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Halogen Atom/Metal Trimer CW Laser Engineering Concept Overview

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A halogen atom/metal vapor laser is discussed in terms of cw power and performance. Fluorine and sodium represent surrogates for the halogen and metal species; other combinations are possible. Lasing may occur from a variety of excited electronic states, and operation is expected to be broadly dispersed over the visible and near uv wavelength regions. The device is a low-pressure, supersonic mixing laser that resembles the HF/DF cw laser, e.g., separate plenums are used for the fluorine and sodium vapors, and each plenum feeds a nozzle array. Sodium trimer formation begins in the nozzle and continues inside the laser cavity. The design of this nozzle is particularly important; the concept of controlled condensation is introduced. Downstream of the nozzle bank, the two vapor streams mix, and the F-Na_3 reaction pumps several electronically excited states that have gain in the blue-green region. Estimates are given for power per unit mass flow rate and power per unit nozzle bank cross-sectional area.

Nomenclature

A^*	= throat cross-sectional area
c	= speed of light
f	= mass fraction of polymers
h	= Planck's constant
k	= equilibrium constant
M	= Mach number
$\dot{m}$	= mass flow rate
N_A	= Avogadro's number
P	= laser power
p	= pressure
p_d	= diluent pressure
p_v	= equilibrium vapor pressure
R	= gas constant
s	= degree of supersaturation
T	= temperature
t	= time
W	= molecular weight
γ	= ratio of specific heats
λ	= laser wavelength
ν	= laser frequency

Subscripts

i	= denotes species i
n	= molecule consisting of n atoms
0	= stagnation condition

I. Introduction

PULSED and cw chemically pumped lasers were invented in the 1960s. All currently known lasers of this type operate in the infrared, a prominent example being the HF/DF laser. Despite an intensive effort, the discovery of a chemically pumped visible laser has eluded the research community. However, Cobb et al.[1,2] have recently measured significant small signal gain on electronically excited diatomic sodium vapor. In their experiment, liquid sodium is vaporized in an oven with the vapor escaping through a small orifice into the low-pressure (10^{-5}–10^{-2} Torr) chamber of a gas-beam device. In the early part of the rapid expansion, some of the vapor forms small molecular clusters. This polymerization process terminates in the jet when the density becomes too low for further collisions. A separate stream of monatomic halogen atoms is introduced into the low-pressure chamber. Some of these atoms are entrained in the sodium vapor jet and react with Na_3, which produces an electronically excited dimer, Na_2^*. With this molecule as the upper state, gain is measured on a number of electronic transitions of the dimer.

A configuration is discussed that circumvents the engineering system difficulties associated with a beam-gas device. The configuration should be able to efficiently produce a laser beam, at one or more visible or uv wavelengths, as a result of the pumping reaction

$$Na_3 + X \rightarrow Na_2^* + NaX \tag{1}$$

where X is a halogen atom, such as F, Cl, Br, or I. As in Refs. 1 and 2, we use sodium for the metal vapor, although lithium potassium, rubidium, and cesium are alternative choices.

The observed[1,2] electronic emission spectra stem from a number of Na_2 bands:

$$A^1\Sigma_u^+ - X^1\Sigma_g^+, \qquad B^1\Pi_u - X^1\Sigma_g^+$$

$$C^1\Pi_u - X^1\Sigma_g^+, \qquad C'^1\Sigma_u^+ - X^1\Sigma_g^+$$

A maximum small signal gain[2] is observed in the Na_2 B-X region at 527 nm. This result is consistent with laser oscillations in the optically pumped sodium dimer laser. As shown in Table I of Ref. 3, the sodium dimer laser can operate on many transitions of the B-X band. These transitions range from 510 to as high as 815 nm and depend on the pump laser wavelength. For a chemically pumped laser, a broad range of laser wavelengths is possible in the visible or near uv, due to lasing on a multiplicity of transitions within a band and from more than one electronic band. The actual wavelengths and band systems with gain are, to a first approximation, determined by the particular choice of a metal vapor and halogen atom.

