Pergamon

Chaos, Solitons & Fractals Vol. 10, No. 4–5, pp. 725–730, 1999

0960-0779/99/$ - see front matter

PII: S0960-0779(98)00021-6

Circling Vortices and Pattern Dynamics in a Unidirectional Photorefractive Ring Oscillator

G. BALZER, C. DENZ, O. KNAUP and T. TSCHUDI

Institut für Angewandte Physik, Technische Hochschule Darmstadt Hochschulstr. 6, D-64289
Darmstadt, Germany

Abstract—We report results on unidirectional oscillation in a photorefractive oscillator implemented with $BaTiO_3$ that is actively stabilized. Dynamic spatial patterns and pattern competition were observed, depending strongly on the Fresnel number of the system. As the origin for spontaneous pattern alternation we identified variations in the cavity length that are in turn mainly due to temperature fluctuations. By varying the cavity length, we were able to adjust stable patterns of different mode families and control pattern dynamics as mode beats, optical vortices and their rotations and more complex pattern dynamics for higher Fresnel numbers. © 1999 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The transverse intensity distribution of photorefractive oscillators often has an odd and irregular spatial structure, which strongly depends on the Fresnel number of the system. These phenomena have been observed in a number of different experimental setups, including uni- and bidirectional photorefractive oscillators with different nonlinearities [1–8]. In a unidirectional oscillator containing a BSO nonlinearity, three different characteristic effects have been classified [1]: periodic alternation, alternation with chaotic temporal existence (chaotic alternation) and temporally and spatially chaotic alternations (chaotic itinerancy). However, the precise origin of these phenomena has not been fully explained, although Chen et al. [2] showed that these pattern dynamics are not due to material characteristics, but are mainly dominated by oscillator dynamics and temperature effects.

Here, we present experimental investigations on the transverse pattern dynamics of a unidirectional ring oscillator amplified by two-beam coupling in photorefractive $BaTiO_3$ with special emphasize on the origin and the control of the parameters causing these pattern dynamics. Several numerical simulations of other authors revealed that if the pump is in resonance with a certain mode family in an unidirectional ring oscillator, mode beating can appear, resulting in circling optical vortices [3] and turbulent states [4]. We will show that these effects can be observed and adjusted with the cavity length as an additional control parameter.

2. EXPERIMENTAL CONFIGURATION

In our experimental setup, we used a ring resonator (perimeter 1 m) with an even number of mirrors that allows to excite all modes in contrast to a setup with an odd number of mirrors [1], where only symmetric modes can be observed (Fig. 1).

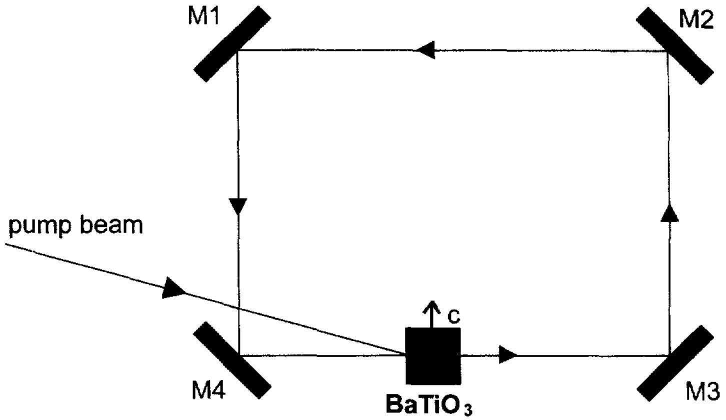

Fig. 1. Schematic setup of a unidirectional ring oscillator.

