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Optical fibers with enhanced performance for excimer laser power transmission at 308 nm

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ABSTRACT

Power transmission of xenon chloride excimer lasers through optical fibers is necessary for medical applications where tissue removal is performed within the human body. The most important application at present is excimer laser coronary angioplasty.

Typical levels of energy densities applied by optical fibers for this application cause color center generation in fused silica leading to transmission decrease called photodegradation. This effect depends essentially on the grade of the fused silica. Important parameters are fiber length, pulse duration, energy density, and the irradiated cross sectional area of the optical fiber endface.

For a new grade of core material the influence of these parameters on the transmission performance is described. The obtained material improvement leads to a significant reduction of the observable transmission decrease as a function of the number of laser pulses applied. Thus continuous operation of the laser in the region of the typical transmission plateaus at considerably higher and constant energy levels at the distal fiber end becomes feasible. This offers a new option for more reliable dosimetry in medical applications.

1. INTRODUCTION

Over the years excimer laser technology has been continually developed in order to improve system reliability, output average power, and beam quality. One of the driving forces is the short emission wavelength leading to advantageous ablation properties for organic and anorganic material [1–5].

Unfortunately average power is generally much lower than that of CO_2 and Nd:YAG lasers. Thus most practical applications are limited to ablation or modification of small amounts of materials for example micromachining, ophthalmology, and angioplasty.

In nearly all applications beam delivery systems are of great importance. Looking at the spectral transmission of synthetic fused silica grades 308 nm radiation can be well transmitted if the distances are shorter than about 10 m. However, photon energies (4 eV) and energy densities are sufficient for excitation of electronic inter–band gap states and for two photon processes.

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In consequence, severe microscopic damage of fused silica optical fibers can occur. This damage is called photodegradation and it results in a significant drop in transmission which has a complex dependence on laser operating and fiber parameter [6–12].

Early material grades showed such strong effects that applications were mostly limited to trials in r & d laboratories. About four years ago a new material grade was introduced on a large volume commercial basis with significantly improved performance. This material provides the basis for the practical success of demanding applications like angioplasty. But it still leaves some concerns considering the time dependent transmission changes and batch to batch variation of material properties.

In January 1991 first results obtained with a new core material for optical fibers were presented [13]. Photodegradation effects less than half of those of the currently widely used standard material were reported. In the following new and standard material are compared on the basis of a first statistical analysis of batch to batch variations. The new material's performance will be precisely characterized for a wide range of operation parameters. In order to guide practical system design, scaling relations will be derived empirically.

2. FIBER SAMPLES AND TEST CONDITIONS

All fibers investigated were drawn from Fluosil [14] preforms with undoped silica core and fluorine doped silica cladding manufactured with a proprietary plasma outside deposition process. The numerical apertures are 0.22 ± 0.02. Two different grades of core materials, standard and improved, were used. Both are high purity undoped silica. The quality differences are due to modifications in the material production process which was optimized with respect to photodegradation for the improved material.

Fiber core and cladding diameter were chosen to be 200 μm and 220 μm, respectively. The coating was UV–acrylate.

As in our previous studies [13] a Lambda Physik XeCl excimer laser (LPX 210, $\lambda = 308$ nm) was used. Only the central part of the laser beam is passed through a circular aperture. In standard transmission measurements, this aperture is imaged onto the fiber endface by a single lens ($f = 50$ mm). During the tests, where only the fiber core was irradiated, the diameter of the aperture and the demagnification were chosen in a way that the laser spot on the fiber front surface was slightly smaller than the fiber core.

The fiber position is adjusted by a XYZ–translation stage under control of a video microscope. Part of the laser beam is split off and monitored by a pyroelectric detector (Laser Precision RjP 735). Simultaneously, the energy at the distal end of the fiber is detected with a second detector of the same type.

A modified setup is used to study the influencence of the coupling aperture on these photodegradation effects. In these cases the laser beam was expanded in the horizontal dimension by a telescope of cylindrical lenses. The beam diameter on the $f = 50$ mm coupling lens was changed by an iris aperture directly in front of the lens to obtain the coupling aperture variation.

