ISSN: 2754-4753

Journal of Physics & Optics Sciences

Research Article

Open Access

Study of the Damage Threshold of Optical Surfaces of High-Power Energy Pulse Lasers with Changing Coefficient of Optical Surface Roughness, and the Damage Threshold is increased by Thermal Treatment of Optical Glass

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ABSTRACT

This paper presents the measurement of the laser Threshold damage of an optical surface at different roughness coefficients. The study procedure is achieved through the manufacturing of two types of parallel-sided borosilicate plate (Glass Bk7, and SF13).

The Laser used is ND: YAG pulsed laser and the longitudinal mode TEM_{00} laser pulses with pulse width τ =30ns and wave length λ=1.064μm, the laser beam is focused using F=30 mm lens. The concentrated laser beam is guided by a converging lens towards the optical surface of the parallel surface plate.

Finally, we obtained a graph of roughness coefficient is drawn in relation the optical Threshold Damage of the optical surface, Before and after processing the optical surface. We were able to raise the threshold by about 15% after conducting thermal treatment of the optical surface.

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Received: December 18, 2020; **Accepted:** December 28, 2020; **Published:** December 31, 2020

Introduction

Optical components are considered as a key element that may limit the potential and the efficiency of new products and applications. Consequently, their specifications and the type of treatment they obtain can effectively influence the potential and efficiency of the whole physical system in many fields of the optical technology.

There are examples in laser processing or in microlithography that show that the nature of treatment the optical components received is closely related to the optical losses and the lifetime of the beam steering or imaging systems.

It is worth noting that when a low-energy laser beams changes in terms of energy, through a transparent optical element or falls on a reflective mirror or on an absorbent medium, on may observe a little effect on the optical element or absolutely nothing.

But when the intensity of the laser beams increases, there will be an irreversible effect that are observed on an optical compound or element such as stress, thermal expansion, rise in temperature, nonlinear permeability, photovoltaic effects, second vibration generation, standard optical vibration and burning of the endothermic element. All these effects are manifested when the laser pulse is sufficiently high in term of average energy, peak energy, or power density [1,2,3].

A greater the increase in the intensity of the laser beam will lead to changes in the material or the compound being used.

The first laboratory laser systems were large in size and often not suitable for industrial and military applications, which led to effort intensification in order to reduce their size and increase their effectiveness at the same time. This generates density of energy and capability to damage components that include laser resonators (such as mirrors, optical windows, beam splitters ...). Effects that modify laser output are important. They include strain absorption and damage laser inducing.

Experiments show that most lasers suffer from at least one of these effects when they work for a long time.

The heterogeneous absorption of the laser beam by an element leads to wave-front distortion and a production of intrusive modes, strain, cracking, and laser beam concentration.

The functioning of the laser system even at low output can lead to mirror deterioration and changing of laser conditions.

The action of lasers at high output levels can lead to a direct single shock and a laser induced damage.

The prolonged operation of laser beams or when it works at high pulse repetition frequency (HPRF) can lead to a cumulative laser-induced degradation of the HPRF.

Since the laser power density is the highest within the laser response and amplifier, it is important to carefully select the elements so that we obtain a system without defects as possible.

The following paragraphs will show how the treatment of an optical element will affect its effectiveness and demonstrate desirable properties to the industry.

Destruction Mechanism

The destruction in a crystal network occurs when it is subjected to a laser beam defined by parameters of matter, wavelength, energy, and the shape of the laser pulse (temporal and spatial shape). The destruction mechanism of the transmitting elements determined by the peak power density, while it is defined completely by the destruction of the highly absorbent materials [1-5].

Laser Damage is Associated with the Following Factors

1. Peak power density (temporal and spatial) in the laser pulse.
2. Maximum spatial energy density of the laser pulse.
3. The average energy density in the pulse spike.
4. Energy density in the pulse, with spike and tail.
5. The total energy density is the average energy density in the pulse train. 6- CW power density (power at given time).

