Ideal Kinetics Study of The 585.4-nm He/Ne/H_2 Nuclear Pumped Laser

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The use of hydrogen as an admixture gas in the $(^3He)^4He$-Ne laser at the $2P_1$-$1S_2$, 585.4-nm Ne transition has been found to be more effective in depopulating the lower excited laser state, $1S_2$, than the use of heavy inert (noble) gases. A general kinetic model was developed, and it estimates the threshold power density to be 40 mW/cm^3 and the laser efficiency to be 18%. The predicted laser parameters were compared with those achieved experimentally by the authors with using the University of Illionis (at Urbana-Champaign) advanced TRIGA reactor.

I. Introduction

Almost 25 years have passed in nuclear-pumped laser (NPL) research[1], and the results from visible lasers are still not satisfactory for advanced applications. One reason for this is the high threshold pumping power required for laser generation, greater than 10 W/cm^3, typically requiring very high thermal neutron fluxes exceeding 10^{15} n/cm^2.sec. Prior investigations on NPLs have mainly considered infrared lasers, which are easier to pump than visible ones although several high threshold visible NPL have been reported[2].

Nuclear laser is generated by direct or indirect pumping of nuclear energy. The direct pumping[3] is carried by depositing the energy from both light (I_{ff}) and heavy (h_{ff}) fragments result from nuclear fission reaction:

$$^1n_0 + {}^{235}U_{92} \rightarrow I_{ff}^{20+} \ \ (95 \text{ MeV}) \qquad (1)$$
$$+h_{ff}^{22+} \ \ (67\text{MeV}) + \text{fast neutrons}$$

In this mechanisms, the kinetic energy of the positively charged fission fragments is converted indirectly to potential energy through ionization, and eventually excitation of the lasing gas. For the indirect pumping[4], the thermal neutrons from nuclear reactor are allowed to interact with atoms of high absorption cross section leading to an emission of energetic charged particles:

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

$$^1n_0 + {}^{10}B_5 \rightarrow {}^4He_2^{2+} + {}^7Li_3 + \ 2.73 \text{ MeV} \qquad (3)$$

The kinetic energy of the charged particles is converted indirectly to potential energy through ionization, and eventually excitation of the lasing gas. The main differences between the direct and indirect nuclear pumping are the amount of energy deposition and the medium temperature. While the energy deposition is higher for the first, the medium temperature is observed lower for the latter. High level of temperature causes a negative effect on laser generation.

The purpose of this paper is to estimate the threshold power, laser efficiency, and pumping efficiency for the present system based on our general kinetic model. In addition, several reactions that could contribute in pumping the upper laser level (ULL) are outlined for the present laser system.

II. Prior Kinetics Study of He/Ne/Ar Laser

Detailed kinetic reactions involving the $2P_1$-S_2 neon transitions, in the He/Ne/Ar(Kr) laser system were first studied in the USSR for e-beam pumped and nuclear-pumped plasmas. Batyrbekov et al.[5] estimated from their kinetic model, based on nuclear-pumped plasmas, that the laser efficiency and the threshold pumping power density for the 585.4-nm Ne line is 1.1% and 8.7 W/cm^3 respectively (corresponding to threshold neutron flux 4×10^{14} n-cm^{-2}-sec^{-1}). However, as they indicated, the calculated values of the laser efficiency and the threshold pumping power density for the 585.4-nm line failed to be achieved experimentally.

Their model is based on solving 150 main kinetic reactions taking place in He-Ne-Ar(Kr) plasma. Of special interest here is that they assumed, the ULL (upper working laser level) is pumped through the dissociate recombination reaction, and the LLL (lower laser level) is quenched through the Penning ionization reaction with argon atoms. The reaction rate constant (in their model) for the Penning ionization reaction:

$$Ne^*(1S_2) + Ar \rightarrow Ar^+ + Ne + e^- \qquad (4)$$

for the LLL is assumed 3×10^{-10} cm^3/sec, which seems to be 30 times higher than $< \sigma v >$ for argon estimated by Hartree theory, 0.93×10^{-11} cm^3/sec. Aleksandrov et al.[6] have obtained similar theoretical results for an e-beam pumped-plasma kinetic model; the laser efficiency is estimated to be 1.1%, and the threshold power to be 12 W/cm^3.

