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STABLE ULTRA — FAST HIGH POWER CO_2 LASER PULSE GENERATION

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Abstract

Some possible approaches towards the generation of ultra-fast infra - red CO_2 laser pulses are discussed. Of these the technique of injection mode-locking in particular, which has been applied to a wide range of CO_2 oscillators, appear to be the most suitable for large aperture high power laser systems. This technique, which essentially consists of the injection of a low power short pulse into the slave laser cavity, to control the temporal behaviour of its emitted radiation, has also permitted the wavelength control of non - dispersive TEA CO_2 laser systems, producing single wavelength ultra — fast CO_2 laser pulses in the GW power range. The experimental results obtained are reported and compared with the predictions of a simple theoretical analysis. Regions of broadening of the injected short pulse have been identified and the pulse compression techniques employed to overcome this intrinsic broadening, along with the simple theoretical models developed to analyse the various pulse shaping effects in the amplifying medium, are also described.

Introduction

Over the past decade, much attention has been directed towards the generation of ultra-fast[1-3] infra-red laser pulses from TE CO_2 oscillators and their amplification to giga-watt[4,5] power levels, due to potential applications in areas such as multiphoton chemistry[6,7], laser fusion research [8,9] and semi-conductor physics. The principle characteristics required of such a pulse are durations of the order of 1 ns or less, a high energy and good optical quality. The generation of such pulses is usually carried out using an oscillator, amplifier (O-A) chain in which a low energy pulse of good optical quality and the required duration, gated[1-3] from a gain switched CO_2 laser pulse produced by a conventional master oscillator, is amplified. However, the small signal gain required in such amplifiers to obtain relatively energetic pulses is often high enough to lead to problems of parasitic oscillations[10,11]. Further, the energy extraction efficiency of subnanosecond pulses passing through CO_2 amplifiers is limited by finite collisional relaxation time of rotational sub-levels[11,12].

An alternative method of generating short pulses is by modelocking[13,14] TE CO_2 lasers. In this approach the axial cavity modes of the laser are locked in phase, leading to the generation of a train of pulses rather than a single pulse as in the O-A configuration. Initially modelocked operation of CO_2 lasers with stable resonators was carried out by actively modulating the intra cavity loss[15,16] or using passive techniques consisting of intra cavity saturable absorbers such as molecular gases[17,18], hot CO_2[19] and p-type Germanium.[20] To ensure good pulse reproducibility and a spatially well defined output beam single transverse mode operation of these lasers was necessary, limiting the output energy to relatively low values ($\approx$ 100 mJ). The advent of unstable resonators[21] and their successful application to high power pulsed TEA CO_2 oscillators[22] demonstrated the possibility of single transverse mode operation of large aperture systems. Unstable resonator TEA CO_2 lasers were subsequently passively modelocked[23,24] using molecular gases such as SF_6, BCl_3 and N_2F_4 as saturable absorbers leading to relatively higher energy trains than their stable resonator counterparts. The duration of individual pulses were, however, limited to about 2 ns, irrespective of the resonator, multiatmosphere CO_2 gain media being required for shorter pulse generation[25,26,27].

A major factor limiting the success of conventional modelocking techniques is the limited bandwidth of long pulse or continuous wave (C.W.) CO_2 lasers and the short gain lifetime of high pressure systems having the bandwidth required for picosecond pulse generation. Besides, scaling to high output powers is also limited by damage to intracavity optical elements and by the requirement that the laser operates close to threshold for reliable modelocked operation.

The technique of injection modelocking (IML), first developed by Belanger et. al[28], clearly demonstrated the possiblity of overcoming these limitations of modelocked high power CO_2 lasers. This technique essentially consists of injecting a short pulse (or a train of pulses) of appropriate frequency, into the oscillator (slave) to be modelocked at approximately the time at which the threshold condition is met during the transient gain cycle. If suitably intense the injected pulse dominates the noise from spontaneous emission and, aside from bandwidth limitations, controls the temporal behaviour of laser emission. Since then IML has gained widespread acceptance and has been performed on a variety of laser systems. In addition to CO_2[4,5,28-37] lasers, flashlamp pumped dye[38], Nd-YAG[39,40] and XeCl[41] lasers have been modelocked and several other laser systems appear to be suitable for modelocking by injection.

Unlike the O-A short pulse system, the output from a modelocked laser consists of a train of short pulses separated by the round trip time (RTT), of the cavity. Such laser oscillators however, replace the more conventional O-A short pulse systems when the relaxation time of the phenomena of interest is less than the time between the pulses in the train. Wavelength control via injection demonstrated first by Dyer and Perera,[42] has also enabled the generation of intense modelocked pulse trains on a large number of rotational lines[43] of CO_2 making this technique more attractive than O-A systems generating individual pulses, in applications such as synchronous modelocked pumping of mid infra-red molecular gas lasers[44] and in the field of i-r laser photochemistry in which the dissociation of molecules occur very rapidly ($\approx$ few nanoseconds). In certain applications however, short individual pulses are required rather than a pulse train. For such experiments the peak power pulse in the train, whose intensity can be as high as that of a single short pulse amplified using the slave as the amplifier[32], can be switched out using a suitable technique, for instance semiconductor reflection gating[45,46] without much loss of energy. Such short pulses gated from an injection modelocked CO_2 laser system have been employed to generate infrared radiation spanning the 3-14 μm wavelength region or an infrared supercontinuum[47], from dielectrics and semiconductor materials.

IML has also provided a basis for studying the pulse broadening mechanism as a function of the cavity magnification and the operating pressure[48] of the slave laser and the intensity[49], duration[50] and wavelength of the injected pulse. It also enables the study[51,52] of pulse evolution in AM modelocked TEA CO_2 lasers while the use of saturable absorbers[48] inside the injection modelocked slave laser cavity has compressed[53] the injected pulse by as much as 50% and has enabled the generation of highly reproducible[54] pulse trains.

Technique of Injection Modelocking

The method of modelocking lasers by short pulse injection is alternately termed IML[30] (injection modelocking) or RAAT[29] (regenerative amplification above threshold). The latter term is appropriate since the process is based on multipass amplification of an injected signal in a resonant cavity. This enables the injected short pulse to efficiently extract energy from the slave laser.

In a pulsed oscillator the output builds up by the regenerative amplification of radiation due to spontaneous emission noise in the cavity at threshold. Hence a pulsed laser is a multipass amplifier of the noise signal. In the case of IML, where a short pulse, whose frequency lies within the natural linewidth of the laser transition, is injected into the cavity approximately at threshold, the initial radiation is a superposition of the injected signal and that due to spontaneous emission. If the injected signal is more intense than that due to spontaneous emission at the instant of gain threshold, it is then expected to dominate the spontaneous emission noise and thus control the laser emission. In contrast to injection locking[55-57], where the injection of external radiation leads to stable single frequency generation, oscillation takes place on a number of longitudinal modes of the slave laser, which are locked in phase to generate a train of intense output pulses.

Time Window

For a given input signal intensity there exists a favourable time window for injection to obtain reliable modelocking. This can be explained using figure 1, that depicts the small signal gain of the active medium, of the slave oscillator. Unlike in an O-A chain, where the pulse is injected at a time $\geq T_M$, when the gain of the amplifier has reached a relatively high value, in IML the optimum time for injection is the threshold time, T_{th}. The time window, T^- to T^+ ($\triangle T$), has been shown[58], using a modified rate equation model, to be approximately symmetric about the threshold time T_{th} and also that its value increases with the injected pulse energy.

For a given intensity, if injection is before T^-, the injected pulse will attenuate due to cavity losses and, at threshold, falls below that of the spontaneous emission; the output would then be the natural laser pulse. Similarly, if injection is after T^+, the natural noise signal is amplified, becoming more intense than the injected signal and the laser emission would again be controlled by spontaneous emission. Hence for reliable modelocked operation the signal must be injected within this time window, T^- to T^+ or $\triangle T$.

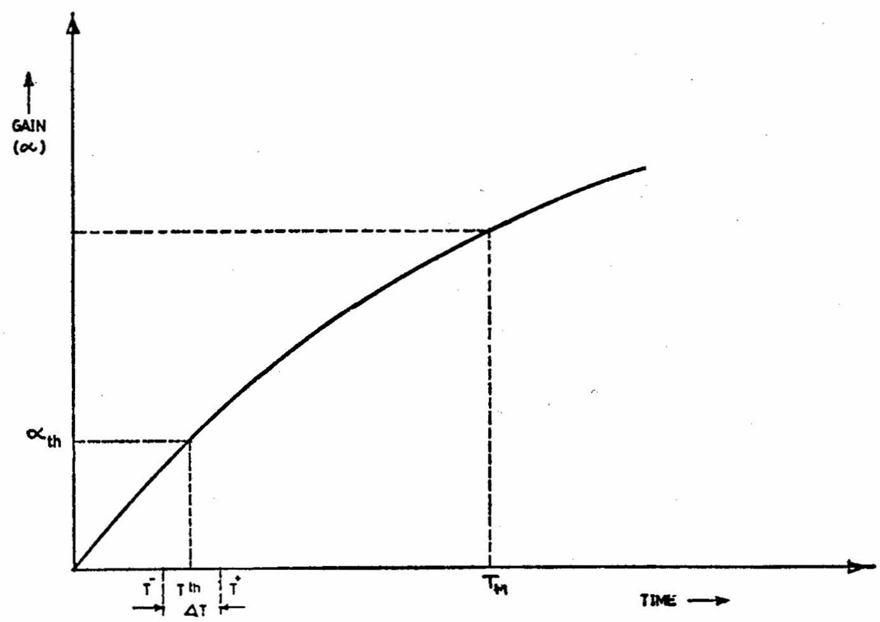

Fig. 1. Small signal gain profile during the time of the laser pulse.
$T^- \leq$ Time of injection for locking $\leq T^+$
Time of injection for amplification $\geq T_M$

Frequency Domain Model for Modelocking

This model[53] describes qualitatively modelocking in the frequency domain and is useful in comparing and contrasting between conventional and injection modelocked laser oscillators.

