# $CO_2$ oscillator–pulse shaper–amplifier system producing 0.1 J in a 500 psec laser pulse*

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**The output of an optical free induction decay pulse generator was amplified up to the 0.1 J level. A pulse width of 500 psec was resolved on a Tektronix 519 oscilloscope using a pyroelectric detector. This agreed well with a linear computer model of the system response.**

## INTRODUCTION

A $CO_2$ laser system capable of producing and amplifying a 500 psec pulse is described. It makes use of the ultrafast switching action of laser induced breakdown[1] and optical free induction decay in a resonant $CO_2$ absorber. It has been recently shown[2,3] that a laser-induced breakdown plasma in combination with a spectral filter is capable of producing an ultrashort pulse. This method has the merit that arbitrary pulse shape and phase can be produced with a high degree of controllability.[4]

In this paper, we shall describe an oscillator–pulse shaper–amplifier system which generates a 500 psec pulse of 0.1 J. Also we report the first direct real time observation of the temporal profile of the sub-nanosecond output pulse produced by this method.

## DESCRIPTION OF APPARATUS

The optical arrangement is shown in Fig. 1. The entire system is mounted on a standard, commercial 1.22×3.66 m optical table. To shield against the electromagnetic interference arising from the high voltage discharges of the TEA lasers, the table was enclosed in an 2.44×4.88 m metallic enclosure. All electrical lines entering the shielded room had low-pass filters. The 6.35 mm polyethylene gas lines for the lasers were brought in through small holes in the wall. The output laser beam itself exited the shielded room through a 2.54 cm diam hole.

The $CO_2$ TEA laser oscillator was of the resistor pin variety.[5] It had about 900 resistors of 1000 $\Omega$ each, acting as a cathode. The anode was a rectangular brass plate about 1 m long. The operating pressure was about 300 Torr, and energy was supplied by a 0.1 $\mu$F capacitor charged to 32 kV. Switching was accomplished with a pressurized triggered spark gap using an automotive spark plug as the cathode.

Feedback in the oscillator was provided by means of an unstable resonator.[6] The rear mirror was a 9 m radius of curvature total reflector while the front mirror was antireflection coated germanium, concave on one side and convex on the other, with a 3 m radius of curvature. The feedback came from a 5 mm gold spot on the convex side. The spacing between the mirrors was 3 m.

Longitudinal mode control was accomplished by an intracavity 1.22 m long, 2.54 cm i.d. cw gain section.[7] Its operating pressure was 2 Torr with a dc discharge current of about 4 mA. Absolute single longitudinal mode operation was actually not necessary. Double mode beating could be tolerated. It was sufficient that the output spectrum was made narrow enough to be fully absorbed by the low pressure $CO_2$ absorption tube.

The oscillator output consisted of a 100 nsec pulse of peak power about 1 MW. At the end of the pulse there was the usual tail associated with $CO_2$ TEA lasers. The transverse spatial profile was typical of an unstable resonator; a 15 mm bright ring surrounding a 5 mm dark central spot.

The beam was immediately focused and recollimated by a lens pair. The lenses were $f/1$ Ge doublets, well corrected for spherical aberrations. Between them, at the focus, a plasma was formed blocking off transmission of the beam. The intensity at which the plasma nucleated fluctuated by a factor of 2. Nevertheless, it could be controlled in a rough manner by varying the flow rate of clean nitrogen gas through the focal region. In this way the breakdown was adjusted to occur near the peak of the oscillator pulse.

By adjusting the spacing of the lens pair, the beam was brought to a gentle focus and then permitted to spread to a diameter of about 45 mm before entering the absorption cell. It was important to spread the beam over such a large area to keep it from saturating the absorption. As an additional precaution against saturation, hot spots in the beam were eliminated by means of a spatial filter. That is, a 1.75 mm iris diaphragm was placed at the focus of the beam expander telescope.

The absorption tube is a 3.05 m long Corning conical glass pipe made of Pyrex with a 5 cm i.d. A 9.75 m heating tape was wrapped spirally around it to ensure a uniform temperature of the hot $CO_2$ absorption gas. The gas is kept warm in order to populate the lower laser level and to thereby obtain a high absorption coefficient. About four layers of 2.54-cm thick glass wool were sufficient insulation to keep the temperature of the tube at 421±5°C with only 400 W of heating power from a Variac. For additional insulation, the glass wool was wrapped in aluminum foil.

