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Long-Range Quantum Magnetism in Atom-Nanophotonic Hybrid Lattices

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14. ABSTRACT
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Abstract

The research program aims at utilizing ultracold atoms trapped near the surface of nanophotonics to emulate long-range quantum magnetism with photon-mediated spin-spin interactions. We explore deterministic loading of an array of ultracold atoms near the surface of high quality nanophotonic resonators to achieve strong, dispersive atom-light interactions with high single-atom cooperativity parameter (C>100). We explore atom-photon coupling on a fabricated microring structure, with the goal to realize rudimentary pairwise-tunable spin interactions between two trapped atomic pseudospins. The ultimate goal of this research program is to enable direct explorations of a remarkable range of quantum spin models beyond conventional condensed matter settings to provide valuable insights for the universal quantum dynamics in long-range many-body systems.

Publications resulting from the AFOSR support:
(* marks Purdue participants)
Peer reviewed publications

1. "Colloquium: Quantum matter built from single atoms and photons" D. E. Chang, J. S. Douglas, A. González-Tudela, C.-L. Hung*, and H. J. Kimble, Review of Modern Physics 90, 031002 (2018).
2. "Microring resonators on a suspended membrane structure for strong atom-light interactions.", Tzu-Han Chang*, Brian Fields*, May E. Kim*, and C.-L. Hung*, Optica 6, 1203-1210 (2019).
3. "Trapping single atoms on a nanophotonic circuit with configurable tweezer lattices" M. E. Kim*, T.-H. Chang*, B. M. Fields*, C. A. Chen*, C.-L. Hung*, Nature Communications 10, 1-8 (2019).
4. "Tow-dimensional photonic crystals for engineering atom-light interactions" S.-P. Yu, J. A. Muniz, C.-L. Hung*, H. J. Kimble, Proc. Natl. Acad. Sci. 116, 12743-12751 (2019).
5. "Efficiently coupled microring circuit for on-chip cavity QED with trapped atoms" Tzu-Han Chang*, Xinchao Zhou*, Ming Zhu*, Brian Fields*, and C-L. Hung*, Appl. Phys. Lett. 117, 174001 (2020).
6. "Resonator-assisted single-molecule quantum state detection" Ming Zhu*, Yan-Cheng Wei, and C.-L. Hung*, Phys. Rev. A 102, 023716 (2020).

Conference papers

7. "Coupling single atoms and molecules to nanophotonic resonators" M Zhu*, TH Chang*, YC Wei, X Zhou*, B Fields*, H Tamura*, CL Hung*, SPIE OPTO Symposium: Optical and Quantum Sensing and Precision Metrology 11700, 117003R (2021).

8. "Microring resonators on a suspended membrane circuit for atom-light interactions" H Tamura*, TH Chang*, X Zhou*, B Fields*, M Zhu*, CL Hung*, SPIE OPTO Symposium: Integrated Optics: Devices, Materials, and Technologies XXV 11689, 116891D (2021).

Selected discussions on publications

Trapping single atoms on a nanophotonic circuit with configurable tweezer lattices [3]

We report laser cooling and localizing cold atoms on silicon nitride nanostructures fabricated on a transparent membrane substrate. Using an optical tweezer that focuses on the surface of a planar nanophotonic structure, cold atoms can be trapped and directly fluorescence imaged on an electron-multiplied charged coupled device camera. It is further shown that an optical tweezer can be converted into an optical conveyor belt, transporting trapped atoms into or out of the tweezer focus for vertical positioning near the planar dielectrics for possible applications in atom-nanophotonics lattice assembly.

