Observation of Magnetically Induced Optical Self-Pulsing in a Fabry-Perot Resonator

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Magnetically induced optical self-pulsing has been observed in a Fabry-Perot resonator containing sodium vapor. Experiments are performed on optically pumped Zeeman sublevels of the Na ground state in the presence of a static transverse magnetic field B. When B exceeds a critical value B_{cr}, self-sustained spin precession occurs, and the transmitted light is found to be modulated at about the Larmor frequency. The use of this tunable current-controlled oscillator in optical FM signal transmission is demonstrated.

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Recently much attention has been attracted by the behavior of two simultaneously excited degenerate modes of a Fabry-Perot cavity coupled by the nonlinear optical interaction with atoms which have Zeeman sublevels in the ground state.[1-6] In this system optical tristability,[1] self-pulsing,[2-4] and multistability[3,4] have been predicted; it was proposed as an all-optical system which gives chaos at attainable laser powers.[5] So far only the occurrence of steady-state optical tristability has been demonstrated experimentally.[6] In this paper we report on experimental studies of the dynamics of a tristable system and especially on the observation of self-pulsing induced and controlled by a static magnetic field. The mechanism underlying our experiment is the "self-sustained spin precession" proposed by Kitano, Yabuzaki, and Ogawa[2]; we closely follow their suggestion.

The predicted phenomenon is due to spin polarization in the ground state of spin-$\frac{1}{2}$ atoms created by optical pumping in the wing of a resonance line. In the case of linearly polarized incident light the three states of the light field within the cavity can be characterized in the following way: (1) The light is linearly polarized (linear state), (2) it is essentially right circularly polarized ("+" state), and (3) it is essentially left circularly polarized ("−" state). When the incident light intensity exceeds a threshold level I_{cr}, the linear state is known to become unstable, and a symmetry-breaking transition to the "+" or "−" state occurs. The transition to the "+" or "−" state is coupled with an orientation of the spin system, i.e., with the creation of a population difference between the states $m=+\frac{1}{2}$ and $m=-\frac{1}{2}$ of the atoms; here m characterizes the spin component with respect to the optical axis (z axis). Thus in the transition to the circularly polarized states a macroscopic magnetization is built up. Obviously the tristable behavior of the system will not be modified by a weak static magnetic field oriented parallel to the z axis as applied in Ref. 6. When, however, a static magnetic field perpendicular to the z axis is applied, the magnetization begins to precess about it, i.e., transitions between the two m states occur. When the magnetic field exceeds a critical value B_{cr} the magnetization can rotate sufficiently far to change the sign of its z component and thus to reverse the spin orientation. This will cause the polarization state of the light field to become unstable, and the system will jump to the complementary state. As a consequence the system will display self-pulsing; for $B \gg B_{\mathrm{cr}}$ the repetition rate is expected to be close to the Larmor frequency and thus to be easily controlled by the magnetic field.

The experimental setup (see Fig. 1) is similar to the one used in bistability experiments reported before.[7,8] A heated stainless-steel cell with slightly tilted antireflection-coated windows contains sodium atoms ($N \cong 10^{13}$ cm^{-3}) in an argon atmosphere ($p \cong 200$ mbar); the length of the

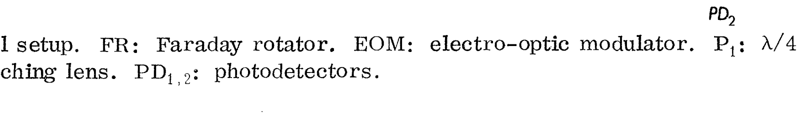

FIG. Experimental setup. FR: Faraday rotator. EOM: electro-optic modulator. P_1: λ/4 or λ/2 plate (see text). L: mode-matching lens. $PD_{1,2}$: photodetectors.

