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研究課題名（英文）Developing a fiber optical quantum interface using trapped atoms and nanofiber based photonic crystal cavity

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研究成果の概要（和文）：本プロジェクトでは、高品質フォトニック結晶（PhC）共振器をナノファイバ上に作製し、その共振器上に光ピンセットベースの単一原子トラップを開発した。PhC共振器は、トラップされた単一原子とナノファイバー導波モードとの効率的なインターフェースとして機能するよう設計した。共振器モード間の干渉により独特のスペクトル特性が観測されることを実証した。PhCナノファイバー共振器モードの光熱効果による安定化を実現し、ファイバ導波モードによる単一原子のトラッピングとリアルタイム観測を実証した。今回の成果は、光ファイバプラットフォーム上で単一原子事象を決定論的に準備する量子フォトニクス技術を可能にするものである。

研究成果の学術的意義や社会的意義
量子情報処理技術は従来の情報通信技術を著しく進歩させ社会に新たな価値を創造し得るものである。そのための重要な課題は、個々の量子系（原子、イオン、固体量子ビットなど）を分離し、それらをファイバ伝播光子により効率的にインターフェースすることである。本プロジェクトでは、トラップされた単一原子をファイバ導波モードに効率的にインターフェースする方法を実現し、それがリアルタイムで観測できることを実証した。本成果は、決定論的な方法で様々な量子フォトニクス実験を実行するための新しいプラットフォームを提供し、量子ネットワークのための新しい技術を可能にするものである。

研究成果の概要（英文）：In this project, we have developed an optical tweezer based single atom trap on a photonic crystal (PhC) nanofiber cavity. Fabrication of high quality PhC cavities on nanofibers was demonstrated. The cavities were designed for efficient interfacing of trapped single atoms to nanofiber guided modes. The interference between the cavity modes leading to unique spectral features was investigated. Photo-thermal stabilization of the PhC nanofiber cavities under ultra-high vacuum conditions was achieved. It was demonstrated that single atoms can be successfully trapped on the nanofiber cavity and can be observed in real-time through the fiber guided modes. This enables deterministic preparation of single atom events for quantum photonics applications on an all-fiber platform.

研究分野：原子・分子・量子エレクトロニクス

キーワード：Quantum Optics　Nanophotonics　Single Atom Tweezer　Nanofiber Cavity QED　Quantum Photonics　Quantum Information

１．研究開始当初の背景

Realizing an efficient quantum interface will enable deterministic control and readout of the quantum states for quantum information processing. In this context, atomic qubits have unique capabilities for scalability and optical interfacing. A recent trend towards optical interfacing is to combine the atomic qubits with nanophotonic platforms and develop hybrid quantum systems, where efficient quantum state-transfer between atoms and photons can be realized.

２．研究の目的

Adiabatically tapered single mode optical fiber with subwavelength diameter waist (nanofiber) provides a unique all-fiber platform for quantum photonics applications. The transverse confinement of photonic modes in the nanofiber enables strong light-matter interaction. Furthermore, the coupling between the atom and the nanofiber guided modes can be substantially improved by introducing an in-line fiber cavity. In this project, we develop an optical tweezer based single atom trap on a nanofiber based photonic crystal (PhC) cavity. This will enable deterministic quantum state-transfer between a single atom and fiber-guided photons.

３．研究の方法

High quality PhC cavities are fabricated on the nanofibers using femtosecond laser ablation technique. Laser-cooled single atoms are trapped using a tightly focused dipole trap enabling an optical tweezer for single atoms. By focusing the tweezer beam on the nanofiber, standing-wave like nanotraps are formed close to nanofiber surface due to reflection from the fiber surface. This enables tight localization of single atoms and efficient interfacing with the nanofiber guided modes.

４．研究成果

In the following we describe the representative results.

