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PROGRESS IN CW HF/DF CHEMICAL LASERS

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ABSTRACT: This paper presents high-energy CW HF/DF chemical lasers developed under the U.S. Navy Sealite program and the Alpha program of the DARPA Triad program, and a brief account of Soviet chemical lasers.

Continuous-wave HF/DF chemical lasers were developed starting in the late sixties as high-power lasers of consistent interest to military circles. These are lasers that have the most matured technology among present-day high-energy lasers. It is hoped that in the near future CW HF/DF chemical lasers can be developed into a space laser weapon to deal with ICBMs.

CW HF/DF chemical lasers are an integration of technologies in gas dynamics, chemistry, fluid chemistry, optics, and lasers. By using the branching chain reaction of heat liberation, inversion of the population ratio is generated to obtain lasers.

In such laser devices, a gas stream containing fluorine atoms is obtained by the combustion of fuel and oxidizer in a combustion device. Then, the gas stream containing the fluorine atoms passes through a set of ultrasonic jet nozzles, becoming an ultrasonic gas stream with adiabatic expansion; meanwhile, it mixes with hydrogen (or deuterium) to generate the branching-chain reaction. Large quantities of heat are liberated in the reaction, to excite the reaction product HF (or DF) into a high-energy level. When the reacting gas stream passes through the resonator cavity downstream of the nozzles, stimulation is caused, to emit a laser beam. The ultrasonic expansion process not only cools down adiabatically the reactants, thereby prolonging the time that the stimulated state is maintained for the stimulated HF (or DF). In addition, the exhaust gas, after stimulation, is quickly discharged from the resonator.

The CW HF/DF chemical lasers have several features suitable to space combat applications. First, the laser efficiency is relatively high, generally 50 to 100kJ in laser energy can be generated per pound of fuel. It is estimated that a conversion efficiency of 200kJ/lb can be obtained for a modern version of the HF chemical laser. Due to its high efficiency, lightweight laser weapon systems may be possibly fabricated for space applications. Second, the device is driven by the combustion of fuel, not requiring any or requiring only a little electric energy to obtain the high-energy laser output. For a chemical laser device in space orbit, tens of seconds of continuous laser

firing can be obtained just by requiring sufficient fuel. Third, the DF laser device emits a 3.8 $\mu$ m laser beam; an HF laser device can emit a 2.7 $\mu$ m laser beam. The 3.8 $\mu$ m laser is suitable for propagation in the atmosphere. Although the 2.7 $\mu$ m laser attenuates seriously in the atmosphere, yet its transmission in space is not affected. Since the laser wavelength is relatively short, it is helpful to reduce the dimensions and weight of an optical system. Or, given certain dimensions of the optical system, a higher-power focusing light beam can be generated. Fourth, the stimulation of a chemical laser can be generated only at very low pressures (about 20 torr), and the exhaust gas contains poisonous HF (or DF) gas. Therefore, a delicately designed pressure expander and vacuum pump system should be attached in ground applications, thus effectively expelling and processing the exhaust gas, for normal operations. However, with respect to space applications, the vacuum environment is suitable for the operation of chemical laser operation, without considering the problems of exhaust gas or toxicity.

The concept of a chemical laser was proposed by an American, Polanyi. In 1965, the first set of pulsed chemical laser device was developed. Thereafter, the research emphasis turned to CW chemical laser devices. In 1967, the Spaceflight Corporation, Ahoko Corporation, and Cornell University, in the United States, successively developed the CW chemical lasers. In 1970, a CW laser device with 1kW power was fabricated. The CW chemical laser device has prospects of generating high-power laser beams;

thus, interest from military circles was stirred. thereafter, the CW chemical lasers became a key development project of the United States, the USSR, and other countries. In the main, through the Navy's Sealite project and the Alpha project of the Defense Advanced Research Projects Agency (DARPA) in the U.S. military that research on CW HF/DF chemical lasers was advanced. In the Soviet Union, the research was furthered by such resourceful research units as the Lebedev Institute of Physics.

#### Sealite Program

In the Sealite Program of the U.S. Navy, shipborne laser weapons are to be developed to deal with attacks from antiship missiles in order to protect such high-priced warships as aircraft carriers. In 1973, the U.S. Navy began to purchase chemical laser devices. The TRW Corporation was the first to enter the field of DF chemical lasers in the early seventies; at that time, the company was at the leading-edge, as the contractor to the U.S. Navy and DARPA for developing a set called the Navy/DARPA chemical laser device (NACL). The NACL laser device generates approximately a 40kW CW laser beam, with 3.8mum wavelength. Fitted with a pointing and tracking device developed by Hughes Aircraft Corporation in 1978, firing tests were conducted at the Capistrano Proving Grounds of the TRW Corporation, to successfully shoot down four TOW antitank missiles and pilotless helicopters flying at high speed. In

addition, an UH-1 helicopter used as a towed target was also destroyed.

The successful experiments in 1978 were an important milestone in the development path of chemical lasers in the United States, promoting further investment for development by the TRW Corporation a set of DF chemical laser devices with 2.2MW output power, called by the Navy the advanced intermediate infrared chemical lasers (MIRACL), which was successfully developed in 1984 for installation on a high-energy laser experimental facility at the White Sands Missile Target Range. It was said that  $\text{NF}_3$  replaced  $\text{F}_2$  as fuel in the MIRACL laser device for firing a high-quality square-cross-section laser beam 12.7cm on a side, in attaining all the technical indicators. Also verified in the experiments, the device can be scaled up by 38-fold, proportionately. In other words, it is possible to develop a chemical laser device with 80MW as output power. Considered by the authoritative circles in the United States, the successful development of the MIRACL laser device illustrates that the United States has mastered the fundamental physical regime and engineering concepts of the linear-type jetting-nozzle array chemical laser device, proving the maturity and simplicity of chemical laser technology, suitable for near-term space applications.

On September 6, 1985, a MIRACL chemical laser device was successfully tested in its destructive property [1]. The target fired at was a Titan model I missile booster fixed on the ground.

To simulate the load that a booster actually sustains in flight, a highly stressed rope cable simulated the load caused by gravity during accelerated flight; and the pressure step-up method was used to stimulate the effect of burning the propellant. As a result, a hole was burned through the booster within several seconds by a laser fired from a MIRACL laser device, thus exploding the booster. As verified in this experiment, the housing of a booster in flight resembles an eggshell under high stresses. Just by weakening it to some extent will cause its self-destruction, without the thought by some people that the casing should be burned through or the propellant agent should be ignited. This experiment also proved the destructive capability of the MIRACL laser device.

