

A fast-tunable and stable fiber microcavity for coupling Ba^+ ions in quantum networks

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We present the design, implementation, and characterization of a high-stability, fast-tunable fiber Fabry-Pérot microcavity system optimized for coupling with Ba^+ ions to form quantum network nodes. The microcavity system integrates multi-wavelength single-mode transmission, rapid and broad-band tunability, high finesse, and exceptional passive mechanical stability. By incorporating a unique vibration isolation structure, the system enables the fiber-optic microcavity (with a finesse of 8000) to remain resonant with the laser for several minutes even without active feedback. Furthermore, we demonstrate active cavity length stabilization using the Pound-Drever-Hall method, which significantly suppresses low-frequency vibrations and enables the cavity length to remain stable for several days. Experimental results show that this fiber microcavity system offers outstanding stability and flexibility for practical quantum network applications, providing reliable technical support for the construction of large-scale quantum networks based on trapped ions.

Keywords: quantum network; trapped ion; fiber microcavity; cavity quantum electrodynamics.

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1. Introduction

Quantum networks can enable distributed quantum computing and communication by linking multiple smaller quantum processors into a larger system^[1–6]. In these networks, flying qubits (photons) transfer entanglement between distant nodes, while stationary qubits (e.g., atoms or ions) store and process quantum information locally^[7,8]. A key challenge is to realize efficient interfaces between photons and stationary qubits. Cavity quantum electrodynamics (cQED) provides a powerful solution: a single atom or ion coupled to a high-finesse optical cavity can act as a quantum network node that both emits and absorbs photons on demand^[9,10]. This cavity-enhanced light-matter coupling enables entanglement swapping, quantum state transfer, and remote gates between nodes, laying the foundation for scalable quantum networks^[11].

Trapped ions are among the most advanced platforms for quantum information processing, offering superb coherence properties, high-fidelity logic gates, and excellent optical state detection^[12–14]. These features make them ideal stationary qubits for quantum networks^[15]. Researchers have successfully coupled optical cavities with trapped ions to demonstrate quantum network connections^[16–18]. However, the rate of

entanglement generation in these networks is limited by the linewidth of the cavity and the coupling strength^[9]. To enhance the coupling between the cavity and matter, and thereby increase the entanglement generation rate, cavity mirrors are miniaturized and directly fabricated onto fiber ends. These cavities are referred to as fiber Fabry-Pérot microcavities (FFPCs)^[19].

FFPCs offer ultra-small mode volumes, high finesse, and direct fiber coupling. Early demonstrations showed that FFPCs can achieve extremely high finesse (up to $\mathcal{F} \geq 13,000$) in cavities only a few hundred micrometers long^[20]. Such miniaturized cavities enable strong atom-photon coupling even at moderate finesse because the optical mode is tightly confined^[19].

These advantages have driven rapid progress in integrating FFPCs with a wide range of quantum systems, including neutral atoms, quantum dots, and color centers^[21–24]. When combined with trapped ions, however, FFPCs face several technical challenges, e.g., dielectric charging and heating can perturb the ion's motion and energy^[25]. More critically, mechanical instabilities of the cavity structure can prevent its length from being stabilized within the cavity linewidth, which can reduce the cooperativity C by more than an order of magnitude^[26]. Therefore, a major challenge in deploying FFPCs in quantum experiments is achieving mechanical stability over extended

periods. To maintain resonance under these conditions, both high passive stability and active stabilization mechanisms are needed^[27–30].

In this work, we present the design and characterization of an FFPC tailored for a Ba^+ trapped-ion quantum network node and the designed cooperativity factor $C \approx 2$. Our FFPC system leverages photonic crystal fibers (PCFs), enabling multi-wavelength operation with broad tunability, high finesse, and extreme stability in a single compact device. It offers single-mode transmission across an ultra-broad wavelength range from 400 to 1700 nm. The cavity, formed by fiber mirrors inside the vacuum chamber, offers a continuous tuning range greater than $3 \mu\text{m}$ in length (exceeding a full free spectral range for our design), which allows us to tune across multiple Ba^+ resonances. We developed a specialized vibration-isolated base structure and decoupled the fiber cavity's tail fiber, ensuring exceptional passive stability for the tunable FFPC system, even under varying laboratory conditions. This design effectively isolates the system from external vibrations, ensuring that the cavity length and laser resonance can be maintained for several minutes without the need for active feedback mechanisms. The integrated structure achieves a mechanical tuning bandwidth of up to about 50 kHz, facilitating active feedback. We demonstrate that a simple Pound–Drever–Hall (PDH) cavity length feedback system can achieve stable locking for several days at a cavity length of $230 \mu\text{m}$ and finesse of 8000 without acoustic isolation.

