Optics Communications 291 (2013) 309–312

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Pattern-based optical memory with low power switching in rubidium vapor

N. Korneev*, Y.M. Torres

Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro # 1, Apt. Postal 51 y 216, Tonantzintla, Puebla CP 72840, Mexico

ARTICLE INFO

Article history:
Received 5 June 2012
Received in revised form
22 October 2012
Accepted 26 October 2012
Available online 21 November 2012

Keywords:
Rubidium vapor
Optical transverse pattern
Optical pattern bistability

ABSTRACT

We report optical pattern bistability switched with $\sim 2\,\mu$W power beam for two waves counter-propagating in warm rubidium vapor in presence of longitudinal magnetic field.

1. Introduction

Transverse optical patterns resulting from resonant light propagation in atomic gases, rubidium vapor in particular, are well-known phenomena [1–5]. The mechanisms for pattern generation have been theoretically and experimentally studied considering the spatial instabilities generated when a wave-mixing process occurs in a nonlinear medium [6–9].

The pattern formation is a general feature of nonlinear propagation with feedback, and it was observed for many optical nonlinear materials, including liquid crystals and photorefractives, and for different types of nonlinearity. In atomic vapors various mechanisms leading to different types of nonlinear response are possible as well. More simple nonlinearities arise when a high power laser beam is detuned relatively far from the transition. In the simplest case, the nonlinearity is modeled by considering a two-level atom, and it is well approximated by a scalar Kerr expression [4]. In sodium vapor with buffer gas, a strong homogeneous broadening exists, and the nonlinearity can be modeled there with $J=1/2$ to $J'=1/2$ transition, which includes two lower and two upper levels [10]. In this configuration, polarization and magneto-optical effects are observed [11,12]. Typical light powers for pattern formation in sodium are in 100 mW range, and detunings from a line broadened to 3.6 GHz are of an order of 15 GHz [13].

In rubidium D1 line (795 nm), complicated dynamic behavior of patterns was reported [14]. In Ref. [15] it was shown that such system can exhibit hysteresis in transition from one pattern type to another if the pump intensity is varied. Typical detunings for these experiments are in the range of 500–1500 MHz, and pump beam intensities in the range of 40–500 mW.

We work here with ^{87}Rb, $F_g=2$ rubidium transition in a heated cell without a buffer gas, and exploit a strong vectorial positive nonlinearity obtainable there for low beam power (10 mW range) deep inside a Doppler-broadened line. The details of this nonlinearity, including computer modeling with a full level structure for rubidium, are given in Ref. [16]. For our conditions, the generated pattern has nearly orthogonal polarization with respect to the pump.

The pattern formation for this nonlinearity is a result of modulation instability process: Even with one pump beam, the noise is exponentially amplified for a pair of symmetric noise waves propagating at a small optimal angle with respect to the pump [4]. The second counterpropagating beam provides a feedback. For a perfect rotational symmetry, the generation occurs on a cone in a far field. If the symmetry is broken with beam profile ellipticity, pump beam misalignment or other factors, the multi-spot pattern with a center of symmetry is formed. If the symmetry-breaking perturbation is adequate, the bistable or multistable situations are possible. The interesting feature of this particular nonlinearity is low power needed for its implementation. On the other hand, requirements to laser frequency stability are much higher here, than for big detuning and high power pumping, since the pattern formation frequency range is limited to approximately 20 MHz.

Recently, it was demonstrated by Dawes et al. [17] that ultra-low-power optical switching can be realized for transverse optical patterns. In the experiment of Ref. [17], the switching was achieved by feeding a very weak additional beam with a frequency corresponding to ^{87}Rb, $F_g=1$ transition for linearly polarized pumps and zero external magnetic field.

In the experiments of Ref. [17], the pattern was returning to its initial position after the signal beam was turned off. In this paper,

* Corresponding author. Tel.: +52 222 2663100; fax: +52 222 2472580.
E-mail address: korneev@inaoep.mx (N. Korneev).

