CHALLENGE FOR HIGHER DIMENSIONAL PHOTONIC CRYSTALS

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ABSTRACT

I believe I shall best introduce the phenomenon by describing the circumstances of my own first acquaintance with it. I was observing the motion of a boat which was rapidly drawn along a channel by a pair of horses, when the boat suddenly stopped - not so the mass of water in the channel which it had put in motion; it accumulated round the prow of the vessel in a state of violent agitation, then suddenly leaving it behind, rolled forward with great velocity, assuming the form of a large solitary wave elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed on horseback, and overtook it still rolling on at a rate of some eight to nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height. Its height gradually diminished, and after a chase of one or two miles I lost it in the windings of the channel.

INTRODUCTION

The major challenge for higher dimensional photonic crystals is in fabrication of these structures, with sufficient precision to prevent scattering losses blurring the crystal properties and with processes that can be robustly mass produced. One promising method of fabrication for two-dimensionally periodic photonic crystals is a photonic-crystal fiber, such as a "holey fiber". Using fiber draw techniques developed for communications fiber it meets these two requirements, and photonic crystal fibers are commercially available. Another promising method for developing two-dimensional photonic crystals is the so-called photonic crystal slab. These structures consist of a slab of material (such as silicon) which can be patterned using techniques borrowed from the semiconductor industry. Such chips offer the potential to combine photonic processing with electronic processing on a single chip.

For three dimensional photonic crystals various technique shave been used including photolithography and etching techniques similar to those used for integrated circuits. Some of these techniques are already commercially available. To circumvent nanotechnological methods with their complex machinery, alternate approaches have been followed to grow photonic crystals as self-assembled structures from colloidal crystals.

Mass-scale 3D photonic crystal films and fibers can now be produced using a shear-assembly technique which stacks 200-300 nm colloidal polymer spheres into perfect films of fcc lattice.

Because the particles have a softer transparent rubber coating the films can be stretched and molded, tuning the photonic bandages and producing striking structural color effects.

TYPES OF SOLITONS:

In optics, the term soliton is used to refer to any optical field that does not change during propagation because of a delicate balance between nonlinear and linear effects in the medium. There are two main kinds of solitons:

- spatial solitons: the nonlinear effect can balance the diffraction. The electromagnetic field can change the refractive index of the medium while propagating, thus creating a structure similar to a graded-index fiber. If the field is also a propagating mode of the guide it has created, then it will remain confined and it will propagate without changing its shape
- temporal solitons: if the electromagnetic field is already spatially confined, it is possible to send pulses that will not change their shape because the nonlinear effects will balance the dispersion. Those solitons were discovered first and they are often simply referred as "solitons" in optics.

SPATIAL SOLITONS:

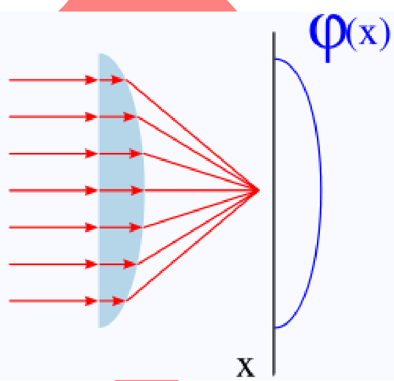

Fig. 1 "How a lens works"

In order to understand how a spatial soliton can exist, we have to make some considerations about a simple convex lens. As shown in the fig. 2.1, an optical field approaches the lens and then it is focused. The effect of the lens is to introduce a non-uniform phase change that causes focusing. This phase change is a function of the space and can be represented with a $\varphi(x)$, whose shape is approximately represented in the figure.

- The phase change can be expressed as the product of the phase constant and the width of the path the field has covered. We can write it as:

$$\varphi(x) = k_0 n L(x)$$

where $L(x)$ is the width of the lens, changing in each point with a shape that is the same of $\varphi(x)$ because k_0 and n are constants. In other words, in order to get a focusing effect we just have to introduce a phase change of such a shape, but we are not obliged to change the width. If we leave the width L fixed in each point, but we change the value of the refractive index $n(x)$ we will get exactly the same effect, but with a completely different approach.

That's the way graded-index fibers work: the change in the refractive index introduces a focusing effect that can balance the natural diffraction of the field. If the two effects balance each other perfectly, then we have a confined field propagating within the fiber.

