Chapter Two

Review of Literature

2.1 : Review of the development of UV gas laser to shorter wavelength laser

The first laser reported by Maiman was in the visible region (red) and almost all early lasers were in the visible region. The first UV laser was developed by Heard in 1963 and it was a nitrogen laser.

Avco Research Laboratories further developed Heard's nitrogen laser and successfully developed a low inductance discharge circuit and the peak power was improved. Shipman [15] then refined Avco's work and produced a 2.5MW pulse of about 4ns duration. Using Shipman's concept of transverse travelling-wave pumping, Hodgson [7] observed VUV laser action in the Lyman bands of molecular hydrogen. Both nitrogen and hydrogen discharge pumped lasers have high gain so that no resonant cavity was needed. These were the earliest traveling-wave amplified spontaneous emission (ASE) devices. Nitrogen laser has been developed much further when compared to the hydrogen laser because it is easier to excite and to setup.

In 1968, Soviet scientists reported on the diatomic excited rare gas molecular (excimer) laser [9]. These excimer lasers produced high energy pulses but the pressure of the gas needed was too high to allow practical operation. Electron beams have to be employed to excite these excimers. Burnham et.al. [16] then reported Xenon fluoride (XeF) laser excitation by transverse electric discharge in 1976. Only a few atmospheres pressure is needed in the laser. This discharge pumping method provided the economy and the simplicity that allowed excimer lasers to become widely used in commercial applications. Further research results have led to other new wavelengths, new pumping methods and a wide variety of applications

2.2 : Excitation methods for shorter wavelength lasers

Gudzenko and Shelepin [17] reported the possibility of extending laser wavelength into the x-ray region. Many methods have been proposed. In the 1980s, soft x-ray lasers have been demonstrated by using dense plasmas created by high energy lasers as the gain media.

Electron impact excitation is one of the most successful methods [18]. In order to achieve a high rate of collisional pumping , generation of high temperature and high density plasma is essential. High density plasma is required so that there will have sufficient collisional pumping rate. Plasma uniformity is very difficult to be achieved when high temperature and high density plasma is to be generated. This will therefore limits the gain length due to the large density gradient. Multiple pumping laser pulses with suitable time delay has been employed to improve the uniformity of plasma.

Another method is by producing plasma in which the ground state of the lasing ions is highly populated. The plasma is produced by using a long laser pulse (a few ns) with several joule pulse energy. The electron temperature is then increased by using a ultrashort laser pulse (~ ps or fs) leading to a fast enhancement of collisional excitation. High gain has been detected for Ne-like Ti at 32.6nm and Ni-like Pd at 14.7nm [19].

Electron beam excitation is one of the most popular pumping method to produce VUV excimer lasers today. A dense and high energy electron beam is accelerated into the laser channel and excite the excimer gas in the channel. An output pulse energy of several tens of milijoule has been observed by this electron beam excitation.

Besides, optical field ionization has been used to obtain population inversion in Li III [20]. Table-top x-ray lasers based on optical-field ionization in an intense laser field provided by commercial femtosecond lasers have been reported. Demonstration of gain to the ground state in low-charged nitrogen ions has been reported [21]. The NIII 3s-2p transition at 45.2nm wavelength were obtained by only 25mJ of linearly polarized 100fs laser pulse.

2.3 : Electrical discharge excitation in gases

All gases at room temperature are excellent electrical insulators. In order to make them electrically conducting, a sufficient number of charge carriers have to be generated. Although there are already a certain number of charge carriers present at room temperature (in atmospheric air approximately 10^6 electron/m^3). This number is too small to produce a measurable electrical conductivity. This small number of charge carriers is however responsible for an electrical breakdown which occurs if a sufficiently high electric field is applied to a pair of electrodes. Breakdown of the originally non-conducting gas establishes a conducting path between the electrodes. Conduction of electrical currents through the electrode gap leads to a phenomenon known as gaseous discharge.

In such a gaseous discharge, the plasma consists of a mixture of ions, electrons and neutral particles. The composition and distribution of plasma between the electrodes is a function of the discharge mode and other discharge parameters. The quantity of current flowing through the channel determines the discharge of the laser.

In low pressure discharge, each electron that leaves the cathode moves towards the anode and produces ionization on the way. The energy of these accelerated electrons are transferred to the atoms or molecules along the discharge path. The transfer of energy is either through elastic collision or inelastic collision. As the current of the discharge increases, the dischage begins to glow visibly and the potential across the tube drops to a constatnt value. As the current continues to increase, the discharge gets brighter. The high current operation of the discharge is termed as arcing.