To investigate the dependence of transmission properties on the laser pulse duration an optical pulse extender (Exitech) was used. Normal pulse duration of the Lambda Physik XeCl excimer laser is about 28 nsec. This beam is directed into the pulse extender. Up to eight beam splitters are then used to create partial beams, which are guided on optical paths of different lengths and recombined again to form an exit beam with a pulse duration of up to 240 nsec. Different pulse durations can be achieved by varying the number of partial beams. In this setup a field lens is used for illumination of the aperture to compensate for power losses within the pulse extender.

3. RESULTS

3.1 Fiber samples with standard and improved undoped silica core

The effect of optimization of material properties with respect to photodegradation is shown in Fig. 1. For the improved core material the transmission decrease during laser irradiation is reduced to less than half of that of the excellent standard grade. These results are described more detailed in previous work [13].

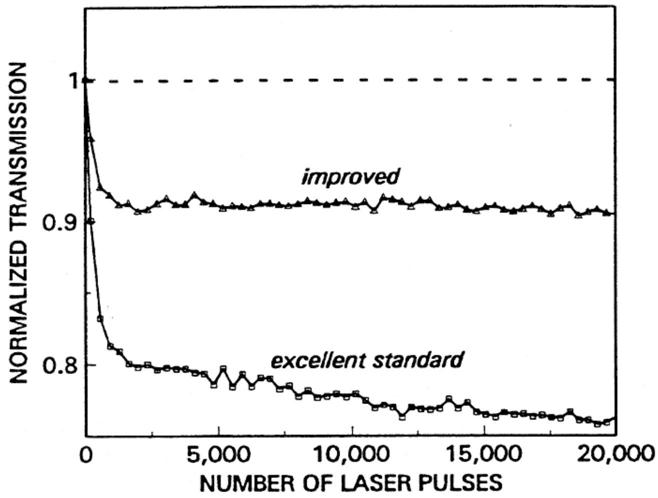

Fig. 1: Transmission variation with number of laser pulses for standard and improved preform quality ($l = 2$ m, $f = 30$ Hz, $F = 12$ J/cm^2, $\tau = 28$ ns)

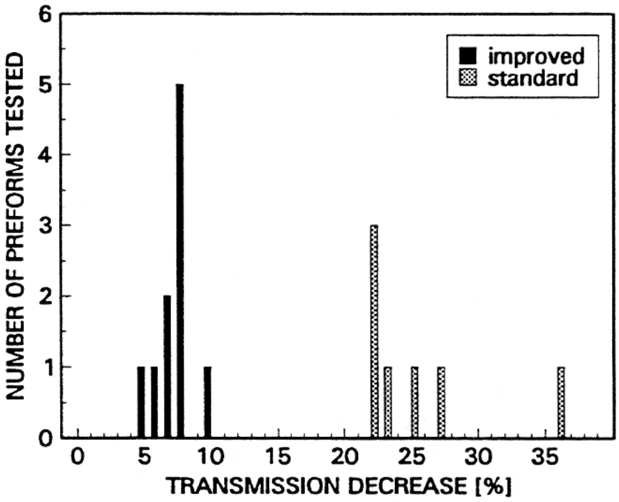

Fig. 2: Transmission decrease after 20,000 laser pulses for different preforms with standard and improved core material (parameters see Fig. 1)

Further investigations enabled us to provide a first statistical basis for the properties to be expected for the standard and improved grades (see Fig. 2). For core irradiation the laser induced transmission changes of the two material grades are clearly separated.

The distribution of the improved material quality is quite narrow indicating the positive effect of the efforts to keep all production parameters very close to their optimum value. The standard grade shows larger photodegradation effects and the distribution is broad.

3.2 Transmission properties of fibers with improved core material

The transmission properties of fiber optical components strongly affect the performance in almost all medical applications where high power laser transmission is necessary. Knowing the influence of different parameters on the energy densities at the distal fiber end enables one to optimize the system parameters for different applications and to extrapolate transmission values when system parameters need to be changed.

In the following, laser induced attenuation is given in terms of decibel.

Pulse duration:

The influence of pulse duration on the XeCl laser induced change in fiber transmission is shown in Fig. 3. With increasing pulse duration the transmission changes become smaller. The pulse energy or pulse energy density was kept constant for all data shown.