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We consider using separate nozzles for the streams containing the metal vapor and the halogen atoms. The metal vapor and halogen nozzles are quite small and are in close proximity. Many such nozzles would be used; they constitute a nozzle array. A key element is the utilization of a metal vapor nozzle whose configuration would control the amount, cluster size, and location of metal vapor condensation. In particular, it would maximize the sodium trimer formation inside the laser cavity, which is located just downstream of the exit plane of the nozzle array.

The technology being addressed borders on the experiments of Refs. 1 and 2, dimer laser technology,[3,4] and conventional cw chemical laser technology.[5,6] Nevertheless, it differs from these technologies and other recent attempts[7] at producing a short wavelength chemical laser. For example, it differs from dimer laser technology in the way excited Na_2^* is produced, and it differs from conventional chemical lasers in the lasing species and in the laser frequency region.

Section II discusses the halogen and metal vapor delivery systems. Section III provides a preliminary analysis of a sodium vapor nozzle, especially from the viewpoint of the condensation process. Laser cavity processes are discussed in Sec. IV, and Sec. V presents a rough estimate of power per unit mass flow rate and per unit nozzle exit area. The final section summarizes our conclusions.

II. Halogen and Metal Vapor Systems

Halogen System

The halogen species (F, Cl, Br, I) normally exist as diatomic molecules in the vapor phase. They are thermally dissociated into atoms in a plenum that feeds a converging/diverging nozzle array. This dissociation can be done in a variety of ways. In our discussion, fluorine is used as a surrogate for any of the halogens. It can be dissociated by mixing it with a hot carrier gas, such as He, N_2, Ar, . . . , where the carrier gas is preheated by an arc, an electric heater, or an alternate device. Fluorine atoms can also be combustively produced by reacting an excess of F_2 with H_2. For ease in handling, the F_2 can be replaced by NF_3. To improve the mixing properties of the halogen jet in the laser cavity, it may be useful to include in the halogen stream a low molecular weight diluent, such as He.

Fluorine may prove to be the halogen that results in the most efficient laser for several reasons. First, F_2 or NF_3 dissociates at a relatively low temperature (about 1400 K). Second, F atoms are extremely reactive and should have a large reactive cross section with Na_3 and with Na_2, when Na_2 is in the lower laser level. Reactions or collisions with electronically excited Na_2^* are less important because they are less efficient than spontaneous and stimulated emission. Spontaneous emission has a very short lifetime,[1] about five orders of magnitude less than vibrationally excited HF. Finally, diffusional mixing on the microscale is more rapid with low molecular weight constituents, and the F atom has the smallest atomic weight of the halogens. These mixing attributes are known from cw chemical laser technology.[5]

The plenum pressure and nozzle area ratio for the halogen-containing stream is chosen so that the nozzle exit pressure approximately matches that of the metal vapor and to avoid thermal choking in the laser cavity. Thermal choking can occur if an average Mach number becomes unity in the cavity as a result of the overall heat addition process. (Reference 6, p. 532, provides a precise description of thermal choking in a mixing laser.) As will be discussed, the metal vapor stream has a Mach number relatively close to unity at the exit of the nozzle. Since both the halogen and metal vapor streams may contain heat-absorbing diluent, a modest exit Mach number of about 3 for the halogen stream should suffice. The small fluorine nozzles of many HF/DF lasers have achieved or exceeded this exit plane nominal Mach number value.

The physical size of both the halogen and metal vapor nozzles are roughly similar to the small oxidizer and fuel nozzles of an HF/DF laser. This means that both the throat width (measured in the direction parallel to the optical beam) and the throat-to-exit plane distance are small. For example, we anticipate a throat width of about 10^{-2} cm and a throat-to-exit plane length of about 0.3 cm for the halogen nozzles. These dimensions are typical for the fluorine nozzles of an HF/DF laser (Ref. 5, p. 279). As is the case with HF/DF fluorine nozzles, there would be a significant laminar boundary layer at the exit plane.

