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科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　６ 年　６ 月 １１ 日現在

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研究課題名（和文） Optically interfacing a single atom tweezer array for quantum photonics

研究課題名（英文） Optically interfacing a single atom tweezer array for quantum photonics

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研究成果の概要（和文）：このプロジェクトでは、ナノファイバーまたはナノファイバーキャビティ上に単一原子のアレイをトラップすることを目指しました。フェムト秒レーザーを使用して、直径 300 nm のナノファイバー上にフォトニック結晶キャビティを作製できることを実証しました。複数の RF トーンで駆動される音響光学偏向器を備えた実験装置を開発し、ピンセットの 1 次元アレイを作成しました。自由空間内のピンセット アレイ内の単一原子のトラップとイメージングを実証しました。
別のアプローチでは、ナノファイバー上の自然放出の強力なプラズモニック増強を実証し、ファイバー誘導モードへの明るく偏光した単一光子放出をもたらしました。

研究成果の学術的意義や社会的意義
量子コンピュータと量子情報技術の研究は進んでおり、近い将来、社会的、学術的に大きな影響を与える可能性があります。そのため、単一原子と単一光子を制御するための新しい技術の開発が不可欠です。このプロジェクトでは、光ピンセットを使用してナノファイバー上の単一原子アレイをトラップすることを目指しました。自由空間での単一原子アレイのトラップとイメージングを実証しました。この単一原子アレイをナノファイバーと組み合わせることで、ファイバー誘導単一光子を制御するための新しいプラットフォームが可能になり、量子ネットワークに使用できます。

研究成果の概要（英文）：In this project, we have aimed to trap an array of single atoms on a nanofiber or nanofiber cavity. We have demonstrated fabrication of photonic crystal cavities on a 300 nm diameter nanofiber using femtosecond laser. This diameter is crucial for trapping single atoms on nanofiber using optical tweezers. We have developed an experimental apparatus equipped with acousto-optic deflector driven by multiple RF-tones to create a 1-D array of tweezers. We have demonstrated trapping and imaging of single atoms in an array of tweezers in free-space.
In a different approach, we have demonstrated strong plasmonic enhancement of spontaneous emission on nanofiber leading to bright and polarized single photon emission into fiber-guided modes.

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

Preparation and coherent control of strongly correlated spin chains is essential for quantum information science. A key requirement is to establish long-range interaction between stable, spatially ordered and individually controlled spin states. In this direction, there has been significant progress to realize a quantum computer using the large dipole moment of special atomic states like Rydberg atoms or polar molecules. In a different approach, one may realize long-range interaction between atoms mediated through a single photonic mode. Photon-mediated atom-atom interaction can be promising for scalable multi-qubit quantum nodes and quantum networks.

２．研究の目的

An optical nanofiber (ONF), a tapered optical fiber with subwavelength diameter waist, has unique capabilities as a quantum interface that is beyond free-space optics. The guided mode of ONF has subwavelength transverse confinement and it can be maintained over a long propagation length. Individual atoms in the vicinity of ONF can strongly couple to ONF guided mode. By trapping an array of atoms on the ONF one can explore the cooperative atom-atom interaction mediated by guided modes. In this project, we aim to develop an optical tweezer-based scheme to trap and interface an array of individually controlled single atoms to the ONF guided modes. We will implement such a platform for controlling the generation and propagation of fiber-guided single photons.

３．研究の方法

ONFs with 300 nm diameter are fabricated by adiabatically tapered single mode optical fibers using heat and pull technique. Photonic crystal nanofiber (PhCN) cavities are fabricated on ONFs using femtosecond laser ablation. Laser-cooled Cs-atoms are prepared using magneto-optical trap (MOT). A 1-D array of tweezer beams is prepared using an acousto-optic deflector (AOD) driven by multitone rf-signal. The number of tweezer spots and the spacing between them is controlled by the multitone RF-frequencies. The tweezer beams are focused down to a beam waist of 1 μm using an aspheric lens. An EMCCD camera is used to image the array of trapped single atoms. A galvo mirror is used to transport the atom array on to the ONF to trap the atom array on the ONF.

４．研究成果

In the following we describe the representative results.

