Research lines of the Quantum and Atom Optics Group at the 
Universitat Autònoma de Barcelona

Líneas de investigación del Grupo de Óptica Cuántica y Atómica de la 
Universitat Autònoma de Barcelona

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ABSTRACT:
The present research of the Quantum Atom Optics Group at the Universitat Autònoma de Barcelona focuses on the coherent control of quantum optical systems with applications in areas ranging from ultra cold atom physics and quantum computation to photoionization and harmonic generation with strong lasers. In this article, we will briefly describe our most recent results on these lines of research.

Keywords: Quantum Optics, Atom Optics, Cold Atoms, Quantum Information, Non-Linear Optics, Strong Fields.

RESUMEN:
La investigación actual del Grupo de Óptica Cuántica y Atómica de la Universitat Autònoma de Barcelona se concentra fundamentalmente en el control coherente de sistemas óptico-cuánticos en varios campos que abarcan desde los átomos ultrafríos y la computación cuántica hasta la fotoionización y la generación de armónicos mediante láseres intensos. En este artículo, describiremos brevemente nuestros resultados más recientes en estas líneas de investigación.

Palabras clave: Óptica Cuántica, Óptica Atómica, Información Cuántica, Óptica No Lineal, Campos Intensos.

REFERENCES AND LINKS
[1]. Website of the Optics Group at the Universitat Autònoma de Barcelona: http://optica.uab.es.


1. Introduction

The Quantum and Atom Optics Group at the Universitat Autònoma de Barcelona (UAB) [1] has a long experience in the study of the quantum optics phenomenology associated to three-level atoms interacting with two laser fields, e.g., on electromagnetically induced transparency, coherent population trapping, stimulated Raman adiabatic passage, and lasing without inversion. Recently, members of the team have demonstrated that most of these phenomena can be straightforwardly extended to the field of matter waves in periodic potentials or optical micro-traps. We have exploited this analogy to develop new techniques to coherently control and manipulate neutral atoms either individual atoms or Bose Einstein condensates in optical potentials. We have exploited this analogy to develop new techniques to coherently control and manipulate neutral atoms either individual atoms or Bose Einstein condensates in optical potentials. This line of research will be briefly outlined in Sections 2(a,b,c). Within this quantum information framework, we will also discuss the coherent control and eventually the use of matter wave lattice solitons as quantum memories, see Section 2d. In Section 3, we will introduce a novel technique to achieve self-induced transparency for a probe laser field interacting with a two-level system while in Section 4 we will present our last investigations on quantum memories for light polarization quantum bits in three-level media. Section 5 will be devoted to discuss the development of an optical analog of the matter wave adiabatic passage by means of three coupled optical waveguides. We will discuss our experimental approach and some possible applications such as light spectral filtering. We have very recently addressed the problem of hydrogen photoionization with light beams carrying angular momentum. We will discuss this research topic in Section 6 and present some of our numerical simulations of photoionization in terms of quantum trajectories á la de Broglie-Bohm. Finally, very recently our group has started an experimental research line on conical refraction obtaining already some results in cascaded conical refraction with two consecutive biaxial crystals. Our latest results on conical refraction will be presented in Section 7. We will summarize our work in Section 8 that presents the conclusions.
2. Engineering of matter waves in optical potentials

Quantum gases trapped in optical potentials, e.g., microtrap arrays or optical lattices, have attracted considerable attention in the field of quantum atom optics for the possibilities they offer to study fundamental quantum mechanical effects as well as for potential applications in quantum information processing (QIP), interferometry and high precision measurements. In this context, we are currently investigating the following topics.

2.1 Coherent manipulation of holes in dipole trap arrays

Quantum registers with single-site addressing of about hundred quantum bits [2] and cluster entangled states of thousands of atoms [3] have been reported, respectively, in 2D optical microtrap arrays and 3D optical lattices. The loading of quantum gases into 3D optical lattices achieving the Mott insulator regime for both bosons and fermions has been experimentally demonstrated [4,5], reaching one of the main goals for QIP with neutral atoms. In this context, we developed a set of coherent and robust tools [6,7], termed three-level atom optics (TLAO) techniques, to adiabatically transport neutral atoms between the two extreme traps of a triple-well potential. We have very recently extended the TLAO techniques to the coherent manipulation of the external degrees of freedom of defects [8], i.e., holes, in single occupancy dipole trap arrays, see Fig. 1, and investigated their potential application to the initialization of defect-free trap domains, the building-up of single atom transistors, and even for QIP with the hole itself being the quantum bit carrier. By means of the Hubbard formalism, we extended the previous results for a single hole in a triple well potential to a single hole in an arbitrarily long trap array. We are presently addressing the application of optimal control methods to the TLAO techniques in order to achieve a high fidelity fast transport with realistic potentials.

