Various techniques for producing a single longitudinal mode TEA$-CO_2$ laser

S.L. CHIN

Techniques used for producing a single longitudinal mode TEA$-CO_2$ laser are described. The simplest technique seems to be a double unstable resonator.

Much laser chemistry or laser interaction work requires the use of a high power CO_2 laser. To do this quantitatively, the laser intensity should be precise and of a sufficiently high value; it should operate at a single stable frequency which is at least line tunable.

A survey has thus been made on the various techniques for producing a pulse from a TEA CO_2 laser that would fit the following requirements:

1. single frequency single longitudinal mode or SLM, smooth pulse,
2. line tunable
3. repetition rate $\geqslant$ 1Hz
4. energy per pulse $>$ 1J,
5. good pulse reproducibility and
6. frequency stabilized.

In principle, to produce a SLM laser pulse, one simply has to vary the cavity length and the active medium such that

$$\frac{c}{2L} > \Delta\nu_g \qquad (1)$$

where $c/2L$ = the distance in frequency between two adjacent longitudinal modes, (c = speed of light, L = laser cavity length) and $\Delta\nu_g$ = the width of the gain curve of the active medium.

Unfortunately, this condition cannot be satisfied by many lasers, in particular, the TEA CO_2 laser. For a typical TEA$-CO_2$ laser oscillator of cavity length 1.5 m, $\Delta\nu_g \approx 3$ GHz whereas $c/2L$ = 100 MHz and thus equation (1) cannot be fulfilled. Multimode oscillation will take place in this case unless something is done to suppress all oscillations except one.

Since a single frequency pulse is required, the laser will also have to oscillate in a single transverse mode – almost always a TEM_{00} mode because of the simplicity of creating such a mode experimentally by limiting the diameter of the laser beam. In the following sections all the techniques used on the TEA CO_2 laser to produce a single frequency pulse while bearing in mind our requirements are summarized. The performance of each technique is tabulated in Table 1. The references are meant to be representative and up-to-date.

Intracavity etalon[1 – 3,5]

With this technique (Fig. 1a) one puts a plane parallel Fabry-Perot etalon (of, say, Ge or GaAs.) into the laser cavity at a slanting angle. Depending on the free spectral range and the finesse of the Fabry-Perot etalon, the net gain region of the oscillator (Fig. 1b) can be adjusted to contain at most a few longitudinal modes. Because of the homogeneous broadening in the gain medium, the mode experiencing the highest gain will grow at the expense of the other modes, as long as the laser operates near threshold. Thus, an SLM can be created but at less than 1 J per pulse. Such a technique is, though line tunable, not easily scalable to high energy because of the damage problem of the etalon due to high laser intensity. It is very sensitive to alignment. A slight change of the etalon angle will lead to a shifting of modes.

Intracavity saturable absorber[6]

By inserting into the laser cavity an absorption cell containing gases such as SF_6 etc., the laser will oscillate on the saturated absorption line of the gas, thus limiting the oscillation to only one mode that coincides with the saturated absorption line. This technique, though easily scalable to higher energy, is not line tunable.

Hybrid system[7 – 10,20]

A cw low pressure CO_2 laser discharge is inserted into the TEA laser cavity (Fig. 2a). The superposition of the narrow gain curve of the low pressure CO_2 discharge with the wide gain curve of the TEA-discharge will limit laser oscillation only within the gain width of the low pressure discharge (Fig. 2b). The CW gain width can be made narrower than the longitudinal mode spacing of the cavity so that SLM oscillation is possible. The CW discharge should be such that it is below the laser oscillation threshold when the TEA selection is not fixed. This will give a stronger SLM pulse than when the CW selection operates above threshold. In the latter case, an early build-up of the pulsed laser oscillation occurs when

---

The author is on leave at the Zentrum für interdisziplinäre Forschung and Fakultät für Physik, Universität Bielefeld, 48 Bielefeld 1, Federal Republic of Germany, from LROL, Dpt of Physics, Laval University, Québec 10, QC, Canada G1K 7P4. Received 17 January 1980

