A high stability TEA CO$_2$ laser system

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The many different TEA CO$_2$ laser designs that have been published, usually suffer from defects affecting amplitude and frequency stability. These problems are examined, and the effectiveness of various solutions discussed. A system designed to minimise these limitations is described. The system will generate pulse powers of several hundred KW in a single axial mode, with an amplitude stability of ±4% at pulse repetition frequencies up to 100 pps over the 10.4µm band. A novel power limiter based on InSb is described that will further increase pulse to pulse reproducibility considerably. Existing limitations are discussed together with future improvements.

1 Introduction

Since it was first reported in the scientific literature, the transversely excited atmospheric (TEA) CO$_2$ laser (Beaulieu 1970) has been the subject of much research and development, so that in theory at least the design of any given system can be calculated with a fair degree of confidence.

Improved techniques for generating large volume glow discharges have led to systems generating laser pulses with very high powers and energies (Richardson et al. 1973a). In order to be useful as a scientific tool however, the various parameters must be strictly controlled. Typical drawbacks of TEA systems are poor pulse to pulse reproducibility, mode beating resulting in high frequency amplitude modulation, poor spatial uniformity and low pulse repetition frequency (PRF).

The various factors affecting stability will be examined, and a laser system designed to minimise the above limitations will be described. Some preliminary results will be given together with a discussion of possible future improvements. The system was designed to be used as a pump for a spin flip Raman laser where any instability in the pump laser amplitude or frequency is reflected in the Raman laser output.

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2 Limitations on stability

2.1 Pulse to pulse reproducibility

If we assume the laser cavity to be infinitely stable, then amplitude variations between laser pulses will be due to fluctuations in the gas discharge. When the discharge is initiated, gain builds up as the N$_2$ molecules (having been vibrationally excited by electron impact) transfer energy to the CO$_2$ molecules via vibrational resonance. The time constant of this effect at atmospheric pressure is $\sim$ 550 ns and is the principal cause of the characteristic delay between the start of the discharge and the laser pulse (Smith et al. 1975). As the gain rises above threshold, the laser flux builds up from spontaneous emission but because it rises faster than the laser flux, the latter builds up rapidly to an intense spike whose height is determined by the available population inversion. Since the photons build up exponentially, the peak power is a rapidly varying function of population inversion. It might be expected therefore that even though there is some limiting present due to gain saturation, the peak laser power will be very sensitive to small changes in the gain and hence the gas discharge from shot to shot.

A typical CO$_2$ laser gas mixture consists of 70–80% He with 10% each of CO$_2$ and N$_2$. Since the gas is initially unionised it is in an insulating state, and will not easily support the distributed glow discharge which is required for population inversion. To do this it is first necessary to make the gas conducting by preionising it, and on the efficiency of this will depend the stability of the main discharge. Various methods for preionisation exist. Cathode photoemission by UV generated with an auxiliary wire discharge (Pearson and Lamberton 1972) provides a simple effective system, but volumetric photoionisation by UV from a secondary arc discharge can improve the efficiency several times (Richardson et al. 1973b). An alternative method injects electrons from a high power electron beam directly into the discharge volume; although efficient this method is costly and requires elaborate vacuum and high voltage engineering.

It has been shown (Kline & Denes 1975) that in order to establish a homogeneous discharge it is necessary for the density of preionisation to be constant only in a plane perpendicular to the applied electric field direction, since

space charge effects take care of non-uniformities in any vertical plane.

2.2 Spatial uniformity

A major cause of optical damage in TEA CO$_2$ laser components is the existence of 'hot spots' in the spatial profile of the beam. These are usually due to the complicated spatial mode structure that appears if the laser mode volume is not confined in the transverse direction. To provide a smooth gaussian profile, it is necessary to limit oscillation in the cavity to the lowest order transverse mode only, the TEM$_{ooq}$ axial modes. This can be achieved either with a stable resonator and suitable aperture, or an unstable resonator for probing large volumes. Spatial uniformity will also depend on the gain uniformity of the discharge; it is known that the gain in a double Rogowski electrode system falls off in the transverse direction parallel to the electrodes.