(1) Fabrication of high quality PhC nanofiber cavities for cavity QED

A unique feature of the nanofiber based cavity, is that the transverse confinement and cavity length can be independently controlled. Therefore, by selecting a proper cavity length, the cavity QED characteristics can be manipulated. We have demonstrated the fabrication of a 1.2 cm long cavity directly on a nanofiber that can operate in both "strong-coupling" and "Purcell" regime of cavity QED with moderate finesse and high transmission. A schematic diagram of the cavity is shown in Fig. 1(a). The cavity is formed by fabricating two photonic crystal structures (PhCNs) on a nanofiber using femtosecond laser ablation. The two PhCNs are separated by 13 mm on a 15 mm long nanofiber waist with highly uniform diameter of 500 nm. A typical scanning electron microscope (SEM) image of the PhCN structure, is shown in the inset. The PhCNs act as high quality Bragg reflectors for the guided light and thus a cavity is formed between the two PhCNs.

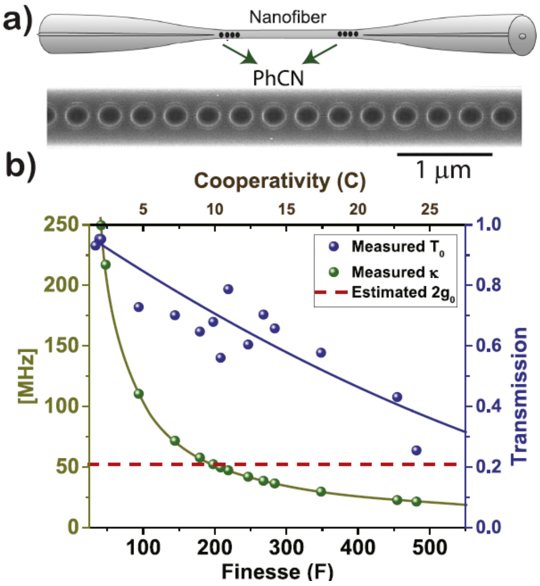

Fig. 1: (a) Schematic diagram of the PhC nanofiber cavity. (b) Cavity QED characteristics. κ: cavity decay rate, T_0: on-resonance transmission, $2g_0$: atom-photon coupling rate.

The cavity characteristics are summarized in Fig. 1(b). The linewidth (κ) of the cavity modes (green dots) and the corresponding on-resonance transmission (T_0) values (blue dots) are plotted against the finesse (F). The atom-photon coupling rate ($2g_0$) shown by the red-dashed line, is estimated for a single Cs-atom trapped 200 nm away from the fiber surface. The cavity modes with finesse value in the range 200-400, can enable "strong-coupling" regime of cavity QED with high single atom cooperativity of 10-20. Such cavity modes can still maintain the transmission between 40-60%, suggesting a one-pass intra-cavity transmission of 99.53%. Other cavity modes, which can enable cooperativity in the range 3-10, show transmission over 60-85% and are suitable for fiber-based single photon sources and quantum nonlinear optics in the "Purcell" regime.

(2) Interference between polarization modes in a PhC nanofiber cavity

The PhCNs act as polarization dependent Bragg reflectors due to the broken cylindrical symmetry of the nanofiber. This leads to formation of two sets of cavity modes with orthogonal polarizations. We have demonstrated that the coherent interaction between the two sets of modes leads to unique spectral features. Fano-type resonances and optical analogue of electro-magnetically induced transparency (EIT) are observed in the weak coupling regime. In the strong coupling regime, avoided-crossing between two photonics modes, is observed. Such interaction arises due to intra-cavity polarization mixing. The observed line shapes were reproduced using a multiple-mode interference model under different coupling regimes. A representative data illustrating the EIT-like spectral features are shown in Fig. 2. Such unique spectral characteristics may further enhance the capabilities of the nanofiber cavity.

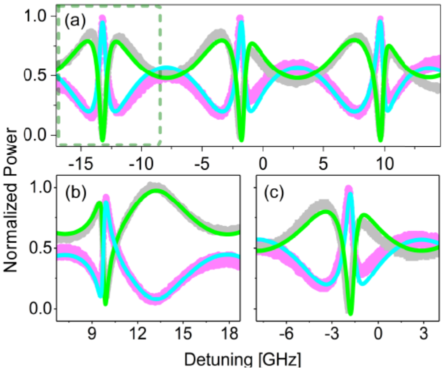

Fig. 2: Two-mode interference in a PhC nanofiber cavity. The gray and magenta traces show the measured transmission and reflection spectra, respectively. The green and cyan curves show the respective fittings using the multiple-mode interference model.