The reaction rate constants, which are the key factors of any kinetic model, suffer from two major problems:

(1) Since many reactions occur at once, the measured rate constants for a single reaction must be unfolded from all the reactions that take place. This make measurements difficult and introduces large uncertainty.

(2) Some rate constants are based on guessing or trail and error; this is because the actual atomic size in the ground and excited states is still undetermined, except in the Hartree theory, which predicts the atom's size in the ground state only.

In conclusion, much work needs to be done to improve the accuracy of rate equations for modeling these and similar gaseous laser systems.

III. The 2P$_1$-1S$_2$, 585.4 nm Ne Line and The Oscillation Problem

The atomic neon transition at 585.4 nm, corresponding to the 2P$_1$-1S$_2$ transition in the Paschen notation (Fig.1), is optically allowed. The excited neon atom in the 2P$_1$ state, the upper laser level, relaxes to the lower laser level, 1S$_2$, in a time period of $\sim 10^{-8}$ sec with 585.4 nm emission. The electron transition from 1S$_2$ to any lower excited states or the ground state is not allowed optically, that is, the transition occurs in a time period from 10^{-3} sec to 10^{-4} sec. Therefore, the 1S$_2$ state represents a metastable state, so lasing between the 2P$_1$ and 1S$_2$ would not be possible unless some technique, such as collision with an additive gas, is used to shorten the 1S$_2$ lifetime.

According to stimulated emission theory, the spontaneously emitted 585.4-nm photon interacts with another neon atom in the excited state 2P$_1$, and if the frequency matches the transition frequency within the uncertainty, equal to $\pm\Delta W$, where ΔW is the atomic line width (either Doppler or collision broadening), then stimulated emission occurs; i.e. a second photon is emitted that is coherent with the incident one.

For lasing, however, the upper state density must exceed the lower state density, corresponding to a population inversion (deviation from thermal equilibrium). Collision de-excitations of the 1S$_2$ state with hetro-type atoms (such as argon, krypton, oxygen, and hydrogen) can depopulate the lower state, potentially leading to inversion. The essential point is to choose an admixture atom that provides quenching of the 1S$_2$ state, without significantly perturbing the 2P$_1$ population, i.e., preserving the effective lifetime of the 2P$_1$ state.