heated zone is about 20 mm. The cell is placed in the center of a near confocal Fabry-Perot (FP) resonator (radius of curvature: 15 cm; finesse with the cold cell in place: 17), which can be tuned piezoelectrically. The dye laser, optically isolated from the FP by means of a Faraday rotator, is detuned by 10 to 20 GHz on either side of the Na D_1 line. The dye-laser beam is approximately mode matched to the FP. Its intensity can be switched by means of an electrooptic modulator (EOM), thus providing input steps of variable height (power: 5–50 mW, typically). When the polarizer P_1 is a $\lambda/4$ plate, the linearly polarized output of the EOM can be transformed to a circularly polarized light beam. In that case optical bistability is observed.[7,8] In this experiment, however, P_1 is a $\lambda/2$ plate allowing an arbitrary choice of linear polarization with respect to the direction of the transverse magnetic field B, which is produced by Helmholtz coils. Normally the direction of polarization was perpendicular to the magnetic field. The right- and left-circular components of the cavity output are separated by means of a $\lambda/4$ plate and a polarizing beam splitter P_2. A pair of photodiodes PD_1 and PD_2 is used for detection. The signals are observed on an oscilloscope or by means of a transient digitizer.

Measurements were performed either in the regime $B < B_{cr}$ or $B > B_{cr}$; depending on experimental conditions B_{cr} was in the range 0.03 to 0.15 mT.

(I) $B < B_{cr}$.—When the input intensity is switched from zero to I_{in} at time $t = 0$ and I_{in} is slightly above a threshold value I_{cr} (typically around 10 mW), then the system stays in the linear state for a time τ_D. This is indicated by equal signals in PD_1 and PD_2, as seen in Fig. 2. I_{cr} and τ_D are of the same order of magnitude as in the analogous bistability experiment.[8] For $t = \tau_D$, however, the signal suddenly increases in one diode, while it decreases in the other one more or less simultaneously. This behavior indicates a transition into either the "+" or the "−" state.

The symmetry breaking responsible for the transition, however, is not spontaneous, but under unchanged experimental conditions the system always jumps into the same circularly polarized state. The opposite state can be reached by slight changes in the polarization of the input beam. This behavior is believed to be due to a strain-induced birefringence of the cell windows: It can easily be shown from the analysis of Ref. 2 that a very small deviation from linear polarization of the incident light predetermines the polarization state in the high-transmission branch, though the complementary polarization state would be stable, too.

(II) $B > B_{cr}$.—When B is increased above a critical value B_{cr}, with other parameters being unchanged, then the circularly polarized states are not stable, but the system starts to switch between the "+" and "−" states. After an initial

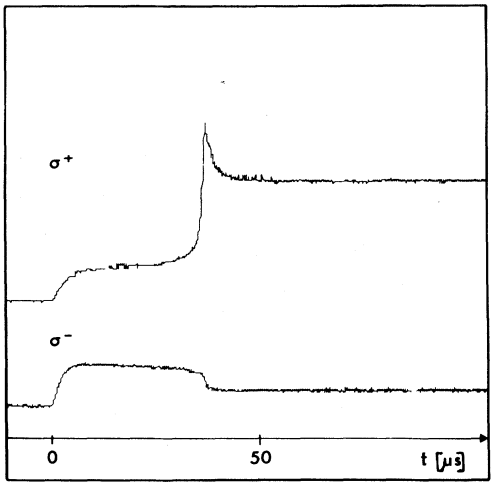

FIG. 2. Transients in optical tristability: The dynamic response of the device to a step input of linearly polarized light is monitored with use of polarization-selective detection (see Fig. 1). Here the switching delay is $\tau_D \simeq 35\,\mu$sec.

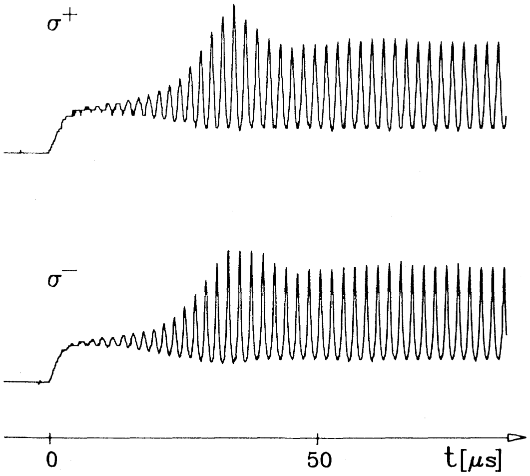

FIG. 3. The onset of self-pulsing. Note that the two circularly polarized components (σ^+ and σ^-) oscillate with opposite phase.

