A Proposed Continuous Wave 585.4-nm ^{4}He/Ne/H_2 Gas Laser Mixture Pumped by α-emitter Radioisotope

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The feasibility of generating a cw 585.4 nm yellow laser in a ^{4}He/Ne/H_2 gas mixture with α-emitter radioisotope is analyzed in this paper. A conventional energy storage system was introduced to extend the lifetime of the laser device. It was found that ~70% of the energy loss (due to continuous emission of α particles) could be recycled to compensate the deficit of the input power declined due to the half-life of the radioisotopes.

I. Introduction

The first use of radioisotope for power generation was launched in 1959[1]. It was in the SNAP-3 program (by NASA) which used polonium-210 as fuel and produced 2.5 W of electricity to power satellites and moon probes. The principle of converting heat to electricity, as the above example, is well known and developed for many fossil and fissile fuel systems.

The objective of this paper is to propose our newly developed nuclear pumped laser system[2], ^{4}He/Ne/H_2 at the wavelength 585.4 nm Ne line, to be pumped with α-emitter radioisotope[1]. The observed threshold power density of this laser is 43 mW/cm^3 pumped with B-10 coated tube (React.1), and this is within the range of the specific input power of some radioisotopes (as will be shown later).

$$^1n_0 + {}^{10}B_5 \rightarrow {}^4He_2^{2+}(1.4\text{MeV}) + {}^7Li_3(0.82\ \text{MeV}) \quad (1)$$

The second motivated reason is the fact that this laser was pumped with alpha particles from ^{10}B nuclear reaction and this experience can be applied directly to generate the 585.4 nm laser with α-emitter radioisotope.

The use of α-emitter radioisotope as a single laser generator was not reported by any laboratory because of its low specific input power (< 600 mW/cm^3). However, Po-210 was used[3] as a secondary source to generate 540.1 nm and 585.4 nm Ne lines in the electric-discharge Ar/He/Ne/H_2 gas mixture. The Feasibility of generating a c.w laser with α-emitter radioisotopes as single source has been thought[4] for low-threshold laser systems. Fewer nuclear pumped laser (NPL) systems were proposed at that time: ^{3}He-Ne at the wavelength 632.8 nm [5], and Ar-Xe at the wavelength 2.03 μm [6]. The observed threshold (critical) power density for both systems were reported less than 5 mW/cm^3 and between 20-100 mW/cm^3 [7], respectively. The first laser was pumped with steady state nuclear reactor, React. 2, and the latter was pumped with pulsed nuclear reactor, React. 3:

$$^1n_0 + {}^3He_2 \rightarrow {}^1P_1 + {}^3T_1 + 0.76\ \text{MeV} \quad (2)$$

$$^1n_0 + {}^{235}U_{92} \rightarrow (ff_I)^{20+}(95\text{MeV}) + (ff_h)^{22+}(67\text{MeV}) + \text{fast neutrons} \quad (3)$$

[1] Patent Number: PI 95024/S5 05/12/95.

where the symbols ff_I and ff_h in React. 3 stand for light and heavy fission fragments respectively. Regardless the doubts that have been raised[8] about the first laser system, it was not feasible to duplicate the ^{3}He-Ne, 632.8 nm c.w laser experiment by other laboratories with the above low critical power density. On the other hand, the experimental results of the Ar-Xe, 2.03 μm (pumped with fission fragments) do not simulate the same behavior of the above system pumped with α-particles sources such as ^{10}B and ^{210}Po.

The energy deposition mechanisms by the fission fragments particles and α particles are different: the charges, the energies, and the masses are not the same. Even though the fission fragments have a velocity comparable with a 2-MeV α particle, the theory of ionization losses is not valid[9]. The slowing down mechanism of the highly charged fission fragments is based on capture atomic electrons. In this process, the captured electrons will have a maximum energy determined by the ionization energy of the orbital energy state of the fission fragments. As the particle velocity is reduced it will capture more atomic electrons, reducing its net ionic charge and consequently its energy losses by ionization and excitation. On the other hand, the slowing down mechanism of α particles (at high and low energy) is mainly due to the inelastic collision with atomic electrons. In this case the maximum energy transfer to the ejected electrons is much higher than that by the fission fragments because of the conservation of momentum. The maximum energy transfer to the ejected electrons is ~ 0.05 % of the α particle energy. These energetic secondary electrons ($\sim$ KeV) cause a secondary ionization (i.e. plasma) faster than that produced by the fission fragments (ff) because of conservation of momentum. Thus, it is concluded that the energy deposition mechanisms from both ff and α particles are different and, consequently, the threshold power density will be observed differently.