In Fiscal Year 1985, the Sealite Program was cancelled. The research tasks done under the Sealite Program were handed over to DARPA and the Strategic Defense Initiative Office. The U.S. Navy continued the tasks based on the SDI program to combine the MIRACL laser device and the large dynamic light beam direction fixing device with the purpose of intercepting and destroying Pershing I-A missile fired at a distance of 10km away, for land-based dynamic destruction experiments against solid-fuel rockets.

#### Alpha Program

Both the NACL laser device and the MIRACL laser device adopt the linear-type jetting-nozzle array. To increase the chemical laser device output power, higher fuel flow and bigger combustion

chamber are required, as well as larger area for the jetting-nozzle array. However, if the jetting nozzle is increased in length, the nozzles have a tendency of bending under fuel flow pressure. Therefore, in 1977, research on cylindrical chemical laser devices with ring-shaped jetting nozzles was developed in the United States. Such cylindrical chemical laser devices are more suitable for space applications.

The space chemical laser research in the United States proceeded in the Alpha program of the Triad program of DARPA. The Alpha program is a ground-based demonstration program of high-energy laser devices with the purpose of solving the key technical problems of space applications for chemical laser devices, in order to master the space chemical laser technology before 1990 to be helpful for space-based chemical laser weapons [2, 3]. The first-generation Alpha laser device will be a CW HF chemical laser device with 5MW output power and 2.7 $\mu$ m emitted wavelength. The fundamental principle of the alpha laser device is similar to that of the MIRACL laser device; however, the assembly involves optimized weight, volume, and dimensions appropriate for space deployment, in order to be launched as one piece and not be assembled in orbit. The fundamental structure is a thin cylindrical chamber. The gas mixture generated passes through a ring-shaped ultrasonic jetting nozzle around a circle to become an ultrasonic gas stream before passing through a ring-shaped stimulation zone at high speed, to generate laser beams to be expelled into the surrounding space.

The Alpha program began in Fiscal Year 1978. The first step was to experiment and to evaluate the nozzle technique. After this test was accomplished in Fiscal Year 1980, the initial design of the ground demonstrator began; conceptual design was completed in that fiscal year. In fiscal year 1983, detailed designs were completed for the gain generator, optical resonator, and exhaust manifold combinations, among others. The length of the laser cavity in this ground demonstrator is shorter than the standard design for the Alpha laser device; the laser power generated is approximately one-third of that for the Alpha laser device. Many parts were duplicated based on standard design for space applications. For example, an aluminum combustion chamber and a nozzle ring component, ammonia cooling [illegible]-made optical system with good thermal conductivity, but little heat anomaly, a seat for the optical device made of aluminum honeycomb materials, and an active optical system for adjusting reflective mirrors and the seat for the optical device are used in the ground demonstrator. Composed of the combustion chamber nozzle ring component, the gain generator consists of 27 rings 1.1m in diameter and 7.62cm in thickness.  $NF_3$ ,  $D_2$ , and He are used for the combustion leading to jetting from these ring nozzles. The generated fluorine atoms and other products are ejected from the nozzles formed by connectors between various rings, to speed up to Mach5. Then hydrogen is ejected from the ejection rod to form the zone of the stimulated HF and the ring-shaped stimulation medium. After the laser beam is generated, the exhaust gas is

expelled to the surrounding environment at approximately 15torr. Increasing the number of rings now can increase the duration of stimulated emission and result in higher output power [3].

In Fiscal Year 1985, the fabrication stage of the ground demonstrator of the Alpha program began. The TRW Corporation was responsible for the manufacture. According to the program, by the end of 1986, the demonstrator was to begin to be tested at the Capistrano Proving Ground. The ground demonstrator will be installed in a simulated space environment in a 15torr vacuum chamber for operation.

In the future, to obtain a high-intensity laser suitable for booster-stage interception, possibly several laser devices are to be assembled into an array, to combine their outputted light beams. It was reported that some progress was obtained on research on the array phase locking technology for this purpose.

#### Research on Chemical Lasers in the Soviet Union

We can see from the published literature in the Soviet Union that in-depth theoretical research was pursued on HF/DF chemical laser devices in the Soviet Union. With respect to the methods of solving the problems of ultrasonic stream heat liberation from the chain-reaction CW chemical laser device as proposed by the Lebedev Institute of Physics, a cylindrical nozzle array is used. Detailed computations were conducted at the Lebedev Institute of Physics on the HF chemical laser device with cylindrical nozzle array and cylindrical resonator. It was proven that when the

nozzle radius equals 20cm, the ultrasonic stream remains almost unchanged for a distance of 10 to 12cm with practical significance. Between 12 and 15cm, an increase in temperature does not render such a serious problem as that of plane-shaped jetting nozzles. When the pressure tangent to the nozzle is 15torr, the maximum output energy ratio can be 800 to 1000J/g. Therefore, a conclusion can be drawn that the properties of the CW chemical laser device can be significantly improved by using the chain reactions of fluorine and hydrogen as well as appropriate geometrical dimensions of the nozzles. As reported by the Pentagon and the State Department, the Soviet Union also recognizes that chemical lasers show promise in applications as weapons. As to output power, the achievements of the Soviet Union in this area give observers an impression of profound work.

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WHAT ARE THE PROSPECTS OF AMERICA'S "STAR WAR"  
PROGRAM (SDI)? PART I

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**ABSTRACT:** Described in this paper are the background and strategic demands of "Star War" program (SDI) as well as the arguments caused by SDI in the U.S. government and the public opinion. The issues on survivability of ballistic missile defense system and some key technical problems are discussed. The SDI's effects on development for sciences and techniques of America in the future and prospect are evaluated.

On March 23, 1983, U.S. president Reagan proposed the SDI program. This is also known as the "Star Wars" program, questioning whether the program can be carried out. Is there any significance to the program? What attitude should we hold toward this problem? This is not only a problem of very great concern to the supreme decision-making levels of the government and the strategic defense experts, but also a problem of interest to the rank-and-file scientific and technical personnel, as well as

peace-loving people concerned with the nation's destiny. This article attempts to make a brief analysis of this problem. The discussion stresses the main weapon system of Star Wars, the development prospects of strategic laser weaponry, and Star Wars program.