0030-4018/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2012.10.075

we propose an optically switchable memory element based on the transverse pattern bistability: The pattern by an appropriate manipulation of the signal beam can be moved between the two positions and remains stable till the next switching event. An attractive feature of this particular geometry is a possibility to induce fast switching ($<10\,\mu s$) using only a few microwatts power beam.

2. Experimental results

The experimental setup is shown in Fig. 1. The two beams derived from a tunable semiconductor laser (780 nm, 50 mW) are nearly counterpropagating in the heated rubidium cell. The beams have elliptic profile with axes 0.5 mm (horizontal) and 2.1 mm (vertical) (FWHM). One of the beams can be rotated around its longitudinal axis to an angle of 60 degrees with respect to another using a Dove prism. The cell is placed within a solenoid producing a longitudinal magnetic field B of 0–0.3 mT, and it is heated to 80–100 °C. The magnetic field shielding (two layers of mu-metal) is used for the cell. When the laser frequency is nearly resonant with $F_g=2$, $F_e=2$ transition of ^{87}Rb, the generation of additional beams can be seen in the observational plane. The laser frequency range for generation is approximately 20 MHz and it is shifted to the high-frequency wing of the $F_g=2$ to $F_e=2$ sub-Doppler feature in saturated absorption spectrum. The generation is observed for linear or weakly elliptic beam polarizations which are close one to another (the principal axes of polarization for two beams form a small angle). The Acousto-Optic Modulator (AOM) is used to modulate the optical switching signal during the experiment.

The resulting pattern in the far field is formed by symmetrical pairs of spots and/or sectors of a ring (Fig. 2). The polarization of the generated beams is close to the orthogonal with respect to pump ones. Typically, the generated pattern includes two to six points in different angular positions on the circle. Their number and position vary according to beam crossing angle, frequency, polarization and magnetic field. The set of patterns in Fig. 2 is observed in an initial setup without Dove prism, where the polarization and frequency are the same in all cases and with $B=0.015$ mT. The beam crossing angle is changed by moving the inclination of one of the mirrors in the experimental setup. When the beams inside cell are aligned, the pattern in the far field is a ring (Fig. 2d). The generated pattern center is shifted in x–y plane according to mirror tilt. The cross in each figure represents the ring center (aligned case) and point in Fig. 2a–c indicates the center of the pattern generated. The center of the pattern shifts vertically at a distance y corresponding to 2.6 mrad to generate two points (Fig. 2a). In the case of four and six points, the shift is produced in both directions. Fig. 2b represents the pattern observed for a shift of $\Delta x=2.7$ mrad and $\Delta y=1.4$ mrad. Fig. 2c shows six points observed when the shift is $\Delta x=2.6$ mrad and $\Delta y=1.3$ mrad.

The appearance of generated beam can be explained as a result of modulation instability type process and a positive feedback from a counterpropagating beam. The theory of such generation for a scalar Kerr nonlinearity can be found in the literature [18,19]. The mechanism in our case is a vectorial interaction (generated beams have an orthogonal polarization with respect to pump). Such nonlinearity, for our conditions, proves to be stronger than the conventional Kerr nonlinearity [16]. From a formal point of view, and for undepleted pump approximation, the mechanisms for scalar and vectorial Kerr nonlinearities are quite similar.

The detailed analysis of nonlinearity is given in Ref. [16]. Our calculations and experiments indicate that the nonlinearity in this case is not local, strongly depends on time of flight of an atom, and has a maximum for certain optimal value of light intensity. For $F_g=1$ transition, this optimal intensity value is lower than it for $F_g=2$ transition, but $F_g=2$ transition gives higher values of nonlinearity. Additionally, nonlinearity strength can be modified (enhanced or diminished) by using weak longitudinal magnetic fields (less than $\sim$0.2 mT) and/or elliptic polarizations. The description of influence of these factors is given in Ref. [16]. Different from the situation in Na, weak transversal magnetic fields are not essential here. The complicated character of non-linearity means, that the adequate theoretical description has to be quite complicated.