Arc discharge has low cathode potential fall when compared with glow discharge in which the cathode potential fall is of the order of hundreds of volts. Small cathode potential fall results from cathode emission mechanisms that differ from those in glow discharge. These mechanisms are capable of supplying a greater electron density from the cathode and can be nearly equal to the total discharge current. This factor eliminates the need for considerable amplification of the electron current , which is the function fullfilled by the high cathode fall in glow discharge.

Arc discharge is characterized by large current, I ~ 1-10^5 A which is much greater than the typical current of glow discharge, I ~10^{-4}-10^{-1} A [22]. The cathode current density of an arc discharge is also greater than in a glow discharge. The current density in arc may be 10^2 A/cm^2 and above while in normal glow discharge, current density usually is below a few hundred A/cm^2 [23][24]. Due to the large amount of energy from this high current arc, the temperature of the plasma may get higher than in normal glow discharge. Most laser action of short wavelength espacially x-ray lasers occur from the transitions of energy levels amongst the inner shells of ions. Therefore, high temperature plasma is essential to ionize the medium.

Currently, excimer lasers are still playing major roles in industrial applications. These lasers emit around a few joules per pulse and the current density of discharge is below 0.1kA/cm^2 . Theoretically, if higher energy is pumped into these systems, the output will increase. However, when higher energy (higher current) is applied, arcs are produced. Uniformity of the plasma when arc discharge occurs is impossible for a large volume. Therefore, this has limited the operation of these lasers to the glow discharge region.

Other methods have been employed to improve the output power of these lasers. For example, almost all high power nitrogen lasers are using intense-electron beam excitation. An efficiency of up to 0.15% has been observed for conversion of electron beam power to laser power at 337.1 nm [25]. The other approach to obtain high output power for nitrogen laser is through the development of more efficient pulsing circuit. Ultra-fast magnetic pulse compression circuit has been employed. A laser pulsed energy of 20 mJ has been achieved under a single-pulse mode with an efficiency of 0.43% to the charging energy [26].

2.4 : Discharge criteria for soft x-ray and xuv laser

Rocca et.al. [12] proposed capillary discharge for soft x-ray and XUV lasers. Dense and nearly totally ionized plasma in a large length-to-diameter column (l/d > 100) is generated from a fast discharge. Subsequently, the plasma is cooled rapidly by heat conduction to the capillary wall. This causes recombination of highly ionized species into ions of lower charge and thus creating population inversion. A decade later, Choi [27] demonstrated a low inductance hollow cathode capillary discharge, which gave peak current of 10 kA and current rise-time of 5 ns.

The key to these shorter wavelength lasers is the generation of high density ionized plasma. Ultra-fast current rise-time is essential to generate highly ionized plasma. The plasma temperature strongly depends on the current density of the discharge. High temperature plasma will be needed to generate dense highly ionized plasma.

Rocca has demonstrated laser pulses at 46.9nm by single pass amplification in 34.5cm long Ne-like Ar capillary discharge plasma and gain saturation is obtained at 12cm –15cm long [13]. To date, milijoule laser pulses and average power of 3.5mW have been obtained from a tabletop soft x-ray laser device [1]. The discharge voltage is supplied through a four stage Marx generator (>200kV). Increasing the length of the discharge scales the output energy of these capillary discharge XUV lasers. Further scaling of these systems will mean higher voltage (>200kV) is necessary.

2.5 : Amplified Spontaneous Emission

Conventional lasers consist of an active medium pumped in some manner to produce a population inversion between two states. This pumped active medium is sandwiched between two mirrors, which form an optical resonant cavity to obtain laser output. However, intense emissions can be observed from some systems without mirrors to form optical cavities. These systems were then termed as amplified spontaneous emission (ASE) systems by Allen and Peters [28]. Almost all UV, VUV and x-ray lasers are ASE systems. However, these ASE systems have a rather low output power when compared to other laser systems.

There are some conditions and properties of ASE that are not so similar with lasers. ASE may not need an optical cavity as resonator. Allen and Peter [29] have developed a theory that there is a threshold condition that may be derived from basic principles. A three-level model as shown in Figure 2.1 has been employed for the development of this theory.

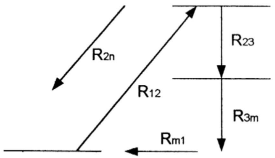

Figure 2.1 : Schematic defining nomenclature of the simple three-energy state system. Pumping occurs from state 1 to 2; lasing from 2 to 3; losses from 2 to n; and lower state depopulation from 3 to m. Replenishment of state 1 can occur for n=1, m=1 or through m to 1 transition.

