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PERSPECTIVE

Atom-light interactions using optical nanofibres—a perspective

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Abstract

Complete control of light-matter interactions at a single quantum level is critical for quantum science applications such as precision measurement and information processing. Nanophotonic devices, developed with recent advancements in nanofabrication techniques, can be used to tailor the interactions between single photons and atoms. One example of such a nanophotonic device is the optical nanofibre, which provides an excellent platform due to the strongly confined transverse light fields, long interaction length, low loss, and diverse optical modes. This facilitates a strong interaction between atoms and guided light, revealing chiral atom-light processes and the prospect of waveguide quantum electrodynamics. This paper highlights recent advances, experimental techniques, and future perspectives of the optical nanofibre-atom hybrid quantum platform.

1. Introduction

With the rapid development of advanced nanofabrication techniques in recent decades, efforts have been made to integrate micro- and nanoscale photonic devices for interfacing atoms and photons in different quantum systems [1–6]. This integration combines the advantages of nanophotonic devices and atomic physics, enabling precise control of atom–photon interactions in a versatile platform for multidisciplinary research encompassing nanophotonics, quantum optics, atomic physics, and condensed matter physics [2, 7]. Nanophotonic devices offer strong light field confinement, scalability, efficient photon collection and integration, enhanced interfaces between atoms, and well-designed optical guided modes [8–10]. For example, direct coupling of quantum emitters to an optical waveguide via evanescent fields is facilitated via such a platform [11–13]. Moreover, it opens up unique research avenues such as chiral light-matter interactions [14, 15] and near-field atom-surface interactions [16–19]. Until now, various photonic devices have been developed for this goal, including high-quality photonic crystal waveguides [1], hollow-core photonic crystal fibres (HCPCF) [20, 21], nanophotonic crystal cavity [22, 23], superconducting circuits [24, 25], and dielectric nanofibres, see figure 1. Among these, we focus on optical nanofibres (ONF) and nanofibre-based platforms for quantum photonics. ONFs, with subwavelength diameters [26–28], feature strong transverse field confinement, a rich compendium of guided modes [29, 30], and an intense evanescent field [31, 32]. Compared to chip-based optical waveguides, optical nanofibres can be easily fabricated using a relatively simple lab-built pulling rig [33–36], eliminating complex nanofabrication processes [37]. The strongly confined optical guided modes with intense near-field electric fields facilitates the coupling of atoms with a small number of photons, interesting for studies in quantum optics [38], waveguide quantum electrodynamics (QEDs) [39], and for atom-photonics networks in quantum information processing [40, 41].

The ONF platform has been used for the sensitive detection of various quantum emitters, including neutral atoms [42], quantum dots [43], nitrogen-vacancy centres in diamond [44, 45], and molecules [46]. Emitters can be detected through atomic spectroscopy from the evanescent field of the ONF, either via the fundamental or higher-order modes. Enhanced atom–photon interactions can be observed near dielectric

