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Nuclear Pumped Gas Lasers

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New areas in plasma physics and plasma dynamics are entered by research on gas lasers directly excited by nuclear reactions. Recent development of high-power, high-pressure gas lasers results in improved aspects of laser pumping by nuclear energy. Population inversion in gaseous laser media can occur as a result of interactions with fission fragment, α-particles, fast protons or γ-rays. Such interactions may be the sole cause of population inversion or they may augment other means of laser pumping. The possibilities of achieving population inversion by nuclear reactions are discussed. Work in this field is reviewed and suggestions for further research are made.

Introduction

THE interest in using nuclear energy for laser power is almost as old as the gas laser itself. Papers dealing with this subject began to appear around 1961. The potential of high-power density inherent to nuclear reactions has appeared attractive in regard to high laser power output.

Various authors have also speculated on higher efficiencies, as compared to electrically excited lasers on the basis of an all-component system analysis which includes the various phases of energy conversion from an original heat source to laser light. In addition, more compact systems were expected with obvious tradeoffs, for example, in space applications.

As power sources, nuclear reactors or radioisotopes have been suggested to pump a laser either indirectly by means of thermal conversion, such as in a thermionic diode arrangement, in which the discharge plasma can exhibit population inversion,[1–3] or directly. In this case, the energetic reaction products, such as fission fragments, recoil particles, and γ-rays, interact with the laser material to produce population inversion.

Methods have been suggested for γ-ray lasers[4–8] by which stimulated emission is obtained from metastable excited nuclei.[9] Isomeres suited for such γ-ray amplification would have an extremely high-energy content in the order of several tens of kev per atom or 10^{12} joules/kg.

Stimulated emission from outer shell transitions of lattice atoms excited by fast particles and gammas have been investigated.[10–24] Much of this research is based on previous investigations of luminescence of solids and liquids induced by nuclear radiation. In several cases γ-irradiation has reduced threshold power for optical pumping. In other experiments such irradiation had adverse effects as to cut off lasing action. The reason is believed to be radiation damages which degrade the optical properties of the lasing material. This paper deals with nuclear pumped gas lasers only.

Earlier reports reflect the limitation of low pressure for gas lasers in the order of 1–10 torr. At this pressure the stopping distance of high-energy particles is much larger than laser tube dimensions and energy deposition in the lasing gas appears to be

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marginal. Therefore, emphasis was put on analyzing systems of possible higher pressures and larger dimensions, and on mechanisms for excitation that are unique with nuclear pumping as to capitalize on its specific characteristics.

To justify the additional complexity of a nuclear system, major advantages have to be shown. One is the potential for high-power densities. For lower power application conventional laser techniques usually suffice. In extraordinary situations, such as in space or in remote terrestrial locations, nuclear pumped lasers may also be useful at low power when combined with existing nuclear energy sources which are basically used for other power needs.

The major difference between nuclear pumped lasers and electrically or chemically powered lasers is that in the nuclear case, the pumping particles have up to 100 Mev energy whereas in electrical or chemical pumping average energies are in the order of a few ev. This difference is reflected in the type of research which is required for the nuclear pumped laser. For example, plasma dynamics appears to be indispensable. Interactions of low-temperature gases and of plasmas at a few ev temperature with heavy particles having a large charge and mass and kinetic energies in the Mev range have to be studied. It is expected that such interactions result in highly nonequilibrium states of the system, which promises to become an interesting new field: nuclear plasma physics. In the following, efforts and progress made up to date are reviewed.

Concepts

Figure 1 shows different concepts for nuclear pumping.

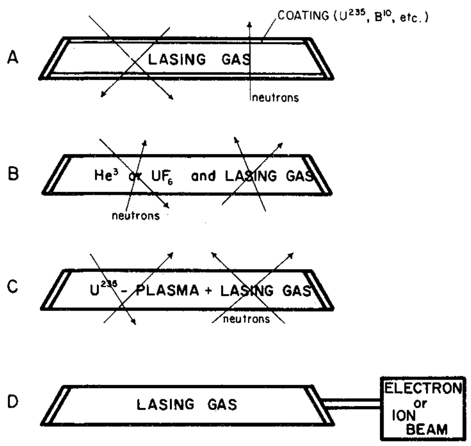

Fig. 1 Basic configuration for nuclear pumped lasers.

