Observation of Optical Tristability in Sodium Vapors

S. Cecchi, G. Giusfredi, E. Petriella,[a] and P. Salieri
Istituto Nazionale di Ottica, Firenze, Italy
(Received 4 October 1982)

Optical tristability via optical pumping has been observed in the transmission of a Fabry-Perot interferometer containing Na vapor irradiated by light from a cw dye laser on the high-frequency wing of the D_1 line. For linearly polarized incident light, three stable states appear in the polarization of the transmitted light: σ_+ dominant, σ_- dominant, and linear polarization.

PACS numbers: 42.65.Gv, 32.80.Bx, 42.10.Nh

This Letter describes the first experimental evidence of the phenomenon of optical tristability (OT), which was theoretically predicted for a Fabry-Perot cavity filled with atoms having degenerate Zeeman sublevels in the ground state, due to spin polarization induced by optical pumping in the region of anomalous dispersion.[1] Sodium vapor has been suggested as a suitable nonlinear medium, as for previous optical bistability experiments.[2,3] The somewhat idealized picture of Na atoms and the assumption of high buffer-gas pressure, to make the transition homogeneous, led to unrealistic suggested values for frequency detuning.[4] By operating at low Ar buffer gas pressure and keeping the laser frequency moderately detuned from the D_1 absorption peak (~1.5 GHz) we can effectively exploit optical pumping and report observation of OT in Na vapor at low input power density (~3 mW/mm^2).

Let us recall briefly the features of polarization-related OT. For linearly polarized incident light the transmitted light can take three stable states in its polarization: in addition to a linearly polarized state, a σ_+ dominant (almost right-circularly polarized) or a σ_- dominant (almost left-circularly polarized) state. In the σ_+ (σ_-) state the atomic spins in the ground state are oriented parallel (antiparallel) to the direction of the incoming light beam. The spontaneous orientation comes from competitive interactions between the σ_+ and σ_- components in the cavity through optical pumping, as, for a $^2S_{1/2}$ to $^2P_{1/2}$ transition, σ_+ (σ_-) light interacts only with spin-down (-up) atoms. The nonlinearity of the coupling of the two circularly polarized light modes modifies the polarizability in such a way that, with the optical feedback provided by the cavity, when the incident light exceeds a threshold level, the linear state becomes unstable and symmetry-breaking transitions to the σ_+ or the σ_- state occur, as above this threshold atomic spins are forced to orient parallel or antiparallel to the optical axis. This macroscopic behavior can be considered as an example of laser-induced polarization anisotropy[5] and self-circular birefringence.[6]

Figure 1 shows the experimental setup. An argon-pumped Coherent 599-21 single-mode rhodamine-6G dye laser, with jitter of less than ± 1 MHz, was tuned on the peak of the D_1 line. The D_1 absorption of linearly polarized light was monitored in a sodium cell kept at the same temperature as the Na-filled OT cavity. We assessed the frequency detuning with a temperature-stabilized etalon. The laser intensity was modulated with a triangular wave at low frequency (12 Hz) and stabilized to 1% through an electro-optical (EO) modulator driven by the signal of a photodiode in a feedback loop. The beam was spatially filtered and collimated to a diameter of 3 mm. By varying the driving voltage of a second modulator we controlled the polarization of the beam entering the OT cavity. The structure of the temperature-stabilized Na-filled Fabry-Perot interferometer that we used as the OT device is described in Ref. 3. For the present experiment we used 93%-reflectivity mirrors with a one-layer criolite

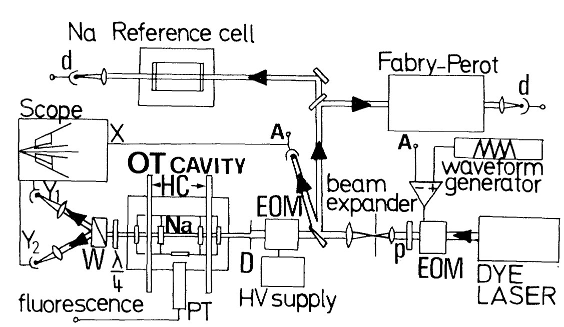

FIG. 1. The experimental arragnement. A, feedback signal; D, diaphragm; d, detector; EOM, Pockels EO modulator; HC, Helmhotz coils; $\lambda/4$, quarter wave plate; p, polarizer; PT, phototube; and W, Wollaston prism.