(1) Fabrication of 300 nm diameter ONF and ONF cavities

In our previous research, we have demonstrated trapping and interfacing individually trapped single Cs-atoms to an ONF cavity using optical tweezer [1]. From this research, we have found that ONF diameter of around 300 nm is the optimum diameter for this optical tweezer-based trapping scheme. The above research was performed using a notch ONF cavity. The ONF waist had a central notch that goes to 300 nm diameter and two flat plateau regions of 500 nm diameter on either side of the notch. The PhCNs were fabricated on the plateau regions (500 nm diameter) using femtosecond laser and the atom was trapped at the central 300 nm diameter region. However, the presence of the intra-cavity notch may induce additional loss. Also, it leads to a longer cavity length.

In this project, we have attempted to fabricate PhCN cavities directly on a 300 nm diameter ONF using femtosecond laser ablation [2]. First, we have optimized our ONF fabrication method to fabricate 300 nm diameter ONFs with high transmission and high reproducibility. We have succeeded in reproducible fabrication of ONFs with diameters 310±5 nm and with transmission of 98±1%.

Next, we have redesigned our femtosecond laser fabrication [2] setup to fabricate PhCN cavities on a 300 nm ONF with desired resonance wavelength around 852 nm (Cs-D2 line). A schematic of the PhCN cavity is shown in Fig. 1(a). Two PhCN structures are fabricated with a gap region on the ONF. A typical scanning electron microscope (SEM) image of the fabricated structure is shown in the inset. One can see that periodic nano-craters are fabricated on an ONF of diameter around 310 nm with a period of around 420 nm. Polarization-resolved transmission spectra are shown in Fig. 1(b). One can see a broad dip due to the reflection band around 850-852 nm and sharp transmission peaks are the cavity modes. From the spacing between cavity modes, we estimate the free spectral range (FSR) of 158 GHz that corresponds to a cavity length of 0.94 mm. This cavity length is 6.5 times smaller than the previous research [1]. For the polarization (X-Pol) along the nano-craters, the cavity modes have a finesse of 100 – 200 with high transmission. From this, we estimate the achievable single atom cooperativity of 10 – 25 and fluorescence coupling efficiency of >90% into ONF guided mode. However, due to the thin diameter of ONF there are various difficulties, and the success probability of fabricating a good cavity is rather less. We are investigating to further improve the success probability.

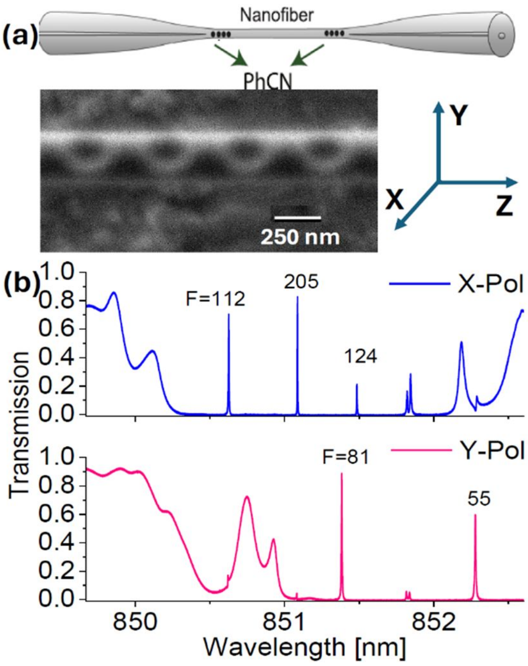

Fig. 1: (a) Schematic diagram of PhCN cavity. Inset shows an SEM image of fabricated structure. (b) Transmission spectra of the PhCN cavity.

(2) Laser cooling and trapping single atoms in a single optical tweezer

We have rebuilt the laser cooling apparatus to cool down Cs-atoms in a MOT down to 100 - 200 μK. The homemade cooling laser is replaced with a commercial diode laser (MogLabs Cat-Eye laser) and the long-term stability has been improved significantly. The cooling laser setup is also equipped with a double-pass acousto-optic modulator (AOM) setup to enable ramping of the power and detuning for polarization gradient cooling (PGC).

