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# Development of Tunable High Pressure CO<sub>2</sub> Laser for Lidar Measurements of Pollutants and Wind Velocities - October 1977 Through January 1979

Jeffry S. Levine, Michael Guerra,  
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CO<sub>2</sub> Laser for Lidar Measurements  
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## Introduction

In the periods covered by this report, the progress on LDC-NASA project, Contract No. NAS1-14885 and its follow-on modifications, have been reported at frequent intervals to Mr. R. V. Hess, the technical representative of this contract. These reports have been presented by LDC personnel in person and in the course of visits (and presentation of formal talks) at NASA Langley Research Center and NASA Headquarters in Washington. The reports have also included extensive discussions and presentation of progress on the occasion of several visits by Mr. Hess and by other NASA LaRC personnel of LDC facilities at Lexington, Mass.

In addition, a comprehensive technical document/proposal prepared by LDC for NASA (submitted to Mr. R.V. Hess) has given a detailed discussion of LDC's work in relation to this NASA contract and the new concepts proposed for the follow-on program. This document (173 pages long) is addressed to the problem of laser energy extraction at a tunable monochromatic frequency from an energetic high-pressure CO<sub>2</sub> pulsed laser plasma, for application to remote sensing of atmospheric pollutants by Differential Absorption Lidar (DIAL) and of wind velocities by Doppler Lidar. The energy extraction principle analyzed in the report is based on a novel approach of transient injection locking at a tunable frequency.

Active remote sensing of the atmosphere by Differential Absorption Lidar (DIAL) including speckle effects has been the subject of extensive computer modeling studies performed by P. Brockman, R. V. Hess, and L. D. Staton at NASA LaRC. Following these computer modeling studies the process of Transient Injection Locking at a tunable frequency proposed by LDC has now been adapted for generation of the

tunable monochromatic radiation needed for NASA's active remote sensing experiments.

In the period covered by this report several critical experiments have been performed for high-gain power amplification by Transient Injection Locking (TIL):

(1) Investigation of TIL process at frequencies detuned from CO<sub>2</sub> line center for CW and pulsed master oscillators, and optimization of operating conditions for a tunable high pressure TIL CO<sub>2</sub> laser used in DIAL applications.

(2) Establishment of the ultimate frequency purity and pulse-to-pulse frequency stability obtainable for line center TIL used in Doppler Lidar.

(3) Determination of resonator frequency stability and practical field operations requirements, needed for the engineering of a compact repetitively pulsed TIL CO<sub>2</sub> laser with an external tunable laser master oscillator as driver.

(4) Investigation of several possibilities for a frequency tunable master oscillator used in TIL of an energetic high pressure CO<sub>2</sub> laser at tunable frequency. (a) A free-running tunable high pressure CO<sub>2</sub> laser followed by an external passive frequency filter which generates a weak single mode pulse at a tunable frequency. (b) A CW high pressure, small volume, CO<sub>2</sub> laser sustained by a mini E-beam. Experimental tests of individual components and a design analysis is performed.

#### Description of Experiments\*

This section describes the experimental procedures for tunable TIL; experimental results are given on page 7.

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\*An appendix containing block diagrams and raw data of the experiments is in preparation and will be available in the near future.

For tunable TIL it is important that the injected radiation source be totally external to the injection-locked laser and decoupled from it. This is accomplished by employing a ring-resonator for the injection-locked laser. In addition to the considerations relating to decoupling of the injection-locked laser from its driving oscillator, the ring resonator arrangement leads to a high efficiency in energy extraction; this is because the driving radiation can be used to excite a unidirectional traveling wave (as opposed to a standing wave) in the injection-locked ring laser. For short duration pulses spatial hole-burning effect in the laser amplifying medium will not occur in the presence of a traveling wave; this leads to an increased energy extraction efficiency.