Fig. 2(A-D) relates to the conventional (modulated) approach to modelocking. The axial modes of a laser cavity are discrete and are separated by a frequency interval $\delta\nu = c/2L_c$, where L_c is the optical length of the cavity. Typically several or many of these modes fall within the laser gain spectrum (fig. 2A), and in general will oscillate simultaneously, in a homogeneously broadened pulsed system (or cw inhomogeneously broadened device), and independently with no fixed phase relationship. In this case the output is modulated, with minimum pulsewidths of $\sim \{1/m\}\delta\nu$ (fig. 2B) where m is the number of oscillating modes, but with no well defined temporal relationship between pulses in the time domain. This effect is quite common in TEA CO_2 lasers[59]. In the presence of an intracavity modelocking element (fig. 2C), a number of these modes will oscillate with their relative phases and amplitudes in a fixed relationship. The laser field becomes a well defined function of time and a modelocked train of pulses results (fig. 2D). The duration of these individual pulses is given by $\tau_p = 1/\Delta\nu$ where $\Delta\nu$ is the oscillating bandwidth of the laser gain profile, and they are separated by the round trip time (RTT) of the cavity $T = 1/\delta\nu$.

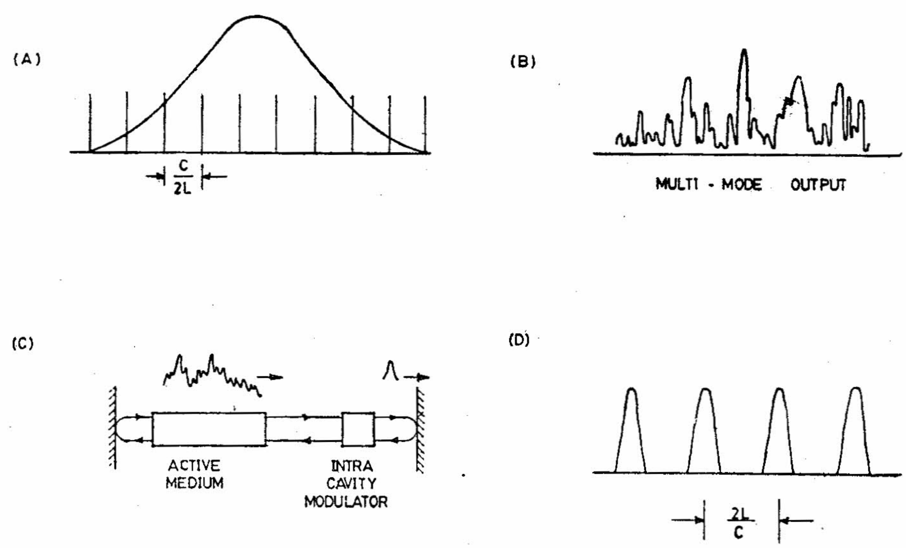

Fig. 2 (A) Gain profile of laser line superimposed on the resonant axial cavity modes.
(B) Time domain of the intensity of a laser cavity without modelocking element.
(C) Recirculating internal field distribution within a laser cavity with an intra cavity modulator.
(D) Time domain of a modelocked laser

The frequency domain model for IML operation is depicted in fig. 3(A-D). The frequency spectrum of the injected pulse (fig. 3A) is shown in fig. 3B and has a width given by $\Delta \nu_p = 1/\tau_p$, where τ_p is the injected pulse duration. In contrast to conventional modelocking, with IML the injected radiation contains the cavity mode frequencies already 'locked' together and dominates the laser emission. Hence only the axial mode frequencies within the frequency spectrum of the injected pulse (fig. 3C) are populated and contribute to the generation of a train of short pulses (fig. 3D). The duration of the individual short pulses in the train, apart from bandwith limitations and saturation effects, is virtually independent of the slave oscillator and depends only on the injected pulse.

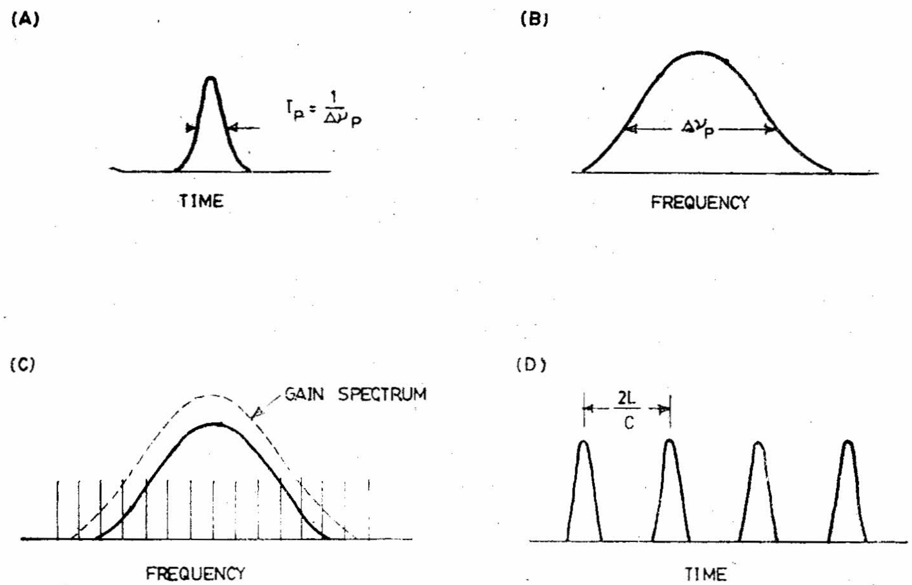

Fig. 3. (A) Temporal profile.
(B) Frequency spectrum of injected pulse.
(C) Laser gain profile and frequency spectrum of injected pulse superimposed on the cavity modes.
(D) Time domain of the output pulse train.

Rate Equation Model for IML

A simplified rate equation model[60] of a TEA CO_2 laser, the basic features of which have been discussed by a number of authors[61-63], was slightly modified[58] to study some of the basic parameters of injection modelocked CO_2 lasers, such as dependence of modelocking on the injection time window and the energy of the injected signal. This model also predicts the optimum conditions for reliable and efficient modelocked operation and is based on the assumption that the net round trip gain of the active medium satisfies $2\alpha L_g < 1$, where α is the gain coefficient and L_g is the length of the gain medium.

The rate equations of an injection modelocked CO_2 oscillator were assumed to remain unchanged from those of a gain switched CO_2 laser[60] except that after the time of injection the initial intracavity radiation was considered to be a superposition of the injected signal and that due to spontaneous emission.

The process of amplification of a signal injected into a slave oscillator at a time T_{inj}, is treated as follows : the injected signal of energy fluence E_{inj}, is amplified to E_{amp} after one cavity round trip and the pulse amplification is calculated using the Frantz — Nordik equation[74]. This amplification causes the upper laser level population to reduce by an amount $\triangle N$ given by,

$$\triangle N = (E_{amp} - E_{inj})/2h\nu L_g \quad \text{.................(1)}$$

where $h\nu$ is the photon energy of the laser transition and L_g is the length of the gain medium. The new populations of the upper and the lower laser levels are respectively,

$$\begin{aligned} n'_1 &= n_1 - \triangle N \\ n'_2 &= n_2 + \triangle N \end{aligned} \quad \text{.................(2)}$$

and the resultant small signal gain is $\propto = \nabla\ (n'_1 - n'_2)$ where ∇ is the stimulated emission cross section. The output energy is,

$$E_{out} = E_{amp} \cdot T'A \quad \text{.................(3)}$$

where T' is the transmission coefficient of the output mirror and A is the cross —section of the optical aperture. If mirror absorption is neglected the new injected energy is given by,

$$E'_{inj} = E_{amp} \cdot R_1 R_2 \quad \text{.................(4)}$$

where R_1 and R_2 are the reflectivities of the two cavity mirrors. This model yielded useful information on the injection time window and the influence of the injected photon density on the locking behaviour and the computed data obtained for a TEA CO_2 laser operated with a $CO_2/N_2/He$ gas mixture of 1/1/8 and having the following parameters :

L_g = 70 cm, L_c = 120 cm, mode volume = 150 cm³, R_1 = 0.95 R_2 = 0.50, pump pulse duration = 3 μs, and $\propto$ = 1.3% cm⁻¹. are reproduced in figures 4-6.

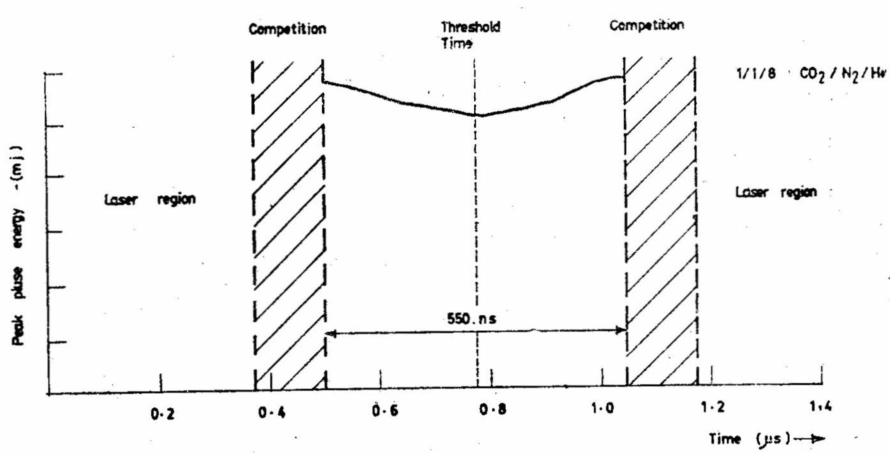

Fig. 4. Characteristics of IML for an injected pulse energy of 10^{-13} J ($\propto$ = 1.3% cm⁻¹).