A detailed description of the absorption tube and the attachment of mirrors and windows is shown in Fig. 2. The normal operating pressure of the absorption tube was 25–30 Torr. The reasons for this choice of operating pressure will be explained in the next section. A double pass through the tube resulted in a factor of 25 000 in absorption. The input beam was slightly convergent so that by the time it was reflected back to the entrance window, it was only 3 mm

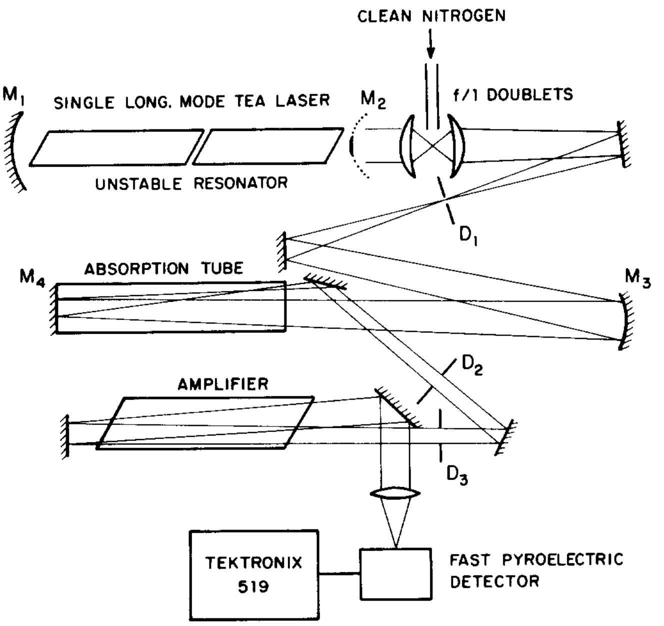

FIG. 1. Experimental setup. Radii of curvature for $M_1$, $M_2$, $M_3$, and $M_4$ are 9 m, 3 m, 4 m, and ∞, respectively. The mirror at the rear of the amplifier has a 10 m radius of curvature. $D_1$ is a 1.75 mm diam pin hole. $D_2$, $D_3$ are diaphragms with a 3.5 mm diam.

in diameter. Therefore the output could be taken from a side edge of the entrance window so that the exit mirror would not interfere with the incoming beam.

The output of the absorption tube was a short pulse of about 250 psec duration. It was sent in double pass through a Lumonics model 103 TEA amplifier equipped with Brewster angle windows. The beam was reflected out of the shielded room to be observed on a Molectron P5-00 pyroelectric detector and a Tektronix 519 high speed oscilloscope.

The very high double pass gain of the amplifier (about 2500) created a serious feedback problem due to stray reflections. The self-oscillation could be quite strong, enough to damage the detector. The problem was solved by passing the beam through two aperture defining iris diaphragms. In passing, we note that the diaphragms had to be tilted somewhat, since a slight amount of normal reflection could provide enough feedback for self-oscillation.

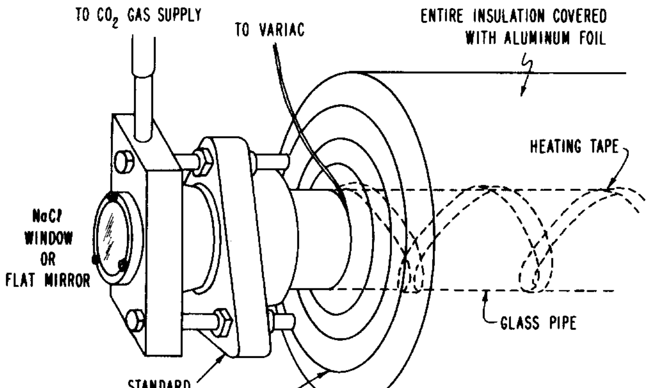

FIG. 2. Construction details of the absorption tube. The tube is 3.05 m long and has a 5 cm i.d. The salt window is mounted 3° away from normal to avoid back reflections.

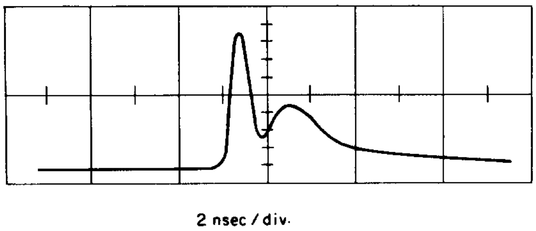

FIG. 3. Output pulse shape as observed with a pyroelectric detector and a Tektronix 519 'scope. Measured FWHM is about 500 psec.

Another source of oscillation was the reflection off the surface of the detector. Since the detector was placed almost at the focus of a lens, any backscattering would be recollimated and sent back exactly along the incident path. The problem was solved by putting the detector 10 m away from the amplifier.