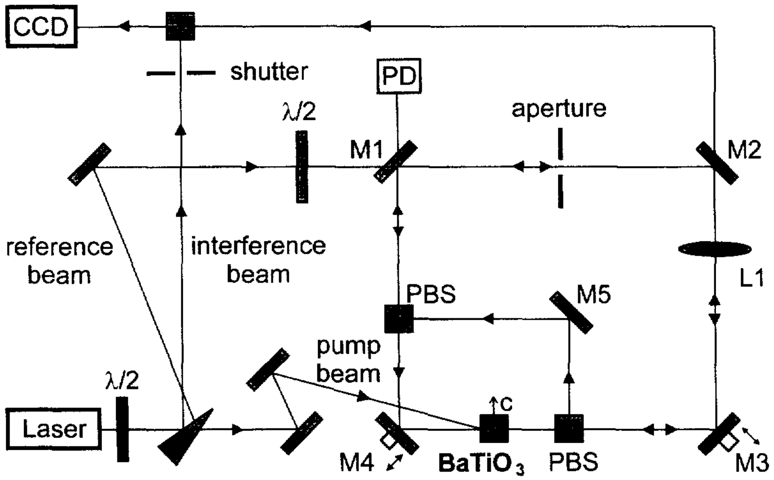

Fig. 2. Experimental setup with active stabilization; PD: photodiode, PBS: polarising beamsplitter.

The $BaTiO_3$ gain medium ($5.5 \times 5.5 \times 5\,mm^3$) was pumped by an Argon ion laser operating at 514 nm in extraordinary polarization. To change the Fresnel number of the resonator and to adjust the losses of different modes, an iris aperture is inserted into the cavity. A lens ($f = 50\,cm$) inside the cavity is used to increase the optical stability of the system. To excite the transverse mode families in the resonator in a reproducible and defined way independent from outer effects, the resonator length was actively stabilized. For that purpose, a reference beam with perpendicular polarization is fed into the cavity, counterpropagating to the cavity signal (Fig. 2).

Both beams, the reference and the resonator signal, are separated before the cavity signal passes through the crystal. Although thus changes in the optical path length in the crystal are neglected, this allows to realize a high-finesse resonator for the reference path (the path containing the crystal is a very low-finesse resonator). The active stabilization is an interferometric one, combined with an electronic feedback compensation due to the piezo-driven mirror adjustment. It is based on adjusting the reference signal to a transmission maximum, and maintaining it by active control adjustment of the mirrors. Because the response time of the crystal is much

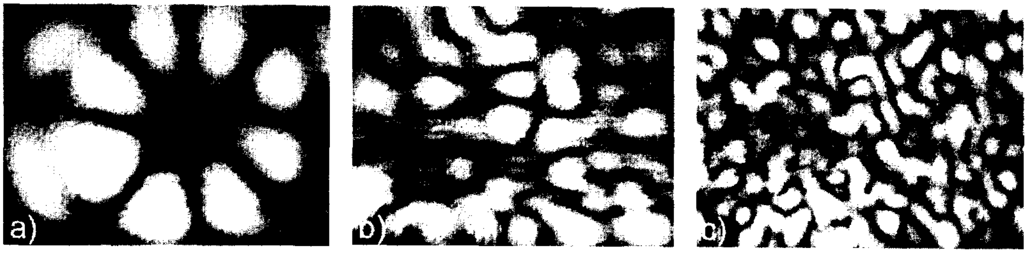

Fig. 3. Examples of transversal patterns for low (F ≈ 3) (a), medium (F ≈ 10) (b), and for high (F ≈ 100) Fresnel numbers (c).

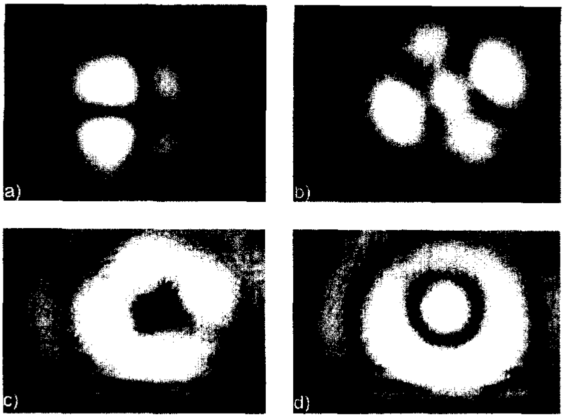

Fig. 4. Stationary modes of the second mode family.

larger than the adjustment time, high-frequency mirror positioning movements do not affect the resonator. With that stabilization, changes in the cavity as well as in the pump wave frequency are compensated.