For injection locking at frequencies detuned from CO<sub>2</sub> line center, a low pressure CW N<sub>2</sub>O laser oscillating on selected lines of its 001-100 band is used as the monochromatic driving radiation source to extract energy from an up to 100 m j/pulse CO<sub>2</sub> laser at frequencies appreciably detuned from the CO<sub>2</sub> lines centers. Test cases up to 1 j/pulse were also demonstrated. The selected N<sub>2</sub>O laser lines lie at frequencies displaced by known amounts from the peak frequencies of several CO<sub>2</sub> 001-100 transitions, e.g., the R(12) line of N<sub>2</sub>O 001-100 band lies at 1920 MHz removed from the peak of the P(14) of the CO<sub>2</sub> 001-100 band. In the energy extraction studies at detuned frequencies, a critical parameter is the ratio  $\delta = (\omega - \omega_0) / \Delta\omega_b$ , where  $\omega_0$  is the CO<sub>2</sub> line center,  $\omega$ , the frequency of the injected radiation and  $\Delta\omega_b$ , the collision broadened bandwidth of the injection-locked high pressure CO<sub>2</sub> laser. In a parametric study of the effect, it is necessary to study the energy extraction process versus the varying parameter  $\delta$ . For the CO<sub>2</sub> laser at

a fixed pressure, the parameter  $\delta$  can be varied by detuning the frequency of the injected radiation from the  $\text{CO}_2$  line-center frequency. Similarly, for the driving injected radiation,  $\omega$ , at a fixed frequency, the parameter  $\delta$  can be varied by varying the gas pressure in the injection locked  $\text{CO}_2$  laser. In this case  $(\omega - \omega_0)$  is kept at a fixed detuned frequency but  $\Delta\omega_b$  is varied via collision-broadening dependence on gas pressure.

The critical parameter to be determined is the intensity of driving injected radiation needed to achieve injection locking; it is determined in the presence of frequency detuning from line center,  $(\omega - \omega_0)$ , and for a cavity detuning,  $\omega - \omega_c$ , where  $\omega_c$  is the center frequency of the injection-locked resonator mode.

In the experiments, a heterodyne approach is adopted to determine the cavity detuning  $\omega - \omega_c$  and adjust it to a pre-selected value. This is done by providing a CW low-pressure  $\text{CO}_2$  or  $\text{N}_2\text{O}$  discharge cell inside the resonator of the energetic pulsed  $\text{CO}_2$  laser oscillator. For instance, in the experiments with an external driving CW  $\text{CO}_2$  laser,  $\omega - \omega_c$  is determined as follows: with the pulsed  $\text{CO}_2$  plasma chamber switched off, the internal low-pressure CW  $\text{CO}_2$  discharge cell is switched on. The resonator grating is then tuned to obtain (single mode) CW oscillation on the appropriate  $\text{CO}_2$  line, and the PZT of this resonator is adjusted so that the oscillation occurs with the cavity mode tuned to the peak of the gain profile of the low pressure  $\text{CO}_2$  laser line; note that in this case, the CW output occurs at a frequency lying at the peak of the resonator mode,  $\omega_c$ . Subsequently, the injected frequency of the external  $\text{CO}_2$  driver laser is compared with  $\omega_c$  by heterodyne frequency mixing. With the PZT fine tuning of the driver laser,  $\omega - \omega_c$  is adjusted to a pre-

selected value. After this adjustment, the internal CO<sub>2</sub> discharge cell is switched off and the energy extraction experiment is subsequently performed: the pulsed CO<sub>2</sub> discharge chamber is switched-on and the injected CO<sub>2</sub> radiation from the external driver laser (which now lies at a known cavity detuning,  $\omega - \omega_c$ ) is introduced in the pulsed CO<sub>2</sub> laser resonator. The injection-locking process at the known cavity detuning is studied versus the injected field intensity. This method is also used to obtain direct information on pulse-to-pulse frequency reproducibility of the CO<sub>2</sub> laser cavity mode.

The provision for placement of a low pressure CO<sub>2</sub> or N<sub>2</sub>O discharge cell in the resonator of the pulsed CO<sub>2</sub> laser has also made it possible to perform experiments with the injected radiation provided by the internal CW discharge cell.

In the absence of injection locking, the free running laser frequency is spread over a large number of resonator modes, covering a range of about 200 MHz. This frequency behavior is extensively reported in the final LDC report describing the first phase of the NASA sponsored LDC work (NASA contractor report 3175).

