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