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Research article

Optics for High Power Lasers

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Abstract

The advent of the laser has placed stringent requirements on the fabrication, performance and quality of optical elements employed within systems for most practical applications. Their high power performance is generally governed by three distinct steps, firstly the absorption of incident optical radiation (governed primarily by various absorption mechanisms); secondly, followed by a temperature increase and response governed primarily by thermal properties and finally the elements thermo-optical and thermomechanical response, e.g., distortion, stress birefringenous fracture, etc. All of which needs to be understood in the design of efficient, compact, reliable and useful for many applications high power systems, under a variety of operating conditions, pulsed, continuous wave, rep-rated or burst mode of varying duty cycles.

Key words: high power optics, cooling, heat exchange, polishing, coatings, optical load.

What is really power optics? In what way do they differ from ordinary optics widely used in cameras, motion-picture projectors, i.e., everyday use? In the late 60s, scientific groups discovered an undesirable consequence of the thermal deformation of optical elements and surfaces during their interaction with powerful incident laser radiation. [1-5]. Undoubtedly, the physical effect observed should have limited many applications requiring high power optical systems under development at that time. The gist of the effect was the following, the optical surface of even a very perfect mirror does not fully reflect radiation that is incident on the surface. A small part of energy, about 0.5–1.0%, is absorbed by the mirror and is transformed into heat. With an increase of laser beam power, even a small absorption is enough to cause an undesirable thermomechanical stress in the mirror, and can distort the geometrical shape of the reflecting surface. Standard requirement for optical surface deformation is $< \lambda/20$, where λ – laser radiation wavelength. This in turn will influence, for example, the performance and optical characteristics of the laser system. We know that thermal deformations of mirrors can not only degrade the basic beam quality but can as well lead to the cessation of lasing in some cases. The response can be either transient or permanent, i.e., catastrophic.

Archaeologists have indicated that man made mirrors five thousand years ago. First, they were made of polished bronze or silver plates. In Roman times there appeared glass mirrors with a tin or lead coating. Since that time, the technology of mirror production has changed many times. Most are either glass or quartz with applied metallic or dielectric coatings. Their early use was limited to low intensity sources, e.g., astronomical observations, illumination, etc.

The occurrence of mirror failure under intense laser radiation appeared from the very beginning with lasers. In lasers of all types lasing occurs in a resonator that consists minimally of a pair of optical mirrors, and through one coherent radiation is emitted. In the early development stages these resonator cavity elements were nothing more than quartz substrates with a mirror
coating. However, lately the power of the laser out has increased hundreds, even thousands of times higher. Today the fabrication of mirrors capable of functioning while keeping their design characteristics under the influence of intense coherent radiation, is one of the key challenges in the development of improved powerful lasers of practical usage. The principal question is whether it is really possible to create mirrors that are not damaged by the powerful incident radiation flow when using the output for practical purposes, e.g., material processing. For contemporary laser systems this value in the resonator can be on the level of 200-300 kW/cm2. Perhaps it is appropriate to suggest a useful definition of damage here. We propose an applied or operative one, namely, damage is said to have occurred when the element or system no longer performs the function for which it was intended within specified limits (whether or not there is permanent or catastrophic damage).

Numerous institutions throughout the world have studied various aspects of these power optics questions from the beginning of the dawning of lasers. In point of fact a Symposium on Optical Materials for High Power Lasers and GCL/HPL have been held annually in the United States and in Europe since 1969. Likewise a related conference "Nonresonant Laser Matter Interactions" also started in 1969 has addressed this subject in Russia. These meetings and their proceedings are the principal forum and repository for research and development activities. The material is readily available. Interest in the subject continues unabated to today. It is their goal, i.e., preventing lasers from committing suicide and demonstrating a high threshold for optical serviceability.

The real power density or the intensity of light at which distortions reach a preset limit can be a defined threshold of optical serviceability. One is not allowed to exceed this threshold because of elastic deformations of an optical element for the intensity distribution of the laser radiation will be altered unacceptably. If the intensity is further increased deformations can be transferred into a non-elastic area and become plastic, and thus result in a non-recoverable effect in the element. The element is said to have failed. So, it is required to fabricate elements which over a long period of time can withstand high optical loads, e.g., from a few hundreds of watts up to several kilowatts per square centimeter of the surface for CW or P-P with high average power scenarios.

