Sección Especial: Óptica No Lineal / Special Section: Non-linear Optics

Modeling nonlinear waves in photonics, plasmonics and cold atoms

Modelado de ondas no lineales en fotónica, plasmónica y átomos fríos

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ABSTRACT:

We review the present status of the different lines of research in the area of Photonics at the Interdisciplinary Modeling Group, InterTech (www.intertech.upv.es) paying special attention to new topics that we have recently incorporated to our research interests: temporal solitons and design of supercontinuum generation, plasmon-soliton interaction, nonlinear effects of the quantum electrodynamics vacuum, and, finally, cold atoms in the mean-field and quantum regimes.

Keywords: Nonlinear Optics, Plasmonics, Cold Atoms.

RESUMEN:

En este artículo presentamos el estado actual de las diferentes líneas de investigación desarrolladas en el área de Fotónica del Grupo de Modelización Interdisciplinar, InterTech (www.intertech.upv.es) prestando especial atención a aquellas que han sido incorporadas recientemente: solitones temporales y diseño de la generación de supercontínuo, interacción plasmón-solitón, efectos no lineales del vacío en electrodinámica cuántica y, finalmente, átomos fríos en el régimen de campo medio y en el régimen cuántico

Palabras clave: Óptica No Lineal, Plasmónica, Átomos Fríos.

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1. Introduction

Nonlinear waves are fundamental objects in media characterized by a nonlinear response. Their modeling and understanding is a fascinating object of study shared by different disciplines. This broad spectrum of topics in which nonlinear waves play a key role makes this subject especially suitable for the characteristic InterTech interdisciplinary approach based on advanced mathematical / physical modeling, demanding computational methods, and the development of new technological applications. We will present here the main lines of research developed in the area of photonics at InterTech during the last years and the present time which include contributions in the following topics: spatial solitons in discrete media, singular optics, temporal solitons and supercontinuum generation, non-paraxial nonlinear optics in photonic crystals, nonlinear liquid crystals, nonlinear plasmonics, cold atoms in the mean-field and quantum regimes and nonlinear effects of the QED vacuum.

2. Spatial solitons in discrete-symmetry media

Spatial solitons are nonlinear light structures that are able to propagate without diffraction due to an exact compensation between diffraction and nonlinear effects. They are mathematically described by Nonlinear Schrödinger Equations (NLSE) or alike [1]. The propagation of spatial solitons in discrete-symmetry media such as periodic dielectric structures provides them with special properties absent in ordinary propagation in homogenous media. The richness and complexity of nonlinear solutions in discrete-symmetry media is highly remarkable. Our group has worked intensively in this topic in the last years. Our main contribution has been to introduce a powerful theoretical tool to classify this panoply of nonlinear solutions in a systematic manner. This mathematical tool is the generalization of discrete group theory to nonlinear equations of the type given by NLSE [2]. In particular, our group showed the possibility of generating spatial solitons solutions (of the fundamental, vortex and dipole type) in photonic crystal fibers [3-5] and nontrivial phenomena involving nonlinear photonic crystals as that of vortex transmutation [6].

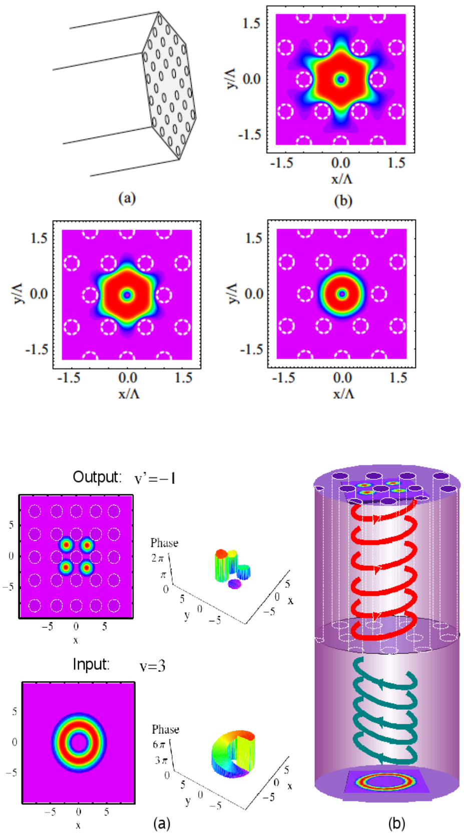

Fig. 1. Vortex soliton solutions for different powers in a photonic crystal fiber (up) as in Ref. [5] and a characteristic example of vortex transmutation (down) as in Ref. [6].