0030-3992/80/020085-04 $02.00 © 1980 IPC Business Press

Table I. Performance of various techniques

Published techniques	SLM operation	Line tunability	Energy A: > 1 joule B: < 1 joule	Repetition rate	Pulse reproducibility and stabilization
Intracavity etalon[1-3,5]	Yes	Yes, difficult	B	Yes	Yes
Intracavity saturable absorber[6]	Yes	No	A	Yes	No
Hybrid (intracavity CW + TEA)[7-10,20]	Yes	Yes	B	Yes	Yes
Injection of SLM-CW-laser into TEA stable oscillator[12-16]	Yes	Yes, difficult	B	Yes	Yes
Injection of SLM pulse into TEA oscillator[17]	Yes	?	A	?	No
Injection of SLM-CW-laser into unstable resonator[16,21]	Yes	Yes, difficult	A	?	Yes
Double stable resonator[4]	Yes	Yes	B	?	?
Double unstable resonator[11]	Yes	?	A	?	Yes

the TEA selection is fixed, thus depleting the energy in the pulsed gain section before the maximum inversion is achieved. The resulting pulse is a long weak SLM pulse. This technique is non-scalable to large diameter because of the small bore diameter needed for the CW tube and also because of the TEM_{00} mode limitation. However, the system is not as sensitive to alignment as the intracavity etalon and is a rather commonly used technique together with an amplifier chain.

Injection of a CW – SLM laser into a TEA-stable resonator[12 – 16]

With this technique one can inject a stabilized CW – SLM laser either into a ring oscillator (Fig. 3a) or an ordinary laser oscillator (Fig. 3b). It should be noted that the CW – SLM laser can be easily obtained by using a short cavity and a low pressure such that equation (1) is satisfied. The stabilized injected CW laser line (master frequency) will experience a phase shift after each round trip in the TEA oscillator. In the steady state, ie after many round trips during the excitation of the TEA section, such a phase shift corresponds to a steady frequency modulation and the injected master frequency is slightly shifted. If this shifted frequency coincides with one of the longitudinal modes of the TEA cavity, the growth of this mode (slaved mode) predominates and SLM output is obtained.

Such coincidence with a slaved longitudinal mode in the TEA cavity can be achieved by adjusting the TEA cavity length with a piezoelectric crystal. With a diaphragm in the TEA cavity, SLM and TEM_{00} mode output has been achieved with small detuning between the master frequency and the slaved frequency. This detuning is the frequency shift the master frequency should experience for SLM operation. Line tunability with this technique is difficult because one has to vary two gratings, one from each oscillator. Also, spatial matching between the master and the TEA oscillator modes is important.

Although good stabilized reproducible SLM pulses have been obtained[16], there still exists a controversy as to why the output pulse sometimes contains some low frequency beating[12,14,16]. Although it has been explained[12,16] that this beating is between the master frequency and the slaved frequency, this does not explain why such beating persists at the same beat frequency even after misaligning the TEA oscillator by tilting one of the mirrors[12].

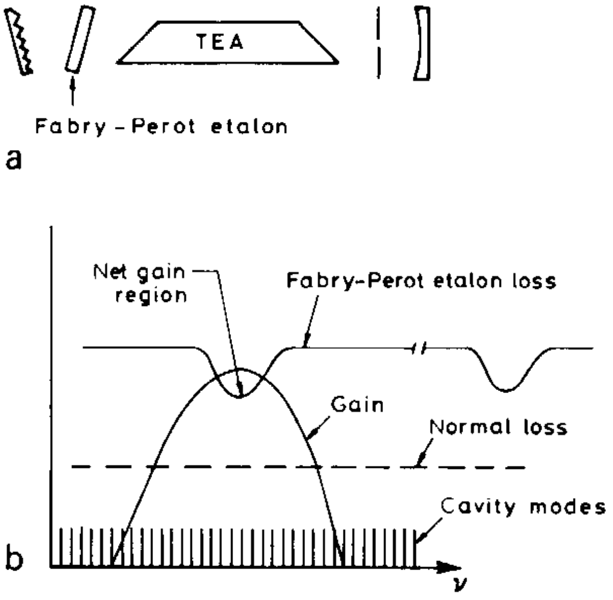

Fig. 1 a – intracavity Fabry-Perot etalon; b – schematic gain and loss curves in the cavity

