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Research Article

Mono-modular Disk Laser - The Best Tool for High Energy Applications

Victor V Apollonov*

A.M. Prokhorov General Physics Institute of Russian Academy of Sciences, Moscow, Russia

Abstract

The mono-module disk laser is an effective concept for diode-pumped solid-state lasers, which allows the realization of lasers with super-high output power/energy, having a very good efficiency and also excellent beam quality. Since the first demonstration by academia. N.G.. Basov, with colleagues of the disk laser, in 1964, increased the output power of the disk to the level of a few kW in continuous wave mode of operation. Well-developed" Zig-Zag" disk laser technology does not look promising for further output parameters. The scaling laws suggested in 2013 mono-module disk laser design show that the limits for continuous wave mode of operation are far beyond 100 kW for output power, and the output energy can be higher than 100 J in high repetition rate pulse-periodic mode of operation (> 30kHz). Due to the efficient cooling technology, an effective solution of amplified spontaneous emission suppression and artificial intelligence involvement, the operation of the large-sized mono-module disk laser is possible in CW and pulse-periodic modes at extremely high output power/energy. A new set of applications is coming.

More Information

***Corresponding author:** Victor V Apollonov, A.M. Prokhorov General Physics Institute of Russian Academy of Sciences, Moscow, Russia,
Email: vapollo@rambler.ru

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One general technical problem

In different sciences - in mathematics, physics, chemistry, astronomy - there are lists of especially important problems, "problems of the century", etc. Prizes are awarded for their solution; the solution of these problems glorifies authors, feeds journalists, and maintains the circulation of journals. There are no such lists in the humanities, and probably there are some reasons for that. However, it is strange that there is no such list in engineering, and if there were, the problem of heat transfer and cooling would be at the top of the list. Because heat is released in almost all processes, and quite often, there is great harm from it. If only because when heat is released, the temperature rises, hence almost all chemical reactions and diffusion accelerate, stresses arise in structures, and the originally precisely set dimensions are changed. The result - new problems arise, and most often, as a result of poor heat dissipation, the life of the product is shortened. In laser technology, the situation has turned out to be partly conventional and partly original. The usual part of the situation is that when a laser is pumped, i.e., energy is injected into the laser medium, some of the energy is converted into heat, and the medium is heated. And what turned out to be original is that heating changes the optical properties of the medium. Specifically, if we are talking about a solid-state laser, the refractive index of the very solid, glass, or crystal from which the "working body" of the laser is made changes. And if this medium, as usual, is a long cylinder cooled from the surface, then the middle, the longitudinal axis of this cylinder, is heated the most. Therefore, the refractive index changes most strongly there, and the closer to the surface, the less it changes [1-4]. The working body turns into a lens, that is, it begins to influence the passage of light, and this influence changes in a complex way depending on the mode of operation of the laser. So we would like to reduce this heating or eliminate it. Physics instantly responds to this - if the medium itself is fixed, i.e., it is impossible to increase its thermal conductivity, then it remains to reduce the distance that the heat must overcome on its way from the place where it is released to the place from where it will be carried away, for example, to the Moscow River by a joyfully and turbulently flowing coolant. That is, the same mighty cylinder, wrapped in a pumping lamp, which adorned the covers of all the science in the 70's, should be turned into a thin thread or ... in a thin disk!