Metal Vapor System

Sodium is used as the surrogate for alternative metals such as Li, K, or Cs. It has a low melting-point temperature of 371 K.[8] Above this temperature, sodium is a liquid with an increasing vapor pressure given by[8]

$$\log_{10} p_v = 6.354 - \frac{5567}{T} - 0.5 \log_{10} T \tag{2}$$

where p_v is in atmospheres and T is in Kelvin. At temperature levels near the melting-point temperature, the vapor consists of Na atoms. With increasing temperature, Na_2 dimers form in the saturated vapor, in accord with the equilibrium reaction

$$2\mathrm{Na} \rightleftharpoons \mathrm{Na}_2$$

The equilibrium constant k_2 for this process is

$$k_2 = p_2/p_1^2 \tag{3}$$

where p_n is the equilibrium partial pressure, in atmospheres, of the Na_n polymer in the saturated vapor. In terms of temperature, k_2 is given by[9]

$$\log_{10} k_2 = -4.3249 + \frac{4002.3}{T} \tag{4}$$

At a relatively high temperature, the Na_4 tetramer starts to form, in accord with

$$4\mathrm{Na} \rightleftharpoons \mathrm{Na}_4$$

The equilibrium constant for this process is

$$k_4 = p_4/p_1^4 \tag{5}$$

where[9]

$$\log_{10} k_4 = -10.6798 + \frac{9069.4}{T} \tag{6}$$

Under conditions where Na_2 and Na_4 form in the vapor, a detectable amount of trimers has not been observed.[9] Apparently, Na_3 is unstable under equilibrium conditions for the saturated vapor. However, the trimer becomes stable at lower temperatures when the vapor is supersaturated, a nonequilibrium condition.

Based on the foregoing relations, Table 1 shows the vapor pressure and mass fractions f_n of Na_n in the equilibrium saturated vapor. As is evident from this table, there is a substantial mass fraction of dimers at 900 K and above. On the other hand, the mass fraction of tetrameres is still quite small at 1200 K.

Table 1 Vapor pressure of saturated sodium vapor and polymer Na_n mass fractions

T, K	p_v, atm	f_1	f_2	f_4
900	0.0491	0.891	0.109	0.00009
1000	0.194	0.855	0.145	0.00048
1100	0.592	0.818	0.180	0.00182
1200	1.50	0.784	0.211	0.00541
1300	3.27	0.748	0.239	0.0132
1400	6.38	0.713	0.260	0.0274

There are a variety of ways of heating solid or liquid sodium to a temperature of about 1000 K. For instance, liquid sodium can be heated by any convenient high temperature external heat source while it flows through a tube or series of tubes. A second possibility is to use an exothermic reactive process, such as

$$CO + \tfrac{1}{2}O_2 \rightarrow CO_2$$

However, CO, O_2, and CO_2 are reactive with sodium vapor,[10] a principle product being solid Na_2O. We observe that any highly exothermic reactive process that would heat and vaporize the sodium would most likely also react with it. Hence, it appears that the most practical way of providing saturated sodium vapor, with a temperature in the vicinity of 1000 K, would be to externally heat it.

Control of the heating process is important. In an experiment, the amount of heat would be gradually altered while monitoring the laser power or small signal gain. An optimum condition occurs when the power or gain is a maximum. This plenum condition may, or may not, correspond to a saturated metal vapor state. At this time, only the saturated state is amenable to analysis; hence, we use it in the analysis of Sec. III.

A survey of the literature[10-12] shows that most molecules generally react with sodium. There appears to be one notable exception; namely, N_2. (Reactions between N_2 and Na occur if an electric discharge is used.) In addition to the $Na - N_2$ discussion in Ref. 10, this assertion is borne out by the absence of any form of sodium nitride in the JANAF tables[12] or in the extensive nitride discussion in Ref. 11.

Controlled Condensation

Reference 13 is a typical review article dealing with condensation in supersonic nozzles. The flow in the nozzle may consist of a pure vapor, say steam, or a vapor mixed with a noncondensing gas. In either case, the vapor becomes supersaturated as it flows through the nozzle. The degree of supersaturation is conveniently described as

$$s = \frac{p_1}{p_v(T)} \tag{7}$$

where $p_v(T)$ is the equilibrium vapor pressure at temperature T and p_1 is the actual, equilibrium or nonequilibrium, monomer partial pressure at the same temperature. Because of the presence of dimers and tetrameres, s is slightly below unity in the metal vapor plenum. As the vapor flows through a nozzle, both p_1 and p_v decrease. By comparing the p_v and f_1 columns in Table 1, we observe that p_v falls more rapidly than does p_1. As expected, s increases as the metal vapor stream flows through the nozzle. An increasing s value means an increasing level of supersaturation.

