SPATIAL PATTERNS IN NONLINEAR OPTICS

Pattern Formation in Optical Cavities With Incoherent Light

Tal Carmon, Hrvoje Buljan, Marin Soljačić and Mordechai Segev

Nonlinear optical cavities attract attention since they exhibit various kinds of nonlinear phenomena such as pattern formation,[1] solitons[2] and chaos.[1] Pattern formation refers to the fact that above a specific threshold, any uniform intensity distribution of light becomes unstable and splits into space- (time-) correlated domains.[1] Thus far, all work on nonlinear optical cavities has been carried out with spatially and temporally coherent light, that is, in cavities in which the characteristic dimensions are much smaller than the spatial and temporal coherence lengths of the light. In such systems, resonance (interference) effects are crucial to the pattern formation process.[1] Here, we summarize recent results on dynamics in the opposite limit: optical cavities with *incoherent* light,[3,4] in which pattern formation occurs despite the lack of interference.

These experimental and theoretical studies have focused on optical cavities the characteristic dimensions of which exceed the temporal coherence length of the light and in which the spatial coherence of the light could be varied from zero to infinity.[3,4] In these cavities, there is no interference between the fields from different cycles. Hence, pattern formation relies on a different physical mechanism than it does in coherent cavities. In particular, the response of the medium is noninstantaneous, so that it is unable to follow the fast phase fluctuations of the incoherent light and thus responds only to the smooth time-averaged intensity. As a first step, we analyzed a cavity with temporally incoherent, but spatially coherent, light.[3] It was shown that patterns form above a well-defined cavity threshold determined by the interplay of nonlinear gain and cavity loss. The patterns of this *non-resonant* system exhibit spatial line narrowing with the increase of feedback, resembling the line narrowing in (resonant) lasers (see Fig. 1). In fact, despite the incoherence of the light, this cavity threshold is analogous to many thresholds in resonant feedback systems with gain.[1] In a subsequent paper, we theoretically analyzed a cavity in which the light was also spatially incoherent.[4] The pattern formation process in such a cavity is always associated with two consecutive thresholds of different character. The first threshold is the point at which the uniform intensity beam becomes unstable as the nonlinearity overcomes the diffusive tendency of spatially incoherent light. In marked contrast to what occurs in coherent cavities, this threshold is independent of the cavity boundary conditions. The second threshold is the aforementioned "cavity threshold." These theoretical results have recently been confirmed experimentally.

In conclusion, we have summarized features of optical pattern formation that result from the interplay between the statistical (coherence) properties of light, the nonlinearity of the medium and the feedback of the cavity. These results open a new direction of research in which nonlinear optical cavities are viewed as a class of statistical systems with variable characteristic length scales: (i) the temporal (spatial) coherence length of the light, (ii) the length of the nonlinear medium and (iii) the length of the cavity. These systems are fundamental to optics, with potential applications using statistical light, and are intimately related to (non-equilibrium) statistical physics in other fields.

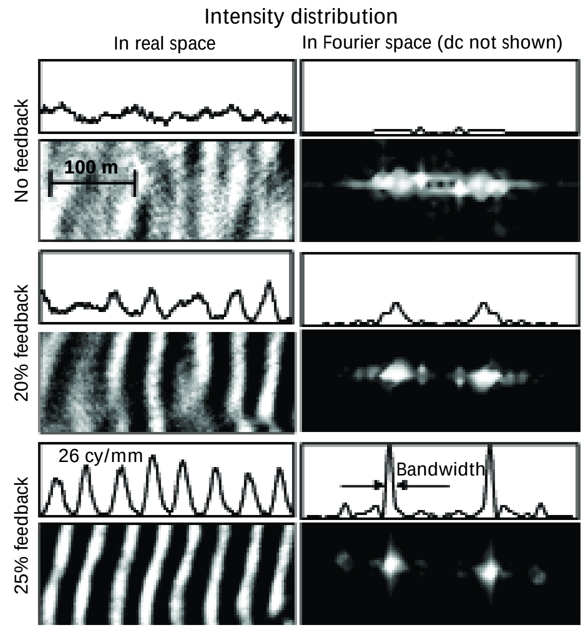

Figure 1. Experimental results, showing pattern formation in a temporally incoherent nonlinear optical cavity, displaying the narrowing of the spatial spectrum of the pattern with increasing feedback intensity. Shown are photographs of the intensity distribution along with their calculated spatial (Fourier) power spectrum (*right*), at various feedback values. The bandwidth narrowing is obvious in these pictures as the stripes become sharper and more regular with increasing feedback.

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Tal Carmon, Hrvoje Buljan (hbuljan@tx.technion.ac.il) and Mordechai Segev are with the Physics Department, Technion - Israel Institute of Technology, Haifa, Israel. Marin Soljačić is with the Physics Department, MIT, Cambridge, Mass.