2. Experiment

We designed an FFPC with a cavity length of $L = 230 \mu\text{m}$ for Ba^+ ions trapped in a vacuum. The cavity coating provides high reflectivity for both the $2P_{1/2} \rightarrow 2D_{3/2}$ and $2P_{1/2} \rightarrow 2S_{1/2}$ transition wavelengths of the Ba^+ ion, corresponding to wavelengths of 650 and 493 nm, respectively. When the curvature radii of the two cavity mirrors are $R_1 = R_2 = 320 \mu\text{m}$, the stability parameter is given by

$$g_1 = g_2 = g = 1 - \frac{L}{R}. \quad (1)$$

This satisfies the stable cavity condition

$$0 < g^2 < 1. \quad (2)$$

The designed cavity has finesse values of $\mathcal{F} = 5000$ for 493 nm wavelength and $\mathcal{F} = 12000$ for 650 nm wavelength, and the cavity linewidth is given by

$$\Delta\nu = \frac{c}{2L\mathcal{F}}. \quad (3)$$

If the change in the resonant wavelength of the cavity is required to be no more than the cavity linewidth $\Delta\nu$, then the cavity length drift needs to be less than $\frac{\lambda}{2\mathcal{F}}$. This implies that when the designed resonant wavelength of the cavity decreases or its finesse increases, it becomes more challenging to maintain

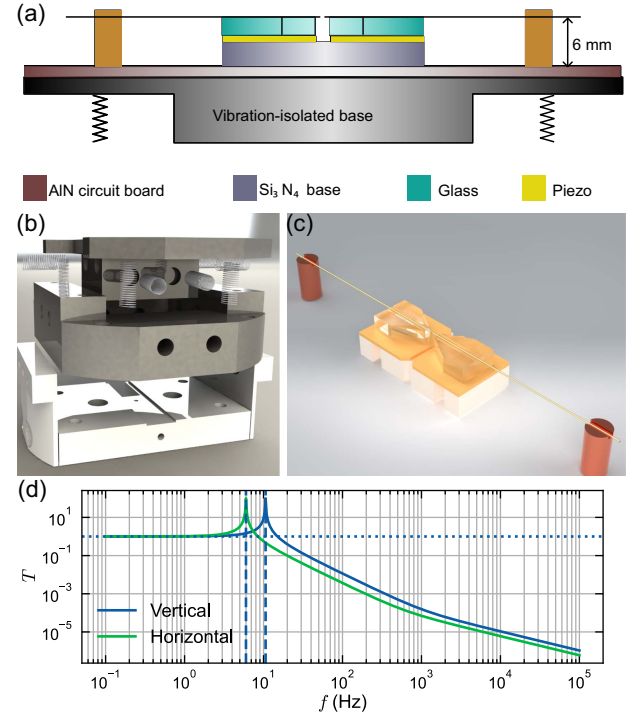


Fig. 1. (a) Schematic diagram of the FFPC and its supporting structure. (b) Structure of the spring vibration isolation system. (c) Microcavity mounting structure, where the gold-plated FFPC is placed in a V-shaped groove on high-borosilicate glass above the shear piezoelectric element, with the tail fiber cut off and in electrical contact with the top of a beryllium-copper pillar with a groove. (d) Estimated lateral and longitudinal transfer functions of the vibration isolation structure as a function of driving frequency.

resonance between the cavity and the laser or between the cavity and the relevant atomic (or ionic) energy-level transition. To enable switching between multiple ion transitions, the cavity length must be tunable over a wide range and at a high speed. This imposes stringent requirements on the cavity's passive stability as well as the mechanical bandwidth of the system.

