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A High-Efficiency, Small, Solid-State Laser for Pyrotechnic Ignition

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A completely self-contained, small, neodymium laser has been designed and demonstrated for use in a pyrotechnic ignition system. A nominal 16 J of laser energy (1.06- μm wavelength, 1-ms duration) was achieved in a rectangular 10.5- X 15.1- X 25.4-cm package weighing 5.14 kg. This high energy-to-weight ratio is encouraging for laser applications in which specific energy efficiency (energy per unit weight or volume) is important. The laser design concepts are described, and some results on pyrotechnic ignition are given. Some details on a laser currently under construction, which will be 1/8 the size of the above laser, are included.

Introduction

The use of a pulsed solid-state laser in aerospace work and other applications such as ranging and communication depends largely on its specific efficiency, i.e., laser energy per unit volume or weight. In the early days of laser development, there was considerable enthusiasm to achieve higher-energy output per unit volume. However, today with less severe restrictions on size, laser energies have reached self-destruction limits on the lasing materials. The design of a highly efficient, portable, solid-state laser is still a most interesting challenge. The problems imposed under the restrictions of weight and size are essentially dependent upon the total efficiency of each link in the chain of laser generation, including the power supply, high-voltage circuitry, capacitor bank, flash lamp, pumping configuration, laser rod, and cooling method. Weight and volume restrictions have *fundamental impacts on the efficient design*, because a good uniform discharge, such as in a pulse-forming network or even a resistive-inductive-capacitive (R-L-C) circuit, is difficult to miniaturize, being limited by the large size of the choke.

Laser Head

The laser rod (1.27-cm diameter, 15.24-cm length) was made from fused silica doped with 3% by weight of Nd_2O_3 with flat-ends configuration. The rough lateral surface ($\sim 0.3\text{-}\mu\text{m}$ roughness) combined with an absorption coefficient $\alpha = 0.18\text{ cm}^{-1}$ (corresponding to the doping level and the effective pumping band of 5700 to 6000 Å) provide a very uniform pumping of the rod; therefore, the optical gain and energy output are quite homogeneous over the cross section of the rod (Ref. 1). The rod is also doped with cerium oxide for anti-solarization purposes, so a UV shield between the flash lamp and the rod is unnecessary. The laser mirrors have a reflectivity of 70 and 100% at $1.06\text{ }\mu\text{m}$. The mirrors are multi-layer ZnS and ThOF_2 films vacuum-deposited on the ends of the rod, which have a $1/20$ wavelength (at $1.06\text{ }\mu\text{m}$) flatness and are parallel to each other within 0.5 seconds of arc.

A helical flash lamp was made from 5-mm ID \times 7-mm OD quartz tubing. The length of the lamp was 12.7 cm, with an ID of 1.3 cm to closely fit the laser rod. Twelve helical turns spaced 3 mm apart were chosen to obtain a homogeneous light irradiance on the surface of the rod. The anode and cathode electrodes were made of tungsten and stainless steel, respectively, and the xenon gas was filled at $4 \times 10^4\text{-N/m}^2$ pressure. The design of the laser cavity is very compact, with the void spaces between the rod and lamp as small as possible. The ratio of volume occupied by the rod to that of the cavity is purposely made as large as possible. The light generated by the flash lamp undergoes multi-reflections and refraction by the lamp walls, the rod, and the cavity reflector. This causes the light energy density inside the cavity to be quite homogeneous. Therefore, the large relative volume of the rod will allow more light to be absorbed for laser action. This is an empirical approach that has proven to be very useful, because, in a helical cavity, the determination of pumping efficiency by ray tracing as used in an elliptical cavity (Ref. 2) is virtually impossible.

In order to avoid the use of large chokes of the order of $10^2\text{ }\mu\text{h}$, an R-C discharge was chosen to excite the flash lamp. An effective arc length of 79 cm and a quartz tubing ID of 5 mm, in conjunction with the $54\text{-}\mu\text{F}$ capacitor bank, were chosen to provide an arc resistance of $9.0\text{ }\Omega$ at 4.9 kV. The resultant average current density of 1000 A/cm^2 corresponds to approximately 7000 K in color temperature, producing a blackbody radiation (Ref. 3) highly rich in the effective pumping band (5700 to 6000 Å) of the neodymium ions. The flash lamp reflector was made from gold-plated, finely polished, half-hard silver foil 0.12 mm thick. The thin gold film protects the silver surface from oxidizing during storage and from the strong irradiation of the flash lamp. It also offers the best spectral reflectivity for the effective pumping band (96% at 5800 Å). The foil tightly wrapped around the flash lamp is also in good contact with the inner liner.