Figure 4 illustrates the modelocking time window for an injected energy of 10^{-13} J and is seen to be approximately symmetric about the time of threshold gain, the threshold condition being $R_1 R_2.e^{2 \propto L_g} = 1$. In this there are three principle operating regions. They are,

(i) a region of modelocking (or the injection time window), in which the injected pulse dominates the laser output,

(ii) two competition regions where the injected pulse and the noise signal are of the same order and

(iii) two regions where the pulse is either injected too early and is attenuated below that of the spontaneous emission noise at thereshold, or is injected too late when the noise signal is significantly amplified above the intensity of the injected pulse.

In the latter two cases the final output is the natural laser pulse, as laser oscillation is dominated by the noise signal, and the injected pulse exercises no control over the system.

The foregoing discussion shows that if an intense signal is injected into the cavity before threshold, it will take a longer time to attenuate to the level of the noise signal at threshold, or if injected later the noise signal will again take a longer time to be amplified to the level of the injected signal, making the injection time window much broader (fig. 5). However, an increase in $\propto L_g$, which means that over a cavity round trip time the noise signal due to spontaneous emission grows at a faster rate, results in a narrower modelocking time window. A similar observation has been made by Alcock et al.[37] with a high pressure gain module, in which the gain rise time decreased with increasing pressure, making the noise signal to grow much faster. This led to a reduction[37] in the injection time window as the pressure in the slave laser was increased.

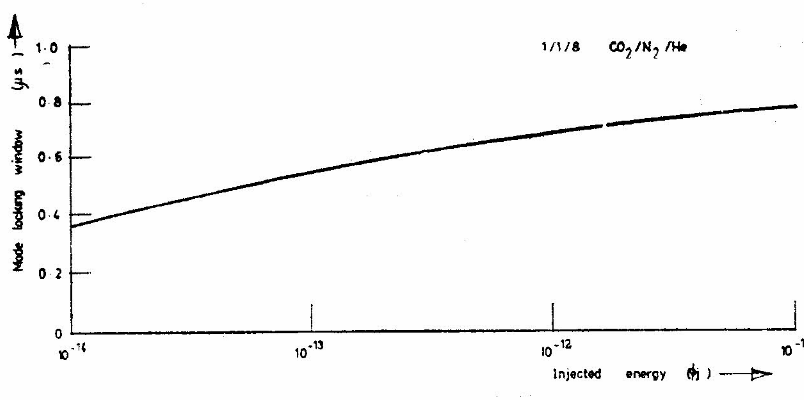

Fig. 5. IML time window vs. injected energy.

It also shows that as the intensity of the injected pulse increases the gain switching action is degraded[48] since saturation occurs at a lower gain, which reduces the peak output power. This result, that is the variation of the energy of the peak power pulse in the train, assuming that the duration of the pulse remains unchanged after amplification, with injected pulse power is plotted in figure 6.

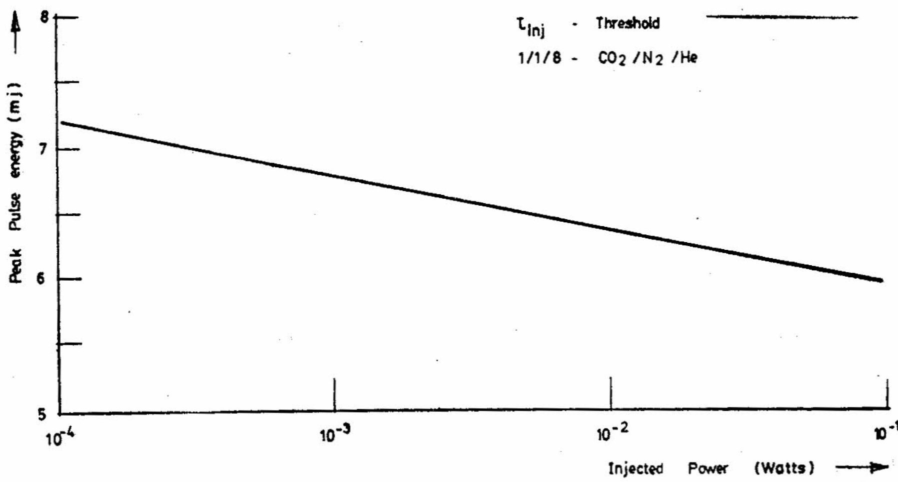

Fig. 6. Energy of the peak power pulse shown as a function of the injected power for a∼1 ns pulse.

In summary, this model indicates that for an injected pulse to dominate laser emission of a slave oscillator, injection should occur within the allowed time window and at all times must be sufficiently more intense than the intracavity noise signal. It is however, necessary to limit the injected power if degradation of the gain switching action is to be avoided. The injection characteristics predicted by the model agreed reasonably well with experimental observations, especially for low gain situations. It however, did not provide any allowance for the duration of the injected pulse though it was assumed to be a few nanoseconds.

Experimental Configuration

The typical experimental configuration (fig. 7) of an IML CO_2 laser system consists of a low power master oscillator to provide a signal for injection, an optical switch and an adjustable delay circuit for the generation of a short pulse at the appropriate time, and the slave oscillator which is to be modelocked. The injected signal can be a short pulse gated from a gain — switched TE, low pressure pulsed[32] or cw[30] CO_2 laser, a single pulse selected from a low powered train of modelocked pulses[29,33], or the full train[37] itself if the round trip time of the slave resonator is precisely matched to the injected train of pulses. The employment of a hybrid — TE CO_2 laser system[4,42], as the master oscillator ensures reliable and consistent operation.

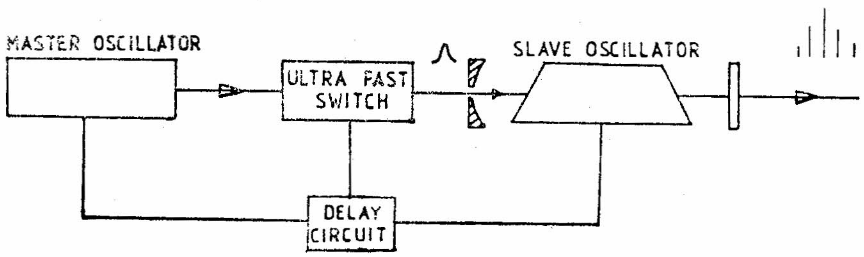

Fig. 7. Experimental configuration of IML.

Although the injected pulse controls the temporal behaviour of the laser emission, the slave resonator determines its transverse mode structure. There fore, single transverse mode operation of the slave, though not essential for IML operation[29], is required for good beam quality. The use of large aperture low loss stable resonators in the slave oscillator has resulted in simultaneous longitudinal and transverse modelocking[64] evidenced by periodic focussing of the injected short pulse with a much higher energy extraction efficiency. The emitted radiation is however, of poor reproducibility and beam quality.

In both stable and unstable single transverse mode resonators, radiation injected on the resonator axis will expand and fill the whole mode volume which enables a number of simple methods of injection to be used. For instance, diffraction coupling through a small hole at the centre of one of the resonator mirrors[28-36], reflection coupling off an intracavity beam splitter[37] and direct coupling through partially transmitting mirrors[51,52], have been used in injection modelocked CO_2 laser systems, while the first and the last coupling geometries have also been employed for modelocking XeCl[41] and dye[38] lasers respectively.

IML on the Strongest P_{10} (20) Emission Line of CO_2

IML was initially carried out on the strongest emission P_{10}(20) line of CO_2. In the very first experiment reported[28,29] in 1974, a TEA CO_2 laser with a gain medium of dimensions 5 x 5 x 180 cm³ was modelocked as a result of injecting a 2 ns pulse to produce a train of pulses with a peak output power ≈ GW. The total output energy of this train of pulses was approximately the same as that obtained in normal gain switched operation but the peak power was five times that of the natural laser pulse. IML was achieved with both stable and unstable resonators on the slave laser cavity. Alcock et al.[30] subsequently demonstrated the simplicity of this technique by injection modelocking a 50 Joule, TEA CO_2 oscillator by the injection of a nanosecond pulse chopped from a 1 W cw CO_2 laser. Power gains for the injected pulse as high as 10^{12} were obtained in this experiment. The injection time window for reliable modelocked operation, which was reasonably high (eg. ~500ns) in the previous system,[29] was still ~200 ns for an injected energy as low as 10^{-11} J.

Multiatmospheric Pressure Slave Lasers

The IML technique was extended to multiatmosphere systems by Alcock et al.[37] in 1976. The slave oscillator used was an unstable resonator TE CO_2 laser capable of operating at pressures upto 10 atm. The injected signal was a low power train of modelocked pulses, obtained from a conventionally modelocked high pressure CO_2 oscillator, and the slave resonator cavity length was precisely matched to the injected train. The injected time window was observed to reduce as the pressure in the slave was increased (fig. 8)[37], making the timing requirements for reliable modelocked operation more stringent. Increasing the pressure, however, decreased the number of pulses in the mode-locked train and at 8 atm. a peak output power of 1 GW was obtained from this small aperture ≈ 1.7 cm², device.