Concept A

The laser tube is covered with a coating which emits heavy particles either under neutron bombardment or by radioactive decay.[25] Typical reactions are as follows. For Boron coating:

$$B^{10} + n \rightarrow \alpha + Li^7 + 2.3 \text{ Mev}$$

$$(\alpha = 1.46 \text{ Mev}; Li^7 = 0.84 \text{ Mev})$$

For U^{235} coating:

$$U^{235} + n \rightarrow ff_h + ff_l + \sim 180 \text{ Mev}$$

$$(ff_h \sim 65 \text{ Mev}; ff_l \sim 97 \text{ Mev}) \qquad ff = \text{fission fragment}$$

For Polonium coating:

$$Po^{210} \rightarrow \alpha + Pb^{206} + 5.3 \text{ Mev} \qquad (\alpha = 5.3 \text{ Mev})$$

The α-particles or the fission fragments generated in these reactions excite the lasing gas.

Concept B

A second possibility is to mix with the lasing gas another gas which serves as a source of heavy particles.[25,26] Typical reactions are:

In the case of He^3 admixture:

$$He^3 + n \rightarrow p + T + 0.76 \text{ Mev}$$

$$(p = 0.57 \text{ Mev}; T = 0.19 \text{ Mev})$$

and in the case of UF_6 admixture the fission reaction is as above.

Concept C

The third method involves a volume source at high temperatures in contrast to the first two possibilities. High temperatures are required for uranium vaporization. The uranium becomes partially ionized. The gaseous nuclear fuel component is thus a uranium plasma.

Concept D

The fourth possibility is to bombard the lasing material with high energy electron or ion beams[26,27] to simulate nuclear interactions. Method C appears to be most attractive because a uranium plasma can be critical and self sustained. Figure 2 gives the predicted vapor pressure curves for uranium together with a few measured points.[28] A relatively high temperature is required to produce an appreciable uranium partial pressure. In Fig. 3 the pressure temperature relation for a reactor (7 ft diam, 7 ft long) with the entire fuel in the plasma state is given. By comparing these relations, it appears that criticality can be achieved at high pressures and temperatures sufficiently high for uranium evaporization.

At the present time it is not known whether the uranium atom or uranium ions have lasing transitions. The composition of a uranium plasma fuel and a lasing gas admixture has been mentioned already. High temperatures involve Doppler broadening of the lines. At a high electron density, Stark broadening could become predominant broadening mechanism. These effects

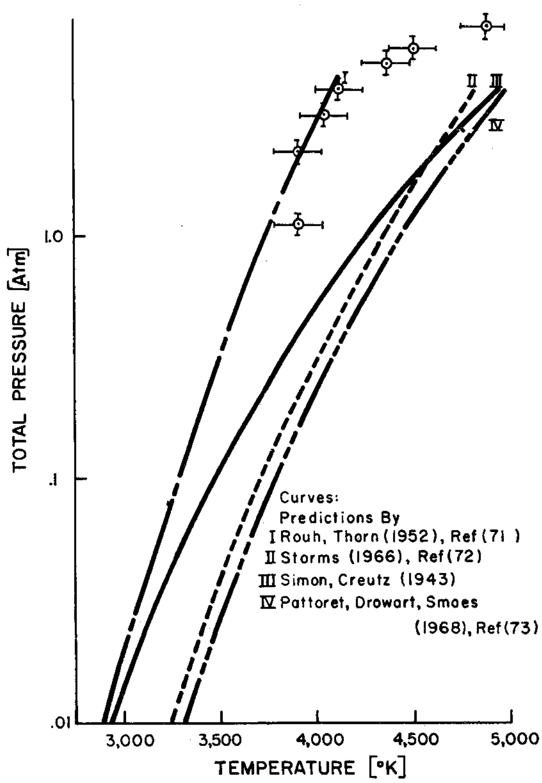

Fig. 2 Total pressure vs boiling temperature. Measured points after Ref. 28.