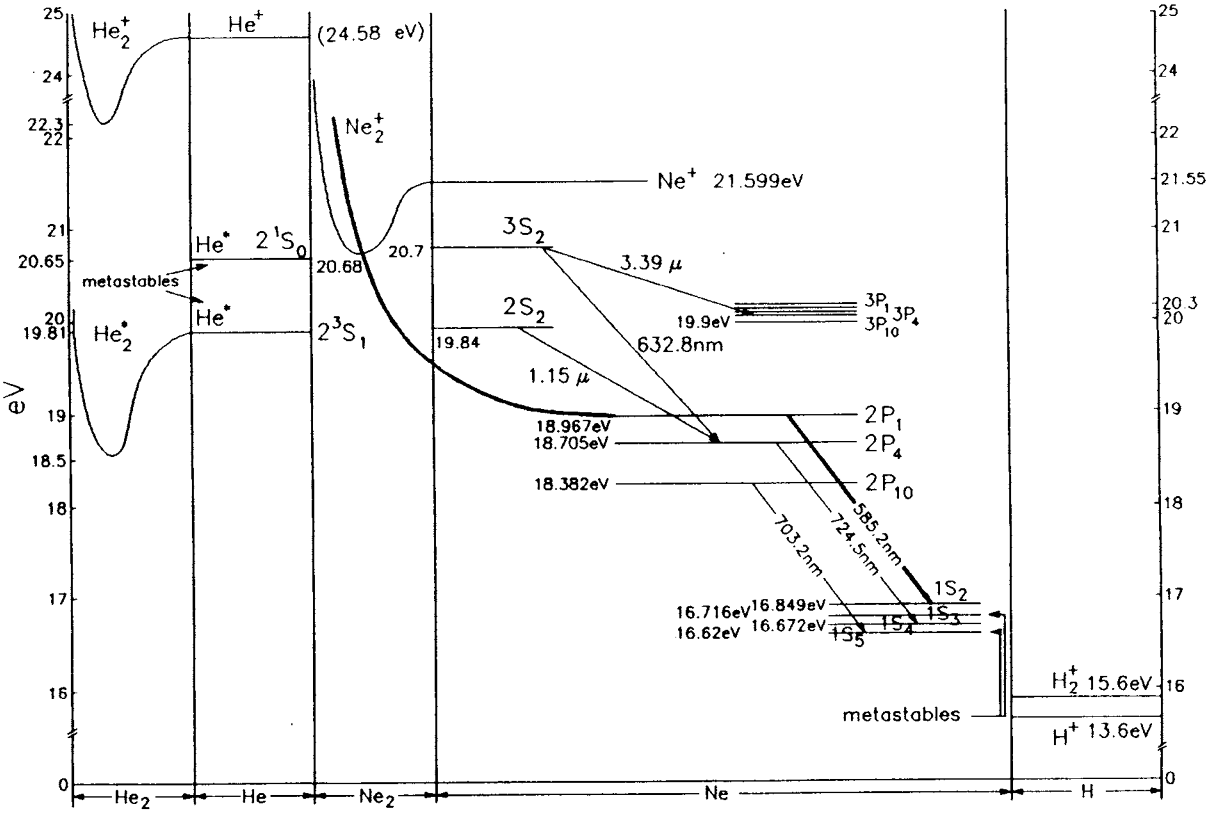

Figure 1. Energy level diagram of He-Ne-H$_2$. The notations used in the text are based on this diagram.

IV. Upper Working Laser Level (2P$_1$) Mechanisms for He/Ne/H$_2$ NPL

Atoms with completely closed shells interact only repulsively with other atoms, so the rare gas atoms do not form chemically stable diatomic molecules. A neon atom in a ground state can interact attractively with a positive neon ion Ne$^+$ to form a stable Ne$_2^+$ homonuclear molecular ion. However, a neon atom in the ground state could interact repulsively with a positive ion Ne through an electron transfer reaction. Therefore, the production rate of Ne$_2^+$ molecules depends on whatever rate is favorable. The above scenario works for all rare gases. The production of homo-nuclear molecular ions Ne$_2^+$ and He$_2^+$ plays an important role in the kinetics of the 2P$_1$-1S$_2$ transition. The dissociate recombination (Reactions 5 and 6) lead to either positive or negative influences on the emission of the 585.4-nm Ne line.

$$Ne_2^+ + e^- \rightarrow Ne^* + Ne \qquad (5)$$

$$Ne_2^+ + e^- \rightarrow Ne + Ne \qquad (6)$$

Depending on the electron energy, the destruction of the neon ion dimers can lead to an excited neon atom in the ULL (Reaction 5); otherwise the destruction will not lead to a desired excited state (Reaction 6). The kinetic energy of the captured electron must satisfy the conservation of energy,

$$E_e = E_j + B.E. - E_e^* \qquad (7)$$

where E_j is the ionization energy of the Ne atom, B.E. is the binding energy (separation energy) of Ne$_2^+$, E_e^* is the kinetic energy of the excited electron in the neon atom, equivalent to the respective energy of excitation of the neon atom. If the neon atom is left in the ground state, the last term in Eq.7 vanishes; this corresponds to Reaction 6. The binding energy (B.E.) of Ne$_2^+$ is weaker than the covalent bond of H$_2^+$, 2.7 eV. The Ne$_2^+$ binding energy (B.E.) is greater than 0.1 eV (the upper limit of the thermal region) and less than 1 eV (the lower limit of the covalent bonds). In any case, it is much smaller than the ionization energy (E_j) of the neon atom, 21.6 eV. It is assumed here that the binding energy (B.E.) of Ne_2^+ is 1 eV. Therefore, for Reaction 5 to occur, the kinetic energy (E_e) of the captured electron must be equal to 22.6 eV. The excitation energy (E_e^*) of the $2P_1$ state is 18.96 eV; therefore, for Reaction 6 to take place the kinetic energy (E_e) of the captured electron must be less than or equal to 3.6 eV and greater than 1 eV.