The highest measured values for damage thresholds are that for a highly purified volumetric materials with compact and transparent close-packed materials having low refractive index

The reason for the threshold damage of materials by laser radiation under special conditions is one of the mechanisms that will be discussed in the following paragraph:

Collapse of the Insulator

Volumetric Effect

Laser-induced damage takes place in volumetric materials when the electromagnetic field intensity provokes the collapse of the material insulation.

These intensities of the electrostatic fields can be induced by a high-density p_D laser beam of 50-1000 MW and in the relationship between the isolation intensity and the damage threshold caused by the laser beam [3-8].

We express the light power density PD in the following equation:

$PD = VB^2/Z1 = VB^2n/Zo$ (1)

Where

Z_1 and Z_0 are the impedance of the dielectric material and the free vacuum, respectively.

n:is the Refractive index

$P_D = E_p/\tau A$ (2)

A: is the parameter of area

τ: is the pulse width at half of the laser beam pulse amplitude.

Any heterogeneity of matter leads to the generation of localized energy density of the laser beam, and to a higher local energy density.

Heterogeneity includes surface cracks and pores. The last two lead mainly to the fact that the damage threshold falls below the theoretical threshold.

Surface Effects

We rarely encounter an impedance breakdown of an insulating glass material such as optical windows, mirrors and optical elements in ordinary laser systems. The impedance breakdown can be represented by a surface damage at the front and rear of laser bar that occurs at a damage threshold lower than that of the optical elements.

The threshold a surface damage measured in air is significantly higher for the frontal surface than for the rear surface of laser rods and other optical elements.

In fact, the localized damage intensities caused by the laser beam are equal for the two exposed surfaces, as long as the reflection on the two surfaces as well as the phase change of the optical fields is taken into account.

In an ideal sample with a refractive index n, the resulting difference between the electric fields of the entry and exit surface (V) follow the relationship represented by the equation (3):

$V=4n^2/(n+1)^2$ (3)

The difference in the electric fields forms a stable wave that has a maximum constructive density at a half wavelength λ / 2) at the front of the surface. This results in a plasma at the point of the arrival of the laser beam. Where λ is the wavelength of the incoming laser.

At the front of the studied optical element, the plasma is located in the air, and in some cases the sample is protected by absorbing the power of the incoming laser beam.

At the end of the optical element: the plasma is formed inside the crystal component of the laser bar or the optical glass. This leads to increasing the intensity of the absorbed power and causing catastrophic damage.

Usually, white sparks happened at the moment of the breakdown, and occur occasionally at an energy density lower than the damage threshold.

The Effect of Scratches

The optical material's damage threshold, which is related to the dielectric breakdown, can only be measured in optically optimal materials. If the material includes heterogeneous optical interruptions, then there will be both a refractive and reflective process of the laser beam as it passed through the studied optical material [6-7].

Accumulation of processes can occur in matter, either in volume or surface, and the collapse will occur at damage thresholds lower than that of the pure state.

We note from the relationship (1) that sever cracks are more dangerous, especially when the materials have high refractive index.

The effect of the electric field is given in the following cases:

1- crack

$V=n^2 Vo$

2- groove

$V = [2n^2 / (n^2+1)] Vo$

3- pore:
$V = [3n^2/(2n^2+1)]\ Vo$

The highest thresholds of laser vaporization can be obtained when fine polishing of the crystal so that scratches and cracks deeper than 1% of the laser wavelength are absent.

Priloan Dispersion
It is made from the internal feedback mechanism that amplifies sound and electromagnetic wave at the expense of the entering laser beam.

At high power levels, damage occurs from the mechanical stresses related to the electromagnetic wave.

Self-Focusing
It is the reduction of laser beam diameter less than the expected refractive index value of the non-radioactive material. It results from any process that leads to an increase in the index of refraction along with the increased light intensity that is associated with or without a high temperature.

Thermal Absorption
Volumetric Absorption
It can be generated by the presence of impurities, electrons of conductivity, or by the crystalline network, and can cause laser damage by heating, thereby melting part of the radiant region.

Surface Absorption
It can be in the form of overlapping surface layers.