With the injection locking, the laser oscillation buildup occurs on a single mode driven by the weak-field injected radiation coupled to that mode. In our observations, the attenuated output of the injection-locked laser is heterodyned against an external CW CO<sub>2</sub> or N<sub>2</sub>O laser to determine the occurrence of the oscillation buildup on the single mode selected by the driving injected field. Furthermore, a study of the resultant beat note gives detailed information on the frequency characteristics of the injection-locked laser, its chirping and other features. In some of the ex-

periments, instead of a separate external CW laser used for the heterodyne studies, a portion of the output of a driver laser (in the injection locking), is employed as local oscillator in heterodyne observations of the output of the injection-locked laser.

In some observations, instead of determining detailed frequency characteristics, we are mainly interested to establish whether an injection locking occurs (on a single mode excited by the injected field). In these cases, it has been sufficient to display the pulse output of the injection-locked laser on a high-speed oscilloscope: When injection locking occurs, a smooth pulse is observed; without the injection locking, irregular beat notes arising from free-running multi-mode operation appears on the high-speed oscilloscope.

### Experimental Results

At a gas pressure above one atmosphere, and for a frequency detuning from line center not exceeding 500 MHz, several tens of  $\mu\text{W}$  injected radiation is sufficient to obtain injection locking if the cavity detuning,  $(\omega - \omega_c)$ , is adjusted to lie below about 200 kHz. For a cavity detuning as large as 20 MHz, about several tens of milliwatt injected radiation will be needed. (This is for a cavity Q corresponding to a 35 MHz cavity half-width.) This means that if about 50 milliwatt injected radiation is available, injection locking can be obtained even if the cavity mismatching is  $\sim 20$  MHz. However, if only tens of microwatts driver output is available, a tight cavity-matching, obtainable over a long time duration with an appropriately designed servo loop, is necessary. In this case, the servo loop maintains the center frequency of a resonator mode in coincidence with the frequency of the external driver laser. Such a servo loop is desirable for other

reasons. For instance in the presence of an appreciable cavity detuning, the oscillation buildup occurs at a frequency which will be shifted towards the peak of the cavity resonance,  $\omega_c$ . In this case, the injection-locked laser will oscillate at a frequency offset with respect to the frequency of the injected radiation. Such a frequency offset can be useful in some applications. This frequency offset can be maintained at a constant value with the aid of a servo control. In this case, the servo control is used to stabilize the center frequency,  $\omega_c$ , of the cavity of the pulsed CO<sub>2</sub> laser at a given offset value with respect to the frequency,  $\omega$ , of the external driver radiation.

For injection frequency detuning from CO<sub>2</sub> line center as large as 2000 MHz, the situation closely resembles the above except that the gas pressure must be larger than 2 atmospheres. In this case, for cavity matching below 200 Khz several tens  $\mu$ W power will be adequate for injection locking; for cavity detuning as much as 25 MHz several tens of mW will be needed. When the gas pressure exceeds a critical value of  $\sim 2.9$  atmospheres\*, injection frequency detuning off line center by 2000 MHz will have the same power requirements as line center injection. On the other hand for a gas pressure below 2 atmospheres but above 1 atmosphere, injection frequency detuning by 2000 MHz will require powers larger than 100 mW for injection locking with close cavity matching.

The situation described above can be obtained for any of the CO<sub>2</sub> P and R branch transitions providing an appreciable gain above loss to allow free-running oscillation, with an appropriately tuned grating resonator, to occur at the corresponding line.

Consider, however, the case where a broad-band resonator, with broad-band reflectors without a grating, is used. In this case, the free-running pulsed CO<sub>2</sub> laser will

(1 atm + 101.3 kPa)

oscillate on its highest gain P(18) line of the 10.6  $\mu\text{m}$  band. With the injection locking, it is possible to extract the laser energy from such a laser at the frequencies of the  $\text{CO}_2$  lines appreciably removed from the P(18) lines. For instance, with an available 25 mW driver power, the laser energy from the broad-band laser can be extracted on lines considerably removed from P(18), up to P(14) on one side and up to P(34) on the other side.

Consider now a high pressure pulsed  $\text{CO}_2$  laser with a grating resonator. Assume the grating to be tuned so that free-running oscillation occurs at frequencies appreciably removed from line center. In this case, the free-running oscillation will occur uncontrollably over a large number of modes. With tens of microwatts available driver power, single mode energy extraction in the region of the peak of the grating response can be obtained. This would require a tight cavity matching corresponding to a detuning  $(\omega - \omega_c)$  below about 200 kHz. For an available driver power of about 10 milliwatts, cavity detuning as large as 20 MHz can be readily tolerated.

