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Invited Paper

Cavity QED with Whispering Gallery Modes of Fused Silica Microspheres

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ABSTRACT

The Whispering Gallery Modes (WGMs) of fused silica microspheres hold the promise for simultaneous acheivement of high Q ($> 10^9$) and small mode volumes ($\lesssim 10^{-14}$ m^3) necessary for strong coupling in cavity QED. Here we present results for high Q measurements into the NIR along with some progress towards experimental implementation in cavity QED.

1. INTRODUCTION

For many different scientific and technological applications, one would like to have access to resonators with the ability to combine large quality factors Q with spatial confinement of the electric field. The Whispering Gallery Modes (WGMs) of fused silica microspheres, whose properties were first experimentally studied in pioneering investigations by Braginsky and co-workers,[1] provide a good example of such devices in the optical domain. These small optical resonators have recently attracted considerable interest due to the potential for such diverse technological and scientific applications as frequency stabilization of semiconductor diode lasers[2] and environmental sensing by trace absorption detection in compact, integrated structures.[3]

Our interests lie primarily within the realm of cavity quantum electrodynamics (QED), where it is necessary to achieve simultaneously small volumes of the cavity mode (for large electric fields per photon $\sim$ kV/m) *and* ultra-low resonator losses (for long photon storage times $\sim$ few μs).[4] With mode volumes of $V \approx 5 \times 10^3$ μm^3 for spheres of diameter ~ 100 μm[5,6] and experimental demonstrations of extremely high Q,[1,7,8] microsphere cavities offer an attractive avenue to achieving these conditions. In the optical domain, such a combination has been produced only by small Fabry-Perot cavities, most recently for experiments in which single atoms are coupled one-by-one to a cavity of mode volume $V \approx 2 \times 10^5$ μm^3 and finesse $\mathcal{F} \approx 2 \times 10^5$.[9]

The focus here is on recent work[10] in achieving high Q and first attempts to characterize the wavelength dependence of the losses. In addition, we discuss technical progress towards achieving interaction of atoms with WGMs in the context of the ultimate goal of strongly-coupled cavity QED.

2. HIGH Q MEASUREMENTS FOR FUSED SILICA MICROSPHERES IN THE NIR

The astounding demonstration by Gorodetsky *et al.* in 1995[8] of $Q \sim 8 \times 10^9$ in a 750 μm diameter silica microsphere reached the intrinsic absorption limit of fused silica at 633 nm and immediately brought about the possibility of even higher Q in the near infrared (NIR). As is well known, the absorption coefficient for bulk silica falls into the NIR, with the minimum close to 1.55 μm offering the tantalizing possibility of absorption-limited Qs approaching 10^{13}.

We undertook a program of exploring the wavelength dependence of losses of the WGMs at three additional wavelengths, namely (670, 780, 850) nm and were able to achieve $\left(8 \times 10^9, 8 \times 10^9, 7 \times 10^9\right)$ in spheres of diameter $(750, 800, 680)$ μm respectively. In particular, the measurement at 850 nm corresponds to a finesse $\mathcal{F} \sim 2 \times 10^6$ which is comparable to the highest value yet reported for a spherical mirror interferometer ($\mathcal{F} = 1.9 \times 10^6$ at 850 nm in Ref. [11]).

In Fig. 1, we plot our three measurements along with the point from Ref. [8] at 633 nm, which, taken together, are the highest Q's for WGMs in the optical domain achieved to date. Also shown in the figure is the expected

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absorption-limited Q for low-OH fibre-grade fused silica and it is immediately obvious that the two points at (780, 850) nm into the NIR lie substantially below this curve. So far, the absorption limit has not been accessed for these longer wavelengths.