3. STATIONARY MODE PATTERNS

For small Fresnel numbers in the oscillator, the transverse structure of the oscillator signal is dominated by pure and dynamically stable modes. Figure 3(a) shows an example of a mode of fourth order for low Fresnel number. For higher Fresnel numbers, pure modes disappear and more complex pattern appear, that are similar to pure modes only in the region near the optical axis. An example is shown in Fig. 3(b) and (c). The spatial dimension in Fig. 3(a) and (b) is in the size of 1 mm, in Fig. 3(c) it is about 1 cm.

Using our active feedback stabilization, we changed the oscillator length in a quasi-stationary way on the free spectral range. Because the gain line of the photorefractive medium is much smaller than the one of the oscillator, the crystal defines the mode which will be excited in the oscillator. A change in the oscillator length thus results in a shift of the oscillator modes relative to the gain line of the photorefractive medium. Thus it is possible to scan through all the modes accessible in the free spectral range. If the change is a quasi-stationary one, allowing the system to built up an oscillation at each length, one can obtain all modes that are able to oscillate in that configuration. Figures 4 and 5 shows some examples for different longitudinal mode families.

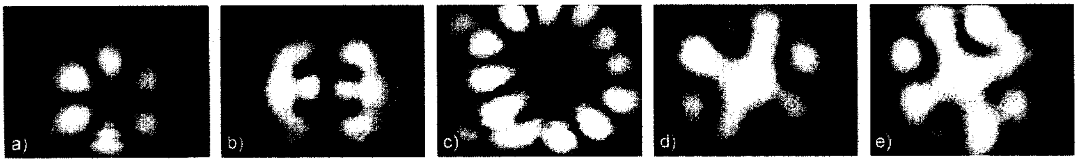

Fig. 5. Stationary modes of the third mode family (a,b), a star mode of order 6 (c) and an example of the superposition of modes of different families when the frequency of the zeroth and fourth mode family is degenerated (d,e).

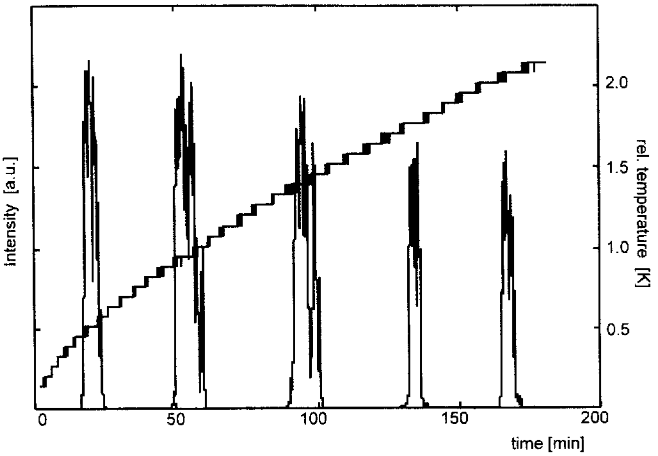

Fig. 6. Cavity signal in comparison to room temperature.

When a transversal mode of higher order lies in the region of the next mode family, superpositions of modes of different families can be observed (see Fig. 5).

4. PATTERN DYNAMICS

Dynamics of the modes can be observed due to the starting dynamics of the system or due to the influence of outer disturbances to the system, especially thermal and mechanical fluctuations and fluctuations of the laser intensity and the intensity of the pump beam.

