Spontaneous pattern formation in a cavity with incoherent light

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Abstract: We present the first experimental observation of spontaneous pattern formation in a nonlinear optical cavity in which the circulating light is both spatially and temporally incoherent.

OCIS codes: (190.4420) Nonlinear optics, transverse effects in; (030.6600) Statistical optics; (230.4320) Nonlinear optical devices.

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1. Introduction

Allan Turing was the first to recognize that organized structures can form spontaneously, from noise, transforming a homogenous state into intricate patterns [1]. Spontaneous pattern formation is a universal phenomenon appearing in diverse systems. Patterns have been found in formations of soil [2], vegetation structures [3], sand [4], nonlinear optical systems [5-6], and many others. This universal phenomenon often occurs in nonlinear systems with feedback. In optics, the most common system with feedback is a nonlinear optical cavity, which supports versatile nonlinear phenomena, e.g., pattern formation [5,6], cavity solitons [7-10], chaotic dynamics [5], etc. The dynamics in an optical cavity is driven by the interference of waves. However, interference (and hence the dynamics) can be considerably affected, or even completely suppressed, if the light circulating in the cavity is partially incoherent. This avenue of research, the study of *nonlinear phenomena in cavities with statistical light*, has not been addressed until recently. Two years ago, our group has studied pattern formation upon a spatially coherent light beam circulating in a (passive) cavity that was longer than the coherence length of the light [11,12], so that interference terms between beams from different cycles did not contribute to the nonlinear index change. The emerging patterns in that experiment exhibited spatial line narrowing with increasing feedback, resembling the line narrowing in lasers, and reminiscent of other order-disorder phase transition phenomena. That experiment, conducted with spatially-coherent light, motivated the first theoretical study and the prediction of cavity pattern formation with spatially-incoherent light [13]. Here, we present the first experimental study of spontaneous pattern formation in a nonlinear optical cavity in which the circulating light is both spatially and temporally incoherent.

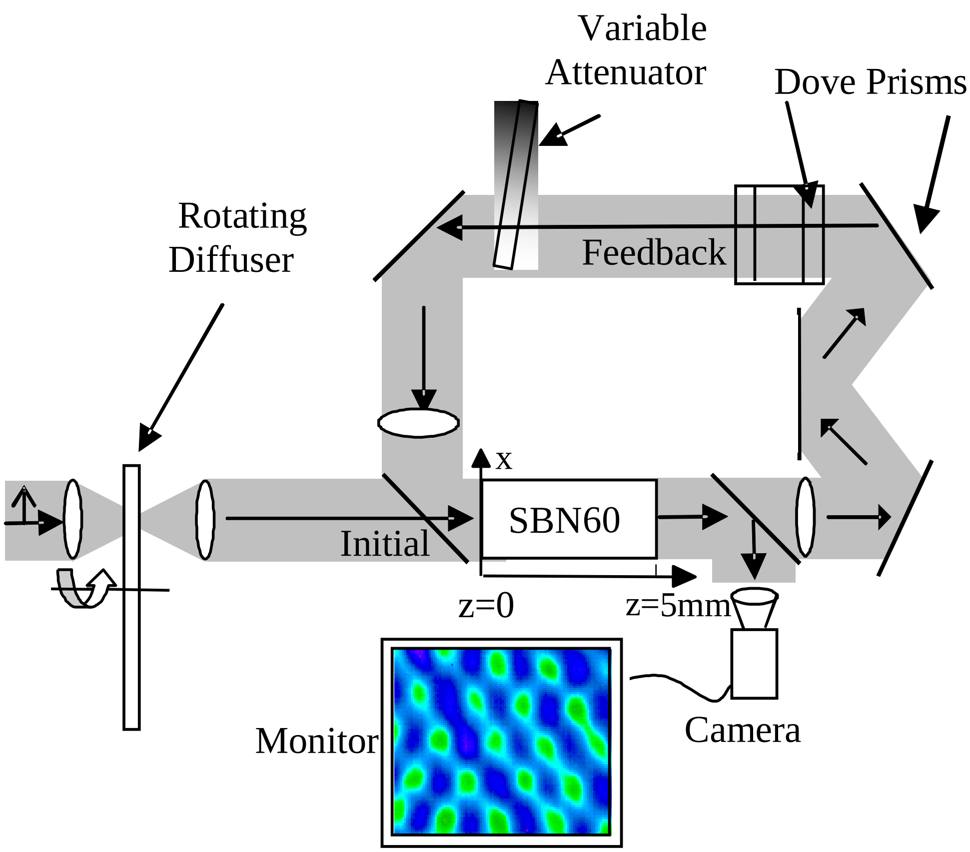

Fig. 1. The experimental setup.