There were several factors considered in the design and application of boron nitride for the cavity inner liner. Because of the compact design of the cavity, it is difficult to remove the heat produced by the flash lamp through air circulation. A diffusive heat sink must be used. The high voltage being

used further required a material with high dielectric strength. It is also impossible to completely enclose the flash lamp with the metallic reflector, which means that some of the dielectric inner liner will be exposed to the flash lamp light. The high UV content of the flash lamp light has a surface burning effect on most dielectric materials such as epoxy, fiberglass, and Teflon. Use of these materials as an inner liner would produce residues that would be deposited on the surfaces of the rod and lamp, leading to laser output deterioration after a small number of operations. Boron nitride has very high thermal conductivity ($0.28 \text{ W-cm/cm}^2\text{-K}$) and dielectric strength ($3.8 \times 10^4 \text{ V/mm}$). For the visible spectrum, it has a reflectivity of 82%, and its resistance to UV radiation has been tested and found to be excellent. Another advantage is its excellent machinability as compared to that of the other popular heat sink ceramics such as alumina or beryllia. Alumina also shows color changes from the irradiation of a xenon flash lamp. Beryllia is not attractive because of its health hazard.

Electronics

The high-voltage energy bank shown in Fig. 1 contains two 5-kV, cylindrical, aluminum-Mylar-foil-type, high-energy density capacitors (44 and $10 \mu\text{F}$) made by the Maxwell Laboratory, Inc. The 5-kV-rated series was chosen because it provides the maximum electrical energy storage per unit volume and weight, and it will have a life usage of over 10,000 discharges. Operational levels up to 5.5 kV have shown it to be quite safe, with breakdown occurring beyond 6 kV. The $44\text{-}\mu\text{F}$ capacitor is 10.2 cm in diameter, is 16.5-cm in length and weighs 2.27 kg, while the $10\text{-}\mu\text{F}$ capacitor is 5.1 cm in diameter, is 16.5 cm in length, and weighs 0.68 kg.

The dimensions of the dc-to-dc high-voltage converter are $8.25 \times 8.25 \times 6.35 \text{ cm}$, and its weight is 1.6 kg. It consists of a regulated 2.7-kHz oscillator, a 11.8-dB amplifier, a $\times 54$ voltage step-up transformer, and rectifiers. The input requires 24 to 28 V dc and a 9-A peak current. The output is adjustable from 3 to 6 kV at 25-mA average current level via a $10\text{-k}\Omega$ potentiometer. The charging time for the $54 \mu\text{F}$ to 4.9 kV is about 8 s, and the overall electrical power efficiency is about 80%. The weight consists mainly of insulation and a thick aluminum case shielding, which can be reduced if desired.

The flash lamp discharge was initiated by a 20-kV, $6.0\text{-}\mu\text{s}$ triggering pulse delivered between the lamp reflector and the ground electrode of the lamp. It was generated by discharging the energy stored in an $8\text{-}\mu\text{F}$ capacitor at 300 V dc through the primary of an EG&G model TR180 cylindrical triggering transformer of $2.62\text{-} \times 4.0\text{-cm}$ size, 28.4-g weight, and 112:1 turn ratio. The capacitor was charged with a small dc-to-dc converter ($3.5 \times 3.5 \times 2.5 \text{ cm}$ in size and 85 g in weight).

The high-current-rated dc input was provided by a battery-pack measuring $5.6 \times 8.4 \times 12.7 \text{ cm}$ and weighing about 0.9 kg. The pack consisted of 19

