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Laser interactions with bundle fiber structures

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Laser damages of materials are in research focus during the last decade. These terms can be understood as useful in the treatment of materials or in theoretical modeling of interactions of laser beams with the material. Also, they can be destructive when it comes to high power density where the nonlinear effects are present, too. In addition to the theory, many detailed experimental work is required for new optical components applications. The experiments with Nd^{3+}: YAG laser (1.064 µm) with defined working regime and power densities and specifically developed optical fiber bundles are the subject of this paper. The fibers are developed in laboratory conditions for specific purposes. Also, commercial optical fiber bundle for dental use are presented and discussed as comparison with the same laser types.

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1. Introduction

There are a large number of experimental and theoretical approaches to the laser damage and disintegration processes, component and system operation reliability, failure in terms of statistical, fundamentally theoretical and practical viewpoints. In the scope of optical fibers with different structures and their significant applications in telecommunications / WDM systems, computer, mining and medical domains, a large number of various situations occur, where fibers are placed in so called "aggressive environment" in terms of chemical, nuclear, electromagnetic or other origins. Quite a number of papers exist where all this is carefully being observed. Many other issues related to the procedures of processing, cutting, and especially of connecting optical fibers in the form of single, multimode, single fiber or bundle types as well as special design exist. All fibers and components of non-commercial type demand special reparation methods, usually the different sorts of connecting [1-4].

The disintegration of the cylinder formations under the influence of thermo-elastic stress, resistance of the fiber based optical elements obtained by various techniques, belong to modern topics. The fibers connected in vacuum conditions exhibit a dense monolithic anisotropic structure concerning to the hardness. The mechanical properties have been a special subject of research and various numbers of samples have been used to obtain reliable statistics data [5,6]. The layer forms could be treated from the thin films point of view. The results of analyses can be described as following:

The glass resistance keeps increasing by decreasing of the surface roughness. The cracks, defects of various types and shapes, residue of abrasive materials, etc., the processing technique, all have a significant impact on hardness. Glass coatings have higher boundary resistance than the fiber's cores. The composite structures hardness is approaching to the boundary values of composite elements. The complex elements are not only the sum of elements, but the anisotropic material as well, with various properties of coatings, cores and other elements and this only concerns the multicomponent structures.

Many simple formulas for disintegration of optical fibers and glasses exist. They include the dependences on: Young module of elasticity, linear coefficient of thermal expansion, coefficient for the given emission, thermal conductivity, boundary fracture [7-11].

Fatigue of the fibers is special subject of research [12-14]. The complexity of occurrence mechanism and analysis of them presuppose the employment of advanced measurement methods in real time. A large number of optical methods, including polarization and holographic type exist.

Alternately, the optical fibers themselves serve as the elements/sensors, to follow the dynamics of composite type materials damaging. Trend of observing a number of parameters by means of introducing measurement fibers into structure exist [15-18].

The examination of the critical conditions of material disintegration in the conditions of the short-term interactions at stronger resistances is being developed to great extent [19-21]. The general picture at the laser damage in free generation regime is not quite clear, especially in ultra short regimes (femto - and atto second pulses). The physical resistance has been limited by the submicron formations. The lasers of commercial and laboratory types have been used. Many other materials can be employed to fiber form (glass or plastic) sensors. On the other hand, there is also experimental-theoretical evidence on decreasing damage thresholds at the points of metallic (or other material) impurities. The laser induced damage processes are related to plasma development or significant thermal stresses. The statistical nature of the laser damages has been examined also in [5,6,22].

2. Contemporary tasks for fiber technology, theories and practice

The numerous data exist on glass damages, variety of defects, window damages, glasses of the spectacles, eye lens, protective glasses, filters and other elements. The effects of polarization, processing mode, etc. all lead to rather complex occurrences. It is not quite clear whether the damage threshold will initially occur with the types: dielectric, thermal, Brillouin, or self-focusing mechanism breakdowns, with induced shock waves and how important are defects impacts.

The calculation of thresholds for various stimulated effects is not always reliable. A number of the induced effects (self-transparancy, self-focusing), occur joined and before the threshold for stimulated Brillouin scattering and the similar induced processes [22-27]. The fibers and fiber lasers naturally represent a link to the stimulated effects, damaged fibers and threshold for lasing. The active materials, pumps (flash lamps) "mirrors" and necessary accessories represent the source of many new facts. The single and multi-exposures from the point of view of cumulative effects are the subjects for discussion. According to the pulse length, the relationships with the relaxation constants of the material are different. The mechanism is related to the electrons, lattice or even to the nucleus, depending on the amplitude of the associated electrical field and pulse length as well as repetition rate. Laser polarization and damages as significant fact are not quite clearly seen within the thermal model. According to many authors following types of disintegration exist:

- under the influence of the thermo-elastic stresses,
- due to crystallites associated with the impurities,
- in the form of a self-focusing processes.

