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Sección Especial en Óptica Cuántica / Special Section on Quantum Optics

Research on nonlinear and quantum optics at the Photonics and Quantum Information Group of the University of Valladolid

Investigación en óptica cuántica y óptica no lineal en el Grupo de Fotónica e Información Cuántica de la Universidad de Valladolid

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ABSTRACT:

We outline the main research lines in nonlinear and quantum optics of the Group of Photonics and Quantum Information at the University of Valladolid. These works focus on optical solitons, quantum information using photonic technologies and the development of new materials for nonlinear optics. The investigations on optical solitons cover both temporal solitons in dispersion managed fiber links and nonparaxial spatial solitons as described by the Nonlinear Helmholtz Equation. Within the Quantum Information research lines of the group, the studies address new photonic schemes for quantum computation and the multiplexing of quantum data. The investigations of the group are, to a large extent, based on intensive and parallel computations. Some associated numerical techniques for the development of the activities described are briefly sketched.

Key words: Optical Solitons, Nonlinear Helmholtz Equation, Dispersion Management, Quantum Information Multiplexing, Quantum Computation, Nonlinear Optical Materials.

RESUMEN:

En este artículo, se describen las líneas de investigación relacionadas con la óptica cuántica y la óptica no lineal en el Grupo de Fotónica e Información Cuántica de la Universidad de Valladolid. Los trabajos reseñados abordan el estudio de solitones ópticos, información cuántica basada en tecnologías fotónicas y el desarrollo de nuevos materiales para aplicaciones en óptica no lineal. Las investigaciones en solitones ópticos abarcan tanto los solitones temporales en sistemas de transmisión por fibra empleando técnicas de gestión de la dispersión como los solitones espaciales no paraxiales obtenidos como soluciones de la ecuación no lineal de Helmholtz. Dentro del campo de la información cuántica, los trabajos realizados se centran tanto en el estudio de nuevos esquemas de computación cuántica como en la multiplexación de datos cuánticos. Para el desarrollo de esta labor de investigación, es esencial el empleo de cálculo masivo y paralelo. Se describen brevemente nuevas técnicas computacionales y su uso en las investigaciones detalladas en este artículo.

Palabras clave: Solitones Ópticos, Ecuación No Lineal de Helmholtz, Gestión de la Dispersión, Multiplexación de Información Cuántica, Computación Cuántica, Materiales No Lineales.

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1. Introduction

In this article, we present an overview of the recent research of the Photonics and Quantum Information Group at the Universidad of Valladolid within the fields of quantum and nonlinear optics. These works represent a large percentage of the total scientific activity of the group which is often conducted in close collaboration with other groups of the University of Valladolid, other universities in Spain and also in collaborations of international character.

The main research lines described here are related either to the field of optical solitons or quantum information and computation. In Section 2 we address one of the most mature research lines of the group: that on spatial solitons as solutions of the nonlinear Helmholtz (NLH) equation. The activities in the field of temporal optical solitons in dispersion managed optical fiber links are summarised in Section 3. Research on quantum information based on photonic schemes has focused on the multiplexing and routing of quantum data and an overview is presented in Section 4. As regards quantum computation, several schemes for optical gates have been proposed and are reviewed in Section 5. Back to nonlinear optics and optical solitons, we have recently started a research line for the development of new materials with high nonlinear optical response. This is briefly reported in Section 6. Transversally to most of the research activities we find a strong computational background. Some specific works in the field of computational photonics are described in Section 7.

2. Helmholtz solitons

The analyses of the propagation properties of spatial optical solitons, their interactions, their behavior at discontinuities and their applications in photonic devices are most often based on the nonlinear Schrödinger (NLS) equation [1] which limits the validity of the studies to paraxial arrangements of the optical field. Notwithstanding, most configurations which are of practical interest for devices based on the behaviour of optical solitons do not fall within the range of validity of this framework and display a strong intrinsic nonparaxiality of angular character. An analysis scheme of broad generality must provide full directional freedom.

Aiming to relieve this paraxial restriction and to the achievement of a more general foundation for the study of the propagation of soliton beams, our group at the University of Valladolid has been working for more than a decade on a nonparaxial theory based on the NLH equation. This work has been conducted in close collaboration with other groups, first, at Imperial College London and, later, at Salford University.

Our Helmholtz approach is clearly distinct from other proposals, where the nonparaxiality results from a strong self-focusing of high-intensity optical beams, in the sense that its key feature is the rotational invariance of the NLH equation and its solutions. Thus, by limiting the analyses to relatively broad beams (on the scale of the optical wavelength), we ensure the firm validity of our scalar model against other perturbations of higher order in the optical intensity, such as vector effects [2].