Considerable work is done on line-center injection locking, using an external CW low-pressure  $\text{CO}_2$  laser, to obtain information on frequency stability and chirping for Doppler wind velocity measurements. We have established that by employing appropriate cavity matching and a suitable warm-up time, and a rugged resonator structure (mechanically decoupled from the  $\text{CO}_2$  laser plasma chamber), pulse-to-pulse frequency jitter of the injection locked laser with respect to the injected radiation remains below several hundred kHz and that the chirping of the injection locked laser during the pulse (for a  $> 1 \mu\text{sec}$  pulse) can

be kept below about 200 kHz/ $\mu$ sec. (Note: A Doppler shift of 200 kHz corresponds to a velocity of 1 m/sec.) Longer duration pulses at reduced chirping are obtainable by preionization below the breakdown voltage, by N<sub>2</sub> rich CO<sub>2</sub>-N<sub>2</sub>-He gas mixtures and/or by laser operation below 1 atmosphere. We have also considered improving the accuracy for Doppler wind velocity measurements by comparing the heterodyned frequency spectrum of a transmitted pulse (with its chirping characteristics) with the frequency spectrum of the returned signal (also observed by heterodyning). Joint evaluation with LaRC personnel indicates that use of information inside the pulse would require a very high signal to noise ratio per pulse.

In another significant experiment, we are able to show that a high-pressure CO<sub>2</sub> laser, at a low output power level of below tens of millijoules per pulse, can be used with an external passive frequency filter as a driver for high stability injection locking of an energetic pulsed CO<sub>2</sub> laser at a tunable frequency. In this arrangement injection locking can be obtained at a well controlled tunable monochromatic frequency mainly determined by the properties of the passive external frequency filter.

In addition to the above we have analyzed for NASA LaRC a number of approaches to utilize the transient injection locking for detection of pollutants and applications to Doppler wind velocity measurements. These include the utilization of simultaneous injection of several CW or pulsed laser lines or model in which the output of an injection locked laser controllably appears over a selected number of equally spaced laser lines or resonator modes. This is useful for simultaneous probing (with each transmitted laser pulse) "on" and "off" pollutant absorption lines in the Differential Absorption Lidar

(DIAL) for remote sensing. Further investigations of 3 atmospheres tunable multiline or multimode injection are being made.

The LDC results are consistent with theoretical analysis of Transient Injection Locking and earlier experiments by R. Sheffield, S. Nazemi, and A. Javan at MIT; the MIT work, however, emphasized controlled multifrequency TIL.\*

We have examined in detail several methods based on heterodyning approaches for frequency calibration and pre-selected laser frequency setting.

Work has been done to obtain a high resolution spectrum of a CO<sub>2</sub> absorption line with a high pressure CO<sub>2</sub> laser followed by a passive frequency filter.

In addition to the above, the work performed has included reconstructions of the power supply of the high-pressure CO<sub>2</sub> laser developed in the first phase of the LDC work under NASA LaRC sponsorship (NASA contractor report 3175). This was done in two stages. The first stage was a reconstruction of the power supply (with fixed energy storage capacitors) for laser operations up to 10 atmospheres. In the second stage, this was modified for operation up to a 3-atmosphere pressure. These changes were dictated following the modeling studies at NASA LaRC. These studies indicated that laser operation at pressures up to 3 atmospheres provides an adequate frequency tuning for NASA's applications. (A wider frequency tuning can be obtained at such pressures by operating with isotopic CO<sub>2</sub> molecules. This resulted in a considerable design simplification relating to laser power supply and its optimal coupling to the CO<sub>2</sub> laser plasma.

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\*Line center TIL also has been previously investigated by United Technology Corp. and groups in Canada.