The second solution was proposed by N.G. Basov as far back as 1964. But at that moment - most likely, just out of inertia - the technology went the other way. Fiber and disk. A thin filament is a fiber laser, the working body of which is an optical fiber. The main advantages are high quality of radiation, small dimensions, and ease of embedding in fiber optic lines. The disadvantage is that its average power cannot be large, and to summarize the radiation of many lasers while maintaining the quality of radiation is a difficult problem. Therefore, the fiber laser has an advantage at low average and peak radiation powers, while the disk laser is preferable in the range of high and very high powers. The advantage of the disk laser over its fiber counterpart is noticeable already in the kilowatt power range. With the large emitting surface of the disk laser, the power density is not critical, for it even at high peak power values. But for a fiber laser, increasing the peak power reduces the reliability of the laser system. Another weak point of a fiber laser is its high sensitivity to the reflected beam, which often occurs when the generated radiation interacts with matter. If a fiber laser is affected by reflected radiation from a target (which is common in metal processing), it must be turned off immediately to preserve the resonator. With a disk laser, the resonator is insensitive to reflected light. Even in the case of highly reflective materials, process operations can be carried out safely. Another advantage of a modern disk laser at multi-kilowatt power levels is its modular design. Individual amplifying modules containing the active disk, its pumping, and cooling can be replaced during service. In this case, the laser as a whole continues to operate after additional tuning of the common resonator, and the cost of repair work is relatively low. A fiber laser has a mono-block resonator; its repair leads to redesign of the whole system, and repair of such a laser costs a considerable amount of money. Summary: fiber laser is convenient at powers up to kilowatts, and for processing dielectric and composite materials, when the reflection is small. But only a disk laser can be applied at high peak powers, especially when it is necessary to provide a sequence of short and powerful pulses. Therefore, disk lasers will dominate among high-repetition-rate pulse-periodic (P-P) sources of coherent radiation of high average and peak powers in the future.

