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Experimental observation of oscillatory instabilities and chaos in a gain-modulated single-mode cw CO_2 laser

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We report the first experimental observation to our knowledge of single-mode instabilities and chaos in a gain-modulated cw CO_2 laser. With the use of detuning as a control parameter, chaos in this system has been found to occur through an intermittent route. We have identified certain regions of detuning over which the normal emission of the laser breaks down, giving rise to periodic, quasiperiodic, or chaotic behavior.

In order to possess a strange attractor, a system, besides being nonlinear, should also have a sufficiently large phase space.[1] The Maxwell-Bloch equations describing a single-mode homogeneously broadened laser, which essentially represents a Haken-Lorenz system,[2] satisfy these conditions and, therefore, can yield chaotic solutions under certain parameter conditions. However, in almost all of the conventional lasers one or two of the variables, out of a total of three, undergo adiabatic elimination since they relax too fast compared to the rest, resulting in a reduced number of coupled equations.[3] Observation of chaos in these systems therefore requires restoring phase-space dimensionality by some external means. One of the obvious ways to achieve this is to temporally modulate the gain of the laser medium, first suggested by Scholz, Yamada, Brand, and Graham[4] and subsequently observed in the emission from both $LiNdP_4O_{12}$ laser[5] and NdP_5O_{14} laser.[6] In this Rapid Communication, we report, for the first time, on the experimental observation of chaos from a gain-modulated single-mode cw CO_2 laser. Our observation is of special significance since these are obtained for modulation frequency significantly lower than those hitherto used for studying dynamical instabilities in single-mode lasers with external modulation.

In the past, chaotic emission has been observed from single-mode cw CO_2 lasers by loss modulation[7] and also by frequency modulation.[8] Tredicce, Abraham, Puccioni, and Arecchi[9] have theoretically compared the effects of loss and gain modulation near the relaxation oscillation frequency on lasers for which polarization can be adiabatically eliminated and the field decays much faster than the population inversion; a condition which is well satisfied for CO_2 lasers.[10] The authors of Ref. 9 find that in order to obtain similar instability results one needs a gain modulation which is much higher than the corresponding loss modulation. An earlier attempt to destabilize the CO_2 laser emission by gain modulation near the relaxation oscillation frequency was unsuccessful.[9] However, in the limit where modulation frequency is much lower, the equations of Ref. 9 will suggest that gain and loss modulation will have the same impact on the system.

On modulating the gain of our system at 100-Hz frequency, chaos was found to evolve through an intermittent route with the use of cavity detuning as a control parameter. We also have identified certain regions of detuning over which the output of the laser is periodic, quasiperiodic, or chaotic. Interestingly, chaos is found to occur only on the lower-frequency side of the gain line center while periodic or quasiperiodic emission occurs on either side. Most of these results are in qualitative agreement with the theoretical predictions of Ref. 4. It should, however, be noted that the conditions, under which calculation of Ref. 4 is made, will not describe the dynamics of CO_2 laser under normal circumstances.

The cw CO_2 laser, which was used for this investigation, operated on a single longitudinal and transverse mode, and also on a single rotational line. The 94-cm-long Invar stabilized resonator cavity, which was placed on a vibration isolation table, is provided with a piezoelectric tuning facility, tunable over more than a free spectral range (FSR) of 159 MHz, and comprises a plane grating and a concave (10-m radius of curvature) ZnSe output mirror of 80% reflectivity. The dc power supply of the laser used a full wave bridge rectifier which essentially produced on the dc discharge current a 100-Hz modulation (50 Hz being the supply frequency), the depth of which could be changed by changing the value of the filter condenser and the ballast resistance. The gain modulation achieved in this way is always synchronized to the line frequency and the possibility of any line frequency pickup is thus completely ruled out. Because of the experimental limitations, the discharge current could not be modulated at any other frequency. The discharge current is set at a value to give maximum gain, which typically is about twice the lasing threshold. The relaxation oscillation frequency of the laser is thus much more than the modulation frequency. The single longitudinal mode condition was established experimentally by tuning the cavity length over a full FSR and the single transverse mode condition was ensured by the use of an intracavity aperture. In order to obtain absolutely no lasing over at least some tuning range, the aperture had to be shut down appropriately to suppress all other transverse modes except the TEM_{00} mode. With the aperture fully open, lasing always occurred over the entire FSR. The claim of the single longitudinal and transverse mode condition is also based on the observed pulsation frequencies, which were always some orders of magnitude smaller than the adjacent mode separation.