Considerable attention is given to find a suitable tunable laser master oscillator for driving transient injection locking of an energetic tunable high pressure pulsed CO<sub>2</sub> laser. The successful demonstration in this progress report of transient injection locking with a tunable high pressure pulsed CO<sub>2</sub> master oscillator laser is very promising, but requires a separate CW tunable laser local oscillator for heterodyning the delayed DIAL return signal. Such tunable local oscillators are available from passive heterodyne radiometer experiments at LaRC, e.g., tunable lead salt diode lasers now in use, and microwave side band modulated CW CO<sub>2</sub> lasers under development. However, use of a CW tunable laser master oscillator is highly desirable with sufficient (if low) power to serve both as local oscillator for heterodyning as well as driver for transient injection locking with large detuning from line center and from cavity modes of an energetic pulsed CO<sub>2</sub> laser (use of a low power tunable CW diode laser would require tight ring-cavity control and small  $\delta = (\omega - \omega_0) / \Delta\omega_c$ ). For this purpose a CW tunable high pressure CO<sub>2</sub> laser is being developed. This development has included experimental tests of individual components and a design of a mini E-beam CO<sub>2</sub> laser capable of CW operation at pressures up to 3 atmospheres. In addition to the considerations related to sustaining a uniform CW high-intensity plasma at several atmospheres pressure (in a flowing gas), considerable work is done towards the design of an electron gun (utilizing a plasma cathode) capable of supplying the needed (100  $\mu\text{amp}/\text{cm}^2$ ) primary electrons in the high pressure gas. In the CO<sub>2</sub> laser plasma, the primary electrons, after multiplication by a multistep secondary ionization process, provide an electron density in excess of  $10^{12}$  cc needed for operation of the laser. This is produced in

a pencil-like thin ( $0.1 \times 0.1 \text{ cm}^2$ ) and long (10 cm) laser volume. An applied sustainer voltage at a value below the avalanche breakdown in the gas will heat the electron temperature to an optimum value for excitation of the  $\text{CO}_2$  levels (in a suitable  $\text{N}_2$ - $\text{CO}_2$ -He mixture), as in previous pulsed E-beam,  $\text{CO}_2$  lasers. The CW performance is achieved by rapid gas recirculation, to remove the heat energy deposited in the gas and to prevent arc formations.

#### Future Work

Based on computer simulations performed at LaRC for atmospheric pollutants/trace constituents  $\text{NH}_3$ ,  $\text{H}_2\text{O}$ ,  $\text{O}_3$ , a tunable three atmosphere transverse flow repetitively pulsed closed cycle  $\text{CO}_2$  and rare isotope laser is being designed for aircraft operation. The laser average power is  $\sim 15 \text{ W}$  with pulse energies  $\sim 50 \text{ mJ/pulse}$  and pulse repetition rates of  $\sim 300 \text{ pps}$ ; and will be scalable for operation at higher pulse energies and correspondingly lower pulse repetition rates. Also included are provisions for long term stabilization with interlocking and automatic frequency tracking of the tunable pulsed laser cavity and the tunable master oscillator; and mechanical isolation of the cavity structure from the plasma chamber.

The electron gun and ionization of a 3 atm laser plasma will be demonstrated, and a design provided of the CW tunable  $\text{CO}_2$  laser.

#### Month by Month Account of the Progress; October 1, 1977 to January 30, 1979

October 1977

During this period considerable work was done to evaluate the application of the novel transient injection locking of a tunable monochromatic pulsed  $\text{CO}_2$  laser for NASA's missions in

remote atmospheric sensing of pollutants. This work included an extensive estimate of the refractive index variation (which can cause frequency chirping) in a gain-switched high-pressure CO<sub>2</sub> laser and its influence on power amplification when this laser is used as super regenerative amplifier of a weak injected radiation. In addition to this work, considerable progress was made in a parametric study of multifrequency energy extraction from a gain-switched high-pressure CO<sub>2</sub> laser. In this study, weak radiation fields at two different pre-selected CO<sub>2</sub> transitions are introduced into the resonator of a gain-switched CO<sub>2</sub> laser. This injection locking effect at both injected frequencies is studied versus the relative intensities of the two injected fields (the weak field radiations were provided by low-pressure CO<sub>2</sub> discharge cells placed inside the grating resonator of the gain-switched laser). This work is done for application of the multifrequency laser to Differential Absorption Lidar (DIAL) studies, as well as in simultaneous probing of several absorption lines in the atmosphere. An optical resonator configuration is designed for a two-frequency output.