Spatial solitons are based on the same principle: the Kerr effect introduces a Self-phase modulation that changes the refractive index according to the intensity:

$$\varphi(x) = k_0 n(x) L = k_0 L[n + n_2 I(x)]$$

If $I(x)$ has a shape similar to the one shown in the figure, then we have created the phase behavior we wanted and the field will show a self-focusing effect. In other words, the field creates a fiber-like guiding structure while propagating. If the field creates a fiber and it is the mode of such a fiber at the same time, it means that the focusing nonlinear and diffractive linear effects are perfectly balanced and the field will propagate forever without changing its shape (as long as the medium does not change and if we can neglect losses, obviously). In order to have a self-focusing effect, we must have a positive n_2, otherwise we will get the opposite effect and we will not notice any nonlinear behavior.

RESULT AND DISCUSSION

Recently, a variety of two- and three-dimensional (2D and 3D) solitons have been investigated in models based on the nonlinear Schrödinger (NLS) or Gross-Pitaevskii (GP) equations with a spatially periodic potential and cubic nonlinearity, see a review. The physical models of this type emerge in the context of Bose-Einstein condensation (BEC) [2, 3, 4, 5, 6, 7], where the periodic potential is created as an optical lattice (OL), i.e., interference pattern formed by coherent beams illuminating the condensate, and in nonlinear optics, where similar models apply to photonic crystals. A different but allied setting is provided by a cylindrical OL ("Bessel lattice"), which can also support stable 2D and 3D solitons. Additionally, models combining a periodic lattice potential and saturable nonlinearity give rise to 2D solitons, that were predicted in Ref. [11] and observed in several experiments. in photorefractive media, including fundamental solitons and vortices [13]. It is also relevant to mention that experimental observation of spatiotemporal self-focusing of light in silica waveguide arrays, in the region of anomalous group-velocity dispersion (GVD), was reported in Ref..

In models with the cubic nonlinearity, these solutions were investigated in a quasi-analytical form, which combines the variational approximation (VA) to predict the shape of the solitons, and the Vakhitov-Kolokolov (VK) criterion to examine their stability. Final results were provided by numerical methods, relying upon direct simulations of the underlying NLS/GP equations. A conclusion obtained by means of these methods is that, unlike their 1D counterparts, multi-dimensional solitons in periodic potentials can exist only in a limited domain of the (N, ε) plane, where N and ε are the norm of the solution and strength of the OL potential, respectively. The most essential limitation on the existence domain of 2D solitons is that N cannot be too small (in a general form, a minimum value of the norm, as a necessary condition for the existence of 2D solitons supported by lattice potentials, was discussed in Ref.. Unlike it, e may be arbitrarily small, as even at ε = 0 the 2D NLS equation has a commonly known weakly unstable solution in the form of the Townes soliton, at a single value of the norm, $N = N_T$ [18] ($N_T \approx 11.7$ for the NLS equation in the usual 2D form,

$$iu_t + \nabla^2 u + |u|^2 u = 0.$$

Small finite ε gives rise to a narrow stability region,

$$0 < N_T - N < (\Delta N)_{max} \sim \varepsilon \qquad (1)$$

for the 2D solitons. Crossing the lower border of the existence domain (1) leads to disintegration of the localized state into linear Bloch waves (radiation).

In the case of the attractive cubic nonlinearity (which corresponds to BEC where atomic collisions are characterized by a negative scattering length, while this is the case of the normal, self-focusing Kerr effect), 2D and 3D solitons can be stabilized not only by the potential lattice whose dimension is equal to that of the ambient space, but also by low-dimensional periodic potentials, whose dimension is smaller by one, i.e., 2D and 3D solitons can be stabilized by a quasi-1D or quasi-2D OL, respectively [in the former case, the qualitative estimate (1) for the width of the stability region at small e is correct too]; however, 3D solitons cannot be stabilized by a quasi-1D lattice potential [this is possible if the 1D potential is applied in combination with the Feshbach-resonance management, i.e., periodic reversal of the sign of the nonlinearity coefficient, or in combination with dispersion management, i.e., periodically alternating sign of the local GVD coefficient. Solitons can exist in such settings because the attractive nonlinearity provides for stable self-localization of the wave function in the free direction (one in which the 2 low-dimensional potential does not act), essentially the same way as in the 1D NLS equation, and, simultaneously, the lattice stabilizes the soliton in the other directions (in the 3D model with the quasi-1D OL potential, the self-localization in the transverse 2D subspace, where the potential does not act, is possible too, but the resulting soliton is unstable, the same way as the above-mentioned Townes soliton). An important aspect of settings based on the low-dimensional

OL potentials is mobility of the solitons along the free direction, which opens the way to study collisions between solitons and related dynamical effects.