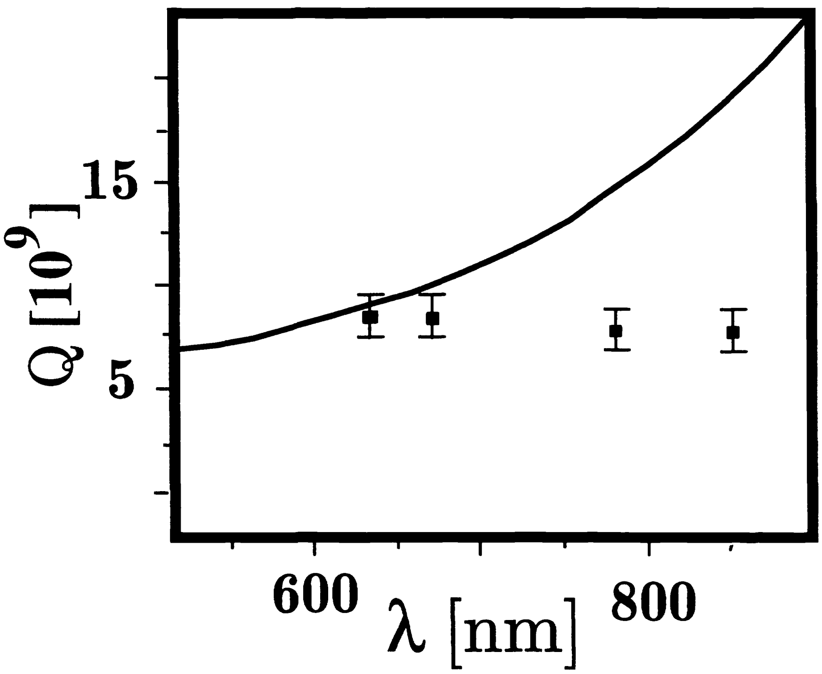

Figure 1. The wavelength dependence for the highest Qs yet measured at 633 nm (from Ref. [8]) and at $(670, 780, 850)$ nm are shown along with the wavelength dependence for Q limited by intrinsic absorption in bulk fused silica (solid line).

A possible mechanism responsible for loss beyond that of bulk absorption is scattering from surface inhomogeneities. Our fabrication procedure is based on the oxygen-hydrogen micro-torch method,[12] and these inhomogeneities seem to be related to the annealing history of the silica ball as it is withdrawn from the flame and cooled. Although we explored scanning electron microscopy (SEM), we have found atomic force microscopy (AFM) to be much more fruitful in providing quantitative data on the surface quality of the microspheres. In Fig. 2, we show typical line scans taken from AFM surface morphology data over a 20 nm $\times$ 20 nm square grid with a nominal vertical resolution of 0.01 nm. We find an rms standard deviation of surface roughness $\sigma \sim 2$ nm and a statistical correlation length $B \sim 5$ nm is identified from an estimate of the power spectrum of surface fluctuations. An exact calculation of the wavelength dependence of the surface scattering-limited Q, given roughness statistics (σ, B), must take into account precisely how the energy of the resonant mode field distribution is scattered into the complete set of modes. While this remains an unsolved problem for a spherical geometry, such calculations have been performed for planar waveguides,[13] and attempts to map those results to the spherical case produce numerical limits to the Q reasonably consistent with the data. Though more rigorous theoretical calculations are clearly desirable, one would also like to extend the measurements further into the blue and NIR to experimentally map more densely the wavelength dependence.