November 1977

Work in the area of multifrequency transient-injection locking (super regenerative amplifications) at tunable frequencies is continued in this period. Parametric studies are performed to examine the stability of a two-frequency operation. It is shown that when the intensities of the injected fields at the two frequencies exceed threshold values, the relative intensities of the output radiations at the two frequencies become insensitive to the exact amplification of an injected field. In addition, considerable theoretical work is performed

to evaluate the extent of frequency chirping during each laser pulse and the effect of resonator instability causing pulse-to-pulse frequency fluctuations. It is shown that for important applications, it will be necessary to stabilize the resonator of the gain-switched CO<sub>2</sub> laser against an external reference frequency to eliminate the long-term drift. Several optical resonator arrangements and servo controls are designed and inspected to achieve the necessary long-term resonator stability.

December 1977 and January 1978

During December and the month of January, design criteria were established to upgrade the performance of the LDC-NASA 10 atmospheres pulsed laser. A preliminary design study was undertaken with the aid of an independent high voltage engineering consultant. This resulted in engineering sketches and specifications for a 150 kV Marx generator operable at a 10 Hz repetition rate. A preliminary design was developed for the requisite gas recirculation system including pump, catalytic purification system, and gas temperature control. The objective has been to use fixed capacitor impedance matched to the CO<sub>2</sub> plasma at 10 atmospheres. The previous design (using a large number of doorknob capacitors placed in parallel) was intended to allow changing the total capacitance for impedance matching with the CO<sub>2</sub> plasma at varying pressure. We now find that the capacitance of a doorknob capacitor decreases as a function of time. This also dictated the desirability of upgrading the design.

Preparation was made for an extensive report of the transient injection locking process to NASA. A detailed (173 pages) unsolicited LDC proposal "Development of High Average

Power Closed Cycle Multi-Atmospheric CO<sub>2</sub> Lasers at Finely Tunable Monochromatic Frequencies for NASA Space Applications" was submitted to LaRC.

February 1978

Engineering details for the 10 Hz Marx generator were finalized in this month and final engineering drawings completed. Bids were solicited from suppliers for the required high voltage components. Construction of both "in-house" and contracted fabricated Marx bank components was begun.

The transient injection locking for a CO<sub>2</sub> pulsed oscillator at a tunable frequency is further analyzed. Emphasis was placed on further estimating the effect of frequency chirping and resonator mismatching (for external injection locking). The result is compared with the use of a multipass amplifier for high-gain power amplification, including the effect of refractive index variations of the multipass amplifier.

March 1978

During this month, experiments were undertaken to establish the bandwidth of a high-pressure pulsed laser as a function of gas pressure, gas composition, and electrical energy loading. A high Q-scanning Fabry-Perot interferometer was used in conjunction with a multiple exposure oscilloscope photographic system to produce direct graphic representation of laser bandwidth. The use of this pulsed laser and Fabry-Perot filter combination was considered for use as high resolution remote sensing device. Design of a complete remote sensing experiment was completed.

Considerable work was done on the PZT timer of the high Q Fabry-Perot interferometer. This work included reconstruction of the unit to obtain a more accurate tuning control.

April 1978

Marx bank triggering and timing electronics were designed and components obtained. Construction of both the electronics and assembly of the Marx bank physical structure were begun.

Preparations were made for transient injection locking experiments. The plans include experiments with an external driving radiation source used for the injection locking. The resonator frequency mismatching was considered theoretically.

May 1978

Experimental work centered on off-line center transient injection locking of a pulsed CO<sub>2</sub> laser. A CW N<sub>2</sub>O laser was built and made to oscillate on a line which overlaps a collision broadened CO<sub>2</sub> line. This was used in injection locking of the CO<sub>2</sub> pulsed laser at a frequency detuned from CO<sub>2</sub> line center. The effect was studied using the CO<sub>2</sub> gas pressure in the injection locked CO<sub>2</sub> laser.

A design of a closed cycle isotopic CO<sub>2</sub> laser was considered and analyzed at length to assess the possibility of operating on a wider range of pollutant absorption lines and, if needed, provide continuous tuning across collision broadened lines, at pressures below 10 atmospheres.

June 1978

Marx bank assembly and shielding was designed and constructed. High voltage trigger circuitry was debugged and Marx bank performance characterized by parametric studies.