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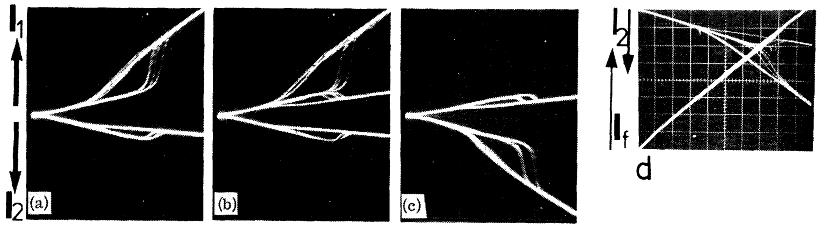


FIG. 2. OT curves (output vs input intensities) as monitored on the scope (see Fig. 2 of Ref. 1 for comparison with theoretical prediction) showing hysteresis for both transmitted light circular components. 1.8 GHz detuning, 8 mbar Ar. As for all the following pictures, we indicate with I_1 and I_2 the two circular-polarization output detector signals. (a) Input-polarization–controlling Pockels-cell bias voltage (PCV) -1 V with respect to (b); hysteresis observed only from linear to σ_+ dominant state. (b) Symmetrical condition. (c) PCV $+1$ V with respect to (b); hysteresis observed only from linear to σ_- polarization dominant state. (d) Fluorescence emission viewed orthogonally to the beam direction (I_f, bottom trace); also transmission for one circular component (I_2, top trace).

antireflection coating that unfortunately deteriorated upon exposure to Na vapor, degrading the cavity finesse from 20 to approximately 6. The cavity was placed between a pair of Helmholtz coils, with axis along the light beam, putting out a weak magnetic field of a few gauss, so as to align the ground-state spins. We analyzed the transmitted intensity with a quarter-wave plate followed by a Wollaston prism and separately recorded its σ_+ and σ_- components with two calibrated photodiodes. Resonance fluorescence was monitored with a phototube orthogonally to the beam direction. The transmitted and incident intensities were displayed as vertical and horizontal deflections on a scope.

Figure 2 shows the experimental OT curves. The horizontally shown input intensity is modulated to approximately 25 mW, while the signals of the two output polarization detectors are displayed symmetrically with opposite sign. Under the proper conditions, as the linearly polarized input intensity is increased to a threshold level, the output light switches from the linear to (in a random way) the σ_+ or the σ_- dominant state, keeping the acquired polarization when the incident intensity is further increased [Fig. 2(b)]. On decreasing the input intensity it is only at lower threshold value that spin orientation is lost and that the output switches back to the linear state. Successive hysteresis loops corresponding to switches from the linear state to both σ_+ and σ_- dominant states are shown, indicating the existence, over a range of input intensity values, of the three stable output states. Different traces correspond to different modulation periods. This symmetrical condition is very sensitive to the degree of input polarization. In fact, the quarter-wave retardation voltage of the Pockels cell being about 600 V, a variation of 1 V or a fraction thereof in the applied voltage (indistinguishable with the analysis of a polarizer) is enough to make the output light switch from the low-transmission input-polarization–preserving state to only one of the two σ_+ or σ_- dominant states [Figs. 2(a) and 2(c)], as the cavity regeneratively amplifies the input unbalance between the σ_+ and σ_- components.

Polarization scanning allowed us to explore the tristable behavior in the polarization transfer function for a nonlinear input polarization. We modulated the EO bias voltage sinusoidally at 4.8 Hz over a 1000 V range, scanning at fixed intensity the input polarization almost fully from $\sigma_{+(-)}$ to $\sigma_{-(+)}$, and, corresponding to jumps from one $\sigma_{+(-)}$ state to the other, observed hysteresis in the output polarization,[7] i.e., the output light remained σ_+ (σ_-) dominant over an interval where the input polarization was unbalanced in favor of the other component, as expected from Fig. 3 of Ref. 1 (Fig. 3).

With input circularly polarized light we observed optical bistability at a lower power (~ 4 mW).[3] Resonance fluorescence emission turned out to be rather insensitive to the analysis with a

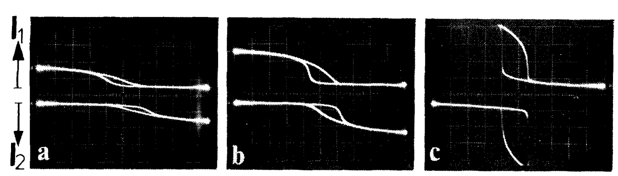


FIG. 3. Hysteresis in the output vs input polarization as the latter is scanned from almost circular polarization to the opposite almost circular polarization, at different light intensities. (a) 5 mW, (b) 20 mW, and (c) 30 mW (both traces partially cut by the scope window).