3. Nonlinear singular optics

The mathematical tools developed for the study of solutions of NLS-like equations were especially well suited for the study of phase singularities. In general, complex scalar solutions of wave equations can present dislocations similar to those found in crystals. The essential mathematical property of these complex scalar functions in the point or line where a dislocation is localized is that its phase is increased or decreased in a multiple of 2π along a closed curve around it. In these points or lines, also known as phase singularities or, in a wide sense, as vortices, the amplitude of the function vanishes and its phase is undetermined. In the case of nonlinear optics, the study of such singularities or vortices is often enclosed in a separated branch called nonlinear singular optics [7]. An important category of optical vortices is that of discrete vortices (DV), or vortices in discrete-symmetry media. We have developed a series of powerful theorems and rules to predict the behaviour of phase singularities propagating in optical media owning discrete rotational symmetry. This includes a vorticity cut-off theorem [8], the demonstration of DV as angular Bloch modes [9], the essential relation between symmetry, winding number and topological charge of DV [10] and the existence of selection rules for the topological charge of DV in interfaces breaking rotational symmetry [11].

4. Nonlinear temporal optics and design of supercontinuum spectra

The behavior of optical pulses in optical fibers and optical fiber devices in the nonlinear regime is also given by an effective NLSE in the time domain for the pulse envelope [12]. Generalized versions of NLSEs are used to include higher order nonlinear effects. Among them, supercontinuum generation, the spectacular enhancement of the spectral width of a pulse in a PCF, is likely the most relevant phenomenon in nonlinear fiber optics in the last years [13]. Supercontinuum generation is a complex phenomenon that strongly depends on the dispersion features of the fiber and the characteristic of the input pulse. This generates

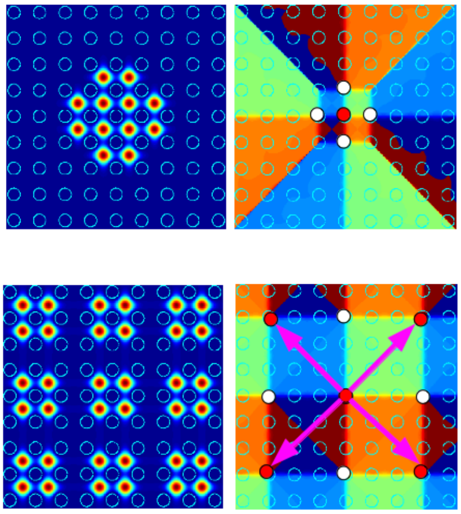

Fig. 2. Examples of the amplitude (left column) and phase (right column) of DV solitons with same rotational behavior under $\pi/2$ discrete rotations: they both have identical angular pseudo-momentum m=-1 (see [9]), but different total topological charge: ν=-3 in the upper case and ν=-1 in the lower case. White circles in phase figures indicate phase singularities with topological charge +1 whereas red circles correspond to charge -1. Classification and behavior of these solutions are given in Ref. [10].

an enormous variety of available output spectra by suitable tuning of these parameters. However, the computational cost to explore all the parameter space is unaffordable. Thus, in order to design useful PCF-based devices yielding spectra for useful applications, a combination of optimization techniques and large computational resources is needed. In this context, we have developed a new computational scheme to design supercontinuum spectra "à la carte" by means of genetic algorithms [14]. Due to the potentially large amount of computations required by this strategy, the deployment of these heuristic algorithms is performed using distributed computing in the form of a Grid platform. The optimization procedure is automated within the Grid platform and permits escalation to large computational Grids. Some examples of designed supercontinua are given in Fig. 3. Potential applications for the design of future photonic devices include the fabrication of light sources for specific targets in nonlinear microscopy and biomedicine.

