Quantum Mechanics with Curved Photonic Structures

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Abstract - *Curved waveguide structures provide an accessible laboratory tool to investigate the optical analogues of many quantum phenomena encountered in atomic, molecular, and condensed-matter physics. In this contribution the most relevant quantum-optical analogies will be reviewed, including coherent destruction of tunneling, Bloch oscillations, coherent population transfer, and quantum Zeno effect.*

Introduction

Similarities between quantum and classical phenomena are not uncommon in physics albeit quantum and classical physics are grounded on different paradigms. Such analogies have been fruitfully exploited in emerging research areas such as photonic crystals, quantum computing, nano-devices and new forms of light (see [1] and references therein). Quantum-classical analogies in apparently unrelated fields have been also successfully exploited to mimic at a macroscopic level many quantum phenomena which are currently not of easy access in microscopic quantum systems. In particular, in the past recent years specially-designed waveguide-based photonic structures have proven to be a useful laboratory tool to investigate the optical analogues of a wide variety of coherent quantum effects encountered in different physical contexts, ranging from atomic, molecular, condensed-matter and matter-wave physics. Among others, we mention here the optical analogues of electronic Bloch oscillations and Zener tunneling [2, 3, 4, 6, 5, 7, 8], dynamic localization [9, 10], coherent enhancement and destruction of tunneling [11, 12], adiabatic stabilization of atoms in strong laser fields [13], Anderson localization [14, 15], and coherent population transfer [17, 18, 19]. In particular, the use of coupled waveguides with a curved optical axis introduces a kind of ”non-inertial forces” for light waves which are capable of mimicking the effects of electric and magnetic fields on the coherent quantum dynamics of a charged particle [16, 20].
It is the aim of the present contribution to review some of the most relevant quantum-optical analogies, including: coherent destruction of tunneling in driven bistable systems; electronic Bloch oscillations and related effects in crystalline potentials; coherent population transfer and adiabatic passage in laser-driven multilevel atomic or molecular systems; ionization suppression and adiabatic stabilization of atoms in ultra-strong laser fields; quantum decay control and Zeno effect in unstable quantum systems. Besides of general interest, the proposed analogies highlight new and unexpected ways to control light transfer and photon tunneling in integrated photonic structures.

Analogies with solid-state physics

The first broad category of quantum-optical analogies is that between light propagation in curved waveguide arrays and coherent electronic dynamics in crystalline potentials subjected to an applied dc or ac electric field. In this case, spatial light propagation along

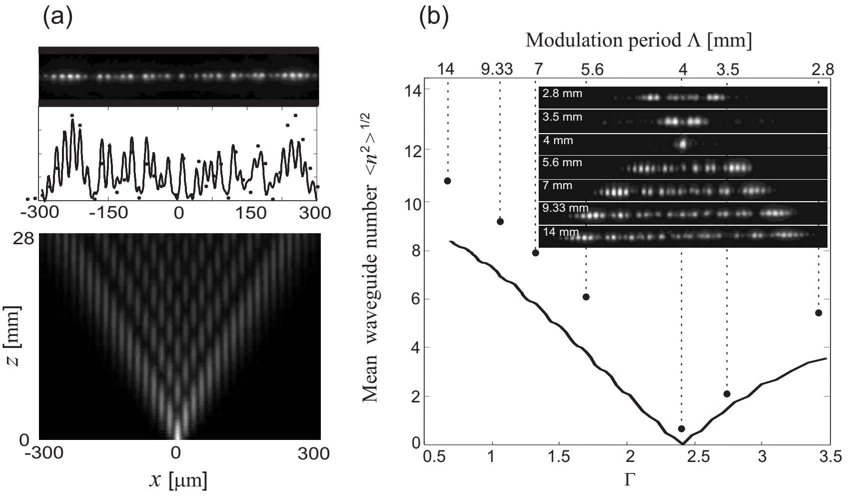

Figure 1: Optical analogue of electronic dynamic localization in an array of sinusoidally-curved waveguides (Ref.[9]). By varying the period Λ of waveguide bending, discrete diffraction in the array [in panel (a)] can be suppressed [see panel (b)].

the curved waveguide array mimics the temporal evolution of an electronic wave packet in the lattice driven by the applied electric field. The use of circularly-curved waveguide arrays mimics the effect of a dc electric field and results in the optical analogue of electronic Bloch oscillations and, at large curvatures, Zener tunneling [2, 3, 4, 6, 7, 8]. In periodically-curved arrays, an ac electric field is instead simulated, which enabled to demonstrate in the optical realm the analogue of dynamic localization [9] of electrons is solids (see Fig.1). Such effects have been observed by mapping the flow of light, visualized from the top of the waveguiding structure, using fluorescence imaging or near-field scanning optical microscopy (SNOM). The introduction of disorder in waveguide arrays have been also proposed and demonstrated to allow for the observation of the optical analogues of Anderson localization and metal-insulator transitions [14, 15]. Additionally, introduction of waveguide twist enables to mimic the dynamics of a Bloch particle in a magnetic field [20].

