Ultraviolet Fabry-Perot cavity with stable finesse under ultrahigh vacuum conditions

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We have constructed an apparatus containing a linear ion trap and a high-finesse optical cavity in the ultraviolet spectral range. In our construction, we have avoided all organic materials inside the ultrahigh vacuum chamber. We show that, unlike previously reported, the optical cavity does not degrade in performance over a time scale of 9 months.

I. INTRODUCTION

Trapped-ion quantum computers require light-matter interfaces for the efficient conversion of the quantum state of stationary trapped-ion qubits onto flying photonic qubits. A common path to reaching this goal is to interface the trapped ions with a single mode of an optical cavity \[1\]-\[3]. By employing the principles of cavity quantum electrodynamics, the quantum state of the ion can be mapped onto the photon field. However, the efficiency of the conversion process is hindered by losses. “Good” losses are the residual transmission of the cavity mirrors since the photon eventually escapes the cavity and can be used for transmitting information over long distances. “Bad” losses are losses in which the photon is absorbed or scattered out of the cavity mode. In principle, the latter can be minimized by employing high-quality optical coatings, the technology of which has steadily improved over the past decades.

Strong optical transitions of trapped ions usually are in the blue and ultraviolet spectral range. Over the past years, high-finesse cavities for such wavelengths have been developed both using conventional mirrors \[1\]-\[8] as well as fiber Fabry-Perot resonators \[11\]. However, in several experiments it was found that intrinsic losses of the cavities increased over time under ultrahigh-vacuum conditions. A possible explanation for this effect was presented in \[13\], namely oxygen diffusion out of the top high-index material of the coating. The effect was reversible by exposing the mirrors to air and could, to a good degree, be prevented by placing a few-nanometer thick protective layer of SiO\(_2\) on the front surface of the mirror. The reversibility of the degradation by exposition to air was also reported in \[11\], however, that experiment observed significant degradation despite a protective SiO\(_2\) coating.

Here, we follow a different route to address and resolve the problem of UV mirror degradation under ultrahigh vacuum conditions. The work of numerous authors \[15\]-\[18\] suggests that hydrocarbons or other outgassing organic compounds deposit under ultrahigh vacuum conditions on the surface of optical coatings in presence of ultraviolet radiation. The shape of deposition was found to reflect the laser mode suggesting a laser-induced cracking and deposition. Since ultrahigh vacuum chambers with ion traps and optical cavities often contain hydrocarbons, for example, as insulating materials for wires and spacers or glue for fixing the mirrors, it is conceivable that UV-enhanced deposition of hydrocarbons contributes also to the widely observed degradation of UV cavity mirrors. Recovery at air exposure would be a result of cleaning hydrocarbons off the mirror surface by full or partial reaction with oxygen contained in air.

II. EXPERIMENTAL SETUP

In order to test the hypothesis, we have designed and built a novel apparatus containing a linear Paul trap and a high-finesse optical cavity under ultraclean conditions and have completely avoided any organic materials in the construction of the apparatus.

A schematic overview of the setup is shown in Figure 1. The ion trap is a linear Paul trap with radiofrequency electrodes made from tungsten and an ion-electrode separation of 0.6 mm. Longitudinal confinement is provided by dc-endcap electrodes made from platinum. The end-cap electrodes have a separation of 2.5 mm and they are hollow with a bore diameter of 0.5 mm in order to provide space for the field of the optical cavity along the symmetry axis of the Paul trap. The trapping frequencies for a single Yb\(^{+}\) ion in this trap are \(\omega_{\perp} = 2\pi \times 0.49\) MHz at a driving voltage of 500 V\(_{pp}\) and \(\omega_{z} = 2\pi \times 0.23\) MHz at an endcap voltage of 10 V.

The optical cavity comprises of two mirrors with radii of curvature of 5 cm and a separation of \(L = 1.4\) cm. With the speed of light \(c\), the corresponding free spectral range is \(\nu_{FSR} = c/(2L) = 10.7\) GHz. The optical coatings of the cavity mirrors feature a top layer made of SiO\(_2\) having a thickness of \(\lambda/(2n)\), where \(\lambda = 370\) nm is the employed resonance wavelength of the resonator, and \(n \simeq 1.4\) is the refractive index of silicon dioxide. Hence, the top layer of the coating is optically inactive and provides a > 100 nm thick protective layer for the mirror. Nominal, the coating features a transmission of \(T = 370\) ppm at 370 nm and losses of \(L \lesssim 100\) ppm.