## I. Background to the Proposal of Star War Program

### 1. Political demand in grabbing global hegemony

In fighting for global hegemony by the U.S. and the USSR. since the end of World War II, both nations engaged in round after round of the arms race, with larger and larger scales and higher and higher levels. Both superpowers shouted arms reduction every day, but engaged in arms expansion every day. Both shouted that nuclear weapons should be destroyed, but optimized their nuclear weaponry every day. Their purpose is not really to put nuclear weapons at zero. The most basic purpose is to weaken the other side and to beat the other side, finally to grab global hegemony for control of the whole world. This is not only a sharp arms race, but also a content in economic resources as well as scientific and technical levels.

### 2. Technical progress

The inauguration of Reagan's Strategic Defense Initiative serves not only to meet political demands, but also the development of the principles of offense and defense. The material foundation of the program is technical progress. Since the sixties, strategic defense was passive defense, with large-

scale retaliation. The principal measures were building tunnels, strengthening fortifications, as well as concealment and camouflage. In the seventies, because of technical progress in accurate tracking, guidance, and homing technology, the concept of guidance and counter-guidance was proposed. The concept has made great progress in the early eighties. However, since the guidance and counter-guidance concept is slow in speed, and low in efficiency, it is difficult to cope with a large-scale surprise attack with thousands or tens of thousands of nuclear warheads. In addition, the defensive airspace is closer, mainly defense during the terminal-flight segment of ballistic missiles. At most, the defense was only up to the mid-flight segment. Therefore, it was unable to satisfy combat requirements: to distinguish real from false enemy warheads, and to extend the defensible airspace to the booster stage and the passive stage of the enemy rockets. This requires antimissile weapons of longer range, faster speed, and higher efficiency. The weapons that can fulfill this role are naturally laser and particle beam systems, which have been pursued for many years. In particular, in the case of laser weapon systems, since its high speed ( $30 \times 10^4$  km/s) and high hit rate (hitting a target moving at tens of kilometers per second is like hitting a stationary target), only with laser beam brightness (energy and direction) can one satisfy the requirements of destroying the missiles, then this is an ideal weapon as defense at the missile booster stage and at the missile passive flight stage. The present problem is why did the U.S.

president not propose the largest, in U.S. defense history, Strategic Defense Initiative, centering on directed-energy weapons, not 10 years sooner, but only in the early eighties. Mainly, there are the following reasons, from a technical approach:

The breakthrough of X-lasers pumped by nuclear explosions: as the world's academic circles were actively discussing various programs of implementing X-lasers, a successful experiment on a high-power X-laser pumped with a nuclear blast was announced in 1981 by the Livermore Lawrence National Laboratory in the United States [1]. The output wavelength was 14 angstroms; the pulse power was  $10^{14}$  W; the pulse width was measured in nanoseconds. This news shocked the world. Since X-lasers are short in wavelength, the photon energy is high and its destructive force is intense, rendering conventional countermeasures impotent. In addition, its size is small, its energy to weight ratio is high, and it is easily transported and fired. It is especially suitable for satellite-borne situations, simultaneously coping with tens of targets with high threat power. Recently, abroad this system was called the third-generation nuclear weapon [2]. Although there is still a great gap from the weapon system being in combat, yet final success seems hopeful. This is one of the major foundations of the Star Wars program that the U.S. president proposed at the time.

The appearance of the U.S. telescope in space: the United States has the technique of placing a 2.4-m diameter space

telescope into space. This telescope can have diffraction-limit resolution; it can observe the edge of the universe as predicted in the big bang theory. The resolution of this telescope is higher by a factor of 7 than a ground system with the same dimensions. If a combinational reflective mirror [3] controlled with dynamics is applied, the dimensions of the space telescope can be even larger. This is a very key system in carrying out the slewing and target pointing of a laser beam in the Star Wars program.

Gigantic progress was attained in self-adaptive optics technology: since self-adaptive optics technology can eliminate vortices in the atmosphere, anomalies of a laser working medium, and the effect on laser beam quality of anomalies in the optical system, thus ensuring that a high quality laser beam hits the target. After many years' efforts, concrete progress was obtained by the U.S. in this technique, thus creating the necessary conditions for executing the Star Wars Program.

New progress in the space energy source system: the establishing of a space weapons system requires solving the problem of the energy source in laser weapons and supplementary systems, as well as maintenance facilities. After years of efforts, the U.S. chose the technology of chemical-electronic pulse energy sources to meet such demand [4].

Technology of chemical lasers and arrays can preliminarily satisfy weaponry requirements: after more than a decade's efforts, the output of MW-level chemical lasers has reached the

diffraction limit. It was verified that the application of array technology and complex structure can provide high-brightness lasers [5] satisfying the fundamental requirements of Star Wars.

Accumulation of necessary transmission of target-hitting data:

The Raman scattering technique can highly effectively convert a multimode laser into a laser with diffraction-limit output.

New progress in other technologies: other than the above-mentioned technical progress, great advancement was also obtained by the United States in excimer lasers, free-electron lasers, high-energy particle beams, long-range high-resolution radar, discrimination between real and false warheads, as well as acquisition, tracking, communication, command, and evaluation of results. Many difficult problems that were unable to be solved previously can be solved, thus pushing the strategic laser weapon to a stage of near-practicality. On the other aspect, much new progress was also obtained by the United States with the development of dynamic-energy weapons, including guidance and counter-guidance technique, electromagnetic railguns, plasma guns, superhigh-speed missiles, chemical booster interceptors, as well as large-scale homing technique. All these advances are the material foundation for the Star Wars program of the United States.

## II. Concept and Purpose of Star Wars Program

Other than the political motives previously mentioned for the Star Wars Program, the main purpose, militarily, is to completely smash enemy attempts of any benefits from a first strike. The fundamental requirement is: I can whip you and kill you, but you are unable to whip me (of course, it is really impossible to achieve this point). Therefore, the purpose of the Star Wars program is to build a multilayer defense network implicitly including the offensive strategy. This network not only includes the space over the United States and its allies, but mainly aims at enclosing the Soviet Union layer by layer so that any activity is under close surveillance by this network. By using the words of Keyworth: "This defense net serves to cover the Soviet Union to prevent any Soviet missile from flying out. This is a shield; this is a cover." [6] Although this net is mainly to defend against ICBMs, it also defends against near- and intermediate-range missiles. Based on four flight stages of the ICBM: 1. booster stage (3 to 5min); 2. passive flight stage (2 to 5min, with separation between rocket and missile); 3. intermediate stage (10 to 20min); and 4. terminal stage, also called reentry stage (1min). In the concepts of the Star Wars Program, 100% of the attacking missiles are to be destroyed in the four stages, with multiple layers of nets.