High-gain power amplification at a tunable frequency was further analyzed and compared to other means (multipass) power amplification. Aspects relating to frequency chirping were considered in relation to applications for high-precision Doppler lidar.

July 1978

Work was begun to set up an experiment for pulse injection locking of a high-pressure regenerative amplifier. The system consists of a broadly tunable pulsed CO<sub>2</sub> laser whose output bandwidth of ~2000 MHz is considerably reduced by a high finesse Fabry-Perot interferometer. The narrow band pulse is injected into the regenerative amplifier at the instant of onset of field growth within the amplifier.

Further work was done on the Marx bank power supply. This work completed construction of this power supply. A short CW CO<sub>2</sub> laser discharge for internal injection locking and laser alignment was also constructed.

Various aspects of transient injection locking at a tunable frequency off CO<sub>2</sub> line center have been analyzed.

August 1978

Experiments with the pulsed injection laser were continued this month. Successful broad-band injection was clearly demonstrated. For this experiment the Fabry-Perot filter was bypassed and output of the injecting laser was introduced directly into the power oscillator. A very long oscillator cavity was chosen to simplify mode matching problems. It was observed that the frequency of the regenerative amplifier was forced to follow that of the oscillator over a wide tuning range amounting to 10 CO<sub>2</sub> transitions. This behavior is in agreement with detailed theoretical analysis of the problem.

It verifies the expected utilization of this system to achieve injection locking at a tunable frequency with a high-pressure CO<sub>2</sub> laser at a low energy per pulse used as the primary driving oscillator at a tunable frequency.

A balanced system to perform atmospheric observation of a pollutant is designed and analyzed. In this system, the transmitted laser radiation pulse is compared with the laser return, using a single detector and a gated detection unit.

September 1978

Real-time investigation of the frequency behavior of an injection locked CO<sub>2</sub> laser pulse was performed using a heterodyne technique. A stable CW line-tuned CO<sub>2</sub> laser was used to injection lock a pulsed laser. Mode matching was achieved by PZT adjustment of the pulsed laser cavity. Only a small fraction of the CW laser output was directed into the pulsed laser cavity. A large fraction of the CW radiation was split off with a beam splitter and made co-linear with the pulsed laser output; those two co-linear beams were directed onto a fast detector. With proper cavity matching, the clear beat note was observed to be superimposed on the characteristic pulse shape. Analysis of photographs thus obtained give detailed information about pulsed laser frequency at any time during the pulse; this analysis is in progress.

The design and construction of the stable line-tuned CO<sub>2</sub> laser for use as a local oscillator has been an important part of the work performed.

The possibility of achieving transient injection locking with an injected short pulse duration  $\tau_{\text{pulse}}$ , and correspondingly larger bandwidth ( $\tau_{\text{pulse}} \times \text{bandwidth} \geq 1$ ) has been further analyzed. For a very short duration large bandwidth pulse

(including  $\approx 3$  cavity modes) the output of the injection locked laser would appear as a mode locked laser. This feature has a number of important applications in NASA's mission relating to detection of atmospheric pollutants. These applications have been discussed in detail with LaRC personnel.

October 1978

The frequency behavior of an injection locked TEA laser was examined during the pulse duration via an optical heterodyne technique. A stable, discrete line-tuned CW CO<sub>2</sub> laser was used both as a source of radiation for transient injection locking of the pulsed laser and also as the local oscillator in the heterodyne detection system. Extreme care was exercised in alignment to ensure parallel wavefronts for the local oscillator at pulsed emission from the pulsed laser. Chirping of several MHz was noted during the approximately 3  $\mu$ sec pulse duration. A possible explanation for this behavior is that feedback from the pulsed laser to the local oscillator pulls the L.O. frequency. A ring resonator arrangement for the injection locked oscillator will eliminate the difficulty.

November 1978

A ring cavity was provided for the pulsed laser. An external suppressor mirror was aligned to provide feedback into the one travelling wave mode of the cavity. Mode competition suppressed the counter-rotating mode and we have obtained a unidirectional output. After an initial brief transient, on the order of the cavity ringing time, there can be no feedback into the CW local oscillator. Using this arrangement, stable beat notes were observed with chirping as low as several hundred

kHz per microsecond. Chirping was observed to go both to higher as well as lower frequencies. The frequency of the beat note could be fine tuned via PZT length adjustments of the local oscillator.