After achieving MOT, we have first built an experimental setup to trap single Cs-atoms in a single optical tweezer. The schematic diagram of the experiment is shown in Fig. 2(a). We have used red-detuned magic wavelength (938 nm diode laser) to trap atoms in an optical tweezer. The tweezer beam is tightly focused down to a beam waist of 1 μm using a high numerical aperture (NA) aspheric lens. The aspheric lens acts as a viewport of ultra-high vacuum (UHV) chamber and is introduced into the UHV chamber using a lens tube. The lens tube is connected to a flexible below so that the lens position can be adjusted to ONF position by using micrometer stages along 3-axes. The tweezer beam path is equipped with galvo mirrors in 4f-configuration to fine tune and align the tweezer spot on the ONF. The same aspheric lens is used to collect the fluorescence of the trapped single atom. The tweezer path and the fluorescence collection paths are combined using a dichroic mirror. The fluorescence photons are detected using a single photon counting module (SPCM). A typical CCD image showing the aspheric lens, MOT and ONF inside UHV chamber is shown in Fig. 2(b).

We have achieved trapping of single atoms in a free-space optical tweezer (tweezer spot moved out of ONF position). Laser-cooled atoms are continuously loaded into the tweezer trap from the MOT. A typical fluorescence signal is shown

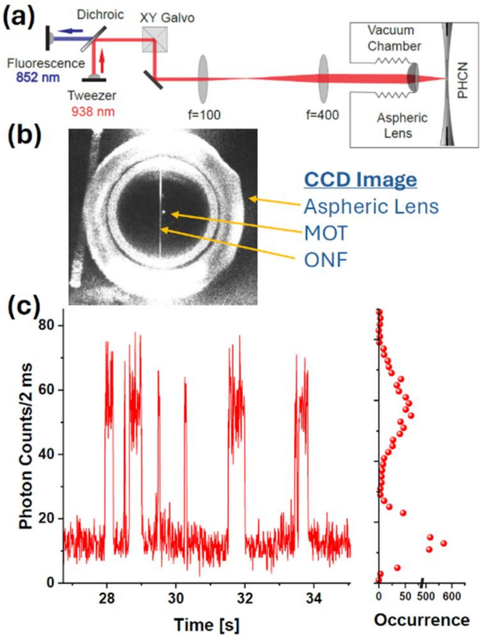

Fig. 2: (a) Schematic diagram of single tweezer experiment. (b) CCD image showing the ONF and MOT. (c) Typical fluorescence signal from trapped single atoms.

in Fig. 2(c). One can see discrete steps like ON-OFF signals. The histogram on the right shows a bimodal distribution of photon counts. This is a signature of single trapped atoms in optical tweezers. It is due to the collisional blockade regime.

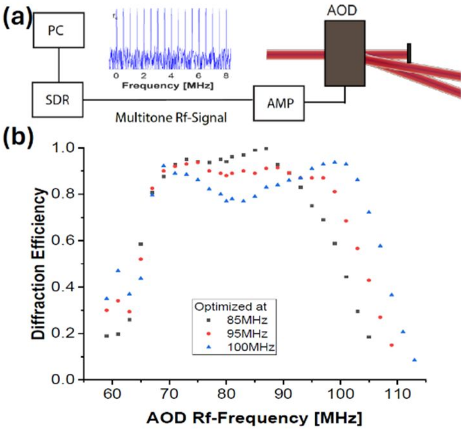

Fig. 3: (a) Schematic diagram of AOD setup. (b) Broadband diffraction efficiency of AOD.

(3) Creation of 1-D array of optical tweezers

To create a 1-D array of tweezers, we have used an AOD (AA Opto-Electronics, DTSX-400-935) driven by multitone Rf-signal. By driving the AOD with a single Rf-tone, a portion of the input beam is deflected (diffracted) by an angle that depends on the frequency of the Rf-tone. By applying different Rf-tones, one can generate multiple beams with different output angles. Therefore, the number of tweezers and the spacing between the tweezer spots can be controlled by choosing the frequencies of the multitone Rf-signal.

We first measured the AOD characteristics in an offline setup. A schematic diagram of the AOD setup is shown in Fig. 3(a). Multitone Rf-signal is generated using a software defined radio (SDR, NI Japan, USRP-2940R-120 MHz) device that is controlled by a computer (PC). We calculate the desired time-domain waveform in the PC and feed it to the SDR. The generated multitone Rf-signal is then amplified (AMP) and fed to the AOD. We adjust the phase of each tone to avoid any interference effects and to reduce the peak to average power ratio.