2.b Adiabatic splitting and self-trapping of a Bose-Einstein condensate in a double-well potential

Weakly linked parts of a Bose-Einstein condensate (BEC) in a double well potential forming a single Josephson junction [9] have been recently experimentally achieved [10]. In this system, interatomic interactions play a crucial role leading to anharmonic Josephson oscillations, if the initial population imbalance of the two wells is below a critical value, and to macroscopic quantum self-trapping i.e., inhibition of large amplitude Josephson oscillations above a threshold for the population imbalance. We have proposed a novel technique [11] to adiabatically control a BEC in a double-well potential extending the TLAO techniques [6,7] to the two-level case. We have shown that the adiabatic dynamics of a BEC in a double well potential can be described in terms of a dark
variable resulting from the combination of the population imbalance and the spatial atomic coherence, see Fig. 2. In terms of this dark variable, we have derived the conditions for adiabatically splitting a BEC as well as for the preparation of an adiabatic self trapping state by the simultaneous variation of the tunnelling rate and the energy bias or the BEC non-linearity, see Fig. 3.

Fig. 2: (a) BEC double-well potential where $\Omega$ is the tunnelling rate and $\varepsilon$ the difference between the on-site energies. $\phi_L, \phi_R$ are the localized ground states of each isolated trap. (b) Three-level mapping of (a) to the density matrix variables and coupling strengths. $w$ is the population difference between the two wells, $u (v)$ is the real (imaginary) part of the spatial coherence, and $U$ is the non-linear self-interaction energy. In the adiabatic limit, the system follows the dark variable $d = w \cos \theta - u \sin \theta$, with $\tan \theta = \Omega / (\varepsilon + U w)$ ($\hbar = 1$).

2.2 Coherent patterning of matter waves with subwavelength localization

Recently, there have been several proposals for subwavelength atom localization based on the interaction of three-level atoms with light having space-dependent amplitude [12-17]. We have introduced a novel method, the Subwavelength Localization via Adiabatic Passage (SLAP) technique [18], to coherently achieve state-selective patterning of matter waves well beyond the diffraction limit. The SLAP technique consists in coupling two partially overlapping and spatially structured laser fields to three internal levels of the matter wave yielding state-selective localization at those positions where the adiabatic passage process does not occur. We have shown that by means of this technique matter wave localization down to the single nanometer scale can be achieved. We have analyzed in detail the potential implementation of the SLAP technique for nano-lithography with an atomic beam of metastable Ne*, see Fig. 4, and for coherent patterning of a two-component $^{87}$Rb Bose-Einstein condensate, see Fig. 5.

Fig. 3: Adiabatic splitting of a BEC (a) and realization of an adiabatic self-trapping state (b) using the temporal variation of the non-linear self-interaction energy $U(t)$ and the tunnelling rate $\Omega(t)$ shown in the corresponding upper figure ($\varepsilon = 0$). All parameters are made dimensionless through the peak amplitude of the tunnelling rate $\Omega_0$. For the definition of the variables see the caption of Fig. 2.

Fig. 4: SLAP technique for a Ne* matter wave. (a) Relevant energy levels and couplings. (b) Final spatial population distribution around a node of the SW. For the parameter setting see Ref. [18]. SW (TW): Standing (Travelling) Wave.
2.4 Matter wave lattice solitons

Bright matter-wave solitons [19-22], i.e. stable mesoscopic atomic wave packets that can propagate without dispersion, provide an exceptional testbed for studying quantum mechanics above the single-atom level. Quasi one-dimensional repulsive condensates loaded in an optical lattice can support bright matter-wave (MW) gap solitons (GSs) created by the interplay between nonlinearity and periodicity [22]. Stability conditions for MW GSs impose severe restrictions on their interactions with a potential well or barrier corresponding to a local modification of the periodic structure. Specifically, we have shown [23] that the MW GS cannot split through the interaction with linear defects, and behaves like a particle exhibiting mesoscopic quantum features. For a fixed kinetic energy, the behaviour of a moving MW GS interacting with a single barrier shows an abrupt transition from complete transmission to complete reflection [23], as the height of the barrier increases for a given width of the barrier. Moreover, we have also addressed [24] the interaction of a MW GS with a double-barrier potential resembling a Fabry-Perot cavity formed by two potential barriers. In this case, three scenarios are identified: complete transmission, trapping into the oscillatory state, and complete reflection, as illustrated in Figs. 6(a-c). It is worth to note that the GS may be trapped in the cavity entirely, without losses. Collisions between an incident soliton with the cavity already occupied by an (identical) earlier trapped GS have been also addressed. Different outcomes of the collisions are observed, depending on time delay between the incidence of the two solitons in the cavity. One example is shown in Fig. 6(d), where the incoming soliton may get trapped by kicking out the previously trapped one.

