CHAPTER 3

DESIGN AND DEVELOPMENT OF THE LASER MARKING SYSTEM

This chapter discusses the design and development of two laser marking systems. The first laser marking system uses a copper vapour laser source while the second laser marking system uses an argon ion laser. The two marking systems share a few common components. These are described in the first section. The second and third sections describe the components specific to the copper vapour and argon ion lasers respectively. The design and construction of the copper vapour laser are also presented in the second section. The fourth section discusses the software requirements to implement the complete marking system. The fifth section introduces the various measurements employed in quantifying the various parameters involved in laser markings. In particular, the emphasis is placed on etching characteristics, laser power and beam profile, and the materials characteristics.
3.1 GENERAL LASER MARKING SYSTEM CONFIGURATION

The laser film marking system consists of the following components:

1) laser system

2) optical system, which includes shutter, beam forming and focusing elements

3) galvanometer scanner

4) film indexing and winding unit

5) microcomputer control system

The general experimental layout of the laser marking system is shown in Figure 3.1 (a) and (b). The laser and optical components are mounted on an optical table. A 19-inch equipment rack houses the microcomputer, power supplies, scanner and beam shutter drivers, and the film winding unit. It also has a light projector unit that projects the films image on the wall for visual inspection of marking quality. The laser and optical systems are presented in the next sections.
Figure 3.1 (a): Overview of the Laser Marking System (with Argon Ion Laser).

Figure 3.1 (b): Block diagram of a Post-objective Laser Film Marking System.
3.1.1 Galvanometer Scanner

A galvanometer scanner is selected for this project because character markings on film are essentially a vector based application. The galvanometer used is a Cambridge Technology model 6450. This scanner has typical settling time of about 0.8 ms with 2.5 gm.cm² mirror load moving through a 1 degree step and settling to within 99% of final position. Short-term repeatability of the scanner is 1.5 microradians.

![Diagram of galvanometer scanner](image)

Image Height (mm) = $2 \times WD \times \tan \theta$

where WD = working distance (mm), $\theta$ = half of total scanning angle (degrees)

Figure 3.2: Scanner’s approximate working area.

The scanner has a total scanning angle of 40 degrees. It can support mirror size up to
16-mm beam diameter. In this project, the mirror set must accommodate the beam diameters of both the copper vapour laser and the argon ion laser used. The copper vapour laser has a beam diameter of 11 mm while argon ion laser has a beam diameter of 2 mm. To accommodate both lasers, a 12-mm beam diameter mirror set is selected. To operate at wavelengths between 454 to 578 nm, an aluminium front-surface-coated mirror set with anti-reflection coating is specified.

To allow some working space between the scanner and the film indexing unit, the target film is placed at 100 mm away from the scanner mirrors. In this configuration, when one axis of the scanner scans through the full angle of 40 degrees, the beam will trace out a straight line of 73 mm as shown in Figure 3.2. With 2 near orthogonal axes, this translates into a working area of 73 mm $\times$ 73 mm. However, as each frame of the film measures only 35 mm $\times$ 19 mm, this is more than adequate. Given that the scanner's repeatability is 1.5 microradians, the position repeatability on the working area is:

$$\text{Position Repeatability} = \frac{1.5 \times 10^{-6} \text{ rad}}{\frac{40^\circ}{360^\circ} \times 2\pi \text{ rad}} \times 73 \text{ mm} = 0.16 \mu\text{m}$$

As shown above, the position repeatability of the scanner can be very high.

The scanner position is commanded by a 0 to 10 V analogue command voltage. If a digital to analogue converter (DAC) card is used to control the scanning position, then the scanner's resolution is limited by the resolution of the DAC. Resolution of the working area
is given by:

\[
\text{Scanning Resolution (mm)} = \frac{\text{Working area (mm)}}{\text{Resolution of DAC (steps)}}
\]

In this project, a 12-bit DAC is used, which has 4096 possible positioning steps. This gives a scanning resolution of 17.8 microns. The maximum positioning error is also bounded by the accuracy of the DAC. If the DAC has accuracy of ±0.5 LSB (Least Significant Bit), then the maximum positioning error is also 17.8 microns.

3.1.1.1 Construction and Operation

The galvanometer is constructed with moving-coil actuators. The coil is wound on a rotor, impregnated with high temperature epoxy and supported by high-quality instrument ball bearings. The coil assembly is suspended between two poles of a magnetic field such that when a current is passed through the coil, a torque is created that is proportional to the current. The neodymium-iron permanent magnets in the stator produce a high flux density. Since the torque does not saturate, extremely high torque can be generated almost instantly. The torque can be approximated by:

\[
\text{Torque} = 2.\pi.N.L.I.B \text{ (Newton-meter)}
\]

Where \( r \) = radius of rotor (m), \( N \) = # of turns, \( L \) = length of coil (m),

\[ I = \text{current (A)}, B = \text{magnetic flux density (tesla)} \]
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The amount of torque that can be generated is limited by mechanical failure due to excessively high peak torque demands and maximum heat dissipation that the rotor can radiate before wire insulation and epoxy softens. The maximum rotor temperature allowed is 150 °C.

3.1.1.2 Position Detection

Angular position of the shaft is detected by a linear capacitive sensor located close to the mirror end of the scanner. A radio frequency signal is generated by a small oscillator in the front of the scanner. This signal is used in conjunction with a moveable dielectric to detect the angular position of the shaft as a capacitance change. This capacitance change is converted to a differential current by electronics within the scanner and sent to the servo drive amplifier. The capacitive sensor has non-linearity of ±0.015% and scale drift of 20 ppm/°C.

3.1.1.3 Servo Amplifier Card

The performance of the scanner is very much dependent on the servo amplifier control card. If the servo electronics are noisy or not well matched to the scanner, this will lead to degraded performance. The basic operation of the servo is to take an analogue input signal voltage and turn it into a stable, repeatable, angular position of the shaft. The servo
amplifier does this by combining the input information (command position) with the feedback information from the scanner’s (actual position) to form an error signal. The servo then strives to force this error signal to zero by rotating the rotor. Effectively, the servo commands the scanner’s position to “follow” the input signal.

