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**DURACIÓN:** 4 años  
**AÑO ETAPA:** 2015  
**TÍTULO PROYECTO:** LOCALIZATION IN DISCRETE NONLINEAR OPTICAL MEDIA: CASE STUDIES  

**DISCIPLINA PRINCIPAL:** SISTEMAS NO LINEALES  
**GRUPO DE ESTUDIO:** FISICA TEORICA Y EXP  
**INVESTIGADOR(A) RESPONSABLE:** MARIO IGNACIO MOLINA GALVEZ  
**DIRECCIÓN:** Las Palmeras 3425  
**COMUNA:** Nunoa  
**CIUDAD:** Santiago  
**REGIÓN:** METROPOLITANA
MODIFICACIONES ACADÉMICAS

El informe no presenta modificaciones académicas.
PROJECT RESULTS:

Describe the results of your research in reference to its original and/or modified Project objectives.

The maximum extension of this section is 5 pages (Arial or Verdana font, size 10).

The main objective of this Project was to carry out the theoretical exploration of several related problems in nonlinear optics and related fields, that fall into the general area of nonlinear localization in discrete structures. In particular, we were interested in the creation and propagation of discrete optical solitons in weakly-coupled, nonlinear, optical waveguide arrays, in the presence of several effects such as the interplay of the simultaneous presence of boundaries, nonlinearity and disorder; the effects of long-range couplings in 2D nonlinear optical arrays; Fano resonances in arrays of split-ring resonators (magnetic metamaterial); discrete embedded optical solitons and localized modes in dipolar Bose-Einstein condensates in deep optical lattices, among others.

I am pleased to announce that virtually all of these objectives have been fulfilled and that 23 ISI articles have been produced as a result, plus 12 presentations in conferences and three radio interviews, where I explained the nature of the research carried out and the possible implications for the society at large. It should be emphasized that some of the research was experimental, thanks to ongoing collaborations with groups abroad. All the experimental work confirmed the theoretical findings.

The problems we worked on and the main results are as follows:

[1] Surface solitons in quasiperiodic photonic lattices. Here we studied discrete surface solitons in semi-infinite, one-dimensional, nonlinear (Kerr), quasiperiodic waveguide arrays of the Fibonacci and Aubry-André types, and explored different families of localized surface modes, as a function of optical power content (“nonlinearity”) and quasiperiodic strength (“disorder”). We found a strong asymmetry in the power content of the mode as a function of the propagation constant, between the cases of focusing and defocusing nonlinearity, in both models. We also examined the dynamical evolution of a completely localized initial excitation at the array surface. We find that, in general, for a given optical power, a smaller quasiperiodic strength is required to effect localization at the surface than in the bulk. Also, for fixed quasiperiodic strength, a smaller optical power is needed to localize the excitation at the edge than inside the bulk.

[2] Anderson localization in a periodic photonic lattice with a disordered boundary. Here we investigated experimentally the light evolution inside a two-dimensional finite periodic array of weakly coupled optical waveguides with a disordered boundary. For a completely localized initial condition away from the surface, we found that the disordered boundary induces an asymptotic localization in the bulk, centered around the initial position of the input beam.

[3] Optical surface modes in the presence of nonlinearity and disorder. Here we investigated numerically the effect of the competition of disorder, nonlinearity, and boundaries on the Anderson localization of light waves in finite-size, one-dimensional waveguide arrays. Using the discrete Anderson-nonlinear Schrödinger equation, the propagation of the mode amplitudes up to some finite distance is monitored. The analysis was based on the calculated localization length and the participation number, two standard measures for the statistical description of Anderson localization. For relatively weak disorder and nonlinearity, a higher disorder strength is required to achieve the same degree of localization at the edge than in the interior of the array, in agreement with recent experimental observations in the linear regime. However, for relatively strong disorder and/or nonlinearity, this behavior is reversed and it is now easier to localize an excitation at the edge than in the interior of the lattice.