The errors at the junctions of fibers and optical cables and inclusion of non-linear properties are especially interesting areas. To obtain data to presume the non-linear parts of the refraction index (hyperpolarisabilities) there are practical formulas depending on the refraction indices for Na_D line, dispersion for glass transitions temperatures and so on. Both, the experiment and the theory often lead to different results. It presupposes the data on large range of thresholds, reliabilities, etc. The simpler assessments are related to the approach to the balance between the self-focusing and refraction processes. The typical is the form of dependence of material disintegration mechanism on the increase of the number of laser pulses and on the thresholds of disintegration for a corresponding cumulative mechanism $N \rightarrow \propto$, which is still fairly.

In this paper the advantage has been given to the experiment which would show the radiation hardness (strength, resistance), structural sensitivity and its change when exposed to Nd^{3+}: YAG laser in chosen working regime (one and multiple pulse exposures). The treated multi layer optical fibers and bundles are of laboratory types developed for specific purposes as well as some of commercial type used in medicine.

3. Experimental

The fiber bundles are exposed to Nd^{3+}: YAG laser beams. They are composed of optical fiber with the glass core for the optical signals passing, coatings of a lower refraction index and an absorbing layer of black glass for preventing crosstalk (Fig. 1).

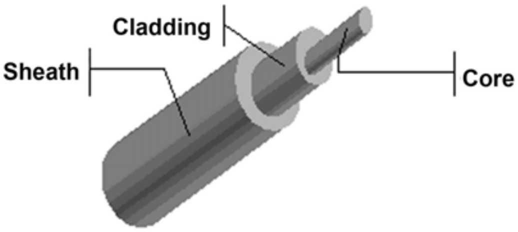

Fig. 1. Three-layer optical fiber: 1. Core, 2. Cladding and 3. Sheath

Glasses for obtaining fiber optical coherent beams have to be rheologicaly compatible and with the adequate thermal coefficients. By sintering processes is fulfilled that core glass is of the least grade and/or higher grade of and thermal coefficients of glasses should be close to each other (usually is fulfilled that thermal coefficient of core is smaller than that for cladding, $\alpha_1<\alpha_2$).

The fibers taken for testing are made of lanthanum glasses (the core-lead crystals) the core, two types of boron-silicate glasses (coatings) and black glass as the third one. The most extreme cases have been examined: the series 1 - glass core is softer than the glass coatings and series 2, the glass core is harder than the coating. The multiple fibers after the two-grade expansion with the 7 μm diameter are produced.

The other types of specimens are the fiber of interest in medicine (dentistry). Numerous fiber applications in medicine appeared in the twentieth century. Practical applications, beside image transmission through tubes, and internal medical endoscopic investigation, include internal illumination during dentistry investigation. The development of laser power delivery systems for applications in surgery, dentistry, dermatology and ophthalmology, demand the hardness (resistance) of optical transmission systems based on fiber to high power densities.

A lot of materials are used for enlargement of transmission range of fiber depending on the application purposes. Well developed telecommunication fibers are not adequate for various medicine purposes. Per example, fluoride fibers are used for guided wavelength transmission, various lasers and other optical sources in medicine. Special glass materials (from which fibers could be drawn) should be developed for optical power transmission beyond 2 μm. Chalcogenide glasses based on sulphides and selenides are very promising materials for medicine as well as various photonic applications. Special attention is paid on the doping of chalcogenide glasses by rare-earth elements (Er, Pr, Nd) [28,29]. As illustration, several fiber type and transmission range are presented in table 1.

Table 1. Selected optical fiber types and range of applications.

Fiber Type	**Transmission**
UV silica	180 nm to 1.15 μm
Sapphire	200 nm to 3.5 μm
Zirconium fluoride	450 nm to 5.0 μm
Water-free (low-OH) silica	580 nm to 1.95 μm
Germanium oxide	1.0 to 3.25 μm
C2 chalcogenide	1.5 to 7.0 μm
Selenium fiber	1.5 to 10 μm
C1 chalcogenide	2.0 to 11 μm
C3 chalcogenide	2.0 to 6.0 μm
Silver halide	4.0 to 18 μm

4. Conditions and results of expositions

4.1 Optical fiber bundles

In our previous investigations, different glass type materials, optical fiber, as well as optical fiber bundles have been exposed to Nd^{3+}:YAG laser beam in various working regimes. In this study, part of investigations is presented and discussed. In table 2 the chosen developed three layer optical fiber structures for special purposes with the principal characteristics are presented.