The schematic diagram of the whole set of the optical fiber cavity and its supporting structure is shown in Fig. 1(a). To ensure the system's passive stability, we designed a vibration isolation structure, as shown in Fig. 1(b). The vibration isolation system comprises three spring assemblies, each providing support in different directions. Each spring system comprises four springs, with the longitudinal support springs having a length of 15 mm and the lateral support springs having a length of 30 mm. To evaluate the performance of the vibration isolation system, we first derived the stiffness of a single stainless steel spiral spring using the shear model for compressed spiral springs,

$$k = \frac{Gd^4}{8D_m^3n}, \quad (4)$$

Where $G = 77 \text{ GPa}$ is the shear modulus of stainless steel, $d = 0.2 \text{ mm}$ is the wire diameter, $D_m = 2.8 \text{ mm}$ is the mean diameter

of the springs, and n is the number of effective coils. For vertical supports ($n = 7$), we obtain $k_v = 1.00 \times 10^2$ N/m, and for horizontal supports ($n = 22$), we obtain $k_h = 3.19 \times 10^1$ N/m. All four springs are connected in parallel. The corresponding equivalent stiffness in the vertical direction is $K_v = 4k_v = 4.01 \times 10^5$ N/m, and in the horizontal direction, it is $K_h = 4k_h = 1.28 \times 10^6$ N/m.

The upper structure of the vibration isolation system has a mass of $m = 0.09$ kg, and the natural frequency of the single-degree-of-freedom system is given by

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K}{m}}, \quad (5)$$

resulting in $f_{n,v} = 10.6$ Hz for the vertical direction and $f_{n,h} = 6.0$ Hz for the horizontal direction. The base excitation transfer function of the system is given by

$$T(r, \zeta) = \sqrt{\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}}, \quad r = \frac{f}{f_n}, \quad (6)$$

where f is the driving frequency, and we approximate the damping ratio for stainless steel as $\zeta \approx 0.005$, and the mechanical performance of the structure is shown in Fig. 1(d). Due to the relatively low damping ratio of metal materials, the vibration isolation system may amplify low-frequency vibrations, but it effectively isolates high-frequency vibrations. If the low-frequency vibration amplification needs to be reduced, damping materials can be added to the isolation system.

The mounting of the FFPC on the isolation system is shown in Fig. 1(c). Two NKT LMA-8 fiber ends are processed using the arc discharge thermal reflow method^[31] and are attached to high-reflectivity dielectric films. These fibers are placed into grooves in high-borosilicate glass, with the glass heads beveled to improve light transmission. The fibers are then glued in place with vacuum ultraviolet curing adhesive, and their outer layers are coated with gold to shield against electrostatic charging, which can disturb ion trapping. The tail fibers are cut to prevent external vibrations from coupling into the fiber or stressing the microcavity alignment, thus maximizing the system's mechanical stability. The FFPC and its borosilicate base are mounted on shear piezoelectrics, where the maximum travel of a single piezoelectric element is $1.55 \mu\text{m}$. The entire structure is assembled on a complete silicon nitride base, as silicon nitride, piezoelectric ceramics, and borosilicate glass have similar thermal expansion coefficients, effectively preventing stress due to temperature variations.

The entire structure is placed in a vacuum and subjected to a seven-day vacuum bake at 120°C . After assembly and baking, the measured finesse of the fiber cavity at a wavelength of 650 nm was found to be $\mathcal{F} = 8000$. To verify the system's passive stability, we coupled a 650 nm laser into the cavity from the tail fiber using an objective lens and a vacuum window. We used a piezoelectric amplifier to drive the shear piezoelectric at the base of the borosilicate glass to tune the cavity length for resonance