[4] Discrete surface bound states in the continuum. Here we introduced the novel concept of surface bound states in the continuum, i.e., surface modes embedded into the linear spectral band of a discrete lattice. We suggested an efficient method for creating such surface modes and the local bounded potential necessary to support the embedded modes. We demonstrated that the surface embedded modes are structurally stable, and the position of their eigenvalues inside the spectral band can be tuned continuously by adding weak nonlinearity.
Diffusion in infinite and semi-infinite lattices with long-range coupling. Here, we proved that for a one-dimensional infinite lattice, with long-range coupling among sites, the diffusion of an initial delta-like pulse in the bulk, is ballistic at all times. We obtained a closed form expression for the mean square displacement (MSD) as a function of time, and show some cases including finite range coupling, exponentially decreasing coupling and power-law decreasing coupling. For the case of an initial excitation at the edge of the lattice, we find an approximate expression for the MSD that predicts ballistic behavior at long times, in agreement with numerical results.

Nonlinear light localization in a core of a holey fiber. We examined localized surface modes in the core of a photonic crystal fiber composed of a finite nonlinear (Kerr) hexagonal waveguide array containing a topological defect in the form of a central void. Using the coupled-modes approach, we found the fundamental surface mode and the staggered and unstaggered ring-shaped modes, and their linear stability windows, for two void diameters. We found that, for a small void diameter, the unstable unstaggered ring mode of the system always requires less power and its instability gain at low powers is smaller than in the case without the void. Also, for the small void case, the unstaggered ring mode does not require a minimum power threshold, in sharp contrast with the case without the void. For a larger void, most of these observations hold, as well. We followed numerically the dynamical evolution of these ring modes to reveal their decay channels at long propagation distances.

Bound states and interactions of vortex solitons in the discrete Ginzburg- Landau equation. Here we used different continuation methods, to unveil a wide region in the parameter space of the discrete cubic-quintic complex Ginzburg-Landau equation, where several families of stable vortex solitons coexist. All these stationary solutions have a symmetric amplitude profile and two different topological charges. We also observed the dynamical formation of a variety of “bound-state” solutions composed of two or more of these vortex solitons. All of these stable composite structures persist in the conservative cubic limit for high values of their power content.

Localized modes in nonlinear photonic kagome nanoribbons. We examined localization of light in nonlinear (Kerr) kagome lattices in the shape of narrow strips of varying width. For the narrowest ribbon, the band structure features a flat band leading to linear dynamical trapping of an initially localized excitation. We also found a geometry-induced bistability of the nonlinear modes as the width of the strip is changed. A crossover from one to two dimensions localization behavior was observed as the width is increased, attaining two-dimensional behavior for relatively narrow ribbons.

Enhanced distribution of a wave-packet in lattices with disorder and nonlinearity. Here we showed, numerically and experimentally, that the presence of weak disorder results in an enhanced energy distribution of an initially localized wave-packet, in one- and two-dimensional finite lattices. The addition of a focusing nonlinearity facilitates the spreading effect even further by increasing the wave-packet effective size. We found a clear transition between the regions of enhanced spreading (weak disorder) and localization (strong disorder).

Experimental observation of superdiffusive transport in random dimer lattices. We experimentally observed anomalous wavepacket evolution in a realization of a one-dimensional finite binary Anderson model in the presence of short-range correlations. To this end, we employ weakly-coupled optical waveguides with propagation constants $\varepsilon_1$ and $\varepsilon_2$. The correlations enforce the creation of dimers, i.e. two adjacent waveguides with the same $\varepsilon$, randomly placed along the lattice. A transition from a ballistic to a superdiffusive wavepacket expansion and, eventually, to localization was observed as the contrast between the two propagation constants increased.