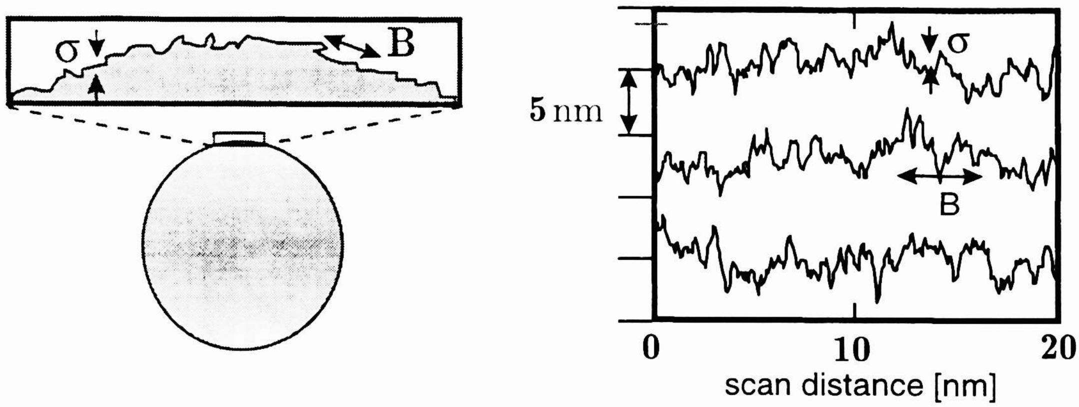

Figure 2. The surface of the microsphere has been characterized with an r.m.s roughness $\sigma \sim 2$ nm and a correlation length $B \sim 5$ nm using AFM techniques.

Future work might push towards a reduction of both surface scattering losses and adsorption of surface OH groups (a discussion of which can be found in Ref. [8]) by surface treatment of the spheres. In addition, this high Q work must be extended down to the realm of sub-100 μm diameter spheres, in which the mode density becomes much more sparse and efficient coupling more difficult to achieve. Nevertheless, note that losses arising from the intrinsic curvature of the sphere (which can be calculated *a priori*) do not become important until the diameter reaches about 20 μm, so that the present emphasis on experimental demonstration of high Q is entirely relevant to any meso-optical implementation of spheres of diameter $\gtrsim 20$ μm.

3. INTERACTION OF ATOMS WITH HIGH Q WHISPERING GALLERY MODES

An atomic dipole coupled to a high finesse resonator can lead to remarkable changes in both the radiative properties of that dipole and also to the characteristics of the cavity itself. In the perturbative regime, the atom and the cavity essentially maintain their individual identities, but one can investigate, for example, changes in the radiative properties of the atom. Dependent upon the detailed structure of its mode spectrum, the ability of a cavity with modes of volume V and maintaining losses characterized by the cavity Q to enhance or inhibit atomic spontaneous emission can be characterized by the ratio $Q\lambda^3/V$.[14]

In a non-perturbative regime, where manifestly quantum-mechanical dynamics become a possible focus of attention, one can no longer speak of individual atom and cavity entities. The driven atom-cavity system in this regime can be thought of essentially as two strongly-coupled, damped oscillators for which the eigenvalues and eigenmodes admit an admixture of both atom and cavity. The transition to strong coupling occurs when the atom field dipole coupling rate, $g \sim \sqrt{\gamma c \lambda^2/V}$, becomes larger than the atomic spontaneous decay rate γ and the cavity decay rate $\kappa = \omega/2Q$; hence, the requirement of simultaneously large cavity Q and small mode volumes V for strongly-coupled cavity QED.

In our case, attempts at atomic interaction with the microsphere take place external to the sphere in the evanescent field of the WGM. Although the magnitude of this external field is much smaller than the field circulating inside the quartz dielectric, the small mode volume means that nevertheless large values of g can be obtained. Quantitative estimates in [5] suggest that it may be possible to get $g/\gamma \sim 50$ near the surface of very small spheres of diameter ~ 20 μm, with $g/\kappa \sim 50$ if $Q = 2 \times 10^9$ could be maintained. In such a situation, it would take much less than one atom $(\sim 10^{-3})$ to have a significant effect on the cavity transmission and likewise only a fraction of a photon $(\sim 10^{-3})$ in the cavity mode would be enough to saturate the atomic response. For more modest values of these parameters, with $(g, \kappa, \gamma)/2\pi \sim (15, 10, 2.5)$ appropriate to initial experiments[15] with 100 μm diameter spheres of $Q \sim 10^7$, it should still be possible to observe a Rabi splitting for only a single quanta of excitation in the coupled atom-cavity system (the so-called vacuum-Rabi splitting) as illustrated in Fig. 3.