The Marx bank power supply is reconverted to a single stage supply to drive the CO<sub>2</sub> laser at pressures up to 5 atmospheres. This modification is introduced following the recent instructions from the work statement. The NASA mission only requires CO<sub>2</sub> laser operation at pressures up to 3 to 4 atmospheres. This has considerably simplified the power supply design. We have extensively investigated the use of isotopic CO<sub>2</sub> in a sealed off laser, with a catalyst to regenerate the CO<sub>2</sub> molecules.

December 1978

A scanning Fabry-Perot filter was constructed to analyze the output of a 1 atmosphere pulsed laser. An intracavity CW CO<sub>2</sub> laser was included in the pulsed laser cavity to permit accurate alignment of the Fabry-Perot and to allow the direct measurement of the filter finesse as 25; the free spectral range was 5 GHz giving a resolution of 200 MHz. A scan of the free running TEA laser (with the intracavity CW laser turned off, no grating in the cavity) revealed that two CO<sub>2</sub> lines oscillated simultaneously; each had a measured width of 1.5 GHz due to multimoding. With the pulsed laser transient injection locked via an external CW laser, single mode operation was observed (utilizing Fabry-Perot spectral analysis).

A high resolution absorption line in heated CO<sub>2</sub> was observed using the broad-band TEA laser and the Fabry-Perot filter. The filtered output of the Fabry-Perot was passed through a 1-meter-long hot cell containing 70 torr\* CO<sub>2</sub>. The

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(1 torr + 133.3 Pa)

temperature of the cell was 150°C. A balanced detection scheme was used; a portion of the infrared pulse entering the cell was split off to a detector and the amplitude recorded. The intensity passing through the cell was measured by a second detector and also recorded. These data were numerically processed to produce a normalized absorption curve. By careful alignment of the Fabry-Perot, it was possible to increase the finesse to 60 giving a resolution of 80 MHz wide absorption dip which is correct for the given conditions of temperature and pressure. This is the first high resolution observation from an absorption line (with a resolution below 80 MHz) using a high pressure CO<sub>2</sub> laser. The ~80 MHz, 10 mJ/pulse laser was also used for transient injection locking of an ~1 J/pulse CO<sub>2</sub> laser.

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A very high gain pulsed laser plasma tube and power supply combination were set up in a conventional two mirror resonator. One mirror was made of lossy P-doped germanium, A.R. coated on the front surface and total reflection coated on its back surface. Such a mirror introduces a nonlinear loss into the cavity and forces the laser to operate in a mode locked configuration. The output spectrum was scanned using a Fabry-Perot filter of approximately 100 MHz resolution.

The objective is to use a high resolution frequency filter at the output of this mode locked laser. Preparation is underway to obtain high resolution absorption spectrum (in hot CO<sub>2</sub> as well as in an ammonia gas) using a tuned filter at the output of the mode locked laser. This system is being explored for use as highly stable driver for injection locking of a high pressure CO<sub>2</sub> laser at single or multimode tunable frequency.

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16 Abstract  The paper reports several critical experiments for high gain power amplification by Transient Injection Locking (TIL) of a pulsed tunable up to 3 atm CO <sub>2</sub> laser. (1) Investigation of process at frequencies detuned from CO <sub>2</sub> line center of a pulsed tunable high pressure CO <sub>2</sub> laser and parametric studies for Differential Absorption Lidar (DIAL) applications. (2) Establishment of ultimate frequency purity and pulse-to-pulse frequency stability for line center TIL used in Doppler Lidar. (3) Determination of resonator frequency stability of a compact repetitively pulsed TIL CO <sub>2</sub> laser with an external tunable laser master oscillator as driver. (4) Evaluation of several frequency tunable master oscillators for TIL of an energetic tunable high pressure pulsed CO <sub>2</sub> laser. (a) A free-running tunable high pressure pulsed CO <sub>2</sub> laser followed by an external passive filter which generates a weak single mode pulse at tunable frequency. (b) A CW high pressure, small volume, CO <sub>2</sub> laser sustained by a mini E-beam. Experimental tests of individual components and a design analysis is performed.					
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