stage a regular pulse train develops in the "+" polarized output, while there is a "complementary" pulse train in the "−" polarized output (see Fig. 3; the shape of the pulses shown in the figure is deformed by the transient digitizer, which operated close to its bandwidth limit). A portion of the pulse trains as observed on the oscilloscope is shown in Fig. 4. These pulse trains last indefinitely in principle; they were easily observed for minutes. Repetition rates between 200 kHz and 13 MHz were obtained. They are essentially given by the Larmor frequency ν_0 [$\nu_0 \cong (7\text{ MHz/mT})B$]; for a constant magnetic field, however, we can vary the repetition rate by more than 1% by changing the cavity mistuning and the input intensity.

The observations show that $B_{\rm cr}$ strongly depends on the parameters of the experiment, i.e., on laser detuning and intensity, cavity mistuning, and particle density. For typical sets of parameter values the critical Larmor frequency $\nu_{\rm cr}$ corresponding to $B_{\rm cr}$ is expected to be in the range Γ to 10Γ on the basis of Ref. 2; here Γ denotes the relaxation rate of the spin polarization. In our experiment Γ is controlled by diffusion and has been determined to be 140 kHz.[8] The experimental values of $B_{\rm cr}$ given above correspond to $\nu_{\rm cr}$ being between 200 kHz and 1 MHz.

When the laser intensity is varied with all other experimental parameters kept fixed, there is only a small range of intensities where self-pulsing is observed. Again this behavior can be expected from the analysis given in Ref. 2. When the intensity is too low, no switching to a high-transmission state occurs. On the other hand, when the intensity is increased, $\nu_{\rm cr}$ also grows. There is an intensity $I_{\rm max}$, where $\nu_{\rm cr} > \nu_0$. Under the experimental conditions used so far we typically find $I_{\rm max} \cong 1.2 I_{\rm cr}$; $I_{\rm cr}$ is the minimum intensity for switching at the given value of ν_0. This is in fair agreement with numerical model calculations based on Ref. 2.

The theoretical pulse shape strongly depends on the parameters. For a wide choice of parameter values, however, two maxima are expected in each pulse. This typical feature was also obtained in the experiment (see Fig. 4).

Let us finally mention that the polarization of the incident light is not critical in the phenomenon of magnetically induced self-pulsing. We would like to emphasize that even with very strong deviations from linear polarization, where no tristability is possible in zero magnetic field, self-pulsing is observed, in accordance with numerical solutions of Eq. (4) in Ref. 2.

Beyond its importance from a theoretical point of view, all-optical self-pulsing as reported here might be of practical interest for engineering purposes. Speaking in technical terms, our apparatus can be considered as a current-controlled oscillator, i.e., an oscillator that can be tuned, wobbled, and frequency modulated by means of the electric current producing the magnetic field. In order to demonstrate the feasibility of a technical application, we performed an experiment that might be termed "optical FM signal transmission."

We set the current such as to give oscillations

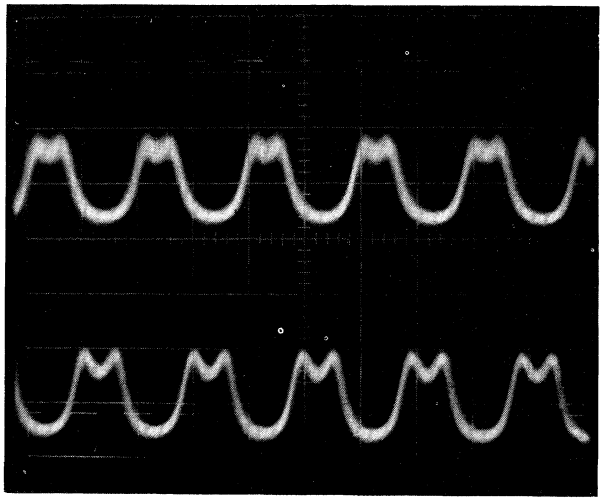

FIG. 4. Self-pulsing on a shorter time scale (200 ns/div; ground lines are at bottom line and middle line of graticule, respectively).