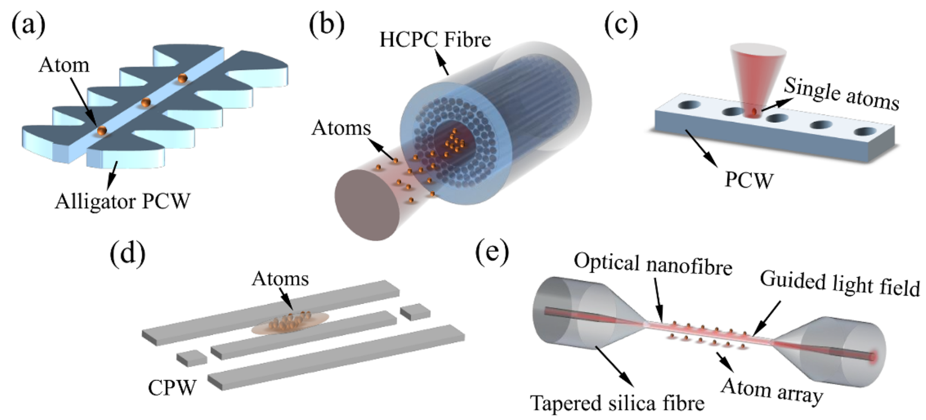

Figure 1. Schematic of nanophotonic systems suitable for strongly interacting single atoms or atomic ensembles with photons. (a) 'Alligator' photonic crystal waveguide (PCW) interfacing trapped cold atoms; (b) laser-cooled atoms are loaded into a hollow-core photonic crystal (HCPC) fibre; (c) single trapped atoms are coupled to a PCW cavity; (d) Atomic ensembles are trapped in a superconducting coplanar waveguide resonator (CPW); (e) 1D arrays of laser-cooled atoms are coupled to the guided light field via an evanescent field surrounding an optical nanofibre, a segment of a tapered silica fibre.

nanofibre surfaces [47–50]. To control atom–photon coupling, two-colour evanescent fields are used for atom trapping near the nanofibre surface [51–53]. This configuration allows for the observation of intriguing physical phenomena, such as large Bragg reflections [54]. Additionally, the direct coupling of quantum systems, such as atoms, to any waveguide introduces an emerging field termed waveguide quantum electrodynamics (wQED) [39, 55, 56]. Due to the confinement of photonic modes inside the waveguide, wQED offers a strong coupling regime between the quantum system and photonic states, similar to cavity quantum electrodynamics (cQED) [19, 57, 58]. In contrast to cQED, the photonic state can propagate through the waveguide, giving rise to information transfer to a desired destination. Two parameters that play leading roles in wQED are, for example of atoms, the number of atoms, and the coupling strength of the atomic emission to the waveguide modes [39]. The unique features of wQED systems have sparked broad interest [39, 59, 60]. Optical nanofibre-based waveguides can meet the aforementioned criteria by offering a large optical depth due to the long interaction length (a few mm), resulting in a large number of atoms next to the waveguide, which is applicable for the observation of modified dipole-dipole interactions near a waveguide proposed by [61]. Moreover, due to their mode profiles with a significant evanescent part extending into the surrounding medium, they could provide a high coupling strength between atoms and photonic modes [62].

Introducing an optical cavity [63, 64] or other nanostructures [65] may enhance or change the atom–photon interaction in the optical waveguide-atom system, possibly leading to collective superstrong coupling, or even strong coherent deterministic interactions for waveguide QEDs [39, 56, 58]. The chiral interface in the nanofibre-based system is a powerful tool for quantum control of atom–photon interactions, such as the realisation of nanophotonic optical isolators or circulators controlled by the internal state of cold atoms [66]. Furthermore, the intense evanescent field outside the optical nanofibres can be used for observing nonlinear phenomena at extremely low powers without requiring a very tightly focussed laser beam [67]. As an example, electromagnetically induced transparency (EIT) has been studied with cold atoms coupled to an ONF with low input powers [40, 68, 69] beneficial for the storage of information (atomic memories) in cold atoms.

In this paper, we review the current approaches for atom-ONF interfaces and provide a perspective on some of the current challenges and future applications for this nanofibre-based atom–photon hybrid platform.

2. Current status

The optical nanofibre platform for interfacing atoms with photons benefits from the well-known advantages of ONFs. These include fibre diameter homogeneity over several millimetres and nearly lossless coupling of light to standard optical fibres through adiabatic tapered sections. These features allow for near-field manipulation and sensitive probing of atoms localised to subwavelength regions through tightly confined guided modes. Crucially, once installed in an ultrahigh vacuum chamber for integration with cold atoms, the same nanofibre can be used for many years without any major degradation. In the next sections, we will

