# CHAPTER 1

# INTRODUCTION

The transversely excited atmospheric-pressure carbon dioxide (TEA $CO_2$) laser is one type of $CO_2$ lasers in which electrical discharge is transverse to the optical axis of the laser with an operating gas mixture pressure of more than one atmosphere. This type of lasers can produce high peak power (in MW region), high pulse energy (in kJ region), variable output pulse length (few tens of ns to few tens of μs), wide bandwidth (9.07 to 11.25 μm for $^{12}C^{16}O_2$ isotope [1, p. 53]), and high energy conversion efficiency (more than 10% for good systems). Furthermore, this type of lasers have no serious vacuum leakage problems due to their operation at high atmospheric pressure and the gas mixtures, which normally consist of $CO_2$, $N_2$ and He, are non-toxic and non-corrosive. This type of lasers was first developed independently by A. J. Beaulieu [2] and R. Dumanchin and J. Rocca-Serra [3] in 1969. A TEA $CO_2$ laser that operates at high pulse repetition frequencies (PRF) is often called a high repetition rate (HRR) TEA $CO_2$ laser. One of the first HRR TEA $CO_2$ lasers, reported by Beaulieu at 1971 [4], was operated at 1200 pulse per second (pps) for a few seconds before serious degradation of the discharge occurred. Besides the HRR TEA $CO_2$ laser, the ultra high-voltage (200 kV to 1 MV), longitudinally pulsed low-pressure $CO_2$ laser was also developed in 1968 by Hill [5].

Due to their high efficiencies and useful IR output, HRR TEA $CO_2$ lasers have been applied in many fields. Some of these applications are laser marking of plastic encapsulated electronic components (industrial); photochemistry (medical); IR-spectroscopy, nonlinear optics, and IR pump FIR laser (research); laser radar and remote sensing (environmental monitoring); and range finder (military). The application for marking of plastic IC with a 4 joule/pulse TEA $CO_2$ laser was studied in our laboratory in 1988 [6].

## 1.1 BRIEF DESCRIPTION OF THE HRR TEA $CO_2$ LASER

Basically, the present project study of a HRR TEA $CO_2$ laser is an extension of the previous study of the TEA $CO_2$ laser. A HRR TEA $CO_2$ laser consists of three major sections: the discharge section, the gas circulation and heat removal section, and the excitation circuit section.

The discharge section of the laser is identical to the TEA $CO_2$ laser in the previous study [6], i.e., it consists of profiled electrodes [7, 8] and a built-in preionizer system. The profiled electrodes are to provide a uniform field across the discharge volume which results in a delay of glow-to-arc formation time [9, 10], whereas the preionizer is for uniformly ionizing the discharge gas volume to a certain level of initial electron density for enhancing the formation of a uniform glow discharge.

Since the laser operates at high repetitive pulse discharge, fresh gas replacement is needed. Typically, the gas mixture traverses the discharge volume in between each pulse. There is therefore an upper limit of PRF for a given gas flow condition. This value is determined by the clearing ratio (CR) [11], which is a measure of the discharge gas removal ability. The hot gas, which is removed from the discharge volume, is then cooled by the heat exchanger and is recirculated into the discharge volume. However, degradation of the active medium is always a problem in HRR TEA $CO_2$ lasers [12, 13, 14, 15]. The gas molecules will be dissociated by electron impact during the pulsed discharge excitation. Furthermore, the dissociated species will react with other particles or gases to form new products. These new products normally affect the glow discharge and laser output owing to their high electronegativity, which in turn form negative ions and cause different modes of instabilities [9, 16, 17]. Normally, a continuous gas mixture feeding into the gas chamber (gas makeup) at a certain flow rate is used for reducing the concentration of the new products and thus maintaining an active laser gas medium.

For a TEA $CO_2$ laser operating at HRR, a proper pulsed power operation is needed [18]. A capacitor charging unit is used to charge up a H.V. storage capacitor. The storage capacitor is then switched by a H.V. switch to form voltage pulse across the discharge volume in between the profiled electrodes. Normally, uniformly distributed peaking capacitors [19, 20, 21, 22] are placed close to the discharge volume to over-volt the electrode gap and incorporated with preionizer elements to initiate a fast and uniform glow discharge. The H.V. switch must have a fast voltage recovery characteristics and the capacitor charging unit must be able to charge up the capacitor before the next switching. Consequently, the circuit can operate the TEA $CO_2$ laser at HRR.

Operating a TEA $CO_2$ laser in the repetitive mode without gas flow is possible for a few pps (pulse per second) for large volume discharge to a few tens of pps for small volume discharge. The maximum PRF in a no gas flow condition depends on the diffusion times of gas particles for exchanging the discharge products and the charge particles decay times through recombination processes [11].

Although the studies of this type of lasers started in the early 1970's, extensive studies continued to this date. This is because of the expanding applications of this type of lasers. Recent interests are (a) to improve the cost of construction of the laser system, (b) to improve the lifetime of the H.V. switching components and sealed off operation, and (c) to design an alternative excitation circuit. As reported in refs. [23] (1992) and [24] (1989), different research groups used catalytic converters to extend the operating time of the HRR TEA $CO_2$ laser in the sealed-off condition. In 1991, K. Yasuoka et al. [25] used an alternative excitation circuit to increase the lifetime ofb the thyratron switch. Besides that, the magnetic and solid-state switches were also used to drive the HRR TEA $CO_2$ lasers in refs. [26] (1990), [27] (1990), and [28] (1985).