Nonlinear Effects and Patterns in a Cold Atomic Cloud

G. Labeyrie, T. Ackemann, B. Klappauf, M. Pesch, G.L. Lippi and R. Kaiser

The nonlinear interaction between an optical medium and an electromagnetic field can induce gradients in the index of refraction distribution, leading to patterns or filamentation in the most diverse nonlinear materials: solids, anisotropic soft matter (liquid crystals), cells containing thermal vapors, etc. One common difficulty in interpreting the results of these experiments and in comparing them to models is that the details of the interaction in these media are very complex. Cold atomic systems have well known linear and nonlinear optical properties, as illustrated in experiments on four wave mixing, electromagnetic induced transparency or slow light propagation. Such samples are thus an excellent candidate for improving the comparison between theory and experiments, but so far to our knowledge no investigations on patterns have been performed in such systems.

Our experiment[1] demonstrates, for the first time to our knowledge, the appearance of transverse optical structures in the field distribution of a high intensity laser beam transmitted through a cold atomic cloud. The measurements are taken in the far field of the transmitted probe for varying probe power. The cold cloud, a magneto-optical trap (MOT), is turned off during probing, and measurements are taken with a gated camera which integrates the transmitted light over time windows varying between 0.25 seconds and 20 seconds—depending on the amount of transmitted light—thus averaging the field intensity distribution of several probing cycles. (The probe is turned off when the MOT is periodically switched on). For these measurements, the shape of the MOT has a nearly Gaussian profile with diameter ~4 mm (FWHM) and reaches a spatial density n_{at} ~4×10^{10} cm^{-3} at the center of the cloud. The corresponding optical thickness, measured with a weak collimated probe, is b_{res} ~18. The atomic velocity distribution, measured with time-of-flight techniques, provides an estimate for v_{rms} ~10 cm s^{-1}. The probe laser is tuned close to the 3<->4' transition of the ^{85}Rb atom.

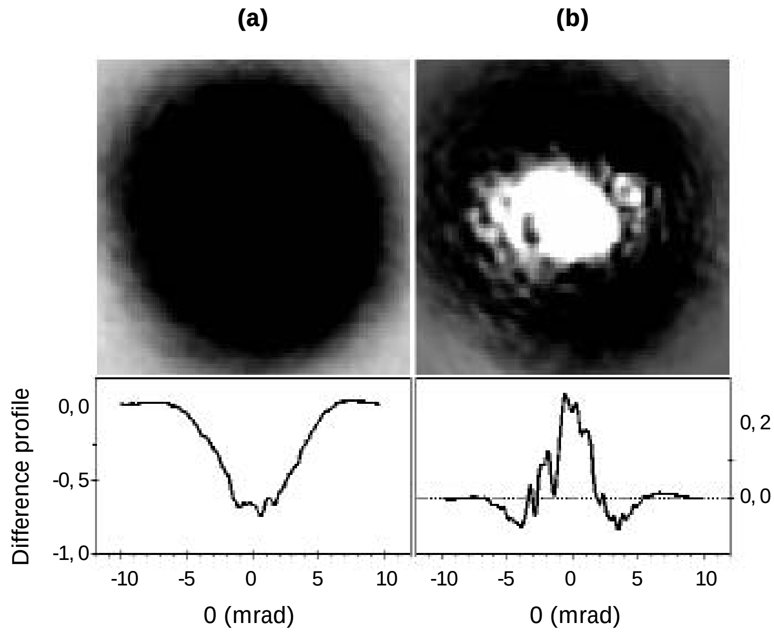

Figure 1. Transmitted intensity profile for small (a) and large (b) saturation of the atomic transition with corresponding radial cuts below.

By subtraction of the incident beam from the one transmitted by the cold atomic sample, one observes the appearance of radial, rotationally symmetric, structures (Fig. 1), which increase by up to 25 percent the amount of power on the optical axis (provided the probe is sufficiently strong). The reshaping holds up to the largest values of saturation we used ($s_0 > 10^4$) and is also detectable in the near field, thus hinting at residual propagation effects.

Simple modeling of the atoms as two-level systems interacting with a resonant beam shows that the main factor determining the beam reshaping in our experiment is related to the position of the incident beam waist relative to a (geometrically) *thin* sample, just as it occurs in *z-scans*. The introduction of the presence of the other (detuned) transitions (3<->2', 3<->3') and of propagation through the length of the cloud introduce minor corrections to the main result, thus confirming the correctness of the simple physical picture. Our measurements also indicate that the sample has not been strongly perturbed by the laser beam.

This experimental observation of spatial beam reshaping by a cold sample—the first to our knowledge—opens the door to investigations on more complex structuring in media which offer excellent experimental control and modeling possibilities.

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G. Labeyrie (Guillaume.Labeyrie@inln.cnrs.fr) and R. Kaiser are with the Laboratoire Ondes et Désordre, Valbonne, France. T. Ackemann and M. Pesch are with the Institut für Angewandte Physik, Westfälische Wilhelms-Universität Münster, Münster, Germany. B. Klappauf is with the Optoelectronics Research Center, University of Southamptpon, Southampton, U.K. G.L. Lippi is with the Institut Non Linéaire de Nice, Valbonne, France.