The generated intensity pattern for a fixed set of parameters can present different types of temporal behavior related to

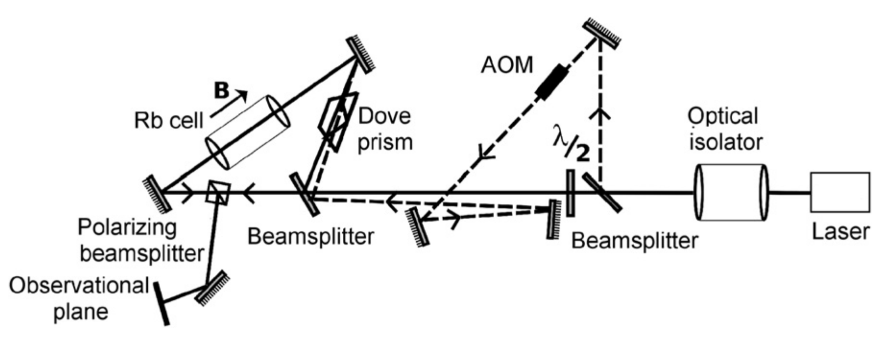

Fig. 1. Experimental setup.

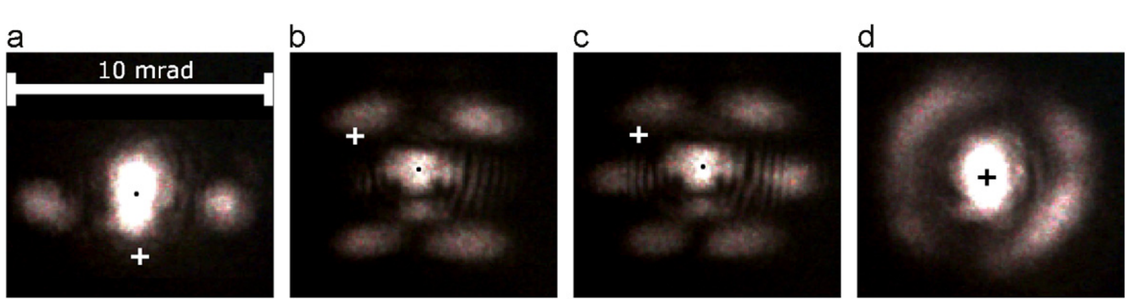

Fig. 2. Intensity patterns generated in the far field plane.

pattern type, similar to the reported in Ref. [14]. For a big crossing angle, only two spots are generated and their intensity is stable in time. For smaller angles, however, the intensity in function of time at a fixed observation point can be nearly sinusoidal, as in the case of a pattern composed by six spots. The characteristic spectrum of this type of signal has a single fundamental frequency. When the visible pattern is composed by two sectors of a ring, the signal spectrum can include a limited number of harmonics, or even represent chaotic series with wide spectra.

For a ring pattern, when two photodetectors are placed in the observation plane in different parts of a ring, there is typically a temporal lag in spike positions, which suggests that visible parts of ring can be in fact formed by a rapid movement of a single spot.

2.1. Bistability

We have also found that for certain parameter values bistable patterns can occur. The example is 1 and 2 configurations, as is illustrated in Fig. 3a, where the varying parameter is the magnetic field. Which configuration is generated, depends on the magnetic field history and/or the history of illumination. The hysteresis due to time-varying magnetic field can be observed even for two pump beam profiles equally oriented (no Dove prism) (Fig. 3b). It is seen that the pattern abruptly switches (the process takes 5–10 μs) from one position to another when a certain threshold field is achieved. The two threshold values are generally different for growing and diminishing field.