Local Absorption Occurs at all Wavelengths
Whether it is a polishing element, unguided crystals or impurities at the boundaries of granules and the threshold of laser damage, one of the following factors is the energy density required to generate partial stress in the host crystal, which is attributed to the expansion of the heated outer shell.

Whether due to a polishing procedure, unoriented crystals, or impurities retained at the grain boundaries. The damage threshold due to a laser beam is related to one of the following factors:
1. The energy density needed to generate a partial stress in the host crystal is attributed to the expansion of the heated outer shell.
2. The energy density required to generate partial tension in the host crystal, which is due to the expansion of the inclusions content [12-14].

Optical components can be damaged by laser irradiation with a sufficiently high energy. At any specific laser irradiation level and operation mode of the laser source, the probability of laser damage is usually higher for the surface of a component than for its bulk. Therefore, the limiting value of an optical component is frequently given by the damage threshold of its surface. Bulk damage is observed when the electrical field strength in the bulk of the component is enhanced by self- focusing, interference, scattering or other effects.

Imperfections, such as inclusions, dislocations, color centers or heterogeneities, can reduce the power-handling capability in the bulk of an optical component. Damage by a single laser pulse is often induced by defects or a mechanical stress on the coating, a contamination of the surface, or an optical absorption, which leads to a catastrophic heating of the surface.

For multiple-pulse operation, not only reversible mechanisms induced by thermal heating and distortion but also irreversible damage mechanisms induced by ageing, micro damage, moisture damage and generation or migration of defects are both observed.

The various parts of this International Standard are concerned with the determination of irreversible damage of the optical surfaces and the bulk of an optical component under the influence of a laser beam. Depending on the environmental conditions, damage is a function of material properties and laser parameters, in particular a wavelength, a spot size and an irradiation duration.

Definitions
- Flatness N: Is the number of Newton rings and its symbol N.
- Irregularity coefficient ΔN: is the anomaly of the created optical surface (Irregularity) from the reference surface [1-5,20], and its symbol is "ΔN ".

It is known that the transmission coefficient of a parallel-sided optical glass plate of type BK7, which has 5 mm in thickness, 25mm in diameter, characterized by a good optical quality, no bubbles, no cracks in the optical structure of the plate. Finally, the parallel between the two surfaces has a value 5" arc second, the irregularity coefficient is ΔN=0.3, and the flatness is N=1.

BK7 is a high quality optical glass that is used whenever the additional benefits of fused silica are not required. Since BK7 performs well in all chemical tests, and no additional or special handling is required, costs of manufacturing are reduced. It is a relatively hard material with extremely low bubble and inclusion content, while providing excellent transmittance through-out the visible and near infrared spectra and down to 350 nm in the ultraviolet.

For all standard optical glass components, or when optical glass is generically requested for custom elements, Glass Dynamics uses normal high quality BK7 optical glass [20].

The graph line of the selected sample BK7 which has not been painted in order to prevent reflection is illustrated in figure (1).

The resulting graph is drawn from the percentage changes of the Transmission with the wavelength variations measured in nanometers [20].

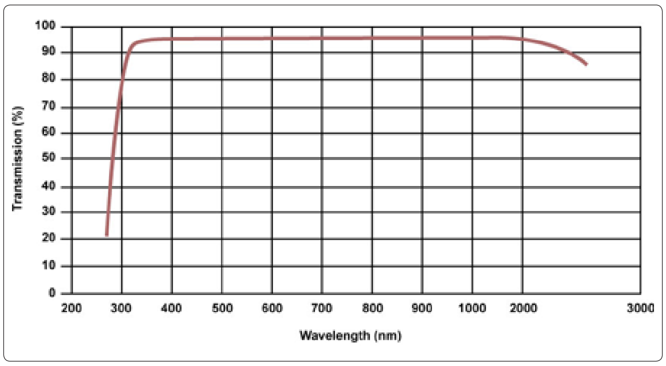

Figure 1: BK7 transmission with the range wavelength 350nm -2μm changes.

The figure (1) indicates that the permeability of the glass is very good and there is no absorption on the visible and the near infrared fields.