II. Radioisotope for laser generation

If the purpose of producing electricity is to get incoherent light or laser, then direct conversion of the kinetic energy from fossil or fissile material into potential energy (e.g. fluorescence) is the most efficient cycle. When an isotope is unstable, it decays and emits radiation. The radiation emitted is of three types: alpha, beta, and gamma. Of our interest, here, is the type that emits alpha radiation. The choices of alpha emitter radioisotopes will be based on the half-life and the specific driven power (W/gm) which must be sufficient to drive the laser, i.e. the power must be greater than the threshold power for laser generation. A compromise must be made here between these two factors. A radioisotope of longer half-life has a lower specific power, and vice versa. Several radioisotopes is presented in Table I as candidates for laser generator.

Table I - Possible radionuclides type alpha emitter used to laser pumped. Power driven (W/gm)

Radionuclide	Symbol	Lifetime	Some alpha Energy (MeV)	Specific Power driven (W/gm)
Fermium	Fm-257	100 d	6.518; ...	~196.0
Californium	Cf-252	2.638 a	6,118; 6.076;...	~19.6
	Cf-248	334 d	6.26; 6.218;	~57.8
Curium	Cm-242	162.8 d	6.10; 6.00;....	121.0
Plutonium	Pu-238	87.7 a	5.49; 5.456;...	0. 58
	Pu-236	2.87 a	5.77; 5.721; ...	18.0
Neptunium	Np-235	1.08 a	5.02; 5.00; ...	~17.4
Thorium	Th-228	1.9 a	5.423; 5.34; ...	~105
Polonium	Po-210	138 d	5.30; ...	140.0
	Po-208	2.89 a	5.10; ...	~18.0

Plutonium-238 emits α-particles (E = 5.49 MeV) with half-lifetime of 86 years, and the specific power is 0.58 W/gm. Plutonium-236 emits α-particles (E = 5.77 MeV) with a half-lifetime of 2.85 years and the specific power of 18 W/gm. Curium-242 emits α-particles (E = 6.2 MeV). Its half-life is 163 days and the specific power density is 121 W/gm. The natural disintegrations of Cu-242, Pu-238, and Pu-236 are presented below.

$$\text{Cm-242} \xrightarrow[162.8\text{d}]{\alpha\ 6.10,6.0} \text{Pu-238} \xrightarrow[87.7\text{a}]{\alpha\ 5.49,5.45} \text{U-234 stable}$$

$$\text{Pu-236} \xrightarrow[2.87\text{a}]{\alpha\ 5.77,5.72} \text{U-232} \xrightarrow[70\text{a}]{\alpha} \text{etc}$$

Polonium-210 emits α-particles (E = 5.3 MeV), the half-life is 139 days, and the specific power density is 140 W/gm. The Po-210 is the most likely the better choice among these radioisotopes because of its high input power and availability. Po-210 and Th-228 are present in natural radioactive decay chains, which ends in stable elements, Pb-206 and Pb-208 respectively. In particular, Th-228 has a long chain of disintegration, including many radionuclides alpha and beta emitter which due to the short half-lifes make a large contribution to the specific power driven. Natural radioactive decay chains of Th-228 and Po-210 are presented below.

$$\text{Th-232} \xrightarrow[1.4\ 10^{10}\ \text{a}]{\alpha} \text{Ra-228} \xrightarrow[5.7\text{a}]{\beta^-} \text{Ac-228} \xrightarrow[6\text{h}]{\beta^-} \boxed{\text{Th228}}$$

$$\boxed{\text{Th-228}} \xrightarrow[1.9\ \text{a}]{\alpha\ 5.42,5.34} \text{Ra-224} \xrightarrow[3.6\text{d}]{\alpha\ 5.68,5.44} \text{Rn220} \xrightarrow[55.6\ \text{s}]{\alpha\ 6.28,...} \text{Po216} \xrightarrow{\alpha\ 6.77,....} \text{Pb-212}$$

$$\text{Pb-212} \xrightarrow[10.6\text{h}]{\beta^-\ .331,.569} \text{Bi-212} \xrightarrow[1\text{h}]{\beta^-\ 2.25} \text{Po-212} \xrightarrow[\mu\ \text{s}]{\alpha\ 8.78,...} \boxed{\text{Pb-208}}\ \text{stable}$$

or

$$\text{Bi-212} \xrightarrow[1.0\text{h}]{\alpha\ 6.0,...} \text{Ti-208} \xrightarrow[3\ \text{m}]{\beta^-\ 1.7,...} \boxed{\text{Pb-208}}\ \text{stable}$$

$$\text{U-238} \xrightarrow[4.5\ 10^{9}\ \text{a}]{\alpha} \text{....etc ...} \longrightarrow \boxed{\text{Po-210}} \xrightarrow[138\text{d}]{\gamma,\alpha\ 5.3,...} \boxed{\text{Pb-206}}\ \text{stable}$$