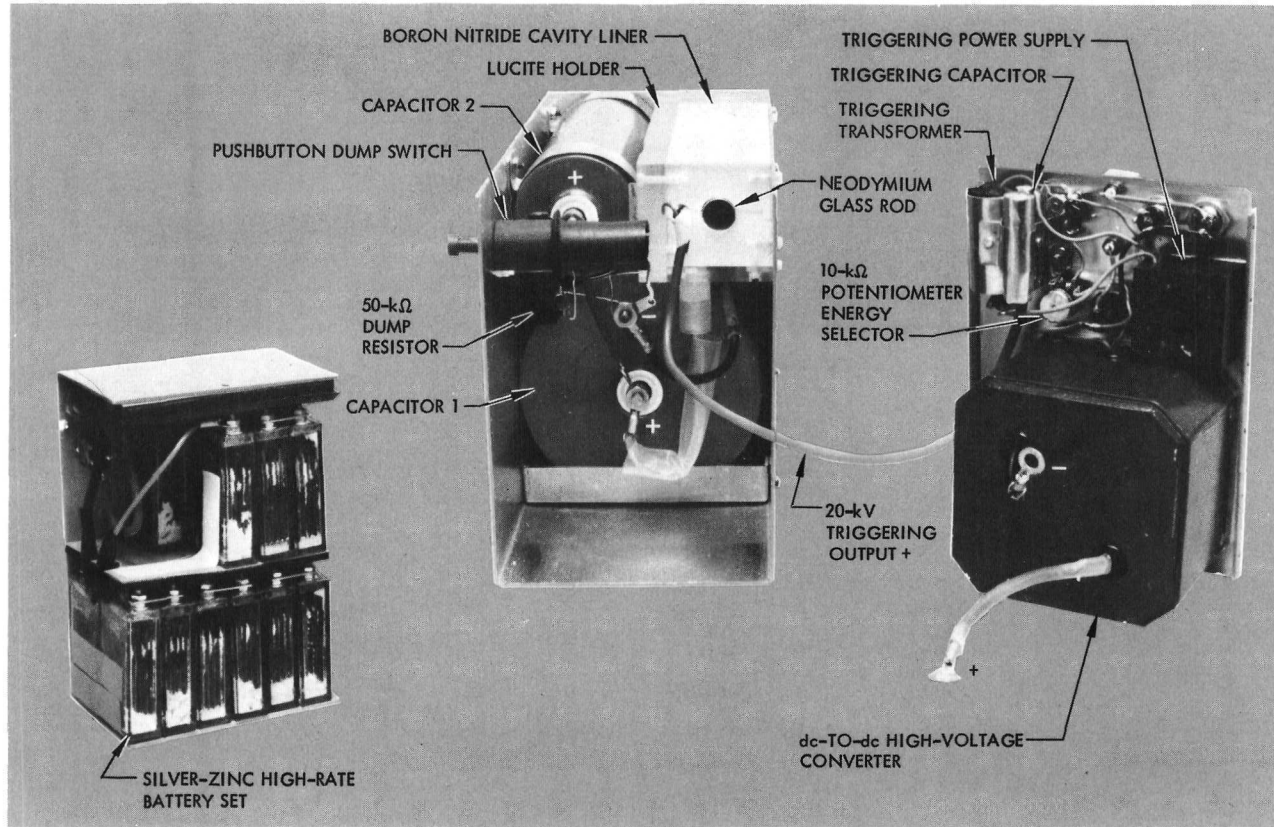


Fig. 1. Interior of laser and battery package, showing electronic components

Yardney HR, 1.5-V, silver-zinc, high-efficiency batteries. At a 9-A discharging rate, it provides 28 V dc with about 1.5-A-hr life, which is sufficient for 50 laser operations at highest laser output levels.

The high-voltage safety factor was designed to be about 20, based on 1.2×10^4 -V/mm insulation strength. A pushbutton dump switch is provided to allow the high-voltage energy to be bypassed and discharged through a 10-W 50-k Ω power resistor.

Laser Performance

Figs. 2a and 2b are oscillograms showing the xenon flash lamp discharge. Voltage and current agreed quite well with the design estimates. Fig. 2c shows the lamp light output at 4.9-kV discharge, as seen by a Korad S-1 vacuum photodiode. Fig. 2d shows the corresponding laser output of 16 J via a MgO reflector and the same diode in the characteristic relaxation manner modulated by the flash lamp light output shape. The lower triggering limit of the flash lamp was about 3.4 kV of bank voltage, which gave a laser output of 4.5 J. The slope efficiency is therefore about 3% and the absolute efficiency is 2.5%, which are fairly close to the maximum yellow-light-band efficiency produced by an xenon flash lamp (Ref. 4). After approximately 300 operations, the maximum laser energy output remained at a constant value of 16 J, even during short-term continuous pulsing (10 shots in series). The interior of the laser head showed no sign of deterioration, which was encouraging with respect to the reliability of the laser.

