Chapter 1

Introduction

1.1 Background of Project

Capillary discharge, which to date is the most efficient electrical discharge scheme for generating XUV laser, requires extremely demanding driving conditions due to its longitudinal discharge configuration. This has impeded the development of electrical discharge VUV and XUV lasers. Therefore, a new transverse discharge mechanism is proposed (a patent is currently being processed for submission [1]), which is more convenient and practical when compared to conventional scheme, for effective pumping of short wavelength laser. The transverse excitation scheme allows lower voltage driving requirement but yet still able to produce discharge conditions as in the capillary discharge.

Two research projects were initiated concurrently to explore the possibility of practical implementation of the proposed scheme. Initial efforts were carried out jointly to realize the arc array concept into practical implementation. In one of the projects [2], the system employed a single high capacitance storage capacitor distributing its energy to 64 individual low capacitance peaking capacitors. This has resulted in slow discharge due to the large inductance of a single large storage capacitor used. However, laser action in nitrogen gas was still obtained. These results are reported in details in the M.Sc thesis of K.S. Goh [2].

In this second project which run concurrently with the first project, a new layout was employed with the single large storage capacitor being replaced by 48 individual low capacitance capacitors. Each storage capacitor will charge up an individual peaking capacitor. With this arrangement, a faster discharge circuit is realised. The electrical behaviour of the new setup is investigated in this study.

1.2 Short Wavelength Radiation

Scanning through the electromagnetic radiation spectrum, beyond the point of ultra-violet is a region identified as vacuum ultra-violet (VUV). Its wavelength ranges from 200 nm down to about 100 nm, it name derives from the fact that the photon associated with these wavelength is easily absorbed by oxygen and nitrogen molecules, therefore its propagation is limited in vacuum only.

Further down the spectrum, one finds a region of XUV or soft x-ray radiation, ranging from the wavelength of 1 nm to 100 nm. These radiations are also absorbed strongly in atmospheric conditions, making it almost non-existent in the natural environment.

Due to the difficulties involved in handling and manipulation of the short wavelength radiation, interest in utilising such radiation is somewhat limited. However, these wavelengths do offer some interesting features. The wavelengths of XUV regime correspond to energy levels of many structural bondings of interest,

especially in chemical and biological structures. Therefore, it may be used as a tool to probe these microscopic world. The shorter wavelength also allows improvement in many optical techniques which are previously impeded by the diffraction-limited of conventional optical sources. The faster time scale associated with short wavelength radiation also permits its utilisation in capturing rapid transient events; especially useful in plasma related studies.

1.3 Sources of VUV and XUV Radiation

The generation of these wavelengths is not a straightforward task. One may notice that the commonly available radiation sources can range from gamma rays to far infra-red, with a big missing gap in the XUV regime. XUV and vacuum ultra-violet can be obtained from high temperature plasma devices such as plasma focus, vacuum spark and laser produced plasmas. These wavelengths can also be obtained from synchrotron radiation. However, the disadvantage associated with these methods is that it radiates incoherently, making it unsuitable for many useful applications.

The search for coherent, high brightness and fast duration XUV and vacuum ultra-violet radiation sources had led to the realisation of short wavelength lasers. The concepts of VUV and x-ray laser started back in the 1960's [3], but VUV lasers were only realised in the 70's [4] and soft x-ray lasers even later into the 80's [5]. Much progress had been reported over the years. XUV laser energies have been scaled to several millijoules [6] and more compact tabletop schemes had been proposed [7].

The advent of short wavelength lasers had opened up many new possibilities in both scientific and technological explorations.

1.4 Applications of Short Wavelength Laser

Short wavelength lasers are finding many applications in various areas of interest, from scientific research to medical protocols to manufacturing processes. Vacuum ultra-violet lasers with short pulse-width are ideal tools for plasma spectroscopy. Besides, due to it higher energy photons, it can be used as a pump source for other lasers such as dye lasers.

Vacuum ultra-violet photons provide excellent laser-matter interaction. Most materials including metals absorb well in the ultra-violet region. Therefore, it is a good tool for ablation processes. Excimer laser is used in medical treatment, such as in Photo Refractive Keractectomy (PRK) to correct one's eyesight. Ion lasers are used in skin treatment and biological analyses. Ultra-violet lasers are also used in confocal microscopy, a new way to look into the microscopic world.

One important industrial application that boosted the advances of short wavelength laser development such as that of excimer lasers is the photo-lithography process in the manufacturing of integrated electronic components. In order to achieve better line resolution of the circuitry for higher number of transistors in a chip, short wavelength coherent light is needed. Krypton fluoride laser at 248 nm [8] is currently the industry standard. Industries are now looking into the shorter wavelength region

where vacuum ultra-violet lasers are gaining more attention. Fluorine laser is the preferred candidate offering high power pulses at 157 nm [9].