Self-trapping threshold in disordered nonlinear photonic lattices. We investigated numerically and experimentally the influence of coupling disorder on the self-trapping dynamics in nonlinear one-dimensional optical waveguide arrays. The existence of a lower and upper bound of the effective average propagation constant allows for a generalized definition of the threshold power for the onset of soliton localization. When compared to perfectly ordered systems, this threshold was found to decrease in the presence of coupling disorder.
[12] **Self-trapping transition in nonlinear cubic lattices.** We explored the question of the critical nonlinearity value needed to dynamically localize energy in discrete nonlinear cubic (Kerr) lattices. We focussed on the effective frequency and participation ratio of the profile to determine the transition into localization in one-, two-, and three-dimensional lattices. A simple and general criterion was developed, for the case of an initially localized excitation, to define the transition region in parameter space (“dynamical tongue”) from a delocalized to a localized profile. We introduce a method for computing the dynamically excited frequencies, which helped us validate our stationary ansatz approach and the effective frequency concept. A general analytical estimate of the critical nonlinearity was obtained, with an extra parameter to be determined. We find this parameter to be almost constant for two-dimensional systems and proved its validity by applying it successfully to two-dimensional binary lattices.

[13] **Defect modes, Fano resonances and Embedded states in Magnetic Metamaterials.** Here we considered a simplified model of a nonlinear magnetic metamaterial, consisting of a weakly-coupled, periodic split-ring resonator (SRR) array capable of nonlinear capacitive response. We analyzed three related problems: (a) The calculation of localized modes around simple magnetoinductive impurities located at the surface or at the bulk of the array, in closed form for both, linear and nonlinear cases. (b) The scattering of magnetoinductive waves across internal (external) capacitive (inductive) defects coupled to the SRR array and the occurrence of Fano resonances, and how to tune them by changing the external parameters of the system. (c) Description of a method for building a stable localized magnetoinductive mode embedded in the linear band of extended states.

[14] **The nonlinear magnetoinductive dimer.** Here we examined a nonlinear magnetoinductive dimer and computed its linear and nonlinear symmetric, antisymmetric and asymmetric modes in closed-form, in the rotating-wave approximation. A linear stability analysis of these modes revealed that the asymmetric mode is always stable, for any allowed value of the coupling parameter and for both, hard and soft nonlinearity. A numerical computation of the dimer dynamics revealed a magnetic energy selftrapping whose threshold increases for increasing dimer coupling.

[15] **Bounded dynamics of finite PT-symmetric magnetoinductive arrays.** We examined the conditions for the existence of bounded dynamical phases for finite PT-symmetric arrays of split-ring resonators. The dimer (N=2), trimer (N=3) and pentamer (N=5) cases are solved in closed form while for N>5 results were computed numerically for several gain/loss spatial distributions. It is found that the parameter stability window decreases monotonically with the size of the array.

[16] **Embedded states in the continuum for PT-symmetric systems.** We introduced the novel concept of a bound state in the continuum (BIC) for a binary lattice satisfying the PT-symmetry condition. We showed how to build such state and the local potential necessary to sustain it. We found that an appropriate choice of the envelope function can bring the system from a PT-symmetric phase into a Hermitian one. For more general envelope functions, the BIC can still be created but the bounded state will force the system to undergo the PT-symmetry breaking transition.

[17] **Self trapping transition for a nonlinear impurity within a linear chain.** In this work we revisited the old issue of the self-trapping dynamical transition at a nonlinear impurity embedded in an otherwise linear lattice. For our Schrodinger chain example, we present rigorous arguments that establish necessary conditions and corresponding parametric bounds for the transition between linear decay and nonlinear persistence of a defect mode. The proofs combine a contraction mapping approach applied in the fully dynamical problem in the case of a 3D-lattice, together with variational arguments for the derivation of parametric bounds for the creation of stationary states associated with the expected fate of the self-trapping dynamical transition. The results are relevant for both power law nonlinearities and saturable ones. The analytical results are corroborated by numerical computations.