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Our experimental system is a passive ring cavity containing a non-instantaneous nonlinear medium, while the light circulating through the cavity is partially spatially and temporally incoherent. The characteristic length-scales of the system are (i) the length of the cavity feedback loop, $l_{cavity} = 0.5$ m, (ii) the length of the nonlinear medium in the cavity, $l_{medium} \sim 5$ mm, (iii) the temporal coherence length of the light, $l_{coh} \sim 5$ cm, and (iv) the spatial correlation distance, l_{spat}, of the light, whose value can be varied from several wavelengths ($\lambda = 488$ nm) to the limit of fully spatially coherent light ($l_{spat} \to \infty$). It should be emphasized that the longitudinal length-scales are ordered as $l_{medium} << l_{coh} << l_{cavity}$. Because of the condition $l_{coh} << l_{cavity}$, the fields that have circulated through the cavity a different number of cycles are completely incoherent with one another, that is, their phases fluctuate in an uncorrelated fashion. Furthermore, every one of these fields is partially spatially-coherent. Here we demonstrate that, in spite of this lack of coherence, organized spatial patterns can form spontaneously from noise. The patterns are typically periodic, with a periodicity several times larger than the spatial correlation distance l_{spat}.

2. Experimental setup

The experimental setup used in our experiments is illustrated in Fig. 1. The nonlinear medium within the cavity is a normal-cut photorefractive $Sr_{0.6}Ba_{0.4}Nb_2O_6$ crystal (SBN60), with a surface reflectivity of 0.17, employing the screening nonlinearity [14]. The surfaces of the crystal were cut in different angle so it will not function as an etalon. A spatially incoherent beam is produced by sending a coherent 488 nm Ar+ laser beam through a rotating diffuser. This pattern-forming beam (henceforth denoted "signal beam") is then made extraordinarily-polarized with respect to the crystalline axes of the photorefractive uniaxial crystal (so as to utilize the largest nonlinear coefficient), and is launched into the cavity. The instantaneous intensity $|E(\mathbf{r},t)|^2$ of the incoherent light consists of randomly fluctuating speckled patterns; where E denotes the electric field of the incoherent light. However, because the response time of the nonlinear medium τ_{medium} is much longer than the coherence time l_{coh}/c (the characteristic time of random fluctuations), the medium responds to the smooth time-averaged intensity $I(r,t) = <|E(r,t)|^2>_{\tau\, medium}$; the time-average is taken over the response time τ_{medium}. In addition to the signal beam, we also launch a second, "background", beam (whose intensity is I_b), which is used to set the degree of saturation of the photorefractive screening nonlinearity [14-16,19]. The background beam is uniform in space and is co-propagating with the pattern-forming beam everywhere in the cavity. To suppress possible modulation instability upon this background beam, we set it to be ordinarily-polarized (polarized orthogonally to the signal beam), which corresponds to a very small nonlinear coefficient [16]. We also make the background beam highly spatially-incoherent (with a spatial correlation distance much shorter than that of the signal beam), so that the background beam is always below the instability threshold [16,17]. Thus, the background beam remains spatially uniform, and does not affect the patterns emerging upon the pattern-forming beam (apart from setting the degree of saturation of the nonlinearity). The screening nonlinearity is of the form $\delta n(I) = -\gamma\eta(I)/(1+I/I_b)$ [19,12], γ being the strength of the nonlinearity, which is proportional to a transverse DC electric field applied on the crystal. The function $\eta(I)$ is defined as $1/\eta(I) = D^{-1}\int_0^D dz(1+I(x)/I_b)^{-1}$ [19]. This term is especially relevant for the analysis of modulation instability [17], as well as for dark solitons [19], where the illumination of the whole crystal by the signal beam significantly changes the photocurrent and consequently the nonlinearity [19]. Note that the nonlinear index change depends on the ratio between the signal and the background beam I/I_b, which in our cavity does not depend on the feedback parameter ε.

