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Observation of absorptive bistability with two-level atoms in a ring cavity

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Observations of steady-state hysteresis in absorptive bistability are reported for well-collimated atomic beams of sodium within a traveling-wave interferometer. The atomic medium approximates a system of homogeneously broadened "two-level" atoms, and effects due to standing waves are eliminated. The experiment thus represents the first demonstration of optical bistability under conditions that have been widely employed in theoretical models. Absolute measurements of switching intensities versus atomic cooperativity C are reported, and a preliminary comparison with Gaussian-beam theory is made.

In analogy with the development of the theory of the laser, much of the early theoretical work on optical bistability has dealt with an intracavity medium composed of "two-level" atoms.[1-6] By considering a medium in which the atoms are assumed to have single nondegenerate ground and excited states and by eliminating the complexity associated with standing waves through the use of a ring or traveling-wave cavity, one is able to examine in a more straightforward fashion many of the dynamical aspects of optical bistability. With this point of view in mind, several groups have initiated experiments with the intent of approximating optical bistability with two-level atoms and of making quantitative comparisons with theory.[7-9] This early work has clearly demonstrated the importance of the transverse structure of the field[7] and has shown the feasibility of studying optical bistability in a two-level system that is predominantly radiatively broadened.[8] However, relative to the theoretical model of bistability with two-level atoms in a traveling-wave cavity, each of these early experiments has been hampered by one of several difficulties involving the questionable validity of the two-level approximation (in Ref. 7 a multilevel, pressure-broadened system was employed and in Ref. 8 no optical prepumping was used), the lack of sufficient frequency stability to carefully explore the steady-state regime in optical bistability,[8] or the presence of excessive Doppler broadening.[9] Only two experiments to date have been performed in traveling-wave resonators,[10,11] and in each case the complexity of the nonlinear susceptibility of the intracavity medium has complicated the interpretation of the results.

In this Rapid Communication we report measurements of bistability that have overcome most of these difficulties. Our work thus provides the first observation of optical bistability in a system that closely approximates what has become one of the canonical theoretical models of optical bistability. Observations of steady-state hysteresis in absorptive bistability are described for a nearly Doppler-free medium of two-level atoms within a ring resonator.

The experimental arrangement has been previously described,[9] and consists of multiple beams of atomic sodium intersecting at 90° the axis of a high-finesse interferometer. Relative to our earlier work, two important modifications have been made in the apparatus. Improved collimation produces ten parallel atomic beams each 0.5×0.5 mm in cross-sectional area and each with a divergence of approximately ± 1 mrad. A trace of the absorption profile of the atomic beams for excitation with circularly polarized light is shown in Fig. 1(a). The single transition shown in the scan corresponds to the $3^2S_{1/2}$, $F=2$, $M_F=2 \rightarrow 3^2P_{3/2}$, $F=3$, $M_F=3$ transition of the D_2 line of atomic sodium. This two-level transition is obtained by optical prepumping of the atomic beams with circularly polarized light in a region of