(3) Tuning and stabilization of a PhC nanofiber cavity

Stabilization of the PhC nanofiber cavity under ultra-high vacuum (UHV) environment is an essential requirement for functional implementation of such cavities for various quantum photonics applications. In this regard, the conventional mechanical feedback based stabilization scheme fails seriously as it induces further instabilities arising due to the onset of mechanical vibrations of such a thin and long tapered fiber. We have demonstrated the photo-thermal tuning and stabilization of a centimeter-long PhC nanofiber cavity, under UHV conditions. We have shown that due to the strong photo-thermal effects, the PhC nanofiber cavity can be stabilized using only a few μW of resonant guided light.

(4) Trapping single atoms on a PhC nanofiber cavity

We have demonstrated an optical tweezer based single atom trap on an optical nanofiber cavity. We show that fluorescence of single atoms trapped on the nanofiber, can be readily observed in real-time through the fiber guided modes. The photon correlation measurements further clarify the atom number and the dynamics of the trap. The trap lifetime was measured to be 50 ms. These results may open new possibilities for deterministic preparation of single atom events for quantum photonics applications on an all-fiber platform.

(4.1) Trapping scheme

A schematic diagram of the experiment is shown in Fig. 3(a). A nanofiber cavity is formed by fabricating two PhCN structures on the nanofiber. Single atoms are trapped on the nanofiber segment between the two

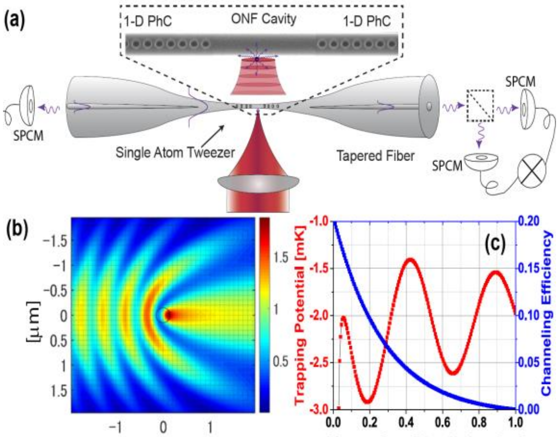

Fig. 3: (a) Schematic diagram of the single atom tweezer on a PhC nanofiber cavity. (b) Intensity pattern of the trapping light around the nanofiber. (c) Estimated trapping potential and corresponding channeling efficiency.

PhCNs. The dipole trap beam is tightly focused to 1 μm beam waist using a high numerical aperture lens introduced into the vacuum chamber, forming an optical tweezer for single atoms. When the tweezer beam hits the nanofiber, it forms standing wave like nanotraps close to nanofiber due to reflection from the fiber surface.

We have found that the key design principle for the success of the trapping scheme, is the choice of nanofiber diameter. From the theoretical simulations, we have found that for trapping Cs-atoms using magic-wavelength of 937 nm, a nanofiber diameter of 300 nm gives the optimum trapping condition. The simulated intensity profile around the nanofiber is shown in Fig. 3(b). The nanofiber position is indicated by a black circle at the center. The beam is irradiated perpendicular to the nanofiber from left side and has a polarization parallel to the fiber axis. It may be seen that standing wave like nanotraps are formed in the irradiation side. In Fig. 3(c), the estimated trapping potential and the corresponding channeling efficiency are plotted as a function of radial distance from the fiber surface. It may be seen that the closest trapping minimum is created within 200 nm from the fiber surface and a channeling efficiency of 10% can be realized at the trap position. Therefore, by implementing a nanofiber cavity with a central region of 300 nm diameter, has enabled the successful demonstration of the trapping scheme.

(4.2) Real-time observation of single atoms trapped on the nanofiber

In the experiment, the tweezer beam is focused on the nanofiber and laser-cooled Cs-atoms are loaded into the trap from a magneto optical trap (MOT). The photon counts measured through the nanofiber cavity are monitored while the trap is being continuously loaded.

The typical photon counts measured through the nanofiber cavity, is shown in Fig. 4(a). It may be seen that discrete step-like signals with a height of 40 counts/ms are observed above a background of 10-20 counts/ms. Typical temporal duration of the step-like signal ranges from 10 to 100 ms. This clearly indicates that single atoms are trapped and interfaced to the nanofiber cavity. The step-like signals are due to the channeling of single atom fluorescence into the nanofiber guided modes.