The servo board requires ±15 V, 100 mA to run the analogue circuitry, and ±28 V, 4 A to supply the output stage current that drives the scanner coil. It accepts a 0 to 10 V analogue command voltage to command the scanner’s position.

3.1.2 Film Indexing and Winding Units

In film marking application, it is necessary to construct a device to position the films accurately on every frame of the film. The device must hold the films firmly during marking and wind them into a spool after marking.

The film indexing and winding unit consists of two detached parts as shown in Figure 3.3 (a) and 3.3 (b). The first part is a film indexing unit. The indexing unit holds the film firmly during laser marking, and advances the film for subsequent markings on other frames. This unit is placed on the optical breadboard and close to the scanner to ensure that vibration during film winding is not transmitted to the film before marking. The second part is the film winding unit. Its purpose is to feed the film to as well as to wind up the film from the film indexing unit. The indexing unit’s precision mechanisms and winding unit’s motor assembly are custom made by Chang Chun Institute of Fine-optics and Mechanics of China.
The indexing unit is modified and mounted into a metal housing fabricated by in-house workshop. The winding unit is also designed and fabricated in-house.

Figure 3.3 (a): Schematic diagram of the film indexing unit.
The film indexing unit comprises of a 5-phase stepper motor, which drives two sprocket roller shafts. The sprocket roller has two rows of sprocket pins on both ends. The sprocket pins are designed to pull the sprocket holes on both edges of the film when it rotates. This mechanism is similar to the tractor feed of a dot-matrix printer. Each complete revolution of the sprocket roller shaft advances the film by 4 frames. The stepper motor has a full-step angle of 0.72 degrees and a half-step angle of 0.36 degrees. In the full-step mode, the rotor and stator’s teeth align exactly opposing each other. This is also known as the
natural detent position. In the half-step mode, the rotor’s teeth can also align between two stators’ tooth position beside the full-step’s natural detent position. This way, the half-step mode has twice the amount of natural detent position. In this project, the half-step mode is used due to the higher resolution required.

Since each frame of the film is about 19 mm in height, and in half-step mode there are 1000 steps per revolution, the resolution of each step is 4.75 microns. The resolution is given by:

\[
\text{Resolution (mm/step)} = \frac{\text{Height of each frame} \times \text{No. of frames per revolution}}{\text{No. of motor steps per revolution}}
\]

Because a stepper motor is used, the film indexing unit can advance or rewind the film in either directions. The motion of the film indexing unit is controlled by the microcomputer using standard TTL signal. The stepper motor is capable of moving the film continuously at a speed of about 28 frames/s or 532 mm/s. It can also advance a frame and stop to allow laser marking. In this start and stop mode, it can feed at a rate of 7 frames/s.

The film is gripped and stretched out firmly in place vertically by the two sprocket-roller shafts assisted by other roller guides. The film is further held steady by a spring-loaded clamped mechanism located at the centre of the two sprocket-rollers. The clamp mechanism has a window with the size of exactly one film frame, which exposes the film to the laser beam during marking. A fume exhaust housing removes the fume generated during marking.
The film winding unit has two identical motor-driven platters. One platter is used to feed the film to the indexing unit, while the other is used to rewind the film after marking. Each platter is directly driven by a torque motor. The torque motor can generate constant torque. It can also be operated with the shaft stopped and not rotating. The constant torque generated will ensure a minimum tension on the film so that the film will not slack and drop onto the floor.

3.1.3 Microcomputer control and interface system

A PC-based microcomputer system is used to control and monitor all the laser marker functions. Among the functions performed by the microcomputer system are:

1) For copper vapour laser (CVL) system, it controls the pulse repetition frequency and operating voltage. The pulse repetition frequency is controlled by an in-built programmable precision timer on the Advantech PCL-818 data acquisition card. The precision timer has better timing accuracy and less timing jitter than the standard 555 timer. Pulse repetition frequency is software limited to operate between 2 to 20 kHz. Furthermore, it allows a master timing system, which can shut off the laser beam without the use of a beam shutter. The data acquisition card has a digital to analogue converter (DAC), which is used to control the operating voltage of the CVL. The 0 to 10 volts output voltage of the DAC is used to program the output voltage (0 to 10 kV) of the high voltage switched-mode power supply section. The advantage of these methods
is that it allows for changes to the CVL’s pulse repetition frequency and operating voltage using software.

2) For argon ion laser system, it controls the acousto-optic modulator used to switch the beam. This is done using a standard TTL output signal.

3) It controls the motion of the scanner. This is done by an Advantech PCL-711 dual-channel 12-bit digital to analogue converter card. A 0 to 10 V output signal commands the scanning angle from -20 to +20 degrees. The laser marking software allows the user to design and plot vector-based patterns, which are translated into the required scanning motion. Precise timing is maintained by an on-board precision counter (with a 10 Mhz crystal clock) so that consistent scanner speed and correct laser beam switching timing can be achieved.

4) It controls the motion of the film’s indexing unit. Here, two standard TTL signals are used to command the direction of rotation of the stepper motor as well as the acceleration and deceleration motion pulses.

5) It monitors the function of various components of the marking system to ensure proper function and safety. Other sensors incorporated are safety interlock switches and over-temperature transducers.

6) It presents a user interface. User can change the various operating parameters and vector patterns to be etched by the marking system. By incorporating the pre-set sequences in the software, the computer can automate repetitive jobs thereby minimising labour.
3.2 COPPER VAPOUR LASER MARKING SYSTEM

![Block diagram of the CVL laser marking system. (Figure 3.4)](image)

3.2.1 Design and construction of the CVL

For use in marking applications, the laser source has to be reliable, easy to use, requires minimal maintenance and has reasonably long lifetimes. Due to these considerations, the sealed tube design is selected. The sealed tube eliminates the need for messy vacuum and gas system. Since the sealed CVL tube is a low powered device, it is designed for totally air-cooled operation. Air-cooled operation is preferred as it eliminates the need for a chiller, cooling tower or running water source. The external vacuum, gas system and water-cooling run the risk of leakage. Furthermore, vacuum pumps, pressure
Figure 3.5 (a): CVL Resonator Structure.