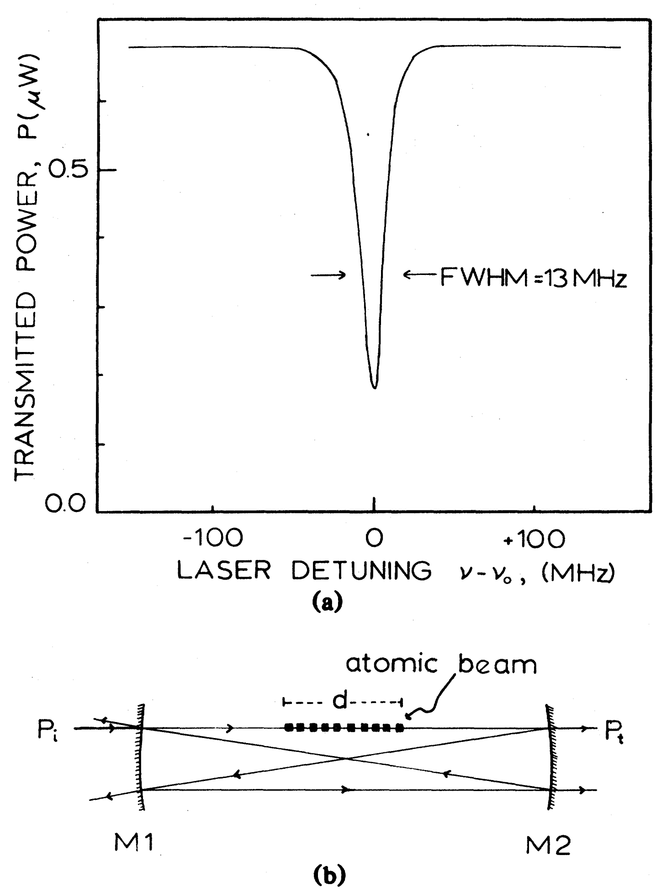

FIG. 1. (a) Transmitted power through the atomic beams as a function of laser frequency. The single absorption feature corresponds to the $3^2S_{1/2}$, $F=2$, $M_F=2 \rightarrow 3^2P_{3/2}$, $F=3$, $M_F=3$ transition in atomic sodium. (b) Schematic illustrating the ring cavity with ten intracavity atomic beams directed out of the plane of the figure. The distance $d=14$ mm.

uniform magnetic field of 1.0 G parallel to the direction of laser propagation.[12] Note that the width of 13 MHz full width at half maximum is close to the natural linewidth of 10 MHz with the dominant broadening mechanism being the finite transit time of the atoms through the mode volume and with a relatively smaller residual Doppler contribution. By varying the temperature of the source oven, the measured resonant absorption $\alpha_m l$ of the atomic beams can be varied over the range $0 \leqslant \alpha_m l \leqslant 3.5$, with α_m referring to intensity and not amplitude loss.

The second important feature of our experiment is the traveling-wave interferometer. Figure 1(b) illustrates the configuration of the atomic beams and resonator. By positioning the cavity mirrors to the confocal spacing and injecting the incident laser as shown in Fig. 1(b), we obtain a ring cavity with only two mirrors, each of radius of curvature 0.05 m and with transmission coefficients $(T_1, T_2) = (1.8 \times 10^{-3}, 4.8 \times 10^{-4})$. The interferometer is located internal to the vacuum system, and the injected laser P_i is matched in transverse profile to the TEM_{00} mode of the cavity[13] with an efficiency of approximately 90%. In the absence of the atomic beams (empty cavity) the peak transmission coefficient $\mathscr{T}_0$ of the cavity is $(3.8 \pm 0.6) \times 10^{-3}$, and the cavity finesse $\mathscr{F}$ is 188 ± 10, corresponding to a cavity decay time of 20 nsec for the intracavity energy, as compared with the 16-nsec lifetime of the atomic transition. The waist ω_0 at the center of the cavity is approximately 69 μm, which is small compared with the 500-μm transverse dimension of the atomic beams.

For our measurements of hysteresis in the cavity characteristics, the incident laser intensity is modulated with an electro-optic modulator at a rate of 175 Hz. Both the transmitted power P_t from the cavity and the intracavity fluorescence I_f from one of the atomic beams are monitored as functions of the incident power P_i on an xy oscilloscope. An example of the hysteresis cycle that we observe for near-zero atomic and cavity detunings is shown in Fig. 2. The traces in the figure give (a) the straight-line response of the cavity when the atomic beams are intercepted before entering the cavity and (b) the input-output characteristic for an intracavity absorption $\alpha_m l = 1.13$. The dashed lines indicate the inferred switching points in the absence of the detector response time. The absence of a nonlinear dispersive contribution for zero atomic detuning is confirmed by the observation of a symmetric dependence of the hysteresis cycle on the sign of the cavity detuning as the detuning is varied over a range of several cavity linewidths.