To measure the diffraction efficiency, we first optimize the alignment for a single Rf-frequency and then measure the efficiency for different Rf-frequencies. The typical diffraction efficiency of the AOD as a function of applied Rf-frequency is plotted in Fig. 3(b). We can obtain high diffraction efficiency over a broadband frequency range. The diffraction efficiency and bandwidth depend on the alignment condition. The center frequency is around 85 MHz and the bandwidth is around 33 MHz. This corresponds to a maximum scan angle of 42 mrad. Based on the lenses used in our tweezer setup, we estimate the maximum separation between two tweezer spots (or the maximum length of the tweezer array) to be around 168 μm. However, the achievable maximum length of the tweezer array will be limited to the field of view of the aspheric lens. For larger angle of incidence on the aspheric lens, the tweezer beam cannot be focused tightly due to aberrations.

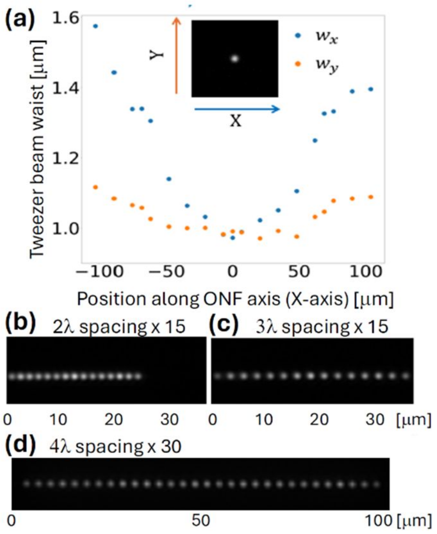

Fig. 4: (a) Tweezer beam waist along the ONF axis (X-axis). (b), (c) and (d) Images of tweezer spots for different spacing and number of tweezers.

To measure the achievable maximum length of the tweezer array, we measure the tweezer beam profile by changing the tweezer spot position along the ONF axis (X-axis). The tweezer spot position is changed by changing the angle of incidence on the aspheric lens. Figure 4(a) shows the measured tweezer beam waist (beam radius) along X-axis (w_x) and along Y-axis (w_y) at different positions along X-axis. Position 0 μm means normal incidence. One can see that as the position along the X-axis is increased (increased angle of incidence) the tweezer spot becomes elliptical and the beam waist along X-axis increases. However, a range of ±50 μm is acceptable for creating a tweezer array.

Next, we investigate the achievable maximum number of tweezer spots. In this project, we aim to arrange single atoms with a spacing of $n\lambda$, where n is an integer and λ is the resonance wavelength (852 nm). We have found that for 1λ spacing the tweezer spots are almost overlapped as the beam waist is 1 μm. Figures 4(b), (c)and (d) show the images of tweezer spots for different spacing and number of tweezers. One can see that for 2λ spacing distinct spots are visible, but the contrast is poor. For 3λ spacing the spots are clearly separated with high contrast. Considering a range of ± 50 μm, we expect 60 and 30 tweezers for 2λ spacing and 4λ spacing, respectively. Figure 4(d) shows an array of 30 tweezers with 4λ spacing and almost uniform intensity distribution.

(4) Trapping and imaging an array of single atoms

A key requirement to trap single atoms in multiple tweezers is to have enough optical power for trapping. We have built a tapered amplifier system to generate high power at Cs-atom magic wavelength (938 nm). We could achieve around 380 mW of fiber-coupled power. Considering the optical losses of the tweezer setup, we expect that we can create around 100 tweezers in free-space and around 50 tweezers on ONF.

