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Optics for high power lasers(Invited)

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Abstract: The advent of the laser has placed stringent requirements for the fabrication, performance and quality of optical elements employed in 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, a temperature increase and response governed primarily by thermal properties and finally the elements thermo-optical and thermomechanical response, e. g., distortion, stress birefringence, fracture, etc. All of which needs to be understood in the design of efficient, compact, reliable and useful for high power systems with many applications, under a variety of operating conditions such as pulsed, continuous wave, rep-rated or burst mode of varying duty cycles.

Key words: high power laser; high power optics; cooling; heat exchange; polishing; coating; optical load

用于高功率激光器的光学元件(特邀)

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摘要: 激光的出现对大多数实际应用系统中的光学元件的性能、质量及其加工提出了严格的要求。激光的高功率性能由3个不同的过程决定: 其一是对入射光辐射的吸收(主要由各种吸收机制决定); 其二是由热学性能决定的温度升高和响应; 其三是元件的热光学和热机械响应, 如变形、应力断裂等。在设计效率高、紧凑性好、可靠性好的应用于不同领域的高功率激光系统时, 需要考虑不同运行条件下的脉冲、连续波、不同占空比的重复频率或突发模式等。

关键词: 高功率激光器; 高功率光学元件; 冷却; 热交换; 抛光; 镀膜; 光学载荷

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1 Introduction

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 1960 s, 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 of requiring high power optical systems under development at that time. The gist of the effect was the following that 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 less than $\lambda/20$ with λ -laser radiation wavelength. This will influence, for example, the performance and optical characteristics of the laser system in turn. We know that thermal deformations of mirrors can not only degrade the basic beam quality but also can lead to the cessation of lasing in some cases as well. The response can be either transient or permanent, i. e., catastrophic.

2 Power optics questions

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 tin or lead coatings. Since that time, the technology of mirror production has changed for 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 the lasers, all types of lasing occurs in a resonator that consists minimally of a pair of optical mirrors, and 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 output has been increased by hundreds, even thousands of times higher. Today the fabrication of mirrors which are 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 the 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, and 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 Gas and Chemical Lasers/High Power Lasers(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, which has addressed this subject in Russia. These meetings and their proceedings are the principal forum and repository for the research and development

activities. The material is readily available. Interest in the subject continues unabated 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 which will be altered unacceptably. If the intensity is further increased, the 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 can withstand high optical loads over a long period of time, 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.

3 Influence factors of power optics

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 the variations in heating from the hand's warmth, and the deformation 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 be changed by more than a micrometer. These types of mirrors are similar to those which are required for

powerful industrial lasers.

To create these power optics, a number of problems which are related to quantum electronics, optics, thermoelasticity and heat exchange, materials study and advanced technologies, *etc.*, need to be addressed. The first step 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 waveband. 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 which 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 1970'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, which was not advisable. But nevertheless, a way out was found—a fully metallic mirror (Fig. 1).

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 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

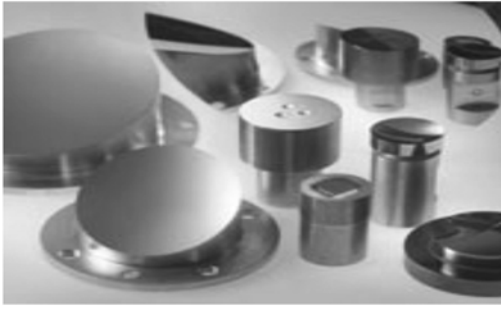


Fig. 1 Metal-based high quality optics

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, *etc.*), 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 1 000 °C. However, it is hardly possible to realize a “perfect” optical quality for the mirror surface. There is a contradiction-convective heat exchange which is greater at high temperatures, while temperatures being close to ambient are desired for the stability of the mirror’s geometrical shape (and other thermo-optical characteristics of the mirror). However, it is possible 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) of this task was not demonstrated. To attack this situation the 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 and 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 mirror surface, *i. e.*, it maintains its initial geometry better (Fig. 2).