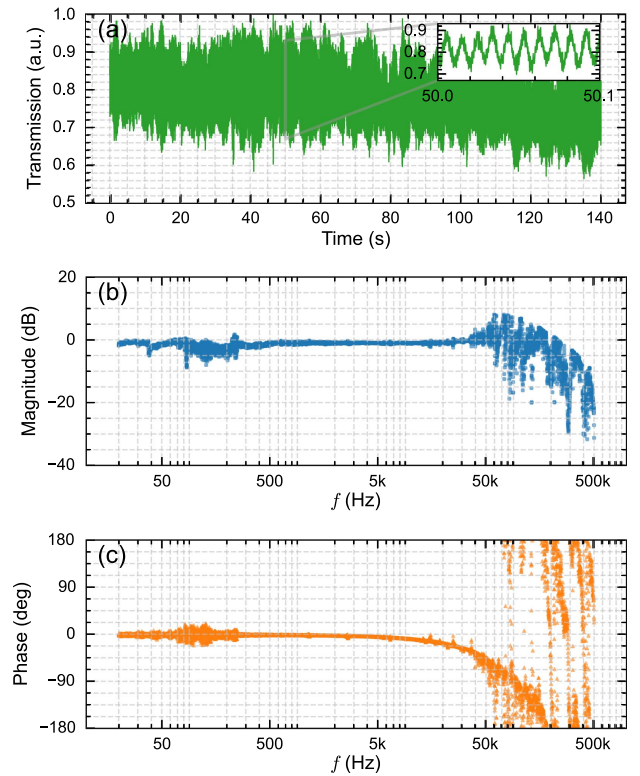


Fig. 2. (a) Cavity length tuned to resonance with 650 nm , recording the transmission intensity of the light as a function of time using a photodetector. (b), (c) Cavity length tuned to 650 nm and the red detuned by half a linewidth, with the mechanical response curve of the structure measured by applying a drive to the piezoelectric element while monitoring the transmission intensity.

with the laser. Without active feedback, we monitored the transmission intensity of the cavity for two minutes. Figure 2(a) shows the transmission intensity variation over 140 s . Over two minutes, the average intensity decreased by only 7% , indicating good long-term passive stability. However, the transmission intensity exhibited additional oscillations at around 100 Hz , likely due to power grid noise or the amplification of low-frequency vibrations by the isolation system. These oscillations caused less than 25% variation in transmission intensity. We measured the mechanical response of the cavity structure without active stabilization by driving the cavity in a different frequency and observing the transmission variation, as shown in Figs. 2(b) and 2(c). The results show that the response bandwidth of the microcavity structure is about 50 kHz , which facilitates fast tuning and active stabilization of the cavity length.

We used a Red Pitaya for active cavity length stabilization via the PDH method. To avoid interference with the ion transitions, we used a 1550 nm laser for cavity locking. This wavelength is far from the typical transition wavelengths of Ba^+ ions, reducing the impact of the locking laser on the ions and allowing single-mode transmission through the photonic crystal fibers used in the microcavity. As shown in Fig. 3, the output laser from this 1550 nm laser was split into two paths: one was modulated by an electro-optic modulator (EOM) to generate a 10 MHz sideband

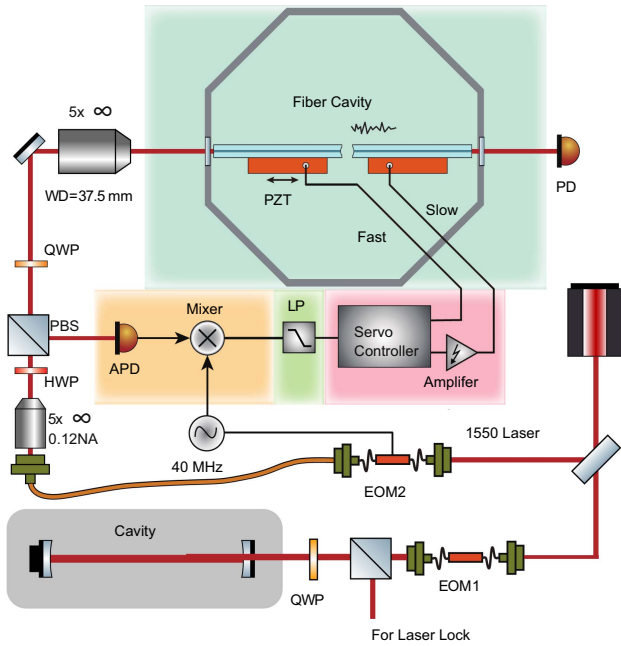


Fig. 3. Principle of active cavity length stabilization. A 1550 nm laser is fed into an ultra-stable cavity for laser wavelength locking, and another path is modulated and coupled into the FFPC. The error signal extracted from the reflected light using the PDH method is fed back to the piezoelectric elements at the fiber ends.