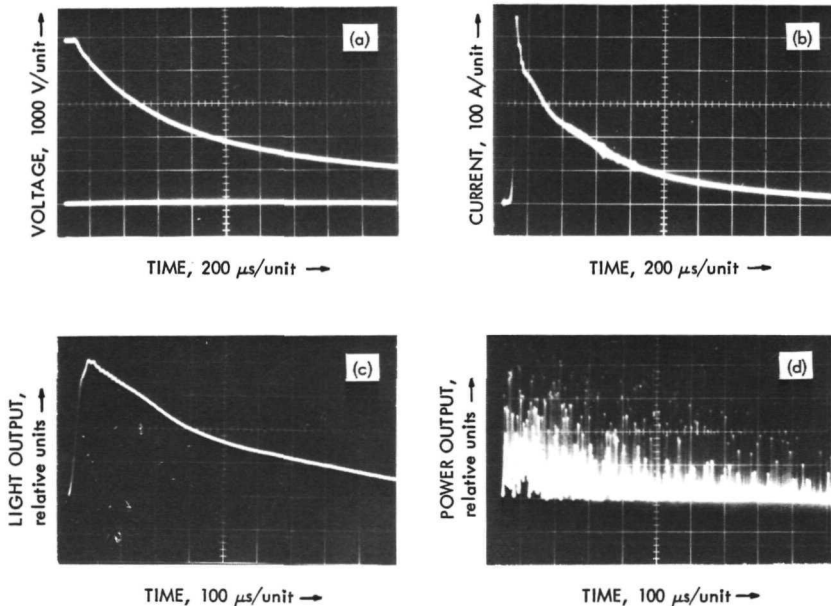


Fig. 2. Laser performance characteristics at 4.9-kV discharge: (a) flash lamp voltage, (b) flash lamp current, (c) flash lamp light intensity output, and (d) laser power output (16 J)

Since both the high-voltage converter and the capacitors have a maximum capability of 6 kV, it is safe to operate the system at a 5.5-kV level. The projected laser energy would then be approximately 20 J. There is space available in the laser package to allow the installation of a passive Q-switch unit. Assuming a 20% Q-switch efficiency, the system is therefore capable of producing more than 3 J of Q-switched output.

Pyrotechnic Ignition

A laser pyrotechnic ignition system consisting of a laser, pyrotechnic devices, and fiber optics has been assembled and is shown in Fig. 3. Fig. 4 shows the laser pyrotechnic ignition device. It has the same external dimensions as the SBASI (single-bridgewire Apollo standard initiator), but the electrical connector has been modified to accept a fiber-optics bundle. The bridgewire/header has been replaced with a glass-to-metal sealed window designed to withstand at least 3.5×10^8 N/m² of pressure. The pyrotechnic mixture is NH₄ClO₄/Zr (50/50). The high light absorption of zirconium in the visible and near IR, combined with the diffusive internal light scattering of NH₄ClO₄ crystals, resulted in an 85% absorptivity for the mix in this spectrum range. The laser sensitivity of the device was 0.77 J/cm² when pressed under 3.45×10^7 N/m² of pressure against the glass window.

Glass was chosen for the fiber optics rather than plastic, because glass has better transmission at 1.06 μ m and better resistance to deterioration under