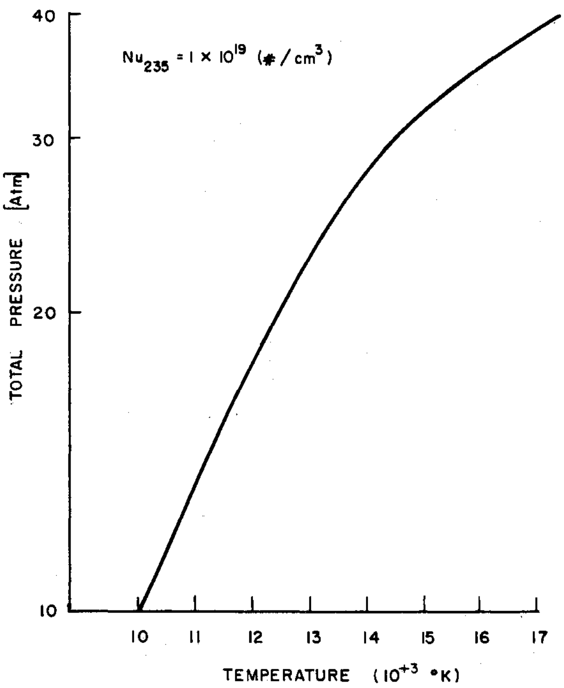

Fig. 3 Pressure trajectory for plasma core criticality.[76]

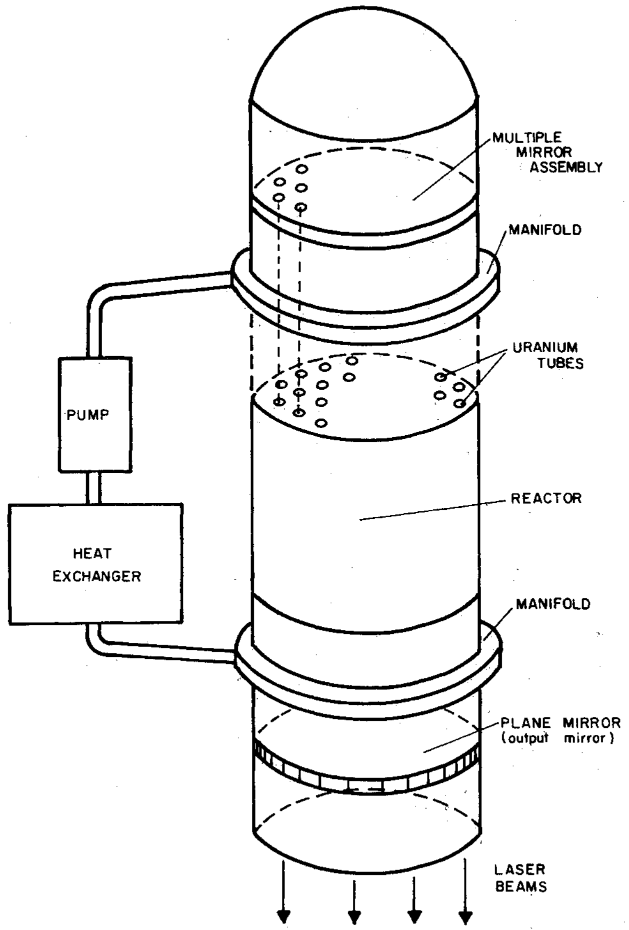

Fig. 4 Laser tube reactor.