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We construct the feedback loop by taking both the signal and the background beams from the output face of the nonlinear crystal and imaging them (with 1:1 magnification) back onto the input face, forming ring cavity circulating light in the counter-clockwise direction (Fig. 1). The input face of the crystal is slightly tilted to eliminate back reflections (that otherwise could have given rise to light circulating also in a clockwise direction). The feedback loop is constructed so that the feedback beams entering the nonlinear crystal is properly aligned with the input beam with no relative tilt between the beams. To do that, we use a 4f system and two dove prisms (one horizontal and one vertical) in the feedback loop (see Fig. 1). We construct dove prisms from mirrors (rather than use standard Dove prisms made of glass), to eliminate polarization-dependant reflections. We verify that the imaging is truly 1:1 by imaging a test object (a thin wire) back on itself, and tune the dove prisms so that the feedback loop does not introduce any tilt or translation. By using a beam splitter in the loop, we split a small fraction of the circulating beam and image the intensity pattern at the output face of the crystal onto a CCD camera. The attenuation of intensity in the loop is controlled with a variable attenuator. It should be emphasized that the intensity structure and statistical properties of the light evolve only while propagating in the nonlinear medium. The statistical properties are unchanged when the light is imaged from the output to the input face of the SBN crystal. The intensity is attenuated in the feedback loop, but its structure is preserved. The cavity finesse is low (~1), hence, the cavity does not act as a filter to increase the temporal coherence. It is important to note here that all of the components in the feedback loop are polarization independent. This ensures that the ratio I/I_b between the (orthogonally polarized) signal (I) and background (I_b) beams stays constant within the loop. Furthermore, because both beams are recycled in the loop, the ratio I/I_b does not depend on the feedback parameter ε .

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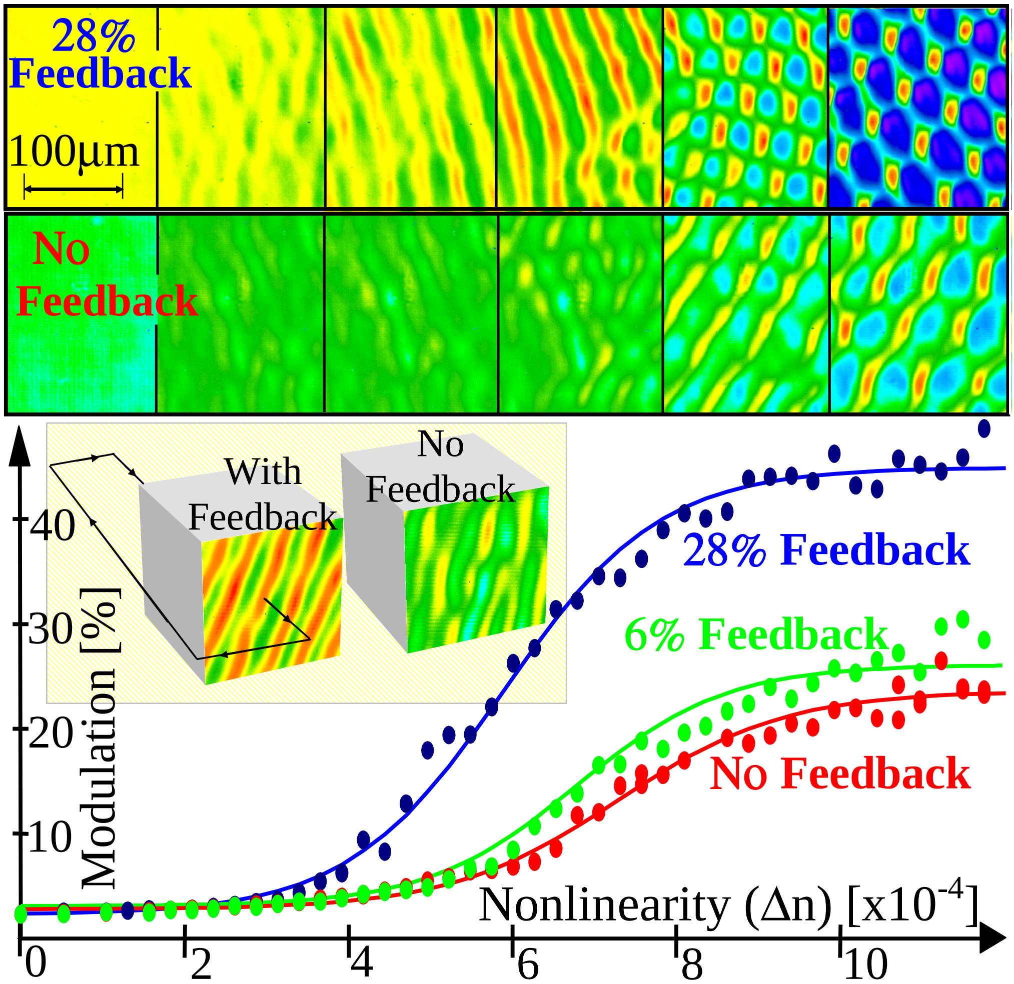