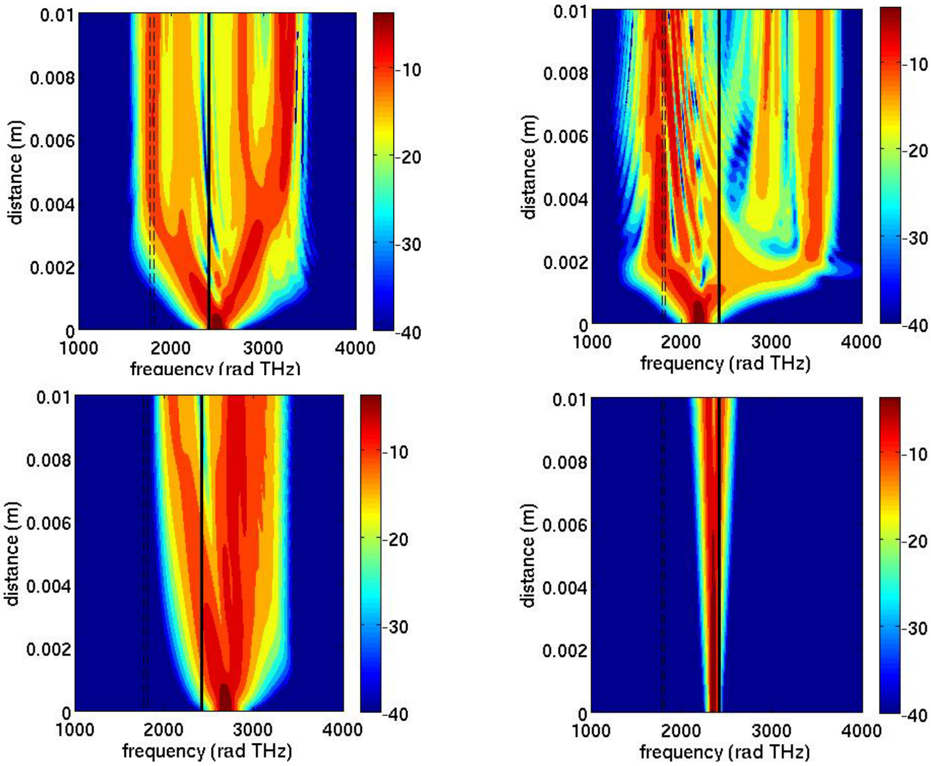

Fig. 3. Spectral evolution examples that belong to the parameter space. Full vertical lines mark the zero GVD and dashed show the targeted spectrum in the anomalous GVD regime. Figs. (a) and (b) correspond to far non optimized results, whereas Figs. (c) and (d) show two optimized cases.

5. Nonlinear liquid crystals

Nematic Liquid Crystal (NLC) devices are being widely studied in the field of Nonlinear Optics due to its large nonlinear response [15]. It allows to generate nonlinear solutions with no change of shape, the so called nematicons at very low optical powers. Its interest range from all optical communication devices to computation. Besides, the nonlocality exhibited by NLC cells has been shown as an efficient mechanism for stabilizing optical complex structures which cannot exist in local nonlinear homogeneous media. The aim of this line of research is presenting a complete realistic model for NLC devices that permits realistic simulations of nonlinear propagation of light in these structures. This model provides new effects absent in ordinary simplified nonlinear nonlocal models.