The development of XUV applications is somewhat scarce, possibly due to the limited availability of coherent sources. But from the current pace of development, it has tremendous potential to expand, together with increasing industrial and economical importance in the near future. One possible application is x-ray holography [10], where more precise rendering of sub-microscopic structures are made possible. Studies of biological specimens in the natural environment and probing of the molecular structures of living cells and tissues in resolution far exceeding other optical techniques can be achieved by using shorter wavelength lasers.

The high brightness of soft x-ray laser makes them ideal tools for probing high density plasmas relevant to astrophysics and inertial confinement fusion (ICF) [11]. X-ray laser interferometry offers the possibility of directly measuring the electron density profile in large and high density plasmas. In most cases of optical interferometry used in laser produced plasma, inverse bremsstrahlung absorption becomes significant for optical probes at electron densities exceeding 10^{20} cm^{-3}. Refraction of the probe beam is sensitive to electron density gradients and ultimately affects spatial resolution and data interpretation. However, the use of soft x-ray probe can mitigate the effects of adsorption and refraction.

Many fundamental processes in nature, such as chemical reactions or phase transition, involve changes in the structural properties of matter and atomic

arrangement. These changes usually occur on ultra fast timescales ranging from femtoseconds to picoseconds, comparable with the natural oscilation periods of atoms and molecules. Probing the stuctural properties of matter needs radiation with wavelength comparable with the inter-atomic distances and can be interacted with the electrons residing in the core atomic levels. Therefore, x-ray laser is of great importance in the field of physical chemistry. Using ultrafast x-ray diffraction, coherent phonon generation and propagation in semiconductor materials had been observed [12].

1.5 Generation of short wavelength radiation

The radiation of a laser is basically generated from the transition of different energy states of a particular excited species of atoms or molecules. Shorter wavelength radiation means higher energy photons which require larger separation of energy levels between the two transition states. Energy levels associated with molecular motions such as bending or stretching, as in the case of maser or infra-red lasers are not possible to generate short wavelength radiation. This is because the vibrational energies involved are too little for generating such high-energy photons.

To generate XUV radiations, electronic transitions of an atomic or molecular species are needed. These schemes essentially involve excited states of an atomic discrete energy level or a molecular energy band and another low-lying energy state or sometimes ground state. One major drawback is that these excited levels usually required enormous energy to pump, making these system inferior in terms of

efficiency. Another disadvantage is that these excited states has a short lifetime, which means laser oscillation is difficult and requires fast pumping scheme [13].

Another hindrance faced by short wavelength laser is that its pumping power is strongly dependent on the frequency of the radiation generated. This has been indicated by Schawlow and Townes [14]. To illustrate this problem, consider the linear optical gain of line center that can be expressed as [15]

$$g = \left(\frac{4\pi^2}{3\hbar c}\right)\mu^2 \Delta n \frac{\nu}{\Delta \nu}$$

Where μ = transition matrix element

Δn = inversion density

ν = transition frequency

$\Delta\nu$ = linewidth

Δn can be approximated as

$$\Delta n \approx R\tau_u$$

τ_u being time needed to populate the upper laser level, and scales as ν^{-3}. The linewidth, $\Delta\nu$ is proportinal to ν for Doppler broadened transition and is proportional to ν^3 for radiatively broadened transition. Therefore we can summarize,

$g \propto R\nu^{-3}$ for Doppler broadened case

$g \propto R\nu^{-5}$ for radiatively broadened case

In order to analyse the pumping power requirement, the corresponding energy rate is $h\nu R$. Therefore, the pump power scales as ν^4 and ν^6 respectively.

1.6 Objective of Research

As discussed, one can say that the potential offered by short wavelength lasers are tremendous. The main purposes of this project is to explore possible new avenue in creating a simpler and convenient way to pump short wavelength lasers. Despite conventional laser systems which are characterised by large volume, homogeneous glow discharge; this project aims to use high energy, stable arc discharge to obtain laser output. By doing so, it is hoped to achieve condition favourable to short wavelength lasing using only electrical excitation method.

In order to create high temperature plasma in electrical discharge, high current density is needed. One way to obtain large current is to increase the discharge voltage. However, it is not easy in an axial discharge; therefore this project employs transverse discharge to overcome the technical difficulties of high voltages. The discharge is made localised with respect to each pin yet with a special arrangement to obtain a long column of uniform active medium.

1.7 Content of Thesis

This thesis is organised in 6 chapters, detailing every aspect of the experiment. Chapter 1 gives the background information on short wavelength laser and its applications. Chapter 2 discusses the development of VUV and XUV laser, detailing the prevailing techniques of obtaining VUV and XUV output, including its

disadvantages and others considerations. This eventually leads to a new scheme to be proposed. Chapter 3 describes the newly proposed scheme, its concept and construction details. Chapter 4 presents the results of the investigation and optimisation on the new scheme, followed by Chapter 5 which discusses in details regarding the experimental results. Finally, Chapter 6 concludes the whole experiment.