Other pumping mechanisms that contribute to the upper working laser level ($2P_1$) 585.4-nm Ne line are as follows.

$$He^*(2^1S_0) + Ne(g.s) \rightarrow Ne^*(3S_2) + He(g.s) \quad (8)$$

$$Ne^*(3S_2) \rightarrow Ne^*(2P_1) + h\nu(1.733eV) \quad (9)$$

$$He^*(2^3S_1) + Ne(g.s) \rightarrow Ne^*(2S_2) + He(g.s) \quad (10)$$

$$Ne^*(2S_2) \rightarrow Ne^*(2P_1) + h\nu(0.873eV) \quad (11)$$

$${}^1P_1[E] + Ne(g.s) \rightarrow Ne^*(2P1) + {}^1P_1[E - 18.9eV] \quad (12)$$

Reactions 8, 9, 10, and 11 can potentially contribute to the ULL $Ne^*(2P_1)$ via relaxation, for two reasons. The first is that the excitation energies of $He^*(2^1S_0)$ and $He^*(2^3S_1)$ match the excitation energies of $Ne^*(3S_2)$ and $Ne^*(2S_2)$ respectively. The second reason is that the reaction probabilities are high: 6×10^{-11} cm^3/sec for reaction 8 and 4×10^{-12} cm^3/sec for reaction 10[7]. The direct excitation of neon atoms by protons (Reaction 12) could be significant at high production rate $< \sigma\phi >$, and for protons kinetic energies less than 21.6 eV.

V. Threshold inversion

The He/Ne/H_2 laser experiments were pumped with the University of Illinois TRIGA reactor at high pressures above 1.3 atm[8]. The following analysis will provide a model for high pressure laser system. At high pressure, atomic transitions are characterized by the Lorentzian (i.e., homogenous) line shape. The line width of the Gaussian line shape, i.e. the Doppler broadening $\Delta\omega_d$, is less than the de-phasing frequency, $\Delta\omega_a$, caused by atomic and molecular collisions at high pressure. The Doppler broadening $\Delta\omega_d$ for the 585.4-nm He/Ne/H_2 laser system is 0.85×10^{10} Hz; compared to the de-phasing frequency, $\Delta\omega_a = 2 \times 10^{10}$ Hz, at 1.4 atm total pressure. The threshold inversion $\Delta N_{\rm th}$ for the Lorentzian line shape can be written as[8]:

$$\Delta N_{\rm th} = \frac{2\pi\delta\Delta\omega_a}{3A_{21}I_g\lambda^2} \quad (13)$$

in which, hereafter, δ is the cavity loss, which in the experimental setup[8] is equal to 10%; I_g is length of the cavity, 105 cm; λ, 585.4 nm; A_{21}, 3×10^8 Hz; and $\Delta\omega_a$ is 1.5×10^{10} Hz. Therefore, $\Delta N_{\rm th}$ is found to be 2×10^7 cm^{-3}.

VI. Pumping mechanism

Spontaneous emission at 585.4 nm occurs as a result of direct and/or indirect relaxation to the ULL ($2P_1$). Formation of the homo-nuclear molecular neon ions (Ne_2^+) depends on whether the neon atom in the ground state and the neon ion interact repulsively (electron transfer reaction), Reaction 14, or attractively (Ne_2^+ formation), Reaction 15.

$$Ne^+(\uparrow) + Ne(\uparrow) \rightarrow Ne + Ne^+ \quad (14)$$

$$Ne^+(\uparrow) + Ne(\downarrow) \rightarrow Ne_2^+ \quad (15)$$

Here ($\uparrow$) and ($\downarrow$) represent the electron's spin up and down, respectively. The outermost sub-shell, 1P, of the neon atom in the first ground state has six electrons. P signifies that the total orbital angular-momentum quantum number, I, is unity. The exclusion principle requires these electrons to be paired together, three having spin up and three having spin down. The outermost sub-shell, 1P, of the neon ion (Ne^+) in the first ground state has five electrons. In the case of the ground state (1P), the potential well of Ne^+ is deeper than that of the neon atom, because the binding energy of the second electron must be larger than 21.6 eV. Therefore, the Ne_2^+ formation reaction occurs because the electron from the outermost sub-shell of the neon atom moves to the outermost sub-shell of the Ne^+ ion.