The emission of the laser was temporally monitored under varying detunings of the oscillation frequency from

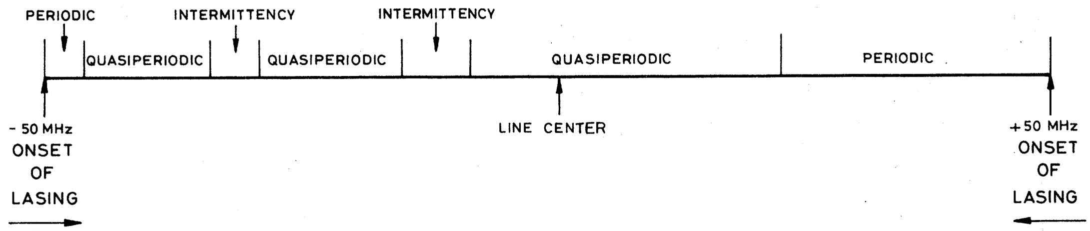

FIG. 1. As seen in this figure, emission of the laser becomes periodic, quadiperiodic, or chaotic (via intermittency) depending on the separation of the frequency of the oscillating mode from the center of molecular frequency (see text for details).

the gain line center. Different regions of detunings, over which periodic, quasiperiodic, or chaotic emission was observed, have been illustrated in Fig. 1, obtained for a gain modulation of 1%. Onset of lasing on either side of the line center follows the 100-Hz modulation up to 46.1 MHz in the low-frequency side from the line center and up to 21.4 MHz in the high-frequency side from the line center. Over a range of 11.9-, 13.6-, and 29.9-MHz width, respectively, centered at -40.2, -22.2, and $+6.4$ MHz from the gain line center, the emission is quasiperiodic where the primary 100-Hz oscillation is modulated at another frequency of 14 Hz (shown in the trace of Fig. 2). The overall amplitude of oscillation here strongly depends on the detuning; the maximum and minimum amplitude differing by a factor of 1.8. Over a range of 5.1- and 6.8-MHz width centered, respectively, at -31.5 and -12 MHz from the line center, the emission culminates in chaos. There now exists numerous theoretical reports showing critical dependence of detuning on the single-mode instability phenomenon in lasers.[11] The observed asymmetry in the instability phenomenon with respect to the line center is clearly attributable to the dynamics of the laser since cavity detuning does not affect any passive laser parameter including the discharge current. Such asymmetrical occurrence of instabilities with respect to the line center is not uncommon in lasers and has been found in the past in Raman laser,[12] optically pumped far infrared laser,[13] and He-Ne laser.[14] It should also be noted that very recently, asymmetry in the instability phenomenon has been observed with respect to other parameters as well, for example, the gain in a cw Co_2 laser.[15]

As seen in Fig. 1, emission breaks down into chaos only

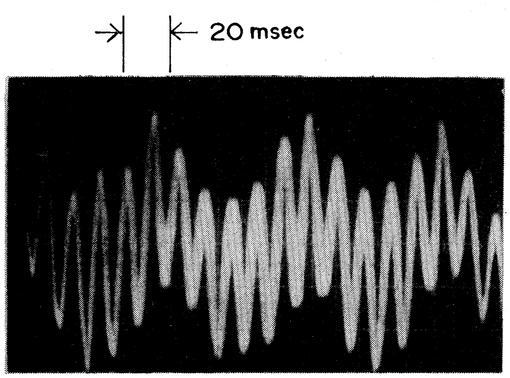

FIG. 2. A typical example of the quasiperiodic emission from the laser; two different oscillation frequencies are readily evident.