The radiation density for a quantity of n photon with frequency ν,

$$\rho(\upsilon) = \frac{nh\,\upsilon}{ac\ \Delta\upsilon_D} \qquad (2.1)$$

where $\Delta\nu_D$ = width of Doppler broadened transition

a = cross section area

ν = frequency of photon passing through the cross-section area

The resonance induced emission cross-section is denoted by σ and

$$(\sigma n)/a = B\rho(\nu) \qquad (2.2)$$

where

$$B = \frac{c^3}{8\pi h\upsilon^3}\frac{1}{\tau_2} \qquad (2.3)$$

τ_2 = natural lifetime of state 2 (for a 3 level system)

B = Einstein coefficient

The rate of change of number of photon due to stimulated emission in volume La in time δt is given by

$$\frac{\delta n}{\delta t} = n\sigma c\Delta N \qquad (2.4)$$

If the threshold condition for ASE is defined as the condition when a spontaneous emission photon at one end of the column (x=0) just induces another photon at the other end (x=L) then $\sigma\Delta NL=1$.

This yields the relation for the critical inversion density ΔN_c to reach threshold

$$\Delta N_2 = \frac{8\pi \Delta \upsilon_D \tau_2}{L\lambda^2 \phi} \qquad (2.5)$$

where ϕ is the branching ratio, i.e $R_{23}/(R_{2n}+R_{23}) = \tau_2/\tau_{23}$

For a given inversion density (2.5), the critical length L_c required to reach threshold is,

$$L_c = \frac{8\pi \Delta \upsilon_D \tau_2}{\Delta N \lambda^2 \phi} \qquad (2.6)$$

Allen and Peters then proved their theory with He-Ne discharge. The experimental results proved that there exists a threshold for ASE to occur. Since nitrogen laser is also an ASE system, the length of the discharge volume has to be investigated in order to produce laser action. The beam divergence of ASE is described by an ASE-geometry, also developed by Peters and Allen too [30].

2.6 : Proposal for new way of scaling high current density discharge

Instead of scaling the output of laser pulses by increasing the length of the discharge, a new way of scaling is proposed in this project. The length or gap of the discharge is maintained at around a few centimeters. This will reduce the breakdown voltage of the discharge from more than 200kV to 20-30kV. An array of arc discharge is setup in such a way that amplification will occur transversely with the discharge. In other words, by the scaling of this high current discharge transversely, laser action may occur. Therefore, the main objective of this project is to investigate the laser action of such an arc array discharge. Nitrogen gas is used as the active medium because it is easier to handle and laser action at the second positive band can be achieved easily.

Besides, such a setup may provide high current density (high temperature plasma) by increasing the supplied voltage. Whereas, in all the previous or conventional transverse discharge pumped lasers, uniformity of the plasma in the laser channel is the key for lasing. Glow discharge, with current density of below $0.1kA/cm^2$ will provide uniform discharge in such a large volume. However, the plasma temperature is rather low. The success of this new discharge method may overcome the limitation of most electrically pumped lasers such as excimer lasers or nitrogen lasers.

The advantages of such an arc array discharge have led to the concept of this project. Investigation will be carried out on the output energy and current density of the discharge with this new setup design. Low inductance circuit will be one of the main concerns for this project. Optical pulses of the laser beam will be studied too. This system is targeted to generate pulses of 337.1nm wavelength. Shorter wavelength for nitrogen such as 45.2nm from NII 3s-2p will be studied in the future because higher energy is needed to pump the laser channel in order to obtain this transition. The main objective of this thesis is to investigate the laser action with arc array discharge.

Nitrogen gas has been chosen as the active medium for this experiment because it is a neutral and non-corrosive gas and is easier to handle. In addition, this UV laser also needs a very fast discharge circuit to lase, which is quite similar to all short wavelength lasers. Detection of the output pulses is not so stringent when compared to VUV or x-ray lasers. Moreover, the lasing line at 337.1nm can be achieved easily and a commercial power meter can measure the output of the laser beam.

2.7 : Discharge Circuits

There are two types of circuits commonly used in pulsed gas lasers. These are the "doubling circuit" or Blumlein circuit and the "charge transfer circuit" or the 'C-to-C' circuit. For both the circuits, two capacitors are needed. The only difference is the position of the laser electrode and the spark gap. In this experiment, a 'C-to-C' circuit has been used.

'C-to-C' pulsing circuit has its advantages. This pulsing circuit can provide a very fast discharge. This is due to the position of the peaking capacitor. This peaking capacitor can be placed very close to the laser discharge channel. This will provide the discharge loop with a rather low inductance. In a 'C-to-C' pulsing circuit, the two capacitors have their specific roles. The function of the peaking capacitor is to temporary store the energy before dumping it to the discharge channel. The storage capacitor, as its name indicates, will store the charges from the power supply.

Actually, the operation of this 'C-to-C' circuit has two stages. Firstly, the storage capacitor C_s is charged up to high voltage through a bypass inductor or resistor. When the spark gap is switched on, the charges stored in the storage capacitor will be transferred to the peaking capacitor C_p. The voltage at the peaking capacitor will increase until a value when it is enough for the laser channel to breakdown and discharge. Once the laser tube discharge, the energy stored in the peaking capacitor will be discharged to the laser channel and excite the gas in the laser cavity.