If the electron from the neon atom pairs with one of the five electrons of the outermost sub-shell of the neon ion, no dimer molecule will form. The repulsive reaction, Reaction 14, occurs with probability equal to 2/5, where 2 is the number of possible spin orientations the electron can have, and 5 is the number of electrons in the outermost sub-shell of the neon ion.

In the attractive reaction, the electron from the neon atom again moves to the outermost sub-shell of the neon ion. Because of the different spin eigenfunction, one of the electrons in the neon ion will be loosely bound to the newly formed neon atom and will move toward the newly formed neon ion. The probability η_h that the attractive reaction, Reaction 15, occurs is 3/5.

Based on Fig. 2, the pumping efficiency η_p is defined as:

$$\eta_p = P_i \times \eta_h \times f_e \tag{16}$$

where P_j, is the probability of forming the IET (Internal Energy Transfer) molecule[8] and represents the probability of transferring energy from the lasing atom to the additive atom in the ground state. In the absence of additive atom P_i is unity, otherwise P_i is evaluated according to the atomic structure[8]. In the present case P_i is equal to 1/2.

The probability η_h that the attractive reaction (Ne_2^+ formation) occurs is 3/5. For direct energy conversion system, i.e., the upper working laser level is directly excited from the ground state η_h is unity.

The fraction f_e of energy that goes to the lasing atoms is a function of W value (amount of energy deposited per ion pair) and the atomic percentage of the present constituent:

$$f_e = \frac{X_i W(X_i)}{X_i W(X_i) + Y_{c1} W(Y_{c1}) + Y_{c2} W(Y_{2c})} \tag{17}$$

Where X_i, Y_{c1}, and Y_{c2} are the percentages of the lasing atoms, Ne; and the constituent (additive) atoms, He and H_2; respectively, and W is equal to 36.8, 42.7, and 36.3 eV/ion-pair for Ne, He, and H_2 respectively. For the homo-atomic laser system f_e is unity. At typical operating $^4He/Ne/H_2$ gas mixture ratio[8], 2.7: 5.7: 1.6, the pumping efficiency η_p, of 16% is obtained.

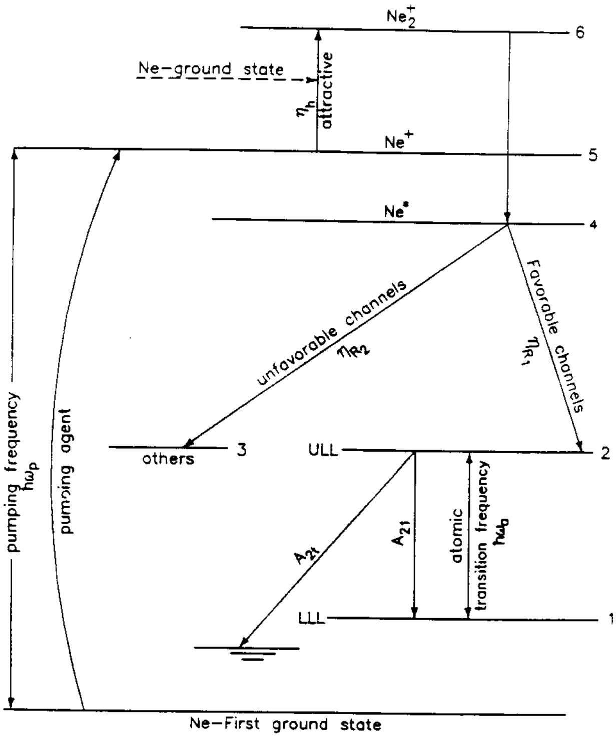

Figure 2. Schematic general pumping mechanism for the present laser system.

