30-psec CO_2 laser pulses generated by optical free induction decay*

H. S. Kwok and Eli Yablonovitch

Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts 02138

(Received 13 September 1976; in final form 29 November 1976)

We have measured the two-photon autocorrelation function of ultrashort CO_2 laser pulses generated by optical free induction decay. The pulse duration was determined as a function of the pressure in the resonant absorber. At a pressure of 250 Torr 30-psec optical pulses were produced.

PACS numbers: 42.60.He, 42.55.Dk, 42.80.Em

Recently, it has been found that the ultrahigh speed of the ionization front in a gaseous laser target leads to an ultrafast optical shutter.[1] This type of electro-optic element has been called the "plasma shutter". It has been synchronized[2] and used for optical isolation. In combination with a spectral filter, it has generated ultrashort optical pulses.[3]

In this paper we determine how fast is the "plasma shutter" and how short are the optical pulses generated by it.

The spectral filter in this experiment is resonant-absorbing hot CO_2 gas, and the short pulse generation is best looked upon as an "optical free induction decay" (OFID).[4] The pulse duration is determined by the precession time of the CO_2 molecules and was varied by changing the gas pressure. Ultimately the pulse width is limited by the speed of the plasma shutter itself. In previous experiments, only an upper bound to the pulse duration was established.[5] Here we report a two-photon correlation measurement of the duration of the ultrashort CO_2 optical free induction decay pulses. This, in turn, determines the speed of the plasma shutter.

Second harmonic generation was employed to measure the two-photon correlation function. This technique has been widely applied to the measurement of mode-locked picosecond pulses.[6] GaAs was chosen as the nonlinear crystal. Tellurium has a larger nonlinearity but also has carrier effects and distorts the original pulse shape.[7] We have also decided to use the GaAs in transmission instead of the more complicated zero background method where it is used in reflection. A theoretical contrast ratio of 3:1 is well known to be the single most important criterion for distinguishing a real short pulse from a burst of noise with picosecond substructure.

The experimental setup is shown in Fig. 1. The laser system has been described adequately in two previous papers.[2,4] It consisted of an ordinary TEA laser and a low-pressure cw section. The low-pressure gain section provided the longitudinal mode control which gave single mode operation.[8] The electrodes of the TEA section are of the pin resistor type and had a helical geometry to ensure lasing in the lowest-order transverse mode.[9] A 200-nsec pulse with 1 MW peak power was produced. The pulse was sharply cut off by the triggered plasma shutter and the hot cell served as an optical free induction decay source producing a precession pulse at the instant of the cutoff.

Absolute single-longitudinal mode operation was not necessary and was difficult to achieve for long periods due to drift in the length of the optical cavity. Therefore the gain in the low-pressure section of the oscillator was adjusted to yield a small number of longitudinal modes. This prevented the introduction of long-term drifts into the averaged signal, at the expense of degrading the signal-to-noise ratio somewhat.

The plasma shutter was externally triggered to fire near the peak of the laser pulse. Previously this was done by means of a small electrical spark ~1 mm away from the focal volume.[2] It would inject initiating electrons for the avalanche into the focal volume by means of uv photoionization.[10] We have found it somewhat simpler to produce the triggering spark by splitting off 7% of the laser beam and focusing it onto an aluminum block, placed about 5 mm from the focal volume. The microplasma thus formed replaced the dc spark. By adjusting the amount of light in the triggering arm the microplasma could be synchronized to form near the peak of the laser pulse with small jitter.

The OFID pulse from the hot cell was spatially filtered, sent to a conventional Michelson interferometer, and focused into the GaAs crystal by a 5-in.-focal-length Ge lens. The fundamental signal was rejected by a sapphire attenuator. Interestingly, it was found necessary to use a spike filter at 5.3 μ to block