2.3 Temporal uniformity

The pressure broadened gain bandwidth of the TEA CO$_2$ laser gas is ~ 4 GHz, so that in a typical resonator length many TEM$_{ooq}$ modes can oscillate simultaneously. Any non-linear interaction in the cavity can phase lock these modes together thus modulating the output pulse envelope at the round trip frequency of the cavity. This effect usually changes from pulse to pulse, and can result in the peak power changing by more than 100% between pulses, even though the pulse energies are equal. Although an intra-cavity etalon can be used to suppress all but one axial mode (Weiss and Goldberg 1972), a very elegant method has been suggested (Gondhalekar et al. 1973) where a low pressure amplifier shares the laser cavity with the TEA section. Due to its much lower bandwidth, the low pressure amplifier provides gain on only one axial mode, which is then amplified by the TEA section. With the low pressure amplifier gain below threshold, the TEA output is in the form of the usual gain switched pulse without any modulation.

2.4 High repetition rate limitations

For TEA laser applications where measurements can be made with a single pulse on a 'one off' basis, a PRF of a few pps is quite adequate. However in many cases the rate of data acquisition is directly proportional to the repetition rate. This would indeed be the case where a TEA laser was being used to pump a spin flip Raman laser where the tuning rate would be limited to one pulse bandwidth per pulse. Clearly a high PRF reduces the time required to scan a given frequency interval. A number of high repetition rate TEA CO$_2$ lasers have been reported (Beaulieu 1970, Turgeon 1971, Pearson et al. 1973). In most cases a closed loop gas recirculation system was used and laser output was found to drop over a period of time, a typical value being 25% within 10 minutes for a laser operating at 110 pps (Hamilton et al. 1975). The various explanations for this effect include accumulation of dissociation products particularly CO (Turgeon 1971), and formation of negative ions (Hamilton et al. 1975). The drop in output can be reduced by increasing the gas bleed rate (slow bleed of fresh gas into the system), but this is not very economic at high bleed rates. A promising approach seems to be to adopt techniques used for completely sealed off lasers (Stark et al. 1975). By careful

choice of electrode material, and additions to the laser gas of small quantities of CO and H$_2$, the successful operation of a sealed system at 2 pps for $> 2 \times 10^6$ shots has been obtained. By adding small amounts of CO to a 25 pps TEA CO$_2$ laser, the required gas bleed through can be reduced by a factor of 10 (Walker 1976).

2.5 Cavity stability

If the methods outlined in 2.3 are to be used to achieve single axial mode operation, and indeed to satisfy the first part of 2.1, it becomes necessary to adopt all the techniques that are used with precision CW lasers to maintain a stable cavity. Although the TEA laser is pulsed, the cavity must remain aligned with one axial mode in the centre of the low pressure amplifier line width. The use of Invar as a temperature stable cavity reference, and differential screw micrometers for fine mirror adjustment are not usually associated with TEA systems, but are essential for long term stability in this case.

2.6 Active power limiting

The band gap of indium antimonide (InSb) is less than the combined energy of two 10.6μm photons, so that InSb acts as a two-photon absorber for CO$_2$ laser radiation. Since the absorption is proportional to the square of the intensity, a thin slice of InSb can be used to attenuate high power pulses, while transmitting low power ones. This effect can be used to reduce the variation in laser output power between pulses. A smoothing factor S can be defined (Gibson et al. 1976) where

$$S = \frac{\Delta I_{in}}{I_{in}} \bigg/ \frac{\Delta I_{out}}{I_{out}}$$

I_{in} and I_{out} are the intensities before and after transmission through the InSb slice; ΔI_{in} is the variation in pulse power. S is given by

$$S = \frac{\exp(-2KL)}{T^2},$$

where

$$T = \frac{I_{out}}{I_{in}} . (T < 1)$$

K is the linear absorption coefficient and L is the thickness. For efficient smoothing, we require KL to be small so that minimum absorption InSb with an equilibrium carrier density of 10^{17} electrons cm^{-3} should be used. T should also be small.

3 Apparatus

3.1 Hybrid cavity TEA laser

A system has been designed around the various requirements of section 2. It consists of a TEA module and low pressure section sharing a cavity which can be length stabilised with Invar (Fig. 1). The optical resonator consists of a gold coated blazed diffraction grating and a 65% reflecting 8m radius of curvature Ge output coupler. The low pressure section is an 80 cm long 2 cm I.D. water cooled pyrex tube with tungsten electrodes.