In a conventional nozzle, condensation suddenly occurs in the diverging portion of the nozzle, where the flow is supersonic and supersaturated with an s value of about 10. This process results in a condensation shock wave of about 1 cm in thickness.[13] Relatively little condensation or cluster formation occurs in the flow upstream of the shock. At the downstream end of the shock, very little uncondensed vapor remains. At this downstream location, the vapor is primarily in the form of an aerosol; each particle generally contains hundreds of monomer molecules.

The condensation process is altered when a small nozzle is used. [The configuration might be a small minimum length nozzle (MLN),[14] which is typically used in gasdynamic lasers. This configuration is not essential for a controlled condensation process but is convenient in the subsequent discussion.] The rate of cooling, measured by $|DT/dt|$, is much larger for a very small nozzle than for the conventional nozzles discussed in Ref. 13. This increased cooling rate is comparable to that in a gas-beam device and is large because the residence time of the vapor inside the nozzle is quite short.

We can qualitatively evaluate condensation in a relatively small nozzle, and downstream of it, by discussing measurements performed for a uranium enrichment process. Reference 15 describes two experiments using an MLN followed by a long, slightly diverging duct. In both cases, the plenum temperature is room temperature. In the first experiment, SF_6 plus diluent was cooled to 55 K; in the other, UF_6 plus diluent was cooled to 50 K. In each case, the measured absorption spectra show a pure monomer at the exit plane of the nozzle. At these low temperatures, the equilibrium vapor pressure of SF_6 and UF_6 is zero. Thus, the s parameter is effectively infinite at the exit plane. Moreover, absorption spectroscopic measurements also show that condensation occurred quite gradually in the supersonic flow in the long duct downstream of the nozzle. We see that very large s values, without condensation, are possible and that a condensation process can proceed at a modest rate, in contrast to that in a condensation shock wave.

Controlled condensation differs from conventional nozzle technology in two major aspects. First, a very small nozzle, both in throat width and in its throat-to-exit length, is used for the metal vapor stream. Second, the flow entering the nozzle already contains metal vapor dimers. This second aspect is also different from the experiments described in Ref. 15.

We observe that two contrasting phenomena are present. The small scale of a metal vapor nozzle results in a short residence time, which in turn inhibits condensation. On the other hand, the dimers act as condensation centers that should enhance further condensation. At this time, a reliable estimate for s, at the exit plane of the nozzle, for efficient laser operation cannot be made. Because of the presence of dimers, we expect that s should not be too large, e.g., much in excess of 10^2. A value larger than this might result in a substantial number of large polymers. On the other hand, too small a value for s would result in too slow a rate for trimer formation, which is also undesirable. In view of this uncertainty, results of a parametric analysis for the metal vapor nozzle are presented in the next section.

III. Analysis of a Sodium Vapor Nozzle

Calculations are provided to assess nozzle performance. The gas in the plenum is saturated sodium vapor consisting of monomers, dimers, and tetrameres in accord with Table 1. The model considers the three cases of no diluent, He diluent, and N_2 diluent. The diluent partial pressure in the plenum is denoted as p_d.

For simplicity, no further polymerization is assumed to occur inside the nozzle. Of course, some polymerization does occur, although the amount is not expected to be large. In particular, dimerization and trimerization given by

$$2Na + M \rightarrow Na_2 + M \tag{8}$$

$$Na_2 + Na + M \rightarrow Na_3 + M \tag{9}$$

occurs where M is any third-body collision partner. Reaction (9) is essential for the laser process. These reactions are useful in the laser cavity; their occurrence inside the nozzle is favorable to the laser process providing the trimer does not further polymerize.