To imagine how difficult this task is, it is enough to describe two examples. Let us take the case of a mirror in an experimenter's hands for only a few seconds. Deformation due to variations in heating from the hand's warmth, of the optical surface can increase the limiting tolerated value. But in this case if the mirror is left to "cool," its original shape is generally fully recovered. In reality mirrors of advanced technological lasers are routinely exposed to power densities of a few kilowatts per square centimeter. This level can be compared with the heat that is radiated into the surrounding space directly from a unit of the Sun's surface. Thus it follows that if we "put" a laser mirror "on the Sun," the shape of its surface would not change by more than a micrometer. These types of mirrors are similar to those required for powerful industrial lasers.

To create these power optics, a number of problems related to quantum electronics, optics, thermoelasticity and heat exchange, materials study and advanced technologies, etc., need to be addressed. The first step in this might be to substitute a semitransparent quartz disk by a metallic one and to extract the radiation externally by diffraction through an aperture in the mirror or at its boundary. Metals exhibit nearly perfect reflectivity in the infrared. They also possess high thermal conductivity which means they can transfer heat from the zone of incident interaction on the mirror surface. However,

pure metals have some disadvantages as well, e.g., a high coefficient of thermal expansion—they can easily change their size or shape when heated—and also a low hardness to which it is generally difficult to polish a dielectric such as quartz. However, recent advances have allowed for excellent finishing of ceramics such as silicon carbide which makes for quite excellent mirror substrates (providing quality coatings are applied). It should be noted that advancements in single point
micromachining by diamond turning and optical polishing of metals are in many ways greatly alleviating general laser mirror problems[6-14].

It is interesting to recall an old occurrence (early 70`s) when physics was applied for the first time came to metallic optics. Consider a request to polish a metal disk in one and the same room as with quartz or Iceland spar. This was simply ridiculous as metallic dust in the workshop where final polishing was performed on precision optics, was not advisable. But nevertheless, a way out was found—a fully metallic mirror (Fig1).

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Fig.1. Metal based high quality optics

Investigating many metals and alloys of possible use for mass production, it was demonstrated that one could increase the threshold of optical serviceability of these new mirrors by ten times as compared to a traditional quartz element. The fact that its suitability was increased by “ten times” was not enough. It became obvious that the required level of power density and thermal loading of the mirror of a very powerful laser, could be reached only with the assistance of substrate cooling.

During cooling by a circulating liquid (usually water, kerosene, alcohol, silicone, ets.), the heat withdrawn is directly proportional to the difference of temperatures of an inert body and the heat carrier. It might not be too difficult to remove thermal power rates at kilowatts per square centimeter if the mirror is heated up to a temperature of about one thousand degrees. However, it is hardly possible to realize a “perfect” optical quality for the mirror surface. There is a contradiction—convective heat exchange is greater at high temperatures, while temperatures close to ambient are desired for the stability of the mirror’s geometrical shape (and other thermo-optical characteristics of the mirror). It is possible however to resolve this contradiction by means of a more efficient heat removal technique. Temperatures of optical surfaces at about 100°C or less (typical for a laser mirror) this task was not demonstrated. To attack this situation experiments were initiated by milling in the back side

of a metal substrate channels through which the tap water was circulated. These cooling channels were placed as close to the surface as possible, but they frequently led to a vibration and deformation due to the water movement. One attempt to resolve this was to make the channels shallower. This approach led to the conclusion that it is much better to use porous capillary substrates that upon sectioning appear like a form rubber. Now the heat exchange was more intensive both due to a large surface thermal cooling as well as an increased mixing of the cooling fluid that travels in the microcapillaries. Moreover, the matrix–skeleton of the porous body functioned as a closely spaced mirror surface supporting structure. Allowing for an improved stability in the irror surface, i.e., it maintains its initial geometry better (Fig 2).

In this situation the cooling fluid engenders a chaotic river flow. The matrix of the porous body resembles the structure of “lace” retaining the smooth character of the surface by these large number of closely spaced supports [15-17].