[18] **Bulk and surface bound states in the continuum.** Here, we examined bulk and surface bound states in the continuum (BIC) that is, square-integrable, localized modes embedded in the linear spectral band of a discrete lattice including interactions to first and second nearest neighbors. We suggested an efficient method for generating such modes and the local bounded potential that
supports the BIC, based on the pioneering Wigner-von Neumann concept. It was shown that the bulk and surface embedded modes are structurally stable and that they decay faster than a power law at long distances from the mode center.

[19] **Nonlinear multicore waveguide array with gain and loss.** Here we studied the existence, stability, and dynamics of linear and nonlinear stationary modes propagating in radially symmetric multi-core waveguides with balanced gain and loss. We demonstrated that, in general, the system can be reduced to an effective PT-symmetric dimer with asymmetric coupling. In the linear case, we found that there exist two modes with real propagation constants before an onset of the PT-symmetry breaking while other modes have always the propagation constants with nonzero imaginary parts. This leads to a stable (unstable) propagation of the modes when gain is localized in the core (ring) of the waveguiding structure. In the case of nonlinear response, we showed that an interplay between nonlinearity, gain, and loss induces a high degree of instability, with only small windows in the parameter space where quasi-stable propagation is observed. We proposed a novel stabilization mechanism based on a periodic modulation of both gain and loss along the propagation direction that allows bounded light propagation in the multi-core waveguiding structures.

[20] **Interplay of disorder and PT-symmetry.** We studied a one-dimensional binary optical lattice in the presence of diagonal disorder and alternating gain and loss, and examined the light transport phenomena for localized and extended input beams. In the pure PT-symmetric case, we derived an exact expression for the behavior of light localization in terms of typical parameters of the system. Within the PT-symmetric region light localization becomes constant as a function of the strength of the gain and loss parameter, but outside the PT-symmetric window, light localization increases as the gain and loss parameter increases. When disorder was added, we observed that the presence of gain and loss inhibits (favors) the transport for localized (extended) excitations.

[21] **Observation of localized states in Lieb photonics lattices.** We presented the first experimental demonstration of a new type of localized state in the continuum, namely, compacton-like linear states in flat-band lattices. To this end, we employed photonic Lieb lattices, which exhibit three tight-binding bands, with one being perfectly flat. Discrete predictions were confirmed by realistic continuous numerical simulations as well as by direct experiments. Our results could be of great importance for fundamental physics as well as for various applications where light needs to be conducted in a diffractionless and localized manner over long distances.

[22] **Phase transition in PT-symmetric active plasmonic systems.** Surface plasmon polaritons (SPPs) are coherent electromagnetic surface waves trapped on an insulator-conductor interface. The SPPs decay exponentially along the propagation due to conductor losses, restricting the SPPs propagation length to few microns. Gain materials can be used to counterbalance the aforementioned losses. We provided an exact expression for the gain, in terms of the optical properties of the interface, for which the losses are eliminated. In addition, we showed that systems characterized by lossless SPP propagation are related to PT-symmetric systems. Furthermore, we derived an analytical critical value of the gain describing a phase transition between lossless and prohibited SPPs propagation. The regime of the aforementioned propagation can be directed by the optical properties of the system under scrutiny. Finally, we performed COMSOL simulations verifying the theoretical findings.