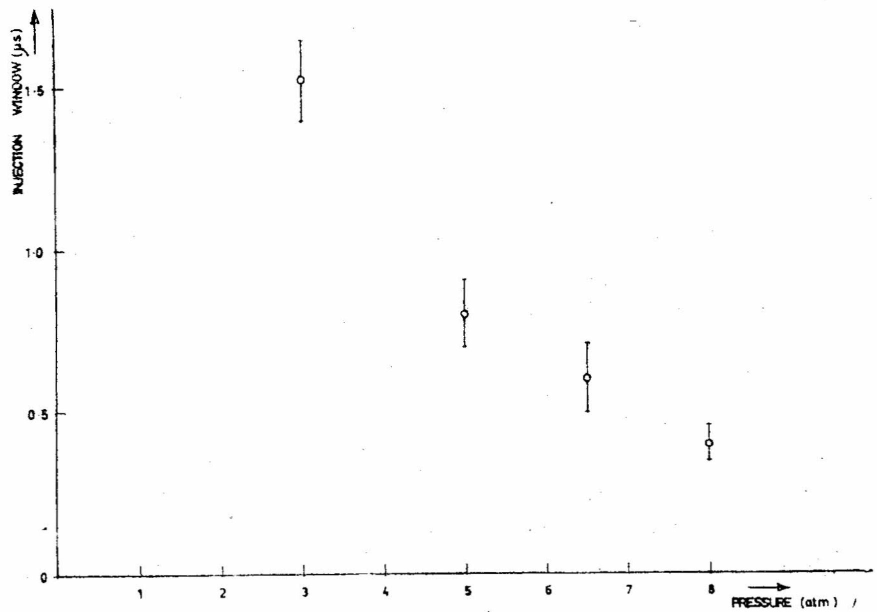

Fig. 8. Variation of injection time window with gas pressure in the slave laser.

In the preceeding experiments[28-30,37] electro-optical switching[65-67] was employed to produce a short pulse for injection using the Pockel's effect in CdTe or GaAs crystals. The duration of the pulses obtained with this technique was in the region of 1 ns or more[68]. However, the development of the laser induced semiconductor reflection switching technique[69-72] permitted the generation of pulses significantly shorter than 1 ns[73] and it enabled Corkum et al[31] to utilize the broad bandwidth of multiatmosphere CO_2 lasers. A dye laser controlled semiconductor reflection switch was used to gate subnanosecond pulses of 10 micron radiation from the output of a 1 W cw CO_2 laser, and upon injection high power modelocked pulses, having a duration of ~200 ps and a peak single pulse energy ~10 mJ, were obtained from a 13 cm³ TE CO_2 oscillator operated at 7 atm. Improvements (also see refs. 3, 46) to this switching technique have realized CO_2 laser pulses of duration ~1 ps and it enabled Corkum[4] to derive power densities in excess of 10^{12} W. cm^{-2} from a 10 atm. TE CO_2 regenerative amplifier having a gain medium of 1 x 1 x 40 cm^3; a plasma breakdown wave travelling with the regeneratively amplified pulse combined with anomalous dispersion in the NaCl window permitting still further compression of these pulses to 600 fs.

Long Cavities

For certain practical applications it is important to be able to control the pulse separation in the modelocked pulse train. For example, large intervals (~50 ns) between pulses is desirable if efficient and simple single pulse selection techniques[45] are to be used in conjunction with IML devices or to simulate single pulse experiments in a relatively slow photochemical reaction. Experiments on an injection modelocked TEA CO_2 laser with slave cavity lengths upto 21 m have been reported by Corkum and Alcock[32] which resulted in pulse separations variable from 15 ns — 140 ns. The peak power in the pulse train was shown to vary as the square root of the cavity length, making the use of long resonators particularly attractive for efficient single pulse generation of high peak power.

Multi-Gigawatt Power Generation

Belanger et al[33] scaled the peak output power of an injection modelocked system to 25 GW by employing a uv preionized TEA CO_2 laser of aperture ~ 200 cm^2, with a positive branch unstable resonator as the slave oscillator. The output of this system was sampled through eight 4.5 cm diameter windows located around the annular output beam and a total output energy of 200 J was calculated taking into account the whole annular surface. The IML of an electron — beam controlled high gain (~ 4.0% cm^{-1}) TEA CO_2 slave laser having an active volume of 1.5 m^3, by injecting an attenuated low energy (~10^{-9} J) nanosecond CO_2 laser pulse, demonstrated the simplicity and the reliability of this technique for generating extremely high power[5] laser pulses. With no signal injection the output of the slave, which was equipped with an unstable resonator of magnification M = 2 and of cavity length 5 m, represented that of a typical multimode gain switched pulse (fig. 9a) while signal injection realized a highly reproducible train of pulses (fig. 9b), the energy of the peak power pulse being ~ 110 J. This clearly demonstrated the advantages of this technique over other conventional methods of modelocking in generating high peak power pulses.

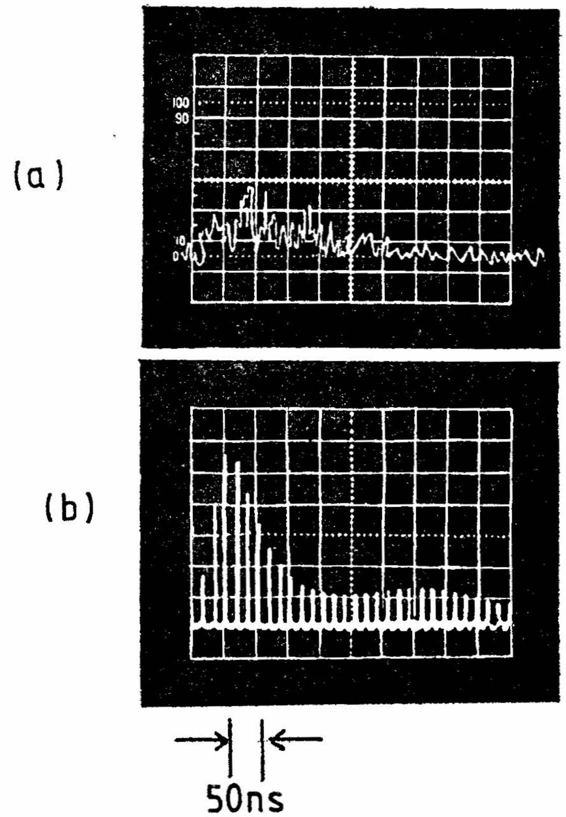

Fig. 9. Temporal profile of (a) multimode gain switched pulse (b) injection modelocked pulse from a E-beam pumped CO_2 laser.

Line Tuned Operation of IML CO_2 Lasers

IML on the strongest emission line of the TEA CO_2 laser provided high power nanosecond pulses of good optical quality[29] required for laser-plasma interaction experiments. The use of these devices were however, limited to applications requiring radiation only on the dominant $P_{10}(20)$ transition. Hence, to extend the field of applications to areas such as laser photochemistry and optical pumping of molecular gas lasers line tunable operation of injection modelocked CO_2 lasers was highly desirable.

To achieve line tuned operation of IML CO_2 lasers two principally different methods have been adopted. They are :

(i) the wavelength control[42,43] of non dispersive TEA CO_2 lasers solely by the injection of a short pulse gated from the output of a TE CO_2 master oscillator and

(ii) IML of a TEA CO_2 laser equipped with a frequency selective resonator configuration.[35]

Wavelength Control of Non Dispersive CO_2 lasers

When a signal is injected into a pulsed laser oscillator, it circulates simultaneously with the noise signal due to spontaneous emission in the laser cavity. The signal which grows the more rapidly will depopulate the active medium before the other enters into a saturation regime and thus will control the laser emission. Although slave CO_2 lasers have been modelocked at their natural frequency, i.e. $P_{10}(20)$, by injecting relatively weak signals[30] (eg $\sim 10^{-1}$ W), it is considerably more difficult[55] to force the laser onto other transitions by injection alone. This can be explained in terms of the gain experienced by the injected signal when tuned away from the $P_{10}(20)$ transition, which is lower to that experienced by the spontaneously emitted radiation lying at the peak of the gain spectrum [i.e. P(20)]. After a number of transits through the gain medium the weak noise signal is preferentially amplfied and competes with the initially dominant injected signal.

The range of wavelengths over which IML can be expected was evaluated by Dyer and Perera.[42] They showed that in a slave laser equipped with a non frequency selective unstable resonator of magnification M and having a gain coefficient α_J that varies linearly from zero to its peak value α_{OJ}, in a time τ, the growth time T_J of the gain switched pulse for an injected photon density ϕ_i is given by[42],

$$T_J = \left\{\frac{\tau \ln M}{\bar{\alpha}_J L}\right\} + \left\{\frac{2\tau \ln(\phi_s/\phi_i)}{\alpha_J c}\right\}^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where ϕ_s is the photon density that produces significant saturation of the transition of interest (i.e. J), c is the velocity of light and $\bar{\alpha}_J$ is the peak small signal gain averaged over the entire cavity length L, such that $\alpha_J = \bar{\alpha}_{OJ} L_g/L$, L_g being the length of the gain medium.

It has also been shown[42] that if an injected pulse on a transition other than P(20) is to dominate oscillation, it is necessary to ensure that its growth time T_J, is shorter than that for P(20), i.e. $T_J < T_{20}$. This requires the injection of a sufficiently high photon density, ϕ_i, at threshold as, from equation 5,

$$\frac{\tau \ln M}{{}_J L} + \left\{\frac{2\tau \ln(\phi_s/\phi_i)}{\bar{\alpha}_J c}\right\}^{\frac{1}{2}} < \frac{\tau \ln M}{\bar{\alpha}_{20} L} + \left\{\frac{2\tau \ln(\phi_s/\phi_{20})}{\bar{\alpha}_{20} c}\right\}^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots(6)$$

where ϕ_{20} is the photon density in the cavity mode at threshold that is due to spontaneous emission on P(20). The appearance in equation (6) of ϕ_i as a logarithmic term indicates that relatively strong signals are required to capture oscillations on weak (low gain) transitions though IML can be attained on the dominant P(20) with very weak signals such that $\phi_i >> \phi_{20} \approx 10^{-10}$ Was demonstrated experimentally by Alcock et al.[30] This can also be deduced by equation (6) with $\bar{\alpha}_J = \bar{\alpha}_{20}$.