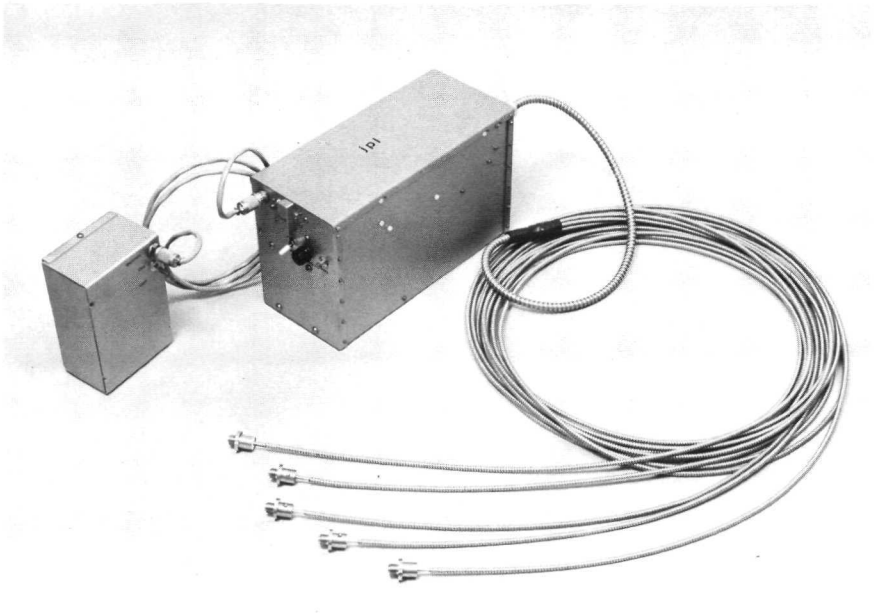


Fig. 3. Laser pyrotechnic ignition system

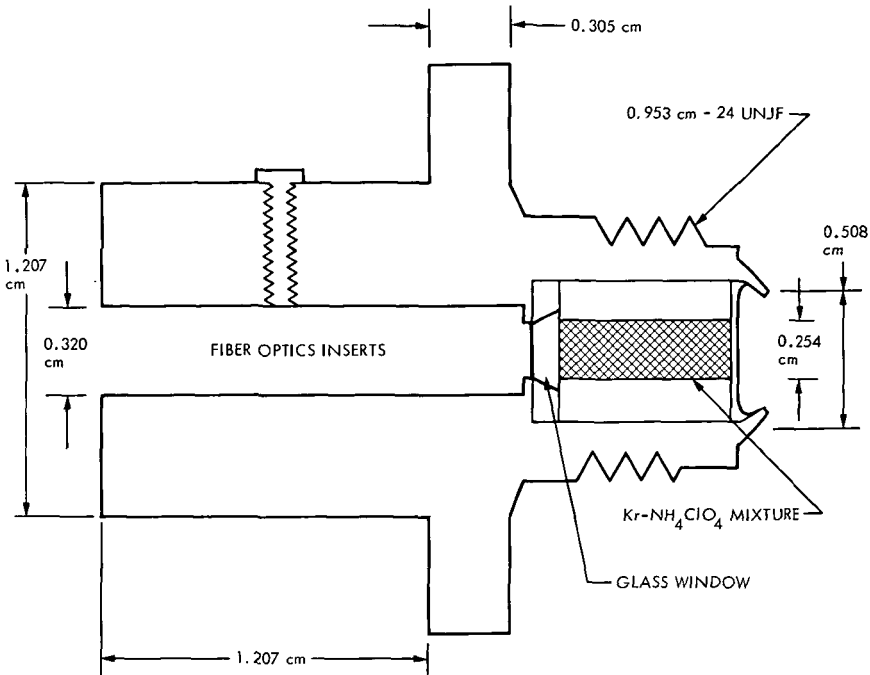


Fig. 4. Laser pyrotechnic ignition device

the intense focused neodymium laser beam. For commercially available glass fiber-optics bundles made from $70\text{-}\mu\text{m}$ -diameter individual fibers, the light transmission at $1.06\ \mu\text{m}$ can be expressed as $I/I_0 = e^{-\alpha x}$, with α typically of the order of $0.4/\text{m}$.

A test was conducted to demonstrate the simultaneous initiation of five pyrotechnic devices. The fiber optics for this particular test was fabricated to have a single input that branched into five identical output fiber optics. The total length to each pyrotechnic device was $3.7\ \text{m}$. Randomization of the individual fibers resulted in equal light splitting within $\pm 5\%$ at each output and independent of the light input distribution. The gas pressure generated by the burning pyrotechnic material was monitored by the same method as that used for spacecraft electroexplosive devices. The system consists of a 1-cm^3 pressure bomb, a Kistler 607A pressure transducer, and a Kistler 504A (or 504, 503) charge amplifier. The results of the test at 16-J laser output energy, as recorded by two oscilloscopes, are shown in Fig. 5. The sharp-rise peak pressure in each channel was reached within approximately $0.2\ \text{ms}$ after the start of the laser pulse. This time can be associated with the burning time through the 0.25-cm -long pyrotechnic column. In other words, due to the high laser energy used in the experiment, the pyrotechnic starts to react in tens of microseconds upon receiving the laser pulse. This type of ignition characteristic is very desirable for the functioning of pyrotechnic devices.