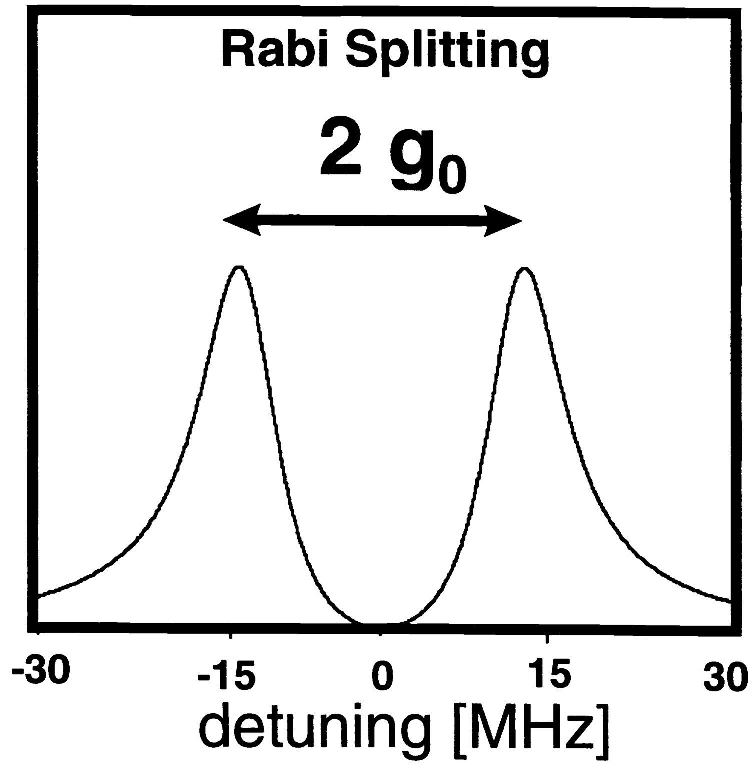

Figure 3. The transmission of a microsphere cavity in which a single quanta of excitation is shared between a two-level atom and a single mode of the cavity with $(g, \kappa, \gamma)/2\pi \sim (15, 10, 2.5)$ appropriate to a 100 μm diameter sphere with a $Q \sim 10^7$. A vacuum Rabi splitting is clearly resolved.

There are many technical issues having to do with these cavities which one has to face before reaching the physics associated with the true strong-coupling limit of atoms coupled to microspheres. These are best enumerated with reference to a picture of a very simple experimental apparatus we have erected appropriate to initial investigations (see Fig. 4). The WGM resonant frequency can be tuned by changing the boundary conditions for the field at the vacuum-dielectric interface. We found this can be done very efficiently by heating or cooling the silica,[12] inside the vacuum chamber, the primary effect of which is a change in the silica's temperature-dependent refractive index. In addition, this temperature can be servoed very easily, with a surprisingly good resulting stability for the ease in which it can be implemented. A second issue is the efficient out-coupling of light from the sphere, which will be very important in order to detect a small number of photons in the field. One technique which is useful for initial work is to use the slight ($\sim 3\%$) ellipticity of the sphere to couple to the so-called precessing modes,[16] for which one has access to an outcoupled port which is free of any in-coupled light. Such modes have the drawback that they cover a larger portion of the sphere's volume, resulting in a reduced confinement of the electric field.

A final, very important issue is the time scale for atomic localization within the mode with respect to the time scale for eigenmode excitation and evolution. Traditional work in cavity QED has used an atomic beam for extremely good transverse localization of atoms within the cavity mode volume. Unfortunately, the atoms transit the cavity in a time scale of about 100 ns, which inevitably means that one must average over many transits in order to see integrated effects, and also deal with inevitable fluctuations in intracavity atomic number. Recent work[9] has changed