1. Missions of the multiple defense layers and weapon deployment.

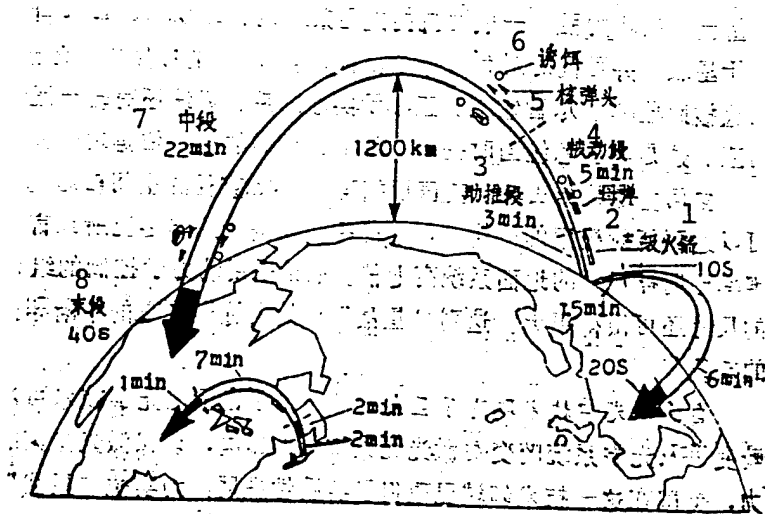


Fig. 1. Diagram shows the ballistic trajectories of an ICBM, submarine-launched missile, and intermediate-range missile  
 KEY: 1 - third-stage of rocket 2 - mother warhead  
 3 - booster-flight stage 4 - passive-flight stage 5 - nuclear warheads 6 - decoys 7 - intermediate stage 8 - final stage

Interception at the booster stage: to the defending side, if the enemy missiles can be destroyed in the booster-flight stage of the rocket, this is the best way because: (1) for missiles in the boost stage, multiple warheads and decoys have not been separated from the carrier rocket therefore, destroying the rocket is equivalent to destroying many warheads and decoys. Thus, the efficiency is very high. In this way, the defensive pressure applied on the later stages can be greatly relieved. (2) If 100% of enemy rockets in the boost stage are unable to be destroyed, then there is the time of little more than 20min for interception at the passive flight stage, intermediate stage, and terminal stage. (3) At the boost stage, enemy rockets are still within the territory of the attacking side, far from the defending side. The explosion of a missile or deviation from

orbit have smaller effects on the defending side. Because of these reasons, the main task of the strategic defense net is to have highly effective interception of enemy rockets in the boost stage. This is the most ideal weapon in accomplishing this mission; of course, first is the directed-energy weapon. Since the laser is fast in speed, high in hit rate, and can be fired repeatedly, even if an enemy applies fast speed boosting rockets (about 100s), a laser weapon still has sufficient time to attack.

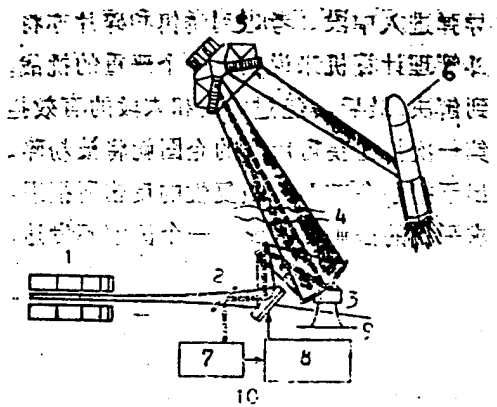


Fig. 2. Schematic diagram on operating principle of self-adaptive optical system deployed in land-based laser weapon system  
 LEGEND: 1 - laser device 2 - aperture distribution panel  
 3 - telescope 4 - atmospheric turbulence 5 - relay reflective mirror 6 - experimental rocket 7 - wavefront sensor  
 8 - conjugate wavefront repeater 9 - deformable reflective mirror 10 - self-adaptive optical control system

Therefore, its threat is the highest. Notwithstanding, since a laser weapon has still not matured, to deploy such weapons is possible only in the 21st century. Therefore, the near- and intermediate-term target of the U.S. Star Wars Program still relies on the satellite-borne dynamic energy weapon systems flying in low-earth orbits. Since the dynamic energy weapons have good destructive effect and low costs, only with

satisfactory command, control, and communication systems can this low-orbit satellite-borne system pose a great threat to enemy ICBMs. It is estimated that this kind of system will be deployed within 5 years.

Interception in passive flight stage: the importance of interception in the passive flight stage is next only to that of the booster-flight stage, because the rocket in this stage is just at the instant of separation between rocket and missile. If missiles can be destroyed in this time period, naturally there is great effectiveness. The defensive weapons practical in this stage include laser weapons, particle beam weapons, and various dynamic energy weapon systems.

Intermediate-stage interception: to intercept missiles passing through the booster-flight stage, passing through the defensive layers in the booster-flight stage and the passive-flight stage, the problem is more complicated. This is mainly because for missiles in this stage, multiple warheads have been separated from the missile, therefore, more targets should be destroyed. In addition, there are large numbers of decoys. This gives more difficulties in interception. First, real and false warheads should be discriminated, then comes the problem of destruction. Weapons with a discrimination mission include a particle beam detection system, laser radar, and microwave radar. Used in this stage, the interception weapons include satellite-based and land-based laser weapons and particle beam weapons, as well as satellite-based and land-based dynamic energy weapon

systems, such as missiles, electromagnetic railguns, plasma guns, and superhigh-speed nuclear guns [7]. Since the time is the longest for missiles in the intermediate flight stage, with better interception in this stage, it is required to set up multiple layers of interceptors in the intermediate stage in order to apply multiple firings if the first firing does not hit the target.

Interception in terminal stage: if the enemy missiles leak through the defensive interception net in the first three stages and reach the terminal stage. At this time, the defending side is in a very dangerous situation. In this situation, the defending side should rely on all the land-based weapon systems (including the dynamic energy and the directed-energy weapons) for interception in the final layer. Since the time spent by missiles in this stage is only about 1min, it is required that the defensive weapons have very high speed and accuracy. The land-based laser weapon and the superhigh-speed gun (20 to 30km/s) will satisfy this requirement.