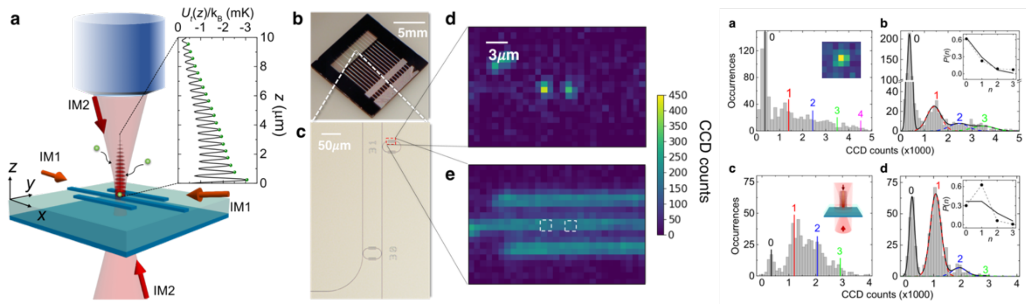

Figure 1 *Trapping and imaging single atoms on a planar nanophotonic circuit. M. E. Kim et al. Nature Communications 10 (1), 1-8 (2019) [3].*

Microring resonators on a suspended membrane circuit for atom–light interactions [2]

We present the first silicon nitride microring resonators on a transparent silicon dioxide-nitride multi-layer membrane as a scalable atom–light photonic interface. We discuss schemes for trapping and sorting laser cooled atoms at around 100 nm from the microring surface, permitting the formation of an organized, strongly interacting atom–photonic hybrid lattice. We demonstrate small radius (around 16 μm) microring and racetrack resonators with a high-quality factor (Q) of 3.2×10^5, projecting a single atom cooperativity parameter (C) of 25 and a vacuum Rabi frequency ($2g$) of $2\pi\times340$ MHz for trapped cesium atoms interacting with a microring resonator mode. This work is published in Optica 6, (9) 1203 (2019) [2].

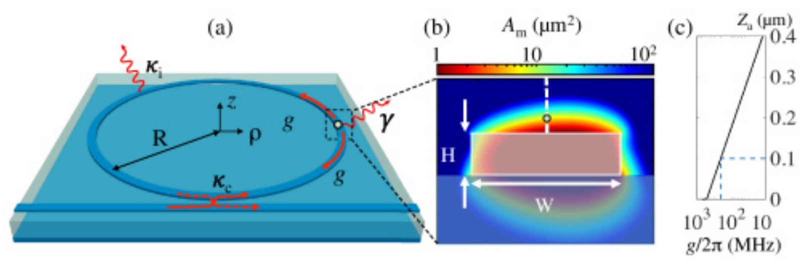

Figure 2 *Microring optimized to achieve strong atom-photon coupling for atom-light interactions in cavity QED.*

Efficiently coupled microring circuit for on-chip cavity QED with trapped atoms [5]

We present a complete fabrication study of an efficiently coupled microring optical circuit tailored for cavity QED with trapped atoms. The microring structures are fabricated on a transparent membrane with high in-vacuum fiber edge-coupling efficiency in a broad frequency band. In addition, a bus waveguide pulley coupler realizes critical coupling to the microrings at both of the cesium D-line frequencies, while high coupling efficiency is achieved at the cesium "magic" wavelengths for creating a lattice of two-color evanescent field traps above a microring. This work is published in a special issue "Hybrid Quantum Devices" in Applied physics letter 117, 174001 (2020) [5].

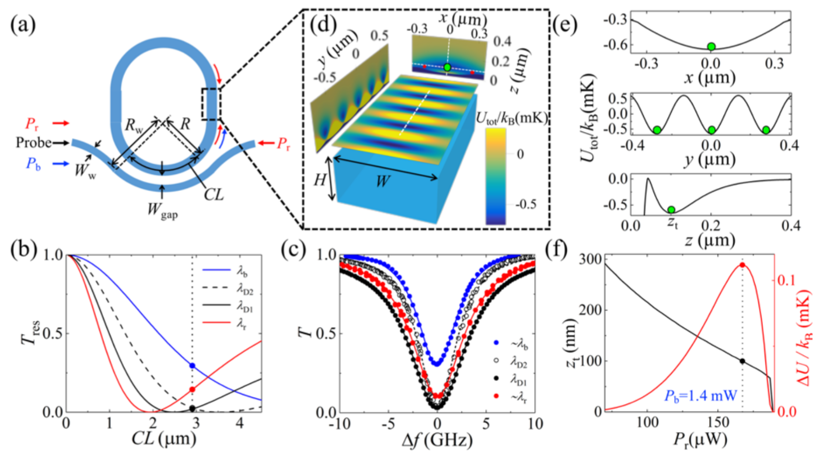

***Figure 3** Efficiently coupled microring at cesium D-lines and the formation of two-color evanescent wave trap.*

Discussions on results during the final funding period

Microring resonators on a suspended membrane circuit for atom–light interactions [8]