Fig. 2. (Movie 2.5 MB) Top row: Intensity patterns at the output of the crystal, with and without feedback; the strength of the nonlinearity is increased from left to right. Plot: Modulation depth of the emerging pattern as a function of nonlinearity for different values of feedback.

3. Experimental results and discussion

Typical photographs depicting the intensity structure of the light emerging from the cavity are shown in two rows in Fig. 2. The upper (lower) row of photographs corresponds to feedback value of 28% (0%), while the strength of the nonlinearity ($\Delta n \propto \gamma$) increases from left to right. We see the formation of organized periodic patterns as the nonlinearity is increased. The pattern periodicity is another spatial length-scale, which emerges spontaneously (from noise) in the system. It is therefore important to compare it with the inherent characteristic spatial length-scale of the system: the spatial correlation distance l_{spat}. In order to verify that the correlation distance l_{spat} is shorter than the pattern periodicity (and hence the optical field values within adjacent features of the periodic pattern are uncorrelated), we compare the characteristic intensity structure of a periodic pattern (Fig. 3, upper photograph) to the highly speckled photograph of the instantaneous intensity of the incoherent light $|E(\mathbf{r},t)|^2$ (Fig. 3, lower photograph). This photograph of the instantaneous intensity is obtained by stopping the rotating diffuser, and capturing the speckled pattern (this measurement was taken when the crystal is temporally removed in order to eliminate distortion caused by the nonlinearity of the medium). The average size of the speckles approximately corresponds to the spatial correlation distance [20]. From Fig. 3, we find the spatial correlation distance to be approximately $l_{spat} = 20$ μm, which is ~4 times smaller than the pattern periodicity. From this data, we conclude that the optical field values within adjacent features of the periodic pattern are uncorrelated.

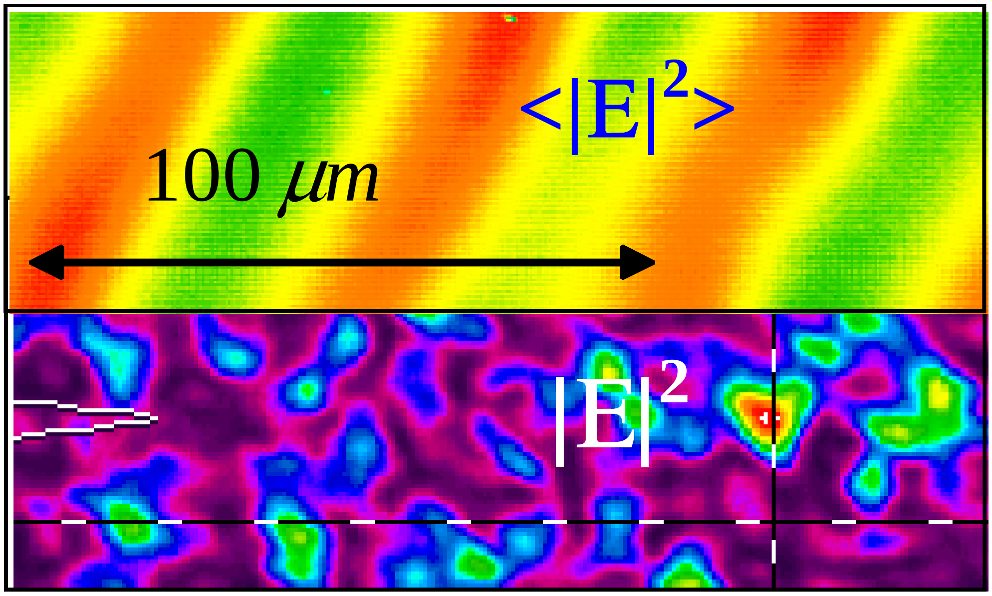

Fig. 3. Upper picture: Characteristic (time-averaged) intensity pattern. Lower picture: The highly speckled structure of the instantaneous intensity of the incoherent beam obtained by stopping the rotating diffuser, and capturing the speckled pattern. The average size of the speckles, which corresponds to the spatial correlation distance, is several times smaller than the pattern periodicity