To obtain well reproducible optical switching we have turned the elliptic profile of one pump beam with a Dove prism to an angle of 60 degrees with respect to another. The angle is related to the hexagonal symmetry, which is often observed, and this helps in preparing better controlled bistable states, though similar (but less reproducible) results can be obtained with beam misalignment only. With Dove prism, the difference in generation for growing and diminishing field is made more pronounced.

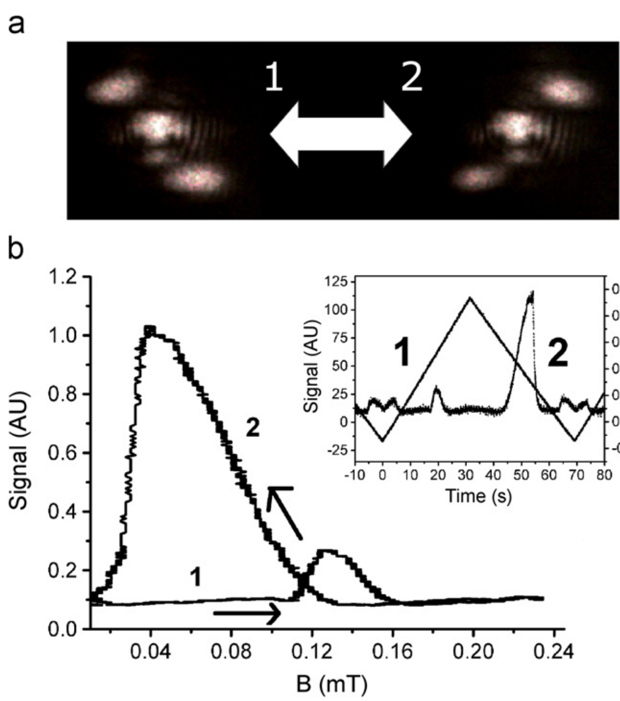

Fig. 3. (a) Two possible generated patterns without Dove prism. (b) The hysteresis of the transversal patterns in (a) is due to a triangular wave. The intensity dependence of the generated spot on the external magnetic field is shown in the square insert at right. The response to rising and decreasing magnetic field is represented by numbers 1 and 2, respectively.

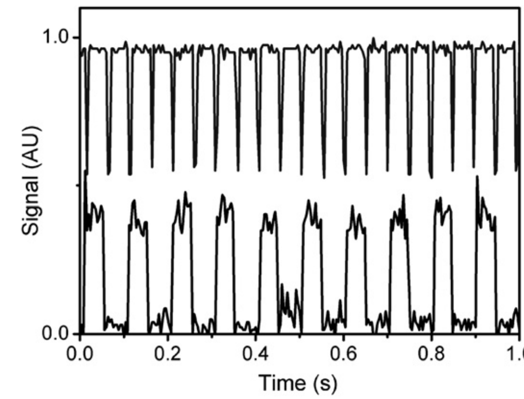

Fig. 4. Mechanical switching. Upper trace: the interruption pulses generated by the device; lower trace: generated spot intensity.

2.2. Optical switching

The optical switching was obtained in different ways. We used three different mechanisms in the following sections.

2.2.1. Mechanical closing of a pump beam

The mechanical interruption device consists of an obstacle mounted on rotating disk. It completely closes one pump beam twice over a rotation period: once the beam is opened lower part first, and once the upper part first. This produces asymmetry in the process of pattern formation. The generation disappears at the moment of beam closing. In the process of beam opening, the pattern is induced in one of the two possible positions (for example 1 in Fig. 3a) and remains there until the next closing event (Fig. 4).

2.2.2. Modulation of a pump beam intensity

The bistable behavior can be also obtained by diminishing/raising pump beam intensity. We performed this with an acousto-optical modulator in one pump. It is seen that hysteresis can exist (Fig. 5), and thus the memory can be switched using temporal manipulations of relatively high-intensity pumps, which is in mW range.