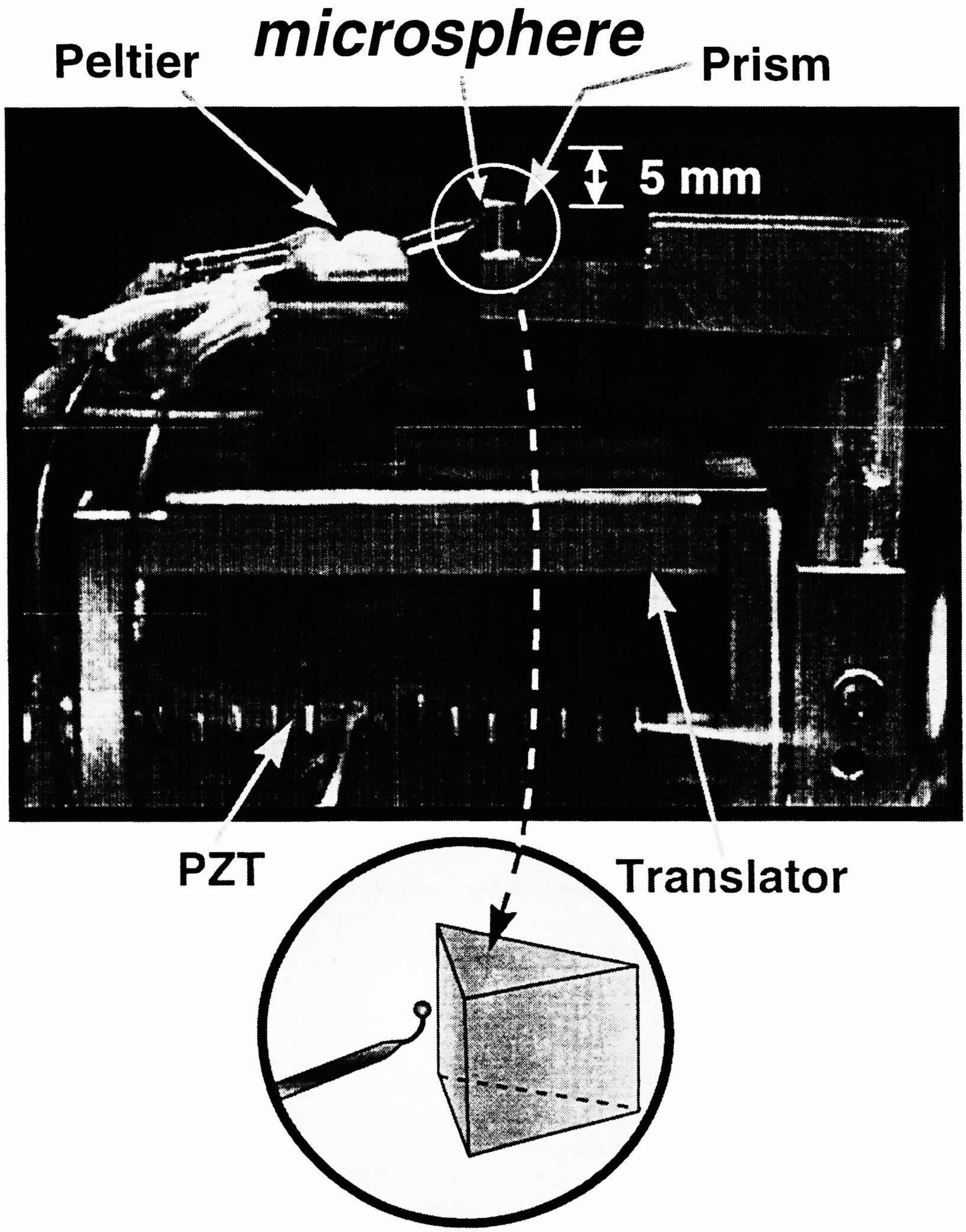

Figure 4. A simple apparatus for investigating the properties of microspheres. The sphere-prism distance is controlled with a micro-translater and the resonance frequency of the mode is tuned by changing the temperature of the silica, and hence its refractive index.

this situation drastically by marrying the technology of cold atoms in a magneto-optical trap (MOT) to very high finesse Fabry-Perot optical resonators. The atomic transit time scale is now about 100 μs, which is slow enough to distinguish individual atomic effects. One would hope initially to repeat such experiments with a microsphere, by localizing a cloud of cold atoms close to the surface of the sphere as shown in Fig. 5.