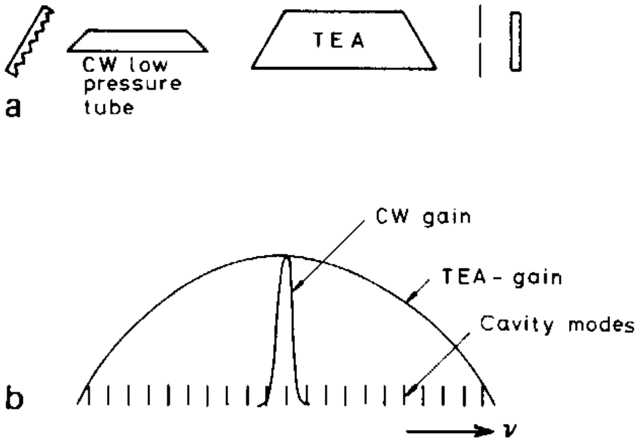

Fig. 2 a – A hybrid TEA-CO_2 laser system; b – selection of single mode through the narrow low pressure CW gain curve

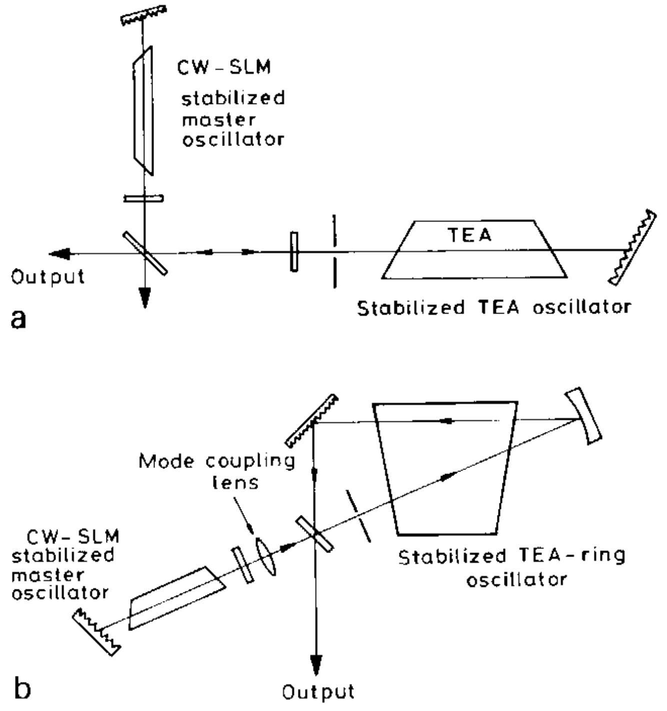

Fig. 3 Injection of a CW SLM laser into a – a stable TEA oscillator; b – a TEA-ring oscillator

Injection of a SLM pulse into a stable resonator[17]

This scheme is similar to the previous one except that the CW master oscillator is replaced by a pulsed one to obtain more energy per pulse. Fig. 4 shows such a scheme. Indeed one does get ~ 10 J per pulse but the reproducibility is bad and the system is non-tunable in the sense that SF_6 was used in the master oscillator to select a SLM pulse. No more detailed study was made on this subject.

Injection of a CW – SLM laser into a TEA unstable resonator[16,21]

Such a scheme (Fig. 5) makes use of the high gain of the TEA CO_2 discharge which allows an unstable resonator to lase. The unstable resonator not only makes efficient use of the whole gain volume but also gives a single transverse mode. Thus, high energy (a few joules) per pulse has been achieved. Line tuning is difficult because one has to tune two gratings and re-align the system.

Injection of SLM pulse into a TEA unstable resonator[18]

This scheme (Fig. 6) gives a very high energy per pulse (> 100 J per pulse) but there is no tunability and the repetition rate is low.

Fig. 4 Injection of an SLM TEA-CO_2 laser pulse into a larger TEA-CO_2 oscillator

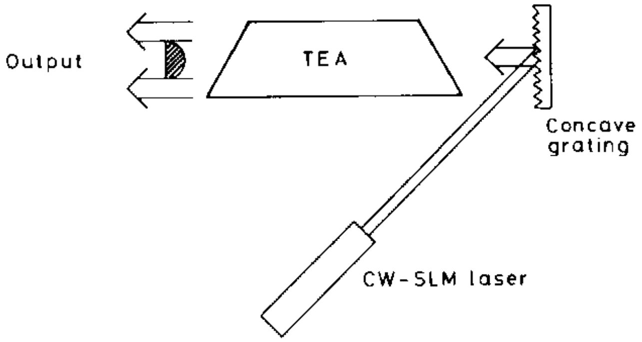

Fig. 5 Injection of a CW SLM CO_2 laser into a TEA unstable resonator

Fig. 6 Injection of an SLM TEA-CO_2 laser pulse into a TEA unstable resonator

Double stable resonators[4]

