Generation of high repetition rate far-infrared laser pulses

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(Received 2 February 1994; accepted for publication 1 April 1994).

We report the generation of pulsed optically pumped far-infrared (FIR) radiation with a repetition rate of 200 kHz. These pulses were obtained in a straightforward method by pumping a FIR resonator with a high repetition rate, rf-excited, waveguide CO_2 laser. Pulses approximately 50 *ns* wide were generated both at 432.6 μm in HCOOH, and 117.7 μm in CH_2F_2. The pulse width of the FIR radiation was studied as a function of the CO_2 pulse width, and the relative delay between the two was measured. Based on this data we conclude that the FIR radiation was gain switched and of a duration which was a function of either the gain bandwidth of the FIR transition, or more likely the FIR cavity parameters.

The production of short far-infrared (FIR) laser pulses has been the subject of a great deal of effort in recent years. Several methods have been developed for the generation of ultrashort pulses ($\tau \leqslant \sim 15$ ns) including super-radiant pulse production using a rapidly truncated CO_2 pulse,[1,2] stimulated Raman emission,[3] cavity dumping an external passive resonator pumped by a free electron laser,[4] FIR pulse termination by optically switching a semiconductor wafer outside the laser cavity,[5] and cavity dumping a FIR laser by optically switching an intracavity semiconductor.[6,7] In contrast, the generation of longer FIR pulses (50–500 ns) has been accomplished principally through two techniques: pumping with a transversely excited atmospheric (TEA) CO_2 laser,[8] and pumping with a Q-switched CO_2 laser.[9,10] Both techniques traditionally have been limited to low kHz repetition rates. The pump pulses in these techniques contain long tails which prevent time-resolved studies including possible delays between the termination of the CO_2 pulse and the onset of the FIR pulse, as are reported in this letter. Furthermore, the former technique tends to produce temporally erratic pulses unless one pumps with a single-mode hybrid[11] TEA CO_2laser.

In this letter we report the generation of FIR pulses as short as 53 ns (full width at half-maximum, FWHM) at record pulse repetition frequency (PRF), 200 kHz, and an average power of 2 mW at 150 kHz PRF. This was accomplished using a United Technologies Optical Systems (UTOS) prototype, single-mode, electro-optically modulated, rf-excited, waveguide CO_2 laser. This laser has the capacity to operate at very high repetition rates with convenient control over the pulse width (adjustable from ~17–125 ns). The PRF and average power obtained for the FIR pulses described herein may prove useful for the study of physical phenomena on this time scale. Furthermore, it may be possible to decrease the FIR pulse width through proper adjustment of the FIR laser-cavity parameters.

The FIR pulses were detected in a corner-cube-mounted Schottky barrier diode.[12] A schematic diagram of the experimental setup is shown in Fig. 1. The Schottky diode is a model 1T7 fabricated by the Semiconductor Device Laboratory of the University of Virginia. While the 4λ whisker-antenna length contacting the diode was optimized for $\lambda = 513$ μm, the response with this configuration was more than adequate for wavelengths as short as 117.7 μm.

The CO_2 beam was focused with a 16 in. focal length mirror and then directed into the FIR laser through 2 mm input-coupling hole. The FIR resonator operated in the half-symmetric Gaussian mode with a 10 m radius of curvature input mirror, a flat, hole-coupled output mirror, and a 73-in.-long 2-in.-ID quartz tube. The FIR beam coupled out of the resonator through a 6 mm output hole and was then collimated with a 9 in. focal length TPX lens. Following the collimating lens, the beam was either directed onto an off-axis parabolic reflector which focused the beam into the Schottky diode, or through a 6 in. focal length TPX lens and into a calorimeter.[13] The latter provided for measurements of the FIR average power. The FIR radiation was attenuated prior to entering the Schottky diode to prevent damage and a wire grid polarizer was used to confirm the polarization of the FIR radiation.

The signal from the Schottky diode was taken from the rf port of a bias tee (HP model 11612A). This tee is rated to work from 45 MHz to 26.5 GHz and thus caused some slight distortion, in the form of undershoot, for pulses longer than ~75 ns. This pulse distortion tends to make pulses appear to be slightly wider than they are. However, the effect will be minimal for the pulse widths presented here. The bias tee was followed by a wide bandwidth amplifier (10 kHz–5 GHz) with a power gain of 18 dB. The output of this amplifier was captured with a 4.5 GHz-bandwidth transient digitizer. The temporal profile of the CO_2 pulses was measured with a LN_2-cooled Ge:Au detector (not shown in Fig. 1). All delay times were calculated from measurements of the electronic and optical-path delays.