6. Nonlinear plasmonics

Plasmonics is an important and quickly developing area of modern physics which offers promising applications in nano-optics and electronics. It deals with the so-called surface-plasmon polaritons (SPP), i.e., collective oscillations of the electromagnetic field and electrons which propagate along a metal-dielectric surface and decay exponentially away from the surface [16]. SPPs are characterized by their frequency and their propagation constant along the interface. SPPs can only interact resonantly with evanescent electromagnetic waves in the dielectric medium. Accordingly, there are two main methods for excitations of plasmons: (i) via the evanescent wave generated at the total internal reflection and (ii) via a periodic structure producing evanescent modes. In this context, we have shown the possibility of resonant interaction between a SPP at a metal surface and a parallel self-focusing beam, in the form of a spatial soliton, in a nonlinear dielectric [17]. A simple two-level model reveals hybridized plasmon-soliton eigenmodes, we refer to as soliplasmon excitations, and their complex nonlinear dynamics which offers plasmon excitation and control using spatial solitons.

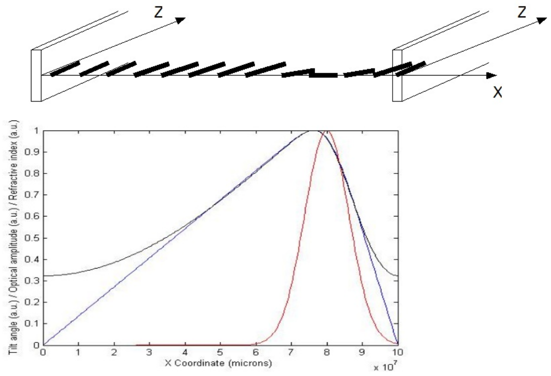

Fig. 4. Calculated angle of rotation of the NLC molecules versus horizontal position for a typical configuration at an arbitrary z axial position (blue line and descriptive figure above), effective refractive induced in light by this molecular distribution (black line) and light field distribution at the same axial slice (red line).

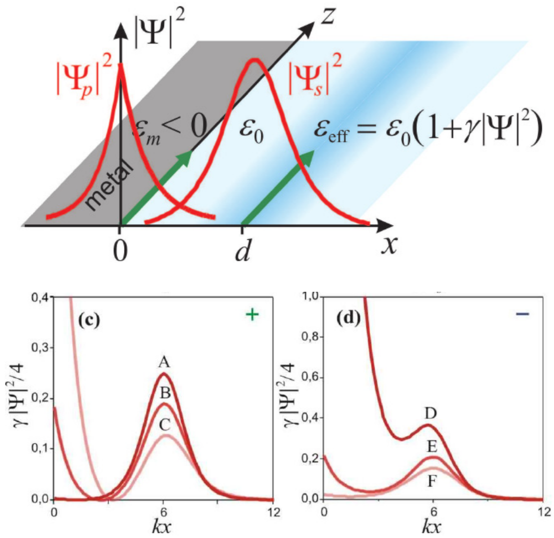

Fig. 5. Characteristic metal/dielectric/Kerr structure supporting soliplasmon excitations (up). Two examples of “antisymmetric” and “symmetric” soliplasmon excitations as appearing in Ref. [17].

7. Cold atoms in the mean-field and quantum regimes

Ultracold matter can be represented by a coherent state, constituted by many atoms, called a Bose-Einstein condensate (BEC). This quantum state can be, in turn, represented by a mean-field wave function that fulfills the so-called Gross-Pitaevskii equation (GPE). The GPE is a temporal equation that describes the dynamics of the BEC wave function and is formally identical to the NLSE in different dimensions. In the particular case of BEC in 2D traps the GPE is identical to NLSE describing the

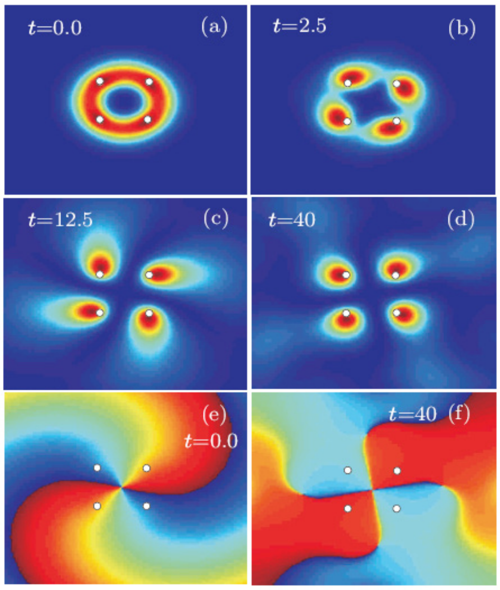

Fig. 6. Different snapshots of the evolution of a charge 2 matter wave vortex under the action of a symmetry breaking potential of order 4. This behavior is consistent with the discrete group theory rules developed in Ref [18].