3. Doppler-free adiabatic self-induced transparency

The ability to render a medium transparent to a resonant laser field opens a wide range of applications, from slow light and dark state polariton physics to light-matter interfaces. In atomic vapours at room temperature, Doppler broadening plays, in general, a negative role tending to reduce transparency. In a two-level (2L) system, Doppler-free transparency can be achieved by means of self-induced transparency (SIT), see Figs. 7(a,d), which consists in preparing an optical pulse propagating in the medium such that an integer number of Rabi oscillations are performed [25,26]. We have proposed a novel approach for Doppler-free transparency in a 2L system [27]. This

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Fig. 5: SLAP technique for a two-component 87Rb BEC. Time evolution of (a) the contour plot of the density distribution of atoms in one of the BEC internal states, and (b) of the FWHM of the central localized structure. SL indicates super-localization. For the parameter setting see Ref. [18].

Fig. 6: Contour plots of the spatiotemporal evolution of a lattice soliton colliding with an effective cavity created by a double barrier potential for conditions of (a) complete transmission, (b) trapping and (c) complete reflection. (d) Illustrates the "recharge" of the cavity by a new soliton that kicks out the initially trapped one.
4. Compact quantum memory for polarization qubits in three-level media

The realization of efficient quantum memories for light is an essential component in quantum information, especially in the context of communication where photons are the preferred information carriers [29]. Among the various ways to encode quantum information in photons, polarization encoding is one of the most used in communication experiments. Up to date, polarization-qubit memories have been realized only in cold atomic ensembles and atomic vapours, where polarization encoding is first transformed into path encoding and then stored into two spatially distinguishable regions. This causes detrimental effects associated to spatial mismatching and unequal efficiencies. In this context, we have shown that the extra step of splitting spatially the input state is not necessary if one relies upon quantum memories based on photon echo techniques [30] in three-level media. We achieve this by considering storage protocols based on controlled reversible inhomogeneous broadening (CRIB) [31-33]. Whereas in previous works on CRIB only two-level systems have been considered, we extend the approach to media composed of three-level atoms, both in \(\Lambda\) and \(V\) configurations. In both cases the medium interacts with two weak pulses, rather than only one as in standard CRIB, see Fig. 9. The treatment applies to pulses described classically or quantum mechanically, as well as to two independent pulses or two components of the same pulse. In particular, an arbitrary polarization qubit can be efficiently stored and retrieved in such a compact scheme, as shown in Fig. 10. The role of the relative phase between atomic levels at different stages of the protocol has been also taken into account, as well as noise effects during storage.
5. Coherent control of light propagation in integrated optical waveguides

Coherent control and manipulation of light propagation in systems of three coupled rib optical waveguides has been addressed. We have shown that by an appropriate variation of the distance among waveguides, it is possible to transfer a light beam between the outermost waveguides with very low excitation of the central one, resembling the quantum transport of atomic population achieved by the application of the Stimulated Raman Adiabatic Passage (STIRAP) technique [28] in three-level lambda atomic systems interacting with two laser pulses (see also Sections 2 and 3 in this review). Numerical simulations for total internal reflection (TIR) waveguides and for anti-resonant reflecting optical waveguides (ARROW) have been performed. In the case of TIR waveguides, we have demonstrated that the system can be designed to be used as a spectral filter. Furthermore, the possibility of using the system as a delay line by chaining a sequence of double STIRAP-type processes has been explored for both TIR and ARROW waveguides. Currently, devices have been fabricated and experimental measurements are being performed at the National Center of Microelectronics (Barcelona) under the collaboration of Dr. A. Llobera.

6. Photoionization with light beams carrying orbital angular momentum

In the past few years a great deal of interest has been devoted to helical beams that are able to transport spin and orbital angular momentum (OAM) in its propagation direction [34], such as Laguerre-Gaussian beams. OAM is related to the transverse profile of the beam. These characteristic transverse profiles have been exploited in a wide range of applications; spanning from optical tweezers to quantum information protocols [35]. For most of them, a suitable model to describe the light-matter interaction is required.