Figure 3.5 (b): Overview of the CVL system.

Figure 3.5: Photographs showing the CVL system.
controller, gas tanks, and chillers are bulky, expensive and require maintenance. With sealed tube, the overall operation becomes simpler. The whole laser design can be made very compact. Figure 3.5 (a) and (b) show the photograph of the CVL system.

![Block diagram of copper vapour laser](image)

Figure 3.6: Block diagram of copper vapour laser

3.2.1.1 Laser Cavity Design

3.2.1.1.1 EEV XL7000 Sealed-off CVL Tube

The EEV XL7000 CVL tube is of sealed-off construction. It has an overall length of 935 mm and diameter of 64 mm. The output beam diameter is 11 mm. The tube is supported on both
Figure 3.7: The sealed-off laser tube with cooling fin attached.
ends by two blocks of perspex holder measuring 80 (L) x 30 (W) x 40 (H) mm. An aluminium bracket fastens the metal ends of the tube to the perspex block.

The tube has been designed to function with heating power of 1.2 to 1.6 kW. The heating factor is given by $\frac{1}{2}CV^2f$, where $C$ is the storage capacitance, $V$ is the voltage on the storage capacitor when it is fully charged and $f$ is the pulse repetition frequency. If the maximum heating factor is exceeded, there is a danger that the tube will be damaged, resulting in a sharp drop in output power.

When operated at the designed heating factor, the temperature of the inner tube will reach an equilibrium of between 1400 to 1500 °C, where the copper vapour partial pressure in the tube reaches an optimum value and the maximum power output is attained. A buffer gas of hydrogen is contained in a reservoir within the tube. Hydrogen is released when the tube is heated. The hydrogen additives decrease the prepulse electron density followed by more rapid plasma recovery after the excitation pulse [5]. If the tube is operated at other temperatures, the hydrogen partial pressure will change and reduce the output. The ideal temperature of the tube can be monitored by measuring the ratio between the two laser lines. This is done by directing the laser output to an dichroic beam splitter, which splits the beam into the green and yellow components. Each component output is measured using a power meter. The tube is set up in the factory at a green to yellow ratio of 1.9:1. Below 1.7:1, thermal runaway can take place and the tube may be irreparably damaged in only a few seconds. The maximum allowable outer tube wall temperature is 200 °C.
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Cooling fins are attached to the metal ends of the tube to remove the heat generated at these points. The design of the cooling fins and the laser tube is shown in Figure 3.7. The tube is cooled by means of forced air flowing transverse to the tube length. The airflow is provided by four 120-mm axial-flow cooling fans. Two of the fans are directed at the cooling fins at both metal ends of the tube. The other two are equally spaced apart in the centre to ensure more even airflow along the length of the tube. Each of the fans is capable of blowing at a rate of 3 m³/min.

The lifetime specification of the tube is such that after 1000 hours it should still be capable of producing more than 3 watts of total power. The end of life mechanism is often copper migration out of the active region.

3.2.1.1.2 CVL Resonator Design

Due to the intrinsic characteristics of the laser transition, CVLs have a high gain coefficient, typically in the order of 0.1 to 1 cm⁻¹. For the laser tube of 1-meter length, such high gain coefficient induces a superradiant emission or Amplified Spontaneous Emission (ASE), with self amplification up to the gain saturation of the active medium. In this condition a large fraction of the available energy stored in the active medium is extracted as noise, with large divergence and low coherence. Techniques to control the ASE using an optical resonator have to minimize this noise problem.

The CVL can be operated in a superradiant mode by placing a single planar mirror at
one end of the laser tube. In this case, the beam divergence is just the aspect ratio of the double-pass copper-vapour medium. When a partial reflecting (8%) flat glass output coupler is placed at the other end of the laser tube completing the plane-plane optical cavity, the beam divergence narrows dramatically. The initial superradiance onset is progressively quenched by the photon flux reflected from one mirror to the other. In fact, with a resonator length of 1.1 meter, only a few passes are allowed within the gain duration. The oncoming oscillation undergoes gain saturation and depletes the initial noise, thereby raising the beam quality. An estimate of the "full angle" beam divergence is given by [32]:

\[
\text{Divergence (rad)} = \frac{\text{Tube diameter}}{\text{No. of round trips} \times \text{Mirror separation}}
\]

If we assume the laser pulse duration to be 30 ns, there is enough time for light to make 4 round trips. With the two reflectors placed at 1.1 metres apart (beam diameter is 11 mm), the beam divergence is estimated to be 2.5 mrad.

Sample film etching is carried out using this plane-plane cavity configuration. The output beam is focused using a 150-mm focal length plano-convex lens. The resulting markings are measured. It is found that the etching's line width is more than 400 microns. The relatively large focal spot obtained is contributed by the large beam divergence and strong ASE at the edge of the beam. Various techniques used to control the ASE using intra-cavity and extra-cavity aperture only achieved minimal gain. Consequently, it is determined that to reduce the etching width to 100 microns, then beam divergence must be reduced further.
To improve divergence, an off-axis positive branch unstable (high-loss) resonator is employed as shown in Figure 3.8. It consists of a concave and a convex reflectors with a common focal point (confocal) producing a parallel beam.

![Diagram of an off-axis unstable resonator](image)

\[ L = \frac{1}{2} \left[ |R_1| - |R_2| \right] \]

Figure 3.8: An off-axis Unstable Resonator design

A positive branch unstable resonator must satisfy the following condition:

\[ g_1 g_2 > 1, \text{ where } g_1 = 1 - L/R_1 \text{ and } g_2 = 1 - L/R_2 \]

with \( R_1 \) and \( R_2 \) being the mirror radius of curvatures and \( L \) the mirror spacing. The resonator's mirrors share a common focal point so they can be described by:

\[ R_2 + R_2 = 2L \]

The magnification of the resonator is given by:
\[ M = -\frac{R_2}{R_1} \]

The radius of curvature of the reflector selected are \( R_1 = -0.6 \) m and \( R_2 = 3 \) m. The resonator formed will have magnification of 5 and mirror separation of 1.2 m.