To relate observations at a given resonant atomic absorption $\alpha_m l$ to the atomic cooperativity parameter C of optical bistability,[1-3] we define an effective cooperativity parameter C_e for our cavity of finesse $\mathscr{F}$ by

$$C_e = \frac{\alpha_m l}{4\pi} \mathscr{F} , \tag{1}$$

which gives C_e as equal to half of the ratio of atomic loss to cavity loss in a round trip within the cavity. The designation of "effective" cooperativity parameter arises since we employ the actual resonant absorption $\alpha_m l$ rather than the absorption loss $\alpha_0 l$ that would arise if the same atomic number density were present in the absence of inhomogeneous broadening. For the distribution of velocities from our oven and for the aperture and focusing geometries used, we estimate that $C_e \simeq 0.96 C$.

Over the range of absorption $\alpha_m l$ available from our apparatus, we have recorded the input-output characteristics as illustrated in Fig. 2. For a given value of $\alpha_m l$ and hence C_e through Eq. (1), we evaluate the incident and transmitted switching powers $(P_i^{(1)}, P_i^{(2)})$ and $(P_t^{(1)}, P_t^{(2)})$. Figure 3 shows these switching powers as functions of C_e. Below the critical onset of bistability, a single point is plotted in the figures corresponding to the region of maximum ac gain in the input-output characteristic. The relative uncertainties of both the switching powers and of the data determining C_e are given at a few points by sets of vertical and horizontal error bars. In addition to these uncertainties is one of the overall scale of C_e arising from the fact that both $\alpha_m l$ and $\mathscr{F}$ are known only indirectly during the course of the experiment. The estimated uncertainty in the absolute value of C_e is $\pm 15\%$.

In order to make a comparison between our results and a Gaussian-beam theory of absorptive optical bistability, one is interested not in the actual powers but rather in the scaled variables[14-16]

$$Y = \frac{P_i}{\pi \omega_0^2 I_s} \epsilon , \quad X = \frac{P_t}{\pi \omega_0^2 I_s T_2} \quad . \tag{2}$$

Here I_s is the saturation intensity for the two-level transition, P_i and P_t are as shown in Fig. 1(b), T_2 is the transmission coefficient of the mirror $M2$, and ϵ is a factor that expresses the ratio of intracavity intensity to incident intensity for the empty cavity. For our cavity a straightforward calculation gives ϵ in terms of T_2 and the peak transmission $\mathscr{T}_0$ of the cavity to be $\epsilon = \mathscr{T}_0 / T_2$. To obtain I_s we choose not the value appropriate for purely radiative relaxation (6.3 mW/cm^2), but rather attempt to incorporate the effect of transit broadening by modifying the transverse relaxation rate $\gamma_\perp$, giving $I_s = 7.3$ mW/cm^2 for the parameters of our experiment. While it is admittedly approximate to treat the transit broadening as a homogeneous process in this way, a

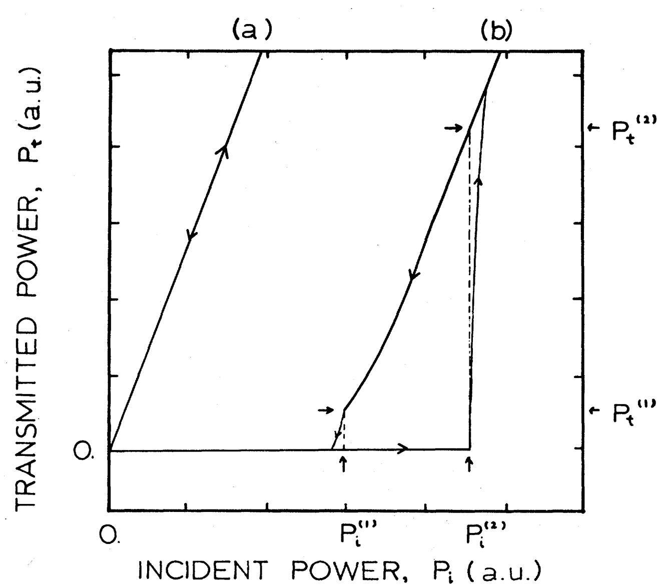

FIG. 2. x-y oscilloscope traces of transmitted laser power P_t vs incident laser power P_i for zero atomic and cavity detunings. (a) No intracavity atomic beams. (b) Intracavity beams with resonant absorption $\alpha_m l = 1.13$ and with $P_i^{(1)} = 70$ μW, $P_i^{(2)} = 104$ μW.