The analysis assesses the effects of diluent gases, plenum stagnation temperature T_0, and exit plane Mach number M. The calculations use Eqs. (2-7), standard values for the specific heats and molecular weights of the various species, and the standard equations for a steady, one-dimensional nozzle flow. The perfect gas flow is assumed to be inviscid with a constant value for γ, which is evaluated in the plenum. Prescribed conditions consist of p_d, T_0, M, and the specific heat and molecular weight of the diluent.

It is essential that any diluent should be inert with respect to the metal vapor and halogen atoms, have a relatively low

molecular weight, and should not absorb the laser radiation. Both He and N_2 fulfill these criteria.

Results are provided in Table 2, where p is the nozzle exit pressure, which also characterizes the laser cavity pressure. Similarly, M and s are evaluated at the exit plane. The pure vapor part of the table, with $M = 1$, shows that s and p are sensitive to T_0, with s rapidly decreasing while p rapidly increases with T_0. This trend persists when the exit Mach number is increased to 1.5. Except for the first two $M = 1$ cases, this part of the table yields either too large a value for s or for p. The rate of mixing of the metal and halogen streams may be unduly slow when p is large.

The use of He diluent does not alter the situation. The rapid increase in s with M is caused by a rapid decrease in the nozzle exit temperature. In turn, this is caused by the relatively large value for γ, which is about 1.6 with no diluent and slightly larger with He diluent. Trends are somewhat different with N_2 diluent, since γ in some cases is as low as 1.34. Because of the reduction in γ, both s and p are less sensitive to T_0.

Small nozzles, of course, have a small characteristic Reynolds number. Thus, boundary layers tend to be laminar and may be of significant thickness by the exit plane of the nozzle. This is the situation for the fluorine nozzle; however, a thick boundary layer should not occur for the sodium nozzle. This nozzle is either sonic or has a small area ratio; hence, the boundary-layer thickness is small because of the very large favorable pressure gradient.

IV. Laser Cavity

The laser cavity starts downstream of the exit plane of the halogen and metal vapor nozzles. Aside from wakes and separated boundary layers, the basic flow is supersonic. As a result of condensation and chemical reactions, some heat release occurs in the cavity. The effect of the heat release is not large because condensation is not a highly exothermic process, the relatively large fraction of chemical energy removed from the cavity by stimulated and spontaneous emission, by the presence of diluent gases, and by the relatively high cavity temperature.

We now describe the dominant physical and chemical processes that occur inside the laser cavity. The metal vapor molecules, monomers and polymers, are in a sonic or supersonic jet at a relatively constant temperature and a gradual condensation process occurs. Although reactions (8) and (9) are dominant, larger polymers can form in accord with

$$\mathrm{Na} + \mathrm{Na}_n + M \rightarrow \mathrm{Na}_{n+1} + M, \qquad n \geq 3 \tag{10}$$

$$\mathrm{Na}_2 + \mathrm{Na}_n + M \rightarrow \mathrm{Na}_{n+2} + M, \qquad n \geq 2 \tag{11}$$

Table 2 Sodium vapor nozzle results

Diluent	p_d, atm	T_0, K	M	s	p, atm
—	0	900	1	3.35 + 1	2.43-2
—	0	1000	1	2.51 + 1	9.61-2
—	0	1100	1	1.22 + 1	0.295
—	0	900	1.5	3.71 + 3	1.23-2
—	0	1100	1.5	4.01 + 2	0.150
—	0	1300	1.5	8.56 + 1	0.839
He	0.25	1100	1	1.37 + 1	0.417
He	0.25	1300	1	6.20	1.77
He	0.25	1100	1.5	5.20 + 2	0.212
He	0.25	1300	1.5	9.15 + 1	0.901
N_2	0.25	950	1	6.05	0.186
N_2	0.25	1050	1	6.63	0.311
N_2	0.25	1150	1	6.73	0.619
N_2	0.25	950	1.5	7.27 + 1	9.63-2
N_2	0.25	1050	1.5	9.44 + 1	0.160
N_2	0.25	1150	1.5	1.04 + 2	0.317
N_2	0.5	850	1.5	7.28 + 1	0.147
N_2	0.5	950	1.5	5.25 + 1	0.166
N_2	0.5	1050	1.5	5.52 + 1	0.230

where the collision partner M may not be necessary when n is sufficiently large. Polymers with $n \geq 4$ are not desirable since they remove Na_n, $n = 1, 2, 3$, that might otherwise contribute to the lasing process.