The scheme is shown in Fig. 7a. The laser will lase only at the frequency where two longitudinal modes, one from each resonator, coincide within the gain curve. (Fig. 7b). The other modes of one resonator are suppressed by the loss of the other and *vice versa*. SLM operation is possible as long as the next coincidence of two modes (one from each resonator) falls outside the gain curve. Since the condition for a second coincidence occurs at:

$$n\left(\frac{c}{2L_2} - \frac{c}{2L_1}\right) = \frac{c}{2L_1} \qquad n = \text{integer}$$

this leads to the result

$$n = \frac{L_2}{L_1 - L_2}$$

Substituting this into the relation

$$\Delta\nu = (n+1)\,\frac{c}{2L_1}$$

gives

$$\Delta\nu = \frac{c}{2(L_1 - L_2)}$$

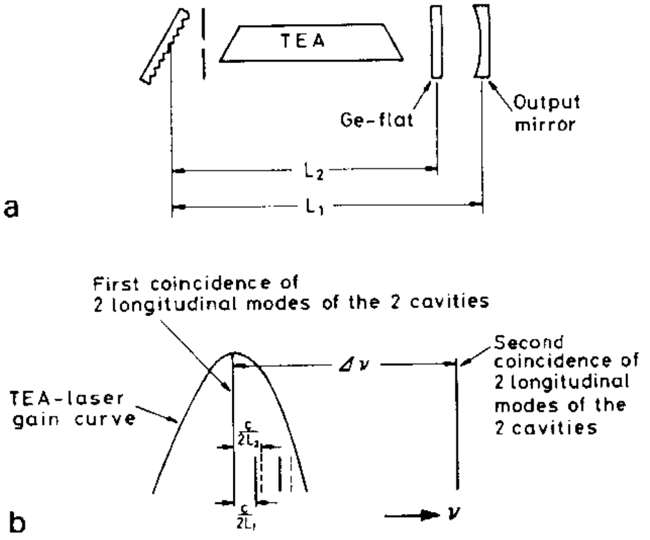

Fig. 7 a – Double stable resonator; b – relation of the modes of the two resonators and the gain curve

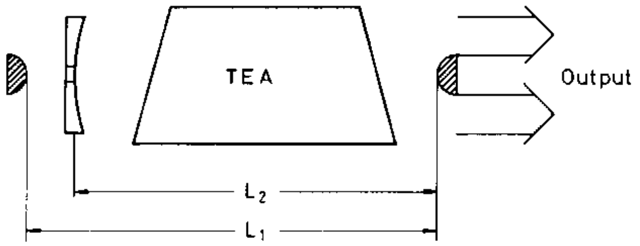

Fig. 8 Double unstable resonator

where $\Delta\nu$ is the spacing between two adjacent coincidences. Hence by varying the relative distance between the two cavities, one can easily make $\Delta\nu$ larger than the gain width. This technique has produced some 150 ns pulses at 5 Hz with a ± 5% amplitude stability. However, the energy per pulse is only ~ 10 mJ.

Double unstable resonators[11]

The scheme (Fig. 8) is similar to that used in the previous section except that the two resonators are unstable. Thus one makes use of the whole gain volume of the active medium. An SLM pulse is produced so long as $(L_1 - L_2)$ is sufficiently small (see previous section). Each unstable resonator alone is below the lasing threshold. Together, the feedback from one resonator into the other and *vice versa* makes the system lase. Energy greater than one joule per pulse with 10% variation in 100 shots has been obtained. However, line tunability is not possible. One idea to obtain line tunability is to replace the convex mirror at the left hand side of Fig. 8 by a grating.

Conclusion

The most attractive technique is that of a double unstable resonator from the point of view of efficient use of energy, compactness and economy. However, this technique needs more research of tunability. If one does not care too much about economy and size, the best straight forward method is a hybrid oscillator coupled to an amplifier chain.