VII. Threshold pumping power density

Consider the general pumping scheme, shown in Fig. 2. The charged particles pump the lasing atoms from the ground state to the ionization state, state 5. At state 6, where the formation of Ne_2^+ (neon ion dimers) takes place, relaxation to state 4 will result from dissociate recombination reactions. The excited state, 4, is a general state, meaning that the energy eigenvalue of state 4 varies from zero to that of the ULL (upper laser level), because the dissociate recombination reactions vary from on system to another (it depends on the electron energy).

There will be two channels for electron transitions from state 4. State 3 is assigned for unfavorable transitions, i.e., non laser transitions. State 2 is assigned for favorable transitions, which can occur directly or indirectly (cascading). Conservation of energy and momentum and the selection rules govern electron transitions from one state to another. The unfavorable transitions come from the atomic inelastic collision (attractive reaction), in which there is energy transfer. The inelastic attractive collision can bring about a transition of the excited neon (lasing) atom to the ground state or to any other excited state, depending on the conservation of energy. Once the electron reaches state 2 (ULL), the electron moves either to state 1 (LLL), with desired spontaneous emission, or to another lower excited state, with unwanted spontaneous emission (it depends on the branching ratio, A_{21}/A_{21}) . Electrons move (downward transitions) to excited states at which the total energy is minimum (yielding stability).

For the inversion to occur, the population of the LLL must be negligible compared to that of the ULL. In order to achieve perfect oscillation, the lower laser level must be deactivated within a time on the order of 1×10^{-9} sec, and the deactivator must provide a reaction rate on the order of 1×10^{-9} cm^3/sec. The mean collision time caused by hydrogen (at H_2 pressure 400 torr) is 3.7×10^{-9} sec, which is in the range of perfect oscillation. Therefore the threshold pumping power density can be written, in (W/cm^3), as:

$$D_{\text{th}} = (\Delta N_{\text{th}}/\eta_p)(h/2\pi)A_{2t} \qquad (18)$$

Multiplying Equation (18) by ω_a/ω_a, where ω_a is the atomic transition frequency, equal to $(2\pi c/\lambda)$, yields

$$\begin{aligned} D_{\text{th}} &= (1/3)(2\pi ch)(1/\eta_p)(A_{2t}/A_{21})(\delta/l_g) \times \\ &\times (1/\lambda^3)(\Delta\omega_a)(\omega_p/\omega_a) \qquad (19) \end{aligned}$$

where c and h are the speed of light and Planck's constant respectively; η_p is the pumping efficiency, given by Equation 16. A_{2t}/A_{21}, is the inverse branching ratio; δ and l_g are the external coupling losses (cavity loss) and the cavity length; λ is the laser transition wavelength; $\Delta\omega_a$ is the effective dephasing frequency (atomic line width), where

$$\Delta\omega_a = \Delta\omega_p + \Delta\omega_d + \tau_1\tau_2/(\tau_1 + \tau_2) \qquad (20)$$

Here, $\Delta\omega_p$, $\Delta\omega_d$, τ_1 and τ_2 are the collision frequency, Doppler frequency, the mean lifetime of the lower laser (10^{-4} sec) and upper laser levels (3×10^{-9} sec), respectively. (ω_p/ω_a) is the ratio of the pumping frequency (21.6 eV) and the atomic transition frequency respectively. Substituting the values of the parameters of Equation 19, the predicted threshold pumping power density for the present 585.4-nm ^{3}He(^{4}He)/Ne/H_2 NPL is ~40 mW/cm^3.