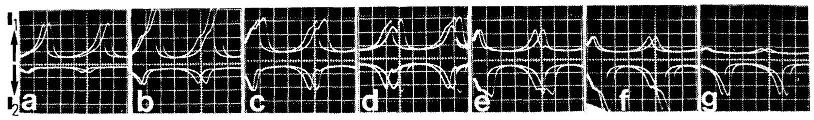


FIG. 4. Scope traces of the transmission function when the length of the cavity is swept (free spectral range, 1.2 GHz). Mirror separation increases to the right. The double trace is due to mechanical hysteresis in the movement of the mirrors. The signals of both circular output components are symmetrically displayed, as the PCV, controlling the input polarization, is varied. Pictures are sequentially shown as the input polarization is varied from almost fully circular to almost fully opposite circular. Figures (c), (d), and (e) should be considered with Figs. 2(a), 2(b), and 2(c), respectively. For each figure PCV values relative to the symmetrical condition are as follows: (a) PCV = − 300 V, input polarization almost fully σ_+: (b) PCV = − 140 V; (c) PCV = − 1 V; (d) symmetrical condition; (e) PCV = +1 V; (f) PCV = +160 V; and (g) PCV = +300 V. Upper trace of (d) and lower trace of (g), 5 V/div. All others, 2 V/div. 1.5 GHz detuning, 25 mW input power, 7 mbar Ar.

linear polarizer. Its intensity did not appreciably vary with the flipping between the two $\sigma_{+(-)}$ dominant states [Fig. 2(d)] and showed only a very small hysteresis. Hysteresis, both in transmission and fluorescence, disappeared upon removal of the weak magnetic field.

OT was reproducibly obtained in different days of observation with the Ar pressure varied in the range 1–30 mbar. Temperature was always kept at 180 C (Na density of $\sim 10^{12}$ cm^{-3}).

In our experiment saturation of anomalous dispersion plays a larger role than saturation of absorption and, as for optical bistability with optical pumping,[3] the OT behavior is not symmetrical with laser frequency variations relative to the D_1 absorption peak. We think that a cw resonant effect of self-focusing, which for an absorbing medium tends to focus the beam in the high-frequency side of the resonance,[8] comes into play. OT has in fact been seen only in the high-frequency wing of the line (~1–2.5 GHz detuning), the same spectral region where, at higher intensity and temperature values, long-range interactions between circularly polarized beams and breakup of linearly polarized light into two beams of opposite circular polarization had been reported.[6] A self-focusing effect is weak at our intensity levels,[9] but would be enhanced by the cavity, especially by our interferometer that turned out to be slightly convex, as seen in an interferometric analysis, because of an unfortunate mirror fabrication tolerance.

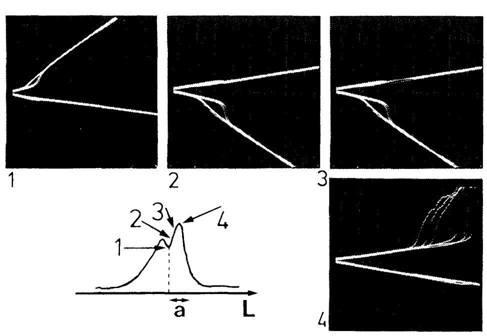


FIG. 5. Observed OT behavior as input intensity is modulated at different values of cavity length L [see Fig. 4(a)]. The drawing shows the transmission of only the σ dominant component. Region a shows the interval in which OT was observed with our available laser power. Outside this interval no instabilities could be seen in the transmitted light which essentially preserved the input polarization. Pictures 1, 2, and 4 show hysteresis for only one σ output polarization. A switch to both σ_- and σ_+ states would have been recorded with longer exposure times.