2.2.3. Modulation of additional beam intensity

A dramatic reduction of switching power can be achieved by feeding into pump intersection region an additional weak beam with a perpendicular polarization. The intensity modulation of this additional beam was made using a couple of acousto-optic modulators which produces a switching beam. Such beam undergoes exponential amplification, thus it can strongly influence the pattern position even if its power is small in comparison both with the pump and the generated beam. Hysteresis due the additional beam intensity can be seen in the signal of upper spot in position 1 of generated pattern (Fig. 6).

3. Discussion and conclusions

The spatio-temporal behavior of optical transverse patterns in the $F_g = 2$ transition line of ^{87}Rb vapor was studied in presence of a weak magnetic field. This simple system demonstrates a number of nonlinear phenomena, including bistability, and dynamic behavior which can vary from periodic to chaotic one. In particular, the vapor cell can be used as an optical memory, providing rapid switching (< 10 μs) for low intensity (∼2 μW). The switching can be performed either by external magnetic field, or by beam manipulation.

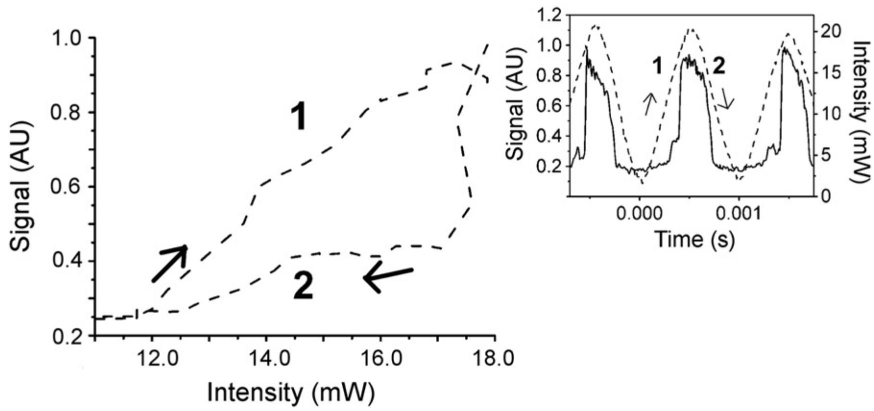

Fig. 5. Hysteresis generated in the signal due to modulation intensity pump beam. Rising and decreasing of pump beam intensities are represented by numbers 1 and 2, respectively.

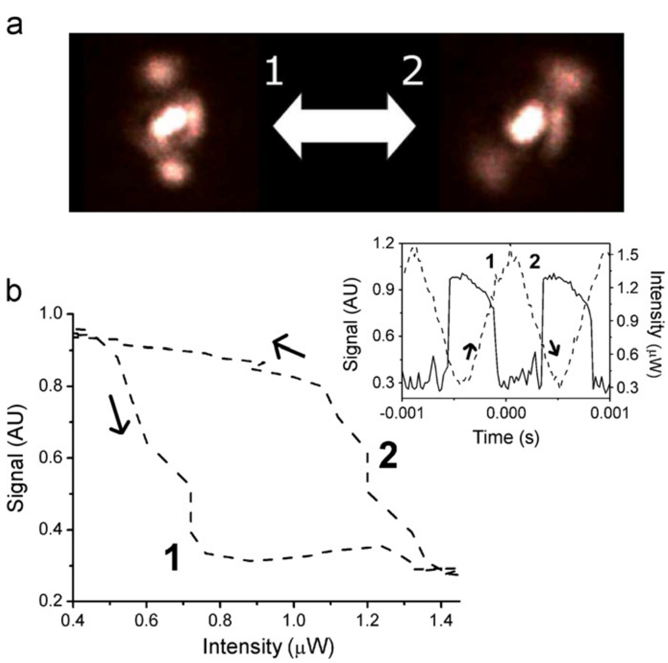

Fig. 6. (a) Patterns of switching in the additional beam configuration. (b) Hysteresis generated in the signal due to an additional beam. Rising and decreasing of additional beam intensities are represented by numbers 1 and 2, respectively.