Design and physics

The working body of a disk laser is a disk made of laser ceramic material or crystal with additives of rare-earth elements. High cooling efficiency is ensured due to the large surface area of the disk and its small thickness - the heat "does not have far to go". That is why the average power of radiation in the beam can be very large. Moreover, the heat that is released in the volume mainly spreads not along the radius, as in rod-element lasers, but along the disk axis, parallel to the amplified radiation. Therefore, there is neither a radial temperature difference nor a lensing effect. In addition, within certain limits, it is possible to increase the laser power by increasing the disk diameter ("scaling") - the temperature difference does not increase. However, another problem arises. In a thin disk, the pump radiation will be poorly absorbed, which is introduced into the active element and creates an inverse population. The way out of this situation is found approximately the same way cats have found. In their eyes, as is known, the light crosses the layer of sensitive cells twice, which increases the efficiency by about two times (this is a simplified model). Approximately the same - but much more effective - solution is applied in a modern disk laser. A multichannel optical system collects several pump beams on the disk. After partial absorption of radiation as it passes through the disk body, part of the beam energy is reflected from a highly reflective mirror on the back of the disk and passes through the disk a second time, as in a cat's eye. But the matter does not end there - this radiation, which has left the disk, is collected by the mirrors and returned to the disk, and so repeatedly, until the pump beam energy is completely absorbed. This achieves high efficiency of pump light energy utilization. Moreover, in such a scheme, to the pump source are not too strict requirements for the angular directivity of the pump source. Therefore, it is possible to use both individual laser diodes and complex laser diode structures with a uniform spatial distribution of intensity. For efficient material processing: cutting, drilling, polishing, and thin film removal from the surface, laser pulses with high peak power and high repetition rate are required. Typical pulse duration of a goodness-modulated disk laser based on yttrium-aluminum garnet with ytterbium (Yb: YAG) is from hundreds of picoseconds to microseconds. The goodness-of-fit modulation is carried out using an acousto-optic modulator. The best results achieved for a single disk laser module today are as follows: pulse repetition rate up to 10 kHz, pulse energy up to 0.4 J, peak power up to several MW, average power up to 4 kW. And a string, three times twisted... The power of disk lasers is limited not only by the pumping power, but also by the medium overheating, losses in the resonator, and losses on amplified spontaneous emission (ASE). The latter is the result of the spontaneous transition of the emitting system from a metastable level to a stable one, i.e., emission and amplification of this "ill-timed" emitted quantum. To avoid overheating, the size of the active medium, i.e., the diameter of the disk, must increase. But at the same time, the losses for amplified spontaneous emission grow exponentially. To prevent this effect, it is necessary to limit the gain, which is determined by the pumping intensity, losses in the medium, and the disk diameter. The back-and-forth gain of the radiation, however, must remain substantially greater than the radiation loss along the same optical path - the difference between the two determines the optical energy that is removed from the resonator. It is also necessary to ensure efficient delivery of pump energy, but for this, we have the above-mentioned mechanism of multiple passages of pump radiation through the medium. To reduce the impact of ASE, it was proposed to place another disk on top of the disk, but already made of unalloyed material. In this case, the spontaneous photon will leave the active layer because it will not reflect from the surface of the active layer; however, it may reflect from the outer surface of the unalloyed disk and try to return to the active layer. To prevent this, the reflection from the outer edge of the disk is suppressed by using an interference coating. In the case of maximum pump power density of the disk laser, its efficiency decreases because a substantial part of the power goes into ASE and is absorbed at the edges of the disk active element. In this case, distributing the pump energy among several small-diameter disks can improve the efficiency of the laser system. Indeed, lasers consisting of a few modules containing disk elements combined in a single resonator have been repeatedly reported. One such laser was created by TRUMPF, a world leader in this class of laser systems. The photo shows a laser consisting of a series of disk modules in one resonator. The figure on the left shows the four disk modules with their individual coolers and optical pumping systems. On the right are three automatically aligned mirrors that provide a single closed resonator. The beam bypasses all these modules, collects the energy, and outputs it through a translucent mirror. The laser channel is encased in quartz tubes that ensure the sterility of the optical components of the multi-module system. It is this last mirror that is in the most stressed state; it limits the number of modules in this broken line - they can not be more than five or six; at this point, a total power of 50 kW is achieved. If it is necessary to get more power, it will be necessary to put in parallel to this broken line another one with its own resonator, but it will be necessary to add the power already on the object; in the resonator it will not be possible to add these additional powers - it will not survive this abuse. If we increase the disk size, the total power in one such broken channel will also increase, and this will happen at the same maximum power density on the disk. And if you remove the spontaneous noise limitation, you don't need to create this garden with many modules in one resonator. And just from one module with an additional mirror for radiation output, you can remove a huge power. Regenerative pulse amplification. Nowadays in research and technology, where lasers with high average power are used, sources operating in two modes - CW and P-P with pulse repetition rate from units to hundreds of hertz and pulse duration from tens of microseconds to units of milliseconds have found application. In most technological processes, the thermal mechanism of influence is realized, i.e., the possibility of a laser source to bring a sufficiently large amount of energy to a small area of the surface of the processed part. High-frequency laser systems with large average power, which operate in the mode of modulation of goodness, can provide pulse durations from units to hundreds of nanoseconds. In this case, it is possible to realize a fundamentally different mechanism of interaction of radiation with matter - ablation, i.e., vaporization without an intermediate liquid phase. This mechanism can significantly expand the area of technological applications of laser sources. Today it is used only at relatively low power levels - up to 1 kW. The reason is the difficulty of applying classical modulation methods to laser systems with high average power. Meanwhile, the creation of more powerful high-frequency (around 100 kHz) pulse-periodic lasers would allow to significantly expand the area of application of such laser systems [5,6]. The use of intracavity modulators in high-power lasers is difficult, since high power density leads to the appearance of plasma on the surfaces of modulator elements, to radiation shielding, and to the destruction of optical elements of the modulator. However, there is another way - regenerative amplification of the signal injected into the resonator of a powerful gas or solid-state laser with classical geometry. In this case, a so-called self-filtering resonator is used, which consists of two cofocus spherical mirrors of different curvature, in the common focal plane of which is located a circular output mirror with a coupling hole. Due to the high degree of loss suppression of the higher modes, the lowest mode is reliably emphasized in the resonator. The long-focus spherical mirror of the resonator is located outside the active medium and contains a modulation unit. The formation of the laser mode should occur fast enough during the rise time of the giant pulse front. With such a laser, it is possible to process materials in ablation mode. Way beyond 100 kW as mentioned above, the disk laser design is ideal for welding and cutting metals where a high optical quality beam generating sufficiently high power is required. This is important for industries such as automotive, transportation, aerospace, and heavy engineering. Disk multi-module laser systems have now mastered the range up to 50 kW, but there are many applications that require an order of magnitude more power. What are the chances for different types of lasers to move into the "beyond 100 kW" range?