Fig. 10 illustrates the variation of the growth time T_J as a function of gain ($\alpha_{OJ} < 2.5\%$ cm^{-1}) for an oscillator with parameters;

$$\tau = 2\mu s, \quad L = 2.6 \text{ m}, \quad L_g = 1 \text{ m}, \quad M = 2 \text{ and}$$
$$\phi_i = 2.6 \times 10^{10} \text{ cm}^{-3} \text{ and } 1.4 \times 10^4 \text{ cm}^{-3}.$$

the upper time limit imposed by the growth of P(20) from noise is shown as a broken line in fig. 10 and assumes that,

$$\alpha_{20} = 2.5\% \text{ cm}^{-1}, \ \phi_{20} = 1 \text{ cm}^{-3} \text{ and } \phi_s = 2 \times 10^{16} \text{ cm}^{-3},$$

representative of the TEA CO_2 laser. It can be seen from fig. 10 that, with $\phi_i = 2.6 \times 10^{10}$ cm^{-3}, the injected signal is predicted to dominate laser oscillation for $\alpha_{OJ} > 1.8\%$ cm^{-1}, the range of gain available for locking reducing considerably as the injected photon density is decreased ($\phi_i = 1.4 \times 10^4$ cm^{-3}) It should however be noted that for each transition within the IML range it is essential to reduce the intensity of the injected signal at threshold to a minimum possible (consistent with reliable operation) in order to generate a high peak power in the gain switched spike, the injection of maximum available power being only necessary for low gain rotational lines or for those $T_J \approx T_{20}$..

The gain spectrum of the 10μm band P and R branch transitions shown in fig. 10 has been calculated using equations given by Weaver et. al.[75] with a vibrational inversion ratio of 2 and a rotational temperature of 375 K. It was normalized to a P(20) gain of 2.27% cm^{-1} with a 10% contribution added to account for hot band transitions[76,77]. As seen from fig. 10 the range for which the injected signal can capture oscillations of the slave, i.e. $T_J < T_{20}$, with $\phi_i = 1.4 \times 10^4$ cm^{-3} corresponds to the P(16)— P(20) transitions and for $\phi_i = 2.6 \times 10^{10}$ cm^{-3} to the P(12) — P(28) and R(12) — R(22) transitions in the 10μm band.

The wavelength control of a bladed cathode double discharge TEA CO_2 oscillator with a discharge volume of 5 cm x 5 cm x 100 cm has been studied experimentally[42] by employing low energy 2 ns pulses switched by means of an electro — optic cell from a 100 mJ, 250 ns duration smooth pulse produced by a small grating tuned wire triggered TE CO_2 master oscillator equipped with a low pressure cw section (fig. 11). The slave laser was operated with a 1/1/6, $CO_2/N_2/He$ gas mixture at a pump energy density of 100 J. litre^{-1}. atm^{-1} and contained a non dispersive unstable resonator of magnification M = 2, the avity length being 2.6 m.

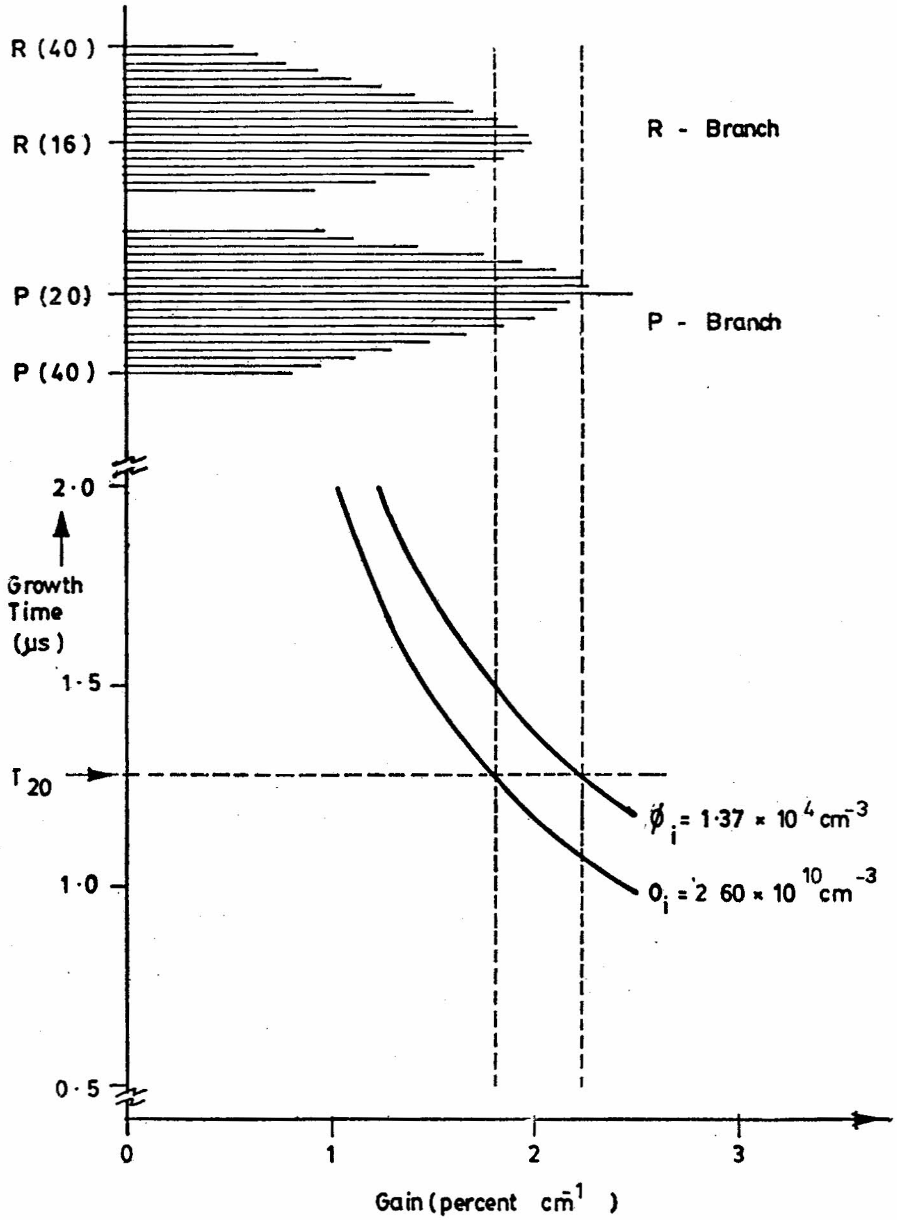

Fig.10. *Lower*—Gain switched pulse growth time for two injected signal levels, ϕi, plotted as a function of gain. T_{20} — growth time of $P_{10}(20)$ transition from spontaneous emission.

Upper—P and R branch gain spectrum with broken lines to indicate limiting transitions available for locking for each ϕi.

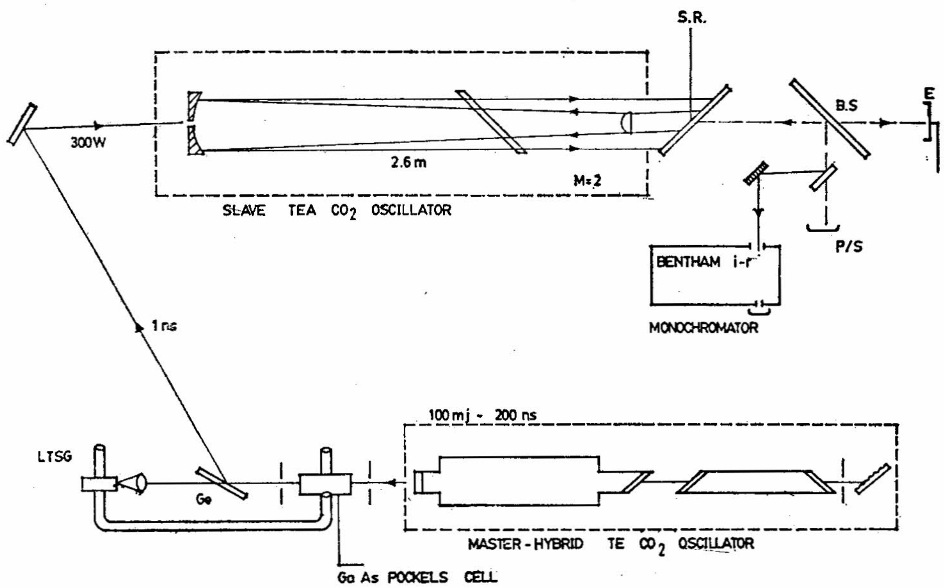

Fig.11. Experimental configuration employed to investigate IML in refs. (35) and (42).

The results obtained with this arrangement, where IML was investigated by tuning the master oscillator to a given transition and then monitoring the slave laser output, is given in table 1[42]; the experimental results for the 10.4 μm band, being in good agreement with those predicted by the theoretical analysis which, with $\phi_i = 2.6 \times 10^{10}$ cm^{-3} and $\alpha_{20} = 2.5\%$ cm^{-1}, was chosen to model this experiment. More than 30 transitions in both the 9μm and 10μm bands were injection modelocked where SF_6 gas was allowed to flow into the cavity airspace to suppress the growth of the dominant P(20), 10.4μm transition when signals on low gain rotational lines especially in the 9μm band were injected. In the 10.4μm band with the exception of the strongest emission lines, the output was duochromatic with P(20) growing in the pulse tail (table 1), while the presence of SF_6 in the cavity has led to the growth of other higher gain transitions along with that of the injected pulse.

By employing this simple technique of controlling the emission wavelength of slave lasers the IML range has been further extended[43] to cover about 42 rotational lines in the two lasing bands of CO_2. In this experiment IML was achieved for all transitions whose gain was greater than 3.3% cm^{-1}. It was a striking confirmation of the linear gain growth model presented by Dyer and Perera[42], as it implies that for a given injected power, modelocking can be obtained as long as the gain at the injected frequency is larger than a certain minimum value. Further, they also observed that for reliable modelocking on extreme rotational lines it was necessary to decrease losses in the slave laser cavity as implied by this model. This was done by adding salt plates and thus increasing the feedback mirror reflectivity.