The next process discussed is the mixing between the halogen and metal vapor jets. This process is enhanced by using nozzles with small exit dimensions and gases with relatively low molecular weights. This aspect somewhat resembles the type of mixing that occurs in a supersonic HF/DF chemical laser cavity. The optimum rate of mixing is not known at this time. It depends on the rate of Na_3 formation and the rate needed for efficient removal of the de-excited Na_2 dimers. It also depends on the rate of collisional deactivation of the electronically excited Na_2^* dimer molecule. As discussed shortly, this latter process is not expected to be dominant.

Rapid mixing is required to suppress reactions (10) and (11). Consequently, both the mixing process and controlled metal vapor condensation require small nozzles. Based on Table 2, we see that the cavity pressure is likely to be higher than for an HF/DF laser, thereby further ensuring the need for small nozzles. The rate of mixing can be enhanced with various trip techniques that have been successfully used for the HF/DF laser, where a highly distorted laminar flow is obtained. At higher Reynolds numbers, turbulence would occur. Regardless of whether trip is or is not used, the two streams must still mix on a microscale level where molecular diffusion is dominant. As discussed earlier, fluorine atoms have a relatively low molecular weight, and the average halogen stream molecular weight can be further reduced with the use of helium diluent.

The pumping reaction for the laser is Eq. (1). The laser process itself is provided by stimulated emission

$$\mathrm{Na}_2^* + h\nu \rightarrow \mathrm{Na}_2 + 2h\nu \tag{12}$$

where $2h\nu$ represents two coherently related photons of the same frequency. The unexcited dimer is in the X electronic state but may be in a variety of vibrational/rotational states. Hence, reaction (12) may result in a variety of laser frequencies, all of which are in the visible or uv spectrum.

The stimulated emission process, reaction (12), is limited by two potential loss mechanisms. These are collisional or reactive deactivation and a relatively short spontaneous emission lifetime.[1] Because the spontaneous and stimulated emission Einstein coefficients are proportional to each other, the per molecule small signal gain will be large when the radiative lifetime is short. Thus, the laser intensity in the cavity is large and results in an efficient stimulated emission process that should dominate the loss mechanisms.

There are several processes for removal of the lower laser level, Na_2, from the laser cavity: 1) convective removal by supersonic flow; 2) nonreactive collisions that change the internal state of the Na_2 (in particular, the nascent Na_2 dimers may not be in their equilibrium rotational or vibrational states; collisions with other atoms or molecules enable these dimers to relax toward their equilibrium state, which depends on the local temperature); and 3) reactive collisions, such as

$$\mathrm{Na}_2 + X \rightarrow \mathrm{Na}X + \mathrm{Na} \tag{13}$$

where X is a halogen atom, are expected to be rapid[1] and thus efficient for removing the lower laser level. Observe that a sodium monomer is produced that promotes Eqs. (8) and (9). Other reactions, such as $Na_2 + Na + M$, may also occur.

Thus, there are a variety of mechanisms for depopulating the lower laser level. Which of these is dominant depends on the mixing rate, temperature, and density. At this time, there is no reason to believe the lower laser level constitutes a bottleneck, thus limiting the laser's efficiency.

V. Performance Estimates

A rough assessment of the potential of this laser is provided. The assessment is *not* necessarily optimistic; rather, it is meant

to be as simple as possible with a few transparent assumptions. The first of these is the use of the second case in Table 2 for the (pure) sodium vapor nozzle flow. This establishes the cavity pressure at about 73 Torr, which is not necessarily unreasonably large. For instance, Wellegehausen[3] notes that optically pumped Na_2^* has lased cw on the $B \rightarrow X$ band with as much as 150 Torr of buffer gas.