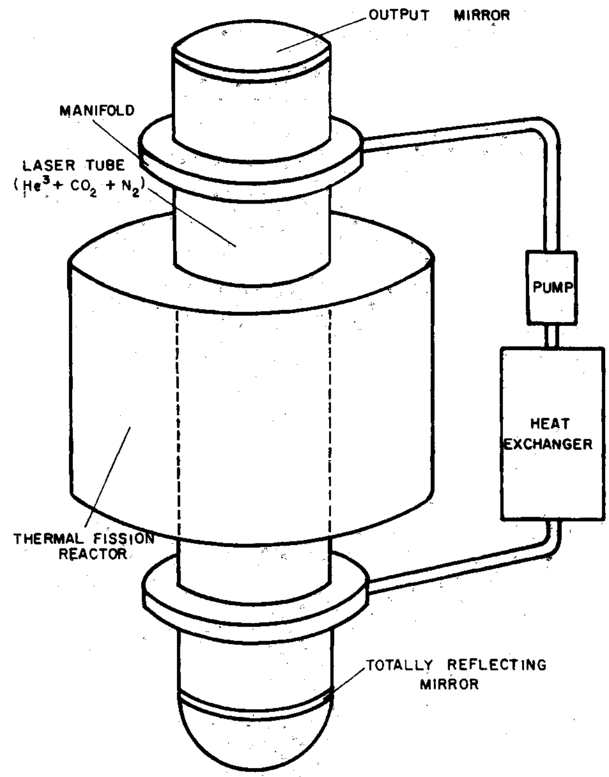

Fig. 5 He[3] reactor laser.

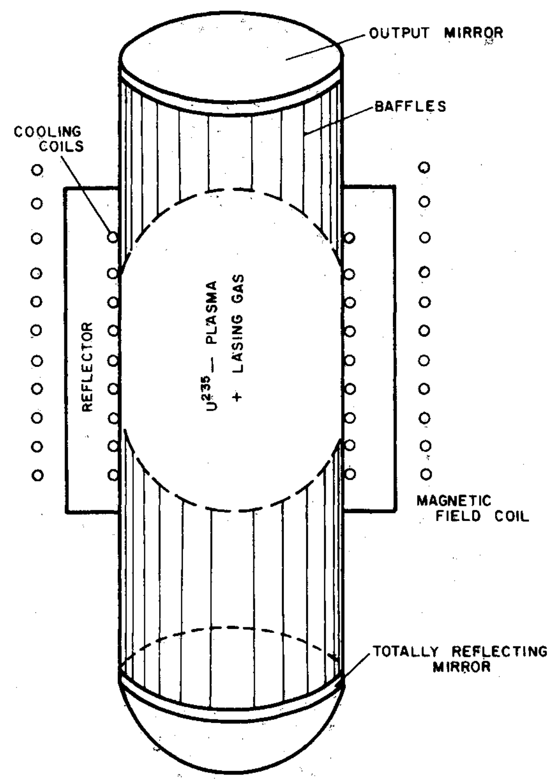

Fig. 6 Plasma core reactor.

are adverse to lasing action. However these adverse effects could be compensated for by the high input power.

It is too early to predict how practical nuclear pumped lasers will work. Speculative applications of the first three concepts are illustrated in Figs. 4–6. Figure 4 shows the laser tube reactor using the method as described in concept A. It consists of 1500 laser tubes[25] each one coated with U^{235} which combined constitutes a critical mass of 7.5 kg. The lasing gas is He–Ne. A circulation system may or may not be used. The light paths can be parallel or folded.

Figure 5 shows the He^3 scheme as described in Concept B. The reaction fragments are generated within the laser volume. A thermal fission reactor surrounding the tube is required as neutron source for the He^3 $(n, p)T$ reaction. The pumping power comes from the He^3 $(n, p)T$ reaction. As a lasing gas the CO_2–He–N_2 laser mixture may be used. Operation at high-laser power requires high flowrate gas circulation. The power for the circulation system may be generated by the fission reactor.

Figure 6 shows a plasma core reactor with a lasing mechanism, according to Concept C. Most of the fuel is in the plasma state at a temperature in excess of 4000°K. The reactor walls have to be cooled. A magnetic field may be added to reduce diffusion of uranium out of the system. Baffles along line of sight collect fuel which diffused out of the system.