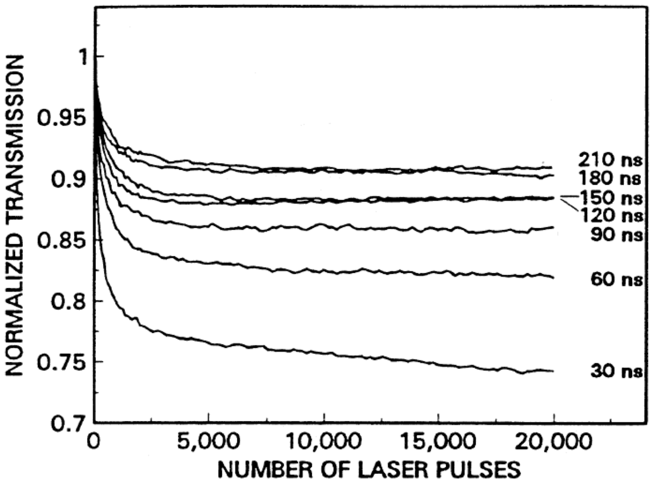

Fig. 3: Transmission change with number of laser pulses for different pulse durations (l = 8 m, F = 8 J/cm², f = 30 Hz)

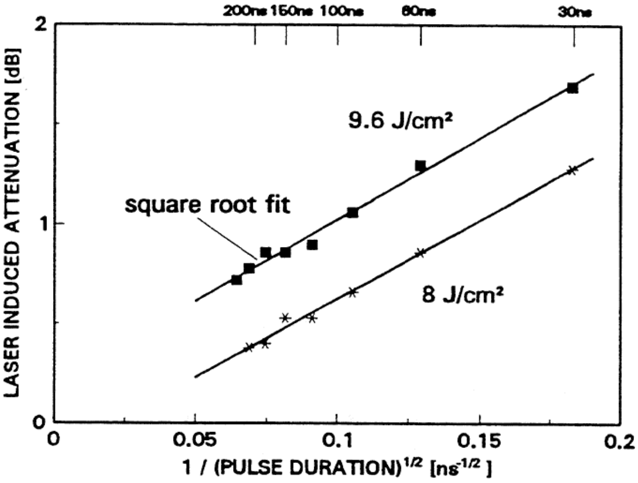

Fig. 4: Laser induced attenuation after 10,000 laser pulses as a function of pulse duration (parameters see Fig. 3)

Two measurement series were performed with 9.6 J/cm^2 and 8 J/cm^2. In Fig. 4 the laser induced attenuation of an 8 m fiber sample after 10.000 laser pulses is plotted versus pulse duration.

The laser induced attenuation is proportional to the reciprocal square root of the pulse duration.

Energy density:

The dependence of photodegradation on the energy density is shown in Fig. 5. Laser induced attenuation is proportional to the coupling energy density. It is important to notice that this is only valid for values between 2 J/cm^2 and 15 J/cm^2.

Our earlier investigations [13] clearly indicate a different relation for values above 15 J/cm^2 where two photon absorption becomes important [15]. New types of defects with different dynamic behavior are created. Below 2 J/cm^2 the induced attenuation is also not a linear function of energy density.

For most medical applications energy densities up to 10 J/cm^2 are typical. Beside the problem of increased defect generation practical applications are also limited by the surface damage threshold of silica which is about 20 J/cm^2 for 30 nsec laser pulses. Therefore, we limited our investigations to the above described parameter range. However, it should be kept in mind, that the surface damage threshold increases proportional with the square root of pulse duration [16,17].

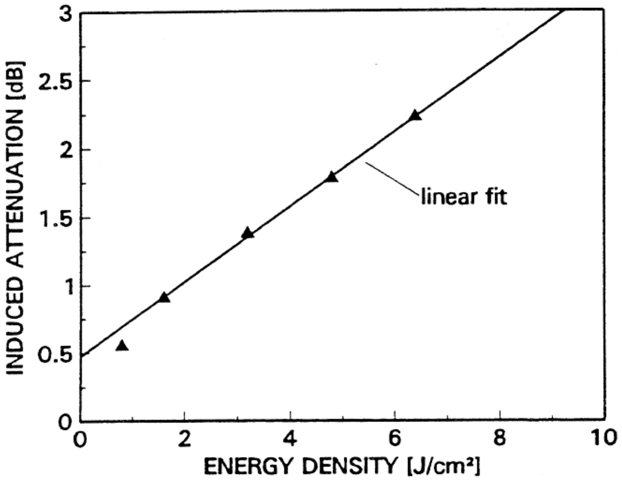

Fig. 5: Laser induced attenuation as a function of energy density at the fiber front face (l = 8 m, f = 30 Hz, τ = 28 ns)