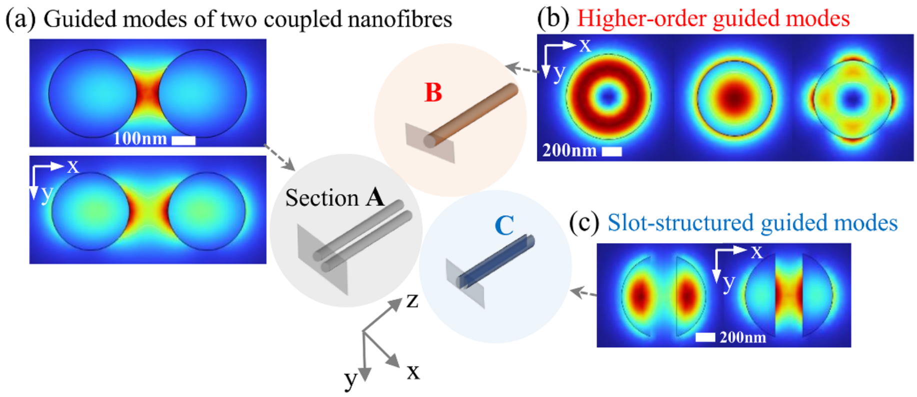

Figure 2. Schematic of an optical nanofibre to show the different modes that can be obtained. (a) section A: Guided modes of two coupled identical optical nanofibres (diameter of 0.4 μm) with two different separation distances of 100 nm and 150 nm. (b) section B: TE_{01}, TM_{01}, and HE_{21} higher-order guided modes; (c) section C: guided modes of a slotted nanofibre illustrating two quasi x- and y-polarized modes with nanofibre diameter of 0.8 μm and a slot width of 300 nm. All plots are for a wavelength of 780 nm.

present recent progress using this platform, with an emphasis on the topics that seem most promising for future advances either in the area of hybrid quantum systems or quantum optics.

2.1. Atom interactions with the fundamental fibre-guided mode

Most atom interactions with ONF-guided modes focus on the fundamental mode, HE_{11}. Optical nanofibres have been shown to serve as sensitive atomic probes, collecting fluorescence photons coupled to the guided modes of the nanofibre, to, for example, probe the quantum statistics of a few laser-cooled atoms [70–72] or to measure the temperature of cold atoms localised around them [73, 74]. Besides, optical nanofibre-based probes with ultralow powers have been applied for observing EIT in ladder-type multilevel atomic systems in both atomic vapour [75] and laser-cooled atoms [68]. Simultaneously, an upconverted 420 nm optical field can be generated with the pumps and signal fields coupled to the guided modes [76]. Note that the nanofibre-based multilevel cascade atomic system allows us to observe two-photon guided-mode coupled excitation of the $5S_{1/2}$-$6S_{1/2}$ transition in ^{87}Rb [77] and the dependence of the generated fluorescence photons on the input polarisation of the excitation field [78]. In addition, this system enabled the observation of electric quadrupole transitions from $5S_{1/2}$ to $4D_{3/2}$ in laser-cooled ^{87}Rb atoms using guided-mode light at 516.5 nm [48, 79], having potential applications in high precision measurements such as parity non-conservation [80]. Furthermore, a highly excited atomic state (i.e. a Rydberg state) can be prepared via a nanofibre-based ladder-type atomic excitation [81, 82], providing an opportunity to study fundamental Rydberg atom characteristics, such as the Rydberg blockade radius and excited state lifetime, based on the interaction with a dielectric medium. This could also provide a fundamental building block for fibre-based quantum gates and quantum memories, photon manipulation systems [83, 84], all-fibre integrated quantum systems [85], and waveguide QED [86].