Light making a round trip is expanded by this telescope configuration so that its divergence is correspondingly reduced by the magnification factor. With \( M = 5 \), light making 3 cavity round trips or more has dropped in divergence by about 125 times (compared to plane-plane mirror cavity) and so is close to the diffraction limit. Since there is only time for about 4 cavity round trips during the laser pulse, it is only during the last half of the laser pulse that very high quality laser light is produced.

### 3.2.1.2 High Voltage Switched-Mode Power Supply

The high voltage (HV) switched-mode power supply is a Model 402OEM by A.L.E Systems Inc. The HV power supply is designed for charging capacitors in laser systems and other pulsed power applications. It is air-cooled and can provide 4,000 watts of average power and can be paralleled for higher total system power. The input voltage requirement is a 3-phase 340-460 V, 50/60 Hz and 15 A maximum.

The HV power supply incorporates a high-frequency Insulated Gate Bipolar Transistor (IGBT) series-resonant inverter for efficient generation of the output power. A
control module precisely regulates the output voltage, automatically compensating for line, load, temperature, repetition rate, and program voltage variations. The system is also protected from normal external fault conditions such as line dropout, open or short circuit load, high voltage arcing and over-temperature.

The output voltage is adjustable from 0 to 10 kV. Regulation is ±1%. The power conversion efficiency is 85% minimum at full load. The HV power supply can provide 1.3 A below 7.5 kV and 1.0A up to 10 kV. The full output current is available at rated voltage to supply a peak charge rate of 5000 Joule/second and the current increases according to \( I = 10,000/V \). Below 75% of the rated voltage, the current is constant.

![Block diagram of the High Voltage Switched-mode Power Supply](image)

Figure 3.9: Block diagram of the High Voltage Switched-mode Power Supply.
Connection to the charging capacitor is done using the supplied two-piece coaxial HV connector that plugs at the back of the unit and a coaxial HV cable with ground shield. The switched mode power supply is mounted on the 19-inch equipment rack.

The HV power supply is rated at 5000 J/s peak and 4000 J/s average charge rate. The peak charge rate determines the capacitor charge time. The average charge rate determines the total power delivered from the power supply. The capacitor can be discharged at a low repetition rate of only 100 J/s. This implies that if the capacitor voltage is higher than the desired voltage setting, regulation to the final voltage will be slow (50 times slower than charging up rate).

![Figure 3.10: Charging voltage waveform](image)

The peak charge rate \( = \frac{1}{2} \frac{CV^2}{T_c} \)

The average charge rate \( = \frac{1}{2} \frac{CV^2}{T_p} \)
The output of the switched-mode power supply is connected to a Maxwell 5 \mu F, 15 kV smoothing capacitor. If the CVL is to be operated up to 15 kV, then the power supply must be able to charge the smoothing capacitor up to half the desired voltage (resonant charging circuit doubles the supply voltage) which is 7.5 kV.

Then the charge time is

\[ T_c = \frac{1}{2} \frac{CV^2}{5000} = \frac{1}{2} \frac{(5 \mu F)(7.5kV)^2}{5000} = 28 \text{ ms} \]

If the CVL is operated at 12 kV, then the HV power supply must charge at 6 kV.

For voltage levels below 75% of the rated voltage of 10kV, the charge time is

\[ T_c = \frac{1}{2} \frac{CV(0.75 \times V_{\text{RATED}})}{5000} = \frac{1}{2} \frac{(5 \mu F)(6kV)(0.75 \times 10kV)}{5000} = 22.5 \text{ ms} \]

3.2.1.3 Air-cooled Thyratron

EEV CX1935A is a hydrogen filled, hollow anode, triple grid (pentode) ceramic thyratron. It is designed for air cooling and features a low-jitter firing time. It can hold 20 kV peak forward anode voltage, and operate at a maximum pulse repetition frequency of 50 kHz [6]. The hollow anode structure enables the tube to cope with inverse voltage and current without consequent reduction in its high voltage hold-off capability due to electrode damage.
Figure 3.11 show the schematic diagram of the thyratron. Before operation, the reservoir heater must be turned on for at least 10 minutes to allow hydrogen pressure to build up. The heater is powered by a 6-volts DC source to achieve minimum jitter. Grid 1 is
biased with a +140 volts DC voltage while grid 2 (control grid) is initially biased with a -140 volts DC voltage. Grid 3 (shield grid) is connected to the cathode by a 10 Ω, 12 W wire-wound resistor to reduce stray capacitance between the anode and grid 2. A 1000 pF, 1 kV ceramic and a 1 μF, 1 kV polypropylene capacitors are connected in parallel across the heater to protect the heater circuits from high voltage spikes generated during switching.

During operation, a +800 V, 0.8 μs trigger pulse superimposed on the -140 V bias voltage on grid 2 will trigger the thyratron into conduction. The trigger pulse is provided by a triggering circuit that will be described in subsequent sections. A large area heat sink mounted on the anode provides cooling. The whole tube is supported by a mounting bracket on the cathode end. The tube is cooled by forced-air blowing directly onto the base and flowing along the tube and anode's heat sink. An axial-flow cooling fan with output of 3 m³/min provides the necessary cooling.

3.2.1.4 Resonant Charging Circuit

Figure 3.12 shows the resonant charging circuit for the CVL. The charging circuit is based on the capacitor transfer scheme in which Cₛ is the energy storage capacitor and Cₚ is the peaking capacitor. The storage capacitor is first charged up by the resonant charger to a high voltage through the charging inductor Lₐ and the diode chain Dₐ. The voltage on storage capacitor will be almost double that of high voltage supply due to inductive charging. When the thyratron is triggered, the charge on the storage capacitor Cₛ is first
transferred to the peaking capacitor $C_p$ until its voltage becomes high enough to induce an electrical breakdown in the laser tube.