The points in the plot of Fig. 2 represent the modulation depth (m) of the patterns as a function of Δn, for different values of feedback. We estimate the modulation depth of the patterns as $m = \Delta I / \langle I \rangle_A$, where $\langle I \rangle_A$ is the mean value of the intensity structure over a broad area of space, A, while ΔI is the standard deviation. We took more than 100 such measurements to characterize the pattern formation process. For all three sets of measurements, at values of nonlinearity below $\Delta n_{th} \approx 0.0003$, the visibility is negligible, i.e., the uniform-intensity beam circulating in the cavity is stable. Increasing Δn beyond the threshold value leads to instability and to the formation of low-visibility patterns. We have recoded the pattern formation process in our cavity as it evolves with time, and show it in the attached movie depicting the intensity structure at a section of the output face of our nonlinear medium. The movie starts with feedback loop being blocked, that is, the patterns correspond to the single pass system. Afterwards, the cavity feedback (of 28%) is turned on, and we observe the amplification of the modulation depth and the enhanced organization of the patterns in the cavity system, as the photorefractive nonlinearity evolves in time from the zero-feedback state to the pattern-supporting state at 28% feedback. Near the end of the movie, the feedback is turned off, the modulation depth of the patterns decreases, while they become less organized in comparison to the cavity system.

From our experimental results we conclude that the instability threshold in our cavity is at the same value (within the experimental errors) as in the corresponding single-pass system [17-19,21-23] [i.e., keeping all parameters identical varying only the feedback value]. This feature is in direct contrast to coherent feedback systems, where the pattern formation

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threshold is critically dependent on the feedback [5], and the (coherent) feedback can suppress modulation instability occurring in a corresponding single-pass system [5]. The feedback in our cavity affects the system after the instability has already occurred. For larger values of feedback, the visibility increases at a faster rate, the patterns are more regular, while the visibility saturates at a larger value.

Inspecting Fig. 2, we observe that the feedback makes the pattern more regular, having a well-defined periodicity (compare images in the first row to those in the second row). Consequently, the spatial bandwidth of the pattern narrows as feedback increases (as in Ref. [11], which was conducted in a cavity with spatially-coherent light). The visibility in our experiment can go up almost to unity, when the nonlinearity is strong enough. However, since the light in our experiment is spatially-incoherent, the pattern forms when the nonlinearity compensates not only for the diffraction broadening of the stripes (arising from their finite width), but also for the diffusive tendency of the incoherence that works to wash the pattern out [13]. This is in contrast to Ref. [11], where the latter process simply does not exist (because the light in [11] was spatially coherent). The direct implication is that the pattern-formation threshold in an incoherent cavity (the current experiment) is higher than that in a spatially-coherent cavity [11], for the same values of the other parameters (e.g., the feedback value, etc.).

4. Conclusion

In conclusion, we have presented the first experimental observation of pattern formation in a nonlinear optical cavity with both spatially and temporally incoherent light, and analyzed the influence of the non-correlated feedback and spatial de-coherence on this process. Studying the dynamics of statistical (partially coherent) waves in nonlinear feedback systems brings about a new direction. The commonly studied limit is when the coherence length scales are much longer than the characteristic size of the cavity ($l_{coh} >> l_{cavity}$). We have analyzed the dynamics in the opposite limit, $l_{coh} << l_{cavity}$. However, a whole class of intermediate systems that may yield the most interesting dynamics is yet unexplored. We expect that cavities with loop-length comparable to the temporal coherence length will lead to interesting phenomena (possibly phase-dependent chaos) driven by different tendencies of the coherent and de-correlated feedback. In this sense, our experiment bridges the gap between pattern formation processes, which are naturally phase-transition phenomena, in correlated (coherent) systems and uncorrelated (incoherent) systems, thereby exemplifies the similarities and differences between the instabilities in phase-dependent and phase-independent systems.

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