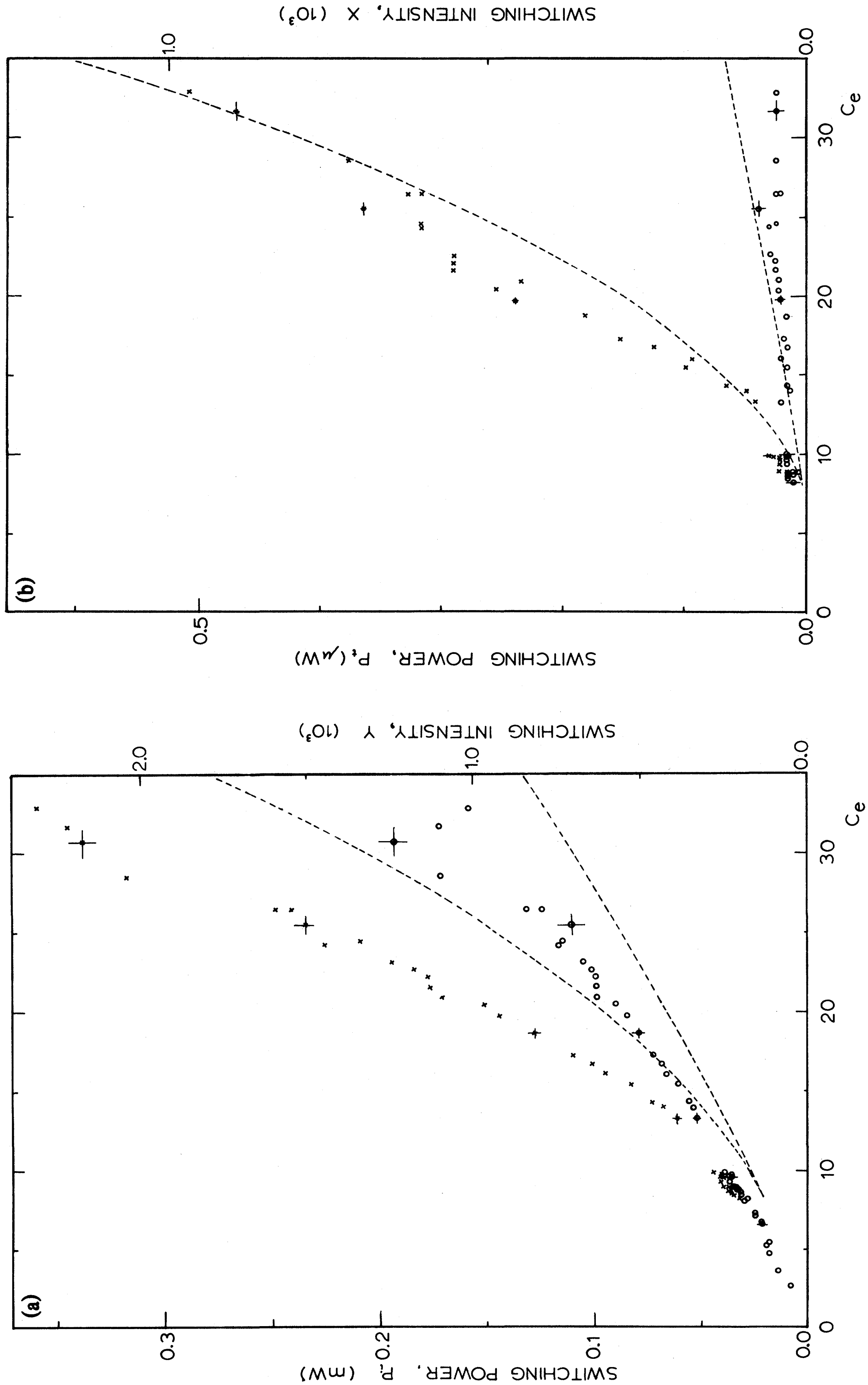

FIG. 3. (a) Incident switching powers $(P_i^{(1)}, P_i^{(2)})$ vs effective atomic cooperativity C_e as determined from Eq. (1). (b) Transmitted switching powers $(P_t^{(1)}, P_t^{(2)})$ vs C_e. The overall determination of C_e is uncertain to $\pm 15\%$. The curves are the theoretical results based upon Eq. (3) and are plotted relative to the right-hand scales, as discussed in the text.