Under the same operating conditions, the threshold power density would be $\sim$ 700 mW/cm^3 if Ar were used in the ^{3}He(^{4}He)/Ne NPL system. This higher threshold power is due to the low reaction reactivity: $< (< \sigma v > P_i) >$ which is 56/1000 as low as the reaction reactivity induced by H_2. This is not surprising, because according to Hartree theory[9], the radius of Ar atom in the ground state is 0.66×10^{-8} cm, vs. 0.51×10^{-8} cm the radius of hydrogen atom in the ground state. However, the combined $< \sigma v >$ factors is larger for Ne*-H_2 collision than for Ne*-Ar; 2×10^{-11} cm^3/sec and 0.9×10^{-11} cm^3/sec respectively. In addition, the P_i factor is 1/16 for Ne*-Ar vs. 1/2 for Ne-H_2 collisions.

The threshold pumping power density is strongly dependent on the laser wavelength. Generally, the shorter wavelength transitions require larger energy than the longer ones. It is also shown from Eq.19 that, low pressure laser systems requires lesser pumping energy than the high pressure one, particularly at longer wavelengths transitions. However the increase in gas pressure leads to an increase in population inversion density, and therefore more laser power is extracted outside the laser cavity. Finally, the pumping frequency must be kept within the frequency of the upper laser level to minimize the spontaneous emissions from unwanted transitions.

VIII. Laser efficiency

The laser efficiency[10] can be written as

$$\eta_1 = \eta_q \times \eta_p \times n_E \qquad (21)$$

where η_q, η_E and η_p are the quantum, extraction, and pumping efficiencies respectively. The quantum efficiency can be written as;

$$\eta_q = (E_2 - E_1)/E_2 \qquad (22)$$

where E_2 and E_1 are the energy eigenvalues of the upper and lower excited laser levels respectively. For the 585.4-nm Ne line, $\eta_q = 11\%$. The extraction efficiency, in the present system, is assumed unity, i.e. that the stimulated emission dominates and the LLL is effectively quenched. Therefore the predicted theoretical laser efficiency from Eq. 21 is 1.8%.

It should be mention that the presence of impurities (e.g. N_2) in the He/Ne/H_2 laser systems affects negatively on the pumping efficiency[18]. This effect could be seen from the earlier (1953) study by Jessy and Sadauskis[11]. They showed that impurities added to noble gases will profoundly perturb ionization produced in the noble gases. Such perturbations will reduce W (which represents the amount of energy deposited in the medium) by increasing the ionization potential. This reduction could also be attributed to the large charge transfer cross-section of N_2 ($\sim 1-3 \times 10^{-9}$ cm^3/sec) with He^+, He_2^+, Ne^+, and Ne_2^+. These ion dimers are the channels in pumping the ULL as indicated before.

For selective laser transition, the laser efficiency depends mainly on the pumping efficiency. In order to obtain high laser efficiency, the three parameters given by Eq. 21 must be optimized with respect to laser cavity and gas mixture. In multiatomic laser system, the additive gas is either used as a buffer gas (a gas of high ionization energy) or as a quencher gas (a gas which is used to depopulate the lower excited laser level with higher rate than the upper laser level).

It was found that, for the electronic (visible) laser transitions[8], if the lasing gas is closed-shell atom, the lower laser level is effectively depopulated for when the quencher gas is open-shell atom. In addition, the population of the ULL is lesser effectively perturbed in the H_2 medium than in the Ar medium. The energy required to quench the ULL with hydrogen and argon atoms is 1.4 eV and 0.3 eV, respectively[18]. This is an advantage for hydrogen, particularly, in the partially ionized nuclear pumped-plasma.

To obtain high laser efficiency, direct energy conversion is preferably used since is high. However this type of laser system usually are not for high power purposes. The high power laser systems such as nuclear laser which employ indirect energy conversion suffer from low laser efficiency because of the excess heat deposited in the laser cavity. Heat removal, during lasing action, from the laser cavity can be performed by using open cavity configuration. The third consideration in the multiatomic laser system is, the lasing atoms must be predominant in the gas mixture. This is true if the admixture gas is not purposely used as a buffer gas. In other words, the resonance excitation transfer between the admixture atom and the lasing atom is not a dominant pumping mechanism to the upper laser level. In the buffer-gas laser system, e.g. He-Ne 632.8 nm Ne transition, the pressure of He atoms (buffer) exceeds the pressure of Ne atoms (lasing). In this case the He atoms store most of the deposited energy in their metastable states, and consequently transfer it to the Ne atoms in the ground state.