A related problem was the scattering of the amplifier output beam back into the absorption cell along the incident light path. This could bleach the absorption and reduce the contrast ratio; i.e., the ratio of the peak power of the short pulse to that in the precursor. The problem was solved by providing a good spatial separation between the input and output beams of the amplifier. Of course, reducing scattering by having high quality Brewster salt windows was also helpful.

## RESULTS AND DISCUSSION

According to Ref. 1, the output of the absorption tube is a short pulse of duration $\approx T_2/N$, where $T_2$ is the inverse linewidth of the absorber, and $N$ is its attenuation in nepers. For the normal operating pressure of 25–30 Torr of $CO_2$ gas, the line is homogeneously broadened with a full-width at half-maximum given by[5]

$$1/\pi T_2 = 7.58(300/T)^{\frac{1}{2}}\ \mathrm{MHz/Torr}.$$

The normal operating temperature $T$ was 421°C. Experimentally, we found that $N = \ln 25\,000 \approx 10$. Therefore the output of the pulse shaper was a pulse of 250 psec duration.

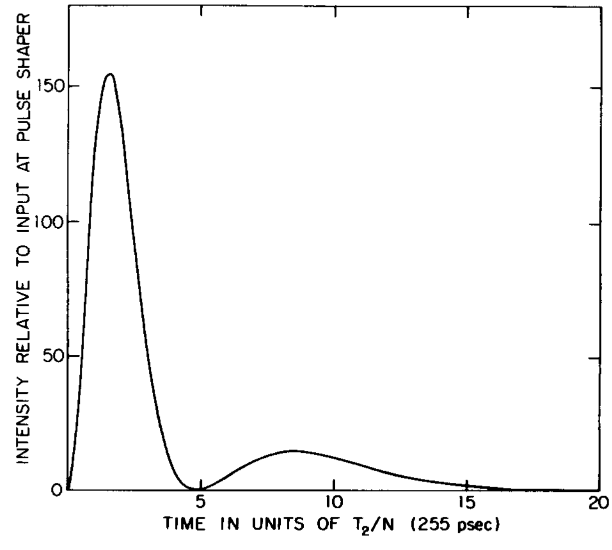

FIG. 4. Theoretically computed pulse shape. An amplifier gain of 625 and an absorption cell pressure of 25 Torr were assumed. The ratio of the tail energy to the main pulse energy is calculated to be $\frac{1}{4}$. FWHM = 510 psec.

The particular operating pressure of 25–30 Torr was chosen because a higher pressure would produce a pulse so short that it would be difficult to amplify it within the available bandwidth in a 1 atm $CO_2$ TEA amplifier. On the other hand, a lower pressure would bring us into the Doppler broadening regime. It would reduce the overall absorption without making the linewidth any narrower. Thus the longest pulse duration that can be produced is limited by Doppler broadening. In practice, 0.5 nsec is the longest pulse that can be generated in the absorption tube while maintaining a good contrast ratio.

Figure 3 shows the amplified pulse after going double pass through the Lumonics 103 amplifier. A Molectron P5-00 pyroelectric detector in combination with a Tektronix 519 oscilloscope were used for detection. The observed pulse is 500 psec wide. This is longer than the input pulse due to the phenomenon of gain narrowing in the amplifier. The measured peak to precursor contrast ratio was 5000 with a peak power of 200 MW.

We confirmed that neither the absorption tube nor the amplifier was being saturated. Therefore, let us model both the pulse shaper and the amplifier as linear with a Lorentzian line-shape. The system transmittance function is

$$H(\Delta\omega)=\exp[-N/2(1+i\Delta\omega T_2)] \times\exp[N'/2(1+i\Delta\omega T_2')],$$

where the first factor is the absorption of the hot cell, and the second factor is the gain of the $CO_2$ TEA amplifier. The homogeneous relaxation times $T_2$ and $T_2'$ can be obtained from the formulas given by Wood.[5] From the measured absorption and gain, $N$ and $N'$ were 10 and 8, respectively. Treating the input from the laser breakdown plasma as being effectively a step function, the Fourier transform of the system output is

$$[1/(2\pi)^{\frac{1}{2}}i\Delta\omega]\times H(\Delta\omega).$$

The inverse transform can be performed on a computer, and Fig. 4 shows the expected pulse shape. It has a rise time of 200 psec and a FWHM of 510 psec. It can be seen that the tail of the observed pulse in Fig. 3 is much bigger than expected. This is probably an artifact of the particular pyroelectric detector we were using. Unfortunately it had been damaged in earlier experiments. Measurements with a Ge:Au photoconductive detector, which acts as an integrator, indicated that the area of the tail was at most $\frac{1}{3}$ of the area in the main peak. This is consistent with the area ratio of $\frac{1}{4}$, determined from the computer calculation in Fig. 4.

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