and entered the ultra-stable cavity for wavelength locking, and the other path was modulated by a second EOM and coupled into the FFPC. The fiber cavity mirrors have high reflectivity for 1550 nm, and their finesse was measured to be $\mathcal{F} = 4500$ after vacuum baking. The cavity linewidth for 1550 nm is $\Delta\gamma = 145$ MHz. Since the cavity linewidth is relatively large, we used PDH locking with a low modulation frequency of 40 MHz to reduce the requirements on the photodetector and loop delay. An avalanche photodiode with a bandwidth of 200 MHz collects the cavity reflection signal and feeds it into the Red Pitaya, where the error signal is obtained after digital demodulation and low-pass filtering. The error signal obtained when the cavity length is scanned in an open loop is shown in the small figure in Fig. 4. The asymmetry of the error signal about the baseline is mainly caused by the asymmetric term of the fiber cavity reflection signal^[32].

When the active feedback was turned on, the error signal was input into the Red Pitaya's built-in PI module. We used a cascaded dual-feedback loop to achieve more stable cavity length locking. The extracted error signal was first fed into a fast feedback loop, where its voltage output was applied directly to one side of the FFPC's shear piezoelectric for rapid feedback. The same voltage was also fed into a slow feedback loop for further stabilization, with the output of this loop passing through a piezoelectric amplifier and a low-pass filter to reduce electrical noise. This slow feedback loop suppressed cavity length drift caused by temperature changes while ensuring that the fast feedback output remained close to zero, preventing lock loss due to

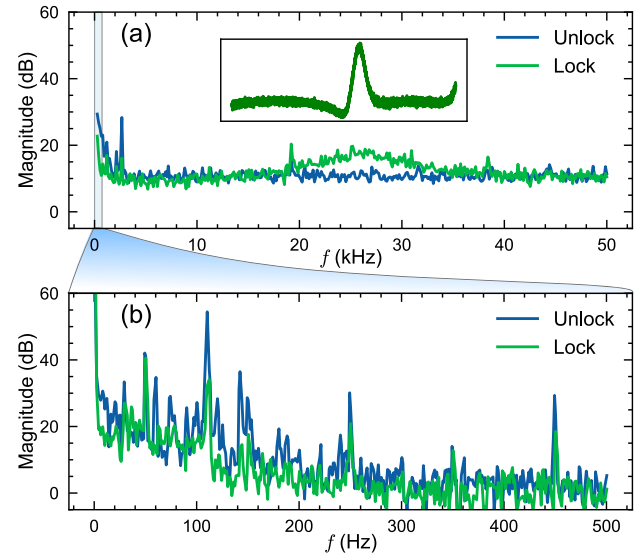


Fig. 4. (a) Error signal frequency spectra before and after turning on active feedback, showing a servo bump around 20 Hz. The inset shows the error signal obtained from a small scan of the cavity length before locking. (b) A more detailed scan of the low-frequency region, showing that low-frequency vibrations, including the original 100 Hz noise, were effectively suppressed after enabling active feedback.

saturation of the fast loop. The error signal frequency spectra before and after feedback are shown in Fig. 4, with low-frequency noise significantly suppressed after enabling feedback. However, a servo bump appeared around 20 Hz, which could be minimized by further optimizing the low-pass filter and the PI parameters of the active feedback system^[33].

3. Conclusion

In this work, we presented the design, implementation, and characterization of a fiber Fabry-Pérot microcavity system optimized for coupling with a Ba^+ ion in a quantum network node. The cavity achieved high performance, with a finesse of 8000 and passive stability lasting several minutes, even without active stabilization, under typical laboratory conditions. Our vibration isolation system effectively mitigated external mechanical noise, ensuring that the cavity length remained stable over long periods. Furthermore, we demonstrated the effectiveness of active cavity length stabilization using the PDH technique, which significantly suppressed low-frequency noise and improved long-term stability.

The versatility of the FFPC, with its multi-wavelength tunability and robust mechanical stability, makes it an excellent candidate for integration into large-scale quantum networks. The experimental results highlight the potential for this system to serve as a building block for scalable quantum networks, offering both high performance and stability under realistic operating conditions.

Future work will focus on improving low-frequency isolation and investigate the integration of additional feedback mechanisms to further improve stability, particularly for cavities with higher finesse. Additionally, we will study the behavior of ions within the FFPC to gain insights into its potential applications in quantum communication and distributed quantum computing.

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