2.2. Alternative fibre-guided modes for atom interactions

Various waveguide designs have already been proposed to engineer guided modes for stronger interaction with quantum systems, specifically cold atoms [87–89]. In nanofibre-based waveguides, aside from the fundamental mode, HE_{11}, three distinct types of guided modes are used for this purpose (see figure 2). These consist of (i) composite guided modes from two identical optical fibres, (ii) higher-order guided modes, and (iii) modes from nanostructured optical nanofibres. In the first case, two coupled identical parallel optical nanofibres have been proposed to manipulate atomic motion by the coupled optical modes [90–93]. While theoretically, this can reveal interesting features, such as optical forces and novel atom traps, it is quite challenging to experimentally obtain complete overlap along the full nanofibre length. The second option exploits higher-order guided modes of optical nanofibres, as they are characterised by longer penetration depths, a larger effective mode volume, and larger fractional powers outside the ONF [8, 29, 32, 52, 94–98]. There has been some experimental success in this area [8], albeit rather limited due to the challenges associated with controlling the mode ratios and fabricating the nanofibre to have a very precise diameter [99, 100]. It is well-known that the transfer of light's angular momentum to atoms is feasible [101] and this should also be possible near an optical nanofibre [102] where interesting features, such as the transverse spin angular momentum, may become apparent. Such effects have been demonstrated using microparticles in the ONF's evanescent field, by playing with the optical modes or the light's polarisation, but not with atoms so far. Finally, nanostructured optical nanofibres with strong tailored guided modes promise excellent performance in atom trapping and guiding [65, 103]. While such an ONF system for atom trapping is still proving elusive for experimentalists, despite having been demonstrated for nanoparticles [103], a very similar system has been developed using atomic vapour and a slotted waveguide [10] illustrating how it has promise as a miniature platform for quantum nonlinear optics.

2.3. Optical nanofibre-based traps for atoms

Atomic states near an optical nanofibre can be probed and manipulated through the evanescent fields [104, 105]. Two-colour (i.e. two-frequency) optical dipole atom traps were proposed [51, 106, 107] and realised with atoms localised about 200 nm distance from the nanofibre surface [53]. Moreover, several schemes for engineering the trap potential configuration by using different combinations of fibre-guided modes and/or polarisations exist [96–98]. To eliminate differential scalar light shifts and suppress vector shifts due to the trapping light fields, a state-insensitive, compensated optical nanofibre-based atom trap was realised for ^{133}Cs atoms by using counterpropagating red- and blue-detuned trapping beams operating at 'magic' wavelengths [108]. Subsequently, a state-insensitive ONF-based atom trap for ^{88}Sr using a double magic wavelength setup was shown to achieve a low trap depth of $\sim$4 μK with reduced optical powers through the ONF [109]. The addition of alkaline-earth atoms to the atom-ONF platform extends the range of applications that can be considered, particularly for precision spectroscopy and metrology. A theoretical study on atom heating in nanophotonic traps developed a general model based on particle-phonon interactions to determine the effect of mechanical vibrations of waveguides on guided light fields [110]. To optimize the number of atoms trapped in fibre-based dipole traps, a machine learning optimisation algorithm was implemented to quickly and effectively search the large experimental parameter space for laser-cooling and trap loading of ^{87}Rb [111]. While the initial outcomes were promising (increasing the number of trapped atoms from about 300 to 450), further improvements could be made by increasing the parameter space to include a wider selection of the experimental controls. However, this would require some changes to the automation of the experiment which must be weighed against possible further improvements. The distribution of the evanescent field around the nanofibre and its polarisation can also be exploited for additional cooling of the trapped atoms to sub-microKelvin temperatures [112]. This system consists of a few thousand trapped ^{133}Cs atoms localised in a one-dimensional lattice, exhibiting long atomic coherence times and high optical depth [113]. It is well-suited for investigating a range of interesting quantum phenomena [114–119], particularly an experimental exploration of collective atom-light interactions mediated by the ONF [120–123], development of novel quantum light sources [124, 125], and for creating collective states resulting from atom–atom interactions through the nanofibre [126]. These phenomena hold great potential for applications in quantum information processing and quantum many-body physics [41, 58, 127].

2.4. Nanofibre-based cavities for interfacing atoms

Optical nanofibre-based cavities have the potential to be further developed for exploring cavity quantum electrodynamics (cQED), enabling, for example, strong coupling between single atoms and single photons. Such cavities can achieve high interaction strengths, arising from the optical nanofibre's tightly confined guided modes, even when the finesse is only moderate. The high scalability and integration of nanofibre-based cavity QED systems make them a promising candidate for realising large-scale, high-fidelity, and scalable quantum networks [128, 129]. This could pave the way for the physical implementation of various protocols in the field of quantum information science [57, 130]. With this objective in mind, several fabrication techniques have been demonstrated for the realisation of different nanofibre cavities, see figure 3 [64, 131–138]. A cQED system based on an optical nanofibre not only facilitates enhanced coupling between single atoms and the guided mode of the cavity [63, 139–141] but also enables the exploration of new physical processes such as the study of thermalisation via heat radiation of an individual object thinner than the thermal wavelength [142]. Additionally, the observation of dressed states and cavity dark modes of distant coupled cavities is made possible [143, 144]. It is important to mention that nanofibre-based cavity QED systems are already exploited as viable technologies for quantum networks, through the establishment of NanoQT Co. Ltd, which claims to be Japan's first quantum computer hardware startup [145].

