Modulational instability and solitons in a periodic dissipative feedback system

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Abstract
We review our recent experimental results on control of the modulational instability, pattern formation, and solitons in a nonlinear discrete dissipative feedback system. We show that the discreetness and bandgap effects can provide efficient control of the nonlinear instability modes of the system. Furthermore, we explore the possibilities for excitation of dissipative discrete solitons in such system through seeding with a narrow addressing beam.

Keywords: dissipative nonlinear system; feedback system; photonic lattices; modulational instability; solitons

Introduction
Periodic photonic structures enable novel possibilities for manipulation of the fundamental aspects of wave propagation [1], including linear dispersion, optical nonlinearity, and emission of light. In the past decade enormous research has been concentrated on various aspects for control of light refraction, diffraction, and dispersion in periodic structures, including demonstration of novel effects such as negative refraction, slow light, and superprism. Enhancement of the nonlinearity has also been a subject of increased interest with the demonstration of low power optical switching and novel nonlinear states [2]. The control of light emission has also been a major application of periodic structures, already with the first proposal in Ref. [3]. The implementation of photonic periodic structures inside a laser cavity has shown great promises for control of laser modes, including important experimental results in polarization and spatial mode selection.

The control of all three factors: linear dispersion, nonlinearity, and light amplification in a single physical system however, has never been demonstrated experimentally. In such a dissipative nonlinear periodic system novel physical phenomena, such as formation of discrete dissipative solitons [4] and discrete dissipative modulational instability (MI) [5] can be observed. Here, we realise experimentally a highly nonlinear periodic system with a photorefractive gain to study experimentally transverse instability and soliton formation in discrete dissipative feedback system.

Experimental arrangement
In our experiments, we combine two concepts: a photorefractive two-wave mixing in a single-mirror configuration [6] and an optically induced photonic lattice [7]. Our experimental setup (Fig. 1) enables us to study how the strength and periodicity of the lattice influence the conditions for MI, and correspondingly the pattern formation and solitons. The part indicated by a solid line in Fig. 1, called a "pattern beam", represents a standard PR two-wave mixing experiment [6] with a tunable single feedback. The crystalline c-axis of the undoped $BaTiO_3$ crystal points towards the feedback mirror, but is rotated by roughly 25° with respect to the pattern beam. At a fixed mirror-crystal distance, a hexagonal pattern is formed above a threshold intensity I_{TH} of the pattern beam. A typical near-field intensity distribution I_{P} is shown in the inset of Fig. 1(top). The lattice is created by a diffraction of a Gaussian beam onto a 1D grating. The $\pm 1^{\mathrm{st}}$ diffraction orders are selected and recombined inside the PR crystal by a $4f$ system. The lattice beams are polarized orthogonally to the pattern beam and are shown with a dotted line in Fig. 1. To provide insight of the interplay between the pattern and the lattice modes, the patterns are being identified by monitoring their far-field (Fourier) distribution.

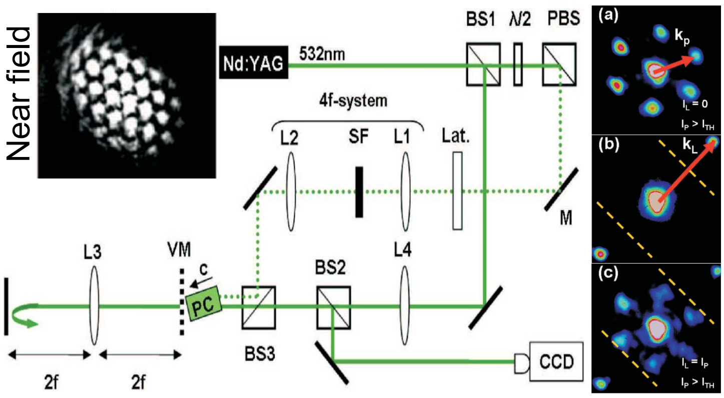

Figure 1: Experimental setup. Right - far-field patterns: (a) hexagonal pattern without lattice and near-field intensity pattern (inset), (b) linear diffraction on the lattice, (c) co-existence between nonlinear pattern and linear diffraction for $k_L \simeq 2.2 k_P$. Dashed lines: the position of the lattice bandgap.