Interception by satellite-based weapons: in addition to using ICBMs for attack, an enemy can also use the future satellite-borne weapon systems for attack. Therefore, the antisatellite weapon system is also one of the important contents in the Star Wars program. At present, both the U.S. and the USSR have their practical systems in the antisatellite systems. Newer and more effective antisatellite technologies are under development. These technologies have attracted attention in

defense circles.

2. Requirements on defensive effects in the various stages

Based on the number of capabilities of rockets stored by both superpowers, when either side launches an attack, it is possible to use  $50 \times 10^4$  to  $100 \times 10^4$  rockets. This is obviously not easy to defend against attacks with such large numbers of missiles. If the intermediate-stage recognition system can cope only with a limited number of decoys, then the defensive efficiency in the booster-flight stage should approach 90%. Even with such a way, by counting  $50 \times 10^4$  missiles, this means 5000 [sic] missiles enter the passive-flight stage. If the interception efficiency in the passive-flight stage is still 90%, then 50 [sic] missiles will enter the intermediate stage. Considering the situation that decoys and fragments will also enter the intermediate stage, therefore, this is still a serious challenge for the sensors and the battle management computers used in the defense in the intermediate stage. However, from the present trend in technical developments, this problem is possibly solvable. Finally, after the effective interceptions in the intermediate stage and the terminal stage, warheads arriving at the defended territory are even fewer. Thus, an enemy's attempt at gaining a victory through the first attack will be smashed. Both sides are unable to destroy the other through surprise attack, then they will be worrying about being destroyed in the retaliation by the other side. Thus, the possibility of initiating a war will be less. This is the rule of balancing by

strength. Therefore if a nation is not developed, but backward, it is only to be whipped and be the underdog.

### III. Dispute Surrounding the Star Wars Program

After President Reagan proposed the Strategic Defense Initiative, a great dispute between opponents and advocates was aroused in the United States. The central problem of the dispute includes the survivability and the lethality of the defense system. Naturally, the dispute also relates to political problems as to whether the Star Wars Program violates the ABM Treaty.

The most typical authoritative position was organized by the American Physical Society in 1984. A 17-member team of experts led by the 1981 Nobel Prize winner, Harvard professor Bloembergen and scientific, engineering, and academic director Podell of the Bell Laboratories of the AT&T. After 18 months of study, in May 1987 a 424-page concluding report, Science and Technology of Directed-Energy Weapons, was published [3]. The report makes an estimation on the gap between the present status and the actual requirements of directed-energy weapons. As pointed out in the report, with respect to the Strategic Defense System, at present there are still 26 key problems, technologically speaking [9]. By generalizing these problems, there turns out to be a large gap between lethality and survivability of directed-energy weapon systems based on strategic requirements. At present, no

prediction can be made as to whether this program is winning or losing.

1. Main points of the opponents:

As a weapon, naturally lethality is the most important, otherwise it will not be a weapon. With respect to the Star Wars Defense system, whether or not enemy missiles can be destroyed in the booster-flight stage and free-flight stage is the major indication when evaluating the system's effectiveness. Based on this requirement, in the view of the 17-member research team of the APS, at present there are no sufficient data capable of supporting a decision as to whether the program is feasible or infeasible. We estimate that even in the best of conditions, 10 years or longer in research can provide the necessary knowledge concerning the potential effectiveness and survivability of the directed-energy weapon system. The paramount points are the following:

With respect to the output power of high-energy laser, there is still quite a gap from the requirements of the weapon system as estimated based on present-day knowledge. There is still a gap of two orders of magnitude with respect to chemical lasers with maximum output at 2MW; there is still a gap of four orders of magnitude with respect to excimer lasers; there is still a gap of six orders of magnitude with respect to the free-electron laser with peak power at 1micrometer wavelength. Now, we still are unable to verify whether the nuclear blast-based X-ray laser can be developed.

There is still a gap of between two to three orders of magnitude for particle beam devices based on weapon requirements of beam current. There are still some important problems to be solved in the transmission of particle beams in the atmosphere.

There are many engineering problems and cooling problems that have not been taken up by satellites providing energy sources for the directed-energy weapons.

The survivability problem of satellite-based facilities is enormous. Such facilities are most easily attacked by the enemy's directed-energy weapons and various dynamic-energy weapons. These attacks are much more effective than the antimissile measures, at much lower costs. In addition, the number of orders of magnitude is much less as concerns the requirements of weapon performance. With respect to land-based systems, especially large facilities related to small numbers of laser systems, these facilities will be the target of attack with high priority.

In supplementary facilities, such as the manufacture of large beam concentration reflective mirrors, high-speed accurate and fast pointing, as well as real-time processing of information and discrimination between real and false targets, the problems in the land-based systems are difficult to be solved within a short time with respect to the atmospheric transmission, monitoring, communication, and command during wartime, and reliability for evaluation. Therefore, the Star Wars program is a project established on an unknown foundation.

## 2. Viewpoints of advocates

The most active supporters of the Star Wars Program are the Strategic Defense Initiative Organization (SDIO). They disputed the report of the APS research team, with different viewpoints [10]. The discussion points of the SDIO are as follows:

In the 17-member APS research team, not a single member had worked in the defense technology field in the previous quarter-century. They failed to understand the actual situation of strategic defense, because technical progress has been much more than their understanding. The understanding of directed-energy weapons by scientists and engineers fails to demonstrate gaps as large as they state.

The actual technical progress has verified or will verify that the output power of the directed-energy weapon can satisfy the requirements of strategic defense. In aspects such as the actual output power of high-energy chemical lasers, there is not a gap of two orders of magnitude, but only several-fold. With respect to the land-based free-electron lasers, the requirements on average output power are not 1GW, but 10MW. Its efficiency is not 20%, but already 40%. The instantaneous output power is about 200-fold that of the advanced intermediate-infrared chemical lasers [10].

The power (1GW) required for neutral particle beams as advanced by the APS is 30 times higher than the practical value. Such weapons are especially important in discriminating during the intermediate stage.

As indicated by a destructive study of lasers, a very high g-load exists in rocket casing in the booster-flight stage because of accelerated flight. Here, the destruction of a missile is not through burning a hole as imagined by some people, but only to weaken the skin to some extent to induce an explosion of the missile [11].