In the case of defocusing nonlinearity, which corresponds to a positive scattering length in the BEC, or self-defocusing nonlinearity in optics (negative Kerr effect), the soliton cannot support itself in the free direction. Localization in that direction may be provided by an additional external confining potential; however, the resulting pulse is not a true multidimensional soliton, but rather a combination of a gap soliton (a weakly localized state created by the interplay of the repulsive nonlinearity and periodic potential,which was recently created experimentally in a 1D BEC in the direction(s) affected by the OL, and of a Thomas-Fermi state, directly confined by the external potential in the remaining direction.

Thus, no soliton can be supported by a low-dimensional lattice in the BEC model (GP equation) with self-repulsion (the latter corresponds to the most common situation in the experiment. On the other hand, a new possibility may be considered in terms of nonlinear optics. Indeed, one may combine three physically relevant ingredients, viz., (i) an effective periodic potential in the transverse direction(s), while the medium is uniform in the propagation direction, (ii) Self-defocusing nonlinearity, and (iii) normal GVD. The latter is readily available, as most optical materials feature normal GVD, in compliance with its name. As concerns the negative cubic nonlinearity, it is possible in semiconductor waveguides, or may be engineered artificially, through the cascading mechanism, in a quadratic ally nonlinear medium with a proper longitudinal quasi-phase-matching. Also quite encouraging for the study of multidimensional solitons proposed in this work are recent observations of 1D and 2D solitons in optically induced waveguide arrays (photonic lattices) with self-defocusing nonlinearity. The setting outlined above can be realized in both 2D and 3D geometry, where the necessary transverse modulation of the refractive index is provided, respectively, by the transverse structure in a planar photonic-crystal waveguide, or in a photonic-crystal fiber. To the best of our knowledge, in either case the model is a novel one. A soliton in this medium, if it exists, will be of a mixed type: in the transverse direction(s), it is, essentially, a 1D or 2D spatial gap soliton, supported by the combination of the effective periodic potential and self-defocusing nonlinearity, while in the longitudinal direction it is a temporal soliton of the ordinary type, which is easily sustained by the joint action of the self-defocusing nonlinearity and normal GVD. Thus, one may anticipate stable spatiotemporal solitons, alias “light bullets”, in this model. Due to their mixed character, they may be called semi-gap solitons. The issue is of considerable interest in view of the lack of success in experiments aimed at the creation of “bullets” in more traditional nonlinear-optical settings. The only earlier proposed scheme for the stabilization of 2D spatiotemporal optical solitons in periodic structures, that we are aware of, assumed the use of a planar waveguide with constant self-focusing nonlinearity and longitudinal dispersion management.

On the other hand, it is necessary to stress that, rigorously speaking, completely localized solutions cannot exist in the present model: its linear spectrum cannot give rise to any true bandgap, in which genuine solitons could be found (see below); instead, one may expect the existence of quasi-solitons, consisting of a well-localized “body” and small non-vanishing “tails” attached to it. Nevertheless, we will produce families of solutions which seem as stable perfectly localized objects. This is possible because the “tails” may readily turn out to be so tiny that they remain completely invisible in numerical results (possibly being smaller than the error of the numerical scheme), and, of course, they will be invisible in any real experiment. An explanation to this feature is provided by the fact that bandgaps, which “almost exist” in the system‟s spectrum, do not exist in the strict sense because they are covered by linear modes with very large wave numbers. , in this case the amplitude of the above-mentioned tails (which are composed of the linear modes with very large wave numbers) is exponentially small. In fact, families of stable “practically existing” solitons in a second-harmonic-generating system with opposite signs of the GVD at the fundamental-frequency and second harmonics, where solitons cannot exist in the rigorous mathematical sense, were explicitly found in that system, in both multi-and one- dimensional settings. Implicitly (without discussion of this issue), “practically existing” solitons (although, in this case, they were unstable against small perturbations) were also found in a recent work , which was dealing with a 2D model of a planar nonlinear waveguide with the cubic nonlinearity, that features a Bragg grating in the longitudinal direction, and is uniform along the transverse coordinate. In the latter model, true solitons cannot exist, as the spectrum of the system does not support a full bandgap.

CONCLUSION

In this work, we have proposed a new type of the multidimensional model in nonlinear optics. It combines self-defocusing nonlinearity and normal group-velocity dispersion with periodic modulation of the local refractive index in the one or two transverse directions (in the 2D and 3D models, respectively). Strictly speaking, multidimensional (spatiotemporal) solitons cannot exist in media of this type, as the system‟s spectrum contains no true bandgap. Nevertheless, solitons which seem as completely localized ones are predicted by the variational approximation, and found in direct simulations. These solitons are solutions of a mixed type, as in the free (longitudinal, alias temporal) direction they are regular solitons, while in the transverse direction(s) they are objects of the gap-soliton type (hence the solution as a whole was called a semi-gap soliton).

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