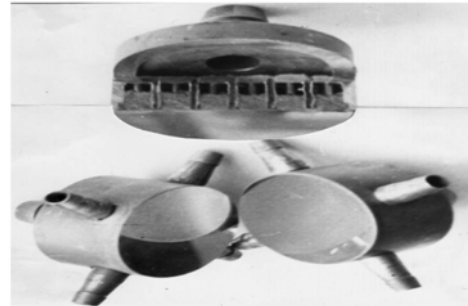


Fig. 2 First high power water-cooled porous mirror

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 – 150 μm); 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 also 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 hill-ocks 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 also more fine grained. Nevertheless, the final scale of unevenness remains too large, i. e. , from 0.01 to 0.1 μm . The structure of intermetallic coatings from the start is very fine, about 0.1 μm 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 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 hardening of metals (Fig. 3).



Fig. 3 Examples of laser cutting (glass, composite, stone, sital)

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 similar to those of the final treatment of the mirror’s surface within the conditions. During the boiling of the coolant, the part of

the absorbed heat is used for steam formation, and thus heat removal efficiency is tens to hundreds of times higher than that 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 be carried away not only by the moving liquid, but also by being transferred to the heated metal itself, 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, and 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 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 anodes of powerful X-ray lithographic installations for microelectronics manufacturers. These devices should endure heat loads between a few tens and hundreds of kilowatts per square centimeter. The highest value of evacuated heat flux, realized in the case of high power optics was measured on the level of 8.2 kW/cm^2 (82 MW/m^2). An important issue in the generation of power optics can be economical by implementation of a number of technical and benefi-

cial solutions for the national economy^[19-22]. Among them, for example, it 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 large 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 $Q > 1\ 000\ \text{W}/\text{cm}^2$. 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 , $K = 3.7\ \text{W}/\text{cm}^{\circ}\text{C}$), diamond ($K = 20\ \text{W}/\text{cm}^{\circ}\text{C}$), *etc*, should be employed. Unfortunately, the effort and cost to produce and treat these materials make 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) SiC has enough electrical impedance, and it can be best treated and is safe from the point of the environment, and it also has a high hardness that is important during optical polishing. Both separate and combined heat removal elements can be made from SiC as well as complete microchanneled or porous heat exchangers. Use of SiC as a thermal heat sink material is also convenient because its coefficient of thermal expansion is close to that of GaAs which is the basis of numerous laser diode compositions. This aids to prevent the material from cracking during, e. g. , soldering. It should be noted that the development of optical grade SiC requisite size is available for solving some optics applications in high power laser systems and for the astronomical purposes(Fig. 4).

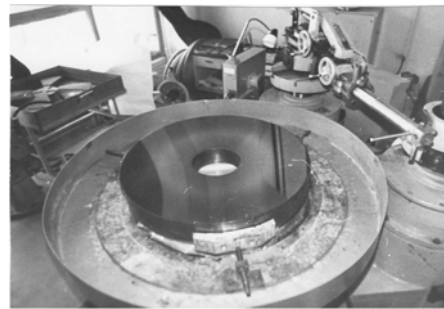


Fig. 4 Large size SiC mirror under polishing

4 Development trends of LD technologies

The results obtained during last decade in 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:

- (1) development of efficient heat-sinking systems for 1-d and 2-d LD arrays;
- (2) improvement of the soldering technology for a linear array and a heat-sink component under taking into account the problem of minimizing the thermal resistance and bending the 1-d array itself;
- (3) creation of a new laser system based on a phase locked 1-d array of LD;
- (4) use of phase-locked systems with efficient injection of radiation into a fiber;
- (5) phase locking of 2-d LD arrays (not realized yet);
- (6) efficient beam steering for the case of high power 2-d matrix of LD radiation (not realized yet);
- (7) development of new configuration of high power solid state lasers, single module scalable disk laser with diameter > 10 cm (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.