With technical progress, many technical problems of defense will be gradually solved.

#### IV. Problem of Survivability

The problem of survivability is a key problem in the Strategic Defense System. Without solving this problem, we are unable to have a realistic effective defense, and it is very difficult to sufficiently exploit the real power of the defensive weapons. Therefore, before deploying the Strategic Defense System, besides solving the problem of the weapon system's lethality, its survivability should also be stressed and considered. These systems include satellite-based systems, land-based systems, maritime-based systems, as well as major supplementary facilities, communication, command, and logistic support systems.

The weakest and most vulnerable is the satellite-based system, in particular, sensors (an optoelectronic receiving and tracking system) deployed on a satellite platform will be the first to be destroyed in a war. This is a decisive action. If a man's eyes are blinded, even if he is very strong, but he is

helpless, only to be beaten. Then, how to consider this problem on the Star Wars Program? The main concept is to have a net to cope with the attack. The reason is very simple: for a multilayer defense net, it is very easily done if you open a hole in the net, but it is very difficult if you have to completely destroy the net. If you are unable to attempt this action, destructive retaliation from the defending side is unavoidable. The result is the destruction of both sides, or both sides are unable to gain an advantage in the first attack. This is the principle of balance of forces. This is of positive significance in the Strategic Defense Initiative for stabilization. As quoted by director Keyworth of the Office of Technology Policy and a science adviser to the U.S. president, basically survivability of a system relies on surplus defensive measures. Consisting of and based on the satellite-based directed-energy weapons, multilayer defense in the booster-flight phase can survive [6]. Of course, here survivability does not mean today, but when the weapon system begins to be deployed.

On today's technical level, how can one avoid the defending system from being attacked? What measures can be adopted? We analyze this problem in the following.

1. Attack on dynamic-energy weapons

The paramount defensive target of the Star Wars Program is to intercept nuclear weapon attacks, which has great destructive power. Since the velocity is slow and it is easy to monitor dynamic-energy weapons, it should not be a problem to cope with

such attack with directed-energy weapons. Besides, at present there are many antimissile techniques that can be used. The dynamic interceptor flight vehicles and automatic homing flight vehicles (among other antimissile weapons) can be used for interception. Also, satellite-borne systems can evade such attacks with automatic maneuvering by early-warning radars and computers. Therefore, the Star Wars Defensive System can cope with attacks from dynamic-energy weapons.

## 2. Attack against directed-energy weapons

In today's world, science and technology have been highly developed. The trump cards held by the two superpowers are roughly at the same level. The main difference is on quality and quantity. Therefore, the greatest threat to satellite-based systems are an enemy's attack with directed-energy weapons. Such an attack may possibly be very effective because only hundreds of watts per square centimeter in power density is required to destroy a sensor. This power density is much lower than the power needed to destroy a missile. In addition, such an attack can end without any reaction from the other side. At present, there are the following kinds of such attacks:

Filter lenses are used to protect optoelectronic sensors: used as directed-energy weapons, high-energy lasers have an output wavelength only in several known numbers. By using a selective medium to coat the lens to produce very high reflectivity at the high-energy laser wavelength, but to have very high penetration rate for the wavelength required for

defense, therefore, destruction on intermediate-power-level laser devices can be avoided, but it is not effective with respect to high-energy lasers.

By using multiple discrimination system with multiple combined receivers: to determine whether or not an enemy attack causes the destruction of the sensing receiver systems, and to decide whether or not retaliation by the defensive net should be carried out, multiple sets of receiving sensor systems and backup sensor systems can be deployed on the satellite-based system platform, capable of withstanding different power limits. If only the receivers of low-destruction-limit are destroyed, and the other receivers are not, then we can determine that the enemy weapons serve just to blind, but are not high-energy weapons. If most of the various receivers are simultaneously destroyed, based on the time sequence of such destruction, although with very minute time differences, however, by using special detection systems and computer analysis, the properties of such destruction can be automatically determined, before deciding whether or not retaliation by the defensive net should be carried out.

By using laser weapons against laser weapons: by using all modern reconnaissance tools of satellites, in advance the position or orbital parameters of enemy laser weapon systems (including land- and satellite-based systems) are determined, at the same time, warning triggering devices are fitted on the most easily attacked locations in our side's laser weapons. When the warning triggering devices are attacked by the enemy's laser

weapons, in addition to sounding the warning alarm and intermediate triggering of our side's laser weapon system to carry out instantaneous destructive retaliation on the enemy.

Generally, survivability is relative. Whatever the system, it is not possible to have 100% safety. In particular, in the case of two superpowers with rival military resources, it is more difficult to have our side completely free from attack. The key point is that you should have a force that can completely destroy the other side, and a defensive net unable to be completely smashed by the other side. The Star Wars Program amounts to higher defensive levels; this is a new content of higher-level weapons by two superpowers. This is a must in the development of weapons technology. In the author's view, the Star Wars system can survive with attack nuclear weapons as its reserve; however, survivability can be carried out only at very great efforts.

(To be continued)

WHAT ARE THE PROSPECTS OF AMERICA'S "STAR WAR"  
PROGRAM (SDI)? PART II

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V. Key Technologies in Star Wars Program

To attain success in the U.S. Star Wars program, several key technologies should be developed. Only with breakthroughs in these key technologies, can the Star Wars program be carried out. What are the concrete subjects included in these key technologies.

1. Monitoring, acquisition, tracking, and evaluation of interception results

Although this category of technologies has some foundations, especially, microwave and infrared technologies have gradually matured. However, there are many problems of major technologies that need solving when used in the Star Wars program, including the entire range of monitoring, tracking, and evaluation of results for ICBMs; discrimination between real and false targets in the intermediate stage; and high-speed processing

discrimination and real-time display of large volumes of monitoring data. Here, the problem concerns optical technology, electronic technology, and computer technology. In solving these problems, it cannot be attained within a year or within half a year. Strenuous efforts are required.