![Diagram of charging circuit for CVL](image)

Figure 3.12: Charging circuit for CVL

The storage capacitor consists of 3 pieces of 2.2 nF, 40 kV ceramic door-knob type capacitors (Matrox). The peaking capacitor consists of 2 pieces of 1.4 nF, 40 kV of the same type of capacitors. Both the capacitors are mounted on the cathode flange. The charging inductor used is an air-core inductor with $L_c \approx 76$ mH. The inductor is made by winding the enameled copper wire on a plastic bobbin. A thin mylar sheet isolates the successive layers of the copper winding. The diode chain is made from 23 pieces of IN5408 diode rated at 3 A, 1 kV PIV. The inductor and diode chain are immersed in oil to prevent corona discharge.
and possible sparking, which will lead to component failure. The oil tank measures about 330 (L) × 330 (W) × 230 (H) mm and is completely sealed to prevent oil leakage. Connections to the thyatron and high voltage power supply are provided by two high voltage coaxial cables running through the side wall and securely fastened with oil-proof cable glands. Finally, an air core 100 μH air-core inductor is used as the bypass inductor.

The efficiency of the charging circuit depends very much on the efficiency of the charge transfer from $C_s$ to $C_p$. If the charge transfer is complete before electrical breakdown occurs in the laser tube, then efficiency is high. To achieve this, the inductance of the electrical paths between the two capacitors, thyatron and laser tube must be kept as low as possible.

3.2.1.5 Triggering System

A solid state thyatron triggering circuit based on the Jones, et. al. [7] 100 kHz thyatron driver design is constructed. The schematic diagram of the circuit is shown in Figure 3.13. The circuit employs a MOSFET and the pulse-forming network to generate an 800 volts, 0.8 ms pulse that triggers the thyatron. A snubber network consisting of 6 nF capacitor and 47 Ω resistors ensures that the MOSFET is not damaged by voltage spikes during switching. The circuit is assembled and housed in a standard 3U-height 19-inch equipment casing. The low voltage MOSFET triggering pulses are provided by the TTL output of a precision timer of the microcomputer control system.
Figure 3.13: Schematic diagram of the solid state thyratron driving circuit
3.2.1.6 Performance of the Copper Vapour Laser

As the primary focus of this thesis is on the marking quality of the CVL, the dependence of output power on various input power parameters including efficiency of the CVL is not investigated. The main interests are good beam quality and operation in the stable output power region.

During operation, the CVL takes about 35 minutes to warm-up before lasing starts. Once lasing starts, the CVL output power rises steadily until full power is achieved in about 60 minutes. After this period, the power remains steady provided the input voltage and frequency are maintained. Since the tube is sealed-off, the tube gas pressure will not change significantly if the tube temperature is maintained within the design range. The tube temperature is not monitored directly with an IR spot thermometer in this experiment, but is monitored indirectly by measuring the ratio of the green and yellow emissions. Due to the sealed-off construction, laser power is only dependent on three parameters. They are input voltage, input frequency, and tube temperature. With the tube operating at 1.6 kW input electrical power, the maximum output power is obtained at the green to yellow ratio of about 2:1.

When operated with a plane-plane resonator cavity, the CVL produces up to 7.5 watts of average output power. The maximum output power of the off-axis unstable resonator is approximately 40% of the plane-plane cavity configuration, which is up to 3 watts. The CVL has been well tested with pulse repetition frequency from 4 to 18 kHz. Whenever the input voltage or frequency is changed, the output of the CVL will change and
stabilise after about 10 minutes. Therefore, film marking is only performed after 10 minutes when the input power is changed.

Sample film marking carried out with the plane-plane cavity is found unsatisfactory. Results of the marking show that the width of the line exceeds 400 microns. The edges of the markings are often irregular and very wide when compared to the desired clear centre area. The centre area often appears yellowish in colour. The poorly defined edges and the large width of the markings are attributed to the poor beam quality caused by strong ASE at the edges of the beam. Attempts to control the intensity of the ASE by apertures placed intra-cavity and extra-cavity has not been successful in improving the marking edges. Only with the off-axis unstable resonator, the marking’s width has been reduced to less than 150 microns. Consequently, further investigations are carried out using the unstable resonator configuration.

At near field, the beam appears to be quite uniform (due to the very high intensity of the beam) with clearly defined edges. There is a darker half-moon shaped spot at the bottom of the beam due to aperturing of the off-axis convex mirror placed in front of the tube. The output beam diameter measured at near field is 11 mm.

At far field, the output of the resonator has a very bright centre followed by a series of progressively larger but lower intensity concentric rings due to diffraction effects. Subsequent propagation and amplification of this seed cause the gain to saturate so that the ASE output is also rapidly reduced in intensity. Repeated round-trips within the resonator produce a step-wise spatial and temporal evolution towards full transverse coherence or
diffraction-limited divergence. A darker spot at the bottom of the beam is also observed due to the small convex output coupler.

3.2.2 Optical beam control

In this experiment, a post-objective scanning system is selected because it is simpler and lower cost to implement. Furthermore, the target film area to be marked is small (30 x 19 mm). If the scanner is placed at a considerable distance away from the target film, the arc focal plane scanned does not vary much throughout the marking area. If a long focal length lens is used, then the depth of field will not be affected so critically by spherical aberration.

As shown in Figure 3.4, the CVL output beam is steered using two adjustable mirrors that directs the beam to a 250-mm focal length achromat focusing lens. Achromat lens is selected for two reasons. The CVL emits in two laser wavelengths. Since focal distance of the lens is dependent on wavelength, the two laser lines will focus on slightly different positions. Achromats bring different wavelengths in the same beam to focus in the same plane. Moreover, achromats have the least spherical aberration among the singlet lenses. The focused beam is directed to the scanner, which guides the focused beam onto the target film. The target film is placed approximately 100 mm away from the scanner.

For the CVL, the divergence of the beam with unstable resonator is not measured.
As a guideline, the spot size can be estimated from the following Gaussian beam approximation:

\[ w = \frac{f\lambda}{\pi w_0} \]

where \( w \) = focused spot radius, \( f \) = focal length, \( \lambda \) = wavelength, \( w_0 \) = input beam radius

For CVL, \( f = 250 \text{ mm}, \lambda = 578 \text{ nm}, w_0 = 5.5 \text{ mm}. \) The estimated spot size is 17 microns.