2.5. Chiral quantum optics

The strong light confinement of optical nanofibres allows for the observation of chiral effects and their utilisation for controlling light-matter interactions in quantum systems; the term *chiral quantum optics* has been adopted for this field [15]. The chiral interface allows for light's polarisation to control the direction of light emission, scattering, and absorption of photons by atoms in a nanophotonic platform. In experiments, directional scattering of photons has been observed through the use of a gold nanoparticle placed on the surface of an optical nanofibre, resulting from the spin–orbit interaction of light [14]. Asymmetric

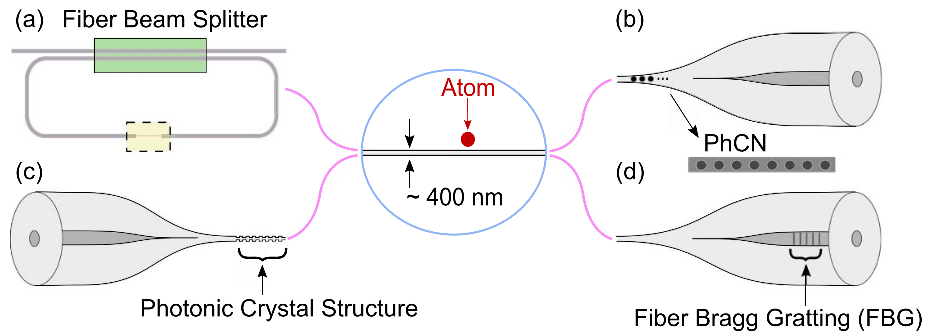

Figure 3. Scheme of different optical nanofibre-based cavities for interfacing light to cold atoms. (a) Optical nanofibre-segment ring cavity, (b) photonic crystal nanofibre (PhCN) cavity fabricated via femtosecond laser ablation, (c) photonic crystal structured nanofibre cavity fabricated via focussed ion beam milling, and (d) nanofibre fibre Bragg grating (FBG) cavity.

transmission using laser-cooled atoms and light guided by a nanofibre has been demonstrated and the scattering of guided light with direction-dependent coupling rates can be treated as analogous to an optical isolator controlled by atomic internal states [66]. The chiral atom-light interface with a 1D atomic chain near a nanofibre enables the realisation of photon routers controlled by atomic states and photon-mediated chiral coupling between atoms for quantum nonlinear optics and quantum many-body physics [15, 49, 146].

3. Challenges

So far, significant progress has been made using optical nanofibres for investigating the coupling between atoms and the fibre-guided evanescent fields, covering a diverse range of applications. However, there are still some challenges that could hinder advances in both experimental and theoretical research using the ONF-atom system. For example, one major goal is to optimise the coupling between single atoms and the fibre-guided modes. Several methods can be used to increase this figure-of-merit. Firstly, on a technical level, reproducible fabrication of a high-quality optical nanofibre is imperative but still challenging, as an ONF of uniform waist over several mm length, that is clean (free of defects/scatterers), and provides ultralow loss transmission is required. While not impossible to achieve, this could be viewed as the biggest challenge for experimentalists wishing to enter the field. The long uniform waist ensures a long interaction region between atoms and guided light. The cleanliness is essential so that powers of the order of several mW can be transmitted through the ONF, providing a high optical depth by simultaneously trapping many atoms using multiple frequencies of guided lights. Requiring ultralow loss ensures high efficiency photon propagation.