Additionally one usually also applied a high reflectance coating on the highly

porous heat exchanger substrate to further reduce the thermal load on the cooled substrate. Then the coating is polished if necessary to achieve the desired reflectivity and figure. The thickness of such coatings should be very small—100-150mkm; otherwise, they can reduce the heat absorbed by the mirror surface. There are several methods used in applying quality multilayers on these highly porous cooled metal substrates. It was frequently solved by employing intermetallics, i.e., chemical compounds of metals. These intermetallic coatings can be achieved, for example, by precipitation from a gas phase (channel vapor deposition, CVD). In such a way it is possible not only to realize a fine separation layer, but if necessary to restore mirror quality. Intermetallic coatings have another important property: their structure makes it possible to obtain mirror surfaces of very high optical quality [18]. If one inspects a polished ordinary metal through a microscope, its surface frequently reminds one of an orange peel, i.e., it is covered with hillocks and cavities. To reduce this micro-structure, additional finishing measures can be employed, e.g., before final polishing the metal substrate can be alloyed to make it not only harder, but more fine grained. Nevertheless, the final scale of unevenness remains too large, i.e., from 0.01 to 0.1mkm. The structure of intermetallic coatings from the start is very fine, about 0.1mkm and after treatment by a diamond tool or by optical polishing, it is possible to realize almost perfect mirror surfaces—with an average scale size of only a few thousandth of a micrometer.

Thus, a solution has been found. Mirrors for powerful "industrial" lasers of continuous and or pulsed formats can employ mirrors containing highly porous heat exchangers, together with the use of a fine separating layer and with a reflecting coating. Industrial lasers with such mirrors have been used successfully for welding, cutting and the hardening of metals (Fig 3).

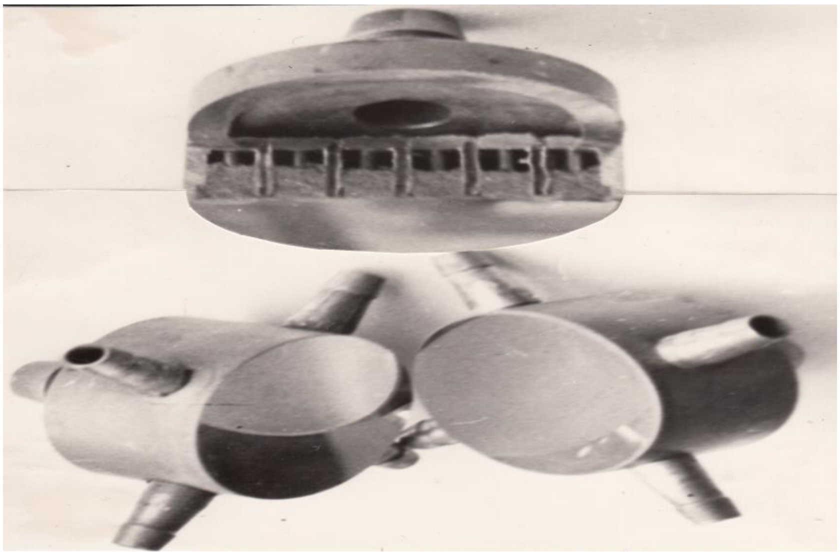

Fig. 2. First high power water cooled porous mirrors

Fig.3. Laser cut examples of technology (glass, composite , stone, sitall)

There are still possibilities to further improve these "power optics." By changing the pressure of the coolant it is possible to force it to boil at room temperature. This is within the conditions similar to those of the final treatment of the mirror's surface. During the boiling of the coolant, part of the absorbed heat is used for steam formation, thus heat removal efficiency is tens to hundreds of times higher than within convective heat transfer. Steam can easily penetrate into porous capillary substrate structure.

Additionally, water can be substituted by a liquid metal. For example, alloys of sodium, potassium and cesium, which have low melting temperatures. The efficiency of the heat removal will increase since the heat would not only be carried away by the moving liquid, but by being transferred to the heated metal itself as well, which would be an almost perfect heat conductor, as metals usually are. Liquid metal heat conductivity allows the removal of heat from reflecting surfaces at a few kilowatts per square centimeter on the surface. Eventually of course as one approaches "perfect" reflectivity for coatings—cooling could be eliminated entirely except to stabilize or homogenize the temperature.