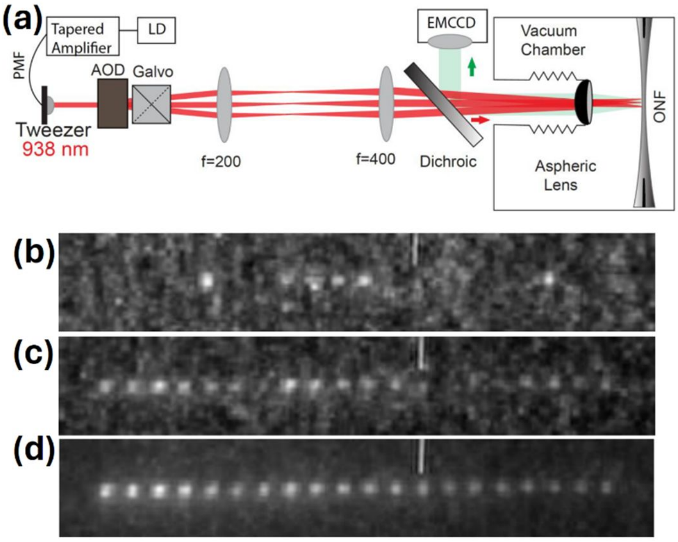

Fig. 5: (a) Schematic diagram of single atom tweezer-array experiment. (b), (c) and (d) Fluorescence images of single atoms trapped in the tweezer-array for different loading conditions.

Next, we demonstrate trapping and imaging an array of single atoms in optical tweezers. A schematic diagram of the experiment is shown in Fig. 5(a). Our single atom tweezer setup shown in Fig. 2(a) is modified to include the AOD to create multiple tweezer spots. The tweezer spots are moved away from the ONF, and the atoms are trapped in free space. 20 tweezer spots are created with a spacing of 4λ. The tweezer beam power is set to create a trap depth of around 0.7 mK. An EMCCD camera (Andor, DU-897U-CS0-EXF_DK) is used to image the trapped single atom array. Two single shot images with exposure time 10 ms are shown in Figs. 5(b) and (c). In Fig. 5(b) only few tweezers are loaded with single atoms. Whereas in Fig. 5(c) many of the tweezers are loaded, and only a few sites are vacant. Figure 5(d) shows a time-averaged image where all the 20 tweezer spots are loaded with single atoms. However, some sites are brighter than others due to the loading probability.

We are currently working on interfacing this tweezer array with ONF to investigate the cooperative atom-atom interaction mediated by guided modes. We will implement such a platform for controlling the generation and propagation of fiber guided single photons.

(5) Other results

Apart from the main research topic of this project, we have also investigated various ways to manipulate spontaneous emission of single solid-state quantum emitters on ONF for single photon generation. One key result is the following [3].

We have demonstrated strong plasmonic enhancement of spontaneous emission on ONF. We show that emission properties of single quantum dots can be strongly enhanced in the presence of single gold nanorods leading to a bright and strongly polarized single-photon emission into ONF guided modes. The brightness (fiber-coupled photon count rate) of the single-photon source is estimated to be 12.2 ± 0.6 MHz, with high single-photon purity [$g2(0) = 0.20 \pm 0.04$] and degree of polarization as high as 94-97 %.

References

[1] K. P. Nayak, J. Wang, and J. Keloth, Phys. Rev. Lett. **123**, 213602 (2019).
[2] J. Keloth, K. P. Nayak, and K. Hakuta, Opt. Lett. **42**, 1003-1006 (2017).
[3] K. M. Shafi, R. Yalla, and Kali P. Nayak, Phys. Rev. Applied **19**, 034008 (2023).

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　0件）

１．著者名 S. Sahu, K. P. Nayak, K. R. Mangipudi, R. Jha	４．巻 124
２．論文標題 Slot waveguide enhanced asymmetric photonic crystal nanofiber cavity for fiber-coupled single photons	５．発行年 2024年
３．雑誌名 Applied Physics Letters	６．最初と最後の頁 34002
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0179893	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 K. M. Shafi, R. Yalla, and Kali P. Nayak	４．巻 19
２．論文標題 Bright and Polarized Fiber In-Line Single-Photon Source Based on Plasmon-Enhanced Emission into Nanofiber Guided Modes	５．発行年 2023年
３．雑誌名 Physical Review Applied	６．最初と最後の頁 34008
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevApplied.19.034008	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 S. Sahu, K. P. Nayak and R. Jha	４．巻 24
２．論文標題 Optimization of nanofiber gratings for efficient single-photon collection	５．発行年 2022年
３．雑誌名 Journal of Optics	６．最初と最後の頁 115401
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/2040-8986/ac9632	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 R. Yalla, Y. Kojima, Y. Fukumoto, H. Suzuki, O. Ariyada, K. M. Shafi, K. P. Nayak, K. Hakuta	４．巻 120
２．論文標題 Integration of silicon-vacancy centers in nanodiamonds with an optical nanofiber	５．発行年 2022年
３．雑誌名 Applied Physics Letters	６．最初と最後の頁 241102
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0093116	査読の有無 有
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1．著者名 R. Yalla, K. M. Shafi, K. P. Nayak、K. Hakuta	4．巻 120
2．論文標題 One-sided composite cavity on an optical nanofiber for cavity QED	5．発行年 2022年
3．雑誌名 Applied Physics Letters	6．最初と最後の頁 71108
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0079624	査読の有無 有
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〔学会発表〕　計12件（うち招待講演　4件／うち国際学会　6件）