It appears below that the optical chart, of the first parallel-sided plate made of BK7 optical glass with geometric dimensions and tolerances, along with second plate which is made of SF13 optical glass, have the same specifications and measurements in Figure (2).

Figure(2-a): present the geometric design of a two-sided plate.
Figure (2-b): Optical interference fringes show the quality of the optical surface by using the Fizeau Interferometer device presented in the following figure (2-c).

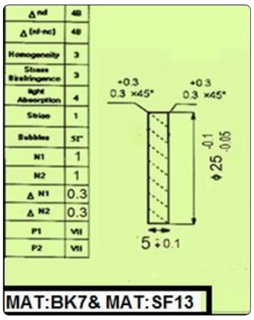

Figure (2-a): Present the geometric design of a two- sided plate.

Figure (2-b): Optical interference the quality of the optical show fringessurface by using the Fizeau Interferometer device presented in the following figure (2-c).

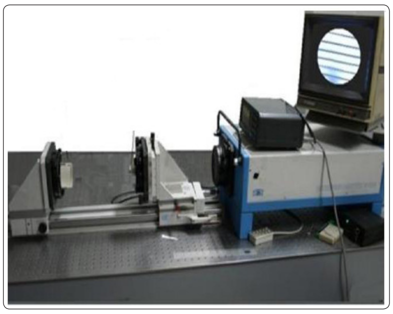

Figure (2-c): Fizeau Interferometer device

Experimental Work
Optical glasses BK7 & SF13 were exposed to a laser beam so that the surface of each of them is located at the focal point of the positive lenses that pass the laser beam as shown in figure (3).

Figure 3: shows the two-sided parallel plate after manufacture, and how to place it on a mechanical stand against lasers

We can take the thermal effect of lasers, using laser-sensitive burning paper, measure their dimensions' spots and then calculate the area of the laser spot, [9- 17] as shown in Figure (4).

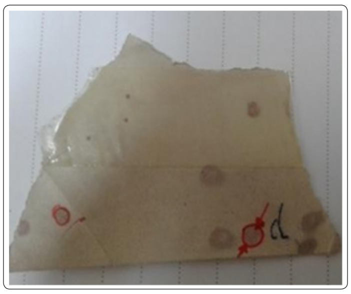

Figure (4-a): The thermal effect of lasers on sensitive burning paper

Figure (4-b): The thermal effect of laser presented as spots on the clean glass BK7

-We can take a digital image of the laser beam at a point located at the focal level of the lens on the studied optical surface of the plate, as shown in Figures (5-a,5- b).

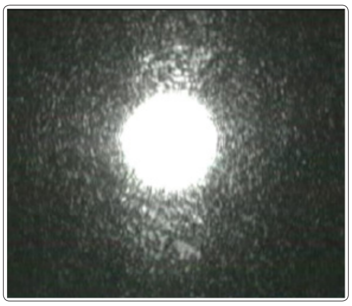

Figure (5-a): Digital image of laser spot on the optical surface

Figure (5-b): Digital image of laser spot on the sensitive burning paper

The intensity of power projected on the glass can be calculated as shown in mathematical equations [6-9].
-video1

As shown in the attached video1, the damage of the real surface located at the focal level of the converging lens is illustrated.

Calculations

The mathematical calculation in a simplified way to the threshold of damage is presented as follows:

$P=(E.TOC / S.\tau)\, f$ $E=200$ [mJ]

$S=\pi r^2$

$P=200*10^{-3} * 10 / \pi*10^{-6} * 30 * 10^{-9}$ $P=2.12207$ GW/cm^2

Where:

P: The optical density of laser power in one area per sec. E: Energy of laser in joule.

TOC: The transmission of the optical element.

S: Area of the laser spot on the optical glass's surface. f: number of laser pulses by second.

r: Spot radius.

Study the intensity of energy in relation to the roughness of the optical surface using neodymium-yag laser:

Table 1 shows the experimental work on glass BK7 type. The threshold damaged which is P_{th} [Mw/cm^2] is examined in relation to the change in roughness coefficient R_n(nm) and the number of grinding hours, for each stage of the glaze grinding & surface finishing (polishing).