To show the influence of temperature changes, we closed the oscillator down to a Fresnel number that allows only the basic Gaussain mode to be excited. When changing the room temperature continously (e.g. 1.8 K), in time, we obtained a change of the oscillator length of about 2400 nm or 4λ thus allowing the oscillator to emit after each change in λ, which corresponds to the longitudinal mode distance, the next transverse mode that can be excited. For an arbitrary change in T, this results in an appropriate change of the modal competition as shown in Fig. 6. It is easily seen that a non monotonic change in temperature will lead to an very complex nonlinear dynamik of the resonator modes. To demonstrate we set the stabilization inactive during a certain time period in the experiment (Fig. 7), the changes of the modes caused by changes of the resonator length are obvious.

As another consequence of this dependence, mode beats can be systematically adjusted. For the case of simultaneously appearing doughnut modes, we observed circling optical vortices. In Fig. 8, the superposition of a doughnut of charge 4 and the TEM_{00}-mode gives four circling vortices in agreement with the theoretical calculations. When the oscillator length is changed

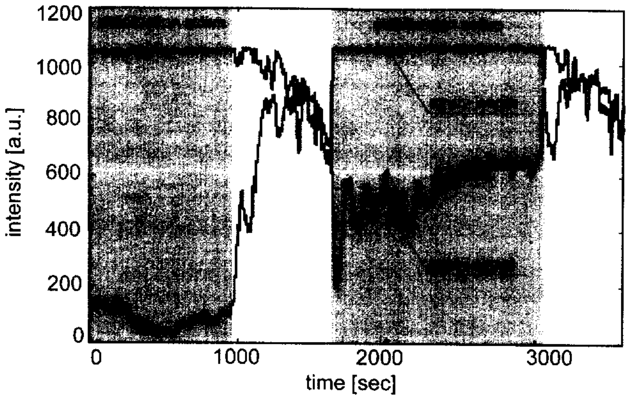

Fig. 7. Comparison of the change of the cavity signal and its length.

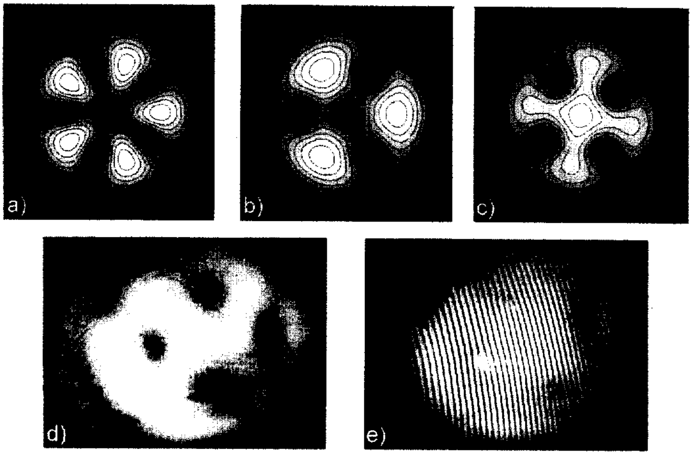

Fig. 8. Superposition of a doughnut mode of charge 4 with a doughnut mode of charge 1 (a,b) or with the TEM_{00} mode (c,d,e); experimental realization (d) and interferogram showing four vortices (e). In (a) the two doughnuts have equal charge, in (b) the charge is different.

during the appearance of such an optical vortice, the amplitudes of the modes that are involved in that process change relative to each other. As an example, Fig. 9 shows how a doughnut of charge 3 can be shifted towards the Gaussian mode. Starting with the pure doughnut mode of charge 3, the vortices are located in the center, the radius of the motion [9] of the vortices is 0. Increasing the intensity of the Gaussian mode by changing the resonator length, the vortices are shifted towards the edge and the radius increases. At the end of the process, the TEM_{00} mode dominates and the radius of the circling optical vortices is shifted towards infinity.