The samples were exposed to Nd^{3+}:YAG laser beam under the working regime presented in table 3. The variation of repetition rate and focusing were performed to find most adequate operation conditions depending on the sample shape and material. The time exposition time varied according to chosen powering condition and was from 4 to 30 ms.

The Fig. 2 represents macroscopic view of three sample series exposed to laser beams.

Fig. 2. Macroscopic view of optical fiber bundles (2.5 mm) with damaged and fractured places (Nd^{3+}: YAG, 4.1 kW, 14J, 2180 J/cm^2).

In Figs. 3. The details of transversal and longitudinal damages of the shortest specimen (Fig.1) are presented.

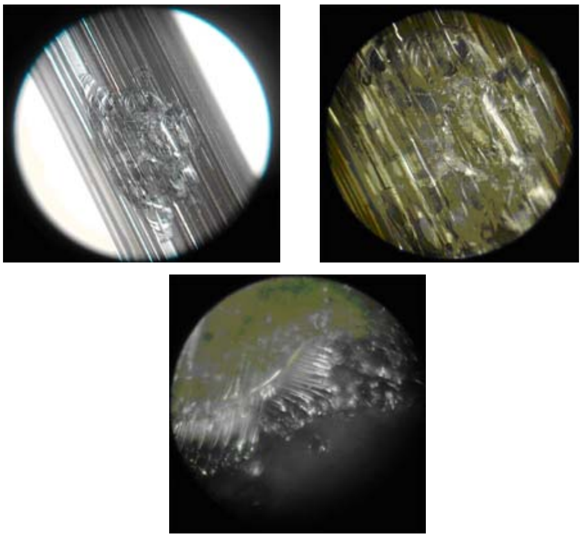

Fig. 3. Light microscope micrographs of a) macro (x 2) and b) micro (x 60) transversal damages of optical fiber bundle after five laser pulses, and c) micro (x 150) longitudinal damages of frontal side of optical fiber bundle after three laser pulses

Table. 2. Properties of used glasses series 1 and 2.

	Glass type	Annealing point , °C	Weaking temperature (Vicat) °C	Melting point °C	Refractive index °C	Thermal expansion coefficient 10^{-7}, °C^{-1}
		$\log \eta=13$	$\log \eta=7.6$	$\log \eta=4$		
Series 1						
Core	Lead crystall	493	651	420	1.54	80
Cladding	Borsilikate glass (AW)	531	711	1028	1.48	89.8
Third layer	Black glass	445	660	900		59.73
Series 2						
Core	Lanthan glass foc1	685	799	950	1.805	74
Cladding	Borsilikate glass (8250)	507	711	1045	1.47	50
Third layer	Black glass	445	660	900		59.73

Damages are not the regular circular shape (Fig.3a) because the targeted surface area is not flat. The edges are not flat because they are covered with molten layers. The border between the fibers (Fig. 3b) is not clear for the same reasons but is discernable. It is evident that eaten fibers under the effect of the laser beam are fractured. The Fig. 4 shows the SEM micrograph of characteristic damaged place.

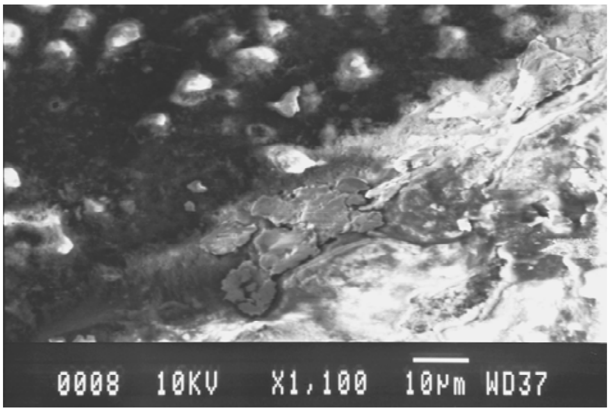

Fig. 4. SEM micrograph of longitudinal (edge) damages of frontal side of optical fiber bundle.

The SEM micrograph (Fig. 4) represents the damage of regular shape. Under the effect of the laser beam the second layer of boron silicate is not completely damaged. The damaged area is covered by molten and then solidified layers in the air.

4.2. The fiber based material of commercial type applied in dentistry for the processes of tooth filling draying

Further analyses are presented in Figs. 5 and 6. The damage is the regular circular shape. In Fig 5, damage core structure can be seen which is sustained in a set of fibers that confirm a hexagonal shape. The analysis shows that the damages are similar. The edge of the damage is presented in Fig. 5. The bottom of the crater is covered by solidified drops of the molten materials. The area of the damage is characterized by the rough solidified layers. It is evident that fibers under the effect of the laser beam are broken.