Diode-pumped solid-state disk lasers are highly efficient

The beam quality of the disk laser is outstanding, allowing the target to be operated from long distances while providing an extremely high concentration of radiation in the interaction zone using focusing optics [7,8]. But the disk size usually is not more than 15 mm, because at larger sizes the energy losses for amplification of spontaneous radiation increase unacceptably. The laser system from a set of disk modules located in a single resonator allows, as mentioned above, the realization of a mode with rather high average power. Parallel operation of such multi-module disk lasers can lead to an increase in the integral average power of the system, but coherent summation or spectral addition of radiation of such complex laser systems requires additional scientific research. Further increase of average power up to the megawatt level seems to be very problematic. Another approach to the realization of scalable solid-state laser systems is also known, which consists of a set of individual active elements in the form of "slabs" (parallelepiped) with subsequent coherent summation of their radiation. Northrop Grumman has created a 100 kW laser with a high quality laser beam and an efficiency of 30%. The authors of the project speak about the advantages of this parallel structure of amplifying channels in terms of ease of further increase of output power, if necessary. But increasing the number of channels to reach an average power level of 1 MW would require coherent power addition or spectral addition of at least 60-80 channels, which does not seem easily realizable, especially for transportable laser systems. Yet, how can the several MW average power needed to remove space debris from near-Earth space, laser-launch missiles, create long-range conductive channels, and the like be achieved? As it was mentioned above, fiber lasers are not applicable for these purposes due to the small area of the fiber exit pupil and, therefore, the impossibility of operation of such lasers in high-repetition rate mode with high peak power at an average power of several MW. A laser system based on "slabs" also does not seem realistic - alignment of such a system and its maintenance in a reliable stable operating state seem to be prohibitively difficult tasks, especially in the case of mobile laser system design. The solution may be a large-diameter mono-module disk laser, provided that ASE along the disk diameter can be suppressed. At megawatt average power levels, the disk diameter would be at least 60 cm, i.e., forty times bigger the size limit used in disk modules today. This is not an easy task, but its solution eliminates the problem of coherent or spectral addition of powers of separate laser systems, and the large diameter of the beam will provide an effective combination of this geometry with a telescope of appropriate diameter to ensure high concentration of radiation on the object of action. At present the solution to the problem of a large diameter mono-modular disk laser has been found, modeled and is waiting for its implementation in practice. It has long become a habit that as soon as new technologies appear, users and experts wonder whether this new technology will not replace the proven methods that are already available. Practice has shown that the new does not often completely supplant the old, but always somehow limits its use and occupies a part of the market. At the same time encouraging the old to improve. Therefore, even if a laser with a mono-modular disk geometry of the active medium becomes the dominant technology, the need for all other types and varieties of lasers will not disappear at once. Therefore, it is necessary to continue to develop and improve them [9-11]. Only the future will show what type of laser will be effectively used for processing materials and solving other important tasks facing science and technological breakthroughs of the future. Nevertheless, it can already be stated that the creation of a megawatt class of high-repetition rate P-P lasers with a large cross-sectional area of the active medium will open up great prospects for their application in solving the tasks of laser launching of small spacecraft, creation of ultra-long conducting channels in space and atmosphere, cleaning the space surrounding the Earth from space debris and other similar high energy based tasks.

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