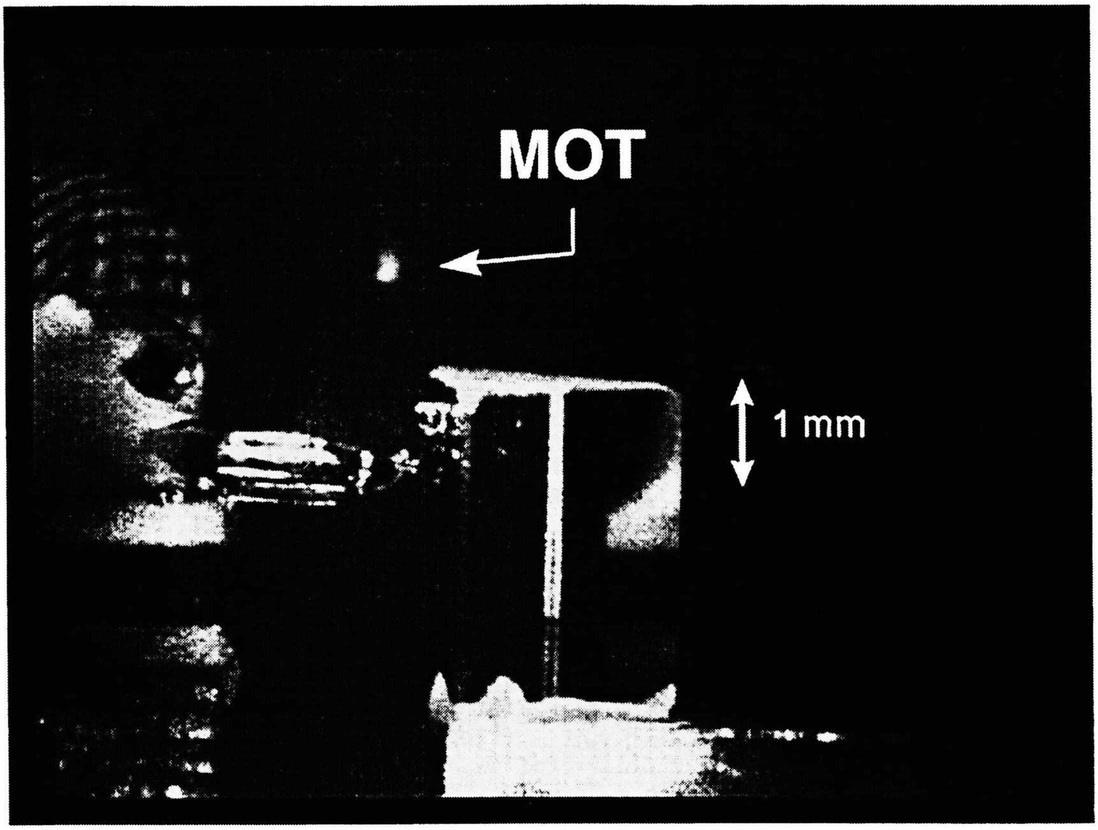

Figure 5. A first milestone would be the interaction of cold atoms from a MOT with a high Q microsphere. One would like to see, in real time, evidence for individual atoms interacting with the cavity field in the spirit of what has been achieved with Fabry-Perot micro-cavities.[9]

In conclusion, we have been able to obtain record high Q for three different wavelengths in the visible and NIR spectrum. This advance, along with technical achievements in mode tuning and coupling are the groundwork for future experiments in which single, cold atoms are coupled to the evanescent WGM field. Though some very important technical hurdles remain to be resolved, it is hopeful that in the future one can see evidence for the interaction of these cold atoms with the cavity field in a regime in which the strong coupling forces one to consider the dynamics of the "atom-cavity molecule".

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