We have employed chemical mechanical polishing (CMP) technique to reduce surface roughness of our membrane substrate. We have achieved more than 10-fold improvement in the quality factor, bringing intrinsic $Q_i > 1$ million and loaded $Q > 5 \times 10^5$ to significantly boost the projected performance of our microring platform (Figure 4).

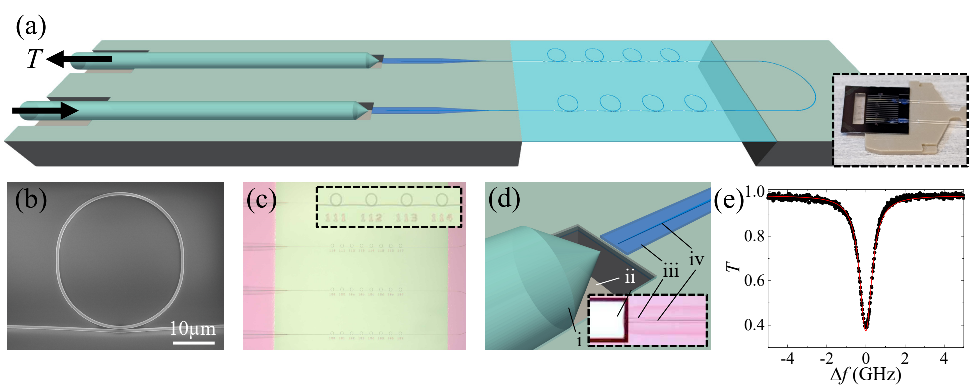

***Figure 4** Overview of the microring circuit. (a) Schematics of microring resonator array. Inset shows a fabricated chip. (b) SEM image of a microring resonator and a bus waveguide coupler. (c) Optical micrograph and a zoom-in view (inset) of the microring resonator array. (d) Schematics and photograph (inset) of a lensed fiber edge--coupler (i) to a top-cladded bus waveguide (iv). (e) Transmission spectrum of a resonant microring near cesium D1-line. Resonator intrinsic linewidth* $< 2\pi \times 700$ *MHz (FWHM), quality factor* $Q > 5 \times 10^5$.

Realization of a nearfield optical hybrid trap on a microring and preliminary demonstration of atom-WGM photon coupling

This is the first-time single atoms can be guided to the nearfield of a planar nanophotonic structure and can be directly probed. The so-called *hybrid* trap utilizes a tightly-focused, bottom-illuminating optical beam, prepared at $\lambda_r = 935$nm, to form a highly localized, *smooth* attractive potential on top of the microring waveguide [Fig. 5 (a)]. In addition, an evanescent field of a whispering gallery mode (WGM), designed at $\lambda_b = 793.5$ nm, forms a short-ranged repulsive potential above a microring, closing the trap near the surface and preventing the hybrid trap from completely opening due to atom-surface Casimir-Polder interaction. This optical micro-trap is designed using all magic wavelengths of cesium D2-transitions, imposing zero differential scalar light shift between the ground ($6S_{1/2}$) and the excited ($6P_{3/2}$) states. For our initial trap realization, nevertheless, we excite a blue detuned WGM at a frequency of ~353.08 THz, which is one free spectral range away from a microring resonance that is locked the cesium D2 line (351.722 THz). The power required to excite the WGM is $\sim$0.5 mW and the trap depth is $\gtrsim$ 0.5 mK, controlled by the power ratio between the red- and blue-detuned light. To ensure trap stability, the frequency of the excitation laser is locked to the WGM resonance, while the microring is feedback stabilized to the cesium D2 line when we perform the experiment. Unlike a top-illuminating optical potential, which forms an optical lattice, this hybrid trap is smooth along the vertical z-axis, supporting single potential minimum at a tunable height around $z_t \approx 260$ nm directly above the dielectric surface of a microring. This smooth potential allows single atoms to be directly loaded into the trap using conventional polarization cooling method.