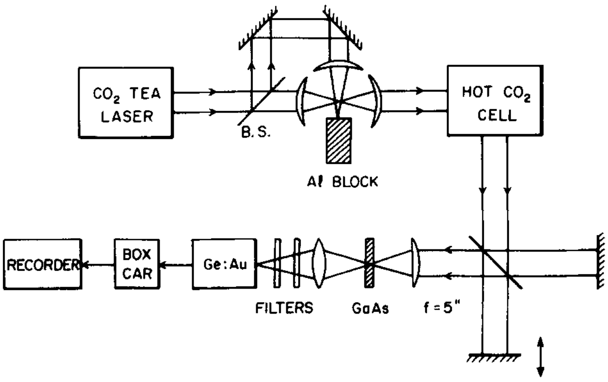

FIG. 1. Experimental setup. The lenses used for the formation of the breakdown plasma were well-corrected *f*/1 germanium doublets. A continuous stream of clean nitrogen gas was flowed through the focus of the lenses to prevent spontaneous gas breakdown and is not shown for clarity. One arm of the Michelson interferometer was motor driven. Preintegration and amplification of the detected signal was performed before entering the boxcar averager.

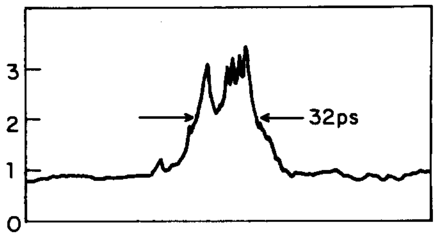

FIG. 2. A two-photon autocorrelation curve of 32 psec FWHM. The noise fluctuations were enhanced near the peak of the autocorrelation due to interferometer effects. This curve was taken at a CO_2 pressure of 250 Torr in the hot cell. T_2/N was 21.0 in this case.

off the thermal radiation from the gas breakdown plasma. The filtered second harmonic signal was then amplified and averaged with a boxcar integrator. A strip chart was used to record the correlation function. We also remark that due to the large index of refraction of GaAs, standing wave effects were very prominent and could give rise to erroneous measurements. The standing waves were suppressed by using a wedged sample so that reflected waves within the crystal would not overlap. Having a 5-mm-thick sample and mounting it at an angle of 10° to the beam were helpful in this regard.

A typical correlation curve is shown in Fig. 2. It has all the usual features of such a measurement. The excess noise structure at the peak of the curve was caused by interferometer effects. Every scan was repeated in the opposite direction to ensure reproducibility. A contrast ratio of 2.4 to 2.7 was typical. In all cases, there was no intermediate shoulder observed, indicating that the short OFID pulse had no noise structure associated with it. According to a linear frequency analysis,[4] the free induction decay pulse is given by

$$E(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\exp(-i\omega t)f(\omega)\exp[-N/2(1-\omega T_2)]\,d\omega,$$

where N is the absorption ratio of the hot cell in nepers, T_2 is the transverse relaxation time of the CO_2 molecules, and $f(\omega)$ is the transmission function of the plasma shutter. $f(\omega)=1/i\omega$ if we assume a step-function cutoff, and $f(\omega)=(1/i\omega)(1-i\omega\tau)$ if the cutoff of the laser beam is exponential with a time constant τ. In general, it will be a complicated function even with simple models.[1] However, at large T_2, the fall time of the plasma shutter is essentially negligible and we can use the step-function approximation. According to this approximation, the pulse has an instantaneous rise, and falls from the peak value with an initial reciprocal slope of T_2/N, which is interpreted as the effective pulse duration. Therefore, we have chosen to plot the full width at half-maximum of the second-order autocorrelation T versus the theoretical pulse width of T_2/N, in Fig. 3(a). The experimental points follow a straight line with a functional relationship $T=1.1(T_2/N)+10$ psec. The constant 1.1 is the pulse-shape-dependent factor that connects the FWHM of the autocorrelation function with the effective pulse duration. The additional 10 psec is indicative of a departure from the step-function approximation due to the finite fall time of the plasma shutter. An earlier paper had already inferred a fall time of 10 psec on the basis of the spectral broadening induced by the plasma shutter.[5] This was interpreted as the time required for the overdense ionization front to propagate across the focal volume and implied a propagation speed of 10^8 cm/sec.

A measurement of the pulse energy dependence on T_2/N indicated that the peak power efficiency of the OFID generator was close to 100% for the longer pulse durations. The efficiency fell to about 40% for a 30-psec pulse. This decrease in efficiency is the main difficulty in generating even shorter pulses.