[23] **Flat bands and PT-symmetry in quasi-one-dimensional lattices.** We examined the effect of adding PT-symmetric gain and loss terms to quasi-one-dimensional lattices (ribbons) that possess flat bands. We focused on three representative cases: the Lieb ribbon, the kagome ribbon, and the stub ribbon. In general, we found that the effect on the flat band depends strongly on the geometrical details of the lattice being examined. One interesting result that emerges from an analytical calculation of the band structure of the Lieb ribbon including gain and loss is that its flat band survives the addition of PT symmetry for any amount of gain and loss and also survives the presence of anisotropic couplings. For the other two lattices, any presence of gain and loss destroys their flat bands. For all three ribbons, there are finite stability windows whose size decreases with the strength of the gain and loss parameter. For the Lieb and kagome cases, the size of this window converges to a finite value. The existence of finite stability windows plus the constancy of the Lieb flat band are in marked contrast to the behavior of a pure one-dimensional lattice.
Transport of localized and extended excitations in chains embedded with randomly distributed linear and nonlinear n-mers. We examined the transport of extended and localized excitations in one-dimensional linear chains populated by linear and nonlinear symmetric identical n-mers (with n=3,4,5 and 6), randomly distributed. First, we examined the transmission of plane waves across a single linear n-mer, paying attention to its resonances, and looking for parameters that allow resonances to merge. Within this parameter regime we examined the transmission of plane waves through a disordered and nonlinear segment composed by n-mers randomly placed inside a linear chain. It was observed that nonlinearity tends to inhibit the transmission, which decayed as a power law at long segment lengths. This behavior still holds when the n-mer parameters do not obey the resonance condition. On the other hand, the mean square displacement exponent of an initially localized excitation does not depend on nonlinearity at long propagation distances z, and showed a super-diffusive behavior \( \sim z^{1.8} \) for all n-mers, when parameters obey the resonance merging condition; otherwise the exponent reverts back to the random dimer model value \( \sim z^{1.5} \).
### PRODUCTOS

#### ARTÍCULOS
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<td>Physical Review A</td>
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A. J. Martinez, M. I. Molina, S. Turitsyn and Y. S. Kivshar,
Nonlinear multicore waveguide array with gain and loss

N. A. Gallo and M. I. Molina
Bulk and surface bound states in the continuum
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Optical surface modes in the presence of nonlinearity and disorder

Phys. Rev. E


Anderson localization in a periodic photonic lattice with a disordered boundary


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Autor (a)(es/as): M. I. Molina
Título (Idioma original): Bulk and surface bound states in the continuum
Nombre del Congreso: QUOST IV
País: CHILE
Ciudad: santiago
Fecha Inicio: 27/10/2013
Fecha Término: 29/10/2013
Archivo Asociado:
Invitacion_M_Molina_QUOST_IV.pdf
QUOST_IV_talk.pdf

N°: 7
Autor (a)(es/as): M. I. Molina
Título (Idioma original): Bulk and Surface localized optical modes in the continuous band
Nombre del Congreso: School on Nonlinear Optics and Nanophotonics,
País: BRASIL
Ciudad: sao paulo
Fecha Inicio: 25/11/2013
Fecha Término: 06/12/2013
Archivo Asociado:

N°: 6
Autor (a)(es/as): M. I. Molina
Título (Idioma original): Bulk and surface bound states in the continuum
Nombre del Congreso: QUOST IV
País: CHILE
Ciudad: santiago
Fecha Inicio: 27/10/2013
Fecha Término: 29/10/2013
Archivo Asociado:
Invitacion_M_Molina_QUOST_IV.pdf
QUOST_IV_talk.pdf

N°: 7
Autor (a)(es/as): M. I. Molina
Título (Idioma original): Bulk and Surface localized optical modes in the continuous band
Nombre del Congreso: School on Nonlinear Optics and Nanophotonics,
País: BRASIL
Ciudad: sao paulo
Fecha Inicio: 25/11/2013
Fecha Término: 06/12/2013
Archivo Asociado:
Nº : 8
Autor (a)(es/as) : M. I. Molina
Título (Idioma original) : Discrete Photonics in Waveguide Arrays
Nombre del Congreso : II Encuentro de Física no lineal
País : CHILE
Ciudad : valparaiso
Fecha Inicio : 24/04/2014
Fecha Término : 25/04/2014
Nombre Publicación :
Año :
Vol. :
Nº :
Páginas :
Envía documento en papel : no
Archivo Asociado :
sao_paulo_invitacion.pdf
sao_paulo_poster.pdf