Results and Discussion

Discrete dissipative feedback MI: Figure 1(a) shows a typical far-field hexagonal pattern formed in the absence of the lattice above the threshold power for pattern formation (20 mW). The lattice strength, on the other hand, is tested by temporarily removing the feedback mirror and monitoring the pattern beam diffraction on the lattice in the far-field. As seen in Fig. 1(b), this diffraction gives rise to two outer spots along the diagonal (obtained at 45° lattice orientation), while the central spot corresponds to the zero-order diffraction. The arrows in Fig. 1(a,b) represent the transverse wavevectors of the hexagonal pattern ($k_{\rm P}$) and the lattice ($k_{\rm L}$). The dashed lines in Fig. 1 correspond to the edges of the first Brillouin zone of the lattice, situated at $k_{\rm L}/2$.

We investigate the effect of the relative magnitude and orientation of $k_{\rm L}$ on the formation of patterns in the system. In the experiments, we create the periodic lattice and then we launch the pattern beam into the medium. First we set the lattice periodicity such that $k_{\rm L} \simeq 2.2k_{\rm P}$, hence all the wavevectors of the instability modes fall within the first Brillouin zone of the lattice [Fig. 1(c)]. In this case, the nonlinear hexagonal pattern co-exists with the 1D lattice diffraction. Note that in this case the optical power of the pattern beam ($\simeq 30$ mW) is larger, because the presence of the lattice in the PR crystal tends to increase the hexagonal pattern threshold.

Next we study the effect of the lattice bandgap on the instability modes of the system. An important condition for bandgap control of the patterns is realised when the periodicity of the lattice is such that $k_{\rm L} = \sqrt{3}k_{\rm P}$. In this case, the propagation constant of the hexagonal instability modes is placed exactly inside the bandgap region of the lattice, as seen in Fig. 2(a) for comparable pattern and lattice beams intensities. By increasing the lattice beam intensity, $I_{\rm L} = 5I_{\rm P}$ [seen by the two brighter outer spots in Fig. 2(b)], the MI can be suppressed in the bandgap region [Fig. 2(b)] due to the fact that the lattice bandgap prohibits the growth (from noise) of instability modes with corresponding propagation constants. Qualitatively similar effect occurs if two spots of the hexagons overlap with the bandgap area for $k_{\rm L}{\simeq}2k_{\rm P}$, again leading to symmetry breaking of the induced patterns. It is important to note that the output differs drastically, when the lattice beam is sent through the crystal after the formation of the pattern. In this case, the established high intensity instability modes shift the lattice bandgap such that the propagation constant of the modes lies outside the bandgap region and suppression of the instability is no longer possible.

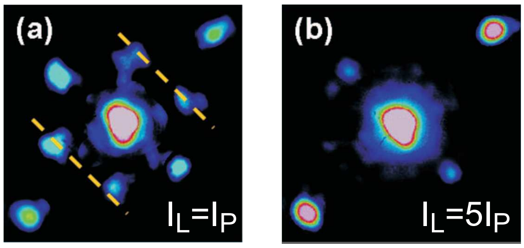

Figure 2: (a,b) Bandgap inhibition of instability modes for for $k_{\rm L} \simeq \sqrt{3}k_{\rm P}$ and two different lattice intensities. $I_{\rm P} > I_{\rm TH}$.

Discrete dissipative feedback solitons: Finally, we explore the formation of solitons in our system. For this purpose, the pattern beam power is set just below the pattern formation threshold and an additional narrow beam with a FWHM of $\sim 20\,\mu$m is sent onto the crystal from the side of the feedback mirror. Preliminary analysis show that in such a way short live localised spots can be excited in the crystal. Further experimental and theoretical analysis are currently under consideration to identify the nature of such localisation.

Conclusions

In conclusion, we have demonstrated the versatility of photonic lattices for manipulation of light in conservative and dissipative systems. In particular, we have shown the control of modulational instability and pattern formation by a photonic lattice in a dissipative feedback system. We have identified three important discrete cavity MI control mechanisms: band-gap inhibition of instability modes; seeding of instability patterns by the lattice periodicity; and lattice-induced pattern reorientation. We believe, that our results open new ways for control of the structure of laser modes by embedded photonic crystals. Furthermore, we explore the possibilities for excitation of discrete feedback solitons in such systems.

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