### 3.3 ARGON ION LASER MARKING SYSTEM

The argon ion laser marking system is constructed as shown in Figure 14 (a) and (b). The components specific to the argon ion laser marking system are presented in the following sections.
Figure 3.14 (a): Photograph of the Argon Ion Laser Marking System.

Figure 3.14 (b): Block diagram of the Argon Ion Laser Marking System.
3.3.1 Argon Ion laser

Figure 3.15: Block diagram of the Argon Ion Laser.

The Chroma 10 argon ion laser by Spectra Physics has maximum output power of 15W. The laser system requires a 3 phase power supply of 400 ±8% VAC, 50/60 Hz. The maximum current consumption is 60A. Power consumption is about 40 kW. Due to the large power consumption, the system requires water-cooling. This is provided by a 15-ton cooling tower.

The argon ion laser has an output beam diameter of less than 2 mm. The laser emits 5 laser lines at 515 nm, 488 nm, 476 nm, 466 nm and 458 nm. A large portion of the power is emitted in 515 nm and 488 nm lines. The specified beam divergence for all lines is less
The argon ion laser is operated by using the remote control unit attached to the power supply unit as shown in Figure 3.15. The remote control unit has a turn-on key switch and an LED display that can show either the tube voltage, tube current or optical output power. Selection of display reading is controlled by a meter function switch. It also has a mode selection switch. The mode switch selects the current or power control mode. In current control mode, plasma tube current is held constant at the level set by the current control knob. In power control mode, plasma tube current is regulated to hold optical output power constant at the level set by the power control knob. The power control mode is used for marking purposes since constant output power is maintained.

3.3.2 Optics and Beam Control

The optical path of the argon ion laser marking unit is more complex than the CVL system. As shown in Figure 3.14, the output of the argon ion laser is steered by an adjustable mirror, which directs the beam to an acousto-optic modulator (AOM). The AOM acts as a beam shutter. A NEOS (model N35085-3) AOM is used. It is mounted on a Bragg mount. This allows the precise adjustment to be made to the angle between the AOM and the input beam so that maximum diffraction efficiency may be obtained. Since the argon ion laser emits in 5 laser lines, the AOM will diffract the individual beams to different angles. To compensate for different diffraction paths, a 7.05° wedge prism made of fused silica is
placed at the output of the AOM. The AOM is driven by a 6-watt RF driver. The RF driver unit is mounted in the 19-inch rack and linked to the microcomputer to allow beam switching. The AOM has typical diffraction efficiency of about 75% for the argon ion wavelengths.

The zero order of the beam is directed to a right angle prism, which deflects it to a beam stop. The first order of the beam (when AOM is switched on) is directed to a second adjustable mirror. This beam is aligned to the optical axis of a beam expander. The beam expander used is a Melles Griot Gallilean-type beam expander with 3× magnification. The entrance concave lens has an aperture of 15 mm while the exit convex lens has an aperture of 25 mm. The separation between the lens can be adjusted by rotating the beam expander assembly. This allows adjustment to be made to the collimation of the output beam.

The beam expander expands the beam to 6 mm. This causes the divergence to improve from 1.1 mrad to 0.37 mrad. The output of the beam expander is directed to a focusing lens. As before, a 250-mm achromat lens is used. The partially focused beam is steered by the scanner to the film target.

The focused spot size is can be estimated as follows:

\[ d = f \times \Delta \theta_{\text{full}} \]  where \( f \) = focal length, \( \Delta \theta_{\text{full}} \) = full scale beam divergence

For \( f = 250 \) mm and \( \Delta \theta_{\text{full}} = 0.37 \) mrad, the estimated spot focused size is 92.5 microns.
3.4 LASER MARKER SOFTWARE DEVELOPMENT

The laser marking system can only be as good as the software that controls its various functions. The software is developed using Borland C++ version 4.5. The software is designed to operate under the MS DOS operating system. This is because DOS is still a single-tasking operating system. Multi-tasking operating systems such as MS Windows are not suitable as task switching can affect the critical scanner’s timing. Accurate timing must be maintained in order to ensure constant scanning velocity. A detailed description of the software programming is beyond the scope of this thesis.

The software is divided into various sections that handles different functions. The sections are:

1) User-friendly interface section. This section allow users input and change various options as follows:

a) marking profiles parameters such as what to mark, position and size of marking, and fonts selection

b) various scanner parameters such as speed, timing delay of the first and last vector position

c) CVL emission parameters such voltage and pulse repetition frequency

65
d) film indexing parameters such as speed of advancement, acceleration rate and number of frames to move

2) Scanner device driver section. It is the interface between the user commands and low level scanner function. The driver translates the user marking profiles or characters into command voltages to move the scanner with constant linear velocity.

3) Laser device driver section. For CVL, it controls the voltage and pulse repetition frequency. For argon ion laser, it controls the AOM that switches the beam on and off in synchronised manner with the scanner motion.

4) Film indexing device driver section. This section handles the acceleration profile of the stepper motor and moves the film frame by frame.

5) Font library section. This section translates ASCII character to be marked into a series of vectors that form the characters. Different languages such as Chinese, Japanese, Arabic can be supported but only Chinese characters have been implemented.

3.5 MEASUREMENT TECHNIQUES

3.5.1 Digital Image Processing and Measurement Technique

The objective of digitising the image is two folds. Digitised image is a convenient way to present the film marking results. Since the laser marks are only 100 microns in
width, direct measurement is difficult. It is more convenient to measure magnified digital images.

The digital image processing system set-up is shown in Figure 3.16. The image processing equipment system consists of a microscope, a black and white camera, a microcomputer system with plug-in overlay and framegrabber board, and two monitors.

![Diagram of digital image processing system set-up]

Figure 3.16. The Digital Image Processing System Set-up.