Separation of a radium ore (Ra-228) from the thorium mines, following a period superior to the life time of Ra-228, can be the first step to obtain Th-228, which will be presented in the radium ore. The second step follows separating Thorium (Th-228) from radium ore (Ra-228). Due to the long life time of Th-232, it is expected few amount of mass of Th-228.

III. ^{4}He/Ne/H_2, 585.4 nm Laser Driven by Po-210 Coated Tube

The boron-10 coated tube, with 0.2 mg/cm^2 optimum density thickness in the Al coating layer is an α emission source (React. 1), which is similar to an α-emitter radioisotope such as Po-210. Both sources generate particles at energies 1.7 MeV and 5.3 MeV, respectively. The input power density from B-10, React. 1, is close to 15 W/cm^3 at thermal neutron flux $\sim 2.5 \times 10^{15}$ n/cm^{2}sec at 1.5 cm tube diameter. The ^{210}Po radioisotope is chosen here because of its availability, low cost, and the high input power compared to other radioisotopes. The optimum density thickness is 6.5 mg/cm^2, and this thickness is 1/2 of the mean free path of the α particle in the aluminum layer. The input power density for 1.5 cm tube diameter (^{210}Po-coated tube) is $\sim$ 600 mW/cm^3.

The lifetime of Po-210 as an energy source can be found directly[10] by

$$A/A_0 = (1/2^n) \tag{4}$$

where A, A_0, n are the activity after one year, initial activity, and the number of half-lifes in one year respectively. Thus the number of half-lifes in one year is 2.62, and the activity will reach 16% of its initial value. That is the power density will be $\sim$95 mW/cm^3 after one year. Since the radioisotope is a continuous source of emission, the energy storage becomes a crucial issue. It may require the introduction of a system involving energy storage, e.g. via O_2 ($^1\Delta$) techniques[11]. This energy storage technique with radioactive lifetime $\sim$ 45 minutes is limited to infrared transition (1.31 μm). A conventional energy storage technique can be used to store up to 70% of the energy loss (i.e. for the time that the laser is not in operation).

The nuclear pumped ^{4}He/Ne/H_2, 585.4 nm laser is a better candidate to be generated with Po-210 coated tube than other laser systems. This laser system (see the details in Refs. 2 & 12) was first generated with He-3 nuclear reaction, and the threshold power density was found $\sim$ 0.5 W/cm^3. This result motivated the authors to generate this laser with B-10 coated tube nuclear reaction. The results were successfully, the optimum threshold power density, in this case, was found to be 43 mW/cm^3. Corresponding to optimum gas mixture ratio, ^{4}He/Ne/H_2, 2.7/5.6/1.7 and 990 torr total pressure. In this case, He-4 was used as a buffer gas, i.e. a gas of high ionization energy.

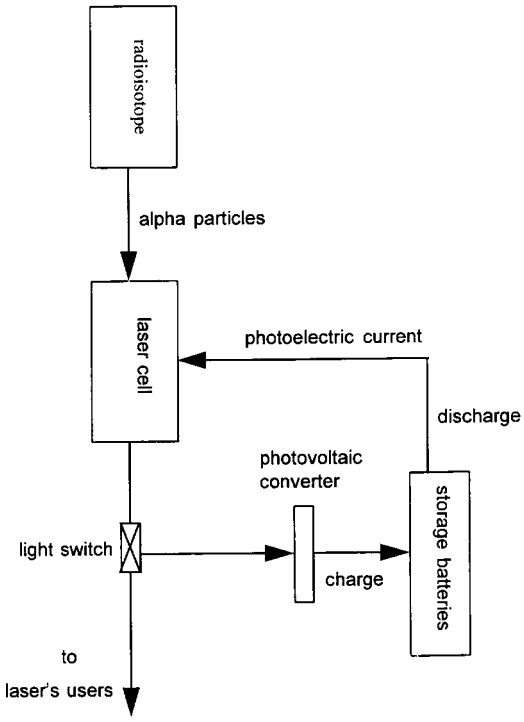

Figure 1. A proposed energy feed back for radioisotope laser generator.