The TEA module consists of a 40 cm long Rogowski profiled cathode, facing a copper grid anode. The Rogowski
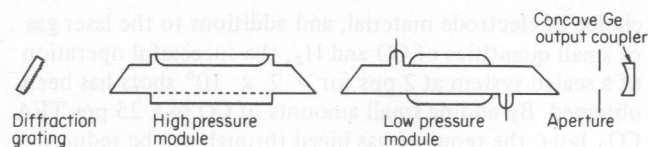
Fig. 1   Schematic diagram of cavity

electrode is 2.5 cm wide and the electrode separation is 1 cm. Behind the anode different preionisers can be placed (Fig. 2). Gas can be circulated using two centrifugal blowers, with a velocity of 35 m s^{-1} in the laser region, estimated from the manufacturer's duty curves. This corresponds to 1000 gas
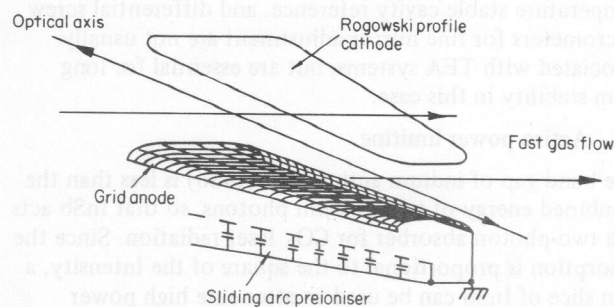

Fig. 2   TEA electrode system

changes per second between the electrodes. The gas passes into the laser via a flow straightener and then through a water cooled heat exchanger back to the blowers. A slow bleed of fresh gas at 3 litres min^{-1} is supplied. The laser is energised with a double thyratron modulator using diode inductive capacitor charging which can operate at up to 100 pps (Fig. 3). The preioniser and main discharge circuits are completely independent and are timed so that the main discharge fires typically 1 μs after the preioniser.

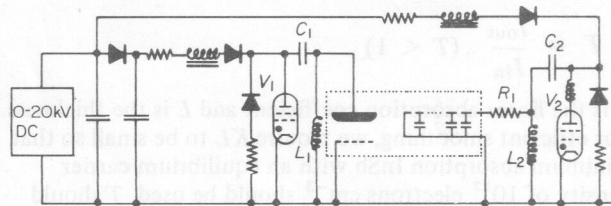Fig. 3   Charging and discharging circuits. C_1 = 0.02 μF, C_2 = 0.01 μF, $L_1 = L_2 = 100 \mu$H, $R_1 = 15\Omega$, V_1, V_2 deuterium thyratrons

Two different preionisers were tested. The first was a modified version of a type developed by Canadian workers (Richardson et al. 1973a) and consisted of a double row of 200Ω resistors connected to a common cathode, and arranged so that a discharge occurred between the resistor wires and the grid anode. The second was of the "sliding arc" type (Richardson et al. 1973b). This used 17 electrodes made from galvanised steel each coupled to the anode via a 180 pF capacitor. When energised a row of arcs was lit between the individual electrodes (Fig. 2).

3.2   InSb power limiter

Some 100μm thick by 1 cm diameter InSb slices were antireflection coated, and placed in a holder that could be translated along the optical axis of a 5 cm focus Ge lens through which the laser light passed (Fig. 4). Photon drag detectors before and after the device could monitor I_{in} and I_{out} simultaneously.
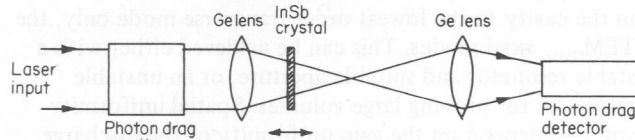

Fig. 4   Construction of InSb limiter

4   Results

4.1   Preioniser

Although both preionisers provided stable glow discharges, the first type using a resistor array resulted in a main discharge with visible structure corresponding to the individual resistor discharges. Because of this, and also because cooling the resistors would have caused a problem at high PRF, the sliding arc preioniser was used for all subsequent work. This produced a stable uniform glow discharge showing no tendency to arc at the highest input energies used.

4.2   Laser output

The TEA section was filled with a mixture of 70% He, 20% CO_2 and 10% N_2. The CW section was evacuated and filled with 8 parts He to 2 parts N_2 with a small amount of CO_2 reduced to the point where the CW section just stopped lasing. With a charging voltage of 30 KV and a main capacitor value of 0.02 μF, 500 KW pulses were obtained at 11 pulses per second on the P20 line of the 10.4 μm band of CO_2, falling to 110 KW and 280 KW on the P8 and P28 lines respectively. Fig. 5 shows a typical pulse. With reduced charging voltage, the laser was operated at 100 pps, and a 1 second exposure of 100 consecutive shots is shown in Fig. 6. The reproducibility is estimated to be ± 4%. A photon drag detector with 1 ns response time and a 400 MHz oscilloscope were used for these measurements.