Nº : 9
Autor (a)(es/as) : M. I. Molina
Título (Idioma original) : Bulk and surface localized optical modes in the continuum band
Nombre del Congreso : International workshop on Control of light and matter waves propagation and localization in photonic lattices
País : SUECIA
Ciudad : linkoping
Fecha Inicio : 06/08/2014
Fecha Término : 07/08/2014
Nombre Publicación :
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Vol. :
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Autor (a)(es/as): M. I. Molina
Título (Idioma original): Embedded modes in a PT-symmetric binary lattice
Nombre del Congreso: Dynamics Days south america
País: CHILE
Ciudad: valparaiso
Fecha Inicio: 03/11/2014
Fecha Término: 07/11/2014
Nombre Publicación: 
Año: 
Vol.: 
Nº: 
Páginas: 
Enviar documento en papel: no
Archivo Asociado: embedded_PTsymmetric.pdf

Nº: 13
Autor (a)(es/as): C. Mejia-Cortes and M. I. Molina
Título (Idioma original): Interplay of disorder and PT-symmetry
Nombre del Congreso: XIX Simposio Chileno de Física
País: CHILE
Ciudad: concepcion
Fecha Inicio: 26/11/2014
Fecha Término: 28/11/2014
Nombre Publicación: 
Año: 
Vol.: 
Nº: 
Páginas: 
Enviar documento en papel: no
Archivo Asociado: disorder_and_PTsymmetry.pdf
Nº : 14
Autor (a)(es/as) : Dany López-González, Rodrigo Vicencio, Alex Szameit and M. I. Molina
Título (Idioma original) : Transporte de excitaciones en cadena 1-d de trímeros aleatorios
Nombre del Congreso : XIX Simposio Chileno de Física
País : CHILE
Ciudad : Concepción
Fecha Inicio : 26/11/2014
Fecha Término : 28/11/2014
Nombre Publicación :
Año :
Vol. :
Nº :
Páginas :
Envía documento en papel : no
Archivo Asociado : transporte_trímeros_poster.pdf

Nº : 15
Autor (a)(es/as) : M. I. Molina
Título (Idioma original) : Discrete photonics in waveguide arrays
Nombre del Congreso : Physicist Day
País : COLOMBIA
Ciudad : Barranquilla
Fecha Inicio : 03/11/2015
Fecha Término : 04/11/2015
Nombre Publicación :
Año :
Vol. :
Nº :
Páginas :
Envía documento en papel : no
Archivo Asociado : discrete_photonics1.pdf

Nº : 16
Autor (a)(es/as) : M. I. Molina
Título (Idioma original) : Localization-delocalization transition in 1D structures with correlated disorder
Nombre del Congreso : Physicist Day
País : COLOMBIA
Ciudad : Barranquilla  
Fecha Inicio : 05/11/2015  
Fecha Término : 05/11/2015  
Nombre Publicación :  
Año :  
Vol. :  
Nº :  
Páginas :  
Envía documento en papel : no  
Archivo Asociado : localization_delocalization.pdf  

Nº : 17  
Autor (a)(es/as) : M. Mattheakis, T. Oikonomou, M. I. Molina, G. P. Tsironis  
Título (Idioma original) : Parity-Time Plasmonic Instability  
Nombre del Congreso : International Symposium on Physics and Applications of Laser Dynamics  
País : FRANCIA  
Ciudad : metz  
Fecha Inicio : 04/11/2015  
Fecha Término : 06/11/2015  
Nombre Publicación :  
Año :  
Vol. :  
Nº :  
Páginas :  
Envía documento en papel : no  
Archivo Asociado : Oikonomou_IS_PALD_2015.pdf  

TESIS/MEMORIAS  
Nº : 1  
Título de Tesis : Transporte de exitaciones extendidas y localizadas en sistemas discretos lineales y no lineales  
Nombre y Apellidos del(de la) Alumno(a) : Dany A. Lopez Gonzalez  
Nombre y Apellidos del(de la) Tutor(a) : Mario I. Molina  
Título Grado : Magister  
Institución : Universidad de Chile  
País : CHILE  
Ciudad : Santiago
ANEXOS

A continuación se detallan los anexos físicos/papel que no se incluyen en el informe en formato PDF.