photonics

Editorial

Special Issue on Optical Quantum Manipulation of Rydberg Atoms

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Citation: Yan, D.; Wu, J.-H. Special Issue on Optical Quantum Manipulation of Rydberg Atoms. *Photonics* **2023**, *10*, 88. https://doi.org/10.3390/photonics10010088

Received: 29 December 2022
Accepted: 11 January 2023
Published: 13 January 2023

Rydberg atoms with large electric dipole moments, strong dipole–dipole interactions, and long radiative lifetimes have attracted great attention and become the subject of intense studies in the past two decades. Benefiting from these unique properties, significant progress has been made, e.g., from fundamental quantum physics and quantum optics to quantum information and precision metrology, by driving Rydberg atoms with coherent optical fields into specific level configurations. The resultant quantum manipulation schemes promise an effective mapping of atom–atom interaction to photon–photon interaction, thus allowing a fine engineering of both atomic and photonic states. This Special Issue aims at presenting cutting-edge research articles predicting, understanding, and exploiting new nonlinear and nonclassical features of Rydberg atoms in the free space or optical lattices, as an attractive neutral-atom platform to implement nontrivial manipulation tasks inaccessible for ordinary atoms. Eight original research papers have been published in this Special Issue, and a brief overview of these papers is presented below.

Gary McCormack et al. studied the chaos and hyperchaos of Rydberg-dressed Bose–Einstein Condensates (BECs) in a one-dimensional optical lattice described by an extended Bose–Hubbard model [1]. They analyzed, in particular, the dynamical stability of such BECs in the mean-field regime by focusing on two configurations with respect to the ground state and the localized state, respectively. Both configurations are found to have multiple positive Lyapunov exponents, hence exhibiting hyperchaotic dynamics. Moreover, linear and hysteresis quenches of the lattice potential and the dressed interaction could lead to distinct dynamics owing to the chaos and hyperchaos, relevant to current research on collective nonlinear dynamics of BECs with long-range interactions. In [2], two-dimensional stable solitons are found to exist in the binary atomic BECs with spin–orbit coupling (SOC) and Rydberg–Rydberg interaction (RRI). This is examined by applying an imaginary time evolution method to solve the Gross–Pitaevskii equations with an emphasis placed on the stability of solitons. It is found that stable zero-vorticity and vortical solitons can be realized and, more importantly, tuned by the local and nonlocal nonlinearities depending on SOC and RRI.

A calculation of the magic wavelength on the $6S_{1/2} \leftrightarrow nP_{3/2}$ transition of Cesium atoms is performed by introducing an auxiliary transition between the Rydberg state $nP_{3/2}$ and a low-excited state [3]. The corresponding magic detuning depends on the polarization angle of a linearly polarized trapping laser and is also related to the principal quantum number n. The resultant magic optical dipole trap can confine both ground-state and Rydberg-state atoms, which is of significance for the application of high-repetition-rate accurate manipulation of Rydberg atoms on high-fidelity entanglement and logic gate operation. In [4], an experiment is done for observing the autoionization and analyzing relevant mechanisms of Cesium atoms excited to the Rydberg state $37D_{5/2}$ by varying the time delay and the Rydberg density. The results show that a change of the Rydberg density can modify not only the initial ion signal but also the evolution of Rydberg atoms, with the initial ionization being mostly attributed to the blackbody radiation (BBR)-induced photoionization and the BBR-induced transitions to nearby easily ionized Rydberg states. These findings are instructive for further investigations on collision dynamics and many-body physics of Rydberg atoms.

An experiment is demonstrated on the formation of a one-dimensional photonic lattice with three-level Rubidium atoms in the regime of electromagnetically induced transparency (EIT) [5]. This is realized by applying a coupling field with a spatially periodic intensity distribution so that an incident probe field suffers a dynamically tunable and spatially modulated susceptibility, as verified by the discrete diffraction pattern observed at the output plane. This work opens the door for introducing strong Rydberg interactions to manipulate light beam dynamics in atomic lattices and also provides an accessible periodic environment for exploring Rydberg-atom physics and applications. In [6], it is shown that a sample of Rydberg atoms can be engineered to realize a two-dimensional electromagnetically induced grating (EIG), as they are driven by a control field periodically modulated in two orthogonal directions. A probe field incident upon this grating exhibits an asymmetric intensity distribution depending on relevant modulation parameters of the control field as well as the atomic density and length. It is of particular interest that higher-order diffraction intensities can be enhanced in different ways and the asymmetric diffraction distribution can be shifted to different quadrants, which may be used to develop new photonic devices required in future all-optical networks.

A theoretical and experimental investigation is presented in [7] to improve and determine the sensitivity of a Rydberg atom-based microwave radio-frequency (RF) sensor. The four-level EIT model refers to a two-color cascading laser excitation from the ground state to a Rydberg state and a microwave RF coupling between this Rydberg state to another Rydberg state. The sensitivity of this atomic RF sensor can be well manipulated by controlling the strengths and detunings of the two applied lasers, especially in the presence of an asymmetrically optical splitting. The corresponding experimental result is $12.50(04)$ $\text{nVcm}^{-1}\text{Hz}^{-1}$, as all parameters have been optimized. A three-level EIT scheme is proposed in [8] to investigate the in-phase and anti-phase correlated evolutions of two Rydberg sub-superatoms (SSAs) formed by two spatially separated atomic sub-ensembles in the blockade regime. It is found that both the correlated evolution and the collective-state entanglement are sensitive to the atomic number in each Rydberg SSAs so that it is viable to manipulate the Rydberg atoms over long distances from the single quantum level to the mesoscopic level by changing the atomic number. This work can be readily extended to the case of many SSAs and may have potential applications in quantum information processing and quantum many-body physics.

Funding: This research received no external funding.

Acknowledgments: We would like to thank all authors for their great contributions to this Special Issue and all reviewers for providing constructive review comments and recommendations. We also appreciate Daisy He and other editors of the Photonics journal for their excellent support with this Special Issue.

Conflicts of Interest: The authors declare no conflict of interest.

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