Pumping Mechanism

Selective Excitation

Lasers are pumped in several ways. The objective of laser pumping is to selectively excite a large fraction of the atoms to an upper laser level while the rest of the atoms remain in the ground state, e.g., optical pumping is a highly selective mechanism. However, in most gases and plasmas optical pumping from the ground state would require vacuum u.v. radiation. Excitation from an excited state is not practical because most of the atoms are supposed to be in the ground state.

Another mechanism would be to excite a gas like helium with electron collisions (e.g., glow discharge) into a Maxwell-Boltzmann distribution of energy states of other distribution then transfer the excitation energy of one state only (the metastable state) by collisions of the second kind to another gas like neon. The requirement for equal excitation energies for the transferring and receiving state ensures a selective excitation of the neon. However, the excitation of other neon states by the same electrons which excite the helium has to be avoided. This limits the power which can be put into the excitation of helium and thus limits the laser power output of gas discharge lasers.

Nuclear Pumping

In the case of nuclear pumping one would try to keep the lasing gas at a low temperature to ensure that most of the gas atoms are in the ground state. By bombarding with high-energy particles an appreciable fraction of the atoms will be ionized. Depending on the gas pressure, ions thus formed will recombine by either radiative or three-body recombination. The cross sections for recombination increase with the main quantum number (excitation energy). Therefore it is expected that highly excited atoms will be preferentially formed. The upper levels of possible transitions will be overpopulated in respect to the lower levels.

In the case of an ion laser, one has to heat the gas to an appreciable temperature in order to form sufficient ion density by equilibrium ionization. Excitation of the ions will occur by interaction with energetic nuclear reaction products. The lower states will be emptied by the recombination of the ions into the atomic states.

Other nuclear pumping mechanisms are described in Ref. 29. In this reference it is supposed that from energetic nuclear particles interaction with the laser gas, an electron energy distribution results which differs from that of electrical excitation. While the latter is Maxwellian with a peak at about a few ev, depending on favorable laser gas pressure, the nuclear induced distribution shows the majority of electrons thermal at about 1 ev, or less, while a small fraction exists with a mean energy above 16 ev. Obviously, such an electron energy distribution would favor population inversion.

In general, nuclear pumping is expected to involve not necessarily the same gas or gas mixtures than other pumping mechanisms nor may it result necessarily in the same spectra of excitation.

Heavy Particles Interactions

Much information about the interactions of energetic heavy particles with gases is available from previous research on radiation effects in the upper atmosphere, on the physics of nuclear detectors, from investigation of using nuclear reactions for ionization enhancement in plasma devices[30–33] and on radiation induced luminescence.[34–38]

Because of the vast difference of energies of lasing atoms (fraction of ev) and fission fragment (about 100 Mev), the energy of the fission fragments can be considered monochromatic in comparison with the energy of the atoms. This results in a selective energy transfer.

If an energetic heavy particle (such as a fission fragment) hits an atom, this atom will be either ionized or excited. Reference 39 gives a simple expression for the average energy W required to form an ion pair;

$$W = \bar{E}_i + (N_x/N_i)\bar{E}_x + \bar{\varepsilon} \qquad (1)$$

In Refs. 40 and 41 this expression is modified for fission fragments and verified experimentally. According to this work: $\bar{E}_i \simeq 1.06\ V_i$ (V_i = ionization potential of the atom); $\bar{E}_x \simeq 0.85\ V_i$ (average energy expended to excite the atoms); $\bar{\varepsilon} \simeq 0.31\ V_i$ (average kinetic energy of the subexcitation electrons). The number of atoms excited (N_x) is related to the number of atoms ionized (N_i) by

$$N_x \simeq 0.53\ N_i \qquad (2)$$

All numbers apply to noble gases only. The equipartition of ionized and excited state represents a substantial deviation from the Maxwell-Boltzmann distribution which would result from an equilibrium deposition of the kinetic energy of the fission fragments.

Radiative transitions used for laser action are a part of processes which tend to equilibriate the system. For sustained population inversion, the lower levels have to be depleted. For high-power systems high gas flow rates are required because the rate of diffusion to the wall will not be sufficient.