We applied a modulation to the piezo controls and, operating in the scanning mode, observed the cavity transmission function of both σ_+ and σ_- output components for different input polarizations (Fig. 4). A pronounced asymmetry with frequency in its right-hand side, namely the appearance of a second peak not seen with the magnetic field turned off, characterizes the transmission of the polarization dominant state [Figs. 4(a)–4(c)]. In Fig. 4(a) a spontaneous switch from one $\sigma_{+(-)}$ dominant state to the other has been recorded as a flip of this peak between the upper and lower traces. This asymmetry is related to the OT hysteresis behavior at different cavity mistuning values (Fig. 5), which qualitatively follows, accounting for the atomic detuning, what was observed and calculated for dispersive optical bistability with optical pumping,[3] provided that the extra transmission peak is taken as the actual cavity resonance. These observed polarization asymmetries will be carefully analyzed. We also plan to investigate OT experimentally in the context of generalized multistability as it applies to a quantum system away from equilibrium.[10]

Fruitful discussions with Professor F. T. Arecchi are acknowledged. We thank him for his careful reading of this manuscript. This work was supported in part by the Consiglio Nazionale delle Ricerche–Istituto Nazionale di Ottica contract.

[(a)]On leave from CEILAP, Buenos Aires, Argentina.

[1]M. Kitano, T. Yabuzaki, and T. Ogawa, Phys. Rev. Lett. 46, 926 (1981).

[2]M. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Phys. Rev. Lett. 36, 1135 (1976); W. J. Sandle and A. Gallagher, Phys. Rev. A 24, 2017 (1981).

[3]F. T. Arecchi, G. Giusfredi, E. Petriella, and P. Salieri, to be published.

[4]For the sake of clarity, we consistently call throughout this Letter "detuning" the frequency offset between the field and the atomic resonance and "mistuning" the offset between the field and cavity frequencies.

[5]P. Bicchi, L. Moi, and B. Zambon, Nuovo Cimento B 49, 9 (1979).

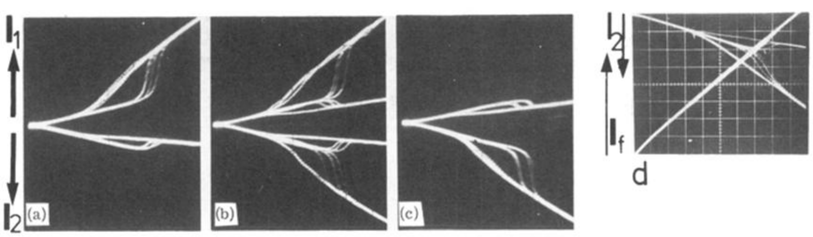
[6]A. C. Tam and W. Happer, Phys. Rev. Lett. 38, 278 (1977).

[7]S. T. Hendow, R. W. Dunn, W. W. Chow, and J. G. Small, Opt. Lett. 7, 356 (1982).

[8]A. Javan and P. L. Kelley, IEEE J. Quantum. Electron. 2, 470 (1966); V. S. Butylkin, A. E. Kaplan, and Yu. G. Khronopulo, Zh. Eksp. Teor. Fiz. 61, 520 (1972) [Sov. Phys. JETP 34, 276 (1972)].

[9]J. E. Bjorkholm and A. Ashkin, Phys. Rev. Lett. 32, 129 (1974).

[10]F. T. Arecchi, R. Meucci, G. Puccioni, and J. Tredicce, Phys. Rev. Lett. 49, 1217 (1982); H. J. Carmichael, C. M. Savage, and D. F. Walls, Opt. Commun. 42, 211 (1982).



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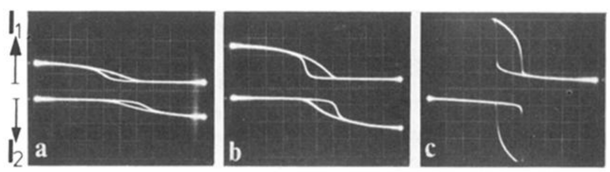

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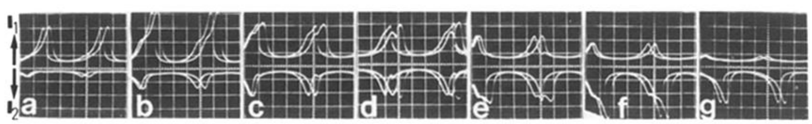

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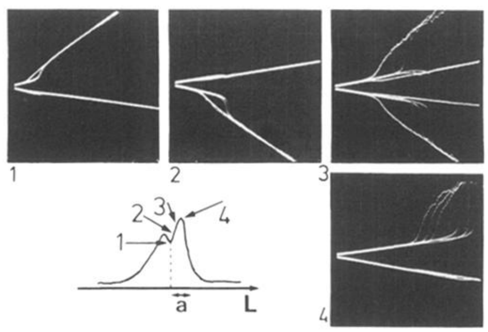

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