Transversal damage details of optical fiber bundle with hexagonal packing and structure from fused structure are presented in Fig.5 by light microscope analysis and SEM micrograph in Fig.6.

Hexagonal structure and packing can be recognized by light microscope. The material based on optical fiber in dentistry for the processes of tooth filling draying was exposed to the same laser type. In Table 3 the details of laser expositions are presented.

The Fig. 5 confirms that cutting with a laser was successfully completed. The surface area of the set of fibers (core) is flat. In cutting, the layer is solidified in elongated drops in a thin layer which cover the cut area of the set of fibers.

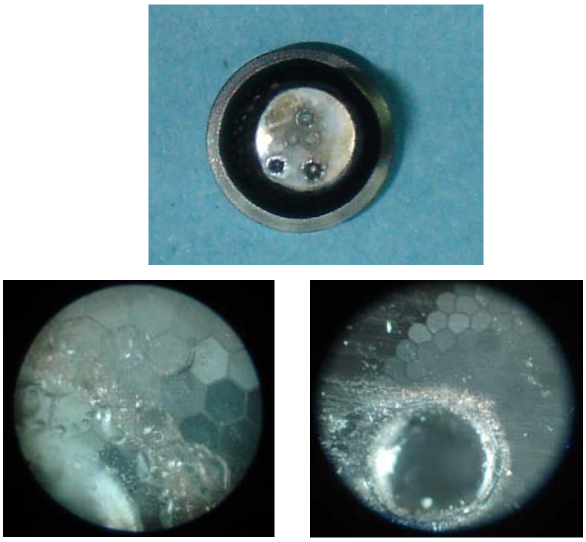

Fig.5 a) Macroscopic view (x 300) of frontal damage of optical fiber bundle of importance in dentistry, b) the details of transversal damage of optical fibers bundle (x 100) and c) (x 120)

Table 3. The laser exposition conditions of samples based fiber technology bundles based material for drying of tooth filling in dentistry.

Samples	kW	J	J/cm^2
The shortest sample (Fig. 2.)	4.1	14	2180
Thicker sample (Fig. 2.)	6.2	75	24795
Thinner sample (Fig. 2.)	3.6	10	1552
First exposition (Fig. 5.)	4.1	26	3157
Second exposition (Fig. 5.)	6.2	78	17231

* Repetition rate was 0.5 Hz.

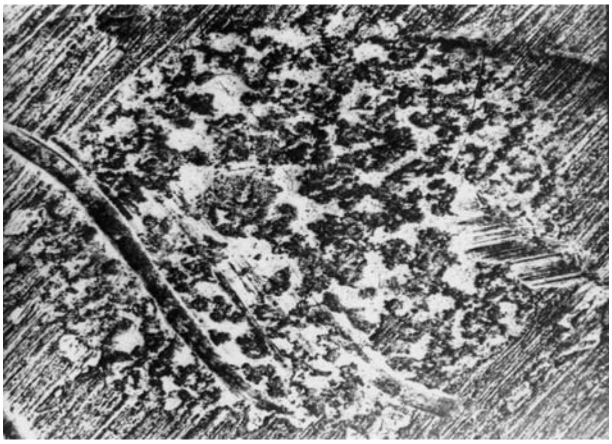

Fig. 6. SEM micrograph of optical bundle of hexagonal type

The analysis of obtained damages of presented samples and material is especially interesting for frontal surface, which present two damages. The both are irregular circular shape which is consequence of the focusing system, laser beam distribution as well as dentistry material.

5. Conclusions

Fiber based material as thin monomode or multimode fibers are large applied in many areas such as telecommunications, optical power supplying, medicine (here dentistry), image transmission and processing and many others. Various materials from which the fibers are drawn are produced by different technological processes. Depending on applications, they may work in different aggressive ambient. The problems of nonlinear optics are solved by fiber based element, as an integral fused optics, etc. On the other hand optical damages provoked by laser of various types applied in all these areas, represent possible usable or damageable cases. The laser damage himself, can be the object of further investigations for chosen material. The determination of the threshold and the relationship between multi and single pulse laser damages, i.e. the question of the process cumulativity is very important. The unsolved questions are also related to bulk or fiber material structure.

The investigation of interaction of Nd^{3+}: YAG laser with the fiber like material type applied in different purposes (laser beam communications, image and power transmissions) is shown in presented paper. In the applied laser working regimes all specimen of fiber and bulk type are damaged. The damages are from shallow surface type up to fiber fractures, cutting, burning but also welding, depending on the power density level and time of exposition.

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