The results obtained have permitted us to identify the properties of the solutions of the NLH equation (transformation and propagation invariants) [3-5], the exact soliton solutions of Kerr Helmholtz solitons in the bright [3,4] and dark [6] cases, and their propagation properties [7] as well as vector soliton solutions of the nonlinear Helmholtz-Manakov equation [5] and a full range of soliton solutions in non-Kerr media [8-13]. The Helmholtz nonparaxial framework has been used to address the interaction behaviour of Kerr solitons at arbitrary angles [14] and the refraction and reflection properties of bright solitons at nonlinear interfaces under the most general angular conditions [15,16]. For the first time, dark solitons at nonlinear interfaces (a problem with a high intrinsic nonparaxiality) have been investigated [17,18] and these studies have resulted in the discovery of new types of refraction properties. A general theoretical corpus for the refraction of bright and dark solitons has been derived with the key result of a nonlinear Snell's law. Figures 1 and 2 illustrate one of the new phenomena reported: the transition of the refraction of a grey soliton at a nonlinear interface from external to internal when the greyness parameter *F* is changed [17].

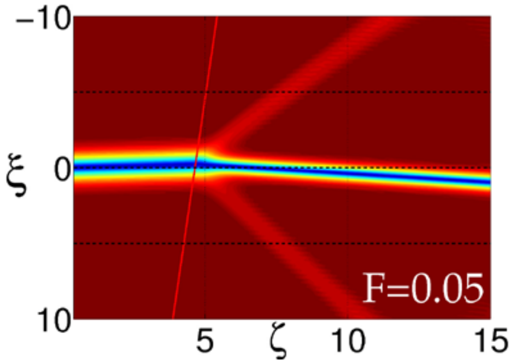

Fig. 1. External refraction of a grey soliton at a nonlinear interface. All parameters, except *F*, are identical to those of Fig. 2.

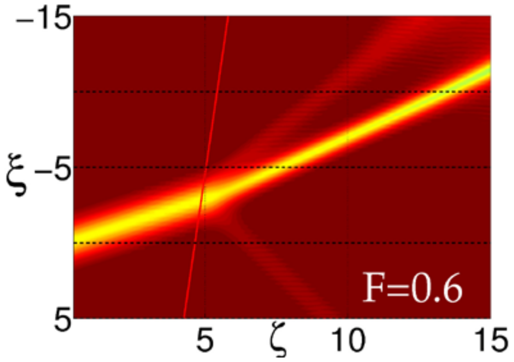

Fig. 2. Internal refraction of a grey soliton at a nonlinear interface.

3. Dispersion managed solitons

A dispersion managed (DM) optical link can be described as a periodic sequence of fiber segments with alternating group velocity dispersion. A linear pulse propagating in such a system sees a local dispersion of large magnitude continuously changing from normal to anomalous and vice versa which produces a quasiperiodic pulse spreading and compression (breathing). On a slower scale, the pulse broadens on average as a result of the residual dispersion which is of much smaller magnitude than the local dispersion and normally of the anomalous type. When fiber nonlinearity comes into play, for a specific value of pulse energy, it can compensate the slow pulse broadening and result in a robust periodic evolution with the periodicity of the dispersion map. This nonlinear pulse is called a DM soliton. The DM soliton has larger energy [19] than its conventional NLS counterpart for the same average dispersion and, thus, a better signal to noise ratio (SNR) and is more robust against amplifier-noise Gordon-Haus timing jitter [20]. Furthermore, the large magnitude of the local dispersion results in a lessening of four wave mixing effects.

DM techniques have permitted optical solitons to become a practical reality in recent years [21]. Nevertheless, several transmission impairments can be even more severe for DM solitons than they are for conventional NLS solitons. Such is the case for the intrachannel interactions under strong dispersion management conditions. Also, as transmission bit rates shift to larger values in the SDH/SONET hierarchy, third order dispersion (TOD) becomes of increasing importance. We have addressed the interaction properties of two co-propagating pulses in two adjacent wavelength division multiplexed (WDM) channels [22,23] or in adjacent positions in the same channel [24]. For this latter case the interaction behaviour of multipulse DM soliton chains have been studied [25]. Our analyses are based on a variational ODE model [26] which includes the effects of TOD and transmission gain and loss. This model permits to address the pulse dynamics in a simplified manner, but still very accurately, which is essential in the numerical studies of large sets of parameter values. Figure 3 shows a comparison of the variational model results and

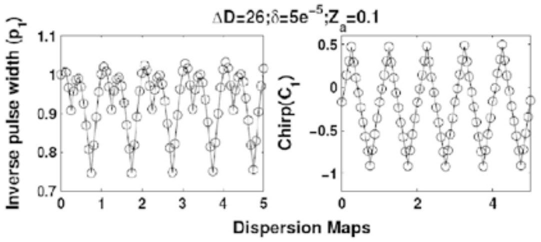

Fig. 3. Comparison between the evolution of a DM soliton under the variational ODE model (solid lines) and the generalized NLS (points) for system parameters as specified in the figure.

the full integration of the underlying generalised NLS model equation showing excellent agreement. This research is being performed in collaboration with the Optical Communications Group at the University of Vigo.