Analogies with atomic and molecular physics

The second broad category of quantum-optical analogies is that between light propagation in curved coupled waveguides and electronic dynamics and coherent population transfer induced by laser fields in atomic or molecular systems. A single waveguide possessing one (or more) guiding mode and the continuous spectrum of radiation modes behaves like an isolated atom. Introduction of a periodic curvature of the waveguide axis mimics the action of a laser field which can induce optical transitions between bound states of the atom or between a bound state and the continuum (ionization). In the optical system the temporal evolution of the electronic state is mapped into the spatial propagation of the light waves, and can be thus visualized in an experiment by fluorescence or SNOM imaging as briefly mentioned above. In this way, one can observe in the optical realm some unusual and still unexplored effects of atomic physics, such as suppression of ion-

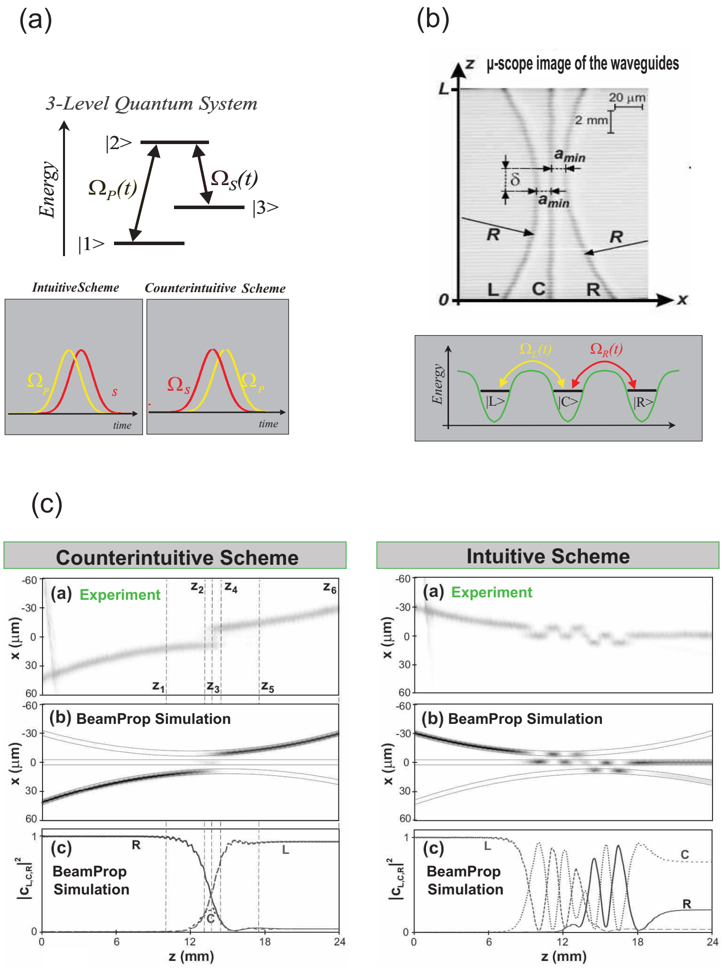

Figure 2: Adiabatic transfer of light in a triple waveguide system which mimics stimulated Raman adiabatic passage (STIRAP). (a) Schematic of coherent population transfer in a three-level atom driven by two delayed optical pulses in the intuitive and counterintuitive schemes. (b) Optical tunneling in a triple waveguide system and quantum-optical correspondence. (c) Light transfer dynamics (theory and experiment) corresponding to an intuitive and counterintuitive (STIRAP) pulse sequence (Ref.[17]).

ization and adiabatic stabilization of atoms in ultrastrong and high-frequency laser fields [13]. Other methods of coherent population transfer in atoms or molecules driven by laser pulses can be also exploited to transfer light among evanescently coupled optical waveguides in a counterintuitive way. For instance, the photonic analogue of stimulated Raman adiabatic passage enables to transfer light between two outer waveguides of an array with negligible excitation of all intermediate waveguides [17, 19](see Fig.2).

Analogies with quantum physics

The third category of quantum-optical analogies can be related to some rather general phenomena encountered in quantum physics. We just mention here coherent control of tunneling in driven bistable potentials and its enhancement [11] or suppression [12], the optical analogues of quantum collapses and revivals [21, 22], the control of quantum decay in unstable systems and the quantum Zeno effect [23, 24].

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