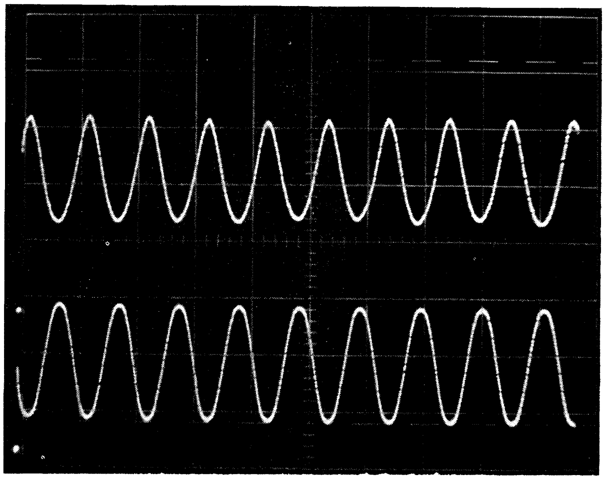

FIG. 5. Optical FM signal transmission (see text).

of 1.5 MHz and then modulated it with a test signal (sine wave of 1 kHz, see Fig. 5, lower trace) by a few percent. One of the detectors now played the role of the receiving station. Its signal was fed into a standard FM demodulator that was tuned to a center frequency of 1.5 MHz. Here the test signal was reproduced (Fig. 5, upper trace).

In conclusion, we have reported on first studies of the dynamics in optical tristability. The experiments have clearly demonstrated the unique phenomenon of self-pulsing induced by a static magnetic field. The observations are in fair agreement with predictions derived from a simple theoretical model. So far there are no indications of period doubling or aperiodic behavior under our present experimental conditions.

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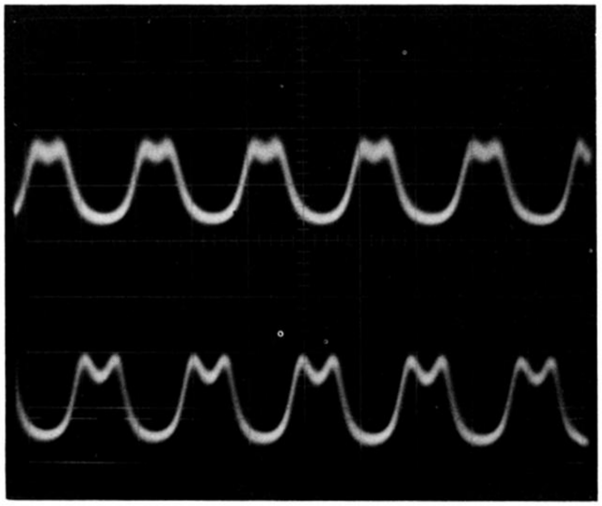

FIG. 4. Self-pulsing on a shorter time scale (200 ns/div; ground lines are at bottom line and middle line of graticule, respectively).

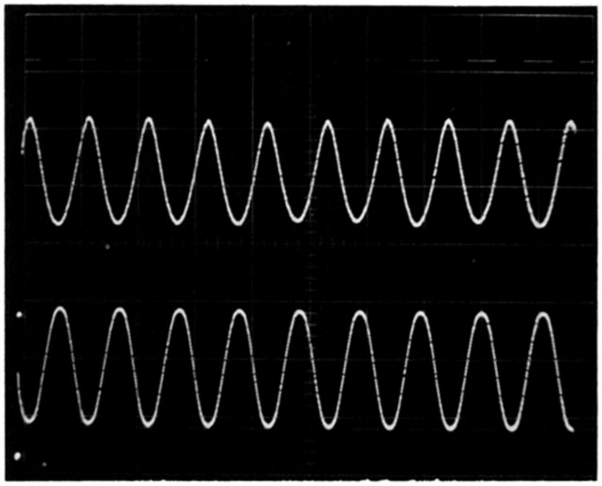

FIG. 5. Optical FM signal transmission (see text).