Table 1: presents the change of roughness coefficient in relation to the intensity of laser energy for glass BK7

P_{th} the Damage Threshold intensity of energy for BK7 glass. [Mw/cm^2]	R_n: roughness coefficient of the optical surface. [nm]	T: Surface grinding time. [hour]
580	324±25	0.5
650	148±15	1.0
970	32±10	1.5
1140	15±5	4
1200	10±3	8
1260	7.7±1.8	20
1480	5±1.5	30
2000	1.5±0.5	48

-Curved energy density with the roughness coefficient of the optical surface for glass BK7, is shown in Figure (6).

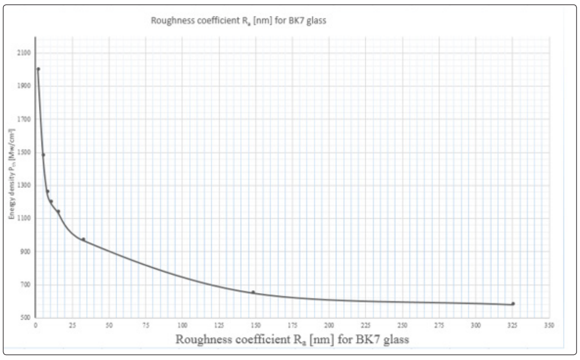

Figure 6: Curved energy density P_{th} [Mw/cm^2] in relation to the optical surface roughness coefficient R_a [nm] for BK7 glass.

- Damage Threshold of the optical surface, using neodymium-yag laser for glass SF13.

Table 2 shows the experimental work of examining the glass SF13 type threshold damaged P_{th} [Mw/cm^2], with the change in the roughness coefficient R_n(nm) and the number of grinding hours, for each stage of the grinding & surface finishing (polishing).

Table 2: presents the change of roughness coefficient in relation to the intensity of laser energy for glass SF13

Damage Threshold Pth [MW/cm^2]	Ra [nm] roughnessSF13	T: Surface grinding time in hour.
580	324±25	0.5
650	148±15	1.0
970	32±10	1.5
1140	15±5	4
1200	10±3	8
1260	7.7±1.8	20
1480	5±1.5	30
2000	1.5±0.5	48

Curved energy density with the roughness coefficient of the optical surface for glass SF13, is shown in Figure (7).

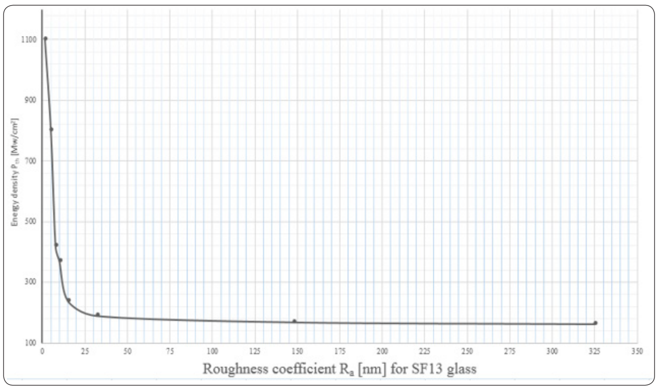

Figure 7: Curved energy density P_{th} [Mw/cm^2] in relation to the optical surface Roughness Coefficient R_a [nm] for SF13 glass

-We can also draw a logarithm, which is almost straight and very close to the theoretical curve, as shown in Figure (8).

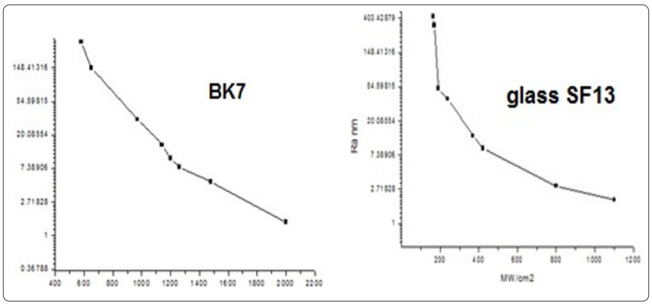

Figure 8: the graph on the left (which presents the BK7 optical glass) is very close to the theoretical curve (vertical axis is drawn on logarithmic scale).