IX. Maximum laser-power extraction

Conceptually, the laser output power increases with the increase of the amount of energy deposited in the laser gases. This increase is restricted at high input power because of the excess heat inside the closed cavity. The high temperature causes a negative effect on the laser generation. This problem can be resolved by using the gas mixture in a gas-dynamic laser system[12]. A gas-dynamic laser expands a high-pressure mixture of laser gases very rapidly through a supersonic nozzle. During the expansion, the gas is turned into a laser medium. The supersonic laser gas then passes into the laser cavity, where the laser beam is extracted perpendicular to the flow. The pressure and temperature of the laser gas, the size of the nozzle, and the optical design of the laser cavity are designed to optimize the laser performance.

The second issue involved in high power extraction is the cavity configuration. It is suggested to use an unstable resonator which offers maximum coupling efficiency. This can be accomplished by changing either the cavity length or the mirror curvature. The use of tapered mirror (a mirror of which the reflectivity changes with radius) was considered[10] for maximum power extraction. This technique will negatively affects the threshold power, i.e. the threshold power will increase because of cavity losses. A trade-off must made here between a practical laser efficiency and a practical threshold power.

X. Comparison with experimental results

The general kinetic model predicts the laser efficiency to be 1.8% for the 585.4- nm Ne line, which is in good agreement with 1.1% predicted by Batyrbekov et al.[5] and Aleksandrov et al.[6]. The experimental value for the laser efficiency of the ^{4}He-Ne-H_2 laser system was measured[8] to be on the order of 1.3×10^{-2} %. This low efficiency is attributed to fact that the cavity and gas conditions were not optimized for maximum power extraction. The experimental nuclear pumped laser efficiency for He-Ne-Ar on the same wavelength was reported by Sandia National Laboratory (USA) to be less than 10^{-2}%. Thus, there appears to be a real in improving the efficiency of these lasers.

The threshold pump power density predicted, here, is 40 mW/cm^3. The experimental value that was measured[8] in the ^{4}He-Ne-H$_2$ experiments was found to be 43 ± 2mW/cm^3. While the Soviets' model[5] predicted the threshold power density to be 8.7 W/cm^3, their experimental results and Sandia's results have shown a higher value greater than 120 W/cm^3. It is not understood why the threshold power density is much higher than the value that is predicted in their model[6]. Indeed, the earlier reports from the USSR on the He-Ne-Ar, 585.4 nm Ne line had claimed a lower threshold pump power density of 5 W/cm^3. This motivated R. DeYoung of NASA and his collaborators at University of Illinois at Urbana-Champaign to duplicate the Soviets' experiments, but there were unsuccessful, again observing threshold pump power density in excess of 120 W/cm^3.

XI. Summary and conclusion

The primarily use of hydrogen in the He-Ne 585.4-nm laser is to transfer the excited energy of the neon metastable state 2^1S_2 through the IET reaction. The main pumping mechanisms for the ULL are the dissociate recombination reaction and excitation transfer between the He metastable states 2^1S_0 and 2^3S_1, and neon atoms in the ground state, via relaxation. The general kinetic model assumes that the lower excited laser level is quenched faster than the mean de-excitation (spontaneous) time of the upper excited laser level.

The general kinetic model estimates the laser efficiency to be 1.8%, the pumping efficiency to be 17%, and the threshold pumping power to be 40 mW/cm^3. Indeed the threshold pumping power for the present system was experimentally achieved, 43 mW/cm^3, very close to the calculated value. Although the ideal laser efficiency ($\sim$ 1.8%) was not approached, it is in good agreement with the measured laser efficiency reported from USSR and Sandia Nat. Lab, 0.1% and 0.01%, respectively, for He-Ne-Ar, 585.4 nm NPL. This indicates that there is a serious problem, perhaps a strong sensitivity to impurities, in all of these experiments. This must be considered in the future to improve the efficiency.

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