The optical cavity requires active control of its length in order to tune the resonance wavelength to the resonance frequency of the trapped ions. To this end, we utilize a piezo-electric transducer to change the position of one of the mirrors. In our setup, we realize this in the following way: The mirror is fixed into a stainless steel tube by a threaded retaining ring (see Figure 2 and the steel tube serves two purposes: (1) it partially covers the mirror surface in order to prevent charge buildup on the dielectric surface and (2) it acts as a glider for
FIG. 1. Schematic drawing of the ion trap placed between the cavity mirrors. A radio-frequency field is applied to four rf-electrodes and axial confinement is provided by hollow endcap electrodes supplied with dc voltages. All electrodes are supported by an Al$_2$O$_3$ structure for electrical isolation. The magnified inset shows a picture of three trapped ions fluorescing at 370 nm.

the mirror inside the stainless steel support structure. The contact surface between the glider and the support is minimized by machining a suitably shaped bore into the support, and the glider is fixed to the support structure by three sheet springs mounted at relative angles of 120°. The piezo-electric transducer is mechanically clamped between the glider and the support structure and clamping pressure (and hence force pre-loading the piezo transducer) can be adjusted by varying the thickness of the sheet springs. It should be noted that the constant load on the piezo reduces the available stroke and hence clamping force and piezo is well matched to provide a travel range of the mirror over at least one free spectral range of the cavity.

Supplying both the ion trap and the piezo-electric transducers of the optical cavity with electrical signals requires a significant amount of wiring inside the ultrahigh vacuum chamber. We exclusively use bare copper wires without any insulating coating. Wherever necessary, we added ceramic spacers and tubes in order to ensure physical separation of conductors. Furthermore, unlike in our previous setups [9, 11], we discarded the passive vibration isolation (by rubber compounds) of the optical cavity inside the vacuum chamber but instead installed vibration damping of the whole ultrahigh-vacuum chamber outside the vacuum. Finally, the ultrahigh vacuum system has been baked at 110°C for one week to facilitate outgassing of the vacuum chamber and the installed components. During the bakeout procedure the cavity mirrors had been removed from the setup in order to not contaminate them. The mirrors have been added after the bakeout and subsequently the vacuum system was pumped down to a base pressure of $\sim 10^{-10}$ mbar without further baking.

III. MEASUREMENTS

We have measured the finesse of the cavity (see Figure 3) using a frequency-doubled titanium:sapphire laser with a nominal linewidth of 100 kHz, much below the cavity linewidth of $\sim 2$ MHz. Spectroscopy on the Fabry-Perot cavity is performed in reflection. Using an electro-optic modulator, we modulate side bands onto the laser light at $\pm 69$ MHz, which we use as frequency markers, and we obtain the cavity linewidth $2\kappa$ from a Lorentzian fit to the reflected cavity signal. The finesse is given by $F = \nu_{FSR}/(2\kappa)$. We determine the mirror losses $\mathcal{L}$ from the cavity finesse by $\mathcal{L} = \pi/F - T$, assuming equal losses per mirror. For all measurements, the laser power incident on the cavity has been on the order of $80 \mu$W. The resulting intracavity intensities are orders of magnitude below the coating damage threshold and thus should not affect the mirror performance even under continuous illumination.

Over a period of 9 months ($\sim 6500$ hours), we have continually measured the cavity losses while maintaining a vacuum chamber pressure well below $10^{-9}$ mbar at room temperature. As shown in Figure 4, we did not observe a significant increase of losses on the considered timescale. A linear model yields a variation of
for the same wavelength was $(12.3 \pm 4.3) \cdot 10^{-3}$ ppm/h, however, with a Ta$_2$O$_5$ top layer of the mirror coating. The other data point from the literature we can compare to is the rate measured in [11] of $(230 \pm 20) \cdot 10^{-3}$ ppm/h, which is considerably larger. In that work, a 120 nm thick SiO$_2$ top layer is present on the mirrors, however, some amounts of hydrocarbons (especially glue) have been used in the assembly of the vacuum system and we suspect that they cause the degradation of the cavity.

In conclusion, we have demonstrated an optical cavity working under ultrahigh-vacuum conditions in the ultraviolet spectral range that operates without degradation for 9 months. By comparison with previous data for the same spectral range [11-14] our experimental approach to remove hydrocarbons from the vacuum system seems to yield a significant improve in the stability of then cavity finesse over time.

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