## 2. Implementation of directed-energy weapons

Directed-energy weapons are the core system of the long-range goal of the Star Wars program. Whether this can be reached determines the success or failure of the Star Wars program. The importance is apparent. Here, problems in the two following aspects are related:

Laser weapon systems: based on many years' research on the laser's destructive effect in atmospheric transmission, generally the problem is understood. What are the requirements on the output properties of lasers to be used as weapons? Based on foreign reports, under the most ideal conditions, the destructive threshold value required for laser energy for strengthened missiles is approximately  $20,000\text{J}/\text{cm}^2$ . If the range is  $1500\text{km}$  and the light spot diameter is  $0.75\text{cm}$ , then the required laser output energy is approximately  $10^8\text{J}$  or  $10^8\text{W/s}$ . If the divergence angle of the light beam is  $0.5\text{microradian}$ , the diameter of the telescope is  $6\text{m}$  with respect to a  $2.7\text{micrometer}$  HF chemical laser, and  $0.6\text{cm}$  for a telescope diameter with respect to an  $249\text{nm}$  (KrF) excimer laser; with respect to an X-ray laser, the telescope diameter can be considerably smaller or even no telescope is required. At present, a  $2.4\text{m}$  diameter space

telescope was built by the United States. Technically speaking, to build 10m diameter telescopes can be generally carried out with some effort in not many years (within 10y). To relieve the requirements on the telescope, it is undoubtedly correct to use shortwave laser system. However, with shrinking telescope diameters, the process requirements for the telescope are continuously increasing, because this is quite difficult in processing to attain  $\lambda/10$  for the shortwave.

With respect to lasers that can be used as weapon systems, HF lasers can basically meet the lowest requirements for strategic weapons by using correlation array technology. However, since the output wavelength 2.7micrometers of such laser seriously degrades in atmospheric transmission, it seems very difficult to be used as a land-based weapon. However, the HF laser does not require a vast energy source provided externally, and its specific power is as high as 200kW/kg. The output of  $10^8$ W requires only 500kg fuel. Moreover, a space telescope 10m in diameter can also possibly appear within 10 years. Therefore, using this laser as a satellite-based weapon can be said to be practical.

With respect to the excimer lasers, at present KrF (249nm) has an output of 10,000J, which is still 10,000 times less than  $10^8$ J. Although the specific energy of such laser is low, only 4J/L, and its atmospheric attenuation is also high, yet the work repeatability can be enhanced by preionization technique using electron beams, thus solving the problem of low specific energy.

Moreover, it is possible to use a coaxial combination technique of multiple sets of excimer Raman cells to solve the difficulties of poor quality of light beam and atmospheric attenuation.

Therefore, such lasers have good prospects for development. In the United States, such lasers have been used as one of the main candidates for land-based weapon systems.

As for free-electron lasers, since their efficiency is high (50%, theoretical) with adjustable wavelength and without the problem of damaging the media, to be able to be free of the effect of atmospheric attenuation, such lasers have been one of the main candidates for land-based and satellite-based weapons in the United States. Suitable for an air-based weapon is the radiofrequency linear accelerator free-electron laser; the inductive linear accelerator free-electron laser is suitable for use as a land-based weapon, since the laser in the former case is light, and the laser is heavy in the latter case. In typical situations, the dimensions and weight of the radiofrequency linear accelerator are smaller than those of the inductive linear accelerator by 10 to 20-fold.

With respect to the nuclear-blast-pumped x-ray lasers, it was reported that the present output power compared to the output power in 1981 in successful experimentation has risen by six orders of magnitude [12]. In addition, the present-day laser can simultaneously attack scores of targets with easy transportability, therefore such lasers are especially suitable as satellite-based weapon systems. However, since there is

interference to communication systems during nuclear blasts, as well as the technical problems of atmospheric attenuation and rapid pointing, practical realization still requires difficult efforts.

Gamma-ray stimulators represent a long-term goal in the Star Wars program, under exploration now.

Particle-beam weapon systems: two kinds of beams (neutral particle beam and electron beam) are selected as particle-beam weapon systems. With respect to neutral particle beams, since this kind of beam can react with the atmosphere resulting in gaseous ionization (thus inducing deflection of ions in geomagnetic fields), therefore its height of range is limited at about 120km. To cause damage to materials, it is required to emit an equivalent electric charge of approximately 1C under the conditions of hundreds of megaelectron volts (in other words, 100MA in current is emitted within 10s) and the divergence of particle beams should be within 0.75 to 1.5microradians. The casualty effect of neutral particle beams is more reliable and effective than the laser damage because the neutral particle beam can penetrate tens of centimeter thick lightweight materials. As verified in experiments, for high-brightness negative ion beam used as the neutral particle beam, the fundamental requirements can be satisfied by an accelerator only 4m long. Therefore, only doubling the neutral particle beam power can enable the beam to be used as a satellite-based strategic defense [10].

We must point out, in particular, that the neutral particle

beams differ from lasers with respect to damage to targets, since the neutral particle beam can penetrate the structural layers of a warhead to induce blasts of explosives, to render ineffective the enemy's anti-light measures. In addition, by using the neutral particle beams in mid-stage recognition of ICBMs (mainly by using radiation of the particle beam same-target function to discriminate between real and false targets) has also a specific important significance. Under this situation, although the requirement on variation of beam power is not stringent, yet the time used on the target can be reduced down to a range between 1/10 to 1/1000.

With respect to the damage done by the particle beam weapon, as verified by firing experiments in July 1986 in the United States, high-intensity proton beams had very high kill properties on reentry rockets if illuminating them.

With respect to high-energy electron beams, to avoid the effect of geomagnetic fields (deviation of 0.5km with flight over 10km distance), such beams require to be transmitted in plasma channels generated by intensive lasers. Thus, the damage distance will be affected. Moreover, how to be synchronized with laser transmission, as well as rapid pointing and repeatability of action (greater than 10Hz), no experimental verification has been done. However, the present power of such electron beams can satisfy weapon requirements. As reported [13], in May 1987 the McDonnell-Douglas Corporation in the United States was awarded a contract of 480 million U.S. dollars in a plan for launching

three satellites (neutral-particle beam accelerator satellite, target satellite, and inspection satellite). All the experiments were completed in February 1991.

### 3. Problem of space-based power supply

To use many space platforms deployed as strategic defense can carry out high-degree and attitude control, a reflective mirror system of operation and cooling directional beacon light, as well as the required power supply for receiving, processing, and sending of information with radar control, it is estimated that a continuous power supply of 100 to 700kW should be available in each platform. To enable such power supply to have long-term power supply capability, it is necessary to deploy approximately 10,000 small nuclear power stations in space. However, such engineering technology has not yet been done in fabricating such power stations on a space platform. In particular, a very difficult task is to solve the power station cooling problem.