Ionization and excitation rates of fission fragments, α-particles and protons in gases of interest for possible laser applications were investigated in Refs. 42–47.

For effective nuclear pumping of gas lasers, a large fraction of the kinetic energy of the nuclear particles must be absorbed in the gas. Previous research on ionization chambers has resulted in data for high-pressure gases (about atmospheric), in which the stopping distance was found to be in the order of centimeters.[40] However at low gas pressure, which was considered more favorable for laser actions, the stopping distance may far exceed the laser tube dimensions. In that case much of the nuclear energy is lost to the walls. Particular investigations have been carried out on the stopping distance in laser gas combinations.[48–51] Tradeoffs resulting from compromising the adverse effects on lasing and the beneficial effects in regard to a greater utilization of the kinetic energy of the nuclear particles at higher pressures have been investigated in Ref. 29.

In Ref. 52, it is suggested that a fair utilization of available kinetic energy can be achieved. In case of a volume source (see Fig. 1B) the energy utilization increases with the square of the pressure because a higher density of nuclear particle source, He^3 $(n, p)T$, and a smaller stopping distance results. In case of area sources (see Fig. 1A) the energy utilization increases linearly with pressure.

Energetic reaction particles such as fission fragments and α-particles which are produced in the fuel coatings of the laser tubes in schemes according to Fig. 1A have to traverse part of the solid fuel material. Detailed investigations on the energy distribution of particles that leave the fuel region and penetrate into the gas have been carried out in Refs. 53 and 54. Roughly a quarter of the produced reaction products penetrate into the gas carrying three-quarters of the initial energy (based on an "infinitely" thick fuel layer, that is, a layer of the thickness of the stopping distance in the solid material).

Calculation of Threshold Densities and Pumping Power

Determination of laser action can be done when a certain set of conditions such as gas mixtures and total pressure has been selected. The analysis involves the solution of rate equations for all possible processes. However, in practical computations one usually tries to identify dominant processes which are then used only, in order to keep the mathematics manageable. The objective is to compute the number density of atoms excited to the upper and lower laser level.

Based on data discussed in the previous sections, threshold calculations have been carried out by various authors[27,29,54–56] particularly as related to Concept A. They have included as a critical parameter the neutron flux density necessary for a sufficiently large number of reactions in the fuel sleeve. It was determined that neutron flux densities of the order of 10^{14}–10^{17} neutrons/cm^2 sec were required depending on the gas laser density and composition.

Reference 55 presents a theoretical analysis of a slightly ionized argon system according to Concept A. The temperature is assumed not to exceed 2000°K. Relevant rate equations are solved simultaneously on a computer. In the analysis not only excitation due to energetic nuclear reaction particles is considered, but also excitation due to recombination of thermal electrons and the associated radiative and collisional decay of such states. Results show that both thermal recombining electrons and direct excitation from high energy particles are important in the formation of population inversion. One inversion ($5s$–$4p$ transition) is formed principally by the process of direct excitation by high-energy particles and another inversion ($4d$–$5p$ transition) is formed indirectly by the recombination of thermal electrons. The gain of the latter transition is an order of magnitude larger than that of the former one. But this is found to depend on the density, as shown in Fig. 7 (Ref. 55). The figure suggests that at higher densities (which are desirable for nuclear pumping) direct excitation may become dominant. However, such a prediction is made with caution because the effect of increased dissociative recombination at large densities are not yet known to a sufficient degree of accuracy.

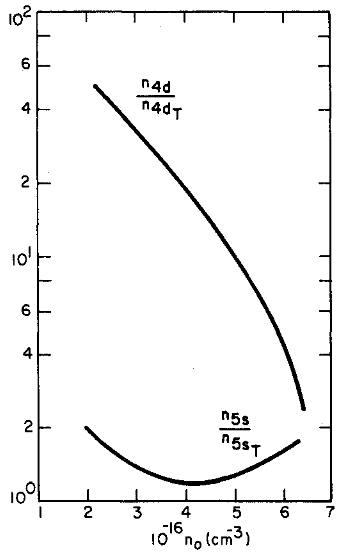

Fig. 7 Threshold population ratios as a function of the atomic density for a neutron flux rate of 2.54 × 10^{14} cm^{-2} sec^{-1}.