1．発表者名 R. Yalla, Y. Kojima, Y. Fukumoto, H. Suzuki, O. Ariyada, K. M. Shafi, K. P. Nayak
2．発表標題 Poster Presentation: Silicon-vacancy nanodiamonds on an optical nanofiber for quantum technologies
3．学会等名 Quantum 2.0, Optica（国際学会）
4．発表年 2023年

1．発表者名 K. M. Shafi, R. Yalla, K. P. Nayak
2．発表標題 Poster Presentation: Plasmon Enhanced Polarized Single Photon Emission into Optical Fiber
3．学会等名 Quantum 2.0, Optica（国際学会）
4．発表年 2023年

1．発表者名 K. P. Nayak
2．発表標題 Quantum Photonics on a Tapered Optical Fiber
3．学会等名 2023 Opto-Electronics and Communications Conference (OECC), IEEE（招待講演）（国際学会）
4．発表年 2023年

１．発表者名
R. Yalla, K. M. Shafi, K. P. Nayak

２．発表標題
Poster Presentation: Single-sided cavity quantum electrodynamics effects on an optical nanofiber

３．学会等名
Frontiers in Optics + Laser Science 2023 (FiO, LS), Optica（国際学会）

４．発表年
2023年

１．発表者名
P. Bhavya, K. Iidawa, K. P. Nayak

２．発表標題
Towards trapping an array of single atoms on a nanofiber

３．学会等名
Optical Nanofiber Applications: From Quantum to Bio Technologies (ONNA2023), OIST, Okinawa

４．発表年
2023年

１．発表者名
K. Haruto, Y. Shitomi, K. P. Nayak

２．発表標題
Fabrication of Photonic Crystal Cavity on a 300 nm Diameter Nanofiber

３．学会等名
Optical Nanofiber Applications: From Quantum to Bio Technologies (ONNA2023), OIST, Okinawa

４．発表年
2023年

１．発表者名
K. P. Nayak

２．発表標題
Interfacing single quantum emitters with fiber-guided photons

３．学会等名
Optical Nanofiber Applications: From Quantum to Bio Technologies (ONNA2023), OIST, Okinawa（招待講演）

４．発表年
2023年

１．発表者名
K. P. Nayak, K. M. Shafi, R. Yalla

２．発表標題
Plasmon Enhanced Polarized Single Photon Emission Into Fiber Guided Modes

３．学会等名
Frontiers in Optics + Laser Science meeting (FIO-LS)（国際学会）

４．発表年
2022年

１．発表者名
K. P. Nayak

２．発表標題
Quantum photonics on an all-fiber platform

３．学会等名
International Conference on Optical Precision Measurements（招待講演）

４．発表年
2022年

１．発表者名
K. P. Nayak, K. M. Shafi, R. Yalla

２．発表標題
Plasmon-enhanced bright and polarized single photon emission into nanofiber guided modes

３．学会等名
The Physical Society of Japan (JPS) 2022 Autumn Meeting

４．発表年
2022年

１．発表者名
K. P. Nayak

２．発表標題
A single atom quantum interface on a tapered optical fiber

３．学会等名
Laser Based Sensors, Optical Sensors Conference (as part of Optica Optical Sensors and Sensing Congress)（招待講演）（国際学会）

４．発表年
2022年

１．発表者名 K. P. Nayak and K. Muhammed Shafi
２．発表標題 Development of photonic crystal cavities on a 300 nm silica nanofiber for single atom quantum interface
３．学会等名 International Symposium on Novel maTerials and quantum Technologies (ISNTT 2021)
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関