The underlying nonlinearity is investigated in detail in Ref. [16]. The generation occurs for a region of observed modulation instability for the mentioned mechanism. The exact frequency location is within a $F_g=2$ $F_e=2$ sub-Doppler feature in a transmission spectrum, where gain/absorption balance is more favorable because of diminished absorption. For circular symmetric conditions, the conic generation (a ring in a far field) is observed. The symmetry breaking permits generation of patterns. Phenomenologically, the bistability can be described in terms of system energy dependence on angular position of the generated spot, but a full ab initio calculation seems rather complicated. It is difficult to expect complete theoretical description of phenomena, because the nonlinearity is not simple—it is vectorial, strongly saturated, and non-local

The setup is extremely sensitive to variations in control parameters; the main instability source is the laser frequency drift. Since we did not use frequency locking, low – intensity induced bistability is observed only for relatively short periods of time (typically less than 1 s), while the laser frequency is correct. For higher intensity switching, stable switching can be achieved for minutes before the frequency drifts. It is probable that stabilizing well the parameters, one can expect further reduction of necessary switching power.

In conclusion, the described system demonstrates bistable behavior of transverse patterns for laser powers in 10 mW range. Switching can be achieved by intensities as low as a few microwatts.

Acknowledgments

The work was performed in the framework of Consejo Nacional de Ciencia y Tecnología project 156891.

References

[1] R. Chang, W.J. Firth, R. Indik, J.V. Moloney, E.M. Wright, Optics Communication 88 (1992) 167.
[2] G. Grynber, A. Maître, A. Petrossian, Physical Review Letters 72 (1994) 2379.
[3] T. Ackemann, W. Lange, Applied Physics B 72 (2001) 21.
[4] P. Zerom, R.W. Boyd, in: R.W. Boyd, S.G. Lukishova, Y.R. Shen (Eds.), Self-Focusing, Past and Present, Topics in Applied Physics, Vol. 114, Springer Science+Business Media, New York, 2009, pp. 231–251.
[5] A. Yariv, D.M. Pepper, Optics Letters 1 (1977) 16.
[6] Y. Silberbeg, I. Bar-Joseph, Journal of the Optical Society of America B: Optical Physics 1 (1984) 662.
[7] G. Grynberg, Optics Communication 66 (1988) 321.
[8] G. Grynberg, J. Paye, Europhysics Letters 8 (1989) 29.
[9] W.J. Firth, A. Fitzgerald, C. Paré, Journal of the Optical Society of America B: Optical Physics 7 (1990) 1087.
[10] A.J. Scroggie, W.J. Firth, Physical Review A: Atomic, Molecular, and Optical Physics 53 (1996) 2752.
[11] A. Aumann, E. Büthe, Yu.A. Logvin, T. Ackemann, W. Lange, Physical Review A: Atomic, Molecular, and Optical Physics 56 (1997) R1709.
[12] A. Aumann, E. Groβe Westhoff, T. Ackemann, W. Lange, Journal of Optics B: Quantum and Semiclassical Optics (2000) 421.
[13] W. Lange, Yu.A. Logvin, T. Ackemann, Physica D: Nonlinear Phenomena 96 (1996) 230.
[14] A. Maître, A. Petrossian, A. Blouin, M. Pinard, G. Grynberg, Optics Communication 116 (1995) 153.
[15] A. Petrossian, M. Pinard, A. Maître, J.Y. Courtois, G. Grynberg, Europhysics Letters 18 (1992) 689.
[16] N. Korneev, C. Gutiérrez Parra, Journal of the Optical Society of America B: Optical Physics 29 (2012) 2588.
[17] A.M.C. Dawes, L. Illing, S.M. Clark, D.J. Gauthier, Science 308 (2005) 672.
[18] G.P. Agrawal, Journal of the Optical Society of America B: Optical Physics 7 (1990) 1072.
[19] W.J. Firth, C. Paré, Optics Letters 13 (1988) 1096.