The author appreciates the fruitful discussions with Prof K.H. Welge.

References

1 **Nicholson, J.P., Lipton, K.S.** 'A tunable stabilized single-mode TEA CO_2 laser' *Appl Phys Let* **31** (1977) 430

2 **Lee, N., Aggarwal, L.** 'Single longitudinal mode TEA CO_2 laser with tilted intracavity etalon' *Appl Opt* **16** (1977) 2620

3 **Hammond, C.R., Juyal, D.P., Thomas, G.C., Zembrod, A.** 'Single longitudinal mode operation of a transversely excited CO_2 laser' *J of Phys E: Sci Ins* **7** (1974) 45

4 **Weiss, J.A., Goldberg, L.S.** 'Single longitudinal mode operation of a transversely excited CO_2 laser' *IEEE J Quant Electron* **QE–8** (1972) 757

5 **Mathieu, P., Izatt, J.R.** 'Narrow-band CO_2-TEA laser for efficient FIR laser pumping' *IEEE J Quant Electron* **QE–13** (1977) 465

6 **Nurmikko, A., DeTemple, T.A., Schwarz, S.E.** 'Single – mode operation and mode locking of high pressure CO_2 lasers by means of saturable absorbers' *Appl Phys Lett* **18** (1971) 130

7 **Girard, A.** 'The effects of the insertion of a CW low pressure CO_2 laser into a TEA CO_2 laser cavity' *Opt Commun* **II** (1974) 346

8 **Gondhalekar, A., Heckenberg, N.R., Holzhauer, E.** 'The mechanism of single – frequency operation of the hybrid-CO_2 laser' *IEEE J Quant Electron* **QE–11** (1975) 103

9 **Gondhalekar, A., Holzhauer, E., Heckenberg, N.R.** 'Single longitudinal mode operation of high pressure pulsed CO_2 laser' *Phys Lett* **46** A (1973) 229

10 **Heckenberg, N.R., Meyer, J.** 'Residual mode beating in a high-pressure – low-pressure hybrid CO_2 laser system' *Opt Commun* **16** (1976) 54

11 **Stamatakis, T., Selden, A.C.** 'CO_2 laser with 30 MW single mode output' *Phys Lett* **58** A (1976) 221

12 **Lachambre, J.L., Lavigne, P., Otis, G, Noe, M.** 'Injection locking and mode selection in TEA–CO_2 laser oscillators' *IEEE J Quant Electron* **QE–12** (1976) 756

13 **Blit, S., Ganiel, U., Teves, D.** 'A tunable single mode, injection-locked flashlamp pumped dye laser', *Appl Phys* **12** (1977) 69

14 **Izatt, J.R., Budhiraja, C., Mathieu, P.** 'Single-mode TEA–CO_2 injection laser' *IEEE J Quant Electron* **QE–13** (1977) 396

15 **Buczek, C.J., Freiberg, R.J.** 'Hybrid injection locking of higher power CO_2 lasers' *IEEE J Quant Electron* **QE–8** (1972) 641

16 **Schmid, W.E., Smith, S.D.** 'The injection – locked single–longitudinal-mode TEA–CO_2 laser' Report PLF/3, of the Max-Planck Gesellschaft zur Förderung der Wissenschaft E.V., Project–gruppe für Laserforschung, Garching (Dec. 1978)

17 **Daigle, R., Bélanger, P.A.,** 'Smooth CO_2 laser pulses of high power' *Opt Commun* **23** (1977) 165

18 **Meyer, J.** 'Single mode CO_2 – laser pulses of high power' *Phys Lett* **58** A (1976) 167

19 **Lachambre, J.L., Lavigne, P., Verreault, M., Otis, G.** 'Frequency and amplitude characteristics of a high repitition rate hybrid TEA–CO_2 laser' *IEEE J Quant Electron* **QE–14** (1978) 170

20 **Tsao, J.Y., Sharp, R.C., Yablonovitch, E.** 'Digital feedback stabilization of a single-axial-mode CO_2 TEA laser' *Rev Sci Instr* **50** (1979) 1023

21 **Lachambre, J.L., Otis, G., Lavigne, P.** 'Simultaneous frequency stabilization and injection in a TEA–CO_2 oscillator' *Appl Opt* **17** (1978) 1015