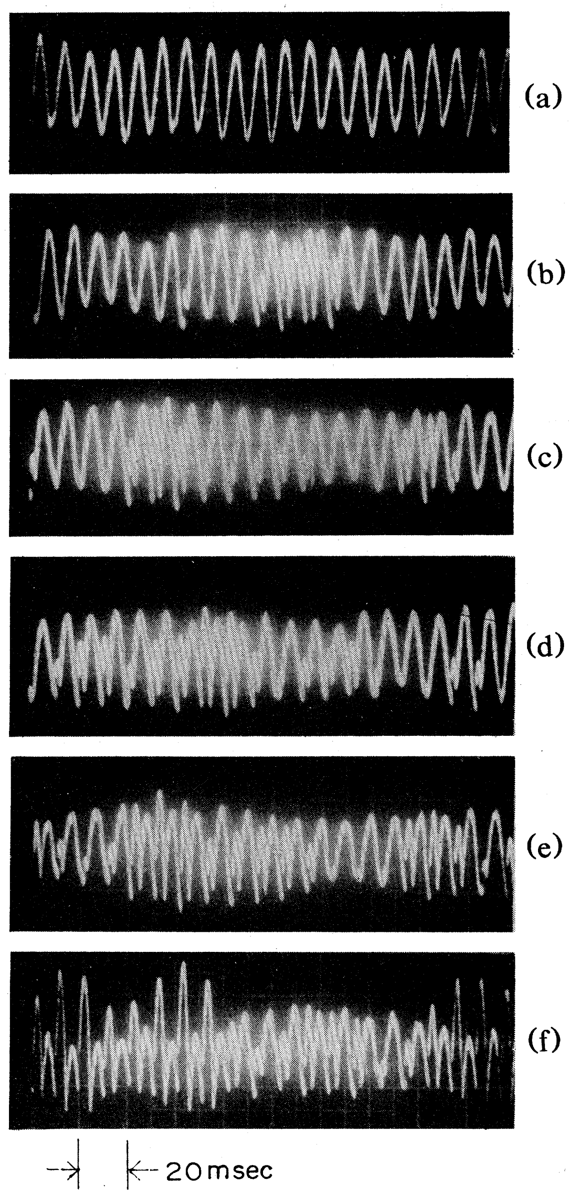

FIG. 3. The intermittent route to chaos with cavity detuning as a control parameter. The periodic emission [trace (a)] becomes interrupted by the appearance of aperiodic bursts [trace (b)] as the control parameter changes. With further change of control parameter these intermittent bursts become more and more frequent [traces (c) to (e)] before eventually culminating in fully developed chaos.

in the low-frequency side of the gain line center. With the use of detuning as a control parameter, an intermittent route to chaos has been observed. This is depicted in Fig. 3, obtained for a modulation value of 1%. As seen, the periodic emission [trace (a)] is interrupted by the appearance of aperiodic bursts [trace (b)] as the control parameter changes. With further change of control parameter, these bursts become more frequent [traces (c) to (e)] before the emission eventually culminates in fully developed chaos [trace (f)]. It should be noted here that throughout the *PZT* tuning over which lasing occurred, the discharge current was continuously monitored, which was always found to contain a pure 100-Hz modulation for all values of detuning. This clearly demonstrates that those effects we report here arise from the active optical cavity alone. Mention should also be made of the fact that this experiment has been carried out in a basement laboratory and on a laser which was carefully stabilized against any thermal and vibrational disturbances.

The instability phenomenon reported here is found to be strongly dependent on the amplitude of modulation; the most optimum result being obtained for a modulation value of 1%. As the depth of modulation increases (decreases) from this value, the window of detuning over which chaos persists abruptly, reduces, and eventually disappears for a modulation of around 5% (0.4%). This result is sharply in contrast with the result of Ref. 7, which finds the instability phenomenon to remain independent for a similar range of values of loss modulation. A qualitative explanation of this is not very difficult. Understandably, both the value of gain and the amplitude of modulation imposed on it plays an important role in destabilizing this system from its normal behavior. Higher modulation is accompanied by a lower value of the minimum gain and vice versa; the interplay between the two thus giving rise to an optimum value of modulation which yields the best instability result. In order to verify this, the following experiment was conducted. The dc value of the gain was brought down to the minimum value of gain, which occurs for 5% modulation, by reducing the discharge current. In this case, even with 1% modulation, which gave the most optimum results earlier, the emission never breaks down in chaos. As expected, little increase in gain brings back chaotic emission into the system.