Figure 4 illustrates the hybrid trap and our initial probing of atom-photon interaction. To confirm that single atoms can be loaded into the hybrid trap, we inject a resonant probe into the microring and record the change in transmission photon count. Due to near-critical bus waveguide coupling, the probe transmissivity is $T_0 \approx 0.03$ for a microring without trapped atoms. Introducing trapped atoms, we observe an increase of transmission by ~ 60% due to an atom-WGM coupling induced transparency effect, similar to an electromagnetically-induced transparency. By further adjusting probe power and record the saturation behavior of the transmission spectra, we have estimated single atom $g \approx 2\pi \times 35$ MHz (trap @ $z \approx 260$ nm) with an average atom number

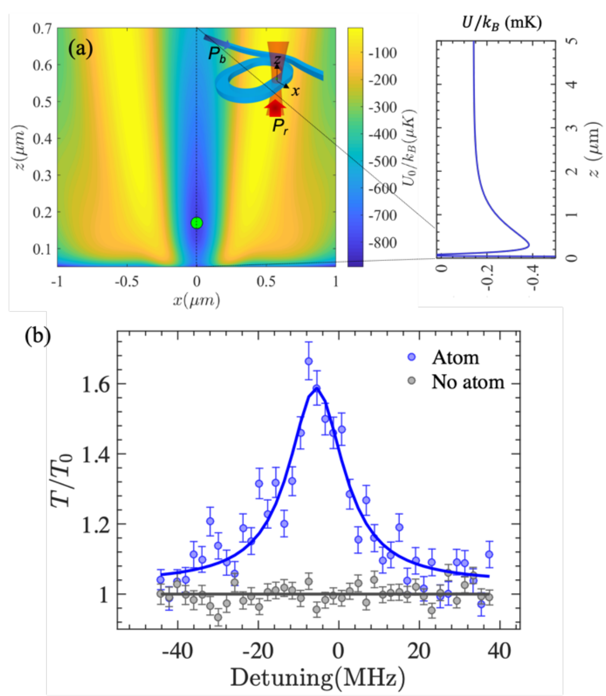

Figure 5 *Preliminary demonstration of atom-WGM photon coupling in a surface micro-trap (a) Hybrid trap potential. (b) Normalized bus waveguide transmission spectrum with and without trapped atoms (Manuscript under preparation).*

$\bar{N} = 1$. We have also performed theoretical fit to the spectrum $T(\delta, g) = |\frac{g^2+(i\delta+\frac{\gamma}{2})(i\delta+\frac{\kappa_i-\kappa_c}{2})}{g^2+(i\delta+\frac{\gamma}{2})(i\delta+\kappa/2)}|^2$, where we have used the resonator linewidth $\kappa = \kappa_c + \kappa_i \approx 2\pi \times 6$GHz, the bus waveguide coupling rate $\kappa_c \approx 0.7\kappa_i$ (intrinsic loss rate), and $\gamma \approx 2\pi \times 5.2$ MHz is the atomic linewidth. This yields a cooperativity parameter $C = 4g^2/\kappa\gamma \approx 0.2$. This rather small cooperativity parameter is anticipated since this is an optical circuit fabricated prior to the pandemic with a lower total quality factor $Q \approx 6 \times 10^4$. We anticipate more than 10-fold increase to $C \gtrsim 10$ after we implement the new optical circuit (chemical mechanical polished) with $Q > 5 \times 10^5$, see Figure 4, and with an improved hybrid trap with trap location $z_t \approx 100\sim150$ nm.