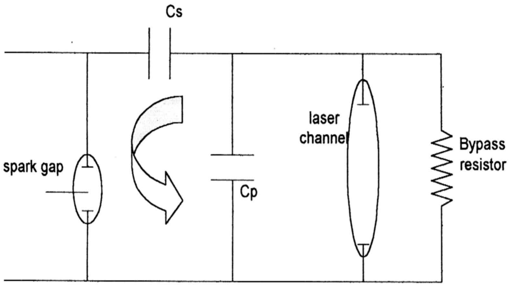

Figure 2.3(a) : C-to-C circuit discharge path when the spark gap is triggered.

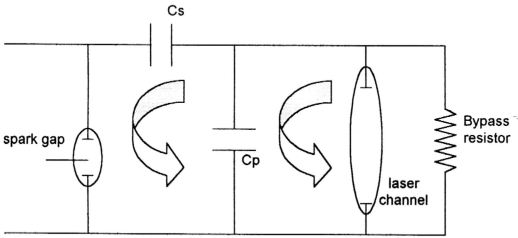

Figure 2.3 : The schematic drawing for the 'C-to-C' pulsing circuit and the operation of charge transfer circuit.

An array of arc discharge is needed in this experiment. Therefore, this array of separated electrodes may need an isolated pulsing circuit. This is necessary because if only one pulsing circuit is employed, when one of the electrodes discharge faster then the others, all the energy will be discharged through this faster discharge electrode and all the other electrodes will not discharge at all. On the other hand, if each of these electrodes is isolated to one separated peaking capacitor, the discharge of each electrode is independent from the others. An array of discharge is possible by this isolated electrodes and peaking capacitors configuration.

There also exist inductance L and resistance R in the laser tube and the spark gap. The inductance and resistance are important (including all other stray inductances) because they determine the efficiency of the charge transfer and also the discharge time. If the inductance in the spark gap is too large, then energy will be lost during the charge transfer because the energy is transferred through the switch (spark gap). Therefore, the complete discharge circuit can be considered as two LCR circuits.

In a LCR circuit, a capacitor is charged to a voltage V_o and discharged, by closing a switch through an inductor L and a resistor R. The energy stored in the capacitor will oscillate in the circuit. From Kirchhoff's second law, the relation between the voltage and current that are varying with time can be written as,

$$L\frac{dI}{dt} + IR = V_o - \frac{\int I dt}{C} \qquad (2.7)$$

Equation (2.7) is differentiated to give,

$$\frac{d^2I}{dt^2}+\frac{R}{L}\frac{dI}{dt}+\frac{I}{LC}=0 \qquad (2.8)$$

The general solution has a form of,

$$I=[A\exp(nt)+B\exp(-nt)]\exp\left(\frac{R}{2L}t\right) \qquad (2.9)$$

where $$n^2=\left(\frac{R}{2L}\right)^2-\frac{1}{LC} \qquad (2.10)$$

The solution as given in (2.9) takes three distinct forms depending on whether n is imaginary, zero or real. By introducing $\alpha=\frac{R}{Z_0}$, where $Z_0=\sqrt{\frac{L}{C}}$ is the surge impedance, then, whether n is imaginary, zero or real depends on the whether α is less than 2, equal to 2 or greater than 2.

Since the discharge is under damped oscillation, thus n=imaginary and α<2.

In this case, the solution becomes,

$$I=\frac{V_0}{Lw}\sin wt\exp\left(-\frac{R}{2L}t\right) \qquad (2.11)$$

For the case of peak current, then, $\sin wt=1$ where $wt=\frac{\pi}{2}$.

Therefore, the peak current can approximately be written as,

$$I_0 = \frac{\pi V_0 C(1+f)}{T} \tag{2.12}$$

where C = capacitance of the LC circuit

V_0 = charging voltage of the LC discharge circuit

f = ratio of the connective peak of the sinusoidal current waveform from the Rogowski coil

T = period of the oscillation waveform

Since the voltage and current of the LCR discharge circuit will oscillate with certain frequency depending on the inductance and capacitance of the circuit, their relation is given by ,

$$T = 2\pi\sqrt{LC} \tag{2.13}$$

Since nitrogen laser needs a rather fast discharge, the inductance of the circuit must be kept as low as possible. The inductance of the circuit is strongly dependent on the cross-section of the current loop of the discharge circuit. Smaller cross-section of the discharge current loop will give a lower inductance for the system. It is found that the capacitances of the driving circuit strongly influence the discharge of the laser channel. This capacitance value influences the resistance of the discharge while their coupling in the circuit influence the inductance of the laser channel [30].