In conclusion, we have demonstrated that moderately low value of temporal modulation on gain may lead to the breakdown of the conventional emission from a single-mode cw CO_2 laser into periodic, quasiperiodic, and more importantly, chaotic behavior as a control parameter; here cavity detuning changes. The results showing a critical dependence of detuning on the instability phenomenon and the existence of a new modulation frequency range, will, we believe, stimulate new theoretical investigations. Furthermore, the inherent simplicity of our experiment, together with the relative ease with which instability and chaos has been observed, clearly identifies this system as particularly suitable for the manifestation of the instability phenomenon for lasers with external modulation.

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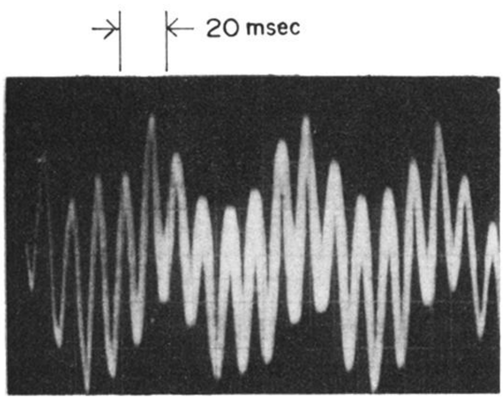

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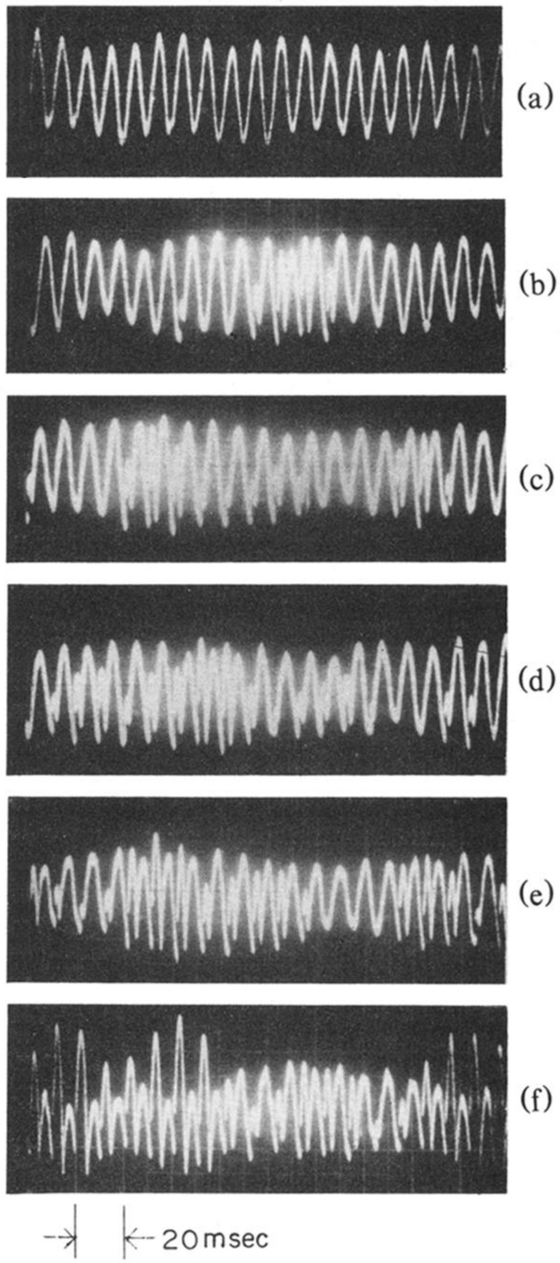

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