(4.3) Photon correlation measurement

We have carried out photon correlation measurements of the fluorescence signal to further clarify the atom number and the dynamics of the trap. A typical normalized photon correlation signal ($g^2(\tau)$) is shown in Fig. 4(b). The blue trace shows the measured correlation signal and the red curve shows the theoretical fit. The correlation signal shows anti-bunching behavior with $g^2(0)=0.47$. The antibunching of the fluorescence signal, confirms that only single atoms are trapped on the nanofiber.

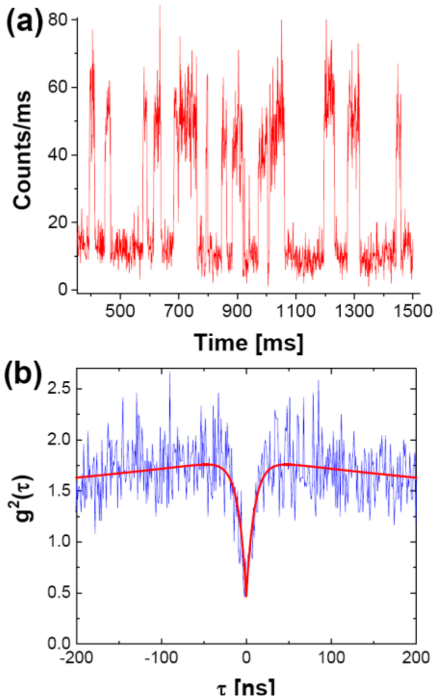

Fig. 4: Real-time observation of trapped single atoms on the nanofiber. (a) Fluorescence signal of trapped single atoms measured through the nanofiber cavity. (b) Photon correlation of the fluorescence signal showing anti-bunching.

(4.4) Trap lifetime measurement

The real-time observation of single atoms trapped on the nanofiber enables various experiments to be performed in a deterministic fashion. Once a single atom is trapped on the nanofiber, a step-increase in the photon counts is observed through the nanofiber. This step-like signal is used to trigger the experimental sequence. As a demonstration experiment, we present the lifetime measurement of the trapped single atoms on the nanofiber. The time sequence of the experiment is shown in Fig. 5(a). The experiment starts with polarization gradient cooling (PGC) for 1 ms, followed by a dark-period of Δt, during which the MOT beams are switched off. After the dark-period, the MOT beams are switched on again to detect the presence of the atom in the trap.

A typical measurement event is shown in Fig. 5(b). It may be seen that the presence of a single atom in the trap was inferred from the sudden rise in the photon counts and the experiment was triggered at 0 ms time. There was a dark-period of 30 ms during which the photon counts were zero. A high level of photon counts after the dark-period indicates that the atom was still present in the trap. The blue dots in Fig. 5(c), show the survival probabilities for different dark times (Δt). The red curve shows the exponential fit. From the fitting, the trap lifetime was estimated to be 50 ms.

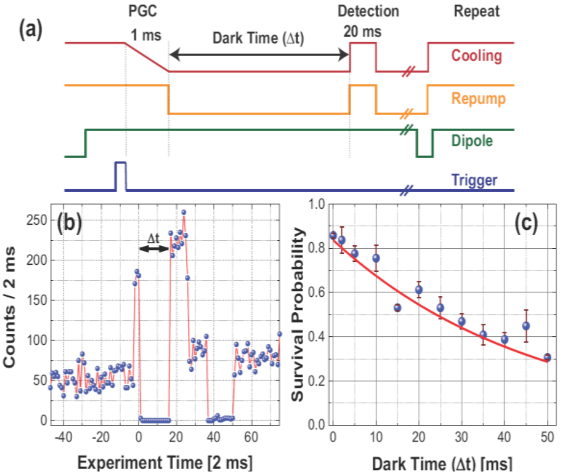

Fig. 5: Lifetime of trapped single atoms on the nanofiber. (a) Time sequence of the experiment. (b) A typical measurement event. (c) Survival probability vs dark time.

５．主な発表論文等

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