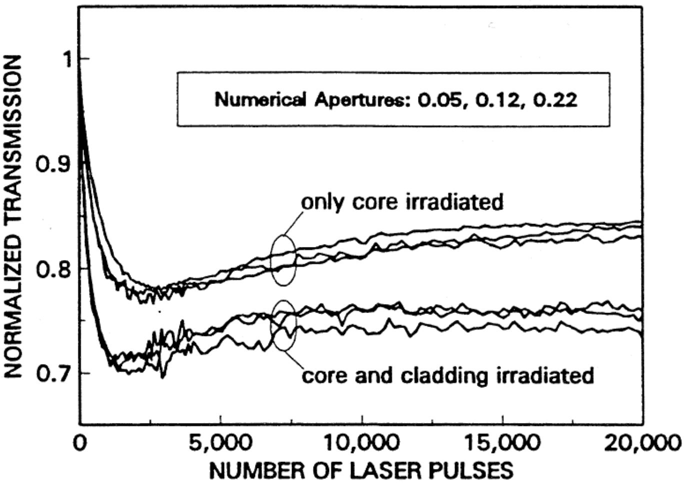

Fig. 6: Influence of launching conditions on laser induced transmission changes (l = 4 m, F = 4 J/cm^2, f = 30 Hz, τ = 28 ns)

Launching conditions:

The transmission changes of optical fibers during high power laser irradiation are not only affected by the core material but also by the cladding. The light penetrates into the cladding section which therefore contributes to the overall optical performance of the fiber. The cladding contribution is smaller than that of the core but is important especially in fiber bundle applications.

We performed irradiation tests with different numerical apertures (NA) of the laser beam coupled into the fiber. The diameter of the incident radiation at the fiber front face was varied to obtain only core or core and cladding irradiation, respectively. The results are shown in Fig. 6.

We do not see any influence of laser beam NA on the laser induced transmission changes. NA's were chosen to cover the range of practical relevance limited by the actual NA of the optical fiber.

The differences between core and cladding irradiation and only core irradiation are significant. The light coupled into the fluorine doped cladding generates additional defects which cause a stronger transmission decrease during laser irradiation. The characteristics of the transmission curves described by the steep initial decrease and the nearly constant values for large numbers of laser pulses remain unchanged. Only the absolute values are affected by the launching conditions.

Fiber length:

The influence of fiber length on the induced attenuation is shown in Fig. 7. The slope of the curve is decreasing for longer fiber length. This behaviour can be explained by the decreasing energy density along the fiber length (also indicated in Fig. 7). As shown above, lower energy densities cause less photodegradation effects.

The energy density is reduced by two factors. One is the basic fiber attenuation which is a linear function of fiber length. The other is the laser induced attenuation which is depending on the actual energy density (see also Fig. 5). The measured actual energy densities are shown in the graph.

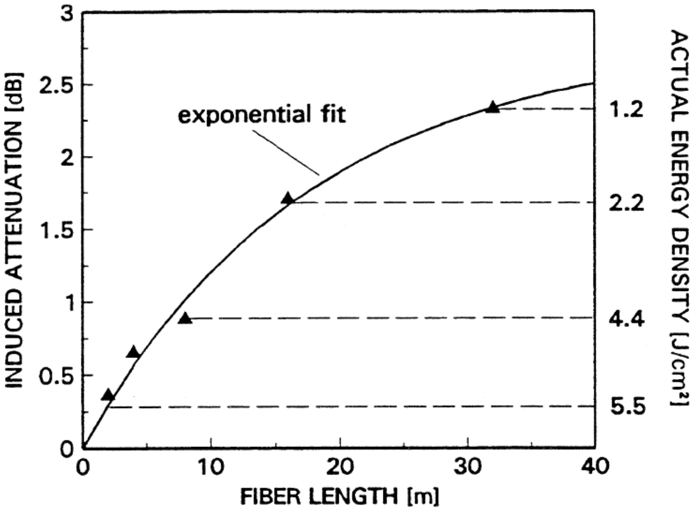

Fig. 7: Laser induced attenuation as a function of fiber length
(F= 7.7 J/cm², f= 30 Hz, τ= 28 ns)