4. Quantum multiplexing using photons

The methods of quantum information can be used to improve existing network applications like switching in packet networks [27]. We have focused particularly in multiple access in optical networks. Light can be described using many alternative quantum bases. We have explored new multiple access schemes based on two of these quantum states of light: Orbital angular momentum (OAM) states and coherent states.

We have proposed two different free-space multiple access schemes based on the OAM of light [28]. The first scheme combines separate channels into the same spatial mode without interference. The second allows transferring the information of many different quantum channels to a single photon.

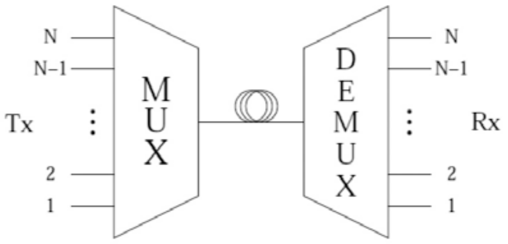

Fig. 4. Classical multiplexer.

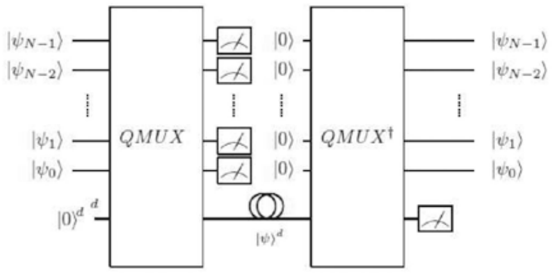

Fig. 5. Quantum multiplexer.

We have also put forward multiple access techniques for coherent state encoding [29]. Our system shares some of the advantages of classical code division multiple access (CDMA) and offers a limited protection against decoherence.

5. Photonic quantum gates

Additionally, we have explored new proposals for optical quantum computation. We have introduced different optical CNOT gates based on the quantum interrogation of a quantum object [30,31]. In these gates, the possibility of absorbing a photon will alter its evolution even though the actual probability of absorption is negligible.

Similarly, we have devised a setup inspired in quantum interrogation but without any quantum object that can be used to build a complete quantum computer based on the OAM of a single photon [32].

6. New nonlinear optical materials

Even though the research activity on temporal and spatial optical solitons started nearly simultaneously in the 1970s, temporal solitons entered the communication market some years ago [21] whereas their spatial counterparts still remain in the lab. The main reason is that the nonlinear propagation effects accumulate with distance and this permits the extremely low nonlinear optical response of the fiber medium to be compensated with the long propagation distances of the pulses over transmission links spanning thousands of kilometres. In order to enable the transition of spatial soliton devices (and other related nonlinear all optical processing technologies) from the lab to the market, it is of paramount importance to develop new materials having large and fast nonlinear responses.

There exist several promising candidates for the development of future nonlinear photonic devices, such as calchogenide glasses [33], organic materials, such as DAST [34] or DDET [35], or organometallic compounds such as methalo-phthalocyanines or methalloporphyrins

[36]. The research in this field is an extension of the joint investigations [37,38] with the TADRUS GIR at the University of Valladolid on new organometallic lanthanide complexes as chromophores in organic light emitting devices [39]. This type of compound has attracted little attention for exploiting their large nonlinear optical response until very recently [40]. This work is carried on in collaboration with the Group of Prof. H. Michinel at the University of Vigo.

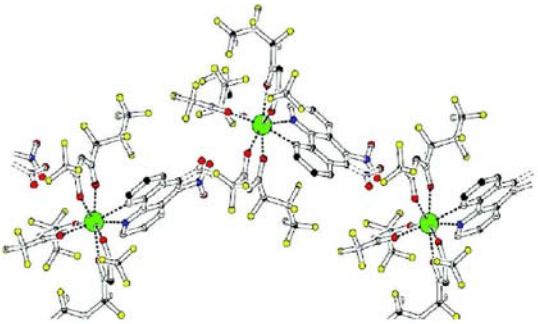

Fig. 6. Structure of one of the newly synthesized complexes under study Er(dfhd)$_3$NO2-phen.

7. Computational photonics

Much of the research activities described in the previous sections rely heavily on intensive numerical computations. The nonparaxial beam propagation method (BPM) presented in [41] has been extensively used in all the Helmholtz investigations. Plus, other numerical techniques [42] have been developed to ease the analysis of the numerical results. The use of the transmission line matrix (TLM) method [43] for the solution of Maxwell's equations in the time domain permits obtaining a new view of the propagation of Helmholtz solitons and provides additional proofs of the stability of the solutions [44].

The parallel implementations of the algorithms are often a requisite for the solution time of a given problem to be reasonable. In [45] an efficient new parallel implementation of the split-step Fourier (SSF) method, widely used in nonlinear optics, has been presented. The proposed computational scheme provides an enhanced performance when compared to conventional effective implementations of the SSF [46] using state-of-the-art parallel FFT routines [47].

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