Table 1

Injection Mode-Locked CO_2-Laser Transitions

Injection Mode-Locked Transition	*Other Transitions*
10 μm Band	
P(14)—P(22) ...	... —
P(12), P(24), P(26)	... Weak P(20) in tail of pulse
P(10), P(28) ...	... Weak P(20) in tail of pulse
R(18) ...	... —
R(12)—R(16), R(20)	... Weak P(20) in tail of pulse
R(22)[a] ...	... Weak P(20) in tail of pulse
9 μm Band	
P(16)—P(20) ...	... P(20) in tail of pulse
P(14)[a], P(22)[a] ...	... P(20) in tail of pulse
P(16)[b], P(18)[b], P(22)[b]	... —
P(12)[b], P(14)[b] P(20)[b], P(24)[b]	... Weak 9 μm P or R line in tail
P(10)[a,b], P(26)[a,b],	... Weak 9 μm P or R line in tail
R(16)[b]	... —
R(12)[b], R(14)[b], R(18)[b], R(22)[b]	... Weak 9 μm P or R line in tail
R(10)[a,b], R(24)[a,b]	... Several transitions in tail

a Poor reliability -jitter limited

b With SF_6 in cavity.

(Ref. 42)

Effect of Injected Signal Level[49]

To illustrate the influence of the intensity of the injected signal on the range of gain available for locking a parameter β was defined as,

$$\beta = \frac{\alpha_{Limit}}{\alpha_{20}}$$

where α_{Limit} is the minimum gain for which the injected signal can control oscillation when the gain on the $P_{10}(20)$ transition is α_{20}. By means of computer simulations the value of α_{Limit} and hence β was found, the variation of which as a function of the injected photon density ϕ_i is depicted in fig. 12[49] for a range of values of M, the resonator magnification.

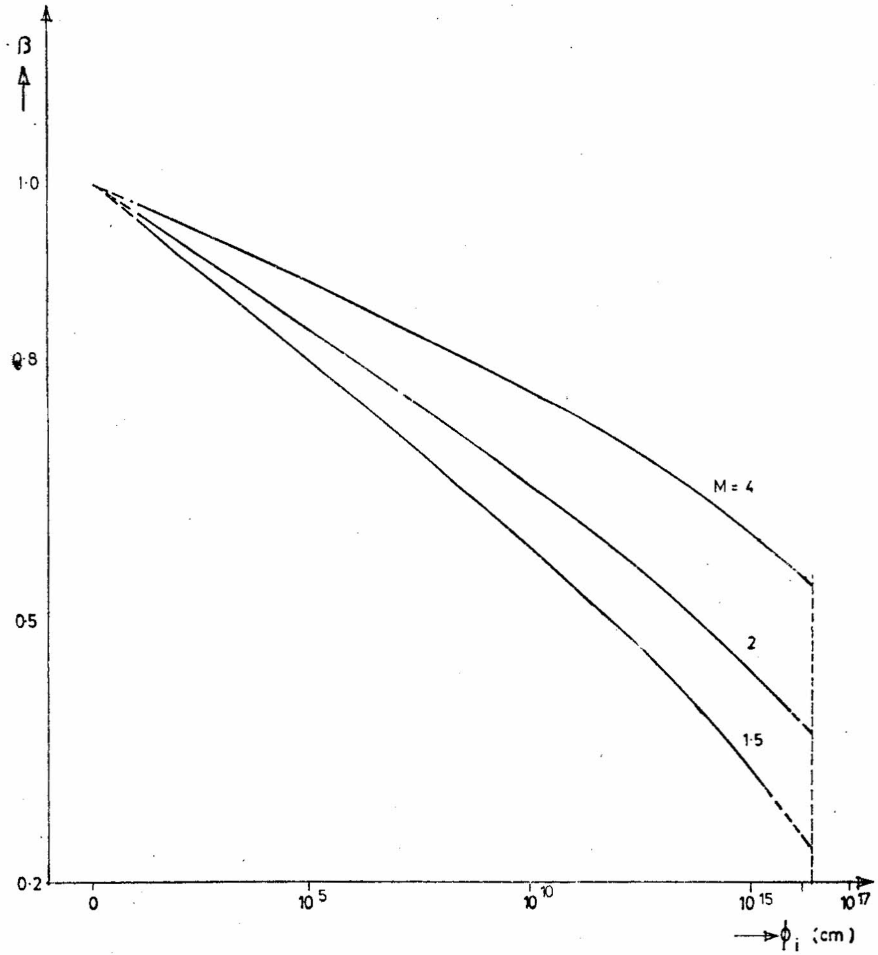

Fig.12. Variation of the parameter (β) with injected photon denisity ϕ_2 for different magnifications.

A wide locking range (i.e. a large number of transitions) is predicted when large injection signals are used. Within the limitations of the model, the minimum photon density required for an injected signal to capture oscillations would be $\phi_i > \phi_N \approx 1\ cm^{-3}$, where ϕ_N is the photon density at threshold due to spontaneous emission, for which $\beta = 1$. Then only $P_{10}(20)$ would be locked. Taking $\phi_i = \phi_s$ as an upper limit on the injected photon density, in which case the growth time T_j, of the laser pulse would be equal to the threshold time T, gives the largest operating gain window, i.e. $\beta \approx 0.4$ for $M = 2$ (fig. 12). However such an intense pulse would saturate the gain instantaneously (i.e. at threshold) and the laser output would be a train of pulses of reducing amplitude (fig. 13)[49]. It should also be noted that the intensity of the first pulse would be less than that of the injected pulse since the net round trip gain would be less than unity.

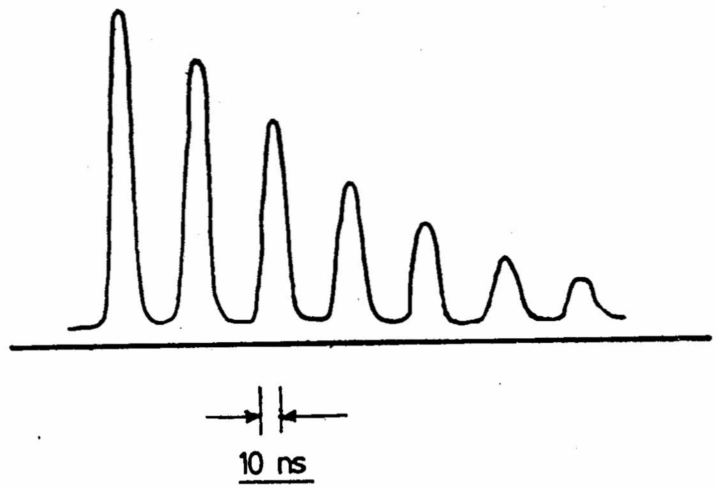

Fig.13. Typical output pulse when injected signal saturates the slave laser gain medium at threshold.

Influence of Slave Resonator Magnification[49]

The effect[49] of the resonator magnification M, of the slave laser on β or a range of injected signal intensities is shown in fig. 14. It is of interest to note that at low M values more transitions in both P and R branches can be injection modelocked by a given signal. This can be explained with reference to fig. 15[49] which illustrates the behaviour of gain of the dominant $P_{10}(20)$ transition and a lower gain transition X(j) during the growth time of the laser pulse, where X denotes a P or R branch transition and j is the corresponding rotational level. In general, the dominant $P_{10}(20)$ transition will reach thereshold before the lower gain transition X(j), and therefore the time interval $\triangle T$, increases with the threshold gain α_T of the laser (fig. 15). During this time interval $\triangle T$, the dominant $P_{10}(20)$ transition will grow and when the lower gain transition reaches threshold, will have an amplitude defined by the value of $\triangle T$, i.e. the higher the value of $\triangle T$ the higher would be the intensity of the $P_{10}(20)$ radiation in the cavity, making it more difficult for the lower gain transition to suppress $P_{10}(20)$ and dominate laser osillation. As the threshold time T is given by the equation,[42]

$$T = \frac{\tau \ln M}{\overline{\alpha}_J L} \qquad \text{.........................(7)}$$

such a condition is obviously achieved at higher resonator magnifications M, since threshold is reached at a later time leading to higher threshold gains, α_T,