5 Conclusion

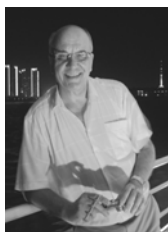
In conclusion, one very important true to life relationship should be mentioned in this rather difficult time for science. The resources invested effectively in the development of any field of advanced technology will afford a feedback as a rule in a number of ancillary applications in other ancillary 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 to the achievements in part 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.

参考文献:

- [1] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. High power CO₂-laser[R]. *Report FIAN*, 1970.
- [2] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. Thermal deformation of solid state surface by laser beam[J]. *JETP Lett.*, 1972; 15.
- [3] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. Optical mirrors losses on scattering measurements[J]. *QE*, 1973, 4(16).
- [4] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. CO₂ laser mirrors investigations[R]. *Report FIAN*, 1973.
- [5] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. Thermal deformation of laser mirrors[C]//Second European conf. on Lasers and Applications, Dresden, Germany, July, 1973.
- [6] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. Optical characteristics of laser mirrors[J]. *Preprint*, FIAN, 1973, 157.
- [7] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. Thermal deformation of laser mirrors[J]. *Radiotechnics and Electronics*, 1974, 1.
- [8] APOLLONOV V V, BARUCHUKOV A I, PROKHOROV A M. Thermal action of laser beam on the surface of laser mirror [J]. *Preprint*, FIAN, 1974, 105.

- [9] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. Optical destruction of heated laser mirrors in CO₂-laser systems[J]. *JEEE QE*, 1974, 10(6):505.
- [10] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. Thermal action of high power laser on the surface of solids [J]. *QE*, 1975, 2(2).
- [11] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. Anastigmat I[R]. *Report FIAN*, 1974.
- [12] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. Absorption coefficients measurements at $\lambda = 10,6$ μm [J]. *Preprint*, FIAN, 1975, 52.
- [13] APOLLONOV V V, BARCHUKOV A I, KONYKHOV V K, *et al.*. Figures of merit for mirrors[J]. *Lett. JTP*, 1975, 1: 11.
- [14] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. R Anastigmat II[R]. *Report FIAN*, 1975.
- [15] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. High intensity porous metal mirror[R]. *Report FIAN*, 1977.
- [16] APOLLONOV V V, PROKHOROV A M. Vapourtron effect for laser mirrors[J]. *Lett. JTP*, 1978, 4:8.
- [17] APOLLONOV V V, BARCHUKOV A I, PROKHOROV A M. Porous structures for high power optics[J]. *Lett. JTP*, 1978, 4:19.
- [18] APOLLONOV V V, BARCHUKOV A I, KONYKHOV V K, *et al.*. Intermetallic coatings for laser mirrors[J]. *QE*, 1978, 5(2).
- [19] APOLLONOV V V, BARCHUKOV A I, KONYKHOV V K, *et al.*. Beam divider for high power laser beam[J]. *Preprint*, 1978, 136.
- [20] APOLLONOV V V, BUNKIN F V, CHETKIN S A, *et al.*. Thermodeformation as a method of laser beam energy distribution measurements[J]. *Lett. JTP*, 1978, 4:17.
- [21] APOLLONOV V V, BYSTROV P I, GONCHAROV A G, *et al.*. Liquid metals as a heat carriers for laser optics[J]. *QE*, 1981, 3.
- [22] APOLLONOV V V, BYSTROV P I, GONCHAROV A G, *et al.*. New heat carriers for high power optics[J]. *Lett. JTP*, 1981.
- [23] APOLLONOV V V, PROKHOROV A M, GUENTHER A H. Power optics, problems, developments and opportunities [J]. *Laser Physics*, 2001, 11(8):1-7.
- [24] APOLLONOV V V, PROKHOROV A M, GUENTHER A H. Mirrors maintain shape under intense laser light[J]. *Laser Focus World*, 2003:101.
- [25] APOLLONOV V V. High power optics and it's new appearances[J]. *Oboronzakaz*, 2012:47.
- [26] APOLLONOV V V. High power optics[C]//Symposium HPLS@ A-2012, Istanbul, TUR, Sep. 10-14, 2012.

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