It can be seen from Fig. 5 that the residual mode beating is very small; it is however very sensitive to mirror alignment. This can be understood by the following argument. The bandwidth of the low pressure section is chosen to be equal to the axial mode spacing. If one mode is at the centre of the linewidth, the two adjacent modes will be in a region of much lower gain at the line edges. This is the condition for single mode operation. If the mirror adjustment is such that two adjacent modes occupy positions either side of the line centre, then both can be amplified by the TEA section and the output pulse will be sine wave modulated. This is the observed pulse shape when alignment is incorrect.

The laser was operated at 20 pps with a charging voltage of 26 KV for 90 minutes, and the output observed with a
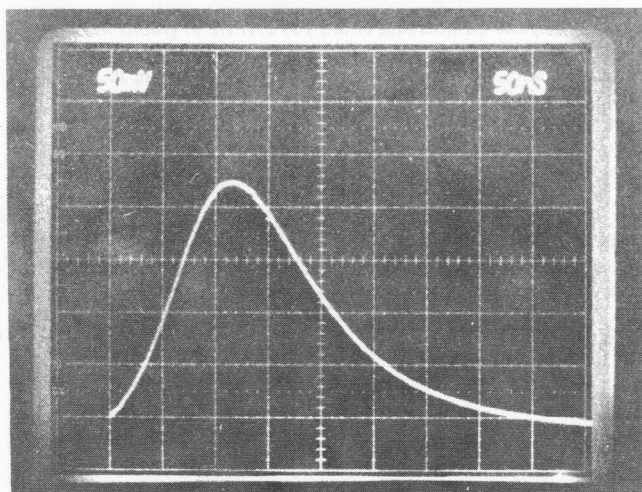
Fig. 5   Single laser pulse. Vertical scale 100 KW per division, horizontal scale 50 ns per division
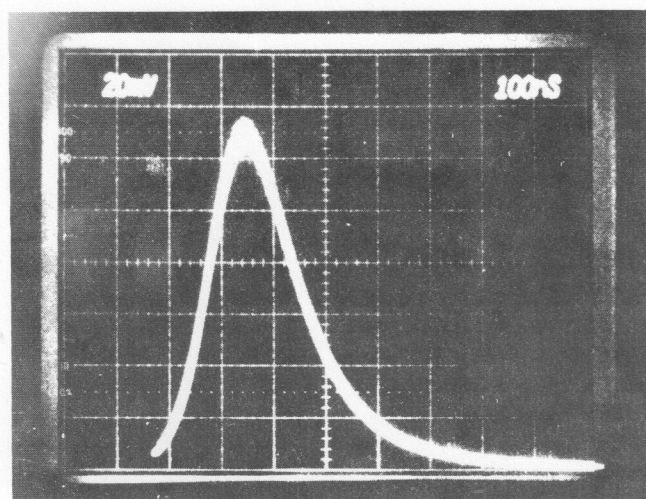

Fig. 6   1 second exposure, with the laser operating at 100 pps. Vertical scale 20 KW per division, horizontal scale 100 ns per division
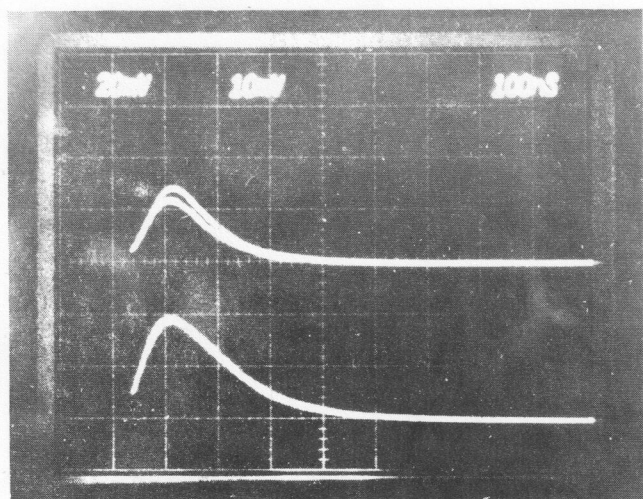

Fig. 7   1 second exposure; laser operating at 10 pps. Upper trace, modulated laser output, average power 2000 KW. Lower trace, limited output, vertical scale 30 KW per division. Both traces horizontal scale 100 ns per division

thermopile and chart-recorder. The short term variations were less than 4% but the output fell over the first hour by 20% and then became approximately constant. The bleed rate was 3 litres min $^{-1}$ as before. When operated at 100 pps with the same charging voltage, the laser output dropped by 20% in 20 minutes.