The Zeiss Axioplan Universal microscope is equipped with a 5x objective and a 10x binocular eyepiece giving 50 times magnification factor. A three-axis specimen stage allows
glass slides containing the sample to be mounted and viewed. The specimen stage allows the selection of viewing area by moving the stage in the XY direction. Focusing is achieved by moving the specimen stage in the Z (up/down) direction. This arrangement is particularly suited for image capture because once the specimen is in focus, the magnification factor remains constant. The specimen stage also has a vernier scale for measurements up to 0.1 mm but it is not used in this project. A halogen bulb illumination below the specimen stage provides transmission type of light source.

A Sony CCD camera mounted on top of the microscope allows video image of the specimen to be viewed on the monitor or captured by the framegrabber card. The CCD functions as a microscope eyepiece with a 10× magnification. It is equipped with an electronic auto-iris function that allows the camera to automatically adjust the image optimum brightness according to the illumination level. The CCD camera is connected to a power supply through a coaxial cable that carries both power and video information. The power supply filters the DC component and outputs a composite video signal, which is fed to the overlay board of the IBM compatible PC system.

The overlay board enables an externally recorded colour video image and the computer output of an IBM compatible PC to be superimposed. The overlay board consists of two functional groups, which are the Colour Graphics Adapter and Video Processor. The Colour Graphics Adapter is compatible with IBM Colour Graphics Adapter. In addition, it supports a resolution of up to 640 × 400 pixels. The Video Processor assumes all video signal processing. It handles image, colours, synchronising and superimposing of the
overlay and frame buffer memory. It accepts standard composite colour or monochrome video signal (1 Vpp) conforming to the PAL and NTSC standard. The board allows an RGB output (0.7 Vpp) and a composite output. When used in conjunction with the framegrabber board, the overlay board can display with overlay (mixture of CGA graphics and video), CGA graphics or on-line video mode. In the overlay mode, the external video image will replace all video output positions previously displayed in black (Black level is interpreted as transparent).

The framegrabber board is an AT-compatible board. It enables images from a video source to be digitised, stored and displayed. In addition, the stored image data can be accessed via the AT-bus. The framegrabber board can capture in $512 \times 512$ pixels, $640 \times 400$ pixels or $748 \times 512$ pixels.

In this project, the emphasis is on investigating the relation of the width of the marked line with various parameters like laser power and scanning rate. Usually in laser cutting application, the parameter of interest is the relation between cutting depth, laser power and cutting rate. The marking width is selected over marking depth because the quality of the line depends on the relative width of Clear Area where emulsion is completely removed and the width of heat affected zone. In optimum condition, the width of the Clear Area should cover about 80% of the total heat affected zone. Furthermore, since the emulsion thickness is only 8 microns, even low levels of laser power can completely remove the emulsion. The depth of incomplete emulsion removal (less than 8 microns) is not only difficult to measure but will not give an indication of etching quality.
CHAPTER 3  DESIGN AND DEVELOPMENT

In order to digitise a marked line, the film is first sandwiched between two microscopic glass slide to keep the surface of the film flat. The mounted slide is placed on the specimen stage and held in place by a spring-loaded clamp. The image of the line is focused by moving the specimen stage in the vertical direction. Once in focus the live image from the CCD camera is captured by the framegrabber card using the Kontron Electronics’ VIDAS (version 2.5) software running under MS DOS 6.22 operating system. The captured image is stored as an array of 512 x 512 pixels. By digitising an image of known dimensions, it is estimated that the width of the captured image is 480 microns wide. Therefore, the resolution of digitised image is approximately 0.94 microns per pixel. The light intensity of each pixel on the image is captured as 256 levels of grey-scale data (8 bits per pixel).

Measurements of the marking width are carried out with the help of another Kontron Electronics’ KS Lite (version 2.00) software running under Windows 3.11 operating system. The software allows the intensity of every image pixel to be displayed in graphical form. Although the laser markings appears white in the centre where emulsions have been removed with dark edges on the either side (heat affected zones), they do not always have a clear boundary especially when low laser power are used. Width measurements carried out by visually selecting the area where intensity changes are very subjective. In order to maintain consistency between the measured width, a systematic and objective method is required. Here, the software allows the user to select the cross-section of the line, and the intensity distribution of the cross-section is displayed as 2D graph. A snapshot of the screen
is shown in Figure 3.17. From the graph, it can be seen that the background emulsion (unirradiated area) intensity appears quite uniform. Where the emulsion is removed, the transmitted light intensity increases rapidly. At both edges of the line, the emulsion appears dark and the intensity drops below that of the background.

![Image of computer screen with digitised graph]

Figure 3.17: Snapshot of the computer screen with digitised image.

In this project, the width of Clear Area is defined as the area where the pixel intensity is higher than the pixel intensity of the background. It is assumed that for the Clear
Area, the emulsion is completely removed. The width of Heat Affected Zone (HAZ) is defined as the area covered by dark edges on both sides of the line where the intensity is below that of the background.

Calibration of the width measurements is carried out with the help of a travelling microscope with the resolution of 1 micron. The calibrated travelling microscope is loaned from Institute of Chang Chun Fine-Optics and Mechanics based in China. The measurement is carried out with both travelling microscope and a reference film-marking sample firmly mounted on an optical table. The film is also back illuminated. Two selected points on the markings are identified (width of a clearly defined boundary of the line with characteristic scratches on the background) and the distance between the two points is read off the scale viewed through the eyepiece of the microscope. The same film-marking sample is digitised and distance between the two selected points displayed on the RGB monitor is measured using a conventional ruler. This reading is used as a reference. Subsequent measurements of other samples using conventional ruler is calibrated with the reference using the following formula:

\[
\text{Sample's line width (\(\mu m\))} = \frac{\text{Sample line width from screen (mm)}}{\text{Reference line width from screen (mm)}} \times \text{Reference line width (\(\mu m\))}
\]

With the conventional ruler measurement reading error of \(\pm 0.5\) mm, the maximum measurement error is estimated to be 7 microns.
3.5.2 Calibration of scanner speed

As described in Section 3.3, the scanner's angular motion follows the analogue command signal from the 12-bit Digital to Analogue (D/A) interface card in the IBM compatible PC. The scanning angle (from -20 to +20 degrees) is linearly proportional to the analogue command voltage (0 to 10 volts). Therefore, the rate of change of the analogue signal output of the D/A card is also the measure of scanner speed.