-From the previous graphic curves, for each of the two types of the studied glass, we conclude that the optical surface absorbs the thermal energy generated by laser, otherwise the real surface contains a greater amount of cracks resulting from the processes of optical grinding during the finishing process [12-18].

When the surface is as clean and free of optical defects, as damage threshold is high.

Thermal Treatment of Optical Glass

After testing the damage threshold for the two previous glass types and marking the relationship between the thermal damage threshold and the roughness coefficient Ra, we will perform thermal treatment of the same two types of glass to improve and raise this threshold in order to obtain optical glass with better physical specifications while maintaining the properties Chemical and optical glass.

This is very useful for heat-resistant glass that can be used in devices with medium and high-capacity laser beams,Because the more laser-tolerant the glass can withstand, the better.

We can avoid the problems of a burning spot on the glass surface, for different visual elements, which will worsen whenever there are bad weather factors, such as moisture and dust, especially the outer surfaces of laser optical systems.

After cleaning the studied glass samples of bk7, SF13, placed in a heat oven that is regularly controlled and slow to a temperature of 250 degrees Celsius for five hours, waiting until the heat cools regularly.

We examine the samples, in the same way as in paragraph 5. And we repeat that after each stage of the grinding,

Then we do the calculations, as in paragraph 6 above, and draw the graph curves. which shows the increase of the threshold, after heat treatment as shown by tables 3 and 4

Table 3 shows the experimental work on glass BK7 type. The threshold damaged which is P_{th} [Mw/cm^2] is examined in relation to the change in roughness coefficient R_n(nm) and the number of grinding hours, for each stage of the glaze grinding & surface finishing (polishing).

Table 3: presents the change of roughness coefficient in relation to the intensity of laser energy for glass BK7

P_{th} the Damage Threshold intensity of energy for BK7 glass. [Mw/cm^2]	R_n: roughness coefficient of the optical surface. [nm]	T: Surface grinding time. [hour]
638	324±25	0.5
715	148±15	1.0
1077	32±10	1.5
1277	15±5	4
1436	10±3	8
1652	7.7±1.8	20
1717	5±1.5	30
2340	1.5±0.5	48

-Curved energy density with the roughness coefficient of the optical surface for glass BK7, is shown in Figure (9).

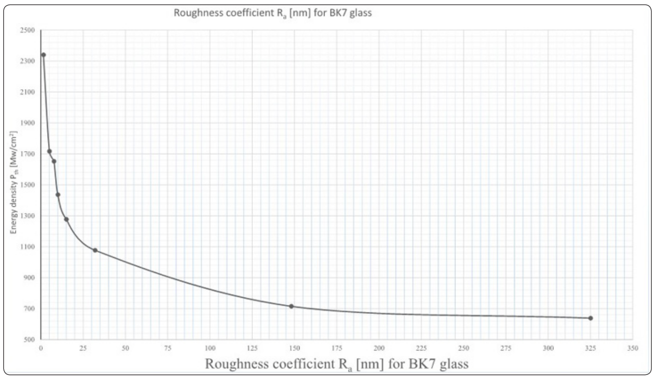

Figure 9: Curved energy density P_{th} [Mw/cm^2] in relation to the optical surface roughness coefficient R_a [nm] for BK7 glass, After heat treatment of glass

- Damage Threshold of the optical surface, using neodymium-yag laser for glass SF13.

Table 4 shows the experimental work of examining the glass SF13 type threshold damaged P_{th} [Mw/cm^2], with the change in the roughness coefficient R_n(nm) and the number of grinding hours, for each stage of the grinding & surface finishing (polishing).

Table 4: presents the change of roughness coefficient in relation to the intensity of laser energy for glass SF13

Damage Threshold Pth [MW/cm^2]	Ra [nm] roughnessSF13	T: Surface grinding time in hour.
180	425±65	0.5
188	327±40	1.0
213	52±20	1.5
270	38±13	4
420	13±4	8
485	9±3	20
928	3±2	30
1287	2±0.5	48

Curved energy density with the roughness coefficient of the optical surface for glass SF13, is shown in Figure (10).