Noteworthy is the fact that with development and gradual practical realization of high-temperature superconductors, as well as improvements in race for materials, this problem perhaps will be gradually solved in the near future. However, the possible route still has to be studied, in satisfying the requirements in the initial Star Wars program, such as the power supply technique of chemical and electric pulses, as mentioned previously. However, there is a fuel supply problem, therefore, a new technology should be created.

#### 4. Phase control array space-based reflective mirror systems

Large reflective mirrors are necessary to transport, relay, and target hits with lasers. We can have a concept of fabricating a highly precise large reflective mirror with apertures as large as 6 to 10m on a satellite, but this is not easy. It is also very difficult to quickly and precisely maneuver such a large object. To relieve the difficulties in launch and control, at present scientists are trying to fabricate a flexible thin film reflecting mirror system, which has obvious advantages. First, its weight is low, so that it is easily launched. Second, its rotating torque is small, and it is easy to maneuver quickly and precisely. Third, it is easy to change its shape so that multiple drivers can be used to change the mirror surface for phase compensation, and to solve the problem of light beam quality. This concept was verified in small-sized flexible mirrors; however, further study is required on the properties of large principal lenses under high laser power.

#### VI. Star Wars Program Will Promote New Developments in Civilian Science and Technology in the United States

We should see that the Star Wars program is a gigantic contest in high science and technology. If successful, undoubtedly the United States will regain the world hegemony. Even if it fails, this brand-new science and technology due to the program will place the United States in the center of the world's power in science and technology. This is a major strategy of the United States, eyeing the developments of the

future and the 21st century.

With the foregoing analysis, we understand that the Star Wars program cannot be completely carried out by relying only on present-day technology. A series of new concepts and new technologies should be required. As historical materialism tells us, society's demands represent a major force in pushing innovations in science and technology. Only with the support of an abundance of funding, can creative inventions and vigor be stimulated to tens of thousands of scientific and technical personnel. With a clarified target and requirements, along with the positiveness of 30 millions scientific and technical personnel, together with the outstanding material conditions for their research and activities, can the major strength in attacking the vital problems be assembled for a pathway to success. The successful development of the atomic bomb is the most powerful evidence. From the late thirties and the early forties, when only milligrams of U-235 isotope was isolated, the United States government made a decision to build the atomic bomb. Compared with the scientific and technical foundations at present with the Star Wars program, undoubtedly, the conditions then were much worse. However, under wartime requirements of life or death, the atomic bomb was built after several years' effort. After the successful building of the atomic bomb, a major development of the peaceful utilization of atomic energy ensued. We can predict that the successful carrying out of the Star Wars program will greatly push forward the aerospace

technology, space development, superhigh-speed optical computational technology, laser-induced nuclear fusion and high-resolution x-ray three-dimensional holographic analytical techniques for crystal structures and life cells, superhigh-resolution X-ray carving technique, superhigh-accuracy tracking technique, highly secure communication technique, as well as optoelectronic technology, with their rapid advances and development. Then, mankind will enter a new era of higher degree of civilization.

## VII. Conclusions

We can compare the following conclusions with the foregoing analysis: 1. there are no difficulties in principle on theory and practice in building high-energy laser devices and high-power particle accelerators, with output power and beam quality satisfying strategic defense requirements. Basically, the output of HF chemical lasers has already satisfied the requirements.

2. There is, in principle, no difficulty in fabricating phase control array large optical reflective mirror systems, used for light-beam guidance and focusing.

3. The land-based directed-energy weapon system not only has higher survivability, but also is more suitable for multiple repetitive operations. The problems of energy supply and other supporting engineering are easily solved. Through several (three, in the general case) space relay reflective mirrors, targets throughout the world can be attacked. Although there is

the problem of atmospheric attenuation, yet such difficulties can be avoided just by selecting appropriate wavelengths. Excimer laser and free-electron lasers are suitable for land-based weapon systems.

4. Although the satellite-based directed-energy systems are easily attacked and damaged, yet these systems can avoid the troublesome atmosphere and are easily arranged for close-range attack. As a three-dimensional strategic defense net, the satellite-based system is indispensable. At present, candidates for satellite-based weapon systems include chemical lasers (especially if a short-wave chemical laser device can be developed to avoid the difficulty of building giant satellite-borne reflective mirrors), x-ray lasers, and gamma-ray stimulators (under emphatic development at present), as well as neutral particle beam weapon systems.

5. At present, there are several practical methods in the intermediate-stage recognition technique, very important for strategic defense. The most important is illuminating real and false targets with neutral particle beams and intensive laser beams. Through analysis, radiative or scattering properties related to mass will be generated under such conditions of high-energy beams. Thus, we can discriminate real warheads from decoys, so that only the real warheads are to be intercepted.

6. At present, there are under development, with respect to monitor, acquisition, tracking, communication, and evaluation of results, with major progress.

7. In the near- or intermediate-stage of the Star Wars program, the dynamic energy weapon systems have several weapon options at present. Some new weapons are under development, such as Brilliant Pebbles, and superhigh-speed cannon rounds (20 or 30km/s). Electric energy, not chemical energy, drives such rounds. This system is used mainly for terminal-stage interception within the atmosphere.

8. Various new sciences and technologies are now, and will in the future obtain new breakthroughs in carrying out the Star Wars program.

In the author's view, the Star Wars program has the feasibility of successful execution. If the two superpowers or more nations have the same level of weapon systems, the world will become more stable and peaceful. On this viewpoint, as a developing major country, although we are still unable to have the economic resources to compete with the superpowers in the Star Wars system, yet we should make some preparations, not be forever among the second-ranking nations, to be on the receiving side of offensives. We should allocate some funds and manpower, even though under limited financial resources, to conduct follow-up research on some long-term and key problems in the Star Wars program, to develop our own superiority and to fill our basic technical voids, to make our contributions to fundamental research on new strategic laser weapon systems (such as x-ray lasers, gamma-ray stimulators, and visible light chemical lasers), sensor systems and superhigh-speed optical computers.

Author's brief resume: Huang Yongkai, male, was born in October 1930, in Renshou County, Sichuan Province. He is an associate researcher. In 1955, he graduated from the physics department, Sichuan University. He was assigned, upon graduation, to the Changchun Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, for setting up optical standards in China. In 1961, he was transferred for research on illumination properties of solid-state laser media. After 1964, he successively engaged in research on laser plasma spectra, gas lasers, solid-state lasers, and laser spectra. Recently, he began to conduct research on x-ray lasers and other topics.

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