For when the laser is not on use, this energy can be saved by passing the laser beam into a photovoltaic converter placed inside the device, as shown in Fig. 1. The produced photocurrent will be stored in a special storage battery. This battery will eventually discharges the laser gases in the beryllia tube. For maximum energy conversion the photon energy (quantum) must be lower than the bandgap E_g of the photovoltaic converter. The cutoff wavelength λ_c is [13]

$$\lambda_c(nm) = 1240/E_g(eV) \tag{5}$$

The conversion efficiency can reach to 70% [13] for bandgap energy 2.5 eV at the wavelength 500 nm. Aluminum arsenide, AlAs semiconductor, has bandgap en-

ergy 2.16 eV close to the quantum energy of the 585.4 nm (2.118 eV) can be used as a photovoltaic converter for the current laser with maximum possible conversion efficiency $\sim$ 70%.

In the storage battery, the cells (electrodes) can be connected either in series or in parallel. The series batteries configuration has larger storage capacity in the minimum volume available[14]. Fig. 2 shows the main components of the radioisotope pumped laser device. The discharge tube is filled with $^4He/Ne/H_2$ mixture ratio 2.7/5.6/1.7 at a pressure of 990 torr (optimum pressure). The discharge tube is cooled by the circulation of water. Beryllia is selectively chosen for the discharge tube because it has a higher thermal conductivity than silica[15].

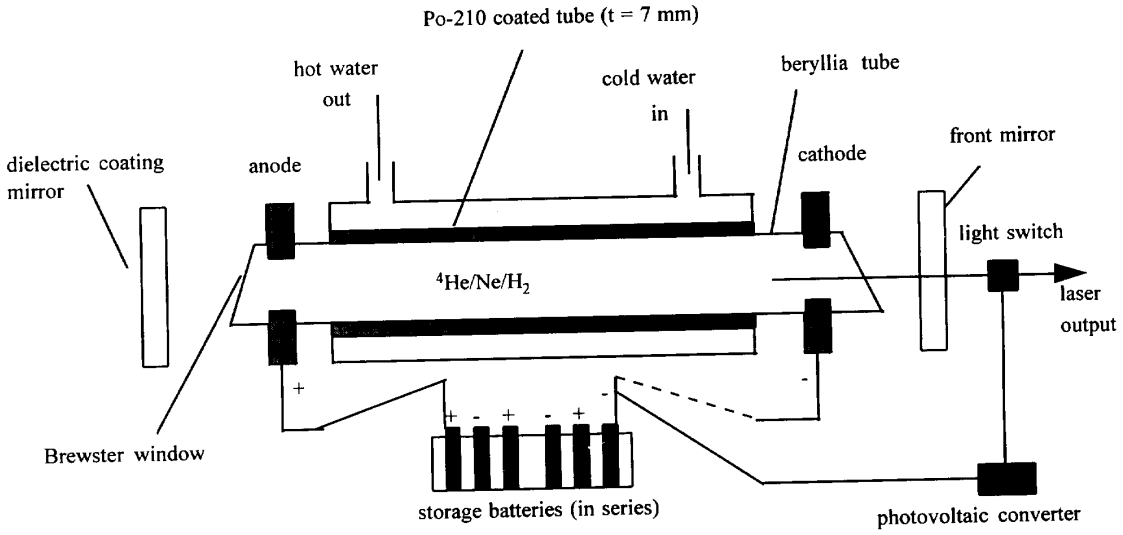

Figure 2. The main components of the radioisotope laser generator.

IV. Conclusion

The feasibility of generating a cw 585.4 nm yellow laser with Po-210 coated tube is very promising. The low threshold power density 43 mW/cm^3 of this laser system is much lower than the maximum input power by Po-210 $\sim$ 600 mWcm^3. The B-10 coated tube which was used to generate the 585.4 nm yellow laser, simulates the energy mechanisms of Po-210, since α particles are the main energy carriers in both cases. Also, a conventional energy storage system was introduced to the laser generator that would save up to 70% of the energy loss which increases the lifetime of the laser device beyond the half-life of the radioisotope.

The present laser system opens a channel to test different types of alpha emitters, listed in Table I. There is a possibility of testing also mixtures of radionuclides, including alpha emitter from waste fuel obtained by nuclear reprocessing or by natural decay chains. In this case, contaminants elements can play a role in the gas systems.

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