Experiments

To show feasibility of nuclear pumping, several experiments have been undertaken.[27,56–70] None of these experiments demonstrated lasing action by nuclear pumping unambiguously. Some of the experiments showed enhancement of the laser output caused by interaction of heavy particles with the plasma. The results of the experiments are summarized in Table 1.

Table 1 Nuclear pumped laser experiments.

Institution	Heavy particles source	Results
Argonne National Lab. Ref. 65	B-10 coating on laser tube Gas: CO_2:N_2:He 1:1.3:11 14 torr no flow	Electrical power necessary to attain threshold decreased as flux was increased to 5 × 10^8 n cm^{-2} sec^{-1} and then increased to greater than the "no flux" level.
Moscow State Univ. Ref. 27	Particle beam of 3 Mev protons (20 w) Gas: CO_2:N_2:He^3 10 torr w/flow	No lasing with proton beam alone; the power consumed by the discharge from the power source decreases the generation power increases. 2–3 power increase.
Ref. 74	He^3 $(n, p)T$ reaction Gas: Hg + He^3	Observed radiation (λ = 6150 Å) ~ 10 mw found to be much higher than expected spontaneous emission.
Northrop Corporate Labs. Ref. 75	B-10 coating Gas: Ne–O_2 10–300 torr Ar, Ne, Kr, X } O_2–HE	Luminosity inside the test section was measured. Emission around known laser transitions was favored and appeared to require a threshold reactor power. Peak intensity did not necessarily correspond to reactor power peak.
Univ. of Illinois Refs. 66, 67, and 68	B-10 coating Gas: He–Ne 9:1	Possible gain at 1.15 μ and 3.39 μ ≤ 4 × 10^{-4} cm^{-1} in He–Ne (9:1) at pressures 5–100 torr.
	No gas flow	Observed reference laser beam passing through gain cell for possible amplification due to neutron pulse.
Ref. 75	He–Ne 9:1 163 torr	Showed abnormally large absorption rather than gain. With air addition at low partial pressure a 15% gain was measured.
Univ. of Florida and Nasa Langley Refs. 56, 69, and 70	He^3 $(n, p)T$ 10 torr Vol. source CO_2:N_2:He^3 BCL_3	Enhancement of laser output (by a factor of 2) was observed. Increase in efficiency larger than factor of 2.

Schemes of Concepts A and B have been investigated. In each of the schemes thermal neutron fluxes were needed to cause nuclear reaction in either the thin film coating (Concept A) or the reactive admixture to the lasing gas (Concept B). Such neutron fluxes were obtained from nuclear reactors. Figure 8 shows the enhancement of laser output power during neutron irradiation.[69,70] The gain obtained at moderate reactor fluxes was as high as twofold. It could be misleading to relate the laser output power to the power of the reactor, because most of the fission energy resides in the reactor fission fragments and is dissipated in the solid fuel rods. In all experiments (A and B concepts) only thermal neutrons of reactor were used. However, in a Concept C scheme the reactor fission fragments would be used for nuclear pumping, constituting a fundamentally different efficiency relation between reactor power and laser output power.

Experimental difficulties were found to be larger than expected. Radiation damage of the mirrors, the requirement of remote alignment and operation, the difficulty of using optical detection

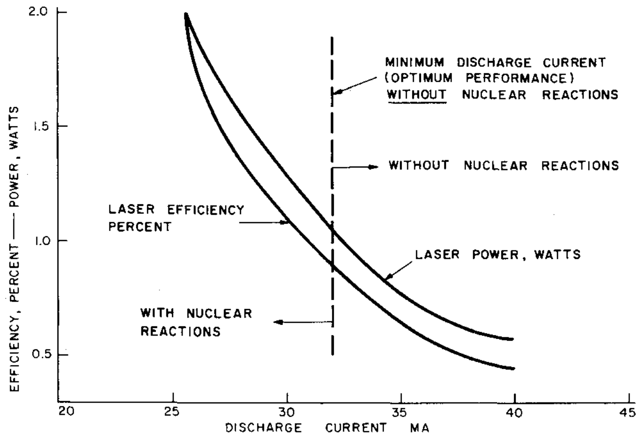

Fig. 8 Effect of nuclear radiation on CO_2 laser.

in a high γ and neutron flux environment, and the compliance with safety regulations are only a few of the host of experimental problems.