It is really interesting, to ask, is there is a limit at present for the amount of heat that can be withdrawn from the surface into the mirror substrates? From the point of view of present day power laser optics the limited heat regime is determined by gas breakdown at the mirror surface, i.e., by plasma formation in the resonator cavity. The developed and demonstrated methods of intensive heat removal may in turn be useful in other fields where there are no such limitations. Using the methods of metallic mirror cooling it is possible to solve, for example, "non-mirror" specific problems, like the cooling of large integrated structures for the present day anodes of powerful X-ray lithographic installations for microelectronics manufacturers. These devices should endure heat loads of between a few tens and hundreds of kilowatts per square centimeter. The highest value of evacuated heat flax, realized in the case of high power optics was measured on the level of 8,2 kW/cm2 (82 MW/m2). An important issue in the generation of power optics can be economical by implementation of a number of technical and beneficial solutions for the national economy [19-22]. Among them, for example, can be diamond turning and the concurrent creation of a large range of machines for high pressure, accuracy and uniformity of treatment. With the help, e.g., of such machines that make memory disks, as well as drums for copy machines and other high tolerance equipment. For "non-mirror" specific uses an obvious application is related to the development of technologies using these various capillary-porous structures plus the application of environmentally benign coatings of high hardness on metals and intermetallics

Consider the integration of a big number of laser diodes (LD) into 1-d and 2-d structures radiating both non-coherent and coherent laser radiation of high power. The difficulty of such integration of LD is in the necessity to retain the temperature of radiating hetero-junctions of LD within a narrow temperature range, insuring in turn the frequency stability of the laser radiation. Heretofore, values of thermal power density at the level of few kilowatts per square centimeter of heat exchange surface at room temperatures were required. In practice such array structures of LD consists of a large number of LD soldered to the surface of a perfectly prepared metal mirror at a high packing density on the above mentioned radiating elements. As the array radiates high intensity laser light (even at today's demonstrated efficiency greater than 60%), heat exchangers should extract, as indicated above, heat flows from an active medium Q> 1000 W/cm2. At this level the displacement of the radiation spectrum conditioned by a thermal increase of the radiating layer, should not increase more than 3 nm relatively to the initial wavelength of lasing, corresponding to a change of temperature of the active layer not more than by 10□C. This is why the heat exchanger of such a device should have a relatively low thermal resistance, of not more than 0.1 K/W.

To obtain these high values of heat removal in the devices high thermal conduction materials, such as: beryllium ceramics (BeO), (K= 3.7 W/cm□C), diamond (K= 20 W/cm□C) etc. should be employed. Unfortunately, the effort and cost to produce and treat these materials makes the process of array fabrication more difficult and expensive. Silicon carbide (SiC) is frequently used as a high thermal conductivity material. Besides high thermal conductivity (in the best cases it is close to copper's thermal conductivity) silicon carbide has enough electrical impedance, it can be best treated and is safe from the point of the environment, it also has a high hardness that is important during optical polishing. Both separate and combined heat removal elements can be made from silicon carbide as well as complete microchanneled or porous heat exchangers. Use of silicon carbide as a thermal heat sink material is also convenient because its coefficient of thermal expansion is close to that of GaAs—the basis of numerous laser diode compositions. This aids to prevent the material from cracking during, e.g., soldering. It should be noted that development of optical grade silicon carbide requisite size is available for solving some optics applications in high power laser systems and for astronomical purposes (Fig.4).

The results obtained during last decade at Russia and the United States are fully consistent with the current trends in the development of the market for LD technologies [23-25].

Indeed, as early as 1991 much attention has been concentrated on the following trends in the development of technologies which are so popular nowadays in research groups and industrial companies throughout the world:

—development of efficient heat-sinking systems for 1-d and 2-d LD arrays;

—improvement of the soldering technology for a linear array and a heat-sink component taking into account the problem of minimizing the thermal resistance
and of bending of the 1-d array itself;

—creation of a new laser system based on a phase locked 1-d array of LD;
—use of phase-locked systems with efficient injection of radiation into a fiber;
—phase locking of 2-d LD arrays (not realized yet);
—efficient beam steering for the case of high power 2-d matrix of LD radiation (not realized yet);
—development of new configuration of high power solid state lasers – single module scalable disk laser with diameter >10cm (not realized yet);

The above trends require maximum concentration of intellectual and financial resources. We already understand well the physical and technical problems encountered in the construction of highly heat-sink components. The evident advantages of technologies involving phase-locking of LD arrays have been demonstrated, which has made it possible to develop new approaches and to implement a range of ideas included in the above list.