propagation of light in 2D optical media. For this reason, all our results based on discrete group theory previously applied in optical systems can be translated to the ultracold matter formalism in a straightforward manner. In this way, the symmetry rules governing the behavior of optical vortices under the presence of discrete-symmetry media also hold for matter vortices when the full continuous rotational symmetry of the potential is broken by the presence of an instantaneous discrete-symmetry potential [18]. Further studies initiated in our group indicates that our symmetry rules are also preserved in the quantum limit, i.e., that in which the number of atoms is so small that the usual GPE approach start to fail because of quantum fluctuations in the atom number. Modeling in this case is performed using the full quantum Bose-Hubbard model for atom traps in the form of a ring showing discrete rotational symmetry.

8. Nonlinear effects of the QED vacuum

This line of research is developed together with Daniele Tommasini and Humberto Michinel from the Optics Laboratory of the Universidad de Vigo at Ourense [19]. This line is devoted to light nonlinearities induced by the QED vacuum, that is, in the absence of any form of matter. Surprisingly, in terms of classical Nonlinear Optics, vacuum excitations, in the form of the quantum generation of virtual electron-positron pairs, can induce effective nonlinearities. However, despite it is a well-known result since long time ago, photon-photon scattering in vacuum has not yet been detected using standard high-energy experiments where the probability of this effect to occur, given by the photon-photon cross section, is maximized. An alternative approach is to perform experiments using ultrahigh power optical lasers, such as

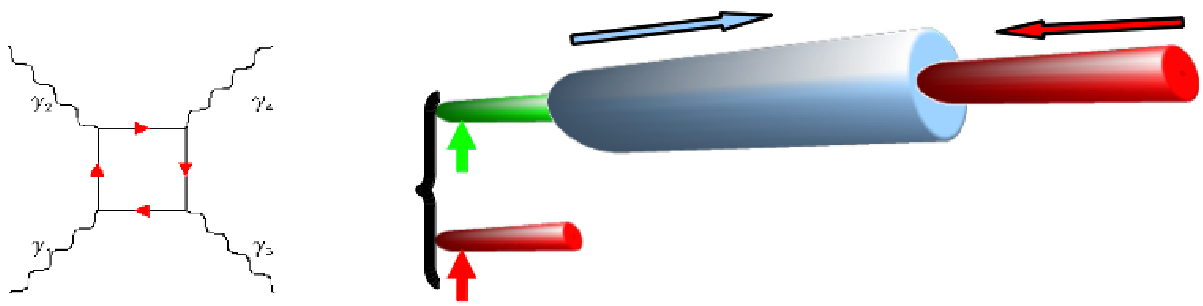

Fig. 7. Characteristic box diagram of photon-photon scattering in vacuum generating effective nonlinearity (left). Schematic representation (right) of a proposed experiment with a high-intensity laser (green) interacting with a low-intensity one (red beam above): nonlinearities induced by the high-intensity laser generate a nonlinear shift in the low-intensity laser that can be measured by interferometric methods using a non-shifted reference low-intensity beam (red beam below).

those that will be available in the near future, in such a way that the high density of photons will compensate the smallness of the cross section. In this case, the small energies characteristic of optical photons (a few eVs) and the effect of photon-photon collisions due to the interchange of virtual electron-positron pairs can be expressed in terms of the effective Euler-Heisenberg nonlinear Lagrangian. This modifies Maxwell's equations transforming them into a Lorentz covariant set of nonlinear equations. Our mixed group has proposed optical experiments based on ultrahigh intensity lasers in which this small effective nonlinearities can be unveiled thus showing for the first time the presence of photon-photon scattering in vacuum [20-22].

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