This amounts to the development of a new technology of experimentation with in-core plasmas. In this respect the cited experiments represent significant progress.

Most devices were gas discharge lasers with gas mixtures which have previously shown laser action. Since, as pointed out before, the nuclear pumping mechanism is different from other pumping mechanisms, the selected gas mixtures might not have been the optimum choice for nuclear pumping. However, it was reasonable to try known laser mixtures first before trying to guess which mixture may be good for nuclear pumping.

Potential Applications

Nuclear pumped lasers are too far from a practical realization to predict details of possible applications. However, possible areas of application can be envisioned. These areas are 1) long range communication: high power and possibly high frequency (the sensitivity of detectors increases with frequency, for instance, the shift from infrared to visible light results in a tenfold increase in sensitivity, also reduced beam spreading at higher frequencies results); 2) power transmission: power for space probes or satellites from power stations on Earth, near-Earth orbit, or on the moon; 3) photochemistry: for large-scale production of chemical compounds; 4) Smog dispersal: by vaporizing the liquid droplets; 5) area illumination: to illuminate whole cities, possibly from a synchronous orbit; 6) source for high-temperature heat for remote melting of materials, for instance, of ores on the moon; 7) finally, if Concept C can be realized, it may be one of the possible means of extracting power from a plasma core nuclear reactor.

Conclusions and Recommendation

Nuclear pumping of gas lasers has not yet been demonstrated unambiguously. Observations of gain in Concept A laser arrangement involving He–Ne are reported in Refs. 67 and 75, within the limits of experimental error. Experiments have been conducted in which nuclear excitation was to augment conventional pumping methods. In a Concept A configuration, the power for electrical pumping was significantly reduced by nuclear interactions. In a Concept B configuration, electrically pumped (CO_2–He^3–N_2) laser yielded an increased power output when exposed to neutron flux (factor of two and more).[69,70]

In a Concept B experiment in which energetic particles from volume reactions were simulated by a fast proton beam, a drastic increase of power output was observed. This indicates that increasing the gas density and the neutron flux in those experiments which were reported in this paper will lead to larger output powers. In Ref. 74, pulsed light output ($\sim$10 mw) which is believed to be laser radiation was observed in a Concept B experiment.

It appears therefore that nuclear pumped lasers are feasible particularly when high power densities can be applied and efficiently utilized. Significant results of previous research is that nuclear pumping is characteristically different from other pumping methods. Therefore gas mixtures which have exhibited lasing in gas discharge lasers are not necessarily the optimum ones for nuclear pumping. Further research may utilize computer techniques for solving the rate equations and for parametric studies, thus determining optimum gas mixture.

In experiments gain measurements in various in-core plasmas should be carried out for correlation with theoretical data.

Basic investigations appear to be advantageous in view of the enormous experimental difficulties of carrying out go–no go experiments in the environment of nuclear reactors.

It appears to us that a Concept C nuclear pumped laser system is an ultimate goal of nuclear pumped laser research because of the direct conversion of the reactor fission energy into light.

Basic research on the optical properties of uranium plasmas and its nonequilibrium states is mandatory. Plasma dynamic effects may be utilized to control nonequilibria leading to ways to produce and maintain population inversion.

Such a Concept C nuclear pumped laser system is essentially a plasma core reactor. The aforementioned required research also supports other currently conducted investigations on plasma core reactors for space propulsion. The possibility of lasing offers additional means of power extraction in the form of direct energy.

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