5. CONCLUSION

In conclusion, we have shown that by an active stabilization of a unidirectional photorefractive oscillator, characteristic mode dynamics can be adjusted. Spontaneous pattern dynamics as mode alternation, rotation or circling optical vortices can be varied and controlled in a definite way by

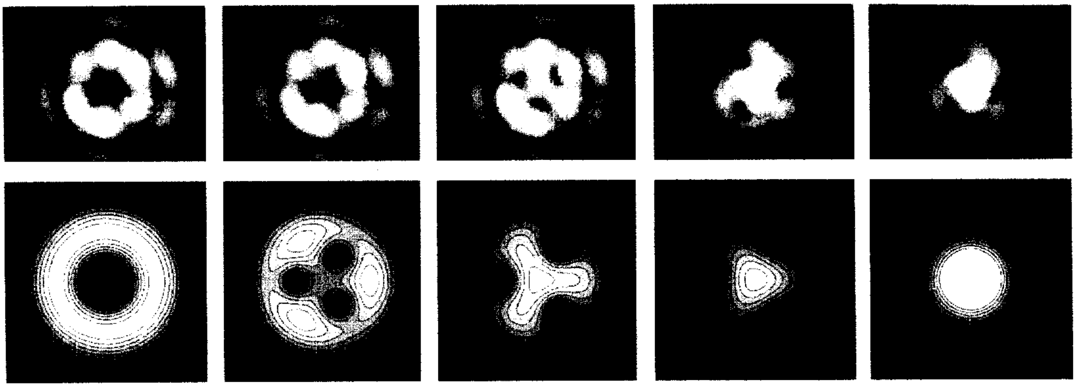

Fig. 9. Change of the relative intensity distribution of a doughnut of charge 3 and TEM_{00} due to changes in the oscillator length: experimental observations (up), numerical calculations (down).

changing the cavity length. In contrast, a carefully aligned and stabilized oscillator shows no spontaneous pattern alternations.

Acknowledgements—The authors are very grateful to M. Vaupel and C. O. Weiss, PTB Braunschweig, Germany, for the help in realizing the active stabilization and many helpful discussions on vortice formation. This work was supported by the Deutsche Forschungsgemeinschaft, Sonderforschungsbereich 185 "Nichtlineare Dynamik".

REFERENCES

1. Arrecchi, F. T., Giacomelli, G., Ramazza, P. and Residori S., Experimental evidence of chaotic itinerancy spatiotemporal chaos in optics. *Phys. Rev. Lett.*, 1990, **65**, 2531; *Phys. Rev. Lett.*, 1991, **67**, 3749.
2. Chen, Z., McGee, D., Abraham, N. B., Bidirectional oscillation in a photorefractive ring resonator. *J. Opt. Soc. Am*, 1996, **B13**, 1482.
3. Vaupel, M., Weiss, C. O., Circling optical vortices. *Phys. Rev. A*, 1995, **51**, 4078.
4. Gil, L., Emilsson, K., Oppo, G. L., Dynamics of spiral waves in a spatially inhomogenious Hopf bifurkation. *Phys. Rev. A*, 1992, **45**, R567.
5. de la Tocnaye, J., Fellat-Finet, P., Huignard, J. P., Effect of using a $Bi_{12}SiO_{20}$ light amplifier on the formation and competition of modes in optical resonator. *J. Opt. Soc. Am*, 1986, **B3**, 315.
6. d'Alessandro, G., Spatiotemporal dynamics of a unidirectional ring oscillator with photorefractive gain. *Phys. Rev. A*, 1992, **46**, 2791.
7. Staliunas, K., Tarroja, M. F. H., Slekys, G., Weiss, C. O., Dambly, L., Analogy between photorefractive oscillators and class-A-lasers. *Phys. Rev. A*, 1995, **51**, 4140.
8. Jost, B. M., Saleh, B. E. A., Spatiotemporal dynamics of coupled transverse mode oscillators in unidirectional photorefractive ring resonators. *Phys. Rev. A*, 1995, **51**, 1539.
9. Malos, J., Vaupel, M., Staliunas, K., Weiss, C. O., Dynamical Structures of a photorefractive oscillator. *Phys. Rev. A*, 1996, **53**, 3559.