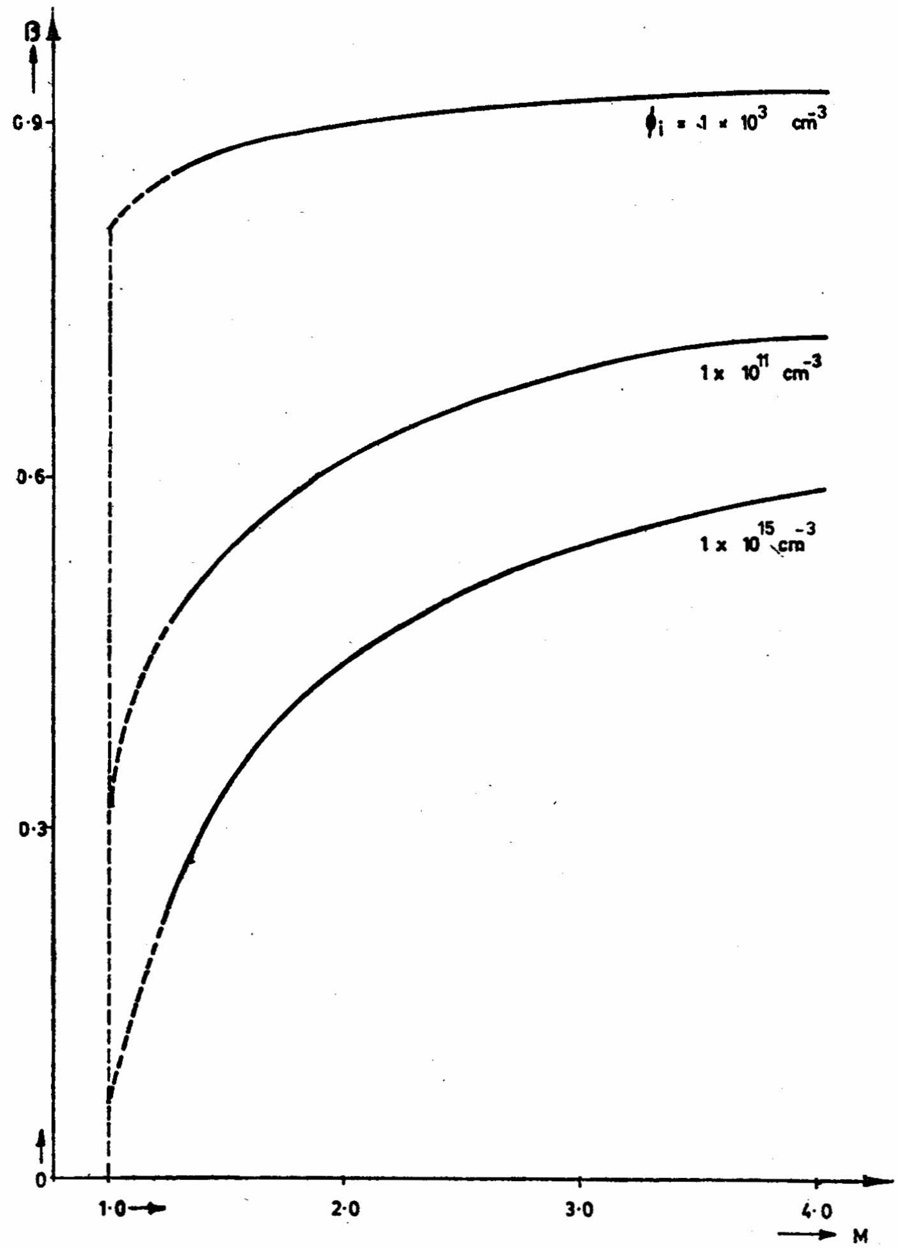

Fig.14. Variation of β with cavity magnification (M), for different injected intensities.

For low M values the gain locking range is largest, i.e. β is a minimum. In the limiting case of M = 1 equation (6) reduces to :

$$\bar{\alpha}_J \geqslant \bar{\alpha}_{20} \frac{ln\,(\phi_s/\,\phi_i)}{ln\,(\phi_s/\phi_{20})} \quad \text{......................(8)}$$

since the threshold time T = 0, an injected singal, of photon density $\phi_i = 1 \times 10^{11}$ cm^{-3}, will dominate laser oscillation on transitions whose parameter $\beta \geqslant 0.3$. However, the low magnification cavities, eg. $M \leqslant 1.2$, have limitations such as poor output coupling, complexity of design and also a high probability of damage due to the high energy densities created by such resonators.

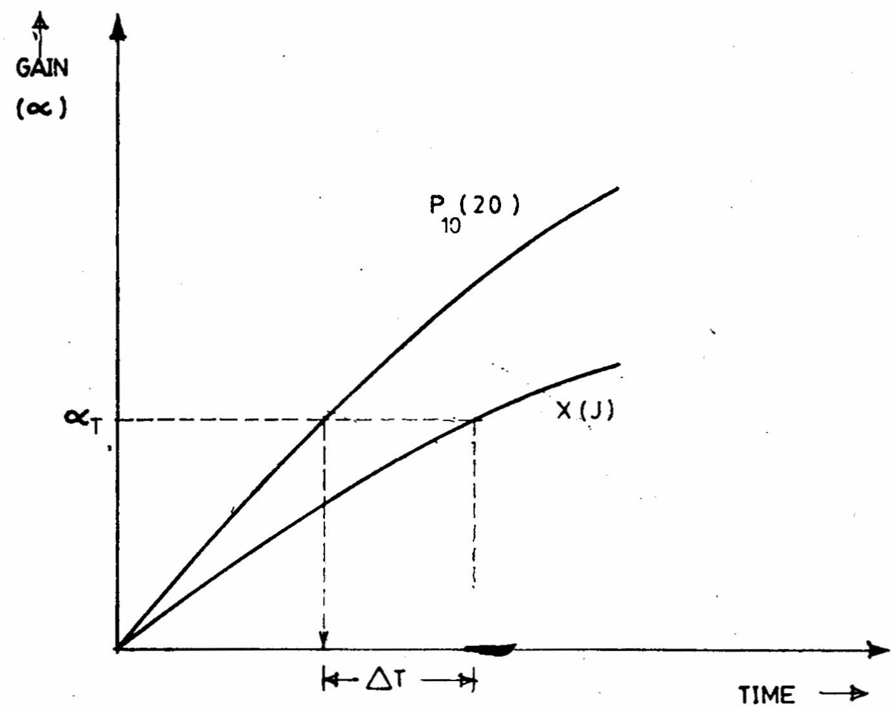

Fig.15. Gain curves of 10 μM band CO_2 laser transitions during the growth of the laser pulse.

IML of a Grating Tuned TEA CO_2 Laser

Injection modelocked operation of a grating tuned TEA CO_2 laser has also been investigated[35] employing the system depicted in fig. 11, but with the slave laser equipped with a three mirror dispersive confocal unstable resonator[78]. In this, with both master and slave oscillators tuned to a common transition, clean monochromatic pulse trains have been obtained on a large number of transitions (i.e. ≈60) on the P and R branches of both the 9— and 10 —μm bands as given in table 2. Clean locking on relatively weak transitions such as the R(30) in the 9 μm band was observed by operating the slave at a high pump energy density (~120 J. l^{-1}. A^{-1}); this transition being inaccessible with the non — dispersive injection locked slave oscillator.[42]

TABLE 2

Transitions of the monochromatic pulse trains generated by the line-tuned injection mode-locked CO_2 laser Transitions

10 μm Band

P—Branch

P(8) — P(34)

P(6)[a], P(36)[a]

R—Branch

R(6) — R(24)

R(26)[a]

R(28)[b], R(30)[b], R(32)[b]

9 μm Band

P—Branch

P(10) — P(34)

P(8)[b], P(36)[b]

R—Branch

R(10) — R(26)

R(8)[b], R(28)[b], R(30)[b]

(*a*) Poor reliability-improved at high pump energy densities ($120J.1^{-1}$ A^{-1})

(*b*) Obtained only at elevated pump energy densities ($120J.1^{-1}$ A^{-1})

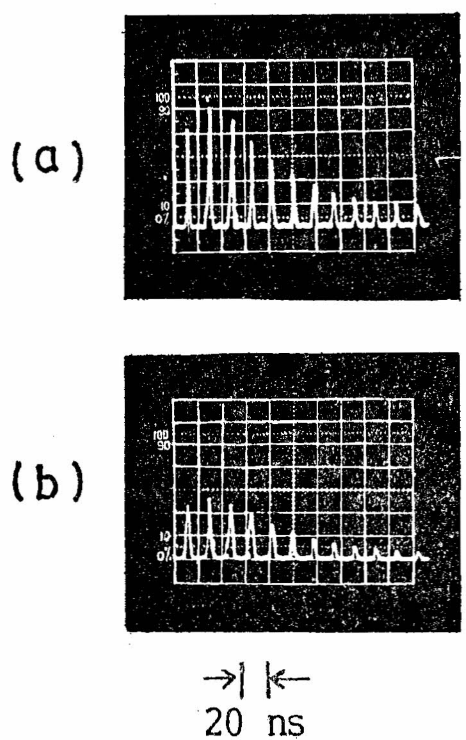

Fig.16 Modelocked pulse trains on low gain rotational lines: (a) P_9 (14) (b) R_9 (30).

Figs. 16(a) and (b) depict examples of such clean pulse trains on the $P_9(14)$ and $R_9(30)$ transitions respectively. The energy output with the slave laser operated at a voltage of 49 kV remained unchanged from that of the gain switched pulse; the total energy on the higher gain lines being about 20 J while on the wings, i.e. on $R_9(30)$ with an operating voltage of 54 kV the energy measured was about 14.5 J.

The broadening of the available range of wavelengths for locking can be attributed to the complete absence of competition from high gain transitions encountered by the injected signal when the slave resonator wavelength is defined by a dispersive cavity. This approach has proved very useful in generating stable pulse trains on low gain rotational lines for applications such as optical pumping of molecular gas lasers[44], NH_3 in particular, for producing ultra-short 12 um laser radiation.

Broadening of Injected Short Pulses

In a conventionally modelocked laser oscillator an intracavity modulator is used to both select a single short pulse from the noise signal and to produce temporal narrowing of the pulse in the face of competition from the inherent pulse broadening mechanism associated with the finite amplification gain bandwidth.