Fig. 4. Big size SiC mirror under polishing

Conclusion

One very important and true to life relationship should be mentioned in this rather difficult time for science. The resources invested effectively in the development of any field of advanced technology will as a rule afford a feedback in a number of ancillary applications in other ancillary and sometimes rather remote fields of science and technology. Thus, phase-locked 1-d and 2-d arrays of LD with high level of radiation and new configuration of solid - state laser – single module scalable disk laser- appears and many other innovations, mentioned at the Symposium HPLS@A-2012, Istanbul 10-14 September, to be due in part to achievements in the field of high power optics [26]. Power optics is a universally recognized contributor to other advanced laser systems and applications for the 21st century. Russia and the United States, in the case of power optics, are leaders in this field.

References

[1]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, High power CO2-laser, Report of FIAN,1970
[2]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Thermal deformation of solid state surface by laser beam, Letters to JETP, т. 15, 1972
[3]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Optical mirrors loses on scattering measurements , QE, т. 4, № 16, 1973
[4]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov CO2 laser mirrors investigations, Report of FIAN, 1973

[5]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Thermal deformation of laser mirrors, Second European conf. «Lasers and applications», Drezden, July, 1973

[6]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Optical characteristics of laser mirrors, Preprint № 157, FIAN, 1973

[7]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Thermal deformation of laser mirrors, Radiotechnics and electronics, V. XIX, № 1, 1974

[8]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov Thermal action of laser beam on the surface of laser mirror, Preprint № 105, FIAN, 1974

[9]. V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Optical destruction of heated laser mirrors in CO2-laser systems, JEEE of QE, №6, 10, 1974, p. 505

[10].V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Thermal action of high power laser on the surface of solids, QE, т. 2, № 2, 1975

[11].V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Anastigmat I , Report of FIAN, 1974

[12].V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, Absorption coefficients measurements at λ=10,6 мкм, Preprint № 52, FIAN, 1975

[13].V. V. Apollonov, A. I. Barchukov, V. K. Konykhov, A. M. Prokhorov, Figures of merit for mirrors, Letters to JTP, v. 1, p. 11, 1975

[14].V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, R Anastigmat II, Report of FIAN, 1975

[15].V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov, High intensity porous metal mirror, Report of FIAN, 1977

[16].V. V. Apollonov, A. M. Prokhorov, Vapourtron effect for laser mirrors, Letters to JTP, v. 4, p. 8, 1978

[17].V. V. Apollonov, A. I. Barchukov, A. M. Prokhorov , Porous structures for high power optics, Letters to JTP, v. 4, p. 19, 1978

[18].V. V. Apollonov, A. I. Barchukov, V. K. Konykhov, A. M. Prokhorov, Intermetallic coatings for laser mirrors, QE, т. 5, № 2, 1978

[19].V. V. Apollonov, A. I. Barchukov, V. K. Konykhov, A. M. Prokhorov Beam divider for high power laser beam, Preprint № 136, 1978

[20].V. V. Apollonov, F. V. Bunkin, S. A. Chetkin, V. Yu. Khomich, Thermodeformation as a method of laser beam energy distribution measurements, Letters to JTP, v. 4, p. 17, 1978

[21].V. V. Apollonov, P. I. Bystrov, A. G. Goncharov, A. M. Prokhorov Liquid metals as a heat carriers for laser optics. QE, № 3, 1981

[22].V. V. Apollonov, P. I. Bystrov, A. G. Goncharov, V. Yu. Khomich, A. M. Prokhorov, New heat carriers for high power optics, Letters to JTP, 1981

[23]. V. V. Apollonov, A. M. Prokhorov, A. H. Guenther, Power Optics, Problems, Developments and Opportunities, Laser Physics V. 11, N.8, 2001

[24].V. V. Apollonov, A. M. Prokhorov, A. H. Guenther, Mirrors maintain shape under intense laser light, Laser Focus World January, p. 101, 2003

[25].V. V. Apollonov, High power optics and it`s new appearances, Oboronzakaz, March 2012, p.47

[26].V. V. Apollonov, High power optics, Symposium HPLS@A-2012, Istanbul 10-14 September.

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