Discrete dissipative switching waves and solitons in 1D-, 2D-, and 3D- nanostructures and metamaterials

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Abstract

In this paper we review and compare the main features of localized structures – switching waves, or kinks, and solitons in discrete dissipative systems. Some of these features have no known analogues in continuous systems. Especially rich are localized structures in magnetic metamaterials driven by coherent radiation, and they include knotted solitons not found in other optical and microwave systems.

1. Introduction

Dissipative optical solitons are the nonlinear waves localized due to the balance of energy gain and dissipation [1]; they are much more stable as compared with conservative solitons. The added stability can be beneficial for application with rigid requirements on operations' precision and reliability. Especially flexible are nonlinear schemes with periodic spatial variation of their characteristics [2], including arrays of weakly interacting nonlinear elements supporting discrete dissipative solitons. Because the discrete nature of such schemes arrests nonlinear wave collapse and modifies essentially the modulation instability, it is much easier to form different 1D-, 2D-, and 3D-stable localized structures. There are many examples of such schemes, and in this paper we compare features of localized states for the two extreme dissipative systems. The first scheme is the coherently and resonantly driven chain of molecules; up to now, the dissipative solitons were considered only in 1D-molecular schemes [1, 3]. The second scheme is a driven array or lattice of nonlinear split-ring resonators [4-12].

2. Spatial bistability, discrete switching waves and solitons in 1D-schemes

In the first – molecular – scheme, the energy input is provided by coherent holding radiation. Individual molecules driven resonantly by the holding beam emit radiation similar to dipoles, and other molecules experience this radiation. Due to the finite size of the chain, there is no "classical" bistability of homogeneous distributions. However, spatial bistability is possible with two smooth distributions of molecular levels' population formed under different initial conditions (Fig. 1, *left*). Therefore switching waves, or kinks, can be formed representing spatial coexistence of two states of bistable system separated by a front that is motionless or moving depending on the holding radiation intensity (Fig. 1, *right*). Fig. 1 was obtained by numerical solution of quantum equations for density matrices of molecules interacting with holding radiation and with secondary radiation emitted by other molecules. Similar structures were obtained for the 1D-array of split-ring resonators with additional peculiarity of hysteresis of switching waves' velocity in dependence of holding radiation intensity [10].

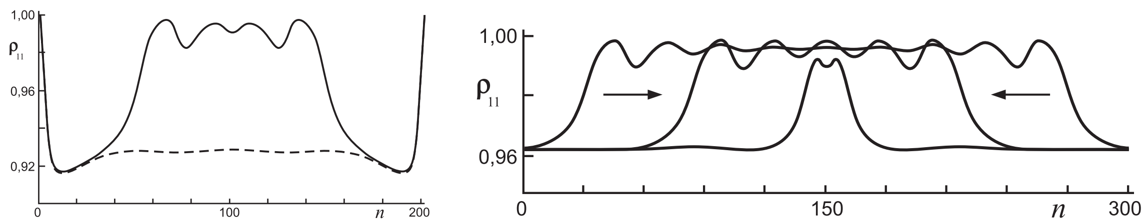

Fig. 1: *Left*: Spatial bistability in a one-dimensional scheme of driven molecular J-aggregate. Solid curve: steady-state population of the molecular ground state for its initial value $\rho_{11} = 0.99$. Dashed curve: the same for the initial population $\rho_{11} = 0.90$; *n* is molecula's number in a chain of 200 molecules. *Right*: Formation of dissipative solitons as a result of collision of two moving switching waves; the widest distribution corresponds to initial state, the narrowest distribution is the stable steady-state discrete soliton.

3. 2D-schemes

For 2D-schemes more convenient is the scheme of lattice of split-ring resonators. Important is anisotropy of coupling of individual resonators connected with their relative orientation. For certain orientation only fairly narrow distributions are stable (Fig. 2), otherwise they are decomposed typically in a series of narrow solitons due to modulational instability.

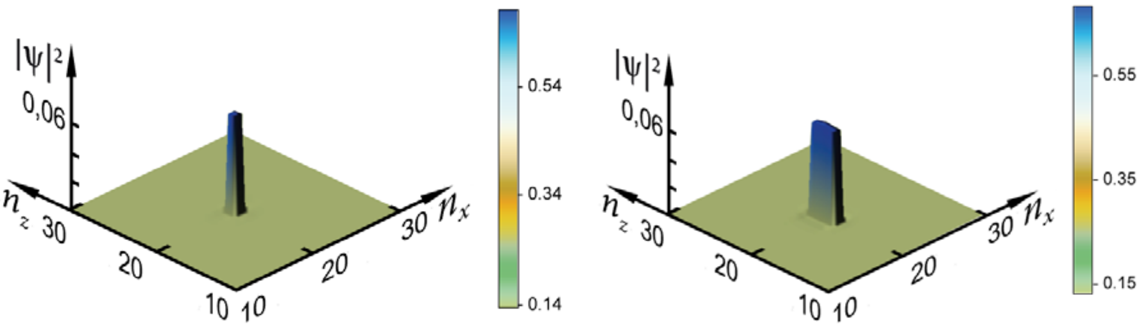

Fig. 2: Two examples of a nonlinear localized mode in a two-dimensional lattice of split-ring resonators, scales for the magnetization $|\psi|^2$ are given on right to figures, position of resonators is given by integer indices n_x and n_z.

3. 3D-schemes

The richest variety of localized structures can be found in 3D-schemes that can be implemented as a driven 3D-lattice of split-ring resonators. In Fig. 3 examples are given of knotted discrete dissipative solitons in such the scheme. Here resonators are excited to the upper state of bistable response along knots – closed lines without intersections.

ISBN 978-952-67611-2-1

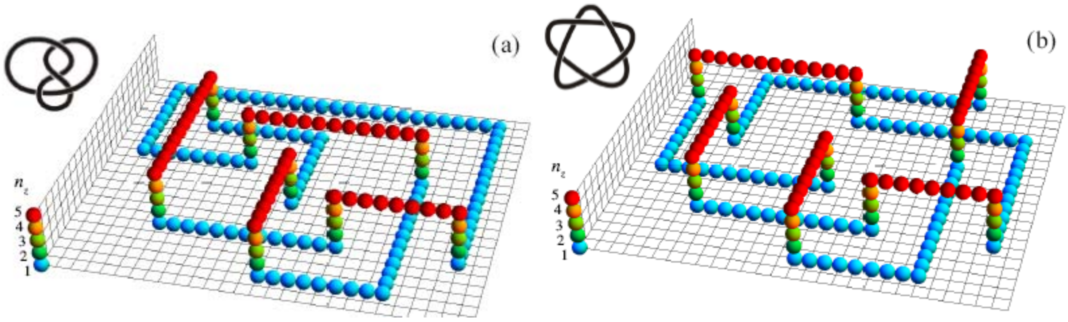

Fig. 3. Discrete knotted solitons with 4 and 5 crossing: (a) figure-eight and (b) cinquefoil knots formed by split-ring resonators excited to the upper branch in a driven lattice.

4. Conclusions

We have demonstrated various stable localized states various stable discrete localized states in molecular nanostructures and in magnetic metamaterials. Though molecular solitons are much narrower and can be supported by optical radiation, 2D- and 3D-structures are easier to form in magnetic metamaterials with microwave holding radiation.

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ISBN 978-952-67611-2-1