4.3 InSb limiter

The InSb limiter was used at the laser output as shown in Fig. 4. In order to facilitate measurement, the output was modulated by attenuating each alternate pulse by about 25% using a synchronised chopper with polythene blades; the laser output as measured by a photon drag monitor (response time ~ 3 ns) is the upper trace in Fig. 6, the lower trace is the limited output measured by a second photon drag detector. The laser repetition frequency was 10 pps and the photograph shows a 1 second exposure of 10 consecutive shots as displayed on a 400 MHz dual beam oscilloscope. The limited pulse power is reduced from 200 KW to 60 KW, but the reproducibility is improved by a factor of at least 5. The technique is limited by the thermal capacity of the InSb slice at present to PRF of ~ 10 pps. Since the absorption is dominated by generated free carrier absorption, the limiting mechanism is tied to the free carrier lifetime, which is ~ 5 ns in the material used. Thus the device will only limit pulses which contain no time variations of 5 ns or less. This condition is easily satified by the laser described.

5   Discussion and conclusion

A TEA CO₂ laser system has been demonstrated, which generates single axial mode pulses with peak powers of several hundred KW over the 10.4 μm band from the P8 to the P28 lines at pulse repetition rates up to 100 pps. Short term power stability between pulses is better than ± 4%, and the laser will run for extended periods at 20 pps using only 3 litres min $^{-1}$ of fresh gas.

Long term laser output stability is strongly affected by fluctuations in the local power line voltage, which are typically 5% during a working day. Several methods of solving this problem are under review. Long term stability is also affected by dissociation products accumulating in the gas system, and it is hoped that the solutions outlined in 2.4 will prove successful in reducing the effects of this problem.

The preioniser is to be rebuilt using tungsten electrodes with a larger and better distributed electrode array, to improve the spatial homogeneity of preionisation.

The InSb limiter can be modified for high PRF by improving the cooling of the crystal. A possible solution might be to optically sandwich the InSb between two Ge etalons which could then be edge cooled.

In conclusion, the various parameters that affect the pulse stability of a TEA CO₂ laser have been examined, and a system has been designed to reduce instabilities to a minimum. Some preliminary results have been given together with possible future developments.

6   Acknowledgements

7 References

Beaulieu, A.J., 1970, *App. Phys. Lett.* Vol. 16, pp 504-505 .

Gibson, A.F., Hatch, C.B., Maggs, P.N.D., Tilley, D.R., and Walker, A.C., 1976, to be published.

Glanford, C.W., Paris, M.F., Pearson, P.R., and Tyte, D.C., 1973, given at the 1st National Quantum Electronics Conference 11-13 September, 1973, University of Manchester.

Gondhalekar, A., Holzhauer, E., and Heckenberg, N.R., 1973, *Phys. Lett.,* Vol. 46A, pp 229-230.

Hamilton, D.C., James, D.J., and Ramsden, S.A., 1975, *J. Phys. E. Sci. Inst.,* Vol. 8, pp 849-852.

Kline, L.E., and Denes, L.J., 1975, *J. App. Phys.,* Vol. 46, pp 1567-1574.

Pearson, P.R., and Lamberton, H.M., 1972, *IEEE J. Quant. Elec.,* Vol. 8, pp 145-149.

Richardson, M.C., Alcock, A.J., Leopold, K. and Burtyn, P., 1973a, *IEEE J. Quant. Elec.,* Vol. 9, pp 236-243.

Richardson, M.C., Leopold, K. and Alcock, A.J. 1973b, *IEEE J. Quant. Elec.,* Vol. 9, pp 934-939.

Smith, A.L.S., Bett, T.H. and Browne, P.G., 1975, *IEEE J. Quant. Elec.,* Vol. 11, pp 335-340.

Stark, D.S., Cross, P.H. and Foster, H., 1975, *IEEE J. Quant. Elec.,* Vol. 11, pp 774-778.

Turgeon, M.F., 1971, *IEEE J. Quant. Elec.,* Vol. 7, pp 495-497.

Walker, B., 1976, Private Communication.

Weiss, J.A. and Goldberg, L.S., 1972, *IEEE J. Quant. Elec.,* Vol. 8, pp 757-758.