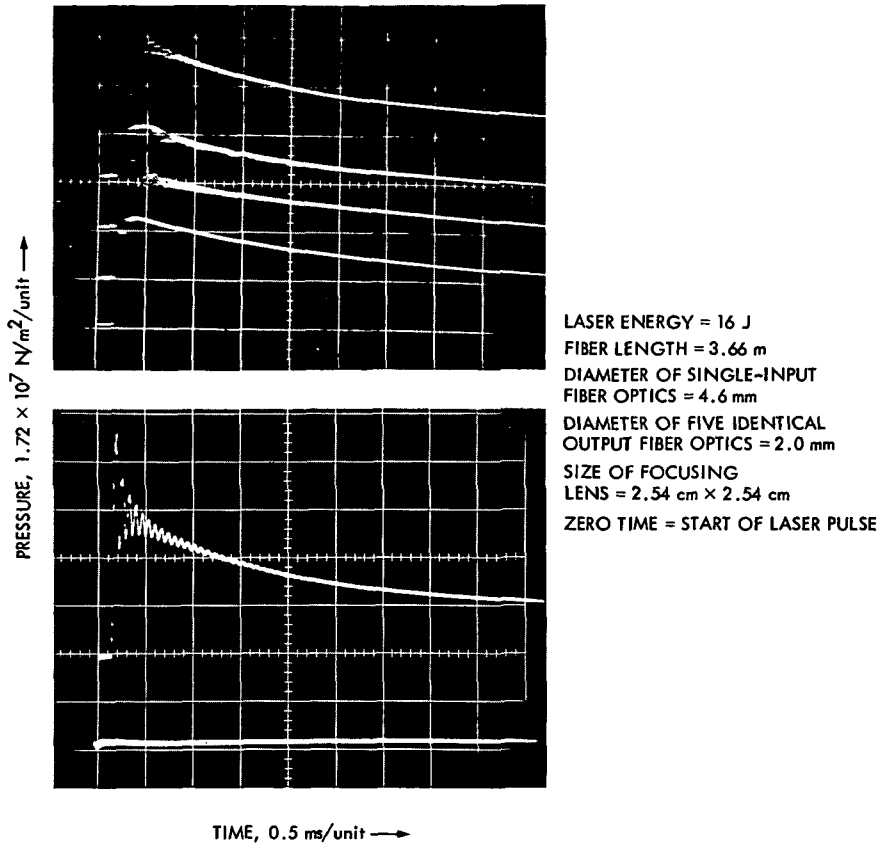


Fig. 5. Test record of simultaneous initiation of laser explosive devices by laser energy

Some Bruceton-type tests are planned in order to establish all fire and no-fire laser energy limits. The 16-J laser energy available in the system is capable of initiating as many as 20 devices simultaneously through a 3-m-long fiber optics or a single device through an 18-m-long fiber optics.

Work in Progress

In view of the progress made, especially in the achievement of high laser efficiency, plans have been made to build a smaller laser pyrotechnic ignition system suitable for spacecraft applications. A laser ignition system of 5.1- × 7.6- × 12.7-cm size, less than 0.7-kg weight, and approximately 2.0-J output will be sufficient to actuate four pyrotechnic devices simultaneously at a distance of 3.0 m (through fiber optics). This would satisfy the requirements of, e.g., the Viking lander separation mechanism. At first glance, it appears to involve a scaling down of the present laser; however, analyses have indicated that some fundamental changes in the design concept have to be adopted. For example, in order to achieve energy storage efficiency and flash lamp spectral efficiency, a linear or annular lamp

should be used instead of the helical lamp. Also, a low-voltage (500-V) capacitor with high capacitance (800 to 1100 μF) should be used. The only types of capacitors that satisfy the size and weight requirements are specially made electrolytic capacitors. Other components such as the triggering transformer have to be further miniaturized. Because of the lower pumping level (~ 100 J electrical), the laser output depends critically on the size of the laser rod and the reflectivity of the output mirror. Therefore, more caution has to be taken in the development. The development is proceeding on schedule and is expected to be finished by the end of fiscal year 1973. A parallel effort exploring the feasibility of adopting better fiber optics is also under way. The latest developments in this area are fused-end glass fiber optics, continuous reflection index cladding fiber, and low-attenuation fiber waveguides.

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