In this context, we have addressed the problem of photoionization [36,37] by means of the interaction of a laser pulse carrying orbital angular momentum with the simplest atom that one can consider: Hydrogen. This academic problem clarifies a fundamental question: the OAM transfer from light to the electron quantum state. We deal with the problem both using analytical and numerical methods. In order to resolve completely the ionization of the electron, we have integrated the corresponding time-dependent Schrödinger equation and discuss its dynamics by means of de Broglie-Bohm quantum trajectories, see Fig. 12.
Fig. 11: Contour plot of the normalized power (integrated over the width of the rib) as a function of the z position and the wavelength λ for the (a) right, (b) central and (c) left waveguides. Top view simulations of the three waveguide system for (d) λ=200 nm and (e) λ=800 nm.

Fig. 12: Results of a simulation with a Laguerre-Gaussian pulse with l = 1 and linearly polarized in the x-direction with a field amplitude of A0w0 = 10^{13}/8 au. (a) Projection of the excited state onto the plane xy at times t=τ, t=2τ, and t=3τ. Temporal evolution of (b) the ionization probability P_i, and (c) the expected value of the angular momentum along the z axis. (d) Projection of the electron quantum state at the end of the pulse into spherical harmonics. Arrows correspond to transitions allowed by the selection rules derived in [36]. (e) Projection of the 3D de Broglie-Bohm trajectories onto the x and y axis over time and in the xy plane. The thick black curves in (e) correspond to the mean value of the electron position.
7. Conical refraction

Conical Refraction (CR) is one of the oldest and more singular phenomena in classical optics, in which a light beam propagating along an optical axis of a biaxial crystal forms a cone inside the crystal and emerges from it as a hollow cylinder. It was first predicted theoretically by Hamilton [38] on the basis of his geometric ray theory and the phase space concept. The prediction was experimentally verified by Lloyd [39] shortly thereafter. Although CR is considered as one of the key points in the acceptance of the transverse light concept, the wave theory of conical refraction has been developed only recently by Belsky and Khapalyuk [40] and later on extended by Belsky and Stepanov [41].

The hollow cylinder of conical refraction is formed by two bright rings separated by the Poggendorff dark ring, see Fig. 13(a). These rings appear in a plane known as the Lloyd plane. The ring intensity patterns appear for natural (unpolarized) light and for circularly polarized input light. For both cases the intensity distribution is uniform along the ring. If the input light beam is linearly polarized a croissant pattern appears in the Lloyd plane as shown in Fig. 14(a). While every two diagonally opposite points either in the ring or the croissant patterns are orthogonally polarized, the polarization distribution does not depend on the polarization state of the incident beam and it is defined by the orientation of the biaxial crystal.

Until recently, almost all experiments have been performed with a single biaxial crystal. To observe conical refraction phenomena in cascaded crystals their axes should be precisely orientated perpendicular to the surfaces and, moreover, the crystals should be almost perfectly aligned with respect to each other. We have started experiments with several (two and more) cascaded biaxial crystals accurately oriented along the light propagation direction. In such a configuration, in the general case, several concentric sets of bright rings (two bright rings separated by the Poggendorff dark ring) with different diameters appear. In Fig. 13(b) our experimental results with two biaxial crystals are presented for an input light beam with circular polarization, while in Fig. 14(b) we present our results for linearly polarized light beams. On the basis of these investigations we have formulated rules that provide a simple but precise explanation of the intensity patterns observed in experiments. With these rules one could easily predict the intensity patterns in the Lloyd ring plane in experiments with any arbitrary number of cascaded biaxial crystals and for different polarizations of the input light beams.

The other present direction of our investigations is to address the birefringence of light propagating close to the optical axis of biaxial crystals. We have shown that the intensity patterns cannot be mapped to the Malus law. It should be noted that the experiments by Malus on light birefringence, from which his famous law was deduced, were one of the first experimental confirmations of the wave theory of light.

8. Conclusions

We have briefly outlined our recent and on progress research on coherent control of quantum-optical systems with particular emphasis on matter wave proposals for quantum information implementations such as
the manipulation of the external degrees of freedom of single atoms and BECs. We have also discussed some implementations of quantum memories with either matter wave solitons or light pulses interacting with three-level media. In a different context, we have also proposed the use of three-level techniques in systems of three coupled optical waveguides with the aim of spectral filtering of light beams. In addition, we have partially reviewed our recent work on the strong lasers field addressing the problem of the photoionization of the hydrogen atom with light beams carrying orbital angular momentum. Finally, very recently we have started up a laboratory on conical refraction and the latest results obtained on cascaded conical refraction have been summarized. We hope that all these examples of the investigation that is presently carried out in the Quantum and Atom Optics Group at the UAB will give to the reader a flavour of our present and future research plans.

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