In contrast, in the injection modelocked laser an injected pulse of fixed spectral content defines the dominant noise signal at threshold and this pulse is subsequently amplified to saturation level. Since, in general, no internal modulator (either passive or active) is present, only the pulse braodening mechanism due to the finite amplifier bandwidth is operative[34]. The extent to which the pulse is broadened in this device can be evaluated by relating the amplified pulse spectrum, $E'(w)$, to that of the injected pulse $E(w)$, through the gain response of the amplifier[48]

$$E'(w) = E(w).\ g(w)^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where $g(w)$ is the round trip amplitude gain and n is the number of round trips during the build up time. Significant simplifications result by assuming a Gaussian amplitude envelope and hence a Gaussian frequency spectrum $E(w)$ for the injected pulse, and by representing the homogeneously broadened (Lorentzian) gain distribution of the TE CO_2 laser by a Gaussian near line centre[48]. In this case, if the duration of the injected pulse is τ_i (full width at e^{-1} intensity) and saturation is neglected, the output pulsewidth (full width at e^{-1}) after amplification had been shown[48] to be

$$\tau_o = \{\tau_i^2 + 16G/\triangle w^2\} \quad \ldots\ldots\ldots\ldots\ldots (10)$$

where $\triangle w = 2\pi\nu_H$, with $\triangle\nu_H$ being the full width at half maximum of the homogeneously broadened transition. G is the net intensity gain experienced by the pulse and is given by

$$G = \frac{cL_g\delta}{L_c}\{\propto_T + \frac{\propto\delta}{2}\} \quad \text{..........(11)}$$

where c, L_g, L_e, $\propto_T$ and $\propto$ have their usual meanings and

$$\delta = \{\frac{2L_c \ln(\phi_s/\phi_T)}{c\propto L_g}\} \quad \text{..................(12)}$$

where ϕ_s/ϕ_T is the ratio of the photon density at saturation to that at threshold.

In the limiting case of very short injected pulses (τ_i negligible) equation 10) reduces to

$$\tau_{Min} = \frac{2G^{\frac{1}{2}}\tau'}{\pi} \quad \text{.......................(13)}$$

where $\tau' = 1/\triangle\nu_H$ is conventionally regarded as the shortest (bandwidth limited) pulse available from a modelocked oscillator. Since G can be large ($\sim$ 50 — 100), the shortest pulsewidths (τ_{Min}) that can be generated from injection modelocked CO_2 lasers considerably exceeds τ' in contrast to a well designed 'conventionally modelocked' system for which τ_{Min} is of the same order as τ'.

Pulse broadening in injection modelocked lasers has also been studied experimentaly[48],50 In one such investigation[48,50]. broadening of an injected short pulse of fixed duration (1.4 ns, fwhm), was examined by varying the bandwidth of the TE CO_2 slave laser by changing its operating pressure, (P$\sim$ 200 — 700 torr). For the experimental parameters employed, $L_c = 275$ cm, Lg = 100 cm, $\overline{\propto} = 1.2 \times 10^{-5}$ cm^{-1} ns^{-1} with an injected signal intensity reduced to give a photon density $\phi_T = 5 \times 10^4$ cm^{-3} and using $\triangle\nu_H = 5.05 \times 10^{-3}$ p G.Hz for the 1/1/6 $CO_2/N_2/He$ gas mixture equation (10) can be written as[48],

$$\gamma = \frac{\tau_o}{\tau_i} = \{1 + \frac{1.1 \times 10^6}{\tau_i^2\, p^2}\} \quad \text{....................(14)}$$

where p is the total gas pressure in torr and γ is a measure of the pulse broadening experienced by the injected pulse. Relatively good agreement was observed between experimental and theoretical data and is depicted in fig. 17 where the parameter γ is plotted against $p\tau_i$ confirming the applicability of this simplified pulse broadening theory over the range investigated.

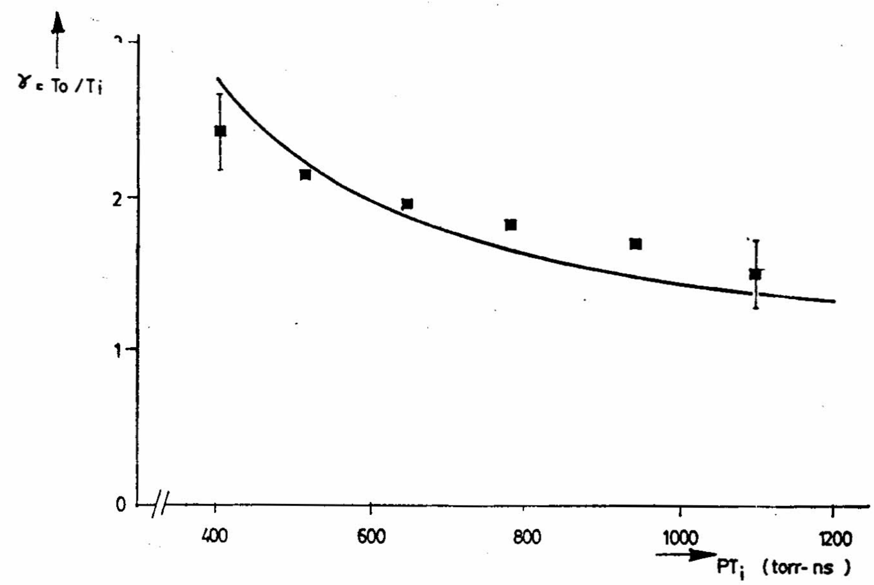

Fig. 17. Variation of the pulse broadening parameter (γ) with PT_i (—) theory, (■) experimental.

The validiy of this simple theory for predicting the widths of pulses generated by injection modelocking a TEA CO_2 laser, was further confirmed by Van Goor et al.[50] who studied the pulse broadening mechanism by injecting a train of short pulses instead of a single pulse. In this investigation the width of the injected gaussian pulse was varied keeping the gas pressure and the other parameters constant. For the system employed it was shown that equation (10) reduces to

$$\tau_0^2 = \tau_i^2 + \text{constant} \qquad \ldots\ldots\ldots\ldots(15)$$

which was in very good agreement[50] with the experimental results obtained.

Injection with intracavity saturable absorbers[48,54]

The use of p—type Ge saturable absorbers within the cavity of injection modelocked TEA CO_2 lasers is an attractive method for generating bandwidth limited pulses[48] with enhanced reproducibility[54]. In this case, the saturable absorber produces strong modulation, overcoming the intrinsic pulse broadening mechanism that occurs with short pulse injection alone.[48] The saturation of this intra — cavity absorber at sufficiently high intensities, effectively broadens the pulse spectrum as it transmits the pulse peak preferentially with respect to the wings narrowing the pulse. The role played by the injected signal is then in providing the dominant noise pulse, thus eliminating the requirement of near threshold operation of the slave laser for effective single pulse selection by the saturable absorber. It also eliminates the shot to shot statistical fluctuations and unreliable performance observed in passively modelocked lasers.

The pulse shaping effects of a saturable absorber in an injection modelocked laser has been explained[53] using a simple analysis where the two modelocking processes are considered separately. For the parameters of interest, this treatment was found[53] to agree reasonably well with the experimental results obtained.

The broadening $\triangle\tau_1$ of the injected pulse of duration τ_i, in the absence of an intra — cavity absorber, can be found by using equation (10), as

$$\triangle\tau_1 = (\tau_o - \tau_i) \qquad \text{.......................(16)}$$

where τ_o is the width of the output pulse.

The extent of pulse narrowing due to the saturable absorber has been evaluated by employing a simple model presented by Feldmann et. al.[26] developed to explain pulse narrowing within a modelocked train. According to this model which considers a Gaussian incident pulse of initial width τ'_i and neglects broadening in the active medium, the pulsewidth (τ'_o) after n round trips through the absorber is given by[26],

$$\tau'_o = \tau_i' \prod_{m=1}^{2n} \exp\left[-\delta(x_m)\right] \qquad \text{.............................(17)}$$

where the parameter δ is a measure of the reduction in pulsewidth.

Hence the duration (τ''_o) of the output pulse in the presence of both injection and passive modelocking processes takes the form,[53]

$$\tau''_o = \tau_i + \triangle\tau_1 + \triangle\tau_2 \qquad \text{........................(18)}$$

where $\triangle\tau_2 = (\tau_o' - \tau'_i)$ is the reduction of the pulsewidth due to the saturable absorber.

IML of a passively modelocked TEA CO_2 oscillator has been investigated[48] using 1.4 ns (fwhm) injected pulses and an AR coated 6 mm thick p — type Ge plate. With this arrangement highly reproducible 750 ps (fwhm) pulses were generated while the value predicted by the simple analysis (equation 18), was 850 ps, implying that reliable sub nanosecond pulses could be produced by this method.

Conclusion

The technique of injection modelocking provides a simple[30] and reliable[34] means for producing ultra — fast 10 um laser pulses, scalable to extremely high peak powers[4,5] from a wide variety of TEA and TE CO_2 oscillators. This process is less sensitive to the short gain lifetime and rapid gain rise time of multi-atmosphere discharges and therefore appear more suitable than conventional modelocking techniques for the generation of bandwidth limited pulses in the picosecond regime.[4]

This has also been applied successfully to modelock wide aperture TEA CO_2 lasers, equipped with dispersive and non dispersive resonators, on a large number of rotational lines in both 9.4 μm and 10.4 μm bands. The first[42] approach adopted, demonstrated the possiblility of controlling the emission wavelength of high power CO_2 lasers solely by an injected short pulse of relatively low power, without recourse to damage prone intra — cavity tuning elements. A simple theoretical analysis[42] based on a linear gain growth model has also been developed to explain this tuning process of large aperture CO_2 lasers and it has been found to agree[43] reasonably well with the experimental results obtained. Secondly the employment of a dispersive resonator on the slave laser completely eliminated the growth of the high gain $P_{10}(20)$ in the tail of the pulse, extending the tuning range to a large number of transitions.

IML also offers an interesting approach to the study of pulse evolution[48] in transient laser systems. As a result of multiple transits in the finite bandwidth gain medium of the slave laser, the pulse broadening that occurs has been shown to limit the minimum pulsewidths obtainable from IML techniques. This intrinsic broadening has been overcome by incorporating[53] a saturable absorber into the cavity of the slave laser. In this case, the injected pulse provides the dominant noise signal eliminating shot-to-shot statistical fluctuations and unreliable performance while the saturable absorber produces strong modulation overcoming the broadening of the amplifying medium.

These investigations are of fundamental importance to the further development of ultra short pulse CO_2 laser systems, and may well lead to the routine generation of single wavelength infra-red high power laser pulses, of sub-picosecond durations.

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