more detailed analysis of the atomic motion through the beam waist requires a considerably more complex analysis, which we are currently undertaking. Using Eq. (2), the value of I_s quoted, and the measured values of T_2, $\mathscr{T}_0$, and ω_0, we have calculated switching intensities Y and X corresponding to the switching powers P_i and P_t. This procedure produces the right-hand scales shown in Figs. 3(a) and 3(b) with overall uncertainties of $\pm 15\%$ in (a) and $\pm 30\%$ in (b).

To make a preliminary comparison between the results of our experiment and the theory of optical bistability in the single transverse-mode approximation, we will relate X and Y through the state equation[14]

$$Y = X\left[1 + \frac{C}{X}\int P(\Delta)\ln\left(1 + \frac{2X}{1+\Delta^2}\right)d\Delta\right]^2 , \tag{3}$$

with $P(\Delta)$ as the inhomogeneous distribution of atomic detunings Δ due to the finite collimation. For the distribution $P(\Delta)$ derived from the known aperture geometry, we have calculated from Eq. (3) the switching intensities (Y_1, Y_2) and (X_1, X_2) corresponding to the points $(P_i^{(1)}, P_i^{(2)})$ and $(P_t^{(1)}, P_t^{(2)})$ indicated in Fig. 2. The curves in Fig. 3 show this theoretical result. Owing to the small amount of inhomogeneous broadening in our experiment, these curves differ from those of the homogeneous limit of Eq. (3) only slightly, with the switching powers in the inhomogeneous case increased by a factor of 1.04 for a given C_e. Note that in the comparison of theory and experiment in Fig. 3 no adjustable parameters are involved; both the ordinate and abscissa are measured in absolute terms.

While the data shown in Figs. 2 and 3 are for values of $C_e \leq 32$, we have as well extended our measurements to atomic absorptions as high as 3.5, or $C_e \simeq 50$. In this range we observe marked qualitative departures in the appearance of the hysteresis cycle itself from the prediction of mean-field steady-state theory. On the upper branch for $Y_1 < Y < Y_2$ the trace of X vs Y is not a straight-line segment as one might expect, but can develop a definite curvature and exhibit switching for nonzero cavity detunings at points other than (Y_1, Y_2).

While at present we do not have a satisfactory explanation for the deviations seen in Fig. 3 and at higher values of C_e, we have repeated the experiment and have reproduced all of the results described to well within the quoted uncertainties. The discrepancies could be due to several sources. In the first place, it is not clear that the two-level approximation is valid at the high intracavity intensities encountered on the upper branch. A value of $X = 10^3$ corresponds to a peak Gaussian intensity of 2000 I_s and hence to a power-broadened linewidth that extends over the whole of the hyperfine structure of the $3\,^2P_{3/2}$ excited state. Previous studies of two-level behavior have been carried out at considerably smaller values of intensity.[12] Furthermore, since the interferometer we have used is confocal and thus mode degenerate,[13] higher-order transverse modes of the cavity that might be excited by the nonlinear polarization would be supported by the cavity. Excitation of these modes would invalidate the single transverse-mode theory for our experiment. Finally, at the highest values of C_e shown in Fig. 3, the resonant absorption $\alpha_m l$ is 2.1, indicating the possibility for departures from mean-field behavior.

In summary, we have reported the first observation of bistability with a nearly Doppler-free medium of two-level atoms in a traveling-wave resonator. A preliminary comparison with theory has been made and discrepancies noted in the absolute scale of the switching intensities and in the qualitative character of the hysteresis for values of $C_e \gtrsim 30$.

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