## 1.2 CHOICE OF CIRCUIT ELEMENTS FOR THE HRR TEA $CO_2$ LASER

The cost of the excitation circuit for this kind of laser mainly depends on the choice of the switching components and capacitor charging unit. A thyratron is the most suitable switch for operating a TEA $CO_2$ laser at HRR [18]. To charge a large storage capacitor at HRR, a switch-mode power supply (SMPS) [18] is the most suitable because it can start to charge the capacitor at a certain delay after the previous thyratron switching. This allows the thyratron to recover and to prevent misfiring. The above charging operation is called the command charging. Besides using the SMPS, a low output impedance D.C. power supply with a charging inductor (saturable or nonsaturable type) is a more economical way for charging the storage capacitor. However, at even higher PRF, another thyratron [29] or a solid state switch (silicon controlled rectifier, SCR) [30] is placed between the charging inductor and the storage capacitor to command-charge the capacitor.

In refs. [26], [27], and [28]; SCRs, step-up pulse transformers, and magnetic switches were used to operate the HRR TEA $CO_2$ lasers. SCRs are used to switch a low voltage from a storage capacitor into the primary of a pulse transformer. The pulse transformer will step up the input signal to a desired high voltage at the secondary and charge up a high voltage storage capacitor. Since SCRs can only operate at relatively low peak current and at a rate of about 100 A/μs of current rise (di/dt), a 2- or 3-stage magnetic pulse compressor (MPC) [31] can be used to compress the current to a higher di/dt value and a higher peak current. By this means, the compressed pulses are able to drive a 95 J/pulse storage of a TEA $CO_2$ laser (1990) [26].

All the switches and the SMPS mentioned above are relatively more expensive in the present available market. Furthermore, the SCRs are sensitive being easily damaged by electrical surge, and are limited in switching power. However, the SCR and magnetic switches have a very long shot life since they are not of the gas discharge type switches [18].

Another type of recently developed switch is the pseudo-spark switch [32, 33]. This pseudo-spark switch has a fast recovery characteristics of a thyratron with high di/dt and high peak current capabilities of the high-pressure spark gap switch (or simply called spark gap), and an ability to stand high reverse current, which is more suitable for HRR TEA $CO_2$ laser. However, a pseudo-spark switch is relatively more difficult and expensive to build than a spark gap switch.

The most economical type of H.V. switch is the high-pressure spark gap. A spark gap consisting of an anode, a cathode and a trigger pin threaded through one of the main electrode is called a trigatron [34]. Spark gap can be homemade easily at low cost. The spark gap electrodes are usually homemade using brass, copper or aluminium materials while the insulator used is normally Perspex, Nylon, Teflon or PVC. The main problem of a spark gap operating at HRR is its slow voltage recovery characteristics. However, if the insulation gas in a spark gap is quickly removed after each firing, the spark gap can be used for HRR applications. A spark gap operating with a flowing air is often called an air-blown or air-blast spark gap [35, 36]. The direction of air flow can be either transversely or radially to the discharge current. It was reported [35] that an air-blast spark gap can be operated up to 50 kHz with a medium-pressure blower of 0.5-0.8 atm and an air flow rate of 10 $m^3$/min. Although the lifetime of high-pressure spark gap is relatively short when compared to a thyratron, which is due to electrode erosion and insulation failure, it is still commonly used in high voltage applications.

A TEA $CO_2$ laser needs a certain time delay for the preionization process before the main discharge occurs. In ref. [37, 38], a 100 ns time delay is needed for a maximum laser output. For commercial systems, self-synchronization with an inherent delay is used for delaying the main discharge from the preionizer discharge. Other systems use electronic delay to trigger both the preionizer and the main discharges. A simpler and low cost device for achieving this time delay is the 2-stage spark gap [37, 38]. This spark gap is a three-electrode spark gap with a trigger pin threaded through the grounded electrode. The middle electrode is connected to the preionizer circuit where as the top electrode is connected to the main circuit. The desired time delay is achieved by changing the gap distance between the middle electrode and the top electrode. If an air flow is applied between the gaps for removing discharge by-products from the previous discharge, this spark gap can be used to drive a UV-preionzed HRR TEA $CO_2$ laser with a controllable synchronization time delay.

In this project, we use an air-blown trigatron as the command charging element and an air-blown 2-stage spark gap as the preionizer and main discharge switch. Since both switches are homemade, together with a low cost air blower, the excitation circuit is relatively cost-effective for a laboratory-scale HRR TEA $CO_2$ laser.

## 1.3 OBJECTIVES OF THIS PROJECT

The main objectives of this project are:

(1) To study the performance and the maximum frequency operation of the air-blown spark gaps.

(2) To characterize the performance and operating conditions of the laser in single-pulse operation.

(3) To study the performance and the maximum frequency of the laser in HRR operation.

## 1.4 OUTLINE OF THIS THESIS

This thesis is divided into five chapters. The following Chapter Two is a review of the TEA $CO_2$ laser and the HRR TEA $CO_2$ laser. Chapter Three describes the design, construction, and experimental setup of this laser system. The performance of the triggering circuits and the air-blown spark gaps are also given in Chapter Three. The experimental results, analyses, and discussions of the laser performances are given in Chapter Four. Chapter Five presents discussions and conclusions on the spark gaps and the laser, and the suggestions for future work.