The CO_2 laser may operate in either continuous-wave (cw), Q-switched, or Q-switched cavity-dumped modes.[14] A typical pulse is shown in Fig. 2(a) for the "Q-switched-only" mode. The broad 125 ns pulse has a sharp spike on its falling edge resulting from a small amount of cavity dumping as the Pockels cell is turned off. When operating in "Q-switch cavity-dumped mode," the pulse width can be adjusted by changing the fall time of the Pockels cell switching voltage,

0003-6951/94/64(25)/3383/3/$6.00
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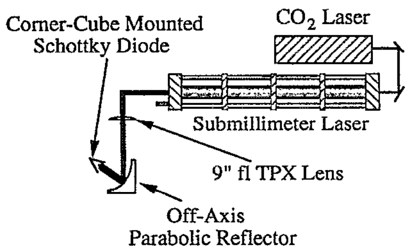

FIG. 1. Schematic of the experimental setup.

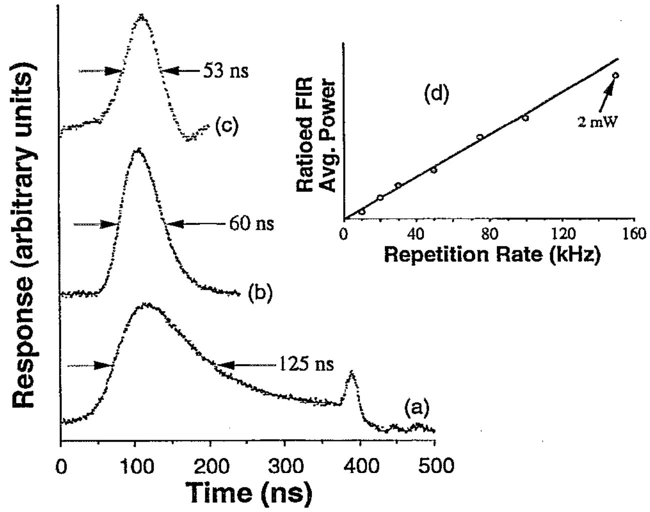

FIG. 2. (a) Q-switched CO_2 pulse, 125 ns FWHM. Note the cavity-dumped spike at the end. (b) Q-Switch cavity-dumped CO_2 pulse, 60 ns FWHM. (c) FIR pulse at 432.6 μm in HCOOH. FWHM=53 ns, pressure=170 mT. (d) Average FIR power (ratioed to the CO_2 power per pulse) vs repetition rate. The scatter in the data is primarily due to the difficulty in accurately measuring low power levels ($\leq$200 μW) with the calorimeter. The straight line is included as an aid to the eye only.

and even the pulse shape may be changed through properly timed adjustment of this voltage. A typical "Q-switched cavity-dumped" pulse is presented in Fig. 2(b). During the setup, the CO_2 laser was operated in cw mode to conveniently optimize the alignment of the optics and FIR resonator.

A typical FIR pulse at 432.6 μm, resulting from pumping with a Q-switched CO_2 pulse like that shown in Fig. 2(a), is presented in Fig. 2(c). While one might expect to be able to operate at significantly higher pressures in pulse mode than in cw mode, this was not found to be true here. The FIR cell was operated at ~170 mT for the 432.6 μm line and at ~350 mT for the 117.7 μm line.

The average FIR power at a PRF of 150 kHz was measured[13] to be 2 mW, assuming 40% total loss in the two TPX lenses used for the power measurements. The average FIR power was not measured above this repetition rate. At 150 kHz, the average CO_2 power was 22 W. The average FIR power, divided by the CO_2 power per pulse, is plotted in Fig. 2(d). (The straight line is included as an aid to the eye only.) There does not appear to be any significant roll off in efficiency up to a PRF of 100 kHz. Above 100 kHz, the apparent roll off is presumably due to the finite vibrational relaxation time in the upper vibrational manifold.

The results of pumping with shorter CO_2 pulses are presented in Table I. In general, pumping with shorter CO_2 pulses lengthened the FIR pulses. As well as becoming longer, the FIR pulses became progressively weaker and less stable as the pump pulse was shortened. This effect is probably due to operating the FIR laser near threshold. Since the bandwidth of the vibrational pump transition is on the order of 10 MHz at these operating pressures,[15] shortening the pump pulse to the extent where it had significantly more frequency content than the pump transition effectively decreased the pumping efficiency.