The 12-bit D/A card has 4096 discrete steps (scanning steps) corresponding to the output voltage of 10 V. This works out to be 2.44 mV/step. In order to correlate the scanning steps with the actual marking distance, an arbitrary scanning step of 2000 or 4.88 V is chosen and the resulting marking line is measured using a digital vernier micrometer with resolution of 0.01 mm. It is determined that the resolution of the scanner is 16.12 microns/scanning step. In order to generate a constant linear speed, the command voltage is ramped at a rate of 1 scanning step or 2.44 mV increments each time at a fixed interval. The scanner's speed is given by:

\[
\text{Scanning speed (mm/s)} = \frac{0.01612 \text{ (mm/step)}}{\text{Interval between steps (s/step)}}
\]

If the scanning step is incremented in 10 μs interval, then the command voltage's rise time will be 2.44 V/s. The scanning speed is 1612 mm/s.
The timing interval is derived from the Advantech PCL-711 Data Acquisition Card’s on-board 16-bit precision interval timer. The precision timer derives its clock from a 10 MHz crystal oscillator that is divided by 10 by a clock divider (to 1 MHz) before being fed to its clock input. This gives the timer a minimum counting time of $1 \mu s$. The timing interval can be programmed by loading the counter with the number of $\mu s$ interval. The loaded counter value will be decremented every clock pulse (every $1 \mu s$) until the counter reaches zero. With a 16-bit counter, the maximum time interval the counter can handle is 65.5 ms. For longer time interval counting, two 16-bit counters can be cascaded.

In practise, the timing interval does not depend on the counter value only. The subroutine machine execution time before the counter value is loaded and polling time to check when the counter reaches zero has to be taken into consideration.

Calibration of the scanner speed is carried out with a Tektronix Digitising Oscilloscope. The oscilloscope is hooked to the D/A card’s analogue output for the x-axis. For the sample markings, an 8-mm horizontal line is scanned using the x-axis of the scanner. This corresponds to a distance of 496 scanning steps or 1.21 V. The beginning of the line is initially positioned at location corresponding to voltage level 2.0 V. The end point of the line is therefore 3.21 V. The oscilloscope is set to trigger when the voltage exceeds 2.0 volt and stops capturing after 1 pass. The time it takes for the voltage to ramp from 2.0 V to 3.21 V is measured. Figure 3.18 shows the voltage output of the D/A card.
The line is repeatedly scanned using different time interval. The voltage waveform is again captured using the oscilloscope and the scanning time measured. The actual timing interval is found to be:

\[
\text{Actual timing interval (\(\mu s\))} = 12 \ \mu s + \text{desired timing interval (\(\mu s\))}.
\]

In this experiment, the various times it takes to scan the 8-mm line are recorded. The scanning speed is computed as follows:

\[
\text{Scanning speed (mm/s)} = \frac{8.0 \text{ (mm)}}{\text{Scanning time (s)}}
\]
3.5.3 Determination of the film’s light transmission characteristics.

A Shimadzu UV-VIS-NIR Scanning Spectrophotometer (Model UV-3101 PC) is used to record light transmission characteristics through the film samples used in the marking experiment. The scanning spectrophotometer can operate on the wavelength ranging from 190 nm (UV) to 900 nm (Near IR) with 1 nm incremental step.

Measurements of the transmission characteristics of the film are carried out with the following settings. The scanning speed is set to 1600 nm min\(^{-1}\) (fast scanning mode). The scanning wavelength is selected from 200 - 800 nm. The reference sample is left blank (air reference). Four measurements are made using uniform black-coloured films and clear films of Polyester and Triacetate substrates respectively. In order to ensure that the base materials are the same, the clear films are carefully chosen from the same reel of film as the black-coloured films. These clear films may still contain emulsions but without most of the colour pigments after processing. As a result, the clear films have some yellowish tint. Figure 3.19 shows the transmission characteristics of the four film samples.
Figure 3.19: Transmission characteristics of the film.
3.5.4 Laser Power Measurement.

Laser power is measured with a power meter/joule head from Scientech. The power meter is 2 inches in diameter. It contains a thermopile detector that has spectral response ranging from 0.25 mm to 35 mm. The detector produces a voltage that is proportional to the temperature difference between the absorbing surface of the detector and its surroundings. This voltage can be converted into reading in either watts or joules and displayed on a digital readout in the front panel of the instrument. The power meter is calibrated with an external constant current source. For CVL, the average power is measured in watts. The Argon Ion laser power output is taken directly from an in-built power meter, which has been cross-checked with the power meter.

3.5.5 Beam Profile Measurement

The beam profile of the Argon Ion laser is measured using a scanning pinhole method. A pin-hole measuring approximately 0.5 mm is punched on a piece of copper plate measuring 15 mm x 15 mm using a needle pin. The pin-holed copper plate is mounted on a pole clamp that is inserted into the one-axis linear translator’s pole holder. The motion path of the linear translator is perpendicular to the direction of the incident beam. The pinhole is initially positioned in the middle of the Argon Ion laser beam by adjusting the translator travel. The pinhole height is also adjustable by moving insertion depth of the pole clamp.
A Newport Digital Power Meter (Model 815) is placed behind the pinhole and the laser source as shown in Figure 3.20. The power meter has a photo-detector head with an aperture of 25 mm in diameter. The power meter is capable of measuring power levels between 1 μW to 100 μW. Higher power level can be measured by placing the supplied neutral density filter on the photo-detector head for measurements up to 1.0W.

The pinhole is scanned across the beam in the horizontal direction by rotating the linear translator’s knob in 0.1 mm incremental steps while the laser power passing through the pinhole is recorded. The pinhole is moved in one direction only to avoid errors due to translator’s backlash. The process is repeated with laser powers from 1.0 to 5.0 watts. The beam profile of various laser powers is shown in Figure 3.21.
Figure 3.21: Beam profile of the Argon Ion laser.