In conclusion, we have made an autocorrelation measurement of the duration of the CO_2 laser pulses generated by optical free induction decay as a function of pressure. The results agreed with linear free induction decay theory and the shortest pulse duration observed was of the order of 30 psec.

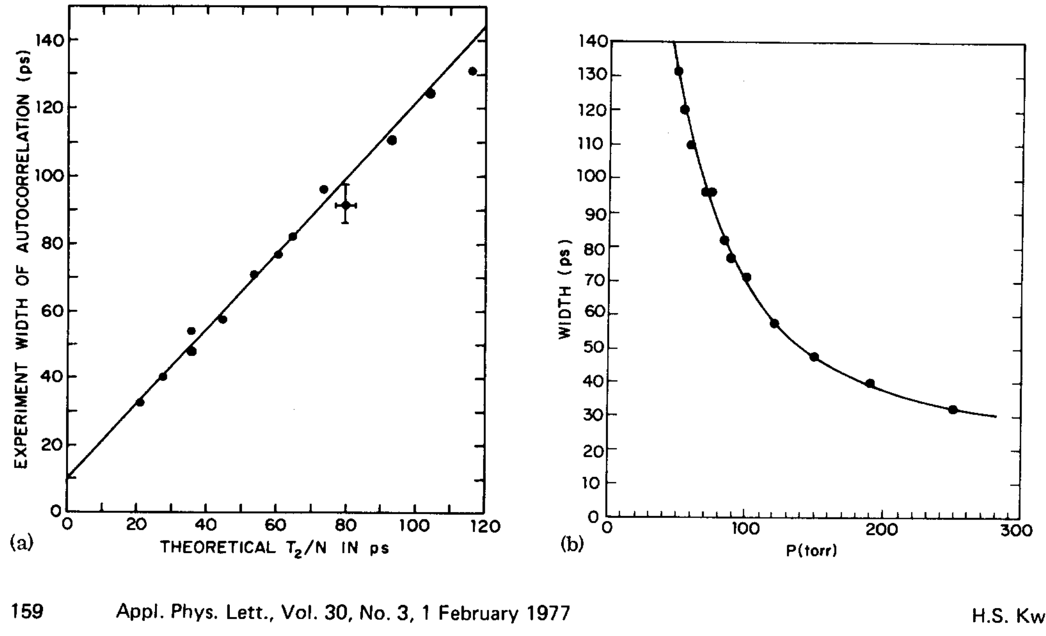

FIG. 3. (a) Experimental result showing the dependence of the FWHM of the two-photon autocorrelation on T_2/N. Typical error is also shown. See text for the explanation of the slope and the intercept of 10 psec. (b) Same data plotted against P, the pressure in the hot cell.

*Research supported by ARPA Contract No. F44620-75-C-0088.

[1]Eli Yablononvitch, Phys. Rev. A **10**, 1888 (1974).
[2]H.S. Kwok and Eli Yablonovitch, Appl. Phys. Lett. **27**, 583 (1975).
[3]Eli Yablonovitch, IEEE J. Quantum Electron. **QE-11**, 789 (1975).
[4]Eli Yablonovitch and J. Goldhar, Appl. Phys. Lett. **25**, 580 (1974).
[5]Eli Yablonovitch, Phys. Rev. Lett. **31**, 877 (1973).
[6]D.J. Bradley and G.H.C. New, Proc. IEEE **62**, 313 (1974); E.P. Ippen, C.V. Shank, and A. Dienes, Appl. Phys. Lett. **21**, 348 (1972).
[7]C.A. Schwartz, J-L. Oudan, and E.M. Batifol, IEEE J. Quantum Electron. **QE-11**, 616 (1975).
[8]A. Gondhalekar, N.R.Heckenberg, and E. Holzhauer, IEEE J. Quantum Electron. **QE-11**, 103 (1975).
[9]R. Fortin, M. Gravel, and R. Tremblay, Can. J. Phys. **49**, 1783 (1971).
[10]D.C. Smith, J. Appl. Phys. **41**, 4501 (1970); A.M. Robinson, Appl. Phys. Lett. **22**, 33 (1973); W.T. Silvast and O.R. Wood II, Appl. Phys. Lett. **25**, 274 (1974).