With the above data in mind, it seemed prudent to try pumping with a CO_2 pulse containing an initially long, low intensity, component followed by a short, high-intensity, spike. We refer to this pulse shape as "pre-pulse spike." Pumping with this type of pulse resulted in the same pulse width shown in Fig. 2(c), but with a dramatic improvement in the FIR pulse-to-pulse stability. Upon digitizing 16 "randomly"chosen pulses, there was no discernible difference among the pulses. One could obtain similar behavior by pumping the FIR cell slightly below threshold with a weak cw CO_2 laser, and periodically injecting a short CO_2 laser pump pulse.

When pumping with a Q-switched CO_2 pulse, the delay time between the beginning of the CO_2 pulse entering the FIR resonator and the beginning of the FIR pulse leaving the resonator, was ~280 ns and fairly stable in time (~30 ns jitter). This long delay indicates that the FIR laser is gain switched. When pumping with shorter CO_2 pulses, the delay time was ~370 ns with ~75 ns jitter. In contrast, when pumping with the "pre-pulse spike" CO_2 waveform, the relative delay between the spike and the FIR pulse decreased to no more than 30 ns and was very stable in time. Since these FIR pulses were of comparable strength to those obtained with the Q-switch pumping, the delay behavior indicates that the "pre-pulse" pumping placed the FIR laser near or below threshold, so when the pumping spike arrived the system was ready to lase. The observed delay and "pre-pulse" pumping behavior suggest that pumping with CO_2 pulses of duration equal to the delay should produce greater power FIR pulses.

Results similar to those observed at 432.6 μm were obtained at 117.7 μm. The shortest FIR pulse width was 55 ns for a 125 ns Q-switched pump pulse. Decreasing the pump pulse width produced longer FIR pulses. "Pre-pulse spike" pumping again resulted in highly stable FIR output with the same pulse width as in the Q-switch pumping case.

It is interesting to note that the typical gain bandwidth of these FIR lines would transform to a pulse width on the order of tens of nanoseconds. However, upon adjusting the pressure by more than a factor of 2 no pressure dependence of the pulse width was observed whereas the gain bandwidth should be a function of pressure. Furthermore, while the gain bandwidth might be expected to be larger at shorter wavelengths, the width of the 117.7 μm pulse was longer than that of the 432.6 μm pulse. The above data do not rule out the gain-bandwidth origin for the pulse width, but the observed

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TABLE I. FIR pulse width vs CO_2 pulse width for the 432.6 μm line.

CO_2 pulse width (ns) FWHM	FIR pulse width (ns) FWHM
125	53
90	72
60	110
26	112

behavior is in better agreement with a cavity lifetime dependence on wavelength.

In an effort to explain and estimate the pulse width based on a simple lifetime model, consider the cavity lifetime. The cavity lifetime in the absence of laser gain is given by[16]

$$\tau_c = \frac{T}{2\alpha_{0p} + \ln\left(\frac{1}{R_{tot}}\right)} = \frac{T}{\delta_c}, \quad (1)$$

where $2\alpha_{0p}$ is the roundtrip internal cavity loss factor, R_{tot} is the product of the input and output mirror reflectivities, T is the cavity round trip transit time, and δ_c is the roundtrip total cavity loss. With the 6 mm output coupler hole size and expected tube losses,[17] the total roundtrip cavity loss can be estimated to be ~20%. With $\delta_c = 20\%$, $\tau_c \approx 60$ ns. This is in good agreement with the observed short pulse widths at both 432.6 and 117.7 μm. Also, tube loss is expected to decrease with decreasing wavelength,[17] which would increase the cavity lifetime and associated pulse width at shorter wavelengths.

If the simple explanation presented above is, in fact, the origin of the observed pulse width, then this width could be shortened (within the limits of the bandwidth of the rotational transition) by modifying the cavity parameters. Specifically, the reflectivity of the output coupler and length of the cavity could be reduced provided the gain remained large enough to permit lasing.

We have measured 53 and 55 ns pulses at 432.6 and 117.7 μm, respectively. These pulses have been generated at record repetition rate (200 kHz) with reasonable average power levels (2 mW at 150 kHz PRF). This straightforward technique for producing high repetition rate, smooth FIR pulses should prove useful for the study of phenomena on this time scale. Furthermore, shorter pulses might be obtained by modification of the FIR laser-cavity parameters.

This work was supported by the US ARMY, FSTC under contract number DAHC90-91-C0028.

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