An additional challenge that may arise is photodarkening of the ONF, as has been observed for nanofibres in air when certain wavelengths of light are used [147, 148]. Changes in temperature have been shown to circumvent this issue [148], but could be harder to control in an ultrahigh vacuum system.

To evaluate the interaction of the evanescent field with the environment, an accurate determination of its diameter is crucial. Several nondestructive methods have been developed for this purpose, including observing cavity resonance modes using a grating mounted on the ONF [149], Rayleigh backscattering [150], and other techniques [151–156], many of which are difficult to integrate into ultrahigh vacuum systems. Moreover, optical fibres exhibit various nonlinear scattering processes, such as Raman scattering (RS) [157], which arises from the inelastic scattering of photons interacting with vibrational modes or thermal phonons of the glass medium. RS can introduce noise in photon generation [158, 159], optical amplification [160] and probe measurements for atoms trapped in ONFs-based dipole traps.

The development of high-quality optical nanofibre-based cavities, capable of achieving large cooperativity for enhancing the coupling between single atoms and guided modes is also challenging. In particular, the fabrication of structured ONF-based devices is difficult, as any nanofabrication process introduces new sources of contamination on the surface of the nanofibre, giving rise to a considerable decrease in the transmission of the fibre-guided light. However, recent developments in nanofabrication techniques have solved this problem to a great extent. For instance, focussed ion beam machines based on Helium ions instead of heavy ions, such as Gallium, have improved the fabrication to an almost contamination-free process [161, 162]. Moreover, introducing a gas injection system (GIS) to Helium ion beam machines has made the fabrication of special nanostructures feasible [163].

Regarding ONF-based dipole traps for cold atoms, single atom (qubit) addressing using fibre-guided light is not trivial. A hybrid system of optical nanofibre and optical tweezers may overcome such a challenge. This could facilitate the study of photon–photon interactions [164], parametric photon generation [165], and other quantum light phenomena in a waveguide with localised quantum emitters, e.g. atoms [39]. However, for the ONF to be a perfect platform for such studies, all trapping sites should be occupied with a single atom which in itself is challenging due to the collisional blockade [166]. At the same time, one cannot control the overall number of atoms trapped which is also an important parameter in photon quantum dynamics, especially for the realisation of atom arrays in high-dimensional lattices. Such limitations may mean the ONF system is not suited for studying the physics of photons interacting with a chain of well-localised quantum emitters and exotic many-body physics in high-dimensional atom arrays.

Finally, one promising approach to enhance atom–photon coupling is to employ highly excited atoms with very large polarizability and dipole moment. This opens up an intriguing and significant challenge to investigate the interface between highly excited (Rydberg) atoms and guided modes of optical nanofibres in both theory and experiment. One could envision the coupling of a giant atom of several micrometres in diameter to the optical fields, yielding interesting physics. The spontaneous emission and energy shifts of a Rydberg sodium atom and rubidium atom near an optical nanofibre have already been studied theoretically [167, 168], as has the interaction between two Rydberg atoms near an ONF [169] with some preliminary experimental results [81, 82]. However, the challenge remains to experimentally explore the behaviour of two or more Rydberg excitations or collective excitations in the atomic ensemble in the vicinity of the nanofibre and to achieve complete control over the Rydberg excitations as a many-body quantum system. Such research has great potential for applications in quantum simulations.

4. Conclusion

In summary, we have reviewed recent experimental progress related to the optical nanofibre-based platform for interfacing light to atoms. This system takes advantage of tight transverse confinement of the propagating light, efficient atom–photon coupling even in a single pass, and potentially long-range atom–atom interactions mediated by the guided photons. These advances enable the exploration of enhanced atom–photon or atom–atom interaction specially imparted by the chiral interface. These attractive features provide this platform with a host of potential applications in areas such as quantum nonlinear optics, waveguide QED, and quantum simulations. While there are some challenges to expanding the research currently conducted, many of these are technical in nature, and not necessarily insurmountable, indicating there is still an exciting future for the simple optical nanofibre in atomic and quantum physics.

Data availability statement

No new data were created or analysed in this study.

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