1-μs laser pulses from XeF†

L. F. Champagne, J. G. Eden,* N. W. Harris, N. Djeu, and S. K. Searles

Naval Research Laboratory, Washington, D. C. 20375

(Received 27 August 1976; in final form 29 November 1976)

Long-pulse operation of the XeF laser has been achieved utilizing electron beam excitation of Ar/Xe/NF_3 gas mixtures. For a total mixture pressure of 2.5 atm, ~0.30 J of 350-nm radiation was obtained in a 1-μs FWHM pulse.

PACS numbers: 42.55.Fn

The performance of rare-gas halide lasers has been considerably improved since their discovery less than two years ago.[1] Advances in laser peak power and efficiency have been demonstrated. However, laser pulse duration has been restricted to less than 220 nsec (KrF).[2] For some applications long-duration pulses are required. We report observation of long essentially cw laser pulses from XeF with electron beam (e-beam) pumping. These pulses, up to 1.5 μs, are a factor of 15 longer than previously reported for XeF.[3]

A diagram of the laser cell is shown in Fig. 1. A Maxwell cold-cathode electron gun[4] was used to generate 300-keV electrons. The current density at the 25-μ-thick Ti foil was 14 A/cm² for a 1.2-μs FWHM pulse, 8 A/cm² for 1.5 μs, and 5.2 A/cm² for 2 μs. The reduction in current density results from the greater anode-cathode spacing required for the longer pulse lengths. The electron beam entered the laser cell with a rectangular cross section of 2.6 cm × 100 cm.

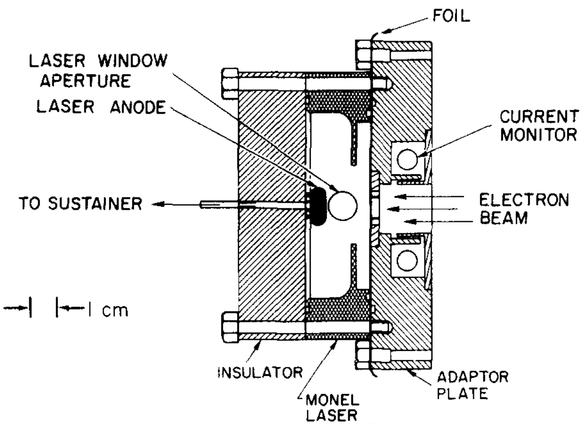

FIG. 1. Schematic diagram of the laser cell. The sustainer electrode was grounded in these experiments.

Laser energy was extracted from a cylindrical volume 100 cm long and 2.22 cm in diameter. Optical-quality CaF_2 or fused silica windows were installed at Brewster's angle. Dielectric-coated mirrors of 3 m radius of curvature separated by 2 m formed the laser cavity. One mirror was > 99% reflecting. The reflectance of the output mirror or quartz flat can be read from the abscissa of Fig. 3. Laser energy coupled out of the laser resonator was measured by a Gen-Tec ED-500 pyroelectric detector. Laser power was mea-

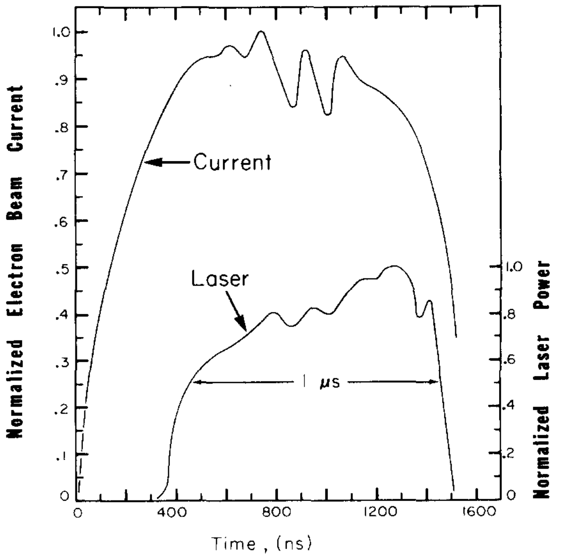

FIG. 2. Electron beam current and laser waveforms. Peak current corresponds to 11 A/cm² at the foil. Total pressure 1 atm.