A conventional HF/DF nozzle bank array is presumed,[5] whose overall dimensions are 2.5×10 cm. A sonic slit, 0.02×2.5 cm, is used for the sodium vapor. On each side of the slit is a base region with the same dimensions as the slit. The exit dimensions for the converging/diverging fluorine nozzle are 0.2×2.5 cm. These exit dimensions result in 77 mixing layers for the nozzle bank, where each layer is transverse to the path of the laser beam.

For the sodium vapor, the nozzle bank mass flow rate is given by

$$\dot{m}_{Na} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \left(\frac{\gamma}{RT_0}\right)^{1/2} p_0 A^*$$

where $\gamma = 1.604$, $R = 335.1$, J/kg-K, $T_0 = 1000$ K, $p_0 = 1.962 \times 10^4$ Pa, and $A^* = 1.925 \times 10^{-4}$ m^2 with the result that $\dot{m}_{Na} = 4.678$ g/s. Note that the stagnation temperature T_0 and pressure p_0 are obtained from Tables 1 and 2.

For simplicity, we assume that the only polymerization process in the nozzle, or in the lasing portion of downstream cavity, is reaction (9). In essence, sodium trimer formation is being limited to the equilibrium dimers that are present in the plenum. Thus, only a small fraction of the sodium flow rate is assumed to be in the form of trimers. Moreover, trimer formation is presumed to be complete before rapid mixing occurs, and the reactive processes in the mixing layers largely suppress the formation of high-order polymers. From Table 1, the dimer mass fraction is 0.145 for the case under consideration. This estimate does not provide an upper limit for the trimers, since reaction (8) is being ignored. Thus, the number of trimers, per unit time, available for reaction (1) is

$$\frac{\dot{m}_{Na} f_2 N_A}{W_{Na_2}} = \frac{4.678 \times 0.145 \times 6.022 \times 10^{23}}{46} = 8.880 \times 10^{21} \text{ 1/s}$$

We assume only F atoms leave the halogen nozzles; any accompanying He diluent would have only a minor effect on the subsequent estimates. To partly compensate for the use of atomic fluorine without diluent, an appreciable excess for its mass flow rate is used. Note that F atoms need only react with the Na_3 and possibly with Na_2 in the X state. We thus assume the F atom flow rate matches the (total) Na atom flow rate, i.e.,

$$\dot{m}_F = \frac{W_F}{W_{Na}} \dot{m}_{Na} = 3.864 \text{ g/s}$$

Hence, the total nozzle bank mass flow rate is

$$\dot{m} = \dot{m}_{Na} + \dot{m}_F = 8.542 \text{ g/s}$$

Lasing may occur from any of the excited electronic states to the X state. All available trimers are assumed to result in stimulated emission. As an average, the 527-nm wavelength $\lambda_{F/Na}$ of the $B \rightarrow X$ band[2] is used, with an energy per molecule of

$$h\nu = \frac{ch}{\lambda} = \frac{2.998 \times 10^8 \times 6.626 \times 10^{-34}}{5.27 \times 10^{-7}} = 3.769 \times 10^{-19} \text{ J}$$

The net laser power is

$$P = \frac{\dot{m}_{Na} f_2 N_A h\nu}{W_{Na_2}} \times 10^{-3} = 3.379 \text{ kW}$$

We thus obtain 0.392 kW/g/s as the power per unit mass flow rate and 0.134 kW/cm^2 as the power per unit nozzle bank area. These values are roughly comparable to those of an HF/DF laser, but the wavelength is now in the blue-green region of the visible rather than in the infrared. This difference is not small, e.g., the wavelength ratio, $\lambda_{DF}/\lambda_{F/Na}$ is about 7.3.

VI. Summary

The halogen atom/metal vapor combination represents a family of promising short wavelength, chemically pumped, cw lasers. An overview is provided that focuses on engineering aspects especially relevant to a fluorine/sodium system. The concept of controlled condensation is introduced; its purpose is to maximize the metal vapor trimer formation, since trimer formation is a key step required for efficient lasing.

Although future research is required to develop realistic models for this type of laser, an estimate of its potential performance can nevertheless be made. An estimate for the F/Na combination shows it to be comparable to the HF/DF laser in terms of power per unit mass flow rate and power per unit nozzle area. The principal advantage, therefore, of this laser lies in its short wavelength.

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