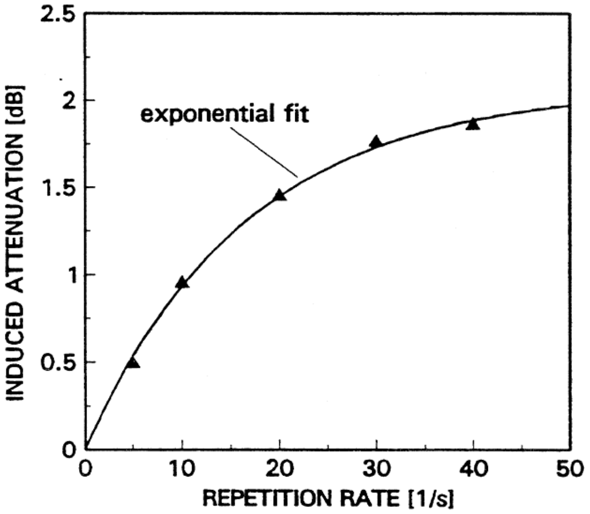

Fig. 8: Laser induced attenuation as a function of pulse repetition rate
(l= 8 m, F= 6.4 J/cm², τ= 28 ns)

Repetition rate:

Our previous investigations [13] showed that laser induced color centers anneal very fast after irradiation is stopped. This annealing occurs already during irradiation especially in the time intervals between laser pulses. This fast defect annealing causes a dependence of induced attenuation on repetition rate. The higher the repetitition rate the shorter the time intervals for annealing and the higher the induced attenuation.

The above described relations are verified by the experimental data shown in Fig. 8. The results were obtained on fiber samples with 8 m length. Tests were performed with energy densities of 6.4 J/cm^2.

4. DISCUSSION

The experimental results show the influence of various system parameters on the transmission properties of optical fibers with improved core material. For medical applications the energy level at the distal fiber end is one of the key parameters because it is determining the ablation yield. The dosimetry and the effectiveness in a medical operation is therefore strongly depending on how well the dependence of the fiber attenuation on the actual system parameters is known.

In Fig. 4, 5, 7, and 8 curves are fitted to the experimental data. These curves are given by quite simple mathematical functions which were not chosen to describe the microscopic physical effects of photodegradation.

With this mathematical approach it is possible to provide expressions for the laser induced attenuation $\alpha(\tau, l, f, F)$ in an optical fiber when only the core is irradiated.

$$\alpha(\tau) = c_1 \cdot \frac{1}{\sqrt{\tau}};$$

τ = pulse duration in ns

$$\alpha(l) = c_2 \cdot \left[1 - e^{(-d_1 \cdot l)}\right];$$

l = fiber length in m

$d_1 = 0.06\ m^{-1}$ for improved material grades

$$\alpha(f) = c_3 \cdot \left[1 - e^{(-d_2 \cdot f)}\right];$$

f = repetition rate in Hz

$d_2 = 0.06$ s for improved material grades

$$\alpha(F) = c_4 \cdot F + a;$$

F = energy density at fiber front face in J/cm^2

a = constant for a fixed set of parameters τ, l, f

c_i: proportionality constants

With these expressions it is possible to estimate the laser induced fiber attenuation for a certain set of parameters. It is important to notice that the factors c_i need to be determined experimentally because they are depending on the actual batch quality (see Fig. 2).

We did not investigate the influence of fiber drawing and fiber diameter on transmission performance. Those results will strongly be affected by the actual set of parameters applied by the fiber manufacturer and are therefore only partly predetermined by material or preform properties.

5. CONCLUSIONS

The excellent performance of a new grade of core material for high power XeCl laser transmission was verified by a first statistical evaluation. The new improved material shows a transmission decrease after 20,000 laser pulses which is less than half of that of the actual standard grade.

For the very small residual photodegradation effects the influence of system parameters like pulse duration, energy density, launching conditions, fiber length, and pulse repetition rate was measured. The experimental data were fitted by simple mathematical functions.

From the obtained results expressions for the laser induced attenuation as a function of system parameters were derived which enable the operator to estimate the energy level at the distal fiber end even when parameters need to be changed.

6. ACKNOWLEDGEMENTS

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