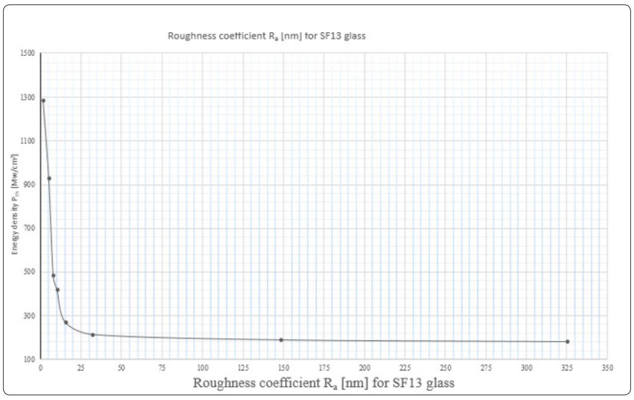

Figure 10: Curved energy density P_{th} [Mw/cm^2] in relation to the optical surface roughness coefficient R_a [nm] for SF13 glass, After heat treatment of glass

We can also explain the effect of heat treatment between the combination of the before and after heat treatment chart as in the following two figures 11-12.

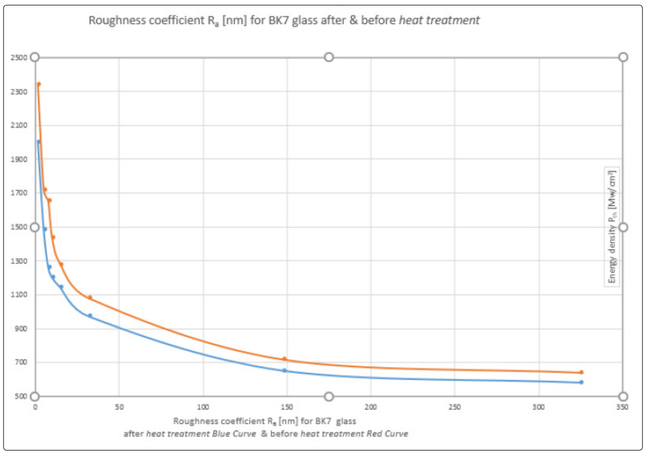

Figure 11: Curved energy density P_{th} [Mw/cm^2] in relation to the optical surface roughness coefficient R_a [nm] for BK7, Before and after the heat treatment of the glass

The lower curve, blue in figure 11, is without heat treatment for samples of BK7 glass,

The upper curve in the shape in red, is after heat treatment, and the amount of increase in the values of the upper curve, is about 10%-15% more than the first value.

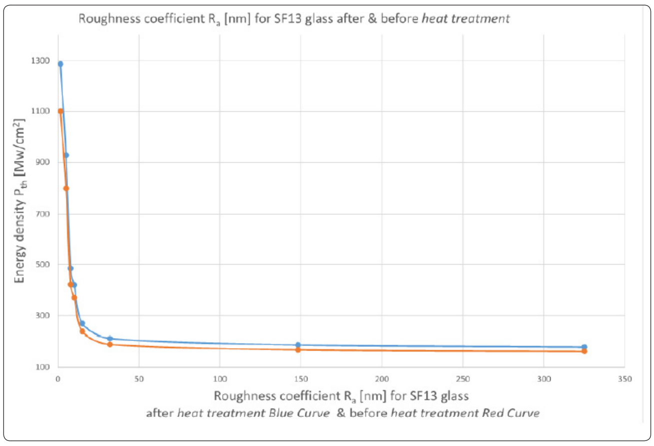

Figure 12: Curved energy density P_{th} [Mw/cm^2] in relation to the optical surface roughness coefficient R_a [nm] for SF13 Before and after the heat treatment of the glass.

The lower curve, red in figure 12, is without heat treatment for samples of SF13 glass,

The upper curve in the shape in blue, is after heat treatment, and the amount of increase in the values of the upper curve, is about 10%-15% more than the first value.

As a result, we note that after heat treatment, the tolerance of the optical surface, for both types of BK7&SF13 glass, has increased by an equal percentage, by about 10%-15%. As a result, we obtained better thermally treated glass, in terms of the optical surface Damage Threshold P_{th} [MW/cm^2] of lasers, as we showed the difference in the chart above, for both types of glass.

Conclusion

We have used ND: YAG pulse laser with longitudinal mode TEM_{00} with a τ=30ns pulse width, concentrated inside BK7, SF13 glass, using a lens to increase the concentration of the focal length of lens F=30mm laser beam.

- The Damage Threshold of light damage is measured, with the change of optical roughness factor during the optical manufacturing of a parallel-sided plate (designed using an optical design program Zemax) that leads to optical damage to the borosilicate, (glass Bk7, SF13) at the wavelength λ=1.064µm. The graph of the roughness factor change is drawn with the optical damage Threshold of the optical surface. [1-8,11,19].
- During the process of optical Manufacturing, and in the final grinding phase, the test study concluded the desired result after 48 hours of continuous grudgingness,
using the diamond powder gradually from the bottom to the graces from 200nm to 3 nm to the smoother surface possible [2-6].

- We studied the change in the R n roughness coefficient with the P the Damage Threshold and charted the graph of this change. We found that the softer the surface, the higher the Damage

Threshold of damage, the better the surface and the greater the ability to load the surface for lasers, because the roughness of the surface is the main cause of its destruction, where the surface cannot dissipate the heat easily, while the surface gets rid of the heat more, and it is Its absorption of laser is less.

We also conclude that bk7 optical glass Damage Threshold is greater than SF13 glass [3-10].

We concluded that the shattering damage Threshold of optical glass becomes better the softer the glass surface, which is illustrated by the density and smoothness curve [6-9].

-We have presented a new approach for improving the interpretation of laser- damage probability curves. Indeed, laser-induced damage in optical material is often a problem of defects, and our aim was to characterize them as well as possible. Then we have proposed to consider that in a given class of defects, each defect has its own threshold, i.e. thresholds of the defect population are distributed. In this paper, a Gaussian distribution of thresholds has been considered. Other models can be used, but they require a preliminary knowledge of these defects (especially size and absorption). To illustrate our investigation, we have shown experimental results obtained on substrates polished according to different techniques. Results achieved on a BK7 & SF13 layer optical glass also shown, which establish a good agreement between theory and experiment. This model is of interest for the study of polishing and cleaning processes since it improves the knowledge on laser-damage precursors.

Bk7 glass is very important because of its strength among the types of glass, where its hardness (HKop) =520kp/mm^2, low refractive dissonance n_d=1,5168 and ape factor ν_d =64.17and made of positive lenses and optical prisms [18-20].

SF13 glass is weaker, with hardness (HKop) =380kp/mm^2, a large refractive presumption n_d =1,74077 and ape factor ν_d =27.6 and negative lenses (telephoto)[16,20].

These two types are often used together to make objective lenses in optical devices.

-The reason for the selection of these two types of glass is because of their wide spread use as beam expander, which are used in optical systems and devices that use lenses in focusing laser beam, they are also used in doublet lenses in medical devices, Industrial, remote sensing, optical communications and imaging system.

The better the process of the surfaces finishing during manufacturing, the less optical loss, so previous applications using various optical elements such as lenses and mirrors and another component become better because they will transmit lasers and optical signals without loss.

-After heat treatment of glass samples, the tolerance of the optical surface, for both types of BK7&SF13 glass, has increased by an equal percentage, by about 10%-15%. As a result, we have a better heat-treated glass, in terms of the optical surface Damage Threshold P_{th} [MW/cm^2] of lasers.

Data Availability

The detailed experimental data used to support the findings of this study is available from the corresponding author upon request https://orcid.org/0000-0003-2657-1605

Acknowledgments

The author would like to thank **Dr. M. Sayem El-Daher** of the higher Institute for laser research at